Seafarers, Silk, and Science:

Oceanographic Data in the Making

Submitted by Gregor Halfmann, to the University of Exeter as a thesis for the degree of Doctor of Philosophy in Philosophy, July 2018.

I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

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Abstract

This thesis comprises an empirical case study of scientific data production in oceanography and a philosophical analysis of the relations between newly created scientific data and the natural world. Based on qualitative interviews with researchers, I reconstruct research practices that lead to the ongoing production of digital data related to long-term developments of plankton biodiversity in the oceans. My analysis is centred on four themes: materiality, scientific representing with data, methodological continuity, and the contribution of non-scientists to epistemic processes. These are critically assessed against the background of today's data-intensive sciences and increased automation and remoteness in oceanographic practices. Sciences of the world's oceans have by and large been disregarded in philosophical scholarship thus far. My thesis opens this field for philosophical analysis and reveals various conditions and constraints of data practices that are largely uncontrollable by ocean scientists. I argue that the creation of useful scientific data depends on the implementation and preservation of material, methodological, and social continuities. These allow scientists to repeatedly transform visually perceived characteristics of research samples into meaningful scientific data stored in a digital database. In my case study, data are not collected but result from active intervention and subsequent manipulation and processing of newly created material objects. My discussion of scientific representing with data suggests that scientists do not extract or read any intrinsic representational relation between data and a target, but make data gradually more computable and compatible with already existing representations of natural systems. My arguments shed light on the epistemological significance of materiality, on limiting factors of scientific agency, and on an inevitable balance between changing conditions of concrete research settings and long-term consistency of data practices.

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Chapter One – Introduction: What is “in-between” science and the world?

This thesis is about the genesis of digital scientific data. It tracks a variety of activities and research practices that underpin the creation of data and shape the scientific knowledge of natural systems. These activities and research practices are not performed in empty space. My thesis reconstructs the conditions and constraints of data practices that result from the material, methodological, technological, economic, and social constraints of studying a dynamic natural system as vast, unexplored, and inaccessible as the world’s oceans and the ecosystems therein. How scientists balance between these variously controllable constraints and manage to generate meaningful scientific data is the leading question of this thesis.

Oceans cover seventy percent of the Earth’s surface and are crucial components of its climate system. They are the habitat of innumerable living organisms, including our planet’s smallest and largest animals. Terrestrial life and societies are deeply affected by the oceans and depend on the biological, physical, and chemical conditions of the seas in various ways. For centuries, thinkers and scientists have made efforts to study oceanic processes, but the physical nature of the seas causes serious constraints for the abilities to observe and record, let alone understand, these processes.

Scientific communities and institutions are today’s main players in studying natural processes and their effects on societies. Observing, tracking, recording, communicating, and making sense of both natural and anthropogenic processes are among the main activities of these communities and institutions. Ocean sciences are, as many other sciences, a research field in which groups, research projects, or even entire institutions have specialised in one of these activities. For this thesis, I have studied the research practices of an oceanographic institution that has specialised since the middle of the twentieth century on continuously recording populations and biodiversity of oceanic plankton and communicates these records to ocean scientists, environmental monitoring agencies, and policy makers. Oceanic plankton comprise all plants and animals that passively drift with the ocean currents, produce around half of the earth's oxygen by photosynthesis, and underpin the marine food web.

Sciences that study the natural environment rely heavily on the ongoing production, the dissemination, and long-term storage of scientific data. I investigate how plankton populations and biodiversity can be recorded and how such records are prepared for dissemination so that they can be used by scientists to advance the understanding of oceanic processes. More specifically, the subject matter of this thesis is the space in which science and scientific technologies make physical contact with the natural environment and with the creatures that populate the oceans, including plankton organisms as well as seafarers, who play a crucial role in the production of plankton data in my case study.

My thesis explores the space "in-between" science and the world and provides arguments for the epistemological significance of processes, practices, and people that occupy this space. Many of these practices and people are involved in the creation of scientific data. The term "in-between" may suggest a clear separation between a world that contains the objects studied by researchers and the scientific practices and knowledge that describe and explain these objects. However, my thesis demonstrates that the practices and people in-between are integral parts of sciences, though they are often driven or affected by processes that are external to science and beyond the control of researchers.

Today's natural sciences, ranging from astronomy to physics, biology, and environmental sciences like oceanography, are embracing technologies which enable the production of highly standardised data products in unprecedented volumes. New technologies also make data readily available to global scientific communities using the world wide web, while the speed at which large volumes of data can be analysed has steadily increased. Using attributions like "data-centric" or "data-intensive", many scholars have focused on the "escalating", high-volume, and high-speed end of the spectrum of scientific practices and explain how these developments fundamentally transform scientific practices, including modes of scientific collaboration, differentiation of labour, and methods of scientific reasoning. While some scientific areas such as molecular biology or particle physics have drawn much attention from scholars, the great diversity of scientific data and associated practices are still sparsely mapped and accounted for by empirical and qualitative scholarship in philosophy of science. In this thesis, the large-scale transformations of science and societies due to new technologies form part of the context in which researchers create scientific data for the study of oceanic processes.

Although new technologies have reconfigured scientific practices on many levels and changed the status of data in science and societies, the transformations and implications of “data-centrism” unfold at the surface of epistemological problems that have been central to philosophy of science for a very long time and have not disappeared: How to observe, represent, and understand the natural world. My thesis addresses these underlying problems by focusing on the birth and development of digital scientific data. The broad reconfigurations of scientific practices have frequently made databases, data banks, and the associated practices of aggregating and re-distributing data the primary objects of investigation. With my thesis, I intend to shift the focus to specific, local practices that are required for digital data to come into existence in the first place.

Akin to Fleck (1935) elucidating the genesis and development of a scientific fact, my thesis is an attempt to unravel the birth and development of digital scientific data, originating in physical interactions between the seas and research technology, in opportunistic collaborations with seafarers, and in various “hands-on”, manual activities in the lab. Fleck argued in 1935 that scientific facts are not discovered but actively constructed as well as culturally and historically conditioned. My thesis builds on the crucial insight that the outcomes of research practices, including scientific data, despite the etymological meaning of the word “data” as something “given”, must be conceived as products shaped by the context of their creation. I argue that what scientists may perceive as resources today — interconnected digital data scattered across a multiplicity of databases — are products of creative practices which are not conceived by isolated creative minds, but the outcome of an assemblage of minds, materials, and technologies. These practices constitute certain kinds of continuities — material, methodological, and social — that occupy the space in-between science and the natural world and nurture researcher's databases and our knowledge of the environment.

The practices of making scientific data are driven by an underlying tension which my thesis brings to light and which has occupied philosophers in a variety of ways for thousands of years. This is a tension between change and continuity. Change, in a very general sense, is alteration of a thing in time (Mortensen 2015); continuity is the absence of gaps or jumps (Bell 2013). The creation of scientific data that are usable for scientific reasoning about long-term changes of dynamic natural systems requires continuity on a variety of levels: samples of organisms must be preserved, methods of sampling and manipulation must remain consistent, specific expertise must pass to new generations of researchers, resources and funding must be available for lengths of time that exceed the common life cycle of research projects. Long-term changes in the object of study require these continuities; but at the same time, research practices themselves are affected by changes that are beyond their control: decay or wear and tear of materials; technological and methodological innovations; progress and change of institutional landscapes, economies, and societies. How to avoid gaps and jumps in a constantly changing environment while studying a constantly changing part of the environment is a challenging balancing act that plays out in practices in-between sciences and the natural world. The various interactions that are part of the balancing act between change and continuity ultimately determine and potentially limit human agency in creating knowledge about the world.

Though I claim kinship with Fleck's (1935) equally philosophical and historical research on the genesis of scientific facts, I primarily pursue philosophical goals and employ ethnographic research methods, whose results I analyse in light of contemporary literature in the philosophy of science, in the tradition of "philosophy of science in practice", as I explain in chapter two. My thesis is grounded in a detailed case study of the Continuous Plankton Recorder Survey, a long-term programme for the creation of physical samples and data related to plankton distributions of the world’s oceans. The survey’s core business is the continuous production of research samples and scientific data; its practices are thus situated precisely in-between the natural world and the scientists that use the plankton-related data for scientific reasoning about biodiversity, marine ecology, or climate change. Since the middle of the twentieth century, the CPR Survey equips commercial ships with mechanical sampling devices that retain plankton organisms by filtering the seawater with bands of silk. The oceans are sampled and the silk samples analysed with unchanged methods since 1958. I focus my analysis on a philosophical account of oceanographic data practices in-between the oceans and scientific knowledge of the earth’s largest ecosystems.

The term “in-between” can be deceptive: it could be interpreted as facilitating a conceptual gap between science and the natural world as separate entities and suggest that sciences bridge a void and extract knowledge from the natural into the cultural sphere. This is not what I intend when using this notion. I use the term “in-between” not to separate science from nature, but to make room in philosophical accounts of science for the real-world conditions and continuities, for the practices and people, that structure and shape our knowledge of natural systems.

1.1 Data-centric, data-intensive, and data-driven research

The importance of data and data practices in the sciences today can hardly be overestimated. Scientists in almost any field work with data in a multitude of ways on a daily basis. Data figure as starting points for scientific enquiries, but also function as evidence for knowledge claims. Observations, recordings, and data have always been crucial for the production of knowledge, but the rise and rapid development of digital network technologies have transformed scientific practices and, above all, the activities and procedures that involve scientific data in unprecedented ways.

In the view of many, sciences have entered a new paradigm with the development and implementation of technologies that enable the production, manipulation, and analysis of large volumes of data at unprecedented speeds, the assimilation and integration of data from many different origins, and the worldwide dissemination as well as long-term storage of scientific data. New technologies have changed sciences in ways that allegedly emphasise epistemic practices related to scientific data and diminish the relevance of theories in knowledge production. These views have peaked in 2008 with a popularised proclamation of “the end of theory” in science,[1] and in 2009 with the idea of a fourth, ‘data-intensive’, scientific paradigm that was brought forward in a Microsoft Research publication (Hey, Tansley, and Tolle 2009b) and also in *Science* (Bell, Hey, and Szalay 2009). As summarised by Kitchin (2014a: 3), this version of a new data-intensive scientific paradigm is coined by statistical exploration and data-mining and follows a computational, ‘pre-Big Data’, paradigm, for which the simulation of complex phenomena was exemplary.[2] According to this paradigm, the role of theory in the creation of knowledge has gradually diminished, so that scientific knowledge creation has become ‘purely inductive’ and empirical,[3] based on the abilities of big data practices to capture phenomena of interest exhaustively and allow data to ‘speak for themselves’ with the application of unbiased analytical tools (Kitchin 2014a: 4).

Bell, Hey, and Szalay (2009) emphasise that the data-intensive paradigm’s unprecedented volumes of digital data are demanding and challenging for scientists in many different fields. Sciences must quickly acquire ‘necessary expertise in database, workflow management, visualization, and cloud

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[1] Anderson (2008) in *Wired* magazine, quoted in Kitchin (2014a: 3).

[2] For the sake of completeness, the first paradigm of these paradigms originated thousands of years ago and was experimental science characterised by empiricism and the description of natural phenomena. The second paradigm, theoretical science characterised by modelling and generalisation, originated a few hundred years ago and ended with the rise of computer technology (Kitchin 2014a: 3; Hey, Tansley, and Tolle 2009a: xviii).

[3] Though induction is a contested philosophical problem, inductive and empirical knowledge can be understood here as knowledge derived only on the basis of past experiences, observations, or records.

computing technologies' (Bell, Hey, and Szalay 2009: 1298). However, as criticism against the purely inductive paradigm suggests, these challenges are not just technical and emerging debates on data-intensive sciences and societies should not bypass philosophical scholarship. Many scholars contest or vehemently oppose the idea of "theory-free", data-intensive or big data science (i.e. Callebaut 2012). According to Leonelli (2012), an 'intuition' that induction from existing data is the new primary form of scientific inference is a key feature of current "data-driven" research methods in biology and biomedical science. Yet, given the variety of ways in which researchers use data for scientific reasoning, the specific meaning of "induction" is all but clear and examples from biological sciences suggest that inductive reasoning does not mean "free of hypothesis" (Leonelli 2012: 2). The conception of theory-free science is based on 'fallacious thinking', Kitchin (2014a: 4–5) argues, pointing out that even data in unprecedented, large volumes remain samples and representations that are shaped by specific technologies, data ontologies, research environments, and the conditions under which they were created. All systems and algorithms as well as any kind of analytics and interpretation of data are based on scientific reasoning and theoretical thinking (Kitchin 2014a: 4–5). As a consequence, the various ways in which knowledge is created, recorded, and communicated — the wide range of scientific "memory practices" (Bowker 2005) — inevitably affect what we know.

As Strasser (2012b: 86) points out, one important novelty of contemporary data-driven science is the 'omnipresence of statistical methods' in the analysis of scientific data. Quantification has been a pronounced feature of natural sciences for centuries, but the rise of statistical methods, which are often viewed as highly objective and free of theory, is a relatively recent development that contrasts with earlier scientists' often exercised subjective judgements in data analysis (Strasser 2012b: 87). From a philosophical perspective, a scientist's choice of statistical algorithms does not appear less theoretical than the machines and systems that were used to create data.

New data technologies may not have driven theories out of scientific practice. Nevertheless, developments in digital technology, data analytics, and so-called “big data” have already transformed science — not in an all-encompassing, paradigmatic way but in a variety of ways that philosophical, sociological, historical, and anthropological scholarship attempt to understand. Rheinberger (2011: 346) sees the role of data shifting as part of a ‘new primacy of data’ in today’s science. As researchers increasingly consult online databases as starting points for scientific enquiries, data have become a resource rather than a result. Epistemologically, this means that data are no longer created and analysed to account for certain phenomena, but ‘generated and pooled as data ponds and streams’ in order to reveal patterns that are still ‘beyond horizon’ at the time of data creation (Rheinberger 2011: 346). This shift goes along with data production ‘on an industrial scale’ that requires appropriate software and computing skills to handle (Rheinberger 2011: 346).

Leonelli (2016: 171) suggests that the popularity of a term like “data-driven” stems from the fact that consulting available data resources has emerged as an ‘obligatory first step for any research project’. This first step of research hardly leads to direct inductive reasoning; its value is rather heuristic and its outcomes certainly shape the directions of the research project (Leonelli 2016: 171–72). In this sense, data literally take a position of “primacy” in research endeavours.

Data and databases have become the standard starting points of scientific enquiries, but as Bowker (2000: 643) points out, databases are increasingly seen as ‘an end in itself’. Bowker sees a disarticulation between scientific knowledge that is published in scientific literature and the data or evidence that support it. Scientific writings published as papers or books used to be the only “end product” of research, but they are now complemented by databases and archives dedicated to the long-term storage of data. Leonelli (2014a: 2) sees ‘the prominence and status acquired by data as scientific commodity and recognised output both within and beyond the sciences’ as one key novelty of big data science. Consequently, databases and archives as increasingly relevant destinations for scientific outputs create demands from researchers that were hitherto less pronounced or even absent: Data must be made reusable, so that they can be accessed and manipulated by other scientists (Bowker 2000: 644).

Making data reusable is a major challenge of data-intensive science, as various scholars have documented (Leonelli 2013, Borgman 2012, Edwards et al. 2011, Zimmerman 2008). It is a task that is challenging for scientists, but one that is increasingly dealt with by experts such as database managers or data curators. The new primacy of data has led to the development of new skills, methods, and infrastructures, which have fostered the emergence of new professions related to these new infrastructures (Leonelli 2014a). Challenges related to aggregating, storing, and making data reusable are addressed through the lens of data curation or stewardship in new, stand-alone scientific journals (Baker and Yarmey 2009). This differentiation of tasks is effectively a division of labour that results in new forms of collaboration and an 'essentially distributed nature of scientific understanding as a collective cognitive achievement' (Leonelli 2014b: 412–13). This means that more than ever before, scientists from around the world are able to work collectively towards a common goal, perhaps without ever seeing each other in person or even knowing each other. People who speak different languages and have different educational backgrounds, who work for different institutions or organisations under different conditions, have to find a common ground to be able to cooperate. In many sciences, including oceanography and other environmental sciences, these new forms of collaboration are required for further advancing the studies of natural systems.

Collective cognitive achievements require the movement of information, data, and knowledge across the globe. Sharing research data and re-using data of other researchers are challenging practices in many ways. As Leonelli (2016: 169) puts it, 'data do not easily flow along the channels devised for their dissemination and reuse'. For data-centric biology, the efforts of researchers to make data re-usable in many different contexts have profound epistemological implications, so that this form of data-centric science is more focused 'on the *processes* through which research is carried out than on its ultimate outcomes' (Leonelli 2016: 170).[4] This means that sciences more than ever reflect and pay attention to the ways they produce knowledge — how scientists know about the natural world has gained considerable relevance in comparison to what scientists actually know. This shift of focus encompasses what counts as

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[4] Emphasis in original.

scientific data, what is considered as relevant background knowledge and skills that researchers have “embodied”, and what counts as necessary theoretical and conceptual commitment (Leonelli 2016: 170). One form in which this new self-reflection of sciences has become manifest, is the integration of data, methods, and explanations, which has become ‘both a practical and normative requirement’ in today’s data-intensive, large-scale sciences, (O’Malley and Soyer 2012: 58). Data integration aims at making a huge variety of data from potentially inconsistent sources comparable and usable in novel combinations. The integration of data may encompass an array of activities and procedures:

> theorizing and modelling databases, quantifying data accurately, developing standardization procedures, cleaning data, and providing efficient and user-friendly interfaces to enable data not only to be reused, but reanalysed and combined in novel ways. (O’Malley and Soyer 2012: 61)

These challenging activities have become ubiquitous in today’s data-intensive sciences and have been the subject of philosophical, sociological, and historical scholarship in fields ranging from astronomy (Hoeppe 2014), to climatology (Edwards 2010), and biology (Leonelli 2013). Yet, this list pertinent to data integration provides only partial insight into the variety of activities that are performed in data-intensive sciences today.

The fact that sciences undergo fundamental, if not disruptive, changes with the new primacy of data is widely recognised by scholars. However, some authors employing historiographic approaches to scientific practices have pointed out that not every development that has been proclaimed as revolutionary is actually entirely new. In particular, scholars have criticised the emphasis on unprecedented, overwhelming data quantities, which is often underlined with metaphorical expressions such as “data deluge” or “data flood” (Leonelli 2012: 3).[5] For example, Müller-Wille and Charmantier (2012) argue that natural history practices of the 17th and 18th century can be regarded as data-driven. The

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[5] The title of Bell, Hey, and Szalay’s (2009) article in *Science* is ‘Beyond the data deluge’. The Royal Society’s (2012) report *Science as an open enterprise* uses the term “data deluge” five times.

innovative taxonomic systems and rules of nomenclature were developed in response to an 'information overload' that resulted from the rapid discovery of new plant and animal species worldwide (Müller-Wille and Charmantier 2012: 4). In this sense, today's epistemological novelties like new forms of collaboration or scientific reasoning are not the first changes to scientific practices that are fuelled by increasing magnitudes of information. Referring to the 'imperial drive to archive information' as a means of exercising control, Bowker (2000: 644) points out that the production of a 'working archive of knowledge' is not entirely new, only its expansion in scale and scope, which today ranges from submicroscopic genes to planetary, atmospheric phenomena and requires technological and methodological innovation to manage. A good example of this is documented in Aronova, Baker, and Oreskes (2010), who reflect on the innovations driven by international "big science" and "big data" programmes in the decades following World War II. Programmes like the International Geophysical Year 1957–58, a collaboration to generate diverse geophysical data on a global scale, led to new ways of organising, storing, and disseminating large quantities of data.

Strasser (2012a: 336) claims that today's digital databases are very similar to the collections of early natural history, as both are 'organized assemblages of standardized objects'. These assemblages allow comparative analysis due to the proximity, mobility, temporary order, and the uniform format of objects inside them. Most striking to Strasser (2012a: 336) in his comparison between early natural history and today's life sciences is that historical collections and digital databases 'have been constituted through similar collecting practices and have been put to use in similar ways for the production of knowledge'. Strasser (2012a: 337–38) concludes that 'collecting and comparing' is a persistent research practice that is central to today's data-driven sciences, but not in a revolutionary or paradigmatic way. Rather, collecting and comparing are key practices in sciences that are concerned with the history of the objects that are studied: for example, natural history, geology, cosmology, and today's life sciences and ecology. Bowker (2000: 644) puts a similar emphasis on collecting in his study of biodiversity research: 'In the relatively new science of biodiversity, this data collection drive assumes its apogee.' Strasser (2012a: 338) argues that the historicity of objects in these sciences contrasts with sciences like physics, chemistry, or mathematics, in which ‘all the entities of one kind … are believed to be structurally identical’ and collecting of data, information, or objects is therefore less pronounced.[6]

Strasser’s conclusions illustrate how the study of data practices may motivate scholars to re-think traditional boundaries of scientific disciplines and emphasise different kinds of historical continuities between research practices. New ways of classifying or demarcating scientific fields are sometimes augmented by labelling practices as “data-driven” or “big data” science. However, several scholars argue that these broad-brush categorisations of practices are insufficient to grasp the dynamics of today’s research practices. O’Malley and Soyer (2012), for example, criticise that the common distinction in “data-driven” and “hypothesis-driven” approaches in the life sciences is too general and insufficient for any fine-grained account of scientific practice.[7] Yet, scholars have accepted this distinction as idealisation and often point out that actual scientific practices consist in hybrid forms in which data-driven, hypothesis-driven, and potentially more approaches complement one another (O’Malley and Soyer 2012: 59). Strasser (2012b: 87), for example, sees today’s life sciences as a combination of data-driven and hypothesis-driven, comparative and exemplary, as well as experimental and natural historical approaches.

The label “big data” seems to be equally problematic, given that various authors emphasise that large quantities are neither the most fundamental nor the most impressive characteristic of data-intensive research and, in some cases, not

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[6] The ‘colossal amounts of data’ that are produced by experiments with the Large Hadron Collider at CERN near Geneva, Switzerland, are a counterexample from contemporary physics; <https://home.cern/about/computing> [accessed 7 June 2018].

[7] O’Malley and Soyer (2012: 58–59) characterise “data-driven” as an approach that is primarily guided by the generation, collection, and analysis of data and leads to the formulation of new hypothesis. Conversely, “hypothesis-driven” research begins with an existing hypothesis that is being tested and subsequently accepted, rejected or modified.

even a novelty (Leonelli 2012: 3). Davies, Frow, and Leonelli (2013: 393) question the rhetoric of large-scale biological research and find that the term “big biology” which may be used to describe practices that involve big data is ‘explicitly divisive’. It automatically makes other practices appear small or ordinary. The attribute “big” may convey a primarily quantitative shift in research practices and obscure the many innovations and epistemological transformations in data-intensive sciences.

In this section, I have avoided sharp differentiations between the terms “data-intensive”, “data-centric”, “data-driven”, “data primacy”, and even “big data”. The transformations of science that I outlined in relation to these terms are not the primary object of my research, but rather the context in which my case study is situated. Scientific data are central in research processes through which we understand the natural world: Data function as a resource and starting point of investigation, diverse data from different sources are integrated, data are a distinct and recognised research output. The centrality of data has driven transformations of scientific practices: the division of labour and differentiation of new professions, new ways of collaboration and collective reasoning, new software and statistical methods that require new skills.

1.2 Conceptions of scientific data

With the term “data” in this thesis, I refer to scientific data. This thesis is about data that are used by scientists and figure in epistemic processes. This excludes “sense-data” and the like which are, if anything, something like ‘mind-dependent objects’ of which humans are directly aware upon perception of an entity or event (Huemer 2011). Although the minds of scientists are used extensively in scientific processes, I do not regard images, thoughts, and other cognitive processes that only happen inside the human brain as scientific data. My focus on scientific data also excludes data in predominantly commercial or governmental contexts. Globally operating IT companies as well as government agencies obtain, store, and analyse huge amounts of data. These companies and agencies might employ scientists and might carry out analyses that are similar to those practised by natural scientists at universities. However, there are great differences to publicly funded research carried out at universities or research institutes, starting with the overall incentives of generating economic profits, fighting crime or terrorism, or exercising control, which rarely align with the aims of advancing scientific knowledge of the environment or societies.[8] I thus do not contend that this thesis' findings about data practices apply in the exact same way to data in the commercial or political sector. I must also clarify that my empirical cases and the majority of scholarly literature I refer to are concerned with environmental data or data used in "classic" natural sciences such as biology or physics. Although similarities with other scientific fields such as social sciences, economics, or medical research are likely, data practices in these fields are beyond the scope of this thesis.

Thinking about the role and status of data in science requires some kind of conception of what data actually are. Although in most sciences today the majority of data are digital and technically stored as sequences of numbers and letters, scientific data still come in a variety of forms and formats. The diversity of data practices not only encompasses the activities related to data, but also the data themselves. Bowker (2000: 643) uses the term "datadiversity" for the heterogeneity of resources that are used in biodiversity research, which Bowker characterises as a data-intensive science.

As scientific data moved into the focus of philosophers of science, scholars faced the difficult task of defining scientific data or data in general. Data are not the same kind of thing across all sciences and not even within one scientific field. To give an example of data diversity, Parsons et al. (2011) reflect on challenges of managing diverse data created during the International Polar Year (IPY) 2007–08, a multi-disciplinary research programme with participants from sixty nations:

> In IPY, scientists collected every possible form and format of data:
> images wide, narrow and panoramic, profiles upward and downward,
> hourly to millennial time series, isotope ratios and fractions, energy
> and material fluxes, species identification and distributions,

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[8] However, publicly funded research may have economic goals as well, which may be secondary or implicit.

> interviews in common and rare languages, disease types and rates, genealogies and genetic sequences, samples and artefacts, singular events and gradual processes, and so on. (Parsons et al. 2011: 556)

Even those data that can be associated with natural sciences seem to come in a variety of different types, even if all of these data are digital: images, profiles, time series, ratios and fractions, fluxes, distributions, sequences, samples.

To Kitchin (2014b: 4), who begins his book on “The Data Revolution” with a discussion of how to conceptualise data, ‘it is clear that data are diverse in their characteristics’. He offers several characteristics by which data broadly vary:

> data vary by form (qualitative or quantitative), structure (structured, semi-structured or unstructured), source (captured, derived, exhaust, transient), producer (primary, secondary, tertiary), and type (indexical, attribute, metadata). (Kitchin 2014b: 4)

Given the diversity of data, it seems hardly possible to pin down an adequate definition of data by compiling either a list of types or an exhaustive set of characteristics.

Leonelli’s (2015) response to the problem of defining data is a framework that wants to give up on definitions that are based on intrinsic properties such as structure, form, source, or level of manipulation. According to the “relational framework” introduced by Leonelli, what counts as scientific data depends on relations to the context and research situation in which data are used. Any output of research activity can become data if the output has potential usefulness as evidence in a given research situation and if it serves as a means of communication (Leonelli 2015: 810–11). These, too, are conditions for what counts as data, but they are not intrinsic, permanent characteristics of objects. The usefulness of data as evidence can change depending on contextual factors. Among these factors are the applicability of adequate tools and technologies, the intelligibility of data given the background knowledge and skills of a researcher, the availability of information about the provenance of the data, or the physical coherence and constitution of data. ‘The same objects may or may not be functioning as data, depending on which role they are made to play in scientific inquiry', Leonelli (2015: 817) clarifies.

Leonelli contrasts her context-dependent, relational framework to context-independent data definitions, such as the following given by the Royal Society (2012: 12): Data are 'numbers, characters or images that designate an attribute of a phenomenon'. Kitchin (2014b: 3), too, maintains that 'data are inherently partial, selective and representative', whereas Leonelli (2015: 811) argues that 'data do not have truth-value in and of themselves, nor can they be seen as straightforward representations of given phenomena'. Data are not data by themselves or due to an intrinsic power; specific actions and decisions are necessary for objects to become data. As Borgman (2012: 1061) also maintains, 'data may exist only in the eye of the beholder: The recognition that an observation, artifact, or record constitutes data is itself a scholarly act'.

The recognition of context as the key to defining data does not mean that philosophers have no general points to make about scientific data. The following two sections discuss conceptions of data that have emphasised some of their fundamental characteristics. These do not define data, but need to be taken into account in philosophical perspectives on data-centric sciences.

1.2.1 Data as physical artefacts

Several scholars have emphasised that scientific data are objects with physical extensions and weight. Even as digitally stored numbers, data leave a physical footprint or trace; data consume resources and never float freely or unhindered. Edwards (2010) follows the history of climatological and meteorological data, which in their form and physical constitution evolved from paper and ink, to punch cards, microfilm, magnetic tape, and finally to hard disk drives and semiconductor electronic devices. 'Computing remains a material process', Edwards (2010: 83) points out; therefore, scientific data, even if they are considered "born digital" (Bell, Hey, and Szalay 2009: 1297) and can be stored in digital clouds, far away from potential users, are never purely virtual.

In chapter three, I elaborate on the notion of materiality from an epistemological point of view: How to understand materiality and its significance for the creation of scientific knowledge. Frequently, scholars have interpreted materiality rather ontologically, with a focus on the characteristics of the elements and fabric that an object is actually made of. According to Edwards (2010: 84) data are “things” with ‘dimensionality, weight, and texture’. Strasser (2012a: 336) also remarks that the difference between data and things is ‘more a matter of degree than a matter of kind’.

Leonelli (2015) shifts the focus from physical characteristics of data to the epistemological significance of their physicality:

> [Data] are, first and foremost, material artifacts; and their physical characteristics, including their format and the medium through which they are conveyed, are as relevant to understanding their epistemic role as their social and conceptual functions. (Leonelli 2015: 811)

Scientific data have physical characteristics which scholars can attempt to trace in knowledge making practices: dimension, weight, texture, but also the format and medium, through which data are accessed. All of these physical variables can change in the course of data-related activities, for example when data in paper format are digitised, when digital data are transferred to a different storage location, but also when materials that store data decay or decompose as it might happen with researchers’ old notebooks if they are not properly stored. This is one instance at which the tension between change and continuity that is the underlying theme of this thesis is brought to bear: If data change their physical characteristics, for whatever reason, how do scientists achieve the continuity that is necessary for scientific reasoning? Due to the importance of medium, format, dimension, weight, and texture of data, I keep track of physical characteristics and their implications for the creation of knowledge throughout my thesis.

As Leonelli (2015: 811) emphasises in the above quote, data are material and they are artefacts. The latter implies that they do not occur naturally, but are created by humans artificially for specific purposes. This fundamental characteristic seems to somewhat clash with the aforementioned views of data as a resource and as things that are collected. As Edwards (2010: 109–10) clarifies, scientific data are not “out there” and waiting to be collected, picked up, or otherwise obtained by scientists from a given repository. Even if a researcher is required to go into nature to record a process of interest, such as changes of sea temperatures or sea level, the data thereby obtained are created by the researcher and usually involve the application of an instrument.

As Rheinberger (2011: 337) notes, the perception of data as being made by humans seems to have turned the etymological meaning of data — from the Latin “data”, the nominative plural of “datum”, meaning “what is given” — into the opposite. Kitchin (2014b: 2) points out that, more precisely, data should have been termed “capta”, meaning “what is taken”. However, even this change would not reflect that data are artefacts, only that they are not given to researchers from nature. If data were only taken, it would suggest the existence of a repository of potential data from which a distinct number of measurements are selected and extracted, which is not the same as creating data by means of observation and recording or intervention into natural systems with a scientific instrument. My thesis provides strong arguments that support an understanding of scientific data as artefacts in a sense that is not compatible with the view of data as collectible items.

The view of data as artificial objects does not require human agency from which data directly result. In the environmental sciences, a wide range of parameters related to natural processes are recorded by highly automated systems. These “machine-born” data count as artificial because the instruments and systems used for their production are conceived, designed, constructed, programmed, and maintained by humans. Hacking (1992: 48), whose work gave considerable weight to the notion of “intervention” in research practices, defines data as uninterpreted ‘marks’ produced by ‘data generators’, which can be both human and non-human.[9] For Hacking, too, data result from ‘making and taking’

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[9] ‘People or teams who count may be data generators. In more sophisticated experiments, there are micrographs, automatic printouts, and the like. There is no need to insist on a sharp distinction in all cases between detector and data-generating device. In the early days a camera taking micrographs from an electron

measurements (Hacking 1992: 48) — not from taking something that is given, but from taking something that has been made.

Yet, the notion of data artificiality leads to even more fundamental and long-standing debates in philosophy of science, as I outline in the following paragraphs. Accepting a view of data as an artificial output of research activity means that a wide range of theoretical assumptions and commitments have contributed to the creation of data. These are necessary to decide what kinds of data to create, where and how often a measurement is taken, which instruments to deploy, and how the data are stored. What philosophers of science have termed the "theory-ladenness" of data contradicts a widely held view of data as unambiguous, "pure" or "raw" manifestations of natural phenomena. The notion of theory-ladenness stems from scepticism against the possibility of objective observation of phenomena.[10] 'The thesis of theory-ladenness of observations, roughly, is the idea that observations are affected by theoretical presuppositions' (Schindler 2013: 89). According to this scepticism, the resulting bias in observing and perceiving the world and its phenomena is an unavoidable aspect of human-nature interaction (Bogen 2013). In case of scientific data that are created by humans, scientific theories, expertise in the subject matter, and assumptions about the functioning of instruments are inevitably involved in producing and analysing data (Leonelli 2015: 814). If data are theory-laden, epistemological problems that bear on the usefulness of scientific data will require consideration. What if data are produced under assumptions, which the very same data are supposed to verify? The notion that data shall serve as evidence for theories, which have affected the production or analysis of the same data, jeopardises data's often proclaimed role as a neutral arbiter.[11]

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microscope was a data generator that photographed a visible image for study, analysis, or the record. Today the camera is more often the detector; the data generator may be a scanner working from the micrograph' (Hacking 1992: 48).

[10] Pierre Duhem, Norwood Hanson, and Thomas Kuhn were among the sceptics of objective observation in science.

[11] Schindler (2013: 89–90) mentions this epistemological problem among others with respect to the theory-ladenness of observation, not data.

An important contribution to this debate is the sharp distinction between data and phenomena introduced by Bogen and Woodward (1988). The distinction is intended to sidestep the problem of theory-ladenness and show that theory-ladenness is actually not very relevant for understanding scientific practices. Scientists 'straightforwardly' observe data and not the phenomena of interest, which are in most cases unobservable, Bogen and Woodward (1988: 305) argue. At the same time, they claim that scientific theories serve as explanations for phenomena and not for the data that are observed.[12] Thus, there would be no direct conflict between the theories and assumptions affecting the data and the theories that explain phenomena. In case of theory-ladenness being applied to data, scientists make great efforts to employ statistical methods and certain experimental practices to establish confidence and reliability in data. These efforts can be seen as reasonably distinct from the theories about phenomena, so that theory-ladenness of data is supposedly less problematic (Schindler 2013: 90).[13] A variety of efforts that enhance confidence and reliability in scientific data are studied and discussed in this thesis. They play a crucial role in the balancing act between changing conditions and continuities of materials and research methods.

By separating unobserved phenomena from observable data, Bogen and Woodward rely on a fundamental evidential relationship between data and phenomena:

> Data […] play the role of evidence for claims about phenomena. As a rough approximation, data are what registers on a measurement or recording device in a form which is accessible to the human perceptual system, and to public inspection. […] Data are typically not viewed as potential objects of explanation by or derivation from general theory; indeed, they typically are of no theoretical interest

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[12] Woodward (1989: 393) defines phenomena as 'relatively stable and general features of the world which are potential objects of explanation and prediction by general theory'.

[13] Schindler (2013) does not advocate this view, but aptly summarises the different approaches by philosophers, historians, and sociologists of science to deflate theory-ladenness.

> except insofar as they constitute evidence for the existence of phenomena. (Woodward 1989: 393–94)[14]

According to this definition, data are observable, they are not explained by scientific theories, and they constitute evidence for the existence of phenomena. The intrinsic evidential relationship between data and phenomena is questionable in light of data being produced without a distinctly targeted phenomenon or hypothesis. Rheinberger (2011: 346) argues that with today's primacy of data in science, large volumes of data are generated without aiming at specific 'epistemic phenomena', but rather in hope of discovering patterns that are yet unknown. Leonelli (2015: 818) also notes that data may be produced without one specifically targeted or designated phenomenon. Moreover, data today are intended to be usable to answer questions in relation to a variety of different phenomena. More than ever before, data are created without knowing all the different ways and contexts in which they are going to be employed (Leonelli 2015). For experimental practices that are not tied to the testing of a specific hypothesis, the term "exploratory experimentation" has been established in the 1990s by Steinle (1997) and Burian (1997). The exploratory way of experimentation includes 'theoretically undirected data gathering' and has been contrasted with more traditional, "theory-driven" experimentation (O'Malley 2007: 354).[15]

Finally, the characteristic of data as something made rather than given has implications for the objects, which scientists and philosophers of science sometimes call "raw" data. Hacking (1992: 48) notes that what he defines as

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[14] The following is a more recent definition of data by Woodward (2010: 792–93): 'Data are the individual outcomes of a measurement or detection process, which may involve instruments or unaided human perception. By extension, records or reports of such outcomes may also be regarded as data. […] Usually data is produced in order to serve as evidence for something else—for features of phenomena.'

[15] Note that theory-driven is not the same as theory-laden. Exploratory experimentation or other research practices not aimed at testing hypothesis or recording already known aspects of the world are still laden with theoretical baggage.

data — marks produced by generators — are sometimes called “raw data” because they are uninterpreted. However, the notion has also been used in reference to data which scientists regard as untouched, unmanipulated, unprocessed, or unmediated. These views tend to entail a notion of data purity that contradicts with theory-ladenness and neglects the mediating role of instruments. After all, if data are artefacts, how could they ever come in a state that is pure or untouched? Some scholars have consequently referred to the notion of “raw data” as an oxymoron (Gitelman 2013) and advocate for dismissing the term entirely (Ribes and Jackson 2013, Harris 2003). Yet, scientists speak of raw data and usually have an understanding of what the term “raw” means in their respective context. From a researcher’s point of view, data serve as a starting point that precedes their own act of interpretation. Leonelli (2015: 812), who does not endorse the category “raw data” at all, understands rawness as an expression to describe those objects that are as close as possible to ‘documenting aspects of a phenomenon of interest in a way that can inform further inquiry, without necessarily attempting to reproduce or represent the phenomenon itself’. Yet, from an epistemological point of view, data are never entirely “raw” but always already “cooked” (Gitelman and Jackson 2013: 2). Resonating with the idea that any object, in a given context, can function as data upon recognition and utilisation as such by a researcher, Gitelman and Jackson (2013: 3) state that ‘data need to be imagined *as* data to exist and function as such, and the imagination of data entails an interpretive base’.[16]

The physicality and artificiality of data, theory-ladenness, the relation between data and natural phenomena, and the status of data as “raw” or “cooked” are aspects that are largely influenced by the practices that contribute to the birth of scientific data. This thesis’ detailed empirical account of scientific data in the making has the potential to add a valuable perspective and depth to these debates.

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[16] Emphasis in original.

1.2.2 Mobility and data journeys

Scientific data of to the environment are typically produced “in the field”, as opposed to “in the lab”. This means that data must be portable in order to be analysed with devices or instruments that are located at research institutions or laboratories. Another reason for portability being required is that a researcher’s output needs assessment, review, and confirmation by peers from the scientific community, who may live and work in different places all over the world (Leonelli 2015: 818–19). It might sound trivial that data can be moved from one site to another, but several different types of data movements, each involving specific restrictions or challenges, are conceivable: from the site of data creation to a database, from one database to another database or into a data archive, or from a database to a scientist’s office computer. Scientific data today may be exchanged and moved between many different actors or sites, each of which constitute a different context with different interests, expertise, and technological or economic constraints; and at each site, data may be the subject of manipulation, transformation, or other kinds of interventions. How these changes of location work, which factors are relevant for their success, and whether these changes have an impact on the produced knowledge is not clear given the diversity of research settings and disciplines. The mobility of data — and of other objects in science — has thus become an important topic in studies of data-centric science, if not a defining feature thereof, as Leonelli (2016: 39) argues.

Several philosophers, sociologists, and historians of science have focused on the movement and circulation of objects in science. Latour (1986) influenced many of these efforts with his study of scientific practice and the mobilisation of what he called “inscriptions”. Scientists transform the phenomena they study into inscriptions, traditionally by using pen and paper and today by employing various technical devices. According to Latour, the central problem of inscriptions is concerned with their mobilisation, which is necessary to present what a scientist has created or observed in one place to an audience of fellow scientists or the public, who are usually scattered across various other places. For this purpose, inscriptions must be preserved in order to withstand their displacement. ‘In sum, you have to invent objects which have the properties of being *mobile* but also *immutable*, *presentable*, *readable* and *combinable* with one another’ (Latour 1986: 7).[17] These objects are what Latour calls “immutable mobiles”. Among their advantages are that they are usually made “flat” like a map, a list, or an index; they are scalable without changing their internal proportions; they can be reproduced at little cost; they can be superimposed; and they can easily merge with written text, as well as with geometry (Latour 1986: 20–22). Rheinberger (2011: 344) claims that ‘data are of the form of Latourian “immutable mobiles”’, or ‘traces’ of an experiment ‘made durable’. Immutability and durability enable data to be stored and retrieved and are a ‘prerequisite for their mobility’ (Rheinberger 2011: 344).

The immutability of mobiles is a central characteristic in Latour’s framework and is motivated by the preservation of inscriptions during their displacement:

> [Inscriptions] are immutable when they move, or at least everything is done to obtain this result: specimens are chloroformed, microbian colonies are stuck into gelatine, even exploding stars are kept on graph papers in each phase of their explosion. (Latour 1986: 21)

Notably, despite the fact that every effort is taken to make inscriptions immutable, this result is not achieved in all cases. As Leonelli (2015: 819) points out, when data are moved from one place to another, they often change their medium, which in turn may affect their usability in epistemic processes. Leonelli (2015: 816) disagrees with Latour’s and Rheinberger’ emphasis on immutability of data and argues that in the case of biological data being moved from their site of creation into databases and from there to new contexts of enquiry, data are ‘anything but stable objects’. Manipulations, changes of format, medium, and shape of data commonly occur at various stages while data are travelling from one place to another (Leonelli 2015: 816).

Leonelli (2016: 39) proposes the ‘data journey’ as a notion that captures the problematic, demanding, and often unpredictable pathways of data. In today’s data-centric sciences, any set of data has unlimited potential destinations within

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[17] Emphasis in original.

and beyond the scientific field in which it was created. The data journey has a strong metaphorical dimension, beginning with the idea that travelling often requires long-term planning, financial resources, and reliable infrastructures, vehicles, and energy supplies; furthermore, 'travelers may encounter obstacles, delays, dead ends, and unexpected shortcuts, which in turn shift the timescales, directions, and destinations of travel' (Leonelli 2016: 39). Neither humans nor scientific data travel in empty space. Rather, journeys frequently need to adapt to the environment, to changes of terrain, climate, or other conditions. As a result, 'journeys can be interrupted, disrupted, and modified as they unfold' (Leonelli 2016: 39). Although data are often generated in order to record or learn about reasonably defined processes or systems, the whole spectrum of pathways along which data may eventually travel is not yet determined at the moment data are created.

Another framework that emphasises the variety of contexts through which objects in science may travel is provided by Star and Griesemer's (1989) case study of research practices at the Museum of Vertebrate Zoology (MVZ) in Berkeley, CA, in the early twentieth century. Star and Griesemer (1989: 388–89) point out that scientific work is 'heterogeneous' and involves 'extremely diverse groups of actors — researchers from different disciplines, amateurs and professionals, humans and animals, functionaries and visionaries', which all inhabit different 'social worlds' (Star and Griesemer 1989: 388–89). In order to explain the functionality of such heterogeneous research settings, Star and Griesemer (1989: 393) introduce 'boundary objects' as an analytic concept. Boundary objects are 'a means of translation' between different local contexts for which they require a certain degree of plasticity to adapt as well as a certain degree of robustness to 'maintain a common identity across sites' (Star and Griesemer 1989: 393). The meaning of boundary objects may change according to context, but their structure is 'common enough' to make them recognisable (Star and Griesemer 1989: 393). The balance between plasticity and integrity that Star and Griesemer (1989) describe enables boundary objects to be portable; this view resonates with the tension between change and continuity introduced earlier in this chapter.

The notion of continuity, which allows change and adaptation without jumps or interruptions, matches with the plasticity and integrity of boundary objects more than with the immutability of mobiles or the unsteadiness of journeys. However, my thesis is not primarily concerned with the smoothness or disruption of data movements between different sites. Rather, I focus on continuities that underpin scientific practices and enable the creation of data capable of travelling and being used for scientific reasoning in a variety of research contexts.

Yet, the focus on different concepts of mobility is important, for scientific data are certainly not the only type of object that scientists from different places frequently exchange. A non-exhaustive list of types and examples of boundary objects provided by Star and Griesemer (1989: 410–11) includes indexed and standardised 'repositories' such as a library itself, which is in fact a rather immobile boundary object with respect to physical changes of location, but nevertheless can be used by actors of various contexts; another is an 'ideal type' such as a diagram or description that is abstracted from contingent, local objects in order to serve as 'road maps' for different actors; yet another type is a 'standardised form', allowing communication across contexts without changing informational content when transported over long distances.[18] Morgan (2011) and the contributors to *How Well Do Facts Travel? The Dissemination of Reliable Knowledge* (Howlett and Morgan 2011) consider things of 'many guises and sizes', including objects that many would preferably call “data”, as facts that travel between different contexts (Morgan 2011: 8). In contributions covering a wide range of scientific disciplines, it becomes clear that facts travel independently in many different and unexpected ways and 'it is in travelling well that they prove how essential they are to our sciences, humanities and society' (Morgan 2011: 36). Morgan (2014) explains different strategies to make locally produced, situated knowledge portable so that knowledge can be “resituated” for use in other local contexts by different researchers. All strategies 'rely on establishing, or making use of, some form of comparability to prompt the resituation of specific local knowledge' (Morgan 2014: 1023). Making local

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[18] In their description of the information-preserving standardised form, Star and Griesemer (1989: 411) refer to Latour's immutable mobiles.

knowledge usable in other local contexts is the first step to knowledge being accepted by peers and acquiring a degree of generality, Morgan argues.

Mobility can be regarded as a feature of many objects that are created or used in science, not least because in my case, not only data are prepared to travel to many different contexts but also mechanical sampling devices are sent from an institution in South-West England across the oceans and back. However, neither portability by itself nor in combination with physicality and artificiality suffice as an exhaustive definition of scientific data. According to Leonelli (2016: 77) 'the value assigned to data as *prospective evidence*',[19] or the evidential value, distinguishes data from other types of objects in science.

A notable characteristic that all three concepts of mobility convey is that scientific data are objects, even if these objects are not necessarily immutable or stable. Digital scientific data in arrays of numbers and letters, stored on hard disk drives or in digital clouds, do not immediately evoke the image of an object with boundaries. In the current discourse on data-intensive science, frequent metaphorical references to data as “streams”, “flows”, a “deluge” or “flood” rather suggest an image of open-ended, messy, or even chaotic, uncontrollable processes. Against these types of naturalising metaphors, the view of a data journey as a process anchored in human agency, with planning, artificial vehicles, designated pathways, and destinations, appears to be an adequate counterproposal.

1.3 Thesis overview

My thesis consists of three introductory chapters, four main empirical chapters, and a conclusion. This chapter has introduced the overall philosophical arch and scope of this thesis. Against the background of data-centrism in science, my thesis tracks the many practices and processes that contribute to the making of digital scientific data in a detailed case study in ocean science. The chapter has reviewed scholarly literature on the reconfigurations of research

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[19] Emphasis in original.

practices that are related to data-centrism in science as well as different conceptualisations of scientific data.

Chapter two introduces my research methods, reviewing first how studies of scientific practice figure in contemporary philosophy of science. My thesis follows a development during which the focus of philosophy, sociology, and history of science has broadened from narrow considerations of research products to include research practices and their technological, institutional, economical, and social conditions. For this purpose, philosophers of science have adopted ethnographic research methods from anthropologists and social scientists. This thesis is based on ethnographic fieldwork in a research institution, complemented by extensive literature and web research.

Chapter three introduces data practices in oceanography. Compared with other scientific disciplines, oceanography is still under-represented in philosophy of science. The practices of ocean scientists have only recently started to draw more attention from sociologists, anthropologists, and especially historians. My introduction of oceanography and its data practices builds on this literature, but also draws from standard oceanography textbooks and oceanography journals to portray the discipline. Oceanography is a loosely defined field that includes traditions and methods from physics, biology, chemistry, and geology. There are no clear demarcations between these and other oceanographic sub-disciplines. Ever since studies of the ocean became a science, observations and data have been fundamental in knowledge making processes and collaborative practices for data production have quickly emerged. The chapter outlines the impact of various technological innovations on how and by whom ocean sciences are practised. New technologies have enhanced the importance of data and of continuity in data practices to further advance knowledge of the oceans. Despite a long established data-centrism and high-volume, large-scale technologies such as satellites and autonomous measuring platforms, large areas and crucial parameters of the oceans remain scarcely sampled due to economic costs, the challenging nature of the seas, and the sheer size of the oceans. Following my portrait of data practices in ocean sciences, chapter three briefly introduces this thesis' main case study, the Continuous Plankton Recorder (CPR) Survey.

My empirical study of the space in-between scientific data and the natural world is centred on four themes, which have emerged from ethnographic interviews and my visits of research sites. The themes are materiality, scientific representing with data, methodological continuity, and the contribution of non-scientists to epistemic processes. One main empirical chapter is dedicated to each of these themes. The overview of each chapters' content briefly reconstructs how the theme has emerged from my visits and conversations with scientists. I then summarise each chapter's main content and philosophical argument. This is in an effort to be as open as possible about my own thought processes and about the genesis of this thesis.

I have conducted ethnographic interviews with staff members of the Sir Alister Hardy Foundation for Ocean Science (SAHFOS), the institution that (until April 2018) was responsible for running the plankton survey that is the main case study of this thesis. The conversations often revolved around technical and methodological details of two main practices carried out routinely by SAHFOS: the sampling of the oceans and the sample analysis. These involve interactions between different materials such as the mechanical sampling device, the flow of seawater through the sampling mechanism, large container ships that tow the sampling device, bands of silk that filter the seawater, and the plankton organisms themselves. Obviously, the functional details needed to be explained to me in order to learn how the so-called Continuous Plankton Recorder (CPR) works. In conversations with various staff members, the importance of physical interactions and their implications for the entire knowledge production process quickly came to the fore and made me consider more fundamental questions regarding materials and materiality in science: How do philosophers of science understand "materiality" and how do material interactions figure in epistemology and philosophical accounts of scientific data production?

Samples that are produced in the CPR Survey are often at the centre of these physical interactions. Hence, materiality and sampling emerged from my empirical study of practice as the first themes that needed to be addressed in order to fill the space in-between scientific data and the world. Chapter four, as the first of four empirical chapters, describes the process of sampling in the

CPR Survey and conceptualises the “materiality” of the samples. Fleshing out the term “materiality”, I argue that ocean scientists create material samples by inducing a “material integration” of physical parts of the ocean ecosystems and physical parts of the sampling technology. The fusion of materials from different origins is the formation of a novel entity with distinct characteristics that take shape in the process of sampling. Preserving the newly created object throughout the epistemic process constitutes “material continuity”, which is crucial for the creation of data in my case. I argue that samples, despite their tangibility, are not fixed entities that are collected or extracted from nature into the scientific world; material continuity constitutes an ongoing process of embodiment that needs to be maintained and conveys the notion of a material object with boundaries. The chapter sharpens the understanding of “materiality” and “material”, which is a widely used attribution to research objects and practices. It also leads to a deeper understanding of samples, which have received much less attention in scholarly literature than scientific data, but are commonly regarded as representations of a population of similar objects. Based on my account, I locate the epistemic value of research samples primarily in their materiality and in the ongoing preservation of material continuity and not in a representational relation to a group of similar objects.

In chronological order, the mechanical sampling of the oceans is followed by sample analysis inside a laboratory in Plymouth, UK. As the analysis involves a variety of manually performed manipulations on the sample, materials and samples play a central role in the lab, too: Microscopes, metal tools, plastic wrapping, and preservation fluids interact physically with the samples. Epistemologically, however, the work inside the laboratory aims at creating records of the microscopic analysis that can be communicated to other scientists and related to plankton populations in the oceans. What interested me in this part of the epistemic process is the step from material samples to quantitative data, which again prompted questions regarding scientific representation and the links between samples, data, and the plankton populations in the oceans. The very first recording of data in the CPR Survey comes in the form of hand-written tally marks as plankton analysts count the organisms they see under the microscope. This is a crucial activity for establishing links between the natural world and digital data products, but as I elaborate in chapter five, it is not always clear what the initial recordings actually account for and how the specific ways of counting plankton are motivated.

Chapter five reconstructs the creation of hand-written tally marks and their processing into digital scientific data. Following Latour (1999), I view scientific representing with data as the result of a series of traceable transformations or translations of perceived qualities of objects into standardised forms. These actions are intended to increase the circulation and computability of data and enable their integration and comparability with already existing representations and records of the past. I argue that the scope of representation changes with each step of transformation and broadens from specific characteristics of an individual sample to processes of the ocean ecosystem as the data gradually become computable and comparable to already existing data. The use of data as representations depends on the data's immediate context, their physical state and their relation to other data, implying that representing is a practical achievement and not an intrinsic property of data. Chapter five reveals a perceivable mismatch between data and the natural world that resonates with the work of scholars who have tried to untie the close coupling between scientific representation and models which has dominated recent philosophical accounts of representation and suggests a fixed model-target relationship (Knuuttila 2010). My chapter shows that the practice of representing does not link data to targets in the natural world and instead enhances their circulation and commensurability with already existing representations. Intentional, traceable change rather than continuity is characteristic for the chains of transformations that co-occupy the space in-between the natural world and scientific knowledge.

Almost every interviewee emphasised the need for methodological consistency in the plankton survey. In some cases, seeking continuity served as an explanation for why certain practices are performed the way they are. Continuing to create samples and data in the same way for multiple decades emerged as a key condition for the usability of the data, as the continuity makes data from different decades comparable so that long-term changes of the ecosystem become visible in the data. Given the high valuation of methodological continuity, I started wondering about the dynamics of scientific change and how a research institution manages the tensions between historical change, innovation, and continuity: How are the creation of new knowledge and progress in science and technologies intertwined with standards of practice that need to remain unchanged for the data to be usable?

To address this question, chapter six broadens the scope of my research and accounts for the conditions of practices in the CPR Survey and how these conditions have changed and affected the survey in the past. It also briefly discusses an effort to coordinate and maintain various long-term marine ecological monitoring programmes around the UK. Scientific practices are performed in certain settings and researchers face challenges on various levels — technological, economical, and social — in trying to keep their methodology unchanged for multiple decades. Applying Caporael, Griesemer, and Wimsatt's (2014a) notion of "scaffolding", a conceptual framework for development in culture, evolution, and other domains, I argue that the continuity of data practices is achieved by assimilating change and modifying or expanding data practices, while the core functionality of the CPR Survey is maintained. The continuity of data practices is not characterised by stasis, an absence of change, or by endless repetition of old-fashioned practices, it is a result of changes and adaptations of data practices. In order to maintain continuity, researchers modify the design of research technologies, expand their scientific repertoire and the scope of their data, establish reliable audit trails, respond to the interests of the scientific community, funding agencies, and the public, transfer local expertise to young generations of researchers, and even redraw conceptual boundaries of sciences. These activities contribute to a continuity that cuts across the material continuity and the traceable series of transformations that act between scientific data and the natural world. The continuity of data practices constitutes an absence of jumps between scientific data of the past and scientific data of today.

The fourth theme encompasses the involvement of a variety of actors in oceanographic data practices who maintain professional or recreational relations to the seas but have no scientific credentials. Seafarers play a central role in my thesis' main case study, due to their regular involvement in the sampling process. This dimension of the CPR Survey was revealed to me in an interview with a member of the survey's operations team, who made it clear that a wide range of continuous relationships to external collaborators link the research institution with its object of study, the oceans. Since its very beginning, the CPR Survey has cooperated with a network of volunteers to conduct its research, which led me to taking a closer look at the epistemic contribution of these non-scientists and to considering the role of volunteers and citizen scientists in oceanographic practices in general. As literally acting "in-between" scientists and the ocean, how are data practices conceived so that they can be performed by volunteers? And in turn, how do volunteers as integral parts of epistemic processes shape our knowledge of the natural environment?

Chapter seven accounts for the involvement of seafarers and other non-scientists in the CPR Survey; it also portrays a relatively young citizen science project in which sailors are encouraged to measure a parameter related to ocean turbidity and submit their data through a mobile phone app to a centralised database. In both cases, ocean scientists exploit the fact that many different people frequently interact with the oceans on their own account and that a wide range of oceanographic data can be produced by following relatively simple instructions. These collaborators actively co-produce data and knowledge of the oceans and are not passive collectors of data or samples. I argue that non-scientists enable sampling conditions and shape the outcomes of research by contributing their particular skills and embodied knowledge related to their seafaring activities. Rather than being tools that are deployed in order to collect data or samples in the name of science, these actors are part of the constantly changing settings researchers must approach in order to create knowledge. The CPR Survey continuously establishes and maintains social relationships to collaborators from a variety of professions. This social continuity between science and seafaring culture is crucial to maintain the network of volunteers and to ensure that the sampling maintains its spatial and temporal regularity over multiple decades. In this regard, social continuity is an indispensable part of the CPR Survey’s data practices, which underpins the practices’ material and methodological continuities.

Chapter eight concludes the thesis by recapitulating my case study of data practices in oceanography and the interweaving continuities, changing conditions, and various activities that sustain the genesis of digital oceanographic data. I draw conclusions in relation to the philosophical study of data-centric sciences and conceptualisations of data, but also in relation to data practices in ocean sciences. Finally, the conclusion explores various potential research avenues that could build on this thesis.

The thesis further includes several appendices related to my empirical research and a glossary that includes some oceanographic terms and all acronyms that appear in the text.

Chapter Two – Methodology

This chapter introduces my research methods, reviewing first how empirical studies of scientific practice figure in contemporary philosophy of science. My thesis builds on a broadening of the scope of philosophical, sociological, and historical studies of science in recent decades: from narrow considerations of research products and idealised preconceptions of making and accumulating scientific knowledge to including research practices and their technological, institutional, economical, an social conditions. For this purpose, philosophers of science have adopted ethnographic research methods from anthropologists and social scientists, including local case studies of research practices. This thesis is based on qualitative ethnographic fieldwork in an oceanographic research institution, complemented by extensive literature and web research, as I elaborate in the second part of this chapter.

2.1 Following the "practice turn" in philosophy, sociology, and history of science

My research can be regarded as empirical philosophy based on a qualitative case study of oceanographic research practices. My thesis follows a methodological and conceptual shift in philosophy, sociology, and history of science towards studying the practices of scientists; this shift has been termed the "practice turn" by many scholars. Soler et al. (2014) reconstruct the origins and most important contributors of the practice turn in the tradition of Anglo-American analytic philosophy of science, which culminated bin the 1980s and early 1990s with titles like Hacking's (1983) *Representing and Intervening* and Pickering's (1992) *Science as Practice and Culture*. Soler et al. (2014: 14–24) identify several key shifts in the course of this turn which contain almost always strong criticism of earlier studies of science, accusing them of conceptualising science in ways that do not reflect what science actually is. I review these shifts and relate each one to the methods I employed in my own research project.

The first shift is the practice turn’s most fundamental, Soler et al. (2014: 15) point out: away from a-priori, too idealised accounts of science and passive scientific agency, towards more empirically based, activity-oriented accounts. This shift came in reaction to traditional, deterministic or formulaic notions of a scientific method such as verificationism or falsificationism, and too linear notions of scientific development and progress as a cumulation of knowledge.[20] Most of these accounts developed in the first half of the twentieth century and were criticised because they ignored local and historical contexts, the material aspects of practising science, the plurality of scientific approaches, and individual motivations and careers of scientists; researchers often appear as overly rational and altruistic minds without limitations in capacities, skills, or background knowledge. This shift requires from philosophers of science a specific attitude and approach to the object of study: Certain scientific modes of operation, for example the formulation and testing of hypothesis, as well as the goals and motivations of scientists should not be presupposed or expected before a philosopher engages with a scientific field. Inspired by anthropological scholarship, Latour and Woolgar’s (1979) seminal *Laboratory Life: The Social Construction of Scientific Facts* tried to approach scientists like an alien tribe with totally unfamiliar practices and conventions. Scholars should not assume one ideal mode of operation, but rather recognise that scientific knowledge is produced in many different ways and contexts and by diverse people driven by different scientific or personal goals and motivations. My most fundamental research question is an open-ended question about the formation of knowledge and the conditions of making scientific data. I neither discuss these topics in relation to idealised images of science, knowledge making, or scientists, nor “test” my case against a blueprint of scientific practice.

Many scholars have rejected idealised accounts of science and advocate philosophical doctrines such as the disunity of science, stating that there is not one kind of knowledge or one kind of scientific method that unifies all scientific disciplines but a multitude of scientific cultures (Knorr Cetina 1999: 2–3), or

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[20] In particular, this shift is seen as a response to the logical positivism and unified views of science advocated by philosophers of the so-called Vienna Circle in the early twentieth century.

scientific pluralism, stating that there are multiple equally legitimate ways of knowing about the world (Dupré 1993: 10). Following the practice turn assumes plurality in relation to the agency of scientists and makes scientific practices the primary object of study instead of knowledge produced by only one particular scientific mode of operation.

The second shift of the practice turn encompasses a rather descriptive instead of normative approach to science. This shift emerged from criticism against logical principles that aimed at demarcating genuine science from pseudo-science or non-science and thereby pretended to know exactly what science is and how it should be. However, normative approaches often failed in adequately describing even some of the most prominent examples of scientific practice. In addition, it was criticised that normative philosophers of science assumed a privileged position outside of scientific practice, judging over the legitimacy of scientists' endeavours. The response was a more modest approach to science that primarily describes what scientists actually do. Yet, many scholars quickly saw disadvantages in a purely descriptive perspective on science and introduced again a normative dimension to their studies, while the exact kind of normativity remains a topic of debates (Soler et al. 2014: 15–16). Lynch (2014: 103) explains that the shift to descriptive perspectives was for many scholars only a stage in a development 'from one normative era to another, better one' in which criticism and recommendations to scientists or policy-makers are grounded in empirical knowledge of actual scientific practices.

My own research pursues broadly descriptive goals, in a sense that it aims for a deeper understanding of the processes and practices by which scientific data are made. I do not offer recommendations directly to scientists or criticise the research practices that I have studied. My arguments rather relate primarily to conceptual notions discussed in contemporary philosophy of science, such as materiality, scientific representing, or different definitions of scientific data. My criticism of such notions is not aimed at the ocean scientists but at the ways their practices have or have not been accounted for in philosophy of science. As part of a larger body of scholarly literature on the epistemology of data-intensive sciences, my research has the potential to underpin critiques of contemporary sciences or recommendations related to the design or valuation of specific research practices.

The third shift of the practice turn primarily relates to historical studies of science and criticises present-centred, rationalised reconstructions of past scientific endeavours. The practice turns entails a historically adequate perspective on practices that contextualises scientific situations and the agency of scientists in their historical setting. Present-centred accounts tend to create the illusion that scientific knowledge progresses rationally and linearly accumulates to the current state of affairs (Soler et al. 2014: 17). Adequate contextualisation is also central in the fourth shift: ‘From Decontextualized, Intellectual, Explicit, Individual, and “Purely Cognitive” to Contextualized, Material, Tacit, Collective, and Psycho-Social Characterizations of Science’ (Soler et al. 2014: 17). This shift is most clearly visible in the many ‘finely contextualized micro-studies of science’ that appeared in philosophy, sociology, and history of science since the practice turn (Soler et al. 2014: 17). These not only adopt a smaller, local scale and pay close attention to the context in which scientists operate, scholars have also shown that science consists of more than a researcher’s cognitive processes and explicit statements in official science publications. Scholars have revealed the epistemological relevance of aspects that were not visible or neglected in earlier accounts of science, such as physical materials, unarticulated or “tacit” knowledge and skills, economic or institutional settings, and background values or beliefs of scientists.

My thesis aims for a contextualised view of scientific practice. I account for material aspects and associated practices in my study of sampling and sample analysis (chapter four). I also discuss scientific data situated in the context of their creation in the lab and in the context of their storage in a digital database (chapter five) and further consider a variety of external, technological and socio-economic factors and non-scientific actors that shape the outcomes of research practices (chapters six and seven). In studying the practices of creating scientific data, my thesis also follows the fifth shift suggested by Soler et al. (2014: 21–22), that is from studying scientific products to scientific processes.

Certainly, some products of scientific practices such as samples or data play a central role in my account. Yet, I am not taking these objects as given starting points of my enquiry, but try to trace their formation processes. Not only material objects may count as products but any stabilised outcome of a research practice, including ‘theories that are taken for granted, experimental facts, mathematical theorems’, and the like (Soler et al. 2014: 21). The main shift of focus is from stabilised objects to unstable entities that are in the making.

Philosophers of science associated with so-called “New Experimentalism” exemplify the shift from products to processes. They no longer accepted the results of scientific experiments as stable, unproblematic facts about phenomena. Hacking (1983) showed how experimental practices actually produce phenomena by intervention. In Rheinberger’s (1997: 15) words, experimental research practices constitute processes that do not converge towards a stable equilibrium, but progress like a ‘meandering river’. My philosophical analysis of data practices draws from Hacking’s and especially from Rheinberger’s contributions in chapters four and five, although I do not study a clear case of laboratory experimentation.

Both Hacking’s and Rheinberger’s contributions also exemplify the final shift of the practice turn: away from science as contemplation of the world and representation towards science as intervention, creation, and transformation of the world (Soler et al. 2014: 22–24). This shift entails questioning a scientists’ situatedness and agency in relation to the object of research. It conceives scientists not as passive observers who perceive and contemplate what exists, but as active investigators who manipulate and probe by intervening with technical instruments even when using visual devices such as microscopes. This revaluation of research practices led to new understandings of scientific representations. They no longer were considered as mere descriptions of the world but served ‘as means for doing things, tools for intervening, and material artifacts for transforming the world’ (Soler et al. 2014: 23). I explicitly question notions of scientific representation as adequate descriptions of the research practices in my case study in chapters four and five. Furthermore, my entire research project can be regarded as an examination of a scientist's situatedness and agency in relation to various contextual factors.

A shift of interest and approaches as substantial as the practice turn requires new or modified research methods in order to capture scientific practice as a new unit of investigation. Chang (2011, 2014), a co-founder of the Society for Philosophy of Science in Practice, proposes a framework for the description and analysis of science 'in terms of activities' (Chang 2011: 18). In this framework, researchers are engaged in what he defines as 'epistemic activities':

> An epistemic activity is a coherent set of mental or physical actions (or operations) that are intended to contribute to the production or improvement of knowledge in a particular way, in accordance with some discernible rules (though the rules may be unarticulated). (Chang 2011: 209)

Philosophers have to keep in mind the aims and intentions of scientists when performing an epistemic activity, Chang emphasises. An identifiable intentionality distinguishes epistemic activities from mere events or 'happenings involving human bodies' (Chang 2014: 72). Further, epistemic activities are not performed in isolation but in relation to other activities that together constitute a 'system of practice' (Chang 2014: 72).[21] Soler and Catinaud (2014) comment on Chang's framework and understand it as a structure with three nested levels: a system of practice at the upper level, epistemic activities at the intermediate level, and mental or physical operations at the lowest level. When a philosopher applies this framework, the aims of the philosophical analysis are important:

> The decision to categorize a given reality as, say, a system of practice rather than an activity or an operation, depends on the project of the analyst. It is not imposed by some inherent property of the reality under scrutiny. Consequently, one and the same targeted reality might legitimately be categorized as a system of practice, or as an activity, or as an operation. (Soler and Catinaud 2014: 82)

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[21] 'A system of practice is formed by a coherent set of epistemic activities performed with a view to achieve certain aims' (Chang 2014: 72).

Additionally, the introduction of three levels is mostly a ‘convenient artifice of presentation’, since any activity or operation could be decomposed into smaller units indefinitely without ever reaching any ‘ultimate fundamental level’ (Soler and Catinaud 2014: 82). In other words, what is identified as a system of practice, an activity, or operation depends on the intentions and perspective of the philosopher and is not an inherent quality of the scientific endeavour under examination.

I do not apply Chang’s framework to my case study rigorously. Chang (2011: 218) himself calls his proposal a ‘very broad and abstract outline of how I think we should be doing our concrete work’ and Soler and Catinaud (2014: 84–86) point to various problematic issues with the framework that still need to be addressed, in particular regarding the individuation of an action or an activity and the identification of an actor’s or a collaborative group of actors’ motives, aims, and values. My thesis focuses on data practices that based on Chang’s framework can be viewed as a system of epistemic activities constituted by a coherent set of mental or physical actions or operations. These operations are intended to contribute to the production or processing of data in a particular way, in accordance with some discernible rules.

As a guideline for the study of science in terms of activities, Chang (2014: 77–78) provides a ‘Checklist for Activity-Based Analysis’.[22] The list contains questions regarding the exact activity, its aims, its systematic context, agents and other persons involved, required capabilities and resources, an agent’s freedom of choice, metaphysical principles, and evaluation of the activity. As I elaborate below, I found myself contemplating many of these aspects of scientific practice during my own ethnographic fieldwork. Chang (2011: 218) admits that his framework is not truly novel and only articulates how many scholars have been thinking and structuring their own research since the practice turn. As a young scholar, I have been inspired by many close-up, contextualised studies of scientific practice and took Chang’s framework as an additional support for my focus on research practices. My philosophical analysis

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[22] Chang presents this list also as a ‘Recipe for the Transformation of Boring Philosophical Issues’ (Chang 2014: 77).

draws on various approaches and concepts employed in philosophy of scientific experimentation (Hacking, Rheinberger), in scholarship that integrates philosophy and history of science (Knuuttila, Morgan, Woodward), in social studies of science and technology (Latour),[23] and decisively in scholarship in which all three traditions — philosophy, sociology, and history of science — intersect (Griesemer, Leonelli).

Finally, Chang's (2014: 76–77) outline of benefits that derive from activity-oriented philosophy of science conveys a promising outlook for my research project: drawing attention to aspects of scientific practice that have been overlooked or deemed unimportant in the past; recognising that even highly abstract objects in science are rooted in actions and agency, which may bring 'all kinds of unexpected things' into a philosopher's scope of analysis; providing a 'natural basis for normative evaluations'; and recognising 'more clearly the continuity between science and the rest of life' (Chang 2014: 77).

2.2 The benefits of qualitative case studies

In contrast to only focusing on the explicit, propositional, and published output of research, the study of research practices appears much more problematic. How can scholars detect and analyse the unarticulated, tacit aspects of scientific practice, identify and capture scientific processes rather than products, or find answers to the questions on Chang's checklist for an activity-based analysis of science? As Wagenknecht, Nersessian, and Andersen (2015: 5) explain, philosophy of science over the past three decades has become considerably more empirical with the introduction of qualitative research methods. Osbeck and Nersessian (2015) identify three types of empirical approaches to enquiry in philosophy of science: historical, observational (or ethnographic), and experimental (or statistical).[24]

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[23] The commonly used acronym "STS" is sometimes used in this thesis to refer to scholarship in science and technology studies which view science and technology as socially embedded enterprises.

[24] Osbeck and Nersessian (2015: 14) have no formula to clearly distinguish empirical from non-empirical, but emphasise that '*the empirical* is rooted in *the instrument*

The practice turn entailed an increased diversity of research methods that scholars applied to sciences. Latour and Woolgar's (1979) *Laboratory Life* or Knorr Cetina's (1981) *The Manufacture of Knowledge* demonstrated how ethnographic and qualitative research methods could be employed in sociological studies of science. Since the so-called "Science Wars" of the 1990s, during which realists and constructivists fiercely debated over the nature and authority of scientific enquiry,[25] philosophers of science have started to incorporate qualitative methods into their repertoire. An important and frequently employed approach to research practices is an empirical case study. Burian (2001: 384) argues for the virtues of using case studies in history and philosophy of science and defines case studies as follows:

> Case studies are concerned with scientific work carried out during a limited time period and are usually restricted to a specified set of scientists, institutions, laboratories, disciplines, or traditions. […] Case studies usually deal with relatively narrow topics. And most of the case studies that interest philosophers of science are organized around a focal issue of broad interest. (Burian 2001: 384–85)

Morgan (2012a: 668) emphasises in her own definition that a case study focuses on a 'bounded whole object of analysis', but that the boundary between object of study and context may not be clear from the beginning and remain variable throughout the process of study. In this sense, case-based research 'maintains a considerable degree of open-endedness' (Morgan 2012a: 668).

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and cannot be understood apart from it' (emphasis in original). Importantly, the researchers themselves count as instruments in observational and ethnographic research, the main empirical methods of my research project.

[25] As Wylie (2000: 228) summarises, scholars of sociological, anthropological, and feminist studies of science and technology argued that sciences are inherently human, social, and political, while questioning the presumption that 'the sciences are uniquely non-parochial in scope and warrant, that they share a body of investigative practices capable of establishing knowledge that decisively transcends the contexts of its production'. Defenders of science reacted by maintaining a 'unique integrity and authority of science as a corporate whole'.

Case studies gain relevance as a research method when philosophers follow some of the practice turn's aforementioned principles, in particular the plurality and disunity of scientific practices and the rejection of too idealised conceptions of scientific knowledge, methods, and agency. As Burian (2001: 399–400) points out, 'science has no essence', no universal or objective scientific method; hence, 'case studies cannot and should not be expected to yield universal methodologies or epistemologies'. More explicitly, Morgan (2012b: xv) states in the preface to a book comprising a series of case studies of economic modelling practices: 'Science is messy' and 'the messy details are important' to understand and explain both micro- and macroscale aspects of science. Case studies are the best way to capture the details of scientific practices and 'to figure out how science goes on' (Morgan 2012b: xv). Case studies are the primary research tool for making the unarticulated and tacit details of scientific practice visible.

Flyvbjerg (2006) addresses several misunderstandings and simplified views of case studies. A common misunderstanding is that general, context-independent knowledge would be more valuable than concrete, context-dependent knowledge. Flyvbjerg (2006: 6–9) responds by highlighting the benefits of case-based research for the philosopher or sociologist: The type of context-dependent learning with case studies is essential for the acquirement of thorough expertise in a specific field of research. Additionally, any research of human affairs inevitably leads to context-dependent knowledge, because 'social science has not succeeded in producing general, context-independent theory and, thus, has in the final instance nothing else to offer than concrete, context-dependent knowledge' (Flyvbjerg 2006: 8). A related, frequently raised scepticism against case studies is the impossibility to generalise on the basis of a single case study. Flyvbjerg (2006: 14) contends that the value of formal generalisation is overestimated whereas the force of exemplification and a case study's potential to falsify expectations and given propositions are underestimated. Rather than confirming a researcher's subjective bias, case studies more frequently make researchers question or rebut preconceived notions (Flyvbjerg 2006: 23). Indeed, as outlined in the thesis overview in the previous chapter, the closeness to concrete research situations made me question my own preconceptions as well as common philosophical conceptions of specific aspects of research practices.

I study data practices by conducting an in-depth local case study because I see case studies as the only way to adequately reconstruct in terms of activities how scientific data are made. My thesis explicitly focuses on the contexts and conditions of making scientific data and a case-based approach seems well-suited for this task. The diversity of practices in data-intensive sciences can only be mapped with more empirical case studies. These are not intended to replace but underpin rather general, comparative perspectives on commonalities or differences between scientific practices. My case study consists of multiple visits to a research institution, qualitative interviews with researchers, and extensive research of scientific literature related directly to my case. Ethnographic interviews as part of case studies are a powerful research tool in sociology and find increasing acceptance among philosophers of science.[26] I used ethnographic research methods in order to establish an empirical basis for my philosophical analysis of scientific practice. The following summary of my empirical research addresses additional questions related to the qualitative interviews and their analysis.

2.3 Empirical methods used for this thesis

My approach to ocean sciences during my PhD project was partly shaped by my own educational background. From 2006 to 2011, I studied geophysics and physical oceanography at the University of Hamburg, Germany. I worked as a student assistant at the Institute of Oceanography and was thereby introduced to a variety of practices, by which oceanographers produce and analyse data. I also worked as a student assistant on two research cruises on the Atlantic Ocean, during which I contributed to the sampling of ocean waters and the production of scientific data. Attending lectures in hydrochemistry, biogeochemistry, hydrodynamics, and marine ecology provided me with

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[26] See for example Osbeck and Nersessian (2015: 26–33) for a detailed description of “Empirical Philosophy of Science in Practice” in bio-engineering, including field observations, audio-recorded interviews, and the analysis of interview data.

additional background knowledge on practices that are not primarily concerned with ocean physics. Between 2011 and 2014, I studied history and culture of science and technology at Technical University Berlin and worked as a student assistant at the Max Planck Institute for the History of Science in a project on large-scale data collection programmes in post-World War II natural sciences. These studies provided me with specific historical perspectives on science that at times, intersected with philosophy of science, as for example in Michel Foucault's (1969) discourse analysis and archaeological method to analyse knowledge and scientific cultures.

This scholarly background gave me broad and useful background knowledge and practical experience in ocean sciences, but left me with a lack of philosophical fundamentals, as I learned in the early stages of my PhD research. Such a disciplinary crossover is not uncommon in contemporary academia. Yet, thinking and writing about science in philosophical terms as well as learning about empirical research methods in philosophy of science comprised a large part of my learning curve, especially during the early stages of my research project. Being a trained oceanographer certainly shapes my understanding of the information I obtain in ethnographic interviews. Laudel and Gläser (2007) reflect on interviewing scientists and the required level of expertise in the science practised by the interviewees. They point out that for in-depth, qualitative, empirical research, understanding the science to some degree is inevitable. My approach can be considered as 'native observation' using Laudel and Gläser's (2007: 96) words, because I am a trained oceanographer studying oceanography. In some cases of native observation, researchers experienced an ambiguity when studying the work of former colleagues or peers. In rare cases, accusations surfaced that in doing native observation, researchers might too easily adopt false assumptions from the researchers under study. However, as Laudel and Gläser (2007: 96–97) summarise, the consequences of native observation for the outcomes of empirical studies are actually unknown.

I was not aware of my case studies' specific data practices prior to beginning my PhD research. My studies in history and culture of science and technology also provided me with critical distance to ocean sciences in such a way that I did not feel “native” when I visited research sites in Plymouth. My background knowledge of oceanic processes and practices certainly aided my understanding of the content of my conversations with oceanographers. I admit that in discussing my research with other philosophers, I sometimes felt that I was less surprised by my case study than scholars that were not familiar with oceanography. Presenting and discussing my research in workshops and at international conferences was therefore crucial for my own interpretation of my empirical data.

My empirical research for this thesis began with a broad literature and online research into contemporary data practices in oceanography. The aim of this research was to broaden my knowledge beyond the rather technical and methodological knowledge that I obtained during my time as an oceanography student. In particular, I intended to gain an overview of important oceanographic data infrastructures, including their participants, funding backgrounds, their scientific scope, impact, and their relation to other oceanographic projects and programmes. The aim was finding oceanographic programmes and projects suitable for an empirical case study within the limited time of a three-year PhD project.[27] Large-scale, multi-national data infrastructures like the International Argo Project, the ocean chemistry observational programme GEOTRACES, or the Global Ocean Data Assimilation Experiment (GODAE) appeared too complex and demanding in this regard. My focus therefore shifted to databases and projects within the UK with a smaller scientific scope and potential access points for ethnographic fieldwork. Among the projects and locations I identified were the Marine Biological Association of the UK (MBA), the Data Archive for Seabed Species and Habitats (DASSH), the Continuous Plankton Recorder (CPR) Survey and the Secchi Disk Project, all based in Plymouth, the National Oceanography Centre (NOC) in Southampton, and the British Oceanographic Data Centre (BODC) in Liverpool.

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[27] See appendix A for a list of criteria for selecting fieldwork sites. These were developed jointly by members of the ERC-funded project “The Epistemology of Data-Intensive Science”.

Towards the end of my first year of research, I started collaborating with people from the MBA, the CPR Survey, DASSH, and the Secchi Disk Project. I visited the MBA building in Plymouth several times throughout 2015 and conducted six ethnographic interviews in a span of six months. I was shown around the building, the laboratory where CPR samples are analysed, the instrumentation workshop, and the CPR Survey's sample archive. The interviews were semi-structured and usually lasted for around one and a half hours. I based the interviews on individual sets of topics and questions intended to guide the conversation while also allowing space for deeper discussions of specific topics, whenever they emerged from the conversation.[28] One theme that all interviews had in common was the scientists' everyday work. I kept asking about the recurring activities and routines of scientific practice, in particular those practices relating to data, required technologies and skills, typical problems, and communication networks related to these activities. On the one hand, I wanted to learn the facts and the functioning of specific instances of scientific work; on the other hand, I wanted to gain insight into the individual realities of scientific work as lived and experienced by people in a specific research setting. One major goal of semi-structured interviews of this type is to learn about constraints, relations, and interactions involved in scientific work, which cannot be uncovered by any other method, for example by researching only published scientific literature. At the same time, the interviews retained an exploratory character because they were also intended to give me deeper knowledge and insight into the work of scientists from which I would be able to select specific aspects to address in my thesis.

During my visits to Plymouth, I have interviewed the following scientists or members of staff: a marine ecologist who is now the Deputy Director of the MBA and chair of the Marine Environmental Change Network (MECN), which oversees a number of long-term environmental time series of the UK; the data manager of DASSH; a marine ecologist and micro-biologist who has launched the Secchi Disk citizen science project; from the Sir Alister Hardy Foundation

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[28] See appendix B for an interview protocol from which I developed specific questionnaires for each interview. The template was developed in the course of the ERC-funded project "The Epistemology of Data-Intensive Science".

(SAHFOS) I interviewed the lab manager, a senior plankton taxonomist; an instrumentation technician, plankton taxonomist, and sample archive curator; the workshop manager and member of the operations team; and a geneticist specialised in plankton ecology. All participants agreed to the interviews being audio-recorded.

Participation in my research was entirely voluntary and only happened after the scientists signed an ethics consent form in which they were able to choose if the interview would be recorded and if their identity would be disclosed. I also asked interviewees to sign a re-use and archiving agreement to decide if transcripts of their interviews could be archived and shared online to be available for future research projects.[29]

Most of the second year of my research was spent with transcribing and analysing the interviews, as I describe below. During the third year of my research I travelled back to Plymouth for another three interviews which were less exploratory and rather aimed at answering follow-up questions and filling gaps in my knowledge of the data practices. By this time, I had settled on the CPR Survey as my main case study for this thesis. The total number of nine interviews, with only six interviewees working directly for the CPR Survey, leaves me with a relatively small sample size. Crouch and McKenzie (2006) argue that small sample sizes in qualitative research with interviews function well for studies which aim at capturing the dynamics of social situations. They further point out that ‘strictly speaking, […] the whole notion of “sample” is not appropriate here since in research of this kind respondents are not drawn (i.e. sampled) from a “target population”’ (Crouch and McKenzie 2006: 492). Indeed, the case I selected is a rather unique example of ocean science and the researchers I interviewed were not chosen as representatives of larger groups of people. For example, the lab manager of the CPR Survey or the data manager of DASSH occupy singular positions in relatively small institutional settings.

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[29] See appendix C for copy of the ethics consent form and appendix D for the re-use and archiving agreement.

For analysis of the interview transcripts, I utilised the data analysis software Nvivo 10. I used the software's "coding" function to mark passages with one or more themes depending on the current topic or question of the conversation.[30] A list of forty different themes emerged from this analysis, which gave me an overview of which topics have occurred more often than others. The themes "storing, archiving, curating", "sample", "questions of analysis", "data uses and re-uses", "material", and "funding" emerged as the most frequent topics. The themes were not pre-determined but rather developed in the course of the analysis. In the following weeks, these topics guided my philosophical thinking and the structuring of my empirical data into potential chapters and papers to present at philosophy of science conferences and workshops. This means that the philosophical themes addressed in my thesis' main chapters emerged from my empirical data and from the reconstruction of the research practices that I studied. I was not initially driven by an intention to find out about, say, scientific representation in ocean sciences.

This thesis is the primary output of my PhD project. It is based on qualitative, empirical philosophy of science and exemplifies what Morgan (2012a: 668) describes as the outcome of a case study:

> A complex, often narrated, account that typically contains some of the raw evidence as well as its analysis and that ties together the many different bits of evidence in the study.

My empirical chapters contain much of the "raw evidence", direct quotations from researchers, which I inserted with the deliberate intention to let the scientists speak for themselves.

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30 See Osbeck and Nersessian (2015: 31–32) for an example of coding interview data in empirical philosophy of science.

Chapter Three – Between scarcity and overload: Data practices in oceanography

Abstract: This chapter introduces data practices in oceanography and briefly introduces this thesis' main case study, the Continuous Plankton Recorder (CPR) Survey. Compared to other scientific disciplines, oceanographic practices are still under-represented in philosophy of science; however, oceanography has recently started to draw more attention from sociologists, anthropologists, and especially historians. My introduction of oceanography builds on this scholarship, but also draws from standard oceanography textbooks and oceanography journals to portray the discipline. Oceanography is a loosely defined field that includes traditions and methods from physics, biology, chemistry, and geology, but there are no clear demarcations between these and other oceanographic sub-disciplines. Ever since studies of the ocean became a science, observations and the production of data have been fundamental in knowledge making processes. Oceanographers have long maintained close ties to the seafaring culture and established international collaborations to increase the scope and volume of data production. Various technological innovations have impacted how and by whom ocean science is practised. New technologies have also enhanced the importance of data and of continuity in data practices to further advance knowledge of the oceans. Despite the long established data-centrism and the implementation of high-volume, large-scale technologies, large parts and crucial parameters of the oceans remain scarcely sampled.

3.1 Introduction

Oceanography is a diverse scientific field and, as I discuss in this chapter, lacks a clear definition as well as distinct topical or methodological boundaries. This chapter reviews the diversity of oceanographic data practices and formulates some cornerstones that characterise the field in view of the following chapter's case study. I intend to draw a broad sketch of oceanographic data practices —

in particular of the practices by which data of the oceans have commonly been created — that is informed by scientific literature and the rather limited scholarship on oceanography in philosophy, sociology, anthropology, and history of science.

I argue that oceanography is a relatively young scientific field in which “data-centric” or “data-intensive” approaches have been prominent from the very beginning. A variety of new technologies have been introduced to ocean sciences since the middle of the twentieth century. These have greatly increased the capacities of ocean scientists to produce oceanographic data. Yet, ironically, a characteristic scarcity of data is still prevalent today as the scope of oceanographic research has expanded from exploratory mapping of ocean phenomena to understanding the oceans’ crucial role in the planetary climate system. The expansion of scope occurred gradually over the course of one century and has transformed the scientific image of the oceans from rather static bodies of water to assemblages of dynamic, interrelated physical and biogeochemical processes. This shift amplified the importance of continuity in the data practices of ocean scientists and spawned a high degree of collaboration between scientific institutions and research organisations across the globe.

For a large part of their history, ocean sciences were closely associated with maritime and seafaring culture, with exploratory voyages and discoveries made exclusively by institutions and male scientists with seafaring capacities and experience. While new platforms for data production like satellites and autonomous sensing networks have opened ocean sciences to a greater diversity of people, some oceanographic practices still require the skills to bring research instruments or entire laboratories on ships right into the adverse conditions of the world’s oceans.

In general, I understand oceanography as an engagement in the oceans and seas that involves the collection of samples, the recording of phenomena, the creation of data, or the production of knowledge from samples, records, or data. This view includes a wide range of activities performed by scientists as well as non-scientists. The objects of study not only encompass the ocean’s and adjacent sea's bodies of water, but also the living organisms within them, organic and inorganic compounds floating with the currents, as well as the constitution and processes across their boundaries, at the sea floor, along coasts, and between oceans and the atmosphere. I do not aim for a general definition or demarcation of oceanography and tend to use the term "ocean sciences" frequently throughout this thesis to signal the plurality of approaches, traditions, and specific objects of study that researchers of the oceans engage with. My view of oceanography or ocean sciences is derived from research into the practices and history of the field conducted for the purpose of this thesis and from my experience as a student and research assistant in physical oceanography.

The chapter first discusses definitions of oceanography given in encyclopaedias, oceanography textbooks and in materials from public representatives of the discipline such as journals, learned societies, and international organisations. The chapter then reviews the limited scholarship on oceanographic practices from historical, philosophical, sociological, and anthropological studies of ocean sciences. The main part of the chapter is formed by a historical sketch of data practices in ocean sciences that briefly introduces the main technologies of data production, research programmes, and innovations that have shaped how oceanography is practised today. Finally, before summarising, I briefly introduce this thesis' main case study, the Continuous Plankton Recorder (CPR) Survey.

3.2 Defining oceanography

Several textbook and encyclopaedia definitions of oceanography are two-fold: They define oceanography first as all science of the oceans and seas and, second, as being traditionally divided into four sub-disciplines dedicated to the oceans' physics, biology, chemistry, and geology, respectively. Sverdrup, Johnson, and Fleming (1942: 1), for example, write in a classic oceanography textbook:

> Oceanography embraces all studies pertaining to the sea and integrates the knowledge gained in the marine sciences that deal with such subjects as the ocean boundaries and bottom topography, the physics and chemistry of sea water, the types of currents, and the many phases of marine biology.[31]

In a more recent introductory textbook for oceanography students, Stowe (1996: 5) claims that the division in physical, biological, chemical, and geological oceanography is ‘customary’ among oceanographers. According to *Encyclopaedia Britannica*, oceanography is the ‘scientific discipline concerned with all aspects of the world’s oceans and seas, including their physical and chemical properties, their origin and geologic framework, and the life forms that inhabit the marine environment’.[32]

Most oceanographic research can probably be regarded as falling under one or more of the four traditionally distinguished sub-disciplines. Among scientists, common labels for these sub-disciplines are “physical oceanography”, “marine biology” or “biological oceanography”,[33] “ocean chemistry”, and “marine geology”. In scientific literature and among oceanographers, the term “oceanography” is often associated only with physical oceanography, especially

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[31] Although geology is not explicitly mentioned, geological research can be regarded as included in ‘subjects such as ocean boundaries and bottom topography’ (Sverdrup, Johnson, and Fleming 1942: 1).

[32] <http://www.britannica.com/EBchecked/topic/424573/oceanography> [accessed 19 November 2015].

[33] Scientists seem to distinguish between marine biology and biological oceanography. A Google search for the “difference between marine biology and biological oceanography” leads to some online discussions and disciplinary descriptions claiming slight differences in thematic scope and tradition. Marine biology is viewed as the study of marine organisms themselves and as a sub-discipline of biology, whereas biological oceanography is rather associated with the study of marine organisms within the physical and chemical environment of the oceans. The latter, as the name suggests, is viewed closer related to oceanography than to biology. In contemporary science, the two fields are closely interrelated and often overlap. For the purpose of this thesis, a distinction is not necessary.

since the rapid rise of physics and natural sciences on research and political agendas during the early Cold War, as I discuss below. Thus, biology, chemistry, geology, and other disciplines are often excluded when the term is used. Throughout this thesis, I use the term "physical oceanography" when specifically referring to research in ocean physics. Instead of "oceanography" and "oceanographers", I frequently use the term "ocean sciences" and "ocean scientists" to include all traditions and research practices related to the oceans.

The four subdisciplines associated with physics, biology, chemistry, and geology of the oceans cover what can be regarded as basic scientific research in oceanography.[34] More applied research fields are also sometimes regarded as sub-disciplines of oceanography, for example operational oceanography, ocean engineering, fisheries management, or marine policy. The goals and interest groups related to these disciplines differ substantially from more basic ocean sciences. Operational oceanography, for instance, is concerned with systematic, routine measurements of ocean parameters combined with rapid interpretation and dissemination for the purpose of deriving forecasts, as well as 'nowcasts' and 'hindcasts'. Among the outputs of operational oceanography are warnings against floods, ice and storm damage, harmful algal blooms or contaminants, and optimised shipping routes.[35]

Most oceanographic sub-disciplines are large and autonomous enough to have journals and learned societies explicitly committed to them, but there are also "general" oceanographic societies, journals, as well as intergovernmental and nongovernmental oceanographic organisations,[36] which aim at covering multiple

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[34] I follow the International Council for Science's (ICSU) definition of 'basic scientific research', given in 2004 as: 'fundamental theoretical or experimental investigative research to advance knowledge without a specifically envisaged or immediately practical application'; <http://www.icsu.org/publications/icsu-position-statements/value-scientific-research> [accessed 21 November 2015].

[35] <http://eurogoos.eu/about-eurogoos/what-is-operational-oceanography/> [accessed 21 November 2015].

[36] For example The Oceanography Society and its journal *Oceanography*, Elsevier's *Progress in Oceanography*, UNESCO's Intergovernmental Oceanographic Commission (IOC), or the nongovernmental Scientific Committee on Oceanic

or all different strands of oceanography. The aims and scope of these societies, journals, and organisations often include more specified focus areas than just the traditional four. For example, the open-access journal *Ocean Science*, published by the European Geosciences Union, covers ocean physics, ocean chemistry, and biological oceanography, but also ‘air-sea interactions’, ‘ocean models – physical, chemical, biological, and biochemical’, ‘coastal and shelf edge processes’, and ‘paleooceanography’.[37] This list is indicative of oceanography’s intersections with other geosciences such as meteorology, biogeochemistry, or palaeontology. In these fields, oceanographic processes are highly relevant and many of their studies may also be regarded as oceanographic.

In my personal experience as a trained physical oceanographer and when visiting and speaking with ocean scientists during research for this thesis, I found that oceanography is relatively open and receptive for scientists trained in other disciplines. Today, in light of the growing variety of teaching programmes, many universities offer stand-alone courses and degrees in oceanography or one of its sub-disciplines. However, many senior oceanographers were educated in other disciplines such as biology, zoology, physics, meteorology, or mathematics and became engaged in studying oceanic processes in the course of their careers.

In summary, rather than finding a straight to the point and readily adoptable definition of oceanography, the impression of a highly diverse and dispersed discipline emerges that is difficult to demarcate. Given the diversity of sub-disciplines, a wide range of methodological and educational traditions among ocean scientists is not a surprise. Consequently, it seems difficult to associate oceanography with a particular label to indicate a preferred methodological or practical approach such as “laboratory”, “experimental”, “field science”, or the like. The *Ocean Science* journal — a title that resonates with my choice of the

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Research (SCOR).

[37] <http://www.ocean-science.net/about/aims_and_scope.html> [accessed 19 November 2015].

term “ocean sciences” — is dedicated to reviewing and publishing ‘papers on all aspects of ocean science: experimental, theoretical, and laboratory’.[38]

3.3 Scholarly views of oceanographic practices

Scholarship in the philosophy of science is almost devoid of research that focuses explicitly on the practices of ocean scientists. Ocean sciences have not drawn interest from philosophers of scientific practice in magnitudes comparable to physics or the life sciences including genetics, microbiology, and medical research. However, given the diverse traditions and practices that can be counted as ocean science, some philosophical research relate either to the practices of ocean scientists or their objects of study. For example, in relation to physics, philosophers have become increasingly interested in numerical modelling practices and prediction in climate science (Parker 2011, Steele and Werndl 2009), which intersect with practices of modelling oceanic currents and biogeochemical cycles. With respect to biology, some scholarship on research of microbial life (O’Malley and Dupré 2007, Schrader, 2017) addresses scientific knowledge of bacteria, microscopic organisms, or viruses that inhabit the oceans; however, the scientific practices by which knowledge of these organisms is produced is usually not the primary concern of these authors. Camprubí’s (2018) very recent analysis of observation practices related to deep ocean currents integrates some philosophical reflection on the epistemological status of diagrams and drawings into a historical reconstruction of oceanographic practices. Such scholarship might indicate that the interest in philosophical analysis of ocean sciences is growing.

In sociology, anthropology, and especially history of science, scholars have more explicitly focused on concrete practices in ocean science and on challenges of observing a natural system as large and inaccessible as the oceans. A growing field of interest are the use and implications of earth observing satellites for global observation of the ocean surface (Lehman 2017, Benson 2012). Haraway (2008: 249–63) discusses the relation between

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[38] <http://www.ocean-science.net/about/aims_and_scope.html> [accessed 19 November 2015].

humans and animals in scenarios where researchers have equipped sea turtles and humpback whales with cameras. As an anthropologist, Helmreich (2009) has accompanied microbiologists who sample the oceans with remotely operated vehicles (ROV) from ships to learn about the climate from microbial DNA, blue-green algae with a potential use in pharmaceutical biotechnology, the ecologies at hydrothermal vents, or the origins of life.

For the purpose of this chapter, the ‘modest existing tradition’ in historical studies of oceanography (Rozwadowski 2014: 335) is most useful. Two specific areas that have drawn attention of historians are, according to Rozwadowski (2014: 336), the role of science in fisheries and the development of oceanography following World War II, when ocean science was heavily influenced by geopolitical agendas and received substantial political and military support. Oreskes (2014) even claims that the oceans have been generally neglected by historians for a long time. If historians ever paid attention to the oceans, ‘they saw them as a literal void, devoid of the stuff of which history is composed: culture, politics, art, and sociability’ (Oreskes 2014: 379). One reason for the historians’ neglect of the oceans is the fact that scientific practices related to the oceans did not exist for a very long time. Until the beginning of the twentieth century, the oceans were mostly not accessible for scientists and only coastal phenomena were within reach to be studied (Oreskes 2014: 381).[39] Oceanography became institutionalised throughout the twentieth century, but, in accord with the observation of the previous section, oceanography ‘remained and remains fragmented as a discipline’, so that it has rarely been viewed and studied as a stand-alone, coherent discipline (Oreskes 2014: 382). As Oreskes (2014: 382) clarifies, ‘oceanography as a discipline still, in some ways, does not quite exist’.

Yet, some historians have engaged in tracing how the oceans or specific parts of the oceans have become scientific objects and how research practices of the oceans have developed over time. A collection of essays edited by Benson and Rozwadowski (2007) closely studies oceanographic expeditions into the

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[39] A notable exception to the disinterest of historians in ocean science is Deacon’s (1971) monograph on research and knowledge of the seas and oceans from ancient philosophy until the late nineteenth century.

extreme conditions of the Arctic and Antarctic during the nineteenth and twentieth century. Covering an even broader scope, Mills' (2009) *The Fluid Envelope of Our Planet: How the Study of Ocean Currents Became a Science* has emerged as a standard regarding the research of ocean currents from the middle of the nineteenth century until the 1960s, when a complete theoretical model of the dynamic planetary ocean circulation first emerged. Covering roughly the same time period, Mills (2012) has also reconstructed how biological oceanography developed as an independent branch of turn-of-the-century ecological science at German, Scandinavian, British, and North American research institutions. Mills' narrative begins with a desire to quantify the biological production of the seas and ends with a convergence of biology, chemistry, physics, and mathematics in late 1960s' numerical plankton models.

The early Cold War period of oceanography and its political dimension are well documented by Hamblin's (2005), who focuses in particular on the question of how international cooperation became one of the most crucial components of oceanography as a 'Cold War science' while being closely tied to national governments and military patronage (Hamblin 2005: xviii). With regard to the definition and scope of oceanography, Hamblin (2005: xviii) shows that oceanographers strategically embraced broad disciplinary understandings of oceanography and expanded its definition by including numerous other scientific fields in order to seek support for their work. Hamblin (2014) also explores disciplinary dynamics within oceanography and distinguishes methodological trends among oceanographers at the middle of the twentieth century, not along traditional disciplinary boundaries such as biology, physics, or chemistry but along a divide between "descriptive" and "dynamic" oceanography. This distinction, adopted from Mills (2009), considers different scientific values among oceanographers, which shape how researchers see the oceans and design their enquiries. Descriptive oceanography was based in the tradition of climatology, included long-term data collection, and centred on the formulation of causal relationships to explain phenomena. By contrast, the dynamic values are grounded in mathematical and statistical methods, hydrodynamics, and thermodynamics, and saw the oceans as an integral part of a large-scale climate system.

Writing more from a military-historical perspective, Weir (2001) covers the relationship between US Navy and ocean scientists between World War I and the 1960s. Weir claims that the mutually beneficial connections between military and science relied on technological and political developments as much as on interpersonal networks between military officials and oceanographers, many of whom had served in the US Navy before seeking professions as scientists. Rainger (2000: 370) shows how physical oceanographers 'embedded' their interests into military objectives; the scientists 'knowingly and willingly' carried out military work for the Navy, which was the dominant party in the relationship (Rainger 2000: 369–70). Note that these relations occurred mainly between the Navy and physical oceanographers, as the oceans' physical properties were the most crucial for military operations.

Much of the historiographic writing on the Cold War era of oceanography is US-centred due to the leading role of American oceanographic institutions and the country's superior technological capabilities of the time. Historians who focused on scientists' engagement with the oceans during the nineteenth century have often considered European activities and the role of expanding empires as well. According to Reidy and Rozwadowski (2014), the oceans became culturally, economically, and politically relevant during the nineteenth century, leading to sustained attention of scientists on the open oceans for the first time in history. The cultural and economic role that the oceans assumed during the nineteenth century, for example in literature, trade, or telegraph communications, and the resulting efforts of Anglo-American science to measure and map the oceans' depth, is documented by Rozwadowski (2005). Politically, nineteenth century empires constructed the oceans as a space open to anybody capable of mastering it. This required reliable knowledge of the oceans and led to a 'mutually sustaining' relation between the oceans, science, and empires before oceanography as a science was institutionalised (Reidy and Rozwadowski 2014: 338).

Rozwadowski (1996) also discussed that early practitioners of ocean science in the nineteenth century shared and identified with experiences of going to sea more than they shared a body of specialised knowledge or scientific practices.

Maritime culture and the production of knowledge of the oceans clearly overlapped and established a ‘scientific maritime culture [that] became the basis for the field practices of the new discipline’ (Rozwadowski 1996: 428). Early oceanographers contributed to a heroic, adventurous, and romanticised image of ocean science by publishing not only scientific works but also personal accounts of seagoing experiences for popular audiences (Rozwadowski 1996: 429). The image of seafaring scientists who ‘defined seagoing as a central element of their science’ prevailed far into the twentieth century (Rozwadowski 1996: 428). Consideration of the cultural and social setting is crucial for an adequate understanding of oceanography’s history, Rozwadowski argues.

An adjacent, but highly relevant, thread of historical literature focuses on disciplines with similarities and intersections with ocean sciences. Similar to oceanography, research on atmospheric weather and regional or global climate deals with highly complex phenomena of the earth, which are governed by fluid motions. These include non-linear behaviour and physical, chemical, and biological feedback loops. The phenomena are often difficult to access and observe, extend from local to planetary spatial scales, and require consistent recording over long durations. Edwards’ (2010) historical work on data practices in climatology and meteorology covers practices from the nineteenth century until today, including the introduction of digital computing technologies, numerical modelling, and earth observing satellites. The history of environmental observation systems has also been studied by Aronova, Baker, and Oreskes (2010), focusing on “big science” in the early cold war, by Conway (2006), discussing an “information overload” in environmental sciences since the introduction of earth-observing satellites, and by Benson (2012) who deals with the diversification and commercialisation of satellite-based data collection during the 1980s. Relating rather to biological practices, Devictor and Bensaude-Vincent (2016) explore the “datafication” and quantification of global biodiversity in the 1980s. Benson (2016) describes data practices in movement ecology, which aim at recording the movement trajectories of various animals for up to several decades.

In summary, scholars of sociology, anthropology, and history of science have not entirely neglected ocean sciences and there appears to be a growing scholarly interest in ocean sciences. However, philosophers of science in particular have yet to explore a wide range of oceanographic practices empirically. My thesis is only one step towards mapping and making sense of the variety of oceanographic practices with tools of analytic philosophy of science.

3.4 Data practices in ocean sciences

In several oceanography textbooks, the expedition of the *Challenger* in 1872–76 is considered to mark the beginning of oceanography (Sverdrup, Johnson, and Fleming 1942: 6; Lalli and Parsons 1997: 7–10). Reidy and Rozwadowski (2014: 348), too, point out that the *Challenger* expedition established 'the modern science of oceanography as the preferred way to interpret ocean space'. Organised by The Royal Society, the British Navy vessel *Challenger* was transformed into a dedicated research vessel with laboratories and workrooms in order to survey the open oceans. The *Challenger* circumnavigated the earth and crossed nearly all ocean basins within four years. Coinciding with the four traditional oceanographic sub-disciplines discussed above, the expedition already 'attempted to integrate biology, chemistry, geology, and physical phenomena' (Lalli and Parsons 1997: 9). The voyage spawned empirical material and data of ocean phenomena which took fifty volumes and nineteen years to get fully analysed and published. Scientists of the *Challenger* expedition 'established systematic data collection using standardized methods' (Lalli and Parsons 1997: 9). It seems that the first instance of research to be recognised by scientists and historians as "oceanographic" was primarily driven by the intention to create scientific data and to establish data practices.

3.4.1 Large-scale data practices and internationalism

Almost seven decades after the *Challenger* expedition, Sverdrup, Johnson, and Fleming (1942: 6) still emphasise that ‘expeditions are needed for filling in gaps and for carrying out systematic exploration of regions from which only scattered data are available’. At the middle of the twentieth century, large-scale oceanography sought to fill these gaps. The International Geophysical Year 1957–58 (IGY) focused on worldwide data collection across several geophysical disciplines, including a programme in oceanography. Funded through national governments and carried out by numerous scientific institutions, sixty thousand scientists and amateurs from more than 67 nations participated in data collection for the IGY (Aronova, Baker, and Oreskes 2010: 194). The IGY has drawn interest from historians partly because scientists and institutions from both Western countries and the Soviet bloc countries participated. The programme was hierarchically structured into different disciplines, into national IGY committees and programmes, and into thousands of individual measuring stations. Historians argue that the IGY programme can be regarded as a ‘data-driven mode of research’ and that it lacked theoretical drivers shared between different organising committees and programmes (Aronova, Baker, and Oreskes 2010: 185).

The oceanographic programme of the IGY consisted of two main parts: scientific cruises with research vessels and a global network of coastal tide gauges to measure the sea level on predetermined dates, the IGY’s so-called ‘World Days’. Although the participating nations planned and conducted oceanographic expeditions mostly on their own, and despite Cold War tensions overshadowing the entire programme, the IGY gave oceanographers a chance to connect with ocean scientists from other countries (Hamblin 2005: 59–98). The IGY further coincided with an era that saw oceanography rapidly gaining geopolitical relevance and funding by the military. The strategic importance of submarines during World War II and the early Cold War resulted in a financial boost for physical oceanography, in particular for research regarding the oceans' density and acoustic properties, and for research on the oceans' bathymetry (Hamblin 2005).[40]

A novelty introduced in the course of the IGY were the so-called World Data Centres (WDC). These centres were responsible for collecting and openly disseminating data. The designers of the IGY felt from the beginning that full and open access should be granted to all participants. Three WDCs were established: one in the United States, one in the Soviet Union, and one data centre spread across several Western European countries and Japan (Korsmo 2010). Like the IGY itself, the WDCs exemplify an aspiration for international cooperation and openness in science which was characteristic for geosciences in the 1950s and 1960s. Oceanography certainly featured prominently in these aspirations. As Aronova, Baker, and Oreskes (2010) point out, however, the American WDC for oceanographic data, operated by Texas A&M College, merged in 1961 into the United States' National Oceanographic Data Centre (NODC). As many other WDCs that originated from the IGY, the oceanographic WDC subsequently lost its international trait and became a national institution. The characteristic as a fundamentally international discipline, however, prevailed in the case of oceanography, as Hamblin (2005: xix) points out:

> The lack of national borders at sea, the indiscriminately hostile environmental conditions, and the global scope of observations have long lent oceanography the reputation of being an inherently international endeavor.

The need of international cooperation due to the oceans' nature has been an ongoing theme throughout the history of ocean sciences. On the occasion of the first International Oceanographic Congress in 1959, the eminent oceanographer Roger Revelle writes that 'the marine sciences are peculiarly international' and it is only appropriate that the congress was held at the Headquarters of the United Nations in New York (Revelle 1961: iii). The oceans, according to Revelle (1961: iii), are 'the property of no man and no nation but the heritage of every man and every nation'.

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[40] Bathymetry is the study of the ocean floors, or the equivalent to topography in the terrestrial sphere.

Rozwadowski (2004: 128) calls ‘the conviction shared by scientists that fish and water masses could be studied effectively only by means of international collaboration’ an ‘environmental necessity’. Indeed, most of the large-scale oceanographic programmes considered successful since the 1950s have been internationally coordinated efforts. According to Rozwadowski (2004), the oceanographic community is among the most successful scientific communities in realising international cooperation. Collaborations have grown since around 1900, and increasingly since 1945, into an ‘integral part of ocean science’ (Rozwadowski 2004: 128). Besides environmental necessity, however, national interests and the political and intellectual context must not be neglected as motivating factors whenever governments decide to fund and encourage international oceanography projects (Rozwadowski 2004). The IGY is a prime example of the way international collaborations in geosciences were subject to political agendas (Hamblin 2005: 59–98). At the same time, international cooperation served as a common denominator for North American and European oceanographers for launching a wide range of projects and activities which ‘might have appeared incongruous or even conflicting’ in times of geopolitical tension (Hamblin 2005: xxiii). Since the Cold War, oceanography has become less relevant to national security and geopolitics; military financing of oceanographic research only grew until the early 1970s (Conway 2006: 129), when space travel, science from space, and environmental topics became more relevant than the oceans as a strategic battlefield. However, with regard to climate change, energy resources, fisheries, global shipping, and tourism, oceanographic research has retained strong political interest until today and has also gained considerable economic relevance.

For ocean scientists worldwide, the IGY was a significant achievement with regard to collecting data of oceanic phenomena. In terms of methodology, however, the oceanographic programme can be regarded as relatively unsystematic. The subsequent decades of ocean sciences were to a great extent coined by efforts to design and develop data practices into connected observation systems and to integrate new technologies.

Until the 1970s, technological constraints restricted the production of oceanographic data mostly to ‘individual surveys, single time series, or spatial sampling with very limited duration’ (Davis 2006: 50). The 1973 Mid-Ocean Dynamics Experiment (MODE) was therefore ‘revolutionary’ for oceanography, as it was ‘the first large-scale observing effort that combined diverse observing tools into a designed system’ (Davis 2006: 50–51). MODE was specifically conceived to investigate mid-ocean phenomena in an area south-west of Bermuda over a period of five months. The idea was to bring enough instrumentation into a relatively small area of the open ocean to be able to create maps of current velocity and water density. These data were intended to cover a time period long enough for an assessment of the dynamical balances controlling the circulation (Bretherton 2006: 20). MODE exemplifies that by the 1970s, long, coast-to-coast hydrographic surveys typical for the IGY and earlier ocean science had become less popular among scientists. This was partly caused by their limited, mostly qualitative usability, which contrasted with MODE’s closer studies of processes by means of new technology. Eminent oceanographer Carl Wunsch claims that MODE was one of the more “dynamic” and ‘more scientific-seeming’ process studies (Wunsch 2006: 187–88).

With regard to new ways of creating data, MODE included an array of 26 subsurface moored current meters and temperature-pressure recorders. A moored measuring platform consists of an anchor, a stack of railroad wheels is commonly used, and a steel wire with various measurement instruments attached to it, with buoyancy bodies at the top to keep the wire in an upright position. Moorings often remain deployed for several years until they are recollected. The ability to store data internally until a mooring is picked up was relatively new when MODE was planned.[41] MODE further featured a grid of 77 hydrographic stations that were each repeated on twelve individual surveys, acoustic and electromagnetic profilers,[42] and twenty neutrally buoyant floats

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[41] Today’s moorings usually transmit data in real-time from surface and sub-surface buoys via satellite. Moorings with surface buoys are further capable of recording meteorological data and data of air-sea interaction phenomena (Weller et al. 2000).

drifting at 1,500 metres depth that were tracked by acoustic signals (Davis 2006: 50–51, MODE Group 1978).

Apart from a small number of German and British scientists and institutions, MODE, was an experiment dominated by American scientists, institutions, and funding bodies. MODE took place within the International Decade of Ocean Exploration (IDOE), but as Hamblin (2005: 264) shows, the IDOE and other similar projects ‘sprang forth from the American marine affairs bureaucracy, not from American scientists, and certainly not from the international community’.

3.4.2 New technologies against data scarcity

Numerical modelling of the earth’s climate based on mathematical theories was envisioned long before any existing technology was able to perform the complex mathematical operations. Most notable are Richardson’s (1922) attempts at numerical weather forecasting in the 1910s and 1920s. The American Institute of Advanced Study (IAS) conducted pioneering work in numerical weather forecasting during World War II. After the war, only few research institutions were equipped with expensive computers capable of numerical modelling of weather, climate, and oceans; renowned American oceanographic laboratories were not among them. Rather, institutions with a focus on climate studies were leading in the development of ocean models, for example the US Weather Bureau General Circulation Laboratory in Princeton, NJ, or the National Center for Atmospheric Research (NCAR) in Boulder, CO.

At the Weather Bureau, numerical ocean modelling began in the early 1960s with two-dimensional models of an ocean basin and simulations of the wind-

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[42] Oceanographers speak of a “profile” when referring to one-dimensional data of a parameter measured in vertical intervals at one geographical location. A temperature profile, for example, is a series of temperature values measured throughout the “water column”, that is between the ocean’s surface and a specific depth or the ocean floor at one distinct location. Profilers are instruments, which record individual profiles of the water column; a series of profiles located along a straight horizontal line is commonly termed a “section” and results in two-dimensional arrays of measured values.

driven oceanic circulation; three-dimensional models appeared in 1969. The growing scope and complexity of numerical ocean models from the 1960s onwards required amounts of data which were not available at the time. The models needed data from regions, which had never been sampled and spatial resolutions higher than those of the data available.

Numerical models were the primary research tool for dynamic oceanographers who sought to address practical problems of the oceans (Hamblin 2014: 353). Dynamic approaches gained popularity among oceanographers in the second half of the twentieth century and often included a rather dismissive view on descriptive oceanography as mere data collecting and not real science (Hamblin 2014: 360–62). Ironically, however, the dynamic approach required the collection of more and more data and made oceanography for several decades 'more descriptive than ever, flooding it with data, most of which sat unused' (Hamblin 2014: 360).

Early global ocean models were often criticised for being unverifiable due to the lack of comparable data and for insufficient knowledge to set the models' initial conditions, boundary conditions, and forcing parameters (Bryan 2006). It appears that the dynamic and descriptive approaches did not come together to resolve this problem, probably because the development of models outpaced the production of data and always required higher resolutions and greater coverage than those achieved by descriptive oceanographers. Regarding the scarcity of oceanographic data, Wunsch recounts:

> Anyone who understood models realized [by 1979] that the more sophisticated the model, the more demanding the requirements on the observations. It was obvious that numerical models of the ocean were about to outstrip any observational capability for testing them. There was a grave danger that the field would produce sophisticated, interesting models, without any ability to calibrate them. (Wunsch 2006: 187)

Today, numerical modelling is an integral part of oceanography and models with a wide range of characteristics are being used. The scales of models range from exemplary process studies, for example vertical diffusion on a scale of centimetres or sea ice formation, to three-dimensional simulations of ocean basins and entire planets. Oceanographic models may or may not be coupled to models of the atmosphere, the biosphere, or the cryosphere, and they may or may not include certain chemical, biological, or geological processes. Needless to say that numerical models produce large amounts of data for scientists to analyse. However, as was the case with the earliest ocean models in the 1960s, today's numerical models still require new data and tend to require more data the more complex they become.

Alongside electronic computers, earth-observing satellites emerged and rapidly progressed as a technology in the course of the Cold War and had a substantial impact on earth sciences. Instruments mounted on satellites led to the production of a new type of data, known as "remote sensing" data. Until the advent of satellites, almost all oceanographic data were "in-situ", meaning that a measuring instrument's sensor has been in direct physical contact with the object or process that is measured, for example when a resistance thermometer is lowered directly into sea water. By contrast, "remote sensing" data are produced when the sensor measures a parameter from a distance and indirectly.

Using radiometry technology, sensors mounted on satellites are able to receive and measure radiation emitted or reflected by the earth's and oceans' surfaces. NASA's Seasat 1, launched in 1978, was the first satellite designed for remote sensing of the world's oceans to use synthetic aperture radar (SAR) which generates higher resolutions than normal radar technology by simulating an extremely large antenna aperture along the satellite's flight path. Seasat 1 was designed to produce data related to sea-surface wind, sea surface temperature (SST), wave height, internal waves, atmospheric water content, sea ice features, and ocean topography.[43] The mission demonstrated the feasibility of

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[43] Ocean topography or sea surface height (SSH) is the height of the sea surface level relative to the earth's geoid, which is the shape that the oceans' surface would take only from gravitational and rotational forces and in absence of winds and tides. Differences between SSH and the geoid indicate variations in density of the underlying sea water.

oceanographic remote sensing despite transmitting only 42 hours of real-time data due to a technical failure.[44] SST is one of the most important parameters measured from space. The ocean water's temperature is relevant for physical, chemical, and biological phenomena, not just in oceanographic but also in meteorological and climatological contexts (Thomson and Emery 2014: 27–35). Two general advantages of remote sensing data are the global coverage of ocean surfaces, which will never be matched by in-situ measurements, and in many cases, near real-time access to data due to highly automated data processing.

However, remote sensing data require complex corrections and calibration with in-situ data, due to the effects of various phenomena such as clouds, winds, or coastlines. Therefore, much effort and a variety of theoretical assumptions are needed to produce usable remote sensing data before any data can be analysed. A major drawback of satellite remote sensing data compared to in-situ measurements from ships is that only phenomena on the ocean's surface are visible, such as the surface temperature, salinity, height, roughness, and water colour. Despite these characteristics, oceanographic remote sensing data have become invaluable for applied and basic oceanographic purposes.

As Conway (2006) shows, satellite technology promised to provide strongly desired spatial data on a global scale, but data volumes were created which most traditional oceanographic institutions could not handle by themselves. As a response to this overload of information, NASA created its own oceanographic data centre for the purpose of validating and distributing data to users in the scientific community. This marks a notable separation between data producers and data users, a division of labour which is a key characteristic of data-intensive sciences and which quickly became a 'new normative practice' in oceanography (Conway 2006: 150).

At least partly in response to the inability to calibrate early numerical models and satellite observations with in-situ data, planning for an international measuring programme, the World Ocean Circulation Experiment (WOCE), began in the late 1970s. The observational phase of WOCE, however, started

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[44] <http://science.nasa.gov/missions/seasat-1/> [accessed 10 December 2015].

only in 1990 and ended in 1998.[45] One of the main goals of WOCE was to survey the global ocean without spatial restrictions in a relatively short time span in order to create a snapshot of the state of the oceans that leaves no major gaps (WOCE International Project Office 2003: 6). Wunsch (2006: 182), who chaired WOCE's International Steering Group, described the programme retrospectively as the 'centerpiece' of oceanographic research during the 1990s. The core of the international programme, in which around thirty countries were involved, was a coordinated ship-based hydrographic measuring programme spanning the entire globe and producing a global oceanographic dataset.[46] 31 countries expressed their intention to commit resources and contribute to WOCE in 1988. 22 countries had been involved by the end of the programme's field phase, with more than fifty percent of the contributions coming from the United States (Thompson, Crease, and Gould 2001: 37).

Until WOCE, the primary mechanism to archive and share data was still through the World Data Centres first implemented in the 1950s as part of the IGY. For WOCE, a new system with seven Data Assembly Centres (DACs) supervised by scientists at research institutions was implemented. The DACs implemented world wide web communication and links to the datasets from as early as 1994 onwards. WOCE achieved 'unprecedented cooperation of scientists in submitting the data' and led to the principle of data sharing being widely accepted in the oceanographic community (Thompson, Crease, and Gould 2001: 39–41).

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[45] WOCE was one of three major programmes of the World Climate Research Programme (WCRP) between 1980 and 2005. WRCP was established in 1980 sponsored by ICSU and the World Meteorological Organization (WMO). The IOC has been a sponsor of WCRP since 1993; <http://www.wcrp-climate.org/about-history> [accessed 7 December 2015].

[46] All of the cruises measured conductivity to calculate salinity, temperature, and depth (CTD) by lowering CTD sensors into the water at predetermined stations in intervals of not more than fifty kilometres. Additionally, most research vessels produced water samples for tracer analysis, meteorological data, bathymetric data, and current profiles (WOCE International Project Office 2003: 7).

As Wunsch (2006) notes, oceanography was different after WOCE than it had been before. Regarding oceanographic data, there were no more completely blank areas on the map. Even though WOCE could not take measurements everywhere, oceans were at least covered to an extent that allowed reasonable estimations of remaining unknowns. WOCE is until today the largest internationally coordinated programme in oceanography ever conducted and provided the scientific community with a quantitative snapshot to be used as a baseline for decades to come. Further, the focus of oceanography shifted during WOCE and towards its expiration. The main challenge was no longer to gain any data at all from previously unknown regions. In light of growing concerns about climate change, the new challenge became the implementation of sustainable, long-term monitoring networks that could record changes over time. A central research problem in relation to climate change is to find out how much of the variation in physical, biological, and chemical characteristics of the oceans is due to natural oscillations and developmental cycles and how much is caused by anthropogenic influences. To disentangle patterns and events in oceanographic data and distinguish long-term responses to climate change from local, high-frequency noise and anomalies continuous, long-term monitoring of the oceans is essential (Hawkins et al. 2013, Sukhotin and Berger 2013). The success of the global WOCE experiment thus also shifted the interest of oceanographers back to regional scales and local variations of processes relative to the global picture (Wunsch 2006). To implement consistent long-term monitoring, the Global Ocean Observing System (GOOS), which is the oceanographic component of the multi-national Global Earth Observing System of Systems (GEOSS),[47] has been planned and implemented since 1991. GOOS is designed to monitor the global oceans permanently for basic scientific and applied purposes using a variety of platforms, such as autonomous floats, buoys, embarked systems on commercial ships, research vessels, launched probes, and moorings.[48]

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[47] GEOSS is created by the Group on Earth Observations (GEO), a partnership of more than one hundred governments and participating organisations based in Geneva, Switzerland; <https://www.earthobservations.org/geo_community.php> [accessed 19 June 2018].

Similar to previous large observational programmes, WOCE introduced new technologies, most notably an array of autonomous measuring instruments named Argo floats. Argo floats produce hydrographic profiles in the ocean's upper 2,000 metres by changing their buoyancy automatically and moving vertically up and down the water column. Upon reaching the surface, the recorded data are transmitted via satellites into a database. A float then descends to its so-called "parking depth", usually around 1,000 metres, and drifts with the ocean currents for ten days before starting another measuring cycle (Argo Science Team 2001). The International Argo Project is responsible for coordinating the worldwide deployment of Argo floats, which began in 2000. Today, thirty countries participate in the Argo project; their contributions vary between sponsorship of only one float and up to fifty percent of the entire array, which is the United States' contribution. The funding is decentralised and distributed over more than fifty research and operational agencies which finance national Argo programmes by a variety of funding mechanisms.[49]

Initially only aiming at a number of 3,000 Argo floats in constant operation, the number of floats as of June 2018 is almost 4,000 with a deployment rate of around 800 floats per year. The permanently drifting Argo floats amount to a dynamic array of measuring instruments covering nearly all areas of the oceans. This includes many locations that are hardly accessible with any other available and affordable oceanographic method, for example the high latitudes in the southern hemisphere, where the world's most powerful ocean current circles Antarctica. With respect to spatial coverage and quantity of in-situ oceanographic data, the Argo project is unprecedented. In 2012, the Argo project celebrated its one millionth measured profile, which is roughly twice the amount of profiles obtained by all research vessels during the twentieth century worldwide (Argo Project Office 2012). While all research vessels worldwide create around 5,000 hydrographic profiles every year, Argo produces more than a hundred thousand, without any bias caused by seasonal conditions that

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48 GOOS is sponsored by the IOC, WMO, ICSU, and the the United Nations Environment Programme (UNEP); <http://www.goosocean.org> [accessed 12 July 2018].

49 <http://www.argo.ucsd.edu/Organisation.html> [accessed 25 February 2016].

restrict the use of ships.[50] In addition to the core hydrographic parameters temperature, salinity, and depth, Argo floats are increasingly equipped with sensors for dissolved oxygen, particle backscattering, sea water turbidity, chlorophyll *a*, nitrate, or pH level (Carval et al. 2014). These parameters extend the scope of Argo data from mostly physical oceanography to biological oceanography and ocean chemistry. Furthermore, the fully automated, real-time quality control and data storage, all within 24 hours of measurement, make Argo data a valuable resource not just for basic scientific, but also for applied, operational purposes.

A major advantage of Argo floats in comparison to ship-based data production is that it reduces the costs of creating in-situ data significantly. Operating a research vessel on the open ocean can cost $20,000 per day with the salaries of researchers not included. The purchase of a single Argo float, which produces data for several years costs approximately $16,000. This makes oceanographic science and data production much more affordable for smaller organisations or countries without dedicated research vessels (Lehman 2017: 73–74).

Just as Argo floats with new sensors have become increasingly useful for chemical and biological research, other technological developments have broadened the scope of oceanographic subdisciplines and blurred the boundaries between them. Sonar technology, for example, originated during World War II and has been employed for physical oceanography in combination with drifting floats to measure ocean currents. But sonar technology became also useful for mapping the bathymetry of ocean basins, for finding fish schools, and detecting and tracking high concentrations of larger zooplankton (Lalli and Parsons 1997: 13).

Satellite remote sensing also produces data highly relevant for biological oceanography and marine biology, thanks to marine organisms' sensitivity to temperatures. Additionally, plankton blooms are made visible via remote sensing of the ocean surface colour. Remote sensing provides 'an unprecedented global time series of satellite-derived parameters relevant to

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[50] <http://www.argo.ucsd.edu/Novel_Argo.html> [accessed 25 February 2016].

algal bloom studies' (Blondeau-Patissier et al. 2014: 139). NASA first launched an ocean colour sensor into space aboard Nimbus-7 in 1978, which operated until 1986. Following a ten-year data gap, several satellite missions since 1996 have used a variety of ocean colour sensors and algorithms, resulting in datasets which allow for the derivation of important ecological baselines (Wilson 2011, Blondeau-Patissier et al. 2014). Viewed from space, ocean colour is also useful for physical oceanographers, as differences in ocean colour make ocean fronts,[51] horizontal currents, or rotational phenomena such as eddies detectable. In light of these examples, it is not uncommon at all that one oceanographic data product is re-used in several research contexts associated with different sub-disciplines.

3.4.3 Limitations and opportunities

Despite earth-observing satellites and other highly automated observing systems, biological oceanography in particular requires ocean scientists to go to sea in order to take water and species samples or to measure biologically relevant parameters inside the oceans. However, sampling the oceans from ships comes with 'many constraints on what can be done, where, and how often' (Widdicombe and Somerfield 2012: 1). There are unknowns such as weather conditions and the ships' and instruments' functionality. The 'fundamental weakness' of ship-based observations, however, is the high cost that is involved in going to sea (Lauro et al. 2014: 1):

> A modern ocean research vessel typically costs more than US$30,000 per day to operate—excluding the full cost of scientists, engineers, and the cost of the research itself. Even an aggressive expansion of oceanographic research budgets would not do much to improve the precision of our probabilistic models, let alone to quickly and more accurately locate missing objects in the huge, moving, three-dimensional seascape. (Lauro et al. 2012: 1)

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[51] Similar to a weather front, an ocean front is a relatively sharp boundary between two water masses characterised by different physical properties.

As a result, the majority of the ocean floors have never been sampled and the vast majority of marine biodiversity records are from waters not deeper than two hundred metres (Widdicombe and Somerfield 2012: 1). The deep pelagic ocean, that is the open ocean and seas below two hundred metres, away from the coasts, and above the seabed, 'remains biodiversity's big wet secret, as it is hugely under-represented in global databases of marine biological records' (Webb, Vanden Berghe, and O'Dor 2010: 1). Hydrothermal vent ecosystems of the deep sea have only been discovered in 1977 by *Alvin*, the first deep-sea submersible capable of carrying passengers.[52]

By the year 2000, the lack of scientific knowledge about life in the open oceans led to a decade of coordinated, ship-based exploration, named the Census of Marine Life (CoML).[53] Around 2,700 scientists from more than 80 countries and associated with more than 670 laboratories around the world formed a community which aimed to create the first systematic delineation of marine organisms on a global scale. The work was organised and implemented by regional and national committees that coordinated more than 540 expeditions in total (Census of Marine Life 2010: 35). Some conceptualised CoML as a 'biological WOCE' (McGowan 1999: 33) which needed to produce a variety of different data, covering a wide range of scales. A proposed list of biological, chemical, and physical parameters to be measured during CoML illustrates the lack of disciplinary boundaries within ocean sciences:

> Micro organisms, phytoplankton and zooplankton, as well as temperature, salinity (for comparison to WOCE), nutrients, particulate organic carbon (for fine scale biomass), acoustics (for coarse grain biomass), and optics. (McGowan 1999: 34)

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[52] In 1974, *Alvin* also contributed to confirming the theory of sea floor spreading along the mid-Atlantic ridge, a fundamental finding in marine geology <http://oceanexplorer.noaa.gov/technology/subs/alvin/alvin.html> [accessed 8 December 2015].

[53] <http://www.coml.org/> [accessed 10 December 2015].

An important component of CoML was the implementation of the Ocean Biogeographic Information System (OBIS),[54] an ‘online, user-friendly system for absorbing, integrating, and accessing data about life in the oceans’, as no such thing had existed until then (Grassle 2000: 5). Furthermore, CoML led to an unprecedented listing of all marine species ever described in the World Register of Marine Species (WoRMS). Today, WoRMS features more than 220,000 described marine species.[55] Yet, results of CoML suggest that around 750,000 species have yet to be described and that over a billion types of microbes live in the oceans (Widdicombe and Somerfield 2012: 1). Similar to the inability to sample the entire ocean spatially, it seems hardly possible that scientists will ever be able to map the ocean’s biodiversity completely.

Since the early 1990s, DNA technology and related methods have brought new data practices and also new types of data to the study of marine organisms. The ways in which scientists study biodiversity have been transformed by methods such as the polymerase chain reaction and associated biological data practices. Around 1990, biological oceanographers and marine biologists began sequencing genes of marine organisms which were collected by ROVs, plankton recorders, or other sampling devices, in order to build genetic ecosystem libraries and to track evolutionary changes. Data are also produced from organisms kept for years in culture collections of natural history museums or other institutions. Through gene sequencing and DNA databasing, marine microbiology has experienced ‘something of a renaissance’, according to Helmreich (2009: 2). DNA sequence data have even further diversified the products of scientific activity that can be regarded as oceanographic data. Helmreich (2009: 2) contends that marine microbiologists have developed their own conception of the oceans as a microbial sea, an ocean that consists of genes and microbes and is not merely a body of water filled with organisms.

Aside from exceedingly expensive high-technology and large-scale scientific programmes which sometimes require decades of planning, oceanographers have tackled data scarcity by exploiting infrastructures and actors that already

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[54] OBIS is a project of IOC; <www.iobis.org> [accessed 10 December 2015].

[55] <http://www.marinespecies.org/> [accessed 10 December 2015].

interact with the oceans on a regular basis. As I will discuss in the introduction of chapter seven, ocean scientists have high hopes that citizen science projects can complement today's integrated observation systems and also reduce the costs of continuous data production considerably.

Commercial ship traffic is also involved in today's efforts to produce more in-situ data of the oceans. The volunteering ships are often referred to as "ships of opportunity" by research organisations. In this thesis' main case study, the CPR Survey, ships of opportunity have routinely been towing sampling devices on their regular shipping routes since the middle of the twentieth century. Several oceanographic research organisations are collaborating with ships of opportunity as a part of their observation networks. These may be equipped with wired probes named expendable bathythermographs (XBT). These are dropped into the water to record the temperature on their way down. An XBT eventually tears off the wire transmitting the data back to the ship and sinks to the ocean floor. Another regularly used technology are thermosalinographs (TSG) which are mounted at the water intake of ships and measure sea surface temperature and salinity.[56] Implications of these types of collaborations in which research technology is handled and operated by a ships' crew and not by scientists are also discussed in chapter seven of this thesis.

Some unique in-situ data are produced from sensors that are attached to living animals. Oceanographers of the UK's National Environmental Research Council's Sea Mammal Research Unit at the University of St. Andrews, for example, equip elephant seals with small and inexpensive CTD data loggers. In addition to tracking the movement of the seals, these recorders create vertical profiles whenever the seal dives and use the same satellite system as the autonomous Argo floats for positioning and sending data in near real-time to a database. Such systems could be complementary to existing sampling technologies, particularly close to coasts and in regions that are rarely visited by humans (Boehme et al. 2009, Carse et al. 2015).

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[56] The National Oceanic and Atmospheric Administration's (NOAA) ship of opportunity programme is part of GOOS and features both XBTs and TSGs; <http://www.aoml.noaa.gov/phod/soop/index.php> [accessed 13 June 2018]

For ocean scientists, data production has gradually become more remote with the implementation of satellite technologies, automated floats, remotely operated vehicles, moorings, and citizen science projects. Lehman (2017) reflects on the shift from ships to robots and the implications for practising ocean science. The increased remoteness of contemporary sensing networks keeps many ocean scientists from experiencing embodied encounters with the oceans. Their object of study seems to become an increasingly abstract field of data from which scientists have been abstracted away, resulting in 'the illusion of not only complete knowledge but also disembodied objectivity' (Lehman 2017: 58). This image is also reflected in the microbiologists' picture of an ocean of genes and DNA sequences (Helmreich 2009). However, as Lehman argues, all practices of producing knowledge are situated, even though remote technologies might obscure the perspective of humans or machines. Moreover, it is virtually impossible to encounter the oceans in an unmediated way: 'The ocean's temperature and pressure extremes and lack of light and oxygen mean that humans must have relationships with machines to make sense of it' (Lehman 2017: 74). The introduction of remote technologies emphasises 'the linked materiality of the ocean and the technologies necessary to sense it' (Lehman 2017: 74). Chapter four explores precisely this material link between oceans and technologies.

Lehman (2017) also makes an important point with regard to those who practice ocean science. New technologies have made oceanography a more inclusive scientific endeavour since data are accessible to any researchers almost anywhere at any time. Traditional ship-based oceanography, Lehman (2017: 73) points out, has been surrounded by 'ideologies of heroism, conquest and adventure' and was conducted almost exclusively by white men. The various new ways of sensing oceanic phenomena defied the romanticised dominance of the seafaring ocean scientists that was established since the beginnings of the discipline, as Rozwadowski (1996) has described. New ocean sensing technologies thereby contributed to reconfiguring not only relations between researchers and the oceans but also the social constellations of practising ocean science.

3.5 The Continuous Plankton Recorder Survey

This thesis' main case study is the Continuous Plankton Recorder (CPR) Survey, a long-term programme for creating samples and scientific data that relate to spatio-temporal plankton distributions in the world's oceans. Until April 2018, the survey was run by the Sir Alister Hardy Foundation for Ocean Science (SAHFOS) from Plymouth, UK.

SAHFOS was an internationally funded charity and employed around 42 people at the time of my empirical research. Slightly more than a quarter of these were employed as plankton analysts, slightly less than a quarter as researchers. Twenty percent were employed in 'operations', eighteen percent in administration, six percent in instrumentation, and four percent in IT (SAHFOS 2016: 4–5). The CPR Survey is funded through grants and contract income from three primary funding organisations, the NERC, the UK Department of Environment, Food, and Rural Affairs (Defra), and the US National Science Foundation (NSF). Additionally, several specific research activities are funded by a range of research and academic organisations such as the British Antarctic Survey, the Royal Society, the European Union, the European Environment Agency, the Institute of Marine Research Norway, the Greenland Institute, and the Canadian Department of Fisheries and Oceans. The labs, offices, and facilities of the CPR Survey are housed right above Plymouth Sound inside the "Citadel Hill Laboratory",[57] which has a long history in marine science. The Laboratory has been home to the MBA since its construction in 1887–88. The MBA has shared the building with the National Marine Biological Library (NMBL) and since 1993 with SAHFOS as well.[58]

During the final months leading up to the completion of this thesis, SAHFOS has merged with the MBA and from April 2018 onwards, the CPR Survey is officially run by the MBA. The name "SAHFOS" has now largely disappeared

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[57] When referring to the "Citadel Hill Laboratory" throughout this thesis, I use the term "Laboratory" capitalised. The actual laboratory of the CPR Survey where plankton samples are analysed is referred to as "laboratory" or "lab", non-capitalised.

[58] <www.mba.ac.uk/nmbl/projects/history/125laboratory> [accessed 13 April 2016].

from websites and official statements related to the CPR Survey.[59] The research for this thesis was conducted in the three and a half years prior to this merger, during which SAHFOS was still running the survey. Therefore, in descriptions of the case I frequently refer to SAHFOS as the institution running the survey and as the organisation that employs the researchers, although as this thesis is being submitted, the survey and its employees work officially under the banner of the MBA.

The CPR Survey has a long history. The mechanical sampling device, which gave the survey its name, was invented by fisheries ecologist Alister Hardy in the 1920s for the purpose of monitoring zooplankton, the key food source of larval fish (McQuatters-Gollop et al. 2015: 2). A 'pioneer period' in the 1930s, in which the design of the CPR and steps of analysis were experimentally developed, was followed by a period of non-activity lasting eight years due to World War II (Reid et al. 2003: 130). The survey resumed in 1946 and as I discuss in chapter six, the methods of sampling and sample analysis have remained largely unchanged since the 1950s (Reid et al. 2003: 131–32). With datasets spanning more than eighty years, the CPR Survey has created some of the longest running time series in environmental and marine science (McQuatters-Gollop et al. 2015: 2). The methodological continuity is one of the most important aspects of the survey and is vital for its reputation and prestige in the scientific community.

Despite having already been recording continuously for some thirty years, it was decided in the 1980s to shut down the CPR survey because politicians did not see any reason to continue this and other long-term environmental time series. At the time, 'monitoring was considered weak science, akin to stamp collecting' (Reid et al. 2003: 141). Long-term marine monitoring programmes in Europe were terminated at an 'alarming' rate with forty percent of European programmes being shut down in the late 1980s, as Duarte, Cebrián, and Marbà (1992: 190) warned in *Nature*. Unlike many other programmes, the projected closing of the CPR Survey led to an international initiative strongly supported by

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[59] <https://www.cprsurvey.org/about-us/the-continuous-plankton-recorder-cpr-survey-has-merged-with-the-marine-biological-association/> [accessed 7 June 2018].

IOC and the International Council for the Exploration of the Sea (ICES) to form a rescue fund and establish SAHFOS as a charity organisation in 1990 (Reid et al. 2003). The survey was conducted until 1950 by the University College of Hull, until 1976 by the Scottish Marine Biological Association in Edinburgh, and until 1990 by the Institute for Marine Environmental Research, which is now the Plymouth Marine Laboratory (PML) located not far from the Laboratory (Reid et al. 2003: 119).

According to its Director, SAHFOS' core work was the running of the CPR Survey:

> SAHFOS' core activity is of course the maintenance of the Continuous Plankton Recorder (CPR) Survey. The CPR Survey started in 1931 and SAHFOS has had the considerable and weighty responsibility of continuing the running and safeguarding of the CPR Survey since 1990. (Owens 2015: 2)

Many activities that amount to "maintenance" of the survey are described and discussed in detail in this thesis' empirical chapters. In addition to this core activity, SAHFOS conducted 'ancillary activities and associated science' (Owens 2015: 2). Researchers were involved in the development and testing of new instruments, in policy-driven work, or in education and outreach. Several research fellows studied environmental change, marine biodiversity, sustainable resources, and health and well-being of marine food sources.[60] A small molecular research team received organisms for analysis first-hand from the CPR samples and other water sampling techniques that a CPR may be equipped with (SAHFOS 2015).

A CPR is a mechanical sampling device towed by commercial ships on their regular shipping routes. As explained in detail in the following chapters, the survey produces hand-sized pieces of silk that have filtered ocean waters and contain plankton organisms. Sample analysts in Plymouth use microscopes to identify and count plankton organisms in order to create scientific data. All samples are preserved and archived in Plymouth to enable re-analysis in the

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[60] <https://www.sahfos.ac.uk/research/our-science/> [accessed 23 April 2016].

future. According to a counter on the survey's website, as of June 2018, more than five million nautical miles have been sampled with CPRs in total and the database contains more than three million taxonomic abundance entries.[61]

The CPR Survey operates mainly in the North Atlantic and the North Sea, where most of the circa twenty-five routes and also the oldest regularly sampled routes are located. Ships that are regularly equipped with CPRs leave from various ports around the UK and Europe, including ports in Norway, Denmark, Iceland, the Netherlands, and Ireland. Two regular routes are operated in the North Pacific between US, Canadian, and Japanese ports, and one in the Southern Ocean between the Falkland Islands and South Georgia (SAHFOS 2016: 12–13). The CPR Survey has several sister surveys in that are run by local research institutions and focus on seas in their region, for example, in the North Pacific CPR Survey or the Australian CPR Survey. In 2011, the regional CPR projects joined to establish the Global Alliance of CPR Surveys (GACS) which works towards developing a global database and ensuring common standards. SAHFOS has supported these surveys with equipment and know-how, organising regular meetings and workshops in Plymouth (SAHFOS 2016: 60–61, SAHFOS 2017: 9).[62] In addition to the regular routes, the CPR Survey seeks cooperation with notable oceanographic expeditions and ships, for example the three-masted clipper *Stad Amsterdam* which recreated a famous voyage made by Charles Darwin, or the Tara, a schooner dedicated to environmental expeditions that towed a CPR through the Arctic Ocean (DR1960: 4).[63]

Since the beginning of the CPR Survey, research based on CPR data has significantly contributed to the understanding of spatio-temporal dynamics of oceanic plankton and their response to anthropogenic pressures and climate variability. Today, the data are also used routinely to inform UK and European marine policy-making and management of the seas (McQuatters-Gollop et al. 2015: 2).

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[61] <https://www.cprsurvey.org/> [accessed 7 June 2018].

[62] <http://www.globalcpr.org> [accessed 23 May 2016].

[63] <https://www.impress.com.au/newsroom/50-innovation/336-76m-clipper-arrives-in-adelaide-on-global-darwin-re-enactment-voyage.html> [accessed 18 June 2018].

3.6 Summary

Oceanography is not a clearly demarcated or defined research field. It encompasses research on the physics, biology, chemistry, and geology of the oceans, but any science related to the oceans and seas is often counted as oceanography. In this thesis, I often use the term “ocean sciences” instead of “oceanography” to emphasise the diversity of ocean-related research. I view oceanography or ocean science as an engagement in the oceans and seas which involves the collection of samples, the observation or recording of phenomena, the creation of data, or the production of knowledge from samples, records, or data. My emphasis on the production of records or data reflects that researchers only have mediated access to almost every object of oceanographic study; scientific observation of oceanic phenomena is only possible by engaging in the oceans with some kind of technical instrument.

I consider four aspects discussed in this chapter as characteristic for ocean sciences and as relevant for a contextualisation of this thesis’ main case study. These are a characteristic scarcity of data, a crucial necessity to create long-term data continuously, widespread multi-national collaborations in data initiatives and networks, and a mutual influence and at times confluence of scientific and seafaring cultures with characteristic notions of ocean science as the exploration or discovery of oceanic phenomena.

Despite increasingly automated and remote monitoring systems that penetrate locations humans could hardly visit, many regions of the oceans remain scarcely sampled, if sampled at all. According to NOAA, more than 95 percent of the oceans’ interior ‘remains unexplored’.[64] The high costs involved in producing in-situ data of the oceans’ interior, the adverse conditions, and the plain size of the oceans are the main factors that limit data production in these areas. Ambitious international efforts like the WOCE or CoML have achieved something like a global snapshot of the oceans and new technologies like satellite remote sensing or Argo floats have caused specific data to be available at unprecedented volumes. Such projects and developments have yielded great progress in ocean sciences, but the questions, research problems, and

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[64] <http://www.noaa.gov/ocean.html> [accessed 28 December 2015].

numerical models of oceanographers have become increasingly complex and diversified in ways that require even higher spatial and temporal resolutions or more parameters to be measured at remote locations. Even if oceanographers technically know how these data could be produced, the high costs of ship-based research limits their capacities. To tackle data scarcity, ocean scientists need to find efficient ways of bringing a sensor to the most remote areas of the oceans regularly.

Several of the most central questions addressed by ocean scientists, as well as contemporary ocean and climate models, require data to be produced over long time periods with reasonably consistent methods. Regarding large-scale processes, the oceans are a system of slow response with time scales that can exceed the typical durations of research projects and the lifespans of measuring instruments by far. The longest continuous oceanographic time series only date back around one hundred years[65] and the CPR Survey has its origin in the 1920s. Most of the contemporary initiatives intended for long-term monitoring like Argo, GOOS, or several earth observing satellites have been in operation for only two or three decades.

Some of the most important current and past oceanographic programmes and data-related initiatives are coined by international collaboration and joint efforts to produce, store, and disseminate data. Many ocean scientists realise that international cooperation in data production and data sharing are beneficial or necessary due to the nature of the oceans. Besides this environmental necessity, international collaborations in the middle of the twentieth century were also often politically motivated. The conviction to collaborate has shaped oceanographic practices and often encompasses the planning of projects, the production of data, as well as the storage and dissemination of data through

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[65] For example, the Western Channel Observatory, currently run by PML and the MBA is a sampling location in the Western English Channel visited weekly by a research ship since 1903; <www.westernchannelobservatory.org.uk> [accessed 21 June 2018]. The Shore Stations Program of Scripps Institution of Oceanography has been measuring temperature and salinity at fixed stations along the Californian coast since 1916; <https://scripps.ucsd.edu/programs/shorestations/> [accessed 21 June 2018].

online data portals such as DACs, OBIS, or WoRMS. The division of labour prevalent in data-intensive sciences is strongly pronounced in oceanography with researchers, projects, or even entire institutions being dedicated to either the production of data, their storage and dissemination, or their analysis.

Ocean scientists not only collaborate with each other, but also with seafarers and other actors rooted in maritime cultures. There is a mutual influence and dependency between scientists and seafarers, as scientist need the skills of seafarers to conduct research at sea and seafarers require certain kinds of knowledge of the seas in order to securely navigate ships. Until remote and autonomous technologies spread among research institutions, many ocean scientists combined skills of both spheres and ocean science was closely tied to adventurous seafaring experiences and discoveries of the unknown which were almost exclusively conducted by white European and North-American men.

Some terminologies used in ocean sciences actually reflect an emphasis on exploration and discovery[66] that resonates with the adventurous but is also due to the fact that so many areas of the oceans are still unobserved and scarcely described. Exploration and discovery could also be viewed as approaches driven by environmental necessity. As the ocean scientists Widdicombe and Somerfield (2012: 1) point out, ‘humans are terrestrial creatures, and those with a deep knowledge of the sea tend to be those associated either with its exploitation or exploration.’ According to this view, the nature of humans and the nature of oceans are related either by exploitative or exploratory activity. Exploitation of the oceans may relate to human activities such as fishing, mining of raw materials, or trading — the activities of non-scientific seafarers. Exploration of the oceans relates to scientific activities leading to the creation of knowledge and to recreational seafarers. In any case, ocean scientists can hardly pick up and take their object of study into a laboratory on land. They

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[66] For example, see NOAA’s statement that 95 percent of the interior oceans are ‘unexplored’, <http://www.noaa.gov/ocean.html> [accessed 28 December 2015]. The title of the CoML’s review of the programme’s first ten years reads *First Census of Marine Life 2010. Highlights of a Decade of Discovery* (Census of Marine Life 2010). The title of Rozwadowski (2005) reads *Fathoming the Ocean: Discovery and Exploration of the Deep Sea*.

need to actively reach out to the sea by installing research instruments or entire laboratories on ships that visit and interact with the phenomena. This approach was already implemented with the transformation of the *Challenger* into a research vessel in the 1870s and is also the heart of this thesis' main case study, in which commercial seafarers take scientific equipment along on their regular shipping routes.

Chapter Four – The epistemic value of materiality: Integration, continuity, and the creation of samples in the CPR Survey

Abstract: This chapter focuses on sampling and on the notion of "materiality". It describes in detail the process of creating hand-sized pieces of silk that contain plankton organisms of the oceans and are prepared for microscopic analysis. Fleshing out the term "materiality", I argue that ocean scientists create material samples by inducing a "material integration" of physical parts of the ocean ecosystems and physical parts of the sampling technology. The fusion of materials from different origins constitutes the formation of a novel entity with distinct characteristics that take shape in the process of sampling. Preserving the newly created object throughout the epistemic process constitutes "material continuity" on which the creation of useful data crucially depends. I argue that samples, despite their tangibility, are not fixed entities that are collected or extracted from a given population in nature into the scientific world; rather, material continuity entails an ongoing process of embodiment that needs to be maintained and conveys the notion of a material object with clear boundaries. The chapter sharpens the understanding of "materiality" and "material", which are a widely used attributions to research objects and practices. It also develops a deeper understanding of samples, which have received much less attention in scholarly literature than scientific data, but are commonly regarded as representations of a population of similar objects. Based on my account, I locate the epistemic value of research samples primarily in their materiality and in the ongoing preservation of material continuity and not in a representational relation to a group of similar objects.

4.1 Introduction

Two kinds of objects play a central role in the research practices of this thesis' main case study: research samples and scientific data. In short, the oceans are sampled with mechanical sampling devices that produce bands of silk which contain plankton organisms; distinct pieces of silk — research samples — are then analysed with microscopes to create scientific data. In recent scholarly literature, samples have received much less attention than scientific data and databases due to the data-intensive developments of science and societies that are outlined in chapter one. While data have risen to new primacy in many research fields, the epistemological significance of sampling seems to be overshadowed, if not neglected.

Traditionally, samples are viewed as representations of a larger group of objects, based on a sample's specific physical or statistical properties, or potentially on both. But neither is it clear how samples differ from objects with similar characteristics such as certain forms of scientific data, nor have philosophers of science sufficiently accounted for the epistemological relevance of the physical constitution and preservation of research samples. Part of this chapter is a precise reconstruction of a sampling process in which physical characteristics and materials of different provenance take centre stage. With a specification of the term "materiality" in relation to objects in science, I anchor the epistemic value[67] of samples primarily in their materiality.

I propose an understanding of materiality as the integration of physical matter from various sources so as to constitute a new entity. The material integration is followed by the preservation of the entity throughout several if not all stages of the epistemic process without a change of medium. Material integration and material continuity are a two-fold characteristic applicable to objects that scientists create and use as well as to scientific practices. This understanding grounds the notion of "materiality" epistemologically rather than ontologically or in dichotomous opposition to attributes such as "nonmaterial", "virtual", or "theoretical". It further sidesteps the close association of samples with concepts of scientific representation, which is problematic for several reasons: In the practices I have studied, sampling in does not involve any form of intentional selection or abstraction of features from an original target to an object that

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[67] For the notion of "epistemic value", I refer to Steel (2010: 18), who defines it as a feature promoting the 'acquisition of true beliefs'. The term "value" is understood as a favourable influence on the outcome or direction of researchers' decisions and actions (Steel 2010: 21).

represents. Further, the sample lacks similarity with the ocean's ecosystems and are not reproducible as many other types of representations. Finally, an absence of jumps between different physical media, as my account implies with material continuity, clashes with the view of samples as straightforward representations that are extracted from nature into the scientific realm.

Material integration accounts for the origin of material objects in science and are part of the genesis of scientific data. Material continuity tracks the journey of these objects and fills part of the conceptual gap between the natural world and scientific institutions that I opened in chapter one.

This chapter begins with a review of philosophical and STS literature on materiality and samples. An empirical section reconstructs the sampling process in the CPR Survey and how samples are preserved and archived. I subsequently elaborate on material integration and continuity before discussing materiality and scientific representation.

4.1.1 Material objects and materialisation

Practices that induce a 'clash of materials' (Rheinberger 2011: 344) between living organisms and research technologies are central to many experimental practices in the life sciences. Objects of study that are part of such a clash or result from it may be described as "material" objects. A wide range of material objects with fundamentally different formation processes and physical characteristics are used in the life sciences: for example, anatomical preparations, model organisms, or species collections in museums.

Some scholars elaborate in relation to these objects what "materiality" implies epistemologically, showing that material interactions and knowledge production processes are often intertwined, but in a variety of ways. The materiality of anatomical preparations, for example, results in an 'indexicality' of the object that points to itself rather than representing something else (Rheinberger 2015: 323). Model organisms have standardised material characteristics that make them usable as 'genetic tools' (Ankeny and Leonelli 2011: 316). The materiality of species collections in a museum provides an epistemological robustness against potential changes of theoretical perspective because a material species can be re-analysed (Griesemer 1990: 83).

While many scholars have focused on specific kinds of material objects or material aspects of their case studies, the terms “material” and “materiality” tend to remain rather loosely defined. Quite often, it seems that “material” is used to signal difference or opposition to other classes of objects or processes which may be labelled “nonmaterial”, “virtual”, “theoretical”, “formal”, “mathematical”, “ideational”, or the like.[68] These oppositions seem to bear on differences in an entity’s physical constitution, stability, or tangibility, but also relate to its ontological status: Mathematical theories or ideas certainly differ ontologically from a sampled biological species. Coopmans et al. (2014: 5) relate a recent enthusiasm about the notion of materiality to scholars moving away from treating “digitality” as a primarily virtual or non-material notion. This shift from virtual to material somewhat reflects the dichotomous classifications of practices or objects, but also opens up the opportunity to flesh out what materiality means in relation to specific research practices.

According to Coopmans et al. (2014: 5) notions of materiality tend to ‘stress the embodied nature of scientific work, as well as the tools, objects, technologies, and environments in and through which science is practiced’. An example of this emphasis on embodied practices could be Rheinberger’s (1997: 28) definition of “epistemic things” as the ‘material entities or processes […] that constitute the objects of inquiry’. In this sense, the attribution “material” seems to relate to the tangibility and the physicality of objects or processes studied by scientists. Tangibility and physicality enable experimental intervention by means of research technologies that could be described as material, too. Coopmans et

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[68] For example, Wimsatt and Griesemer (2007: 296): ‘Changing technology—material or ideational—is never instantaneous.’ Knuuttila (2005: 1267): ‘All objects of human culture have both ideal (or virtual, if you like) and material dimensions.’ Morgan (2003: 231) attributes experiments different degrees of materiality: “material”, “semimaterial”, “pseudo-material”, “nonmaterial”, or “mathematical”. Griesemer (2014: 28–29) distinguishes “material” and “formal” ways of reproduction.

al.’s (2014) suggestion still leaves room for diverging interpretations and descriptions of material practices and objects. In some contexts, the meaning of materiality has been contested by scholars, for example, Morgan (2003) and Parker (2009) debate how to understand “materiality” in the context of experimental practices. Parker (2009: 492–93) criticises that computer simulations are often not seen as material experiments, despite the inevitable physical manifestation of all computing processes. Parker suggests that the emphasis on “stuff” may be misplaced and that epistemologically, the behaviour of a system is more important than any kind of ontological classification.

In STS literature, the meaning of materiality has been discussed in relation to a growing scholarly interest in ontology. As Woolgar and Lezaun (2013: 326) argue, what qualifies an object as “material” should be treated as a practical achievement; “materiality” should therefore be understood as an ‘upshot of practices’ of a certain kind. Reflecting on the range of material domains addressed in current STS scholarship, Coopmans et al. (2014: 5) broadly claim that material domains ‘constitute an infrastructure for scientific engagement with worldly phenomena’.

How the engagement with worldly phenomena unfolds in scientific practice is the central subject-matter of this chapter and may provide classifications involving “material”, “non-material”, or similar attributes with crucial context and a more solid grounding. Moreover, my study of infrastructures and practices to engage with natural systems and create material samples is an attempt to reveal and frame the epistemological significance of materiality.

Several feminist perspectives on materials and bodies account for “materialisation” or the formation and becoming of material entities. Although primarily referring to human bodies, feminist scholars like Judith Butler have thought of matter as ‘a process of materialisation that stabilises over time to produce the effect of boundary, fixity … we call matter’ (Butler 1993: 9, cited by Lennon 2014). This form of materialisation conveys the image of an ongoing process which, as Lennon (2014) points out, makes it impossible to account for materials and bodies as concise and fixed entities; reflecting the dynamics of discursive formations in the sense of Foucault (1969), the ongoing discourse creates its own objects. At the same time, however, possible alternative formation processes that could produce similar effects of boundary need to be explored (Lennon 2014). What I draw from this is the necessity to study the formation processes of material entities and to take into account the possibility that boundaries and the stability of objects are the effects of processes which could play out differently under different conditions, leading to potentially profound implications on how those bodies are perceived and conceptualised. The stabilising processes that convey the image of a material body take me back to the tension between change and continuity that underlie the research practices I have studied.

4.1.2 Statistical and material samples

Compared to other objects that are frequently generated and used in research situations, samples have received relatively little explicit attention from philosophers, historians, and sociologists of science.[69]

The relatively limited philosophical literature that mentions research samples suggests a close relation between data and samples, but leaves room for at least two possible epistemic constellations involving both types of objects: first, the creation of a sample from a set of data; and second, the creation of data from previously obtained samples. Additionally, it is not clear whether samples and data are to be regarded as generic research objects which require conceptional distinction, or as belonging to the same class or group of objects. Kitchin (2014a: 4–5) contends that even in research settings with unprecedented amounts of data, data are still ‘both a representation and a sample’. This overall lack of clarity might contribute to the scarcity of conceptional literature on research samples.

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[69] As for objects other than samples, see introductory chapter one for literature on data, Morgan (2012) on models, Ankeny and Leonelli (2011) on model organisms, de Regt and Parker (2014) on simulations and visualisations, Rheinberger (2010) on preparations, Devictor and Bensaude-Vincent (2016) on records.

Romeijn (2016), writing on the philosophy of statistics, claims that statistics focus on the relation between data and hypotheses. In this context, Romeijn defines data as follows:

> The *data* are recordings of observations or events in a scientific study, e.g., a set of measurements of individuals from a population. The data actually obtained are variously called the *sample*, the *sample data*, or simply the *data*. (Romeijn 2016)[70]

This definition suggests that there is not much of a difference between samples, data, and what Romeijn refers to as “sample data”; speaking of “sample” or “data” is then perhaps just a matter of terminological preference or disciplinary convention. A blurring of the two terms “sample” and “data” might be a relatively recent side-effect of ongoing discussions regarding the impacts of big data on science. Leonelli (2014a: 3) mentions a general disregard of debates about sampling due to the assumption that in big data science, all possible data relating to a specific phenomenon are always available for analysis. High-speed digital technologies and enormous storage capacities make worries about sampling appear obsolete. This view is made explicit in best-selling books such as *Big Data: A Revolution That Will Transform How We Live, Work, and Think*, in which Mayer-Schönberger and Cukier (2013: 31) argue that the constraints of sampling will no longer play a dominant role in the analysis of data: ‘Reaching for a random sample in the age of big data is like clutching at a horse whip in the era of the motor car.’ This quote illustrates how sampling and samples are overshadowed by discourses centred on data. Leonelli (2014a: 7) strongly disagrees with this belittlement of sampling, pointing out that her research on how biological data travel between locations and actors has highlighted ‘the ever-growing significance of sampling methods’; hence, ‘assuming that Big Data does away with the need to consider sampling is highly problematic’ (Leonelli 2014a: 7).

Whether or not to distinguish between samples and data has been debated by Woodward (2010) and Glymour (2000). As introduced in chapter one, Woodward primarily argues in favour of a sharp distinction between scientific

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[70] Emphasis in original.

data and phenomena. Glymour suggests that this distinction is not necessary, because the relation between data and phenomena is of the same statistical nature as the relation between samples and a population. Due to the extensive literature on statistical inference, Woodward's 'terminological reform' would be unnecessary and potentially misleading (Glymour 2000: 34). Woodward (2010: 802) responds that not all reasoning from data to phenomena can be viewed as statistical and that one cannot assume a single population for different measurements. The disagreement in this debate seems to stem from different understandings of a sample's relation to a population: Glymour emphasises a statistical understanding while Woodward suggests that there is more than just statistical relations.

The statistical understanding of a sample exemplified in Glymour's and Romeijn's works corresponds to one of several meanings of "sample" listed by the *Oxford English Dictionary* (OED): 'a portion drawn from a population, the study of which is intended to lead to statistical estimates of the attributes of the whole population'.[71] Romeijn (2016) explains that statistics relate 'empirical facts and hypotheses of a particular kind', more particularly that the empirical facts must be 'codified and structured into data sets' while the hypotheses must take the form of 'probability distributions over possible data sets'. It seems that the statistical understanding of a sample only applies to cases in which a sample is created from a codified and structured data set and hypotheses involve mathematical equations or tables stating the probabilities of an experiment's potential outcomes.

Two other meanings given by the OED seem relevant for my case, both suggest a material rather than a statistical understanding of "sample" and neither seems to always require structured data sets and mathematical probability distributions: 'a relatively small quantity of material, or an individual object, from which the quality of the mass, group, species, etc. which it represents may be inferred' and 'a specimen taken for scientific testing or analysis'.[72] Leonelli (2015: 817) seems to allude to these material understandings of "sample" in a

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[71] OED Online. 2016. 'sample, n.' (Oxford University Press), <http://www.oed.com/view/Entry/170414?rskey=GL5tpO&result=1> [accessed 13 May 2016].

list of examples compiled for the relational framework to conceptualise scientific data that I introduced in chapter one. Due to the crucial relations to the context of their use, data can include ‘experimental results, field observations, samples of organic materials, results of simulations and mathematical modeling, and even specimens’. According to this list, “samples of organic materials” have the potential to be used as data. In accordance with Leonelli’s (2015) framework, they are physical, portable artefacts that may potentially serve as evidence for knowledge claims. Yet, it remains unclear if samples and data are of the same category, if samples are a specific form or format of data, a sub-category of data, or something entirely different which only turns into data in a specific context. Notably, only a particular type of sample is explicitly included by Leonelli (2015: 817) when referring to “samples of organic material” in the context of biological science. Such samples are usually made from substances taken directly from the target population or manufactured from substances that imitate the target’s physical constitution.

Bogen and Woodward (1988) also employ the term “sample” with a material connotation in their discussion of data, phenomena, and theories, but rather as an actors’ category and without conceptualising samples in relation to data. Measuring practices to determine the melting point of lead involve a ‘sample of lead’ (Bogen and Woodward 1988: 308). The motivation to speak of samples is certainly due to the material similarity that small portions of lead in the laboratory share with each and every object made of lead. Similarly, Mody and Lynch (2010: 423) refer throughout their study of “test objects” to silicon samples with a specific atomic surface configuration. The emergence of these samples as preferred test objects among scientists is grounded primarily in similarity of physical characteristics with a range of other materials used in science and engineering. Although not clearly focusing on the epistemic role of samples or their use as representations, Mody and Lynch (2010: 458) count samples to a ‘“family” of objects’ including ‘model organisms, material standards, samples and so on’. These objects undergo historical shifts

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[72] OED Online. 2016. ‘sample, n.’ (Oxford University Press), <http://www.oed.com/view/Entry/170414?rskey=GL5tpO&result=1> [accessed 13 May 2016].

regarding their ‘epistemic status’: They can transform from novel entities into unsolved problems and into standard practices of an entire scientific community (Mody and Lynch 2010: 458). This variety of scenarios involving samples and similar objects suggests that, similar to scientific data, samples can be different things in different contexts. Consequently, their value for knowledge making processes might be grounded in specific relations to the context of use.

Ribes and Jackson’s (2013) case study of long-term ecological data production in hydrochemistry cannot be counted to the bulk of scholarly literature that tends to disregard the role of samples in science. Ribes and Jackson (2013) describe in detail how scientists and students create samples of stream waters in an urban area on a weekly basis and how data are routinely produced from the samples for long-term monitoring of the water’s chemical structure. The authors clarify what samples are in their case:

> Producing those data means isolating and transporting little bits of streams back to labs in ways that preserve meaningful relationships to those streams. These bits are called “samples”: a straightforward term that belies the work that meaningfully sustains them as representing a stream at a particular point in time. (Ribes and Jackson 2013: 162)

In this case, material “bits” or portions of the target are obtained in order to represent the stream based on similarity between the sampled water volumes and the water that remains flowing in the respective stream. For this representation, a relation between the sample and the stream, together with information on the context of sampling, must be established and preserved. The CPR Survey and Ribes and Jackson’s (2013) case are very similar with respect to the constellation of samples and data in research practice: Data related to a specific natural system are produced from previously created physical samples.

In summary, scholarly literature indicates that the primary role of samples in science is to function as a representation of a larger group of objects or a population. Further, scholars seem to allude to one of at least two ways in which samples are used as representations: either by virtue of statistical relations or by virtue of material similarity.[73] The focus on a sample's function as a representation suggests that the samples' usability as a representation is the primary reason for its epistemic value. My empirical study of a sampling practice is intended to reveal if and how this epistemic value is generated and planted into a sample.

Figure 4.1: External body of a Continuous Plankton Recorder (CPR).

4.2 Creating CPR samples

A Continuous Plankton Recorder (CPR) is a mechanical device designed for the uptake, retention, and temporary storage of marine organisms. Commercial ships tow CPRs via a steel wire at a depth of seven to ten metres. A CPR is made of steel and has a shape somewhat similar to a small bobsleigh; it weighs around ninety kilograms at a length of around one metre. A CPR consists of two main parts, an external body (fig. 4.1) and an internal cassette (fig. 4.2) that

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[73] The notion of "similarity" appears in conceptions of scientific representation. Giere (2010: 269), for example, views "similarity" as the 'basic relationship' between a representation and whatever is represented. Hacking (1983: 139) also mentions "similarity" but more often uses 'likeness' to describe this relation.

also made of steel and commonly just referred to as the “internal”. As of 2015, SAHFOS’ fleet of CPRs comprised 54 CPR bodies and 118 internals (SAHFOS 2016: 8). Most of the CPRs’ steel components are laser-cut so that all internal cassettes and external bodies are perfectly compatible with each other and have exactly identical shapes and edges. Only some of the oldest CPR bodies and internals that are still in used are hand-made.[74]

Figure 4.2: An internal cassette of a CPR that is not prepared for despatch.

4.2.1 The sampling process

A CPR gets assembled, set up, and boxed up at the CPR operations workshop at the ground floor of the Laboratory before a courier company takes the box to a port and the port logistics transfer it to the ship of opportunity scheduled to make the tow. The assembly begins with the manual preparation of silk rolls which are going to be used for filtering the sea water and fixating the organisms. The silk comes from a Chinese company in standardised rolls and is not specifically manufactured for use as a plankton filter (DR0533: 9).

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[74] The older CPR externals only have a few internal cassettes fitting into them. The CPRs are manufactured by a local engineering company (DR2901: 2).

As a first step, the person preparing the silk inspects the fabric and discards silk rolls with distortions, big creases, and too excessive curves. For each tow, two rolls of silk are loaded into the CPR's internal, a filtering silk that actually filters the sea water and a covering silk that rolls off on top of the filtering silk and fixates the organisms. These are prepared differently: The filtering silk is rolled out on a long workbench and a straight line is drawn every two inches across the length of the silk with a pen. This divides the silk into one hundred equal divisions, which is long enough for a tow of five hundred nautical miles. Each division is stamped by hand with an ascending number. The filtering silk is then rolled up and stored in a drawer that serves as a clean and dry environment. The covering silk is rolled out and the edges along the length of the silk roll are marked at a distance of one inch from each side of the silk band. These edges are then folded inwards by hand and the roll runs through a rotary iron. The purpose of the fold is to avoid plankton organisms to wash out at the sides of the silk roll.[75] To avoid crinkling of the silk when it is rolled up, a triangular area of silk is removed with scissors from the folds every four inches. The tips of the remaining folds are glued onto the filtering silk. Staff members preparing the silk need to be careful with the glue, as big blobs of glue may cause a jam in the CPR's internal mechanisms. The covering silk goes through the rotary iron one more time after gluing and then both silk rolls are ready to be loaded into the internal (DR1960).

As the preparation of the silk, loading the internal is done with bare hands. A steel tank is removed from the inside of the internal and filled with small pieces of cotton wool. Right before despatch of the CPR, the wool is impregnated with a forty percent formalin solution. During the tow and until the CPR is back in Plymouth, the cotton wool dilutes the water in the storage tank continuously in order to preserve the organisms in the tank (Ripley et al. 2008: 120). The silk rolls are then placed into the internal and the ends of the rolls drawn parallel through the mechanism into the storage tank, where they are glued onto a spool and pulled tight. Finally, a mechanisms 'analogous to that used in a camera' needs to be charged with a wire that keeps the silk under tension as it is going

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[75] The covering silk comes from a silk roll that is exactly two inches wider than the filtering silk. Once folded, both silk bands are of identical width.

to be drawn into the storage tank during the tow (DR1960, Reid et al. 2010: 126). After putting in the formalin, the internal is placed inside the CPR's external body, which has a shock absorber and steel wire attached to it that can be connected to a ship's winch with shackles. Several additional instruments might be attached to the external body of the CPR but for the purpose of this chapter, I focus only on the samples and data created from the silk rolls placed inside the CPR. They are the equipment that the device was originally designed for and the continued creation and analysis of silk samples are the survey's core activities.

How the internal CPR mechanism works has been documented very well in several journal papers, for example in Reid et al. (2003) and Batten et al. (2003). Besides an instructional video that covers preparation, unloading, and maintenance of a CPR, I have also been shown a video that documents how a CPR is first lowered into the water from a ship of opportunity and later hauled in. The transportation of boxed CPRs between the Laboratory in Plymouth, the ports, and the ships is described in chapter six.

When it is time to begin towing aboard a ship of opportunity, the CPR gets connected to a ship's winch with the shackle. The CPR is lifted over the bulwark and the wire is paid out until a coloured mark settles on the sea surface, indicating that the CPR has reached the desired depth between seven and ten metres. As the ships do not stop or even slow down for this process, the steel body hits the turbulent wake of the ship at up to twenty knots, putting significant tension on the wire, the CPR's body, and the shock absorber. The CPR jumps on the sea surface for several seconds before submerging (DR1960). Once the CPR is below the sea surface, the external body's design causes it to assume a horizontal position. Sea water enters the external body through a small opening at its nose. The entrance aperture measures only around one and a half square centimetres (SAHFOS 2016: 18).[76] The tunnel, through which the water has

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[76] The exact size of the aperture is stated slightly differently in different publications. While SAHFOS' 2015 annual report states 1.61 square centimetres, the edges each measure 1.2 centimetres, according to Reid et al. (2003: 126), resulting in an aperture of 1.44 square centimetres. According to Batten et al. (2003: 196), the aperture is only 1.27 square centimetres.

entered, leads into the internal cassette and widens significantly until it reaches the filtering silk (fig. 4.3). This enlargement of the tunnel to cross-sectional dimensions of five by ten centimetres decreases the speed of the water flow by a factor of around thirty (Batten et al. 2003: 196, Warner and Hays 1994: 238). The slower speed decreases the impact on the organisms when they collide with the filtering silk, as SAHFOS technician Rob Camp explains:

> "From the nose of the CPR, water comes in and the hole in the nose is of a certain size and it expands, the space inside, which reduces the pressure. Therefore it means that the pressure on the silk that is collecting is not as high as in the water; because we are towing at maybe up to twenty knots or more, which would damage the plankton, if we were collecting at that speed." (DR2901: 2)

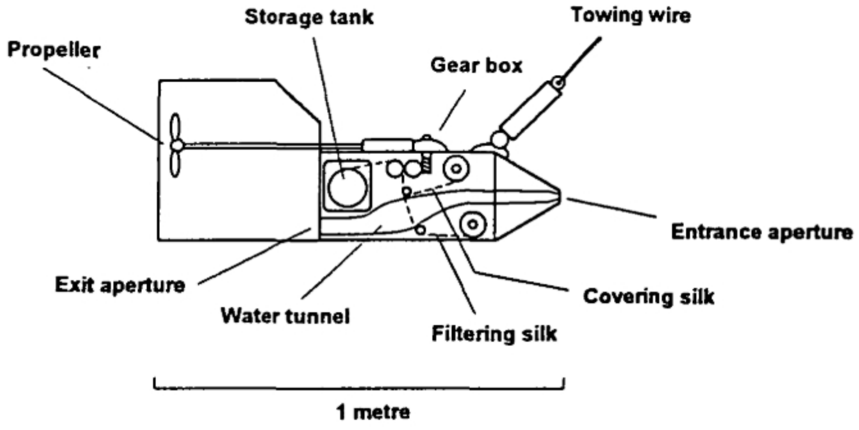

Figure 4.3: Schematic view of the CPR, from Hays (1994: 404).

The mechanism to pull the silk into the storage tank is powered by a propeller which is part of the external body and connected to the internal via a gear box. The gearbox then rotates the storage spool in the preservation chamber, drawing in the filtering silk and the covering silk (Batten et al. 2003: 195–96). The covering silk meets the other band right above the water tunnel and ensures that the organisms are kept in place as the silk is wound up.

The silk's mesh size is 270 micrometres and has a leno weave which is a single threat in one direction and a double twisted thread in the other direction. This type of weave prevents silk distortion and variable mesh sizes under pressure, as would happen more easily if a plane weave with only one thread in each direction was used (Batten et al. 2003: 196). Only a share of the organisms that have entered the CPR's internal are retained by the silk, covered up by the second silk roll, and end up in the formalin-filled storage tank. Mesh sizes typically used for collecting phytoplankton are only up to fifty micrometres; the mesh size used in CPRs is thus significantly larger with 270 micrometres. This size was chosen by Alister Hardy almost a hundred years ago, because he designed the device for monitoring relatively large zooplankton organisms, which are the primary food source of larval fish.[77] Yet, the silk actually retains organisms that are significantly smaller than the mesh size, thanks to different physical interactions, as lab manager David Johns explains:

> "These are coccolithophores, they are calcareous and they are tiny; really, really tiny, ten microns. When you look down there, you can see a sample and there is a silk mesh. The gap in the mesh is about 300 microns across. So it is quite a big gap. And we had people saying that there is no way that we can see coccolithophores, they said 'no, it is going to go straight through your mesh, because they are only ten microns.' But they do stay there, so we took photos and we published some of it and say 'actually, we can see these.'"
> (DR0934: 6)

Coccolithophores are a group of unicellular, eukaryotic phytoplankton species which are around a magnitude smaller than the gap between the silk threads.[78]

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[77] Zooplankton are animals living near the surface of the sea that usually drift with the currents, although some are weak swimmers. Zooplankton are distinguished into holoplankton, which remain part of the plankton permanently, and meroplankton, a group of temporary plankton consisting mostly of larval forms of crustaceans, sea stars, marine worms, and most fish. Like the much smaller phytoplankton, zooplankon are a key component of the marine food web; <http://marinebio.org/oceans/zooplankton/index.aspx> [accessed 4 January 2017].

[78] Phytoplankton are microscopic single-celled plants, protists, or bacteria. They consume carbon dioxide by photosynthesis and require sunlight and nutrients like terrestrial plants. The uptake of carbon and subsequent transfer to the deep ocean

Yet, a constant share of phytoplankton species is retained, due to different physical interactions during sampling, as Johns explains:

> "[They do not go through] probably because of the other phytoplankton that are there. So you get spiny bits sticking out; the mesh is made of silk, which is spinous as well, so they get stuck to that." (DR0934: 6)

Physical interactions between organisms of different sizes, shapes, and constitution and between organisms and the silk's double-twisted leno weave are responsible for capturing organisms significantly smaller than the mesh size. By contrast, most other plankton samplers use a plain weave of nylon that is heat-fused at each crossing. This results in a much smoother mesh without any rough threads or narrow gaps in the twisted silk that small organisms could get caught in.

For several reasons, however, the ratio between small and large species and the composition of species on the silk differ from the ratios and composition of species in the open ocean. The filter efficiency is much smaller for tiny organisms than for larger ones, as several experiments have shown (Hays 1994).[79] Additionally, some large zooplankton species capable of swimming sometimes manage to actively avoid entering the small aperture at the nose of the CPR. This is not the case with typical plankton nets that have diameters of fifty centimetres or more (Richardson et al. 2006: 61). The CPR is also not a perfectly sealed instrument and it is assumed that some leakage can occur around the edges of the silk roll despite the folded edges, so that organisms

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make phytoplankton a crucial component of the global carbon cycle and climate system. As the primary food of zooplankton, many fish species, and whales, phytoplankton are the foundation of the aquatic food web; <http://earthobservatory.nasa.gov/Features/Phytoplankton/> [accessed 1 December 2016].

[79] The lower retention rates for smaller species becomes important when the silk samples are being analysed after they have been returned to Plymouth, as I explain in chapter five.

actually might be able to escape the silk. This effect, however, is estimated to be insignificant (Batten et al. 2003: 206).

An important process affecting not only the retention rates but also the volume of filtered sea water is silk clogging (Hunt and Hosie 2006). In areas with high plankton abundances, the silk might get clogged with organisms, in particular if gelatinous species happen to enter the CPR and stick to the silk. Clogging varies seasonally and occurs more often in summer than in winter due to higher plankton abundances (Hays 1994: 409). The effects of silk clogging have been examined in experiments and show that with a growing amount of plankton on the silk, the filter efficiency tends to increase:

> As more and more organisms are filtered onto the mesh the open apertures are progressively clogged and reduce the effective mesh size. So as more large organisms are retained, smaller organisms, which at the start of the sampling would have been extruded, will be retained progressively more effectively (Batten et al. 2003: 206).

Such higher-order effects make the evaluation of retention rates very difficult and illustrate the complexity of interaction between organisms of different sizes and texture and the silk. Batten et al. (2003: 206) highlight another obstacle in this regard:

> The effect is hard to quantify since the ambient concentrations of organisms (needed to determine the true proportion retained) will never be known for a specific patch of sea water at a specific time.

Even the immediate area surrounding a CPR is affected by the sampling procedure, due to the CPR being towed behind a large ship, which creates a turbulent wake and mixes the upper layer of water. All of these interactions between water, plankton organisms, ships of opportunity, and sampling device influence exactly what species are retained at which quantity by the silk. As a result, the relative quantities of different species on the silk are not equal to those in the ocean water or as they would be if ocean water was being removed with a large bucket or a glass bottle.

The sampling method also has effects on the level of individual organisms. Certain groups of plankton organisms frequently get damaged and deformed during the sampling process. They may collide with the steel walls of the CPR or with other organisms that are already retained by the silk. Although the water pressure decreases inside the tunnel, the bodies of plankton species may get pressed severely against each other or against the silk. The biggest cause of deformation is, however, the sandwiching of organisms between the two silk layers before the silk enters the formalin-filled storage tank. With regard to some of the larger zooplankton species, Johns explains that “the stuff is squashed” and “it is very, very flat”, when it arrives in Plymouth (DR0934: 19). This process can make the identification of some plankton species very difficult, as I explain in chapter five. No plankton organism survives the sampling process but the formalin solution in storage tank prevents the organism’s decay.

4.2.2 From continuous silk rolls to discrete samples

After the CPR has been hauled in by the ship’s crew, it is placed back into the box as it is and shipped back to Plymouth from the ship’s destination port. At the Laboratory, the internal cassette is unloaded and the silk roll is removed from the preservation chamber. For temporary storage, the silk roll is put into a plastic pot with a four percent formalin solution (DR1960).

Before the silk can be analysed, the entire silk of one tow is rolled out, with the silk “sandwich” of filtering and covering silk matching as accurately as possible. The silk bands are cut into individual pieces in such a way that the distance between each cut corresponds to ten nautical miles of the tow. Depending on how fast the ship has been sailing during the tow, the cut pieces are slightly more or less than ten centimetres long. A software produces the so-called cutting point sheet, which shows where the silk needs to be cut relative to the two inch divisions marked and stamped onto the silk prior to despatch. Due to the tunnel width of ten centimetres inside the internal cassette, the area of the cut silk that has filtered sea water is roughly square. It is such an individual pair of silk pieces, one filtering silk and one covering silk, that the CPR Survey staff regard as a “sample”. Johns explains:

> “That is one sample, yeah. So it is ten nautical miles of the CPR going through sea water. And it filters around three cubic metre of sea water. So it represents three cubic metres of sea water.”
> (DR0934: 1)

For the survey’s staff, a sample represents a distance that a CPR has travelled and the volume of water flowing through the CPR along that section of the tow.[80] One has to keep in mind, though, that the silk is drawn through the CPR mechanism continuously and not in discrete steps. The silk is not exchanged every ten nautical miles so that only the water and organisms of those ten nautical miles would make contact with one ten by ten centimetre area of silk. The continuous advancement of the silk, as opposed to a step-wise advancement, results in an overlap or “smear”, as Johns calls it (DR0533: 10), between adjacent samples. To illustrate this, an organism that enters the CPR at a moment when a future cutting point — a boundary between two adjacent samples — is at the centre of the water tunnel could end up on either of the two adjacent samples. Effectively, each sample has filtered seawater along fifteen nautical miles, with five miles on both ends of the sample overlapping with the previous and the following sample, respectively. As Richardson et al. (2006: 32–33) explain, ‘of the plankton on the cut samples, 50% comes from the central 5-mile section of tow, and 25% from each of the preceding and following 5-mile sections’.

Each sample is labelled with a single letter or letter combination to indicate the route of the tow, with an ascending tow number pertaining to that route, with a “block number” indicating the position of the sample in the length of the tow, and with a sample analyst number that indicates to whom the sample is allocated for analysis (SAHFOS 2016). The silk samples, again soaked with a four percent formalin solution to stay moist, are folded in a standard way on a sheet of

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[80] A similar phrasing regarding the representational relation of the sample can be found in an oceanographic paper about a plankton colour dataset, which is also created from the silk samples: ‘CPRs were towed across the English Channel from Roscoff to Plymouth consecutively for each of 8 months producing 76 standard CPR samples, each representing 10 nautical miles of tow’ (Raitsos et al. 2013: 158).

transparent plastic so that the plastic forms an envelope containing the sample. The label, a white slip of paper, is placed inside the envelope so that it is easily readable when the folded sample is stored. The envelopes are placed on formalin-soaked cotton wool inside plastic boxes which contain all samples of one or more tows in consecutive order. The boxes are stored in a cabinet until a sample is taken into the lab for microscopic analysis (DR8112: 11).[81]

There is no guarantee that the process of producing a usable sample is successful. For recent years, the survey claims an overall sampling success rate above ninety percent (SAHFOS, 2015, 2016, 2017). In cases of unsuccessful sampling, mechanical failures may have occurred, as Camp explains:

> “You do sometimes get jams, occasionally the mechanism fails, damage might happen to the CPR, or something has not worked quite right and the silk has not moved on or not properly and therefore you are not filtering it at the correct rate, and therefore you can’t be sure where things are.” (DR2901: 9)

Other cases of samples being unusable have to do with failed preservation or interference of other materials:

> “And then some samples are maybe rotten, they have not preserved properly. That very rarely happens, but sometimes they have not preserved. Sometimes, because it is so much material, it overwhelmed the amount of formalin we put in. So it has not preserved and it is very mushy and smelly. And then we had examples in the past where there have been really high amounts of fungus in the water, which coloured it black and makes it very difficult to see things. Or through patches of sewage or blobs of oil or other things like that, which just make it very difficult to analyse.” (DR2901: 9)

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[81] The first step of analysis, a visual assessment of the silk colour, that I describe in the following chapter, actually happens right when the silk is cut and before the samples are folded into plastic envelopes.

Cases like these are rare, however, as Camp estimates that only one sample in a hundred tows is completely unusable (DR2901: 9–10). The sample analysts will work with such samples as much as they can or, if necessary, make a note that the sample is just not analysable.

On almost every tow, the samples labelled with an odd number are analysed by a taxonomist in order to create data, while all samples with an even number are moved directly into the sample archive for long-term storage. Effectively, only every other sample is analysed in the laboratory (Batten et al. 2003: 196). Camp, who is also charge of curating the archive, explains this practice:

> "We only analyse the odd samples, not the even ones. The even ones are cut and then preserved and put into the store, so that if for any reason we needed to look at a completely unanalysed sample with no effect, we can look at that one. Also of course, if anyone wants to maybe use the samples for any other reason, if anyone wanted to do analysis on the actual samples or maybe try a different technology that has not even been brought up yet, something that you could do with them, there are preserved samples that have been untouched by us, apart from just cutting them and storing them, that can be looked at by the people." (DR2901: 7)

This rule of analysing alternate samples applies to almost every tow. Only if the towing distance is shorter than 180 kilometres or if higher detailed data of specific areas are desired, the plankton taxonomists will analyse every sample of a tow (Batten et al. 2010: 196). Camp describes the even-numbered samples as the survey's "pristine untouched samples" (DR2904: 2), despite the manual unloading, cutting, and folding.

After microscopic analysis, the samples are put back into plastic boxes and stored in the survey's sample archive, which contains approximately half a million individual samples dating back to the 1950s (SAHFOS 2016: 25). One box contains the samples from around five to eight individual tows. The preservation of samples is not always successful and some samples might get contaminated and start rotting. Camp, who is in charge of the sample archive, explains:

> "Of course the boxes are not completely airtight; otherwise there would not be any formalin in the air. So over time, there is some evaporation and once they start to dry out, the formalin level will drop and the opportunity is there for bacteria and fungus to start growing." (DR2903: 1–2)

Every time Camp enters the sample archive, he measures the formalin level in the air. The archive comprises several long shelves with boxes of samples inside a warehouse of PML several hundred metres away from the CPR Survey's labs and offices.

Camp spends as little time as possible in the archive because the formalin in the air and the slight smell make it "not the most pleasant of environments to be in" (DR2903: 1). The condition of a sample can worsen at different speeds because some organisms preserve better than others and because contamination can spread within one box of samples quite easily once a single sample is contaminated. Yet, early signs of bacteria and fungus only show as a slight discolouration that makes only the rather "faint" organisms invisible, while more solid, larger organisms are still identifiable with a microscope (DR2901: 2–3). A list of all boxes with a colour code indicating the quality of the box is attached at the head of each aisle in the archive, with five gradations from "very poor" to "excellent". Once degradation of a sample has set in, the process cannot be reversed, as Camp explains:

> "You could add more formalin and at least stop it getting worse, but it is probably unlikely that you will ever make it better. So you might just decide, well at some point, this is in such a poor condition that they throw it out." (DR2903: 2)

Camp also points out that checking on the condition of samples is an ongoing process that aims at keeping a record of the sample conditions. If necessary, cotton wool soaked in formalin is added to the boxes:

> “So you basically start at the beginning and work your way through. And once you get to the end, you start back at the beginning again and you go through and you would just […] maybe look at the box. Is it still moist? Has it completely dried out? Does the formalin level need any topping up? Some will maybe look wetter than others.” (DR2903: 3)

With the ongoing record keeping, Camp and his colleagues can give advice as to which samples’ re-analysis could be more or less promising. Camp further remarked that the storage space in the warehouse will most likely reach a limit within circa two years and the survey is already looking for a new place that is more adequate for the storage of CPR samples. A facility with room for workbenches, microscopes, and computers would make curation of the samples much easier (DR2903: 4).

4.3 Material integration and continuity

It is beyond question that materials and physicality are central in the CPR Survey’s sampling practice. The silk samples could be regarded as “material” objects simply because they consist of a combination of fabric and other substances. They are also tangible, they can be moved around in the lab, and they can be stored and retrieved. With their standardised spatial dimensions and plastic wrapping, they seem to have clear boundaries. This chapter has reconstructed the formation processes — the materialisation or embodiment — that evokes the somewhat stable image of a material object.

This process begins with what I call “material integration”. The motivation to speak of integration stems from the fact that materials of the target system and of the technology, the ocean and the silk, are integrated over a distinct period of time along a distinct spatial distance. A novel, unified object, the silk roll with plankton organisms, is constituted during the process of material integration.[82]

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[82] In the Merriam-Webster dictionary, the first meaning of “to integrate” is ‘to form, coordinate, or blend into a functioning or unified whole’; <https://www.merriam-webster.com/dictionary/integrating> [accessed 31 May 2018].

The process of integration takes place in the course of an “intersection” between the CPR and the ocean ecosystem. Rheinberger (2010: 217–18) describes an ‘intersection’ as a ‘surface’, ‘plane’, or ‘point of contact’ between a ‘technical object’ and an ‘epistemic thing’, leading to a ‘fertile analytical constellation’ of instrument and target. Epistemic things are ‘material entities or processes […] that constitute the objects of inquiry’ (Rheinberger 1997: 28). Technical objects, or experimental conditions, ‘embed’ epistemic things, while they also restrict and contain them (Rheinberger 1997: 29). In my case, the plankton organisms are quite literally embedded into the silk and at the same time, restricted and contained by it.

The process of integration as the constitution of something new can also be regarded in Harré’s (2003: 28–31) words as an ‘apparatus-world complex’. A technical device is capable of being ‘integrated into a unitary entity by fusion with nature’ (Harré 2003: 28). And further:

> An apparatus is not something transcendent to the world, outside it, interacting casually with nature. […] The apparatus and the neighbouring part of the world in which it is embedded constitute one thing. (Harré 2003: 29).

What I intend to emphasise is that the material integration, the intersection or apparatus-world complex, realised in case of the CPR Survey is a constellation that results in the constitution of a new thing or a new research object. The sample is literally created rather than drawn or collected from a pre-existing population. Moreover, the samples are created in a very specific way, even though a variety of interactions of materials during integration cannot be controlled or even observed by any researcher. However, each sampling process is meticulously prepared for it to progress in a certain way. Besides the unloading, cutting, and labelling of samples, the preparation of each tow constitutes much of the researchers’ agency in the sample creation process.

The novel character of the sample that results from integration is manifest in the various effects of physical interactions between the technology and the object of research: the more effective retention of larger organisms due to the silk’s mesh size, smaller plankton sticking to larger organisms or being caught in between fibrous and twisted silk threads, clogging of the filtering, the flattened bodies of some zooplankton species, and the overlap between adjacent samples caused by the continuous rather than discrete character of the mechanism. These effects of physical interactions are part of the material integration process and shape the resulting object.

What the CPR Survey treats as a research sample consists not only of the plankton organisms that have been retained during the filtering process. The organisms are inextricably connected to two pieces of silk by virtue of the constitutive interactions of various materials during integration. For the survey's main purposes, researchers never handle individual or distinct groups of organisms, but always the two labelled and archivable pieces of silk, soaked in formalin and wrapped in plastic. Silk, label, preservative, and wrapping are integral parts of a sample. Asked whether he or other SAHFOS employees would agree with this view, Johns explains that most would probably view the silk as the filtering mechanism and the actual organisms as the sample, however, Johns immediately admits that "of course you couldn't really have the sample without [the silk]" (DR0533: 9).

Despite the clear spatial dimensions and the portability of a sample, its boundaries are actually not that clear. The overlap or "smear" between adjacent samples somewhat undermines their separation and association with two distinctly different geographic locations. Additionally, when samples are first folded, then opened and re-folded for analysis, preservation fluid may be added or leak out. Even properly handled samples may happen to be contaminated and initiate or accelerate a process of decay. In this sense, materiality resonates with Butler's (1993) account of materialisation as a multitude of stabilising or de-stabilising processes that generate the image of a material object.

Material integration ends when the CPR is hauled in. An indispensable second but not secondary aspect of materiality is what I call "material continuity". The very materials that were integrated during a tow are preserved in form of a sample for the purpose of analysis and indefinite storage in the survey's sample archive. Unloading the CPR, cutting the silk, and subsequent labelling, folding, analysing, and archiving of samples are activities performed with high confidence or even certainty regarding the origin of the sample and with awareness of the various effects and potential interactions during material integration. Besides preparing samples for analysis, storage, or re-analysis, the activities aim at preserving continuity in a sense that there are no jumps, interruptions, or breaking points between the sample's material and the sample's origin.

I use the term "origin" with caution, in particular in relation to material objects. With respect to "traces" which are 'material manifestations' in experimental settings before they are turned into data, Rheinberger (2011: 338–39) argues that an origin does not exist and has never existed. With "origin" I refer here to an individual sample's process of material integration which has shaped the sample in the various ways described above. The silk, the steel, and the plankton organisms, as separated materials that become integrated, have their respective origins in factories, plankton life cycles, or in times and locations even further back.

In his account of biological reproduction, Griesemer (2014: 26–27) uses the term 'material continuity' to describe a material 'overlap' between parent and offspring when 'organized material parts' are transferred between the two. Form or information are transferred materially and not by any kind of impression or translation to a different medium. In my case, although being pressed severely into the silk, the plankton organisms usually remain sufficiently organised for the sample analyst to identify and count the organisms using certain tools and methods of manipulation, as I discuss in chapter five. Important here is the absence of jumps or breaking points between the plankton populations in the oceans and the organisms on silk samples in CPR Survey's sample archive. In case of the CPR samples, a translation or jump to a different medium is hardly possible. Although the sample is not self-sufficient and actively needs to be preserved, everything about the sample is an integral part of it, including the silk, formalin, the wrapping, and the label.

Preservation is a key aspect of material continuity. The certainty regarding a sample's connection to a distinct origin is grounded in various practices in which the labelling is instrumental. Just from looking at a sample and being aware of effects of material integration, nobody could connect one particular sample with the time and the location of this particular sample's integration. The connection is represented by the label given to the sample upon cutting the silk roll. It contains the route's ID, the tow number, and the position of the sample along the length of the tow. This contextual information is indispensable for a meaningful analysis of the sample. Other practices that underpin material continuity are the adding of preservation fluid and the airtight folding and storage. This is why the label, the formalin, and even the wrapping are integral parts of the sample. They preserve the effect of boundary that constitutes the material object, but they also preserve material continuity and the usability of the sample.

The epistemic value of a sample, the feature promoting the 'acquisition of true beliefs' (Steel 2010: 18), stems from materiality, understood as material integration and continuity. This two-fold characteristic initiates and maintains both the connection between a sample and nature, as well as the usability of a sample for the creation of meaningful scientific data. Material continuity means that whatever may become interesting to a researcher during a sample analysis has always been and will remain attached to the very material that was physically integrated out in the oceans. In this sense, material continuity may be regarded as an intrinsic characteristic of the samples in my case. As long as a sample exists in its material form, it is linked to a specific origin. Even if the connection was for whatever reason no longer traceable, a sense of continuity would remain. In this case, however, the silk and the organisms could no longer be used for the creation of meaningful data. If a CPR sample lost traceability, it would inevitably lose its status as a research sample in that particular context. In fact, a sample that has become unusable or is no longer traceable to its origin may be used for training purposes in the lab, but this would be a context different from the routine sample analysis and creation of scientific data. In this sense, the status of an object as a research sample depends on the context, much like scientific data in Leonelli's (2015) relational framework.

4.4 Materiality versus representation

This chapter introduced the common view of samples in science as being used as representations that are grounded in either material similarity or statistical relations. Although within the CPR Survey, a silk sample is regarded as a representation of “around three cubic metres of [filtered] sea water” or as “ten nautical miles of the CPR going through sea water” (DR0934: 1), pinning down what target a CPR sample may represent and what the grounding for this representation may be is not straightforward. The above quotation relates a sample neither to any aspect or segment of the ocean ecosystem, nor to any organisms or populations in the sea water; instead, there seems to be a relation between a silk sample and a section of a tow or a volume of water that interacted with a CPR. Establishing this relation is obviously motivated by the sample’s physical characteristics: The sample is actually made of the very materials that have been physically involved in the interactions between technology and the research object, between the silk, the steel, and all kinds of materials that are part of the ecosystem and have flowed through the CPR’s internal water tunnel.

However, as I have argued above, sampling in my case involves the constitution of a novel research object, one that is shaped by the variety of physical interactions during integration. As a result, despite continuity of materials, new physical characteristics are constituted: plankton organisms sticking together, organisms being deformed, and at a later stage, contamination and decay may change the physical characteristics even more drastically while material continuity remains. This continuity despite potential change is a manifestation on the material level of the tension between change and continuity that I have introduced in chapter one.

Due to the integration into a novel research object there is no straightforward material similarity that justifies a representational relation, neither with a volume of filtered seawater nor with a specific section of a tow. Further, because of the smear between adjacent samples and the different retention rates depending on organism size and other factors, the sample is also not a straightforward representation of a plankton population. As I will argue in the following chapter, not the sample itself, but rather the data obtained from sample analysis could serve as a quantitative representation of a plankton population, but even this representational relation turns out to be problematic.

Following the path of material continuity as I have done in this chapter does not suggest any kind of representational relation between the sample and something else. In fact, material continuity rather suggests the opposite: The process of sample creation involves continuity — the absence of jumps — and no kind of translation, creation of an image, or impression onto a new medium. The very material that was integrated during a CPR tow is packaged, transported, and divided into new research objects. Further, unlike many images or abstractions, which are established and used as representations of other entities, it is obvious that a CPR sample is not reproducible by any means.[83]

Rheinberger (2015: 323–25) assigns preparations a materiality and durability that is similar to that of the research samples in the CPR Survey. Preparations 'participate in, are part of, the very materiality of the object under scrutiny'. Their 'configuration' is expressed in physical, biological, and chemical properties (Rheinberger 2015: 323). Similarly, and in addition to the terminological affinity to the meticulous preparation process before each tow, a CPR silk sample has assumed a specific configuration that makes it analysable. This configuration is preserved by material continuity. Rheinberger (2015: 323) argues that 'preparations are renderings, not representations'; they possess a 'particular indexicality' that points to themselves and not to something that is represented by the preparation. If anything, the material characteristics of a silk sample seem to point to the processes involved in their formation, they point back to the process of the material integration rather than to a target of a representational relation.

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[83] Although not all representations may be reproducible, the reproducibility of research components like model organisms or the silicon samples in Mody and Lynch's (2010) case is a fundamental feature of at least some kinds of representations.

Reconsidering the bottles filled with stream water that constitute the samples in Ribes and Jackson's (2013) case study leads to similar conclusions. Their samples are isolated 'little bits of streams' that are transported 'back to labs in ways that preserve meaningful relationships to those streams' (Ribes and Jackson 2013: 162). Both material integration and continuity are hidden in this description. "Isolating" entails bottles and the creation of samples by integration. The preservation of meaningful relationships to a stream is material continuity and the preservation of its traceability. Although Ribes and Jackson (2013: 162) claim that the samples are capable of 'representing a stream at a particular point in time', and it is clear that this association is motivated by material characteristics of the sample, the epistemic value stems, as in my case, directly from the sample's material integration and continuity.

4.5 Conclusion

On the basis of an empirical case study of a long-standing sampling practice in ocean science, this chapter fleshed out how the "materiality" of a research object is constituted and how the epistemic value of a sample is grounded in materiality. In my account, materiality consists of two fundamental, complementary aspects: material integration and material continuity. While material integration is the formation of novel research objects by entanglement and fusion of materials from both the research technology and the research target, material continuity refers to the handling, processing, and preservation of the very material that was integrated. Meticulous preparation is necessary for the material integration to proceed in a very specific, desired way; but still, the various physical interactions between research technology and parts of the natural system during integration shape the newly created research object in largely uncontrollable ways.

The materiality of an object is not "finalised" after physical matter from various sources has been integrated. Material continuity extends the process of materialisation and must actively be preserved to maintain a sample's epistemic value. In the conceptual void between science and nature that I have sketched in chapter one, material continuity encompasses one important assemblage of practices and processes that fills this gap. By the same token, representation, as a relation that supposedly connects science with nature by producing truthful or at least similar images or abstractions of natural processes is no longer required to account for the epistemic value and for the crucial connection between samples and natural phenomena.

Based on my view of samples as newly constituted research objects, I challenge the view of samples as entities that are collected from a population of the same or a similar kind. Samples result from creation (integration) and ongoing processes of embodiment (continuity) and are not extracted from the natural into the cultural sphere as a representation of the former. However, the question of representing natural systems is only suspended for now, because this chapter has not even touched upon the creation of actual scientific data and their potential to be used as representations of natural systems. This is why chapter five begins with a more elaborate review of philosophical accounts of scientific representation.

Chapter Five – Targets of scientific representing: The creation of data in the CPR Survey

Abstract: This chapter reconstructs the analysis of CPR samples and the processing of hand-written tally marks into digital scientific data. Building on the work of Hacking (1983), Latour (1999), and Rheinberger (1995), I view scientific representing with data as the result of a series of transformations or translations of perceived qualities of objects into standardised forms. These actions are intended to increase the circulation and computability of data and enable their integration and comparability with already existing representations. I argue that the scope of representation changes with each transformation and broadens from specific characteristics of an individual sample to processes of the ocean ecosystem as the data gradually become more compatible with already existing data. The use of data as representations depends on the data's immediate context, their physical state and their relation to other data, implying that representing is a context-dependent, practical achievement and not an intrinsic property of data. My empirical research reveals a perceivable mismatch between data and the natural world that resonates with attempts to untie the close coupling between scientific representation and models which has recently dominated philosophical accounts of representation and suggests a fixed representational relation between a model and a target object or system (Knuuttila 2010).

5.1 Introduction

This chapter is about the creation of scientific data and their relation to objects or processes of real-world systems[84] such as the ocean ecosystem. In many

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[84] The terms "real-world target" and "real-world system" are used in this thesis to refer to phenomena and processes of the natural environment, which ocean scientists ultimately intend to study and create knowledge of. I do not imply that objects in laboratories or other artificial environments are not part of the real world. My usage of the term "real world" is not intended as a philosophical stance on scientific realism.

sciences, data are used as representations of such systems, but how scientific representation actually works is a controversial topic in philosophy of science. Discussions and accounts of scientific representation have seemingly narrowed down to representation with models. Many of these accounts are based on a view of representing that assumes relatively stable or even permanent relations between a model and a target. This chapter's account of scientific representation takes the activity of data creation and not scientific modelling as a starting point.

The CPR Survey's data practices exemplify that scientific representation with data occurs at different stages of an epistemic process in which the ability and purposes of representing with data depend on the data's immediate context and format. In my case study, the difference is apparent in the stages before and after data which have been created with microscopes in a laboratory are transcribed from hand-written notebooks into digital databases. A consequence of the dependency on context is that representational relations — intentionally established denotations of a target with an object — are not intrinsic or permanent qualities of data. Scientific data and their representational functions are practical achievements that depend on a variety of conditions. They are not given qualities or intrinsic to an object in a way that allows scientists to simply extract or read them.

The practice of data creation studied for this thesis suggests that representing functions as a series of transformations or translations of perceived qualities of objects into standardised forms. These actions are intended to increase the circulation and computability of data and enable their integration with other existing representations. Hacking's (1983) view of scientific representing as well as Latour's (1999) and Rheinberger's (1995) studies of scientific practice suggest that assuming straightforward and truthful relations between representations and the world is problematic. Some of the terminology I encountered during my empirical research indicate a sort of mismatch and an uncertainty regarding correspondence between data and real-world systems. I thus follow Hacking's, Latour's and Rheinberger's accounts and argue that representing is not about establishing correspondence between data and an origin that is part of a real-world system. Rather, representing makes data gradually more compatible and usable with already existing representations.

This chapter continues the in-depth empirical study of the CPR Survey, focusing now on the creation of scientific data in the lab. CPR data are created in successive steps of analysing pieces of silk which have retained plankton organisms during a CPR tow, as I have described in the previous chapter. A crucial change of context is achieved when hand-written data that have been recorded on paper during the sample analysis turn into digitised quantities in the survey's database. The paper-based data are created as representations of characteristics of an individual sample or tow. The majority of these data are in the form of tally marks in a sample analyst's personal notebook. This context limits the ability to circulate or integrate the data with other existing data. In the context of a digital database, the CPR data are processed into spatial and temporal averages before they are circulated to external scientists and used for reasoning about real-world systems. The key for inferring scientific claims is not the establishing of permanent representational relations between data and the real world. The key is making data compatible and integrable with other data. These include the CPR Survey's own records of the past which have been created using the same methodology. The paper-based data have a narrow representational scope that only encompasses the individual sample or the individual tow from which they originate. By contrast, the digital data's representational scope encompasses parts or processes of the actual environment by virtue of transient, context-dependent relations between data and other existing representations.

This chapter focuses on scientific representation while deliberately side-stepping a deeper discussion of scientific modelling. As Knuuttila (2011) remarks, philosophical accounts of scientific representation have 'focused almost exclusively on modelling', resulting in a rather limited view of both scientific representation and modelling. Grounded in my empirical research, this chapter discusses the creation and the handling of data as representations, not as models, even if some philosophers might argue that this distinction is not needed. The chapter concludes with thoughts on a conceptual distinction between data and samples, taking into account the previous chapter's conclusions regarding a sample's materiality and this chapter's account of representing with data. I suggest that samples are primarily characterised by a material relation to a real-world target, while data are characterised by transient representational relations. It is important that neither of these relations can be viewed as intrinsic but rather as practically achieved by a variety of epistemic activities.

The following two sections review some of the extensive scholarly literature on scientific representation. I focus first on intentionality and the relation to scientific models, I then review several accounts of representation in scientific practice and discuss the notion of representational scope. This chapter's empirical part accounts for analysis of CPR samples and discusses the context, format, and representational scope of data created at different stages of the analysis. My description roughly follows the survey's workflow chronologically, beginning with the very first step of analysis, a visual assessment of an entire sample's degree of greenness, followed by three steps of microscopic analysis performed on the samples.

5.1.1 Scientific representation, models, and data

Representation is one of the most central topics of philosophy, bearing on countless scholarly debates throughout the history of philosophical study. Yet, as Elgin (2010: 2) notes, 'the term "representation" is irritatingly imprecise'. In many research fields, scientists create, handle, and reason on the basis of a variety of objects or things which they use as representations in many different ways and for a wide range of purposes: Among these objects are data or data sets, models, samples, records, simulations, model organisms, preparations, and visualisations. Representations of parts or processes of the real world, but also of imagined or fictional entities, are crucial for scientific reasoning and philosophers have put much effort into understanding how scientists create and use representations in practice.

A few main problems have emerged in philosophical accounts of scientific representation, including problems of style, ontology, accuracy, how to demarcate scientific from non-scientific representation, and what constitutes an object as a scientific representation in the first place (Frigg and Nguyen 2016). The latter question regarding the creation or establishing of scientific representation, the “constitutive problem”, is addressed in this chapter’s empirical account. This chapter’s analysis is grounded in a very distinct case of practice in which one specific style of representing dominates. This style involves numerical, quantitative data, even though these data may later be processed into objects of different styles, for example plotted graphs or maps. Certain steps of data processing also relate to questions of accuracy and ontology, but these issues are not central to my argument about the context-dependency of data.

Callender and Cohen (2006: 75) take a strong position towards the constitutive problem by arguing that a scientific representation is constituted ‘by virtue of the mental states of their makers/users’.[85] Most conceptions of scientific representation indeed share the idea that representation requires an agent and an intentional act of establishing a representational relation (Frigg and Nguyen 2016). For example, Giere’s (2010: 269) ‘intentional conception of scientific representation’ proposes that scientific representation requires four elements: a model that represents, a target that is represented, the intention of an actor, and a specific purpose. Because of the intentional character of representation, I aim to avoid the impression that objects or things can be regarded as representations per se and I also argue for this view on the basis of my own case study. However, this is sometimes complicated by the convenience of stating that “this object represents something else” instead of “this object is intentionally used as a representation of something else by this person”. Even if not explicitly formulated like the latter expression, my view of representation implies the presence of an agent who is actively establishing a representational relation.

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[85] In Frigg and Nguyen (2016), the line of thinking about scientific representation based on this ‘radical’ view is called ‘General Griceanism and Stipulative Fiat’.

Including actors and intentions into conceptions of scientific representation is a change of viewpoint that is potentially beneficial for the study of scientific practice. As Chang (2011: 208) suggests in his ‘philosophical grammar of scientific practice’, the ‘simple linguistic trick’ of using verb forms instead of common nouns — “representing” instead of “representation” — structures philosophers’ thinking differently. Consequently, ‘a whole range of questions regarding actions emerge naturally, almost without any effort: who is doing what, why, how, and in what context?’ (Chang 2011: 208).

Given that representing is realised by a variety of people using a wide range of objects and in a variety of scientific and non-scientific contexts, Knuuttila’s (2010, 2011) observation that philosophical discussions of scientific representation have almost exclusively elaborated on modelling may be worrisome. Knuuttila (2010: 142) has identified a ‘model-target dyad’, a representational relation between a single model and a target system that is represented, as the ‘basic unit’ of many current philosophical accounts of scientific representation. Giere’s (2010) conception, for example, does include an actor’s intention and a purpose but also contains the dyad between a model that represents and a represented target. Frigg and Nguyen (2016) remark, too, that the majority of philosophical literature on scientific representation is ‘predominantly concerned with scientific models’. This is presumably a result of philosophers having recognised the role of scientific models as ‘principal instruments of modern science’ (Frigg and Hartmann 2017). The numerous objects which scientists use as representations, tend to be subsumed by the notion of models in this view. Yet, despite the growing importance of scientific models, environmental sciences such as oceanography heavily rely on the use of scientific data as representations. Arguably, scientists in those fields tend to maintain sharp distinctions between scientific models, data resulting from modelling practices, and empirical, observational data.

The notion of “data models” merges the two terms and accounts for scientific representation with data by explicitly employing an interpretation of data as models. This move is motivated by the idea that in scientific practice, data used by scientists for representing are always processed and manipulated to an extent that makes them a model of the originally acquired data, which are often termed “raw data” (Harris 2003). Data models ‘impose order’, they ‘regiment and streamline data’, explains Elgin (2010: 12). Thereby, processed data incorporate decisions driven by theories, background knowledge, and research goals. Harris (2003: 1515) argues, however, that even the data created or acquired at the lowest, least manipulated level have embodied theoretical principles and commitments of scientists.[86] Therefore even these low-level data should be viewed as models ‘that involve interpretation from the start’ (Harris 2003: 1515). The data are not copies of a real-world target, but models that ‘represent inexactly’ (Harris 2003: 1509). Harris comes to the conclusion that data creation or acquisition in most scientific cases cannot readily be viewed in separation from data manipulation and processing. The two activities are not independent of each other (Harris 2003: 1516). My chapter follows this suggestion and studies empirically how scientists create and process data for the purpose of representing real-world targets.

Data models as a concept emphasise the constructed, manipulated, and theory-laden character of scientific data. However, they introduce the danger of conflating the two categories and their associated practices from the start. Despite some common features, data and models are arguably products of different epistemic practices: data practices which include sampling and modelling. These are associated with different roles and meanings in many scientific disciplines. Further, there is no reason to assume that any given type of data created and used by scientists fits into existing modelling conceptions because they are manipulated and have inaccuracies. If that was the case, philosophers could abandon the notion of data altogether. I thus do not rely on the concept of data models for my account of representing with data.

That representations used by scientists are inexact or inaccurate has been emphasised by a variety of scholars. It needs to be clear that the idea of an absolutely truthful or perfectly accurate scientific representation is a misconception. Scientific representations are not mirror images, copies, and in most cases not even imitations of what they are supposed to represent (Frigg

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[86] See my discussion of “theory-ladenness” of data in chapter one.

and Nguyen 2016). Even the idea of similarity between a representation and its target, which has often been put forward as the key to constituting a representation, should be considered only as one of many specific styles of representing or as a normative criterion for accurate representation, as Frigg and Nguyen (2016) note.[87] Ian Hacking (1983: 145) already pointed out with regard to the variety of elaborate and often competing representations of targets in physics that 'there is no final truth of the matter, only a barrage of more or less instructive representations'.[88]

5.1.2 Specifying representation in studies of scientific practice

Examples of concrete practices of representing shed light on how instructive or useless scientific representations may be. In Leonelli's (2016: 811) view, the 'prospective usefulness as evidence' for 'knowledge claims of interest to the researchers involved' is a defining aspect of data. Further, data can only be identified with respect to specific research situations and contexts of enquiry in which they may be useful (Leonelli 2016: 818). I follow this emphasis on concrete research situations by focusing on the local context of newly created data and examining their prospective usefulness for scientific claims.

To consider the "prospective usefulness" of a given set of data is not a straightforward task, because it requires taking into account claims and reasoning based on the potential of data to represent certain targets. Of course, philosophers study scientific practice and examine how representing with data figures in concrete epistemic processes which have led to the formulation of scientific claims or theories. However, the possibilities of a given set of data to

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[87] As Elgin (2010: 1) clarifies, 'mimetic accounts of representation fail to do justice to our representational practices. Many seemingly powerful and effective representations turn out on a mimetic account to be at best flawed, at worst unintelligible.'

[88] Note that inaccuracy and misrepresentation are qualities that theories of scientific representation need to account for, according to Frigg and Nguyen (2016). Though inaccurate, an object can still be used to denote or stand for a target without losing its status as a representation.

function as evidence for claims can never be exhaustively known at any point in time. This gap between known data applications and potential use as evidence is particularly salient in data-intensive sciences in which many types of data are generated without clearly formulated purposes or specific representational targets and in which data are stored, made accessible, manipulated, re-purposed, or integrated with other data multiple times.

Despite this gap, philosophers have made an effort towards conceptualising scientific representing of specific targets. Morgan (2003) argues that there is a difference between an object being “representative of” a target and “representative for” a target. Taking the example of a laboratory mouse which is a typical model organism, Morgan (2003: 228) explains that the mouse is representative of other mice but can also be representative for other types of organisms, humans, for example. Being “representative of” a target involves a relation similar to the one between a sample and a population: being ‘of the same case’ or ‘the same type and the same stuff’ (Morgan 2003: 228). Establishing an object as a representation for targets of different types usually relies on additional evidence and similarity reasoning (Morgan 2003: 228). Ankeny and Leonelli (2011: 315) claim that the “representative of”-type of representing encompasses a narrow, endogenous scope, while the “representative for”-type of representing encompasses a broader, exogenous scope. They advocate a specification of representing that operates one level above Morgan’s. The endogenous/exogenous distinction applies to a model’s “representational scope”, but not to its “representational target” (Ankeny and Leonelli 2011: 315). Although arguing as Morgan with regard to representation with models and model organisms in particular, Ankeny and Leonelli claim that the representational scope refers to the spectrum of potential applications and scenarios in which a model could produce evidence for claims. The representational target, however, refers to a specific type of entity or feature that is represented by the model in each scenario.

A set of temperature data measured in a cooling body of water will always have a water body’s temperature as its representational target, yet the scope of such data can vary: The data could potentially be used as evidence for knowledge claims related to physical, chemical, or biological processes in the very body of water in which the temperature was measured but also in bodies of water with comparable conditions. The latter could include artificial water basins, natural lakes, oceans, or even fictional scenarios realised in numerical models or thought experiments. These distinctions are certainly helpful tools to describe and conceptualise scientific representation in concrete research situations. Yet, an uneasy feeling remains with regard to both the gap between known applications and potential data uses and also with regard to the dyad of model and target. The identification of endogenous or exogenous and representative scopes and targets might actually reinforce the model-target dyad.

In his study of creating soil samples in the Amazon Forest, Latour (1999: 69–73) criticises the 'canonical view' which puts the world and representations in opposition and thereby creates the 'radical gap that must be reduced through the search for correspondence, for reference, between words and the world' (Latour 1999: 69). Latour proposes instead a chain of transformations which translate or convert matter into a certain form. This chain grows from a starting point towards two extremities: Through reduction towards local and particular research contexts on one end and through amplification towards standardisation, circulation, and increased compatibility on the other end (Latour 1999: 71). In this view, a chain of adequate transformations could turn temperature data from a distinct body of water into data that are capable of representing ocean phenomena. The scope of the data is thus amplified. Latour's chain also allows for reduction towards the particular: The data could be transformed and used as a representation of phenomena that have occurred in the very body of water that was part of the experiment. An important requirement for moving along the chain either direction is traceability of all transformations (Latour 1999: 69).

Data can 'easily be construed as a starting point for scientific reasoning about a variety of phenomena' (Leonelli 2015: 811–12), but in Latour's framework, there is no pre-determined direction for the creation of the chain. Moving towards a rather narrow, localised scope via steps of reduction and moving towards a broader scope via steps of amplification are equally possible. In principle, Latour’s chain of reference extends infinitely into both directions. It thus conveys a similar perspective on representation as Rheinberger’s (1995: 51) claim that ‘the activity of scientific representation is to be conceived as a process without “referent” and without “origins”’:

> There is no such thing as a representation *of* an object in science’. Basically, my argument is that anything “represented,” any referent, upon closer inspection and as soon as we try to get hold of it, is turned itself into a representation. (Rheinberger 1995: 51)[89]

There is no real world filled with potential targets that is external to the representations a scientist creates. Each transformation creates a real entity that can, again, be brought into a certain form for specific epistemic purposes.

It becomes clear from Latour’s chain of transformations that something specific happens at each stage of the epistemic process. Each transformation either functions as a way of amplifying or reducing the representational scope of data. Morgan (2012: 322–28) points out in reference to Hacking’s (1983) *Representing and Intervening* that scientists interfere rather than represent by using a microscope. Such an interference has a “scoping” effect which ‘enables us to see and investigate *hidden* things’ (Morgan 2012: 322).[90] Making features visible that are otherwise obscured can be achieved by amplifying specific features or by reducing noise but a variety of epistemic activities may be involved in these steps. Elgin (2010) elaborates on representations as exemplification: Scientific experiments exemplify because ‘they select, highlight, control and manipulate things so that features of interest are brought to the fore and their relevant characteristics and interactions made manifest’ (Elgin 2010: 6).

The empirical part of this chapter tracks epistemic actions with a scoping effect in an example of scientific data creation. I intend to employ two understandings of the term “scope”. The first is motivated by the representational scope as explained by Ankeny and Leonelli (2016). Although I am not interested in

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[89] Emphasis in original.

[90] Emphasis in original.

distinguishing between a scope and a target of a representation, scientists who create data undeniably have a certain spectrum of applications and scenarios in mind in which created data are expected to serve as starting points for scientific reasoning. The second understanding is motivated by the scoping effect of interventions that act on an object and amplify or reduce only some of its characteristics. Since microscopes are crucial for the data creation in my case study, this understanding works quite literally.

5.2 The creation of CPR data

The process of sample analysis in the CPR Survey has been documented and published in several marine biological and oceanographic journals.[91] My description of the sample analysis is informed by these papers but is also firmly grounded in observations I made in the survey's lab and in ethnographic interviews with the lab manager and sample analysts.

After the silk rolls have been unloaded from the CPR, cut into individual samples, and labelled as described in chapter four, they are stored in a cabinet between the survey's operations workshop area and the laboratory. The sample analysis consists of four steps which are performed in a strict order: The first step, an assessment of the silk colour, already happens right when the silk is cut into individual samples. The other three steps are performed with microscopes after the silk has been cut into samples and after the sample has been allocated to an analyst. The three microscopic steps are then performed in immediate succession so that a sample will be unpacked from its temporary storage in the cabinet only once.

5.2.1 Visual assessment of the silk colour

The very first of the four steps is performed when the entire band of silk is rolled out by the cutter. After the positions of individual samples have been marked on the silk, the overall colour of each sample is assessed by the cutter using the

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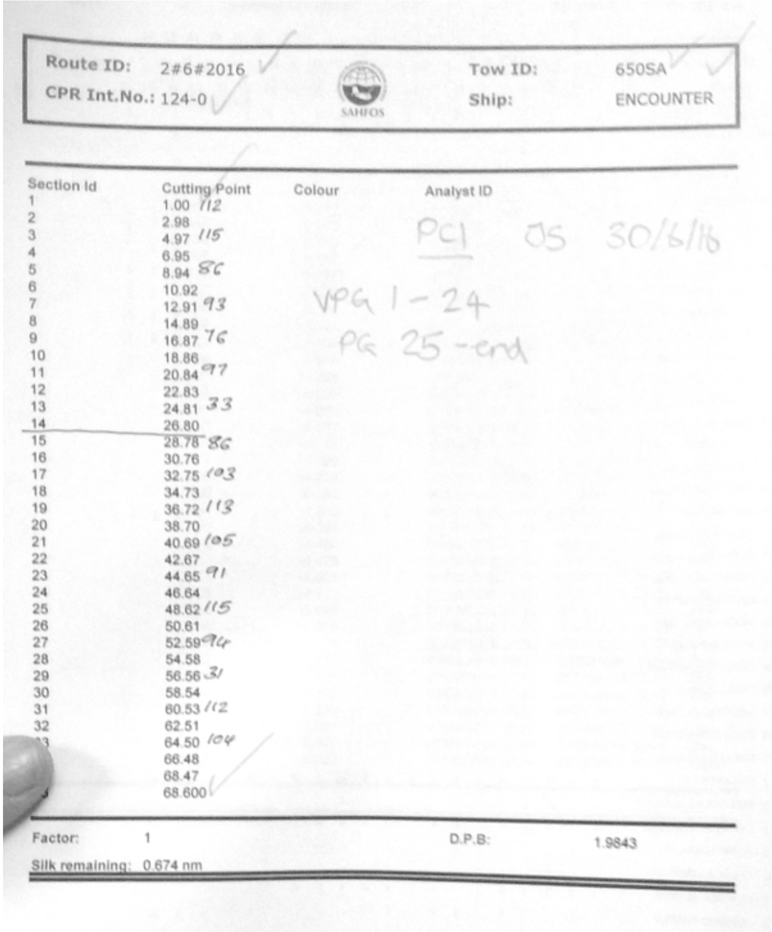
[91] See for example Reid et al. (2003), Batten et al. (2003), Richardson et al. (2006), and Raitsos et al. (2013).

naked eye (Richardson et al. 2006: 67). This step of analysis is conducted as early as possible after the CPR has returned to Plymouth because the plankton organisms lose their colour in the formalin solution as time progresses (Raitsos et al. 2013: 162). This also means that the colour analysis can only be performed once with each sample. From the colour assessment, scientists derive a ‘proxy of the phytoplankton biomass’ that has been used widely ‘to describe major temporal and spatial patterns of phytoplankton in the North Atlantic’ since 1931 (Raitsos et al. 2013: 159).



Route ID: 2#6#2016 ✓
CPR Int.No.: 124-0 ✓
Tow ID: 650SA ✓ ✓
Ship: ENCOUNTER

Section Id	Cutting Point		Colour	Analyst ID
1	1.00	112		
2	2.98			
3	4.97	115		
4	6.95			
5	8.94	86		
6	10.92			
7	12.91	93		
8	14.89			
9	16.87	76		
10	18.86			
11	20.84	97		
12	22.83			
13	24.81	33		
14	26.80			
15	28.78	86		
16	30.76			
17	32.75	103		
18	34.73			
19	36.72	113		
20	38.70			
21	40.69	105		
22	42.67			
23	44.65	91		
24	46.64			
25	48.62	115		
26	50.61			
27	52.59	94		
28	54.58			
29	56.56	31		
30	58.54			
31	60.53	112		
32	62.51			
[illegible]	64.50	104		
[illegible]	66.48			
[illegible]	68.47			
[illegible]	68.600 ✓			

PCI JS 30/6/16

VPG 1 - 24
PG 25 - end

Factor: 1
D.P.B: 1.9843
Silk remaining: 0.674 nm

Figure 5.1: Cutting point sheet of tow 650SA (650th tow on the SA route). From left to right column: sections of the silk band marked prior to deployment, actual cutting point in accordance with the ship’s speed, handwritten ID number of the analyst to whom a sample is allocated, colour assessment (PCI), and cutter’s ID number and date (DR8112).

In order to assess the colour, a daylight bulb is turned on and a black-out blind in the room has to be closed for proper visual assessment of the silk colour. A white background is slid behind the silk and the colour impression of the filtering silk is evaluated in reference to a four-category colour chart. The colour is categorised as either ‘Nil – no colour’, ‘VPG – very pale green/brown’, ‘PG – pale green/brown’ , or ‘G – green/brown’.[92] As an additional reference, the analyst cutting the silk may look at “tram lines” along the silk’s two opposite sides, where the silk has run through the internal CPR mechanism. These lines are not covered with plankton and the silk has therefore largely retained its original colour. According to the survey’s standard procedures, the cutter also needs to make sure that the greenness of the sample is not obscured by certain zooplankton organisms of rather brown colour. The cutter therefore needs to lift the covering silk and look for the presence of zooplankton. On the so-called cutting point sheet, where the exact cutting points of the silk band are noted, the cutter records the impression. A typical recording of the sample colour on the sheet would be “VPG 1–24” and “PG 24–end”, indicating that the first 24 samples of that tow look very pale green and the remaining samples look pale green (fig 5.1).

At the moment of noting the colour impression on the cutting point sheet, the sample cutter creates scientific data. These data are physical artefacts, created by the cutter as representations of a characteristic of the sample, specifically, the sample’s colour impression. Data creation involves a new medium: a paper sheet on which a sample characteristic that has been assessed and categorised by a data generator, the cutter of the silk, is inscribed. The paper and writing provide portability and readability and thereby enable communication and circulation of the sample’s recorded property. Furthermore, the cutting point sheet containing the data can also be stored and retrieved. While the colour of the silk fades during storage of the sample, the data creation captures a sample’s temporary characteristic and inscribes it onto a more durable medium. What makes these data physical artefacts is not just the inscription on a physical piece of paper with a pen or pencil. The data are also generated intentionally in a certain way, under specific, artificial conditions, using a specific colour chart for reference, and as one of four possible values. While the

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[92] Quoted from an excerpt of the survey’s standard procedures that explains the plankton colour analysis.

greenness of the sample is a given for the person who is cutting the sample, the data on the cutting point sheet are clearly artefacts.

The previous paragraph contains several terminological "pointers" to other scholarship on scientific data.[93] I am not interested in comparing or testing the data in my case against these accounts, instead, I intend to draw attention to the context of the hand-written data, to their representational scope, which the context at least partly determines, and to the scoping effect achieved by the data creation.

The cutting point sheet is stapled together with several other sheets that relate to one specific tow and contain a variety of metadata: The original ship's log form that is returned from the ship contains locations and times of the beginning and the end of the tow as well as course alterations; an additional tow log form generated after the tow which matches the ship's tow log but contains additional information on the ship's speed, the tow length, the numbers of the CPR's internal cassette and propeller, and additional instruments that were attached to the CPR; the sample positions sheet which matches each sample's position along the silk band with geographic locations and the time of sampling; and lastly, a sheet added by the workshop team after checking the CPR's technical components following a tow. Claire Taylor, deputy lab manager and an experienced sample analyst, says that some of the sheets are not really used, but 'everything that pertains to this route is held together' (DR8112: 7–8). While the sheets enable communication of data and metadata relating to one tow, they only circulate within SAHFOS. One of their main purposes is being a reference for 'cross-comparing everything', Taylor explains (DR8112: 7). A majority of data and metadata on the sheets shown to me were ticked off by a person making sure that every bit of information relating to one tow is consistent and double-checked (fig. 5.1).

The data in this format and context are closely attached to an individual tow. On the basis of the data as they are on the cutting point sheets, no scientific claims

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[93] Portability, communication, and physical artefact (Leonelli 2015); inscription (Latour 1986); data generator (Hacking 1992); storing, retrieving, and durability (Rheinberger 2011).

about the phytoplankton population in the oceans are made. The data are not used as representations of a real-world system's parts or processes. Data inscribed as "VPG 1–24" relate primarily to qualitative characteristics of a specific tow's samples. The representational scope, the range of objects or processes these data represent in the context of the cutting procedure and the stapled sheets, is thus relatively narrow. It is restricted to a tow's samples and does not encompass any aspect of the real-world ecosystem. Despite this relatively narrow scope, the data generation is a step towards standardisation and circulation of a sample's characteristics. Transient qualities of matter are transformed into form in a very specific, standardised way so that the information can circulate and be traced back if necessary. In Latour's terminology, the creation of data on the cutting point sheets is an amplification and a first step away from the particular.

Another amplification is achieved through further processing and moving of the data into a digital database. The colour values are entered manually into the CPR Survey's database, but not as qualitative values expressing a degree of greenness: The four categories are converted to numerical values, according to the so-called Phytoplankton Colour Index (PCI). Since the 1960s, the values "no colour", "very pale green/brown", "pale green/brown", and "green/brown" have been converted into the numerical values 0, 1, 2, and 6.5, respectively. These quantities indicate the relative mass of chlorophyll *a* on a sample. For example, a sample identified as "pale green" is estimated to contain double the amount of phytoplankton biomass than a sample identified as "very pale green". A "green" sample is estimated to contain 6.5 times the phytoplankton biomass of a "very pale green" sample. Experiments involving extractions of chlorophyll *a* from a sample were conducted in the 1960s to derive the four PCI values (Raitsos et al. 2013: 159–60).

The digitisation and conversion of the qualitative colour data to quantitative PCI values open up a wide range of potential data uses and increase the representational scope of the data. The database contains all previously created PCI data, which allows for comparisons and, most importantly, for the computation of spatial and temporal averages. At least since the 1970s, the

CPR Survey has been using 41 pre-defined standard areas routinely for spatial averaging of their data (fig. 5.2). The North Atlantic and the North Sea, where the majority of CPRs are towed, are divided into 41 areas. Many of these follow the edge of the continental shelf which is defined at the one hundred fathom contour, equivalent to a depth of circa two hundred metres. The size of the boxes on the shelf are smaller than those on the open ocean ‘to reflect the more dynamic physical environment, larger biological variability’ and the higher number of CPR samples from these areas (Richardson et al. 2006: 63). Transformations of this kind clearly aim at increasing the scope to a level that encompasses the natural system, because the system’s dynamics and topography are taken into account.

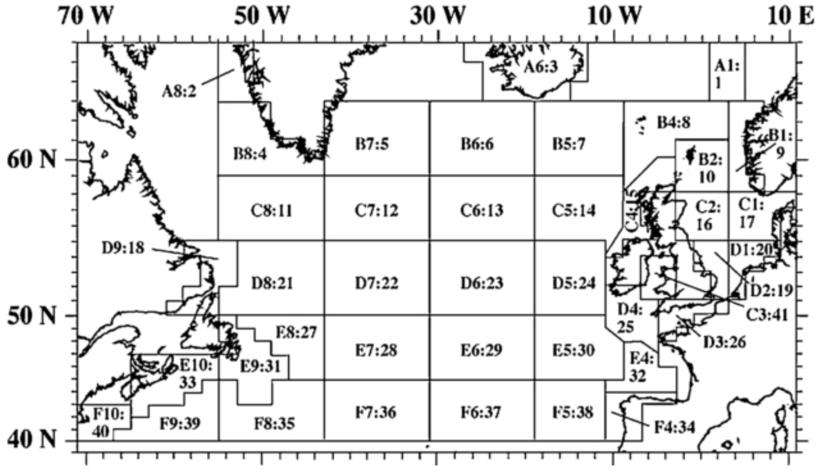

Figure 5.2: The CPR Survey’s 41 standard areas in the North Atlantic and the North Sea which are routinely used to average data spatially (Barton et al. 2003: 339).

In an example of data use, Barton et al. (2003: 340) have taken the PCI data as ‘qualitative monthly measures of relative phytoplankton abundance’.[94] They relate the data to multi-decadal physical processes of the oceans, such as the North Atlantic Oscillation[95] (Barton et al. 2003: 340), for which monthly means of

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[94] “Qualitative” indicates here that the data are based on a qualitative assessment. The authors have certainly used quantities to calculate monthly means.

[95] The North Atlantic Oscillation describes cyclical anomalies in sea surface air pressure between pressure centres near Iceland and above the Azores. The anomalies influence temperatures and precipitation in the Northern hemisphere; <http://climate.ncsu.edu/climate/patterns/NAO.html> [accessed 1 December 2016].

the PCI values for the 41 standard areas have been calculated for the years 1948 to 2000.

Lab manager David Johns explains that the general scientific purpose of the colour assessment is to be able to reason about changes in phytoplankton biomass in the oceans:

> “The whole idea of that is, it gives you a very broad indicator of phytoplankton biomass, just by visual assessment. And I would think that sounds like really woolly science, you know, ‘It’s kind of dark green, it’s kind of pretty green.’ But it actually matches up. We have got sixty or seventy years and it actually matches up with satellite data really well. So if we say ‘This is a really green sample in this area,’ it represents high biomass and then we would check satellite records and they recorded high chlorophyll levels as well. So it is a good initial assessment.” (DR0934: 1–2)

An assessment using the naked eye may sound “woolly” and Raitsos et al. (2013: 162) admit as well that the colour assessment ‘could be characterized as a crude approach’. However, the method’s ‘strength lies in a time series that extends over sixty years for much of the western European shelf collected and assessed in a consistent manner’ (Raitsos et al. 2013: 162). The relative PCI values of previous decades have been confirmed by extracting the chlorophyll from the samples and measuring its mass per sample with a much larger sample size than the original experiments of the 1960s (Raitsos et al. 2013).

It may not be surprising that the very first data recordings from a silk sample, the hand-written, qualitative colour values, are not yet ready to be used as a basis for scientific claims about the ocean ecosystem. In order to be used as evidence for claims, data in almost every scientific field usually require calibration, cleaning, averaging, digital storing and accessibility, and other steps of processing. My analysis emphasises that the requirement of these epistemic activities makes the status of scientific data as representations a context-dependent practical achievement. Data have no representational power built into them. The use of data as representations of real-world systems such as parts or processes of an ocean’s ecosystem is only possible after moving data into a new context and translating them to a new medium: from the stapled sheets pertinent to an individual tow to a digital database where all data the survey has created in the past are linked together and computable. In the course of this transition, the representational scope of the data broadens from an individual tow to processes of the real-world ecosystem.

5.2.2 Microscopic analysis of sub-samples

Unlike the colour assessment and the PCI data, the three steps of microscopic sample analysis aim at the creation of data related to distinct taxonomic entities. The CPR Survey distinguishes around 800 different taxa routinely in their identification and counting practice.[96]

In this section, I argue that scientific representation with the data created in the microscopic analysis is realised in a procedure analogue to the PCI data I have described in the previous section. However, hand-written data that are created during the microscopic analysis have a representational scope that is even more narrow and only relates to one individual sample and not to an individual tow. Using the data for representation of real-world targets is only possible after the data have been further processed and moved into a new context.

For the microscopic analysis, individual samples are allocated to a sample analyst, also frequently called a plankton taxonomist, who retrieves the sample from the temporary storage. The microscopic analysis is divided into three steps, which relate to organisms of different size ranges: the phytoplankton stage which accounts for the ocean’s smallest organisms, the “zooplankton traverse” which accounts for zooplankton organisms with sizes up to two millimetres, and the “zooplankton eyecount” which focuses on all zooplankton larger than two millimetres. All three steps involve identification and counting of

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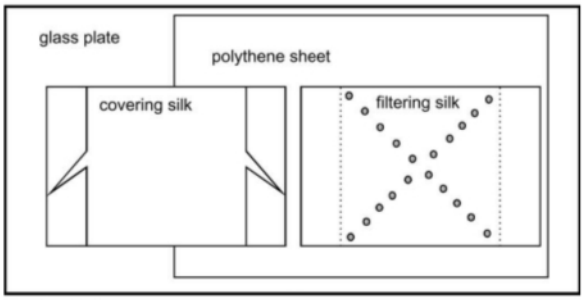
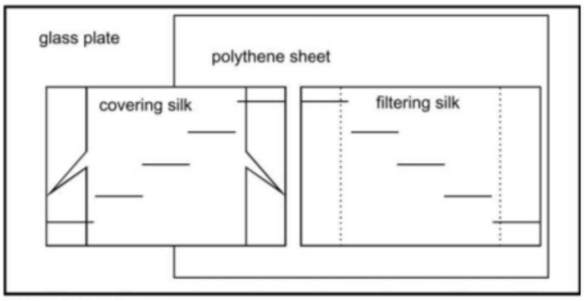
[96] Individual samples certainly never contain this huge number of different taxa. The composition of plankton species on one sample depends on the regional ecosystem through which the CPR has been towed.

plankton organisms. The method, however, by which the samples and the organisms are examined and counted varies with each step.



(b) Phytoplankton Analysis



(c) Zooplankton Traverse

Figure 5.3: Parts of the silk analysed in the phytoplankton and zooplankton traverse stages. Top: small circles along the filtering silk's diagonals indicate the twenty microscopic fields of view that a taxonomist examines in the phytoplankton stage. Bottom: staggered horizontal lines on the filtering and covering silk indicate the traverses along which organisms are identified and counted in the zooplankton traverse (Richardson et al. 2006: 34).

An important aspect of steps one and two is that not the entire sample is analysed but instead, the two pieces of silk are sub-sampled. In the phytoplankton stage, a taxonomist only looks at twenty microscopic fields of view along the filtering silk's two diagonals (fig. 5.3). The sampled area amounts to only 1/15,000 of the filtering silk's total area, according to Johns (DR0934: 2).[97] At 625x magnification, the field of view has a diameter of 295 micrometres, which is just slightly larger than the silk's mesh size of 270 micrometres. Johns explains that a taxonomist always focuses the field of view on one single mesh for phytoplankton identification (DR0934: 2).

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[97] According to Richardson et al. (2006: 33), the twenty fields of view amount to 1/10,000 of a sample. According to Batten et al. (2003: 198) the analysed area amounts to only 1/8,000 of a sample.

In the second stage, the zooplankton traverse, the microscope is set to 62.5x magnification, resulting in a field of view with a diameter of 2.06 millimetres, circa ten times larger than in the phytoplankton analysis. This stage is named the ‘zooplankton traverse’ because the taxonomist moves the field of view stepwise across the silk, creating a horizontal traverse along which organisms are identified (Batten et al. 2003: 198, Reid et al. 2003: 127). The area analysed during the traverse is ‘staggered’ in a way that each piece of silk is crossed along five horizontal lines (Batten et al. 2003: 198).[98] The traverses on both the filtering and the covering silk result in circa 1/50 part of the whole sample being analysed with the microscope (Richardson et al. 2006: 35–36).[99]

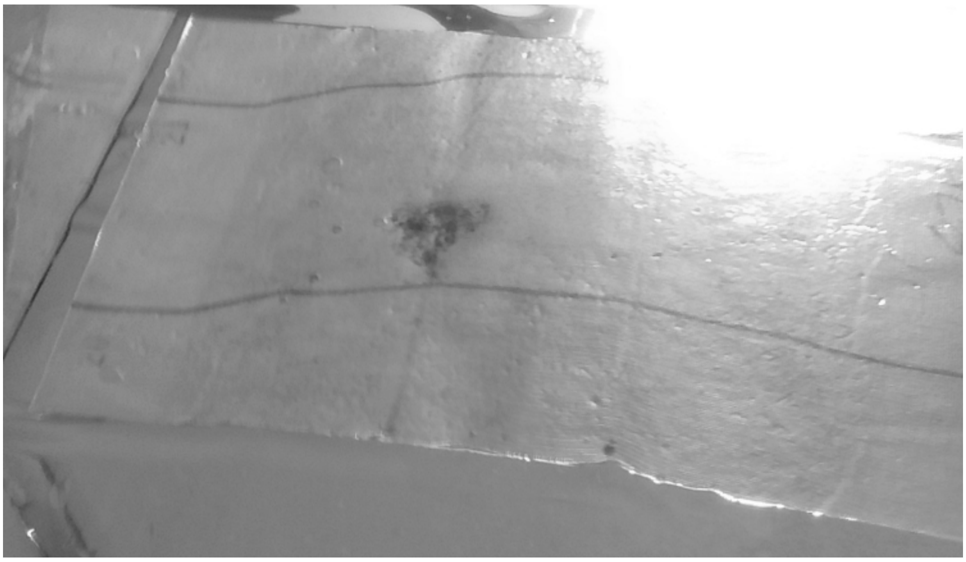

Figure 5.4: Silk sample with a green pile of zooplankton scraped together for removal from the filtering silk. The horizontal lines are the two-inch divisions on the filtering silk that are marked in preparation of the silk. The curves along the lines are a sign of silk distortion during the sampling process.

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[98] The zooplankton traverse is performed on the filtering and the covering silk in this way, because although retained by the silk, the plankton may not stay firmly fixed on the filtering silk and ‘planktonic material may be transferred to the covering silk during sampling or processing’ (Batten et al. 2003: 198).

[99] Again, this number is slightly different in other publications. In Reid et al. (2003: 127) the zooplankton traverse is stated to result in 1/40 of the sample being sub-sampled, while Batten et al. (2003: 198) claim that the ‘traverse represents a subsample of about 1/49 of the sample’.

In step three, the zooplankton eyecount, the sample is not sub-sampled but the taxonomist removes the zooplankton organisms from the silk and puts them into a Bogorov tray, which makes their identification much easier. Using a so-called “cranesbill forceps”, an analyst scrapes the larger organisms on the filtering silk together to form a little green pile in the middle of the sample (fig. 5.4). The pile is removed from the silk and spread out evenly in the Bogorov tray. The tray is put under another microscope set at the same magnification as in the zooplankton traverse. The removal of organisms is necessary because, as I have described in the previous chapter, especially the large zooplankton are severely deformed during the sampling stage. Additionally, the two most important large zooplankton species of the North Atlantic and the North Sea, *Calanus finmarchicus* and *Calanus helgolandicus*, look very similar and are identified primarily by the shape of their fifth pair of swimming legs (Richardson et al. 2006: 47). Johns explains:

> “There are a couple of species that are very, very similar, for example the *Calanus* species. And they co-occur, they are like three millimetres, and the only way to tell them apart is to look at their tiny little last leg and the teeth on the tiny little last leg.” (DR0533: 3)

Making this distinction is much easier with the organisms not sticking to the fibrous silk between the other plankton, but rather floating freely in a transparent tray. Johns continues:

> “It is just so much easier to identify them. You can’t do it on the silk very easily. It is so much easier, you take them off, put them into that tray, add some fluid and then you can manipulate them easily, flip them around. Because a lot of them, depending on how they are lying, they can hide their identification features, so you need to kind of manipulate them 360.” (DR0533: 6)

Plankton organisms are identified and counted according to a list of taxonomic entities that contains more than 800 species or species groups, as I further explain in chapter six. The counting procedure differs between the three steps of analysis. In the phytoplankton stage, only the presence of a taxonomic entity in one of the twenty microscopic fields of view is relevant, not how many organisms are actually visible in the field. For each microscopic field of view in which a taxonomic entity has been identified the taxonomist writes down the name of the taxon in a hand-written notebook and a tally mark is added next to the name. The analyst proceeds from one field to the next and adds tally marks for each field in which a specific organism has been encountered. After examining all twenty fields across the filtering silk, a hand-written list of taxonomic entities with tally marks has been created (fig. 5.5).

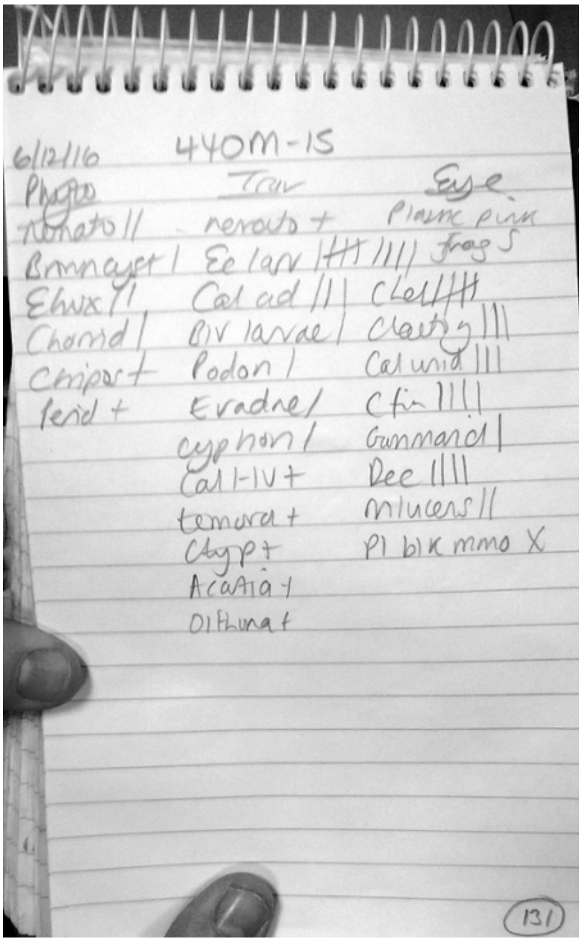

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Figure 5.5: A page in a plankton taxonomist's notebook with data created during a sample analysis organised in three columns. From left to right: phytoplankton stage, zooplankton traverse, and zooplankton eyecount (DR8112).

The tally marks do not correspond to the total number of organisms of a taxonomic entity that the analyst has actually encountered but only to the fields of view in which they were present. The maximum value for each taxonomic entity in the phytoplankton stage is thus twenty, because only twenty fields of view are analysed per sample. By contrast, in the two zooplankton stages, the organisms identified by a taxonomist are counted numerically. In both cases, the analyst writes down the name of the identified organism but this time adds a tally mark for each individual of that taxon along the entire traverse or in the Bogorov tray, respectively.

It may occur during the traverse and the eyecount that organisms are encountered that were not detected at an earlier analysis stage, although they should have been detected then. A small zooplankton organism, for example, may not have been located in the area of the traverse sub-sample, but it might end up in a Bogorov tray during the eyecount. Instead of counting these organisms numerically, the taxonomist records a "+" in the notebook, as can be seen for several taxonomic entities in figure 5.5, indicating that this taxonomic entity was present. Some taxa are also quite difficult to count numerically because the organism has been damaged during sampling or because organisms are significantly larger than the field of view so that one and the same individual might be visible in multiple fields. Only the presence is recorded in these cases as well (Richardson et al. 2006: 58, DR8112: 7).

Quite literally, the tally marks in a taxonomist's notebook are 'marks' that are recorded by human 'data generators' (Hacking 1992: 48) and they should thus be regarded as data just like the hand-written colour data on the cutting point sheets. Further, similar to the colour assessment, the data are created as representations of characteristics of a sample: The tally marks do not denote or refer to any plankton population in the oceans but rather translate an individual sample's specific qualities to a standardised form. These qualities result from the very particular examination procedure in which the configuration of the microscopes, the selection of a sub-sample, and the manual removal of plankton from the silk play a decisive role. As can be seen in figure 5.5, the hand-written data of the microscopic analysis, also referred to as "notebook data" for the remainder of this chapter, are organised in three columns, one for each stage of analysis. A tally mark in column one, however, represents not just a different species than a tally mark in columns two or three but a different kind of property, due to the different counting procedures in each stage. The tally marks in the notebook, as they are recorded by a taxonomist, represent characteristics of a sample that is embedded in the laboratory context with all of its instruments and practices, including different sub-samples, magnifications, and microscopes.

Figure 5.6: Index page of a taxonomist's notebook. Each box is associated with one of the CPR routes and contains entries in the form "tow number – page number" (DR8112).

Each sample analyst uses a personal notebook, but the same notation system is employed by all analysts. This allows for quality checking of another taxonomist's record, even if that person is absent. Lab manager Johns, who is also analysing samples regularly, explains that all analysts employ "kind of" the same system of notation:

> “Everybody is supposed to. We have a standardised procedure written for how you are meant to write it in. But it is meant to be one sample per page, which I never do. That’s kind of how I write mine down. Most of them are fairly readable, but …” (DR0533: 3)

Like the stapled paper sheets described in the previous section are pertinent to one individual tow, one page in a sample analyst’s notebook is supposed to be pertinent to one individual sample. As a taxonomist is never allocated adjacent samples of one tow in order to avoid a potential taxonomist bias,[100] the data on the previous and following pages of the notebook are created from samples of different routes and different tows. In order to be able to find the data of one particular sample, each notebook features an index, which the taxonomists need to keep up to date (fig. 5.6). Plankton taxonomist Taylor comments on the indexing of notebooks:

> “It’s the most boring thing in the world, but if you don’t have it, it will be a pain in the bum trying to sit there and go back through books.” (DR8112: 4)

Taylor has been analysing samples for fourteen years and is currently working with her thirteenth notebook. She continues:

> “Some people have been here double the amount of time. So we do keep all of these as well in one central place. In theory you can go back through and check.” (DR8112: 4)

Rather than being the basis for claims about phenomena in the oceans, the notebooks provide space for the quantification of a sample’s qualities and function as a medium for storing and communicating the quantities. As the stapled sheets that relate to a tow, the notebooks never circulate beyond SAHFOS. From the above quotations, it seems that they are rarely retrieved to re-examine what exactly a taxonomist has recorded. Yet they serve as a backup of data so that a person can potentially track down notebook data that have been created by a different taxonomist many years ago.

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[100] See the ID numbers of various taxonomists on the cutting point sheet in figure 5.1.

The representational scope of the notebook data encompasses only specific qualities of one individual sample. The organisms are made visible and identifiable by virtue of microscopes and a scoping effect literally amplifies certain areas of the silk in a way that the amplified matter can be transformed into standardised data that can circulate within SAHFOS.

5.2.3 Transcription and processing to broaden the scope

Much like the PCI data, the notebook data undergo a change of medium and context from a paper-based form into the digital database. This transfer and subsequent data processing widen the data's representational scope, enable the use of computation and visualisation tools, and thereby enable scientists to make inferences about the real-world ecosystem. As I explain in this section, the processing involves a category system and a statistical conversion which transform the tally marks from representations of specific qualities of only a sub-sample into estimated quantities of organisms of a taxonomic entity on an entire sample.

For the transcription of the notebook data, two analysts sit together in an office room and enter the data from the notebooks into the digital database. Using a "buddy-buddy system" (DR8112: 7), two analysts check on each other in order to avoid transcription errors (DR0533: 1–2). The number of tally marks in the notebook are entered but once digitised, the recorded value is processed: In the phytoplankton stage, the number of fields in which a taxonomic entity was present is converted into an 'accepted value, representing the total number of cells of that taxon present in those twenty fields' (Richardson et al. 2006: 35). This conversion is based on the Poisson distribution under the assumption that 'organisms are randomly distributed on the silk' (Richardson et al. 2006: 34).[101]

According to the survey's conversion rules, if a taxon is present in only one of the twenty analysed fields of view, the accepted value will also be one. Four

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[101] Random distribution here means that an organism that has entered the internal tunnel of the CPR ends up in a spot that is randomly located on the silk area that is exposed to the water flow in that moment.

fields of view in which a taxon is present lead to an accepted value of four. Five fields of view, however, lead to an accepted value of six. This means that if the taxon is identified in five fields, a total of six individuals of that taxon will be estimated to be present in the twenty analysed fields. The accepted values increase further with each step: Ten fields of view are converted to an accepted value of fourteen, fifteen fields are converted to twenty-eight, and twenty fields are converted to ninety. Thus, if a species is present in all twenty of the analysed fields of view, a total quantity of ninety individuals of this species will be estimated for all twenty examined fields. The accepted value is subsequently multiplied by ten thousand to obtain an estimate of the total quantity of organisms of a taxonomic entity on one entire silk sample (Richardson et al. 2006: 35).

A similar system of conversion is used for the data from the zooplankton traverse and the zooplankton eyecount. Here, the numbers resulting from the tally marks are assigned one of twelve abundance categories: Exactly one counted organism on the sample corresponds to category one. Analogous to the conversion in the phytoplankton stage, each category also has an accepted value, which is one in case of category one. The accepted value is then multiplied by fifty in order to estimate the total number of organisms of one taxon on the whole sample. Two counted organisms along the traverse correspond to category two and an accepted value of two. Through multiplication by fifty, this leads to an estimate of one hundred organisms of this taxon on the entire sample. Beginning with the fourth category, the range of number counts covered by each category increases. Category four is for recorded values between four and eleven. In this case, the accepted value is six and the estimated abundance per sample is three hundred for all data in this range. The higher the category, the broader is the covered range of counts. Category seven already covers quantities between 51 and 125 with an accepted value of 75 and an estimated abundance per sample of 3,750. Category twelve is the highest category and corresponds to counts between 2,001 and 4,000: The accepted value is 2,690 and the estimated abundance per sample is thus 134,500 (Richardson et al. 2006: 36).[102] As Richardson et al. (2006: 36) explain, this ‘category counting system’ is used to speed up the analysis while it makes the abundance estimates for each sample ‘semi-quantitative’.

In higher categories, the accepted value is closer to the lower bound of the category’s range than to the higher. For example, the accepted value of category seven is 75, which is much closer to 51 than to 125. This takes into account that ‘the abundance values are not uniformly distributed, but instead low abundances predominate’ (Warner and Hays 1994: 240). To illustrate this, if a taxonomist comes to the conclusion that the number of organisms on the traverse is somewhere between 51 and 125, it will be more likely that the exact quantity is closer to 51 than to 125.

Although the category system is a ‘tradeoff’ that effectively causes a ‘loss of information’ (Richardson et al. 2006: 36), it enables taxonomists to say that a sample is, say, category seven as soon as it becomes apparent that the sampled area contains more than 50 but less than 125 organisms. Taylor explains that these judgements are also a matter of experience and younger taxonomists, who tend to be relatively slow with their analysis, sometimes have to be reminded not to count everything they see but only what is required to infer the category. Taylor says that it takes some time to find the “balance of efficiency and accuracy” (DR8112: 5).

One more step of processing is applied in the phytoplankton stage: What is called the ‘recorded abundance per sample’ is an averaged value of every two possible abundance values:

> Unfortunately, because of historical data storage limitations before computers were used, these 20 abundance values are compressed into 10 by averaging. (Richardson et al. 2006: 34–35)

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[102] Such high quantities which would require drawing hundreds of tally marks are quite rare and only occur during strong plankton blooms. In these cases, the sample analysts estimate the number of organisms instead of counting exactly or the sub-sample is divided into even smaller sub-samples.

For example, if a species is present in nine fields of view, the accepted value will be twelve and the abundance per sample will be 120,000. If a taxonomic entity is present in ten fields of view, the accepted value will be fourteen and the abundance per sample will be 140,000. Yet, the two resulting abundances are compressed by averaging and in both cases, 130,000 will be the 'recorded abundance per sample' (Richardson et al. 2006: 35). This method has been employed since 1958, when the number of analysed fields of view was increased from five on both the filtering and the covering silk to twenty analysed fields on only the filtering silk (Richardson et al. 2006: 37). Johns comments:

> "I am never really clear why [the compression] was done. I think it was computer limitations. So yeah, people would look in twenty fields and then actually, if it is seen in only one or two, it becomes a one. If it is three or four it becomes a two." (DR0533: 4)

With today's computers, handling twenty abundance categories would be unproblematic, but the method remains unchanged. Johns explains that a change would be "too difficult" and risky in light of potential uncertainties that a change of method would introduce (DR0533: 4). The category system employed in the zooplankton traverse is based on comparisons with raw counts of individuals conducted in the very early stages of CPR development in the late 1930s (Richardson et al. 2006: 36). The traverse method has remained unchanged since 1948 (Warner and Hays 1994: 240).

The same category system as in the zooplankton traverse is employed in the eyecount, only without the final multiplication because the sample is not sub-sampled for this stage of analysis. In this case, the accepted value is equal to the estimated abundance on the entire sample (Richardson et al. 2006: 36). Only if the sample is very densely filled with organisms, the taxonomist may sub-sample it as well by only looking at half or a quarter of the zooplankton laid out in the Bogorov tray.[103]

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[103] In fact, a mixture of fully numerical and sub-sampling may be applied. If a sample is filled with zooplankton very densely, usually just one or two plankton species will be highly abundant. The sub-sampling is then only applied to these taxa. As Johns explains, "then we would pick through the remainder for the larger things that you

Despite all data being in numerical form in the database, the data are often referred to in the literature and by survey employees as “semi-quantitative” (Richardson et al. 2006: 36, DR2901: 6). The main reason for using this term is because the numbers stored in the database would not match up with actual abundances in the ocean. As I have described in the previous chapter, the sampling method causes differences in the silk’s filter efficiency, depending on the size, shape, or activity of different organisms. Further, the sub-sampling, identification, and counting procedures described in this chapter make the CPR data only an estimate of the distribution of organisms on a sample. As a result, it is extremely difficult to infer estimates of total quantities of a plankton population in the ocean from CPR data alone. CPR data are therefore usually not expressed in units such as organisms per cubic metre of sea water, but instead remain expressed in the unit ‘numbers per sample’, as they have been derived from the hand-written records with the category system and conversion factors (Richardson et al. 2006: 62).[104]

With the standard unit of CPR data being “numbers per sample”, it seems that the data still primarily represent characteristics of individual samples. The key to representing aspects of the actual ocean ecosystem with semi-quantitative data lies in the fact that the survey has accumulated data over several decades with consistent methodology and that these data are already linked and computable artefacts in the database. As Richardson et al. (2006: 61) explain,

> there is considerable evidence that [CPR sampling] captures a roughly consistent fraction of the in situ abundance of each taxon and thus reflects the major patterns observed in the plankton.

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could pick out easily, but you don’t need to sub-sample, because there are not so many there” (DR0533: 6).

[104] As roughly three cubic metres of sea water have run through the CPR in the same period of time that silk of the length of one sample has been exposed to the flow, one could convert to per cubic metre values by dividing the estimate per sample by three. However, ‘abundance estimates are seldom converted to per m^3 estimates in practice’ (Richardson et al. 2006: 62).

Inter-annual as well as seasonal changes are reflected in CPR data (Richardson et al. 2006: 61) and the continuity and length of the survey are mainly responsible for the usability of the data. Johns elaborates:

> "We want to keep that consistent time series. And there are a lot of potential sort of foibles in the dataset. But the fact [is] that it has always been done in the same way. […] You get lots of people who, it's not an accuse, but who would say 'well you under-count certain things'. Well yeah, we do, but they have been consistently under-counted for sixty years. So you can just ignore the abundance values and just look at the trend to see what is happening. So yeah, if you were starting it from scratch, you would do it completely differently." (DR0533: 4)

A major part of the CPR data's value and relevance stem from the continuity of the methods described in this chapter. In fact, not every part of the process may seem reasonable from today's perspective, as Taylor comments:

> "Sometimes there is no logic in how you record it, it is just the way we have always done it. So we keep the continuity going of how we have recorded that before." (DR8112: 7)

The continuity as well as the spatial coverage of the CPR Survey allow for averaging data over large geographic areas of interest and time intervals of months, years, or decades. This reduces many of the imprecisions that are introduced in the analysis of a single sample and alleviates the "foibles" of the methods:

> Abundance estimates from individual plankton samples are inherently imprecise because of variable zooplankton behaviour such as diel vertical migration and local weather conditions that can concentrate or disperse fine-scale patches […], as well as the "broad-brush" counting procedures. To subsume much of this fine-scale variability, CPR data are commonly averaged spatially in

> geographic areas of interest and temporally as monthly or annual means. (Richardson et al. 2006: 63)

SAHFOS thus commonly provides researchers with averaged data and not with data from individual samples. Asked if the unprocessed plankton counts are ever requested, Johns explains: “No, that is sort of raw data. Most people don’t want that. They normally want monthly means by a given area” (DR0533: 4).

The broadening of the data’s representational scope with the change of context from paper to the digital database is also indicated by the final step of quality checking before data are “finalised” and are ready for use. In this step, one of three senior taxonomists, including Johns and Taylor, checks the data of an entire tow in the digital database. At this point, the taxonomist looks for unusual records or gaps which seem unreasonable with respect to the actual ocean ecosystem. Taylor explains:

> “The three of us will go through the actual route looking for gaps. […] We can pick up a particular weakness in an area and we might have a look at that a bit more thoroughly. Or we’ll identify things that we don’t think are in that area. So any regional things we would say ‘hang on a minute’; but that only comes with time. So once you have been here for a time, you start to get a feel for what you should see in each area.” (DR8112: 7)

With “area”, Taylor refers to a distinct region of the ocean and the local ecosystem through which the CPR has been towed. The data are thus actively related to a real-world ecosystem and the close relation to an individual tow or sample somewhat fades into the background. Taylor admits that “it is all a bit subjective” and the senior analysts checking the data frequently consult each other for their opinion if a certain record should be scrutinised by re-analysis (DR8112: 9).[105] The subjectivity of these decisions is a display of the intentionality of scientific representation: Scientists actively establish the

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[105] If data seem unreasonable, a sample will be re-analysed for the questionable taxonomic entity by a different taxonomist than the one who conducted the original analysis (DR0934: 19).

relations between data and real-world systems and these relations are rooted in subjective practices and artificial objects, not in intrinsic properties that are extracted identically by every taxonomist.

5.3 Scientific representing: Increasing compatibility and circulation

The previous section draws attention to changes of context and format which influence the representational scope of scientific data. In paper form, restricted to circulation within SAHFOS, and without practical links to previously created data, the representational scope of the CPR data is relatively narrow. It only encompasses the very entity of which qualities have been recorded as data in a specific kind of laboratory practice. The shift to a digital format links the data of an individual tow or sample with all other data the CPR Survey has produced using the same methods over several decades. Further, the shift makes the data tangible with computing and visualisation tools. In this context, the data's representational scope encompasses parts or processes of the real-world ocean ecosystem. Table 5.1 summarises the different contexts, the corresponding representational scope of data, and the scoping effect achieved by creating the respective representation.

Context	Representational scope	Scoping effect
Cutting point sheet	Samples of one individual tow	Amplification, standardisation and circulation within institution, potential re-examination by a different taxonomist
Personal notebooks	One individual sample	
Digital database	Parts or processes of real-world ecosystems	Amplification, computability and visualisation, circulation beyond institution

Table 5.1: Different data contexts and corresponding representational scope and scoping effect in the CPR Survey.

What I call the representational scope is a contextual quality. The scope is not pre-determined by the geographic location and the time of sampling. These metadata are indispensable to use the data, but my analysis shows that a variety of local conditions under which data are created, processed, and stored shape the scope of scientific data as well. The representational scope, which is crucial for the usability of data, is thus neither an intrinsic nor an independent quality of data. Scientists intentionally perform transformations and translations in order to amplify specific qualities of matter in a standardised way. These epistemic activities shape the spectrum of potential data applications. Latour (1999: 34) calls the sample of an Amazon forest plant a ‘silent witness’ for a scientific claim. The materials in Latour’s and in my case are indeed silent: They do not speak for themselves and they neither contain nor carry claims about real world systems that scientists only need to extract or read.

A number of wordings I encountered in my interviews and in research publications suggest that the relations between data and the real world are not straightforward and clearly defined: Data are termed “semi-quantitative”, they contain “foibles”, “tradeoffs”, a “loss of information”, and are “inherently imprecise”, because the methods are somewhat “woolly”, “crude”, and “broad-brush”. These expressions may characterise the scraping of the silk with a metal tool, the broad categorisation of plankton counts, and the colour assessment with the naked eye, but they further hint at a certain mismatch between the representations scientists create and real-world systems scientists intend to create knowledge of. These “foibles” neither compromise nor invalidate this practice,[106] but indicate that creating reference and finding exact correspondence between representations and the world are indeed problematic conceptions of scientific representing.

As Latour (1999: 30) notes, ‘sciences do not speak of the world but, rather, construct representations that seem always to push it away, but also to bring it closer’. Each step of representing is a move away from particular and complex

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[106] The term “foible” seems very fitting, as it indicates a ‘minor flaw or shortcoming’, but not a complete fault or failure. Persons or things with foibles are still valued and useful, despite minor shortcomings; <https://www.merriam-webster.com/dictionary/foible> [accessed 24 August 2017].

local conditions in which sciences operate and constitutes a step towards compatibility and computability for the integration of data with other, already existing representations of real-world systems. As Porter (1995: viii–ix) contends, quantified data are a ‘technology of distance’ and a ‘strategy of communication’.[107] Representing is a possibility to generate distance between complex matter and data packages that are made for circulation and communication. Barton et al. (2003) compared the PCI data to representations of the North Atlantic Oscillation and newly created CPR data are examined with respect to already existing data before their final release into the database. The gaps that scientists have to close by comparing, integrating, or calibrating newly created data are thus not between representations and fixed targets of the real world, but between representations and other representations.

The methodological continuity which has been exercised over decades is a crucial condition for the practice of representing in the CPR Survey. Data could not be compared to historical records and temporal averages could not be calculated without the strict adherence to methods that might seem outdated in today’s scientific landscape. The continuity allows data that are created today to be checked for their plausibility by experienced analysts. They have gained their knowledge and developed their reference for the examination during years of practising sample analysis and working with CPR data, as well as other resources. The analyst’s expectation has formed by interacting with multiple already existing representations of a natural system. Rheinberger’s (1995) view of representation involves interventions which create difference, but not in comparison to an original or true value. Experimental practices, Rheinberger (1995: 88) writes, have ‘no ultimate perspective, no vanishing point at which the research movement could come to a rest’. Similarly, the continuous creation of CPR data is an ongoing and never finalised generation of differences to existing representations, not to a distinct origin. The following chapter further elaborates on the longitudinal dimension of the CPR Survey and the efforts that assure methodological continuity.

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107 Leonelli (2015: 810) also characterises data as ‘tools for communication’.

5.4 Conclusion

This chapter has tracked the creation of scientific data from their first recording during the analysis of a material sample, through changes of medium and stages of processing, to their provisional destination in a digital database. My account reveals that data are used as representations for different targets at different stages of their genesis, depending on their immediate context and the intention of a researcher. I argue that the primary purpose of creating and processing data is to enhance the data's function as a means of communication within and beyond their site of creation. Further, representing is intended to make data compatible and integrable with other, already existing representations. Scientific representing is constituted by successive epistemic activities — steps of transformations in which data are digitised, processed, and linked to historical records in order to make data usable for scientific reasoning about real-world systems. This view implies that scientific representation is a practical achievement and not an intrinsic property of data.

My empirical research suggests a mismatch between the digital data and real-world targets that resonates with scepticism against straightforward model-target relationships as the basic unit of scientific representation. I argue that the series of transformations actually move data away from the local conditions of research practice and away from the real-world systems that scientists aim to observe. At the same time, by means of standardising and broadening their scope, practices of representing move the data into a space where already existing records are available to compare, calibrate, or integrate the data. Rather than establishing a relation between data and a real-world target, the processing and representing enables or actually establishes possible links to already existing representations.

Is scientific representing consequently an infinite regress towards other existing representations in which truthful correspondence with real-world targets is never achieved? Taking into account the previous chapter's conclusion, the "truthful" link to real-world targets exists in the material continuity from the sample's origin in the sampling device and in the ocean throughout the epistemic process until the sample is archived. Additionally, the series of transformations that provisionally end with the release of data into the digital database must remain traceable all the way back to each individual act of species identification and counting. Intentional, traceable change rather than continuity is characteristic for the chains of transformations that co-occupy the space in-between the natural world and scientific knowledge.

This chapter's view of representing thus adds a new dimension to my account of the genesis of scientific data. The focus has shifted from data-world relations to data-data relations. Given that data are generated in diverse contexts, this shift raises the problem of data commensurability and comparability, in particular if data from different decades are involved. This issue is addressed in the following chapter on the continuity of data practices.

Chapters four and five have shown that both samples and data are portable artefacts that can be moved and used far away from the site and context of their creation. While material samples close this distance with the achievement of material integration and continuity, scientific data are part of a traceable chain that connects them with the sample and the context of data creation. Samples are material 'renderings' (Rheinberger 2015) with a primary purpose of making materials movable in an analysable form. Representations in the form of data serve as a means of communication. They enable computation (Porter 1995) and they serve as a starting point for scientific reasoning due to their compatibility and comparability to existing representations.

Enhanced compatibility does not necessarily make data more accurate. As my analysis shows, the more steps of analysis and transformation are involved, the more uncertainties and "foibles" are introduced. Data creation is associated with an inevitable "loss of information", whereas no information is to be lost in the creation of CPR samples. Rather, the silk samples could be conceived as the first integration of materials in a way that allows a scientist to perceive and record relevant qualities as information. These divergent characteristics of samples and data shed light on an issue introduced in chapter four: that samples and data are hardly distinguished in some literature and whether or not a conceptual distinction is justified. However, this issue is not central to my argument and becomes less relevant in light of the relational character and context-dependency of both samples and data.

Chapter Six – Dynamic adaptation and reliable audit trails: Scaffolding the continuity of data practices

Abstract: This chapter accounts for the conditions under which the CPR Survey creates data and how these conditions have changed and affected the survey in the past. It also briefly discusses an effort to coordinate and maintain various long-term marine ecological monitoring programmes around the UK. Due to historically changing technological, economical, and social conditions, researchers face challenges in trying to keep their research practices unchanged for multiple decades. Applying Caporael, Griesemer, and Wimsatt's (2014a) notion of "scaffolding", a conceptual framework for development in culture, evolution, and other domains, I argue that the continuity of data practices is achieved by assimilating change and modifying or expanding data practices, while the core functionality of the CPR Survey is maintained. The continuity of data practices is not characterised by stasis, an absence of change, or by repetitive application of an old-fashioned method. Rather, it is a result of changes and adaptations of data practices. In order to maintain continuity, researchers modify the design of research technologies, expand their scientific repertoire and the scope of their data, establish reliable audit trails, respond to the interests of the scientific community, funding agencies, and the public, transfer local expertise to younger generations of researchers, and even redraw conceptual boundaries of sciences. These activities contribute to a continuity that constitutes an absence of jumps between scientific data of the past and scientific data of today.

6.1 Introduction

This chapter aims at a deeper understanding of the dynamics of change and continuity of scientific practices. Environmental sciences often study natural processes and systems that change very slowly compared to the typical time frames of research projects. The ocean is a prime example of such a system, as the ocean's physical, chemical, or biological characteristics may respond to a change of conditions in the course of centuries or even millennia. This kind of inertia requires methodologically consistent observations over very long time frames in order to make claims about the dynamics and long-term changes in such systems.

But how are scientists capable of performing practices consistently over multiple decades or even centuries? Research technologies, background knowledge, and scientific theories advance permanently, research staff is constantly replaced, and the political, institutional, and economic settings of research practice can take unpredicted turns. The empirical part of this chapter tracks how research methods in this thesis' main case study, the CPR Survey, as well as the operation of the survey itself, have been maintained despite technological progress and historical changes of conditions that scientists are unable to control. The CPR Survey is committed to strict methodological continuity and to keeping their decades-old time series running indefinitely. Since the late 1950s, the methods of sampling and sample analysis have remained stable so that data which have been created up to seventy years apart are commensurable and form a concise, yet growing, body of records without any gaps.

In this chapter, I argue that the stability of practices in the CPR Survey and the usefulness of data created over the course of decades are "scaffolded" and remain stable due to adaptation and development of data practices. "Scaffolding" has been advocated as a concept and metaphor for artefacts, infrastructures, and people that support and enhance developmental processes in culture, cognition, and biological evolution (Caporael, Griesemer, and Wimsatt 2014a). In my case study, a variety of conditions for practising research are beyond the control of the researchers and challenge the continuity of the time series and the usability of created data. In order to adapt to the changing context and conditions and to support methodological continuity, different types of scaffolds become temporary components of the survey.

Some of the most important scaffolds are rooted in focused experimental research of the survey's technical details and uncertainties. These investigations lead to development of the survey in different forms: as physical modifications of research technology which preserve functionality, as new knowledge that enhances confidence in the data’s consistency, or as an expansion of the survey’s research capacities and scope that attracts funding and the interest of research communities. Other important scaffolds are the implementation of comprehensible audit trails that document data practices of the past and the informal and “on-the-job” transfer of local ecological expertise to younger researchers. Ultimately, these various small-scale developments and modifications of the survey’s data practices preserve the long-term continuity and the existence of the survey.

This chapter shows how scientific practices are situated in a web of relations shaped by technological, scientific, and socio-economic developments. These external developments have a profound impact on data practices by engendering various forms of adaptation. Continuity and consistency of data practices and data are thus not solely determined from within the traditional boundaries of scientific research. A wide range of scholars, especially from STS, feminist, and anthropological studies of science, have shown that research is not performed “inside a vacuum” and that research outputs are influenced by external conditions and dynamics (Knorr Cetina 1981, Longino 1990). My case illustrates that scientific practices are affected by external developments and inevitably change, even in an effort to maintain continuity and regularity of practices. Methodological continuity in science is not characterised by stasis or the repeated execution of research methods that quickly become “old-fashioned” as science, technology, and societies progress. The key to successful maintenance and continuity of practices lies in adaptability and the dynamic development of data practices.

The chapter first reviews scholarly literature on scientific change and standardisation in scientific fields with diverse data practices. Another introductory section focuses on scaffolds, scientific repertoires, and how these could figure in accounts of achieving continuity in research. The empirical part of this chapter focuses first on the challenges of re-creating and preserving marine biological surveys in the UK before analysing in detail how continuity is achieved in the CPR Survey.

6.1.1 Standardising data and working with diversity

Various scholars have studied and analysed scientific change, often trying to conceptualise what constitutes scientific progress or advancement (Kitcher 1995). This chapter is not asking questions regarding scientific progress but examines activities and responses to historical change which are not directly driven by classical "enlightenment" motifs such as rationality and the accumulation of truthful knowledge. I focus on a particular balancing act that researchers may face if they want to continue producing outputs that are usable and valuable for the scientific community. This is a balance between on the one hand, achieving and maintaining the highest possible consistency and reliability within a body of data that has grown for multiple decades, and on the other hand, adjusting to new technologies and to shifting interests of research communities, the public, and funding agencies.

Ankeny and Leonelli's (2016) proposed "post-Kuhnian" way of tracking scientific change, supported by their notion of "repertoires", aligns well with this chapter's goals. Kuhn's (1962) central concept of research "paradigms" can hardly reflect the dynamics of today's science and gives preference to theoretical knowledge in its description of scientific change.[108] By contrast, Ankeny and Leonelli's (2016: 26) framework allows for a view of scientific change that accounts for 'administrative, material, technological, and institutional innovations' and the 'non-conceptual aspects of scientific practice [that] are not often discussed within scholarly publications'. I consider these innovations and aspects as essential parts of the context in which research practices are performed.

Ocean sciences are not the only scientific field that faces challenges regarding the commensurability of data that have been created many years apart. Scientists across many disciplines compare or integrate data created at different times, under different conditions, and sometimes for different epistemic purposes. In his historical study of meteorology and climate science, Edwards

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[108] See for example Galison (1997) for an account of scientific change in twentieth century physics that is driven by technology. Andersen (2010) discusses scientific change in light of distributed cognition, heterogeneous expertise, and joint acceptance of scientific claims.

(2010) describes the great efforts that are necessary in order to make data of the past consistent and comparable with new data and vice-versa. The methods and technologies to create environmental data have rapidly developed and, at times, have been replaced rather quickly throughout the history of environmental sciences. Not to mention the fact that even for fundamental environmental parameters such as temperature, a variety of practices have been employed across observational sites around the world. Edwards et al. (2011: 669) explain that any kind of “interface” between organisations, machines, or people is ‘a point of resistance where data can be garbled, misinterpreted, or lost’. Edwards et al. (2011) use the term “friction” for this phenomenon, motivated by the image of two surfaces that touch at their interface and create friction when moved against each other. Data friction may cause ‘conflicts, disagreements, and inexact, unruly processes’ and scientific institutions might be forced to spend ‘enormous expenditures of time, energy, and attention’ to resolve these conflicts (Edwards et al. 2011: 669–70).

With regard to long-term observation of the environment, Edwards claims that ‘in climatology, time itself is an interface between two data surfaces: the present and the past’ (Edwards 2010: 98). Scientific methods, technologies, and societies change over years and the more decades pass between the creation of two or more records, the more challenging the integration of those records tends to be. Shavit and Griesemer (2009, 2011) document the attempt of researchers at the Museum of Vertebrate Zoology at Berkeley to replicate a survey of animal distribution in California after one hundred years. A species’ locality, one of the most basic ecological parameters to be recorded, turned out to be difficult to replicate for the researchers, even with the use of fine-grained latitude-longitude data and GPS technology. Shavit and Griesemer find species locality to involve an ambiguous concept of space, but one that only became problematic when museum staff tried to integrate practices of the past with today’s digital databases and GPS technology:

> We do not see a secular shift over the twentieth century from theoretical projects and programs to technology-driven applied research, but rather theoretical research that moves into a world

> transformed by GPS-technology and thus science taking place within a changed context of application. (Shavit and Griesemer 2011: 189)

The study of the MVZ's data practices illustrates the friction and challenges caused by historical changes of context if a scientific practice is intended to remain unchanged.

The struggle to make data from different contexts commensurable has been encountered by many scholars studying practices of various scientific disciplines. In biology and biomedical research, animals, patients, or entire communities are often observed or repeatedly surveyed longitudinally for extended time periods. These sciences are also prime examples of research fields in which data have typically been created in complex, highly variable, and non-standardised ways, and which may have undergone lengthy processes of standardisation (Leonelli 2012; Aronova, von Oertzen, and Sepkoski 2017).

In order to minimise the potential for data friction, many sciences aiming for the study of global phenomena, including climatology and ecology, have gone through processes of standardisation which involve not only technical but also political and conceptional challenges (Edwards 2010, Devictor and Bensaude-Vincent 2016). Focusing on rather local research settings, Star and Griesemer (1989) have described the role of standardising methods for creating a common ground between actors from different social and professional backgrounds. Zimmerman (2008) claims that standardisation is a way to transport scientific knowledge from local to public spheres, but warns that local context, which may be crucial for data re-use, is often 'left behind'.[109]

With respect to biodiversity, Bowker (2000: 675) expects that the construction of a truly global, consistent, long-term database that is able to track life forms on earth coherently will result in an 'unholy mess', due to the great diversity of data practices in biodiversity research. In most cases, Bowker contends, more than just measurement standards need to be known about the data in a database in

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[109] The previous chapter introduced Latour's (1999) account of data creation, which involves chains of transformations that also "amplify" standardisation but increase the distance to local conditions of research practice.

order to be able to use them. Bowker (2000: 645) strongly argues for an engagement of philosophers and STS scholars in developing ways to manage and store diverse data, so that databases become flexible and the ‘social, political and organizational context is interwoven with statistics, classification systems and observational results in a generative fashion’.

Leonelli (2013) and Hoeppe (2014) have studied cases which suggest that pushing standardisation is not the only possible answer to methodological and data diversity. In her assessment of biological data infrastructures, Leonelli (2013: 450) finds that databases face an ambiguous challenge: They need to maximise the global circulation of data, which requires common standards, while at the same time, the data must be adoptable in local research contexts. As a result, the databases studied by Leonelli do not rigorously standardise and homogenise knowledge, data, terminologies, and methods, but rather attempt to make the diversity along these dimensions visible for users. Incorporating diversity is, however, ‘the most complex and labour-intensive task’ in the development of the databases.

Studying the field of astronomy, Hoeppe (2014: 264) observes how astronomers themselves are ‘working data together’ by ‘sequentially and reflexively engaging diverse evidential contexts as contexts of accountability’. This practice seems to maintain the diversity of practices and contexts, since the working together of data is a local achievement by astronomers, who want to address certain phenomena of the sky. Hoeppe (2014: 264) points out that data in astronomy are viewed as ‘malleable’ objects, whereas the sky itself functions as a stable reference. However, this stability of the research object is a specific characteristic of astronomy, so that the strategy of reflexive and sequential work on data accountability is likely more pronounced in astronomy than in sciences focusing on more dynamic systems such as biodiversity.

Challenges to make data of different times and contexts commensurable and comparable with each other are a key characteristic of today’s data-intensive sciences. This is a common problem in sciences that focus on distinct systems or populations for long time periods during which the context and conditions of practice — technology, background knowledge, institutional landscape, and society — progresses in ways that affect the continuous operation of research programmes and require additional efforts from scientists and research organisations. Scholarly work suggests that answers to these challenges are complex and cannot be reduced to standardising research methods.

6.1.2 “Scaffolding” as a concept of development and maintenance

Scientists engage in a variety of activities to resolve or work around the challenges caused by the integration of data from various contexts. These activities can be viewed as a development of a scientist’s or research institution’s practices and capacities to work successfully with diverse data. In this chapter, I discuss developments of the CPR Survey’s practices using a concept of development that is grounded in the notion of “scaffolding” as utilised in Caporael, Griesemer, and Wimsatt (2014b). Scaffolding can be understood as using dynamic structures of conceptualisations, practices, theories, technologies, or personal relationships that facilitate the development of specific capacities or skills of the entity to which a scaffold is applied. Metaphorically, scaffolding alludes to a painter’s or construction worker’s scaffold that becomes an integral yet transient physical component of a building during a phase in which a new quality or capacity is acquired. Following this phase of development, the scaffold may be removed and discarded, but it is also possible that scaffolds are ‘internalized as system parts or assimilated as symbionts’ so that ‘features of environments *become* features of systems’ (Griesemer, Caporael, and Wimsatt 2014: 367).[110]

Wimsatt and Griesemer (2007) have coined the scaffolding concept in relation to the development of culture and it has since been employed in various domains, including scientific practice (Wylie 2016). The rich collection of essays edited by Caporael, Griesemer, and Wimsatt (2014b) demonstrates its usability for developmental processes in three very broad domains: evolution, culture, and cognition. A central concern of the book is to provide an alternative to the employment of neo-Darwinian, evolutionary models of development to other,

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[110] Emphasis in original.

non-biological domains (Caporael, Griesemer, and Wimsatt 2014a).[111] An appeal of the scaffolding framework is that ‘there is nothing intrinsically biological about scaffolding or the general concept of development’, as Griesemer (2014: 47) clarifies. The framework is not theoretically rooted in models derived from certain practices in experimental biology and is applicable to dynamic developmental processes that are not specifically biological.

Caporael, Griesemer, and Wimsatt (2014a) introduce scaffolding as a widespread feature which facilitates or supports development in those scenarios in which growth or the acquisition of new capacities would be much more costly or even impossible without a supporting structure or process. Processes that lack any kind of ‘productive resistance or challenge’ are not scaffolding (Caporael, Griesemer, and Wimsatt 2014a: 15). Three types of scaffolds are proposed: artefacts such as tools or vehicles that are typically used temporarily by agents, more persistent infrastructures such as buildings or institutions, and cooperative developmental agents such as teachers or mentors. These scaffolds are capable of supporting or enabling maintenance, growth, or development by interacting with certain actors (Caporael, Griesemer, and Wimsatt 2014a: 15).

In relation to the challenges of data commensurability over several decades, maintaining a research practice is a central goal and a strategy to reduce data friction. It seems counter-intuitive to think of development when the goal is to keep a practice unchanged. However, as Caporael, Griesemer, and Wimsatt (2014a: 16) remark, maintenance and development seem more different from each other than they actually are. Maintenance in a dynamic system ‘preserves organization in the face of stress, deterioration, and change’ and is hence as much a ‘change operation’ as development (Caporael, Griesemer, and Wimsatt 2014a: 16). Buildings, vehicles, or computers are systems in which maintaining consistent functionality is a dynamic activity: Buildings and vehicles need maintenance in the face of external stress such as extreme weather, rust, or wear and tear. Computers need regular updates to maintain the system’s

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[111] Several points of criticism against the extrapolation of neo-Darwinian models of development to other domains such as culture are put forward in contributions to Caporael, Griesemer, and Wimsatt (2014b), but I do not focus on this issue here.

functionality against external threats such as viruses or malware and to maintain its compatibility with new systems. At the same time, preserving an “old-fashioned” system might become increasingly difficult, because spare parts and people with very specific know-how for vintage cars or computer systems can get scarce.

Wylie (2016) argues that scaffolding is crucially involved in archaeology to determine how material traces of the past can be interpreted as evidence. She points out some important epistemological consequences of scaffolding by emphasising that scaffolds are always provisional and new ways of data interpretation, driven by technological or conceptional innovation, are capable of calling assumptions based on established scaffolds into question. Wylie is concerned with methodological innovations that could affect established interpretations of data. By contrast, this chapter focuses on methodological stability in order to maintain the value and usability of established data interpretations. Yet, both cases show how deeply the development of data practices and changes of historical context are intertwined.

Ankeny and Leonelli (2016: 19) propose a framework for the study of scientific change that can be linked with the notion of scaffolding: They define “repertoires” as ‘the material, social, and epistemic conditions under which individuals are able to join together to perform projects and achieve common goals’. The notion carries a distinct performative quality and encompasses material and conceptual elements in addition to the social structures and knowledge how to perform activities in an intended way (Ankeny and Leonelli 2016: 20–21). A repertoire is not a necessary condition to create scientific knowledge, but it makes ways of performing research ‘relatively robust over time despite environmental and other types of changes’. Additionally, a repertoire ‘can be transferred to and learnt by other groups interested in similar goals’ (Ankeny and Leonelli 2016: 19).

Robustness and transferability make the tracking of a research group’s repertoires particularly interesting with respect to the dynamics of methodological stability and scientific change. If repertoires support the robustness of research practices against historical changes of context, the adoption and internalisation of a new instrument and an associated method may scaffold the continuity and preservation of data practices.[112] This chapter intends to track how a research group's capacities are developed internally in order to adapt to historical changes of research conditions, but without the primary goal of collaborating with other groups and achieving a common goal.[113]

6.2 Scaffolding long-term marine biology in the UK

Maintenance and standardisation of data practices are core issues in the following examples of marine biological surveys around the UK which illustrate the complex interplay between scaffolds and repertoires as well as the context in which the CPR Survey's development takes place. In 2007, the MBA conducted a benthic ecology re-survey of the Eddystone reef,[114] a rock formation located approximately twelve miles south-west of Plymouth Sound in the Western English Channel. This took place 112 years after researchers from Plymouth had first sampled the area in the late nineteenth century (Capasso et al. 2010). Matthew Frost, deputy director of the MBA, explains why the re-survey was successful:

> "We did a lot of projects repeating that work to look at comparisons and that was great because we had all the original notebooks, so […] we were able to transcribe all the notebooks and do the work to interpret what they meant in their notebooks. We could then compare those notebooks to the papers they actually published and the

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[112] An example put forward by Ankeny and Leonelli (2016: 21) is the proliferating use of a small group of model organisms, which now dominate experimental molecular biology, because the repertoire has been adopted by many research groups across the world. This repertoire not only includes specific research practices and a shared conceptualisation of certain organisms as models but an entire infrastructure and set of norms around sharing data and acquiring funding.

[113] Keep in mind that scaffolding can happen on an individual level and without collaboration between people or common goals. By contrast, repertoires are characterised by collaborative performance, not just by an ability to do something.

[114] The benthic zone comprises the lowest level of a body of water including several layers of sediments.

> reports, and not only that, the actual specimens and stuff they collected was all in the natural history museum. So […] we logged all the species that they had collected, which are all in jars there and all labelled. What we found is this phenomenally good audit trail that we have got. Not only that, but […] the actual dredges they used were still here. So we could go back and look at the dredge and say 'can we rebuild this in the same way?' All of those things make life much, much easier, if you have got all of that, really good audit trails."
> (DR6427: 16–17)

An infrastructure with "really good audit trails", including museums and archives, scaffolded the re-survey of the Eddystone reef after an extensive hiatus during which technology, institutions, and research practices have changed significantly. As Capasso et al. (2010: 1163–64) state in their publication of the survey's results, 'aims, efforts, methods, taxonomic expertise and the state of scientific art have changed over the course of time […] and this makes achieving proper comparisons difficult'. Besides utilising original notebooks, the researchers had to superimpose the original survey's taxonomic structure on the newly created data and adapt to the original data's semi-quantitative nature. The audit trails enabled the MBA to acquire and re-enact data practices that were first performed more than a hundred years ago in a very different context. The scaffolding by comprehensible audit trails leads to certain forms of maintenance and growth: maintenance of the historical data's value and usability for current research questions and growth of data volume and knowledge about ecosystem change. Both of these developments could not have been achieved without the scaffolding by audit trails.

Frost headed the Marine Environmental Change Network (MECN) which was an attempt to coordinate and preserve the UK's long-term marine environmental surveys. According to Frost, the MECN was set up in recognition of "the whole other area of monitoring" (DR6427: 11), which refers to practices that were not initiated for statutory monitoring that the UK is legally required to do.[115] In a

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[115] Frost mentions the UK's Bathing Water Directive, the Habitats Directive and various European directives (DR6427: 11).

series of workshops, the MECN compiled an overview of long-term surveys in UK seas which have been going on for years before today's legal directives were issued. These "other" time series, which are not used day-by-day for statutory monitoring, include the Eddystone reef surveys, the CPR Survey, as well as twelve other surveys conducted by various institutions for a variety of reasons. Since many of these surveys were threatened to run out of funding and, as Frost says, "there was a danger that they were just disappearing" (DR6427: 12), the MECN acted as a 'knowledge transfer mechanism' which attempted to show how the long-term data could be used strategically by policy bodies and organisations for the management and monitoring of the UK seas (Frost, Jefferson, and Hawkins 2006: 7).

Frost further explains that "when we started the MECN, there was a real push" to make all the surveys' methods consistent (DR6427: 17). However, as he continues,

> "you can't always do that, because if you have been doing that the same way for fifty years, you can't just change it overnight. I mean, you can change it, so you might be able to add stuff […] but you can't stop some of the stuff you have been doing. If you have been monitoring every summer for fifty years it is pretty hard to say 'well, would you mind doing it in the winter instead?' You can say 'I'll do it in the winter as well,' that's great. SAHFOS has this issue all the time with the Continuous Plankton Recorder. They are developing the whole time, 'we want to add more equipment to our tows.' That's just the way it is, you can't go back and change things." (DR6427: 17)

Frost expresses here how "developing the whole time" is an almost inevitable process for research practices, in particular when different institutions intend to collaborate to form a "transfer mechanism" for their data. Obviously, data practices that have been performed for decades cannot be changed retrospectively. In this case and if standardising practices is not an option because it causes discontinuities in the time series, researchers can only try to calibrate data with the help of external resources. As Frost explains, some data of MECN time series have been calibrated with sea surface temperature data produced by earth observing satellites (DR6427: 16).

The brief examples of the Eddystone reef survey and the MECN illustrate some of the problems that may occur when data practices are re-performed in altered contexts. The institutional landscape, funding, research methods, as well as research priorities may have changed substantially and without efforts to preserve certain practices, including the preservation of comprehensible audit trails,[116] valuable environmental time series are potentially discontinued and lost. Frost's reflection of the conditions for long-term marine environmental surveys in the late 1980s, when the majority of programmes were funded by NERC, illustrates how quickly the context may change:

> "NERC closed down a lot of them. They just said 'we don't see why we're doing this.' Within about five years, climate change shot up the agenda and everybody said 'what we really need are people to go out and collect data over decades.' So very quickly, everybody was scrambling to get all these things ready again." (DR6427: 10)

Yet, in order to survive, the time series overseen by the MECN had to be transformed, or developed, from individual, not widely-known observation routines with specific methods into visible and valuable contributions to long-term, nationwide, or even global monitoring programmes. The goal was apparently the transformation of individual, diverse data practices that were unfit for collaborative practices into a repertoire of practices that institutions perform collectively to achieve a common goal, hence the initial push for standardisation or data calibration and the attempt to make the time series usable for statutory monitoring of UK seas. This transformation has been successful with some reservations, as Frost explains: While the importance of the long-term

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[116] For clarification, the ambiguity about species location in the MVZ survey in Shavit and Griesemer's (2011) case was not due to bad audit trails but because two different concepts of space were employed that became problematic when the survey was replicated after one hundred years. Compare these conceptions of species location on land with the ways species locations have been recorded in marine ecological practices would be an interesting research opportunity.

observations has been widely recognised, it is still unclear who is going to pay for the continuous operation of many of the surveys in the future (DR6427).

Frost further reflects on the diversity of practices in ocean sciences from his experience with the MECN:

> “There is also, of course, that different organisations have different drivers and this is the problem we had with the long-term monitoring group. People were saying ‘we do it for our own reasons’ and they can’t always just change it. […] It might be done opportunistically. They might do it, because that’s when the boats are available, you know, that sort of thing.” (DR6437: 17)

From the perspective of the MECN, many of these somewhat contingent drivers, and similarly, the contexts of funding, public interest or political agenda, cannot be controlled. Yet, these are factors that researchers have to deal with, especially if they collide with shared goals such as long-term continuity of data practices.

Challenge	Scaffold	Development
Replication of the Eddystone reef survey after a 112-year gap	Comprehensible audit trails including museums and archives	Maintaining the value and usability of historical data, contribution to a consistent dataset and knowledge of the reef’s ecosystem
Preservation and continuation of diverse long-term marine biological time series in the UK	Knowledge transfer and collaboration to develop a shared scientific repertoire	Maintaining of historical data practices, development of diverse data practices into strategically relevant environmental monitoring

Table 6.1: Challenges, scaffolds, and developments involved in replicating and maintaining long-term marine biological time series in the UK.

Table 6.1 summarises two distinct challenges that can be identified in this section's empirical examples: first, the replication of a specific survey after an extensive hiatus and second, the preservation and continuous operation of diverse data practices.[117] The former was scaffolded by an infrastructure and artefacts that amount to comprehensible audit trails, the latter was scaffolded by an infrastructure acting as a "knowledge transfer mechanism" that involved the development of individual data practices into a shared repertoire, even though the originally performed practices need to remain unchanged.

6.3 Changes of context and development of the CPR Survey

For the in-depth study of maintaining continuity in the CPR Survey, I have organised the survey's development in two sub-sections: the first on technology, the second on scientific background knowledge and socio-economic aspects. Several of my ethnographic interviews were centred on technical aspects of the CPR. Hence, I am able to discuss some technological developments in detail, whereas the scientific background knowledge on oceanic ecosystems as well as the socio-economic context of research are far too complex for an exhaustive elaboration. However, sketching a few important developments, some of which are not exclusive to the CPR Survey, serves my argument regarding the maintenance of a scientific practice in light of historical changes of research conditions.

Discussing certain developments as technological, scientific, or socio-economic is not meant to categorise them exclusively under one of these labels. All developments are somewhat interrelated: There is always an economic aspect to technological progress and new technology may foster progress in scientific knowledge. Further, research technologies and scientific knowledge cannot be

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[117] Frost remarks that the former, picking up an abandoned survey after a long hiatus, is much more difficult and requires more work than the latter, adopting or continuing an ongoing practice from a different institution or research group (DR6427: 15–16). The difficulties caused by long gaps are visible in the Eddystone reef survey and in the MVZ's re-survey of California.

detached from social aspects of science. Neither science nor the development of specific aspects of scientific practices happen in isolation but within dynamic relations to contexts, artefacts, infrastructures, and people, as many contributions in Caporael, Griesemer, and Wimsatt (2014b) highlight.

6.3.1 The technological context

The CPR Survey is a case of ecological research with similarities to the MVZ's practice that Shavit and Griesemer (2011) have analysed. In both examples, the location of a species in the natural environment and the time of its recording are arguably the most fundamental information contained in the recorded data.[118] Today, CPR samples are localised by virtue of the Global Positioning System (GPS) track of the ship of opportunity that conducts the tow. Members of the ship's crew fill in a tow log form where the starting and end location of the tow as well as course alterations are noted. The crew members refer to the real-time GPS tracking of the ship. Occasionally, a plankton taxonomists who enters data into the CPR Survey's digital database checks the data in the log form against the actual GPS track. The tracks of ships are viewable online thanks to the Automatic Identification System (AIS) for marine entities.

AIS is a 'maritime technical standard' required for all internationally voyaging ships by the International Maritime Organisation (IMO).[119] AIS combines dynamic GPS data, a ship's course, position, and speed, with information such as ship identity, size, and destination. The data are exchanged between nearby ships, AIS base stations on land, and satellites. Ships use AIS to monitor the traffic in their vicinity, while the data can also be used to create global real-time maps of ship traffic.[120] Obviously, this tracking infrastructure was not available when the CPR Survey started operating in the middle of the twentieth century.

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[118] To illustrate the centrality of time and location, consider Baker and Yarmey (2009: 13) on the origin of data: 'A point in time and a geographic location together typically define the origin of a field measurement which, when recorded, becomes data.'

[119] <http://www.allaboutais.com> [accessed 23 April 2016].

[120] <http://www.marinetraffic.com/> [accessed 23 April 2016].

Data practices and research outcomes depend on the technologies that are available at the time, as Lance Thomas, a member of CPR Survey's workshop and operations team, explains:

> "The CPR is a great instrument for large areas and the large amounts of time that we sampled in. We are making it more accurate as the technology allows us. We have been going for 86 years now, so the first ones didn't have GPS. They didn't have Decca. So some of our original tow logs would have been done by sun sights and star sights, because that is how the people navigated. But that was great and it has slightly improved all the time. That is not to say that what happened before was wrong." (DR1960: 13)

While the technology of marine navigation has developed from sun and star sights to the Decca Navigator System[121] and on to GPS, SAHFOS has treated the information about the ship's track the same way throughout the years. As Camp explains:

> "Because each sample is effectively a ten nautical mile area, a deviation by maybe a minute or two in the time that they shot it or hauled it does not matter for what we do with the data. And the same with exactly its position; it does not matter whether or not it may be a nautical mile or two off from where it is reported. We are not making those claims that this plankton is from this exact spot. It is 'This is the plankton collected within this sea area.' And therefore those slight differences don't make a difference." (DR2901: 5)

It is not necessary for SAHFOS to name an exact spot that is the location of a sample. Additionally, the "smear" (DR0533: 10) between adjacent samples that results from the continuity of the sampling mechanism, as I have described in chapter four, has always offset the inaccuracy of recorded sampling locations. It

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[121] Decca was a hyperbolic radio navigation system that was first used in World War II. Adoption peaked in the 1970s but Decca was replaced by GPS in the 1990s and finally shut down in 2001; <https://en.wikipedia.org/wiki/Decca_Navigator_System> [accessed 02 April 2018].

is thus impossible to name an exact spot as the origin of a sampled organism because the organism could have entered the nose of the CPR anywhere along a ten to fifteen mile section of a tow. The CPR is a “macro-scale” method, says Johns, who relates this characteristic to the natural patchiness of plankton:

> “Plankton by their nature are patchy. […] There was a paper here lying around on plankton patchiness, basically saying that actually if you took a sample here on one side of the boat and took a sample here on the other side of the boat, they would be totally different, like, nine times out of ten, because plankton is just in these discrete patches around.” (DR0533: 10)

The continuous mechanism of the CPR is the reason why CPR data cannot resolve the plankton patches, thus restricting the use of the data, as Johns further explains:

> “I never say to anybody ‘actually, you could use our data to look at frontal zones’. They quite often think that. A frontal zone is an area of convergence and it might be high productivity, but our samples are almost useless there, because it is a ten-nautical mile smear. You might pick it up, but it's not a fine enough resolution for that.” (DR0533: 11)

The large-scale spatial averaging that is commonly applied when data are processed and prepared for use is an additional step to enlarge the spatial scope of the data so that organisms are associated with a geographical area rather than an exact spot.

Given this relation between data and species location, the change of context from less accurate positioning systems to GPS technology is relatively unproblematic for the CPR Survey. The increased precision of GPS and scientific questions that could be asked about fine-grained locations are at odds with the CPR method’s “smear” and averaging. This form of friction remains somewhat unresolved, as the survey continues its handling of location data the way it has done for decades, although with the same restrictions regarding scientific questions that can be addressed with the data. Unless the locations derived from the tow logs seem unreasonable due to transcription errors or mistakes by the crew, a sample analyst will not make an effort to look up the exact GPS track of the ship. Nevertheless, the survey has been working towards creating a tow log automatically. Thomas assumes that reliance on GPS and the automated tow log are the “logical progression”, although the CPR Survey seems to be “a long way from that at the moment” (DR1960: 13).

The development of GPS has not caused a productive resistance that would require scaffolding in order to maintain its methodological continuity. For the way the survey processes and uses location data, it is not relevant how the geographic locations from which a ship’s track is derived have been produced. Although they are not a direct response to productive resistance, GPS and AIS for the tracking and identification of ships can be viewed as an infrastructural scaffold that develops the sample analysts’ ability to verify the location data and minimise errors. Eventually, reducing errors would be the main reason for automating the entire process. For the same reason, CPRs have been equipped for several years now with an electronic instrument package that records the shoot and haul times of a tow automatically. These times mark the exact beginning and the end of a tow and can be compared to the times that have been noted in the hand-written tow log. Together with the GPS track, these data form the basis of the electronic tow log.

An electronic instrument package to record the shoot and haul times of a tow automatically is only one example of a number of devices that can be attached to the external body of the CPR. Advances in micro-electronics have resulted in a wide range of oceanographic instruments which are small and light enough to be fitted onto the steel body of the CPR. Among these are small CTD units and instruments that measure chlorophyll *a*, fluorescence, ambient light, and orientation in three dimensions. As of 2017, a gas sensor for carbon dioxide is under development (SAHFOS 2017: 6–7).

The instruments are relatively small and light-weight, but as Johns explains, when deploying a new instrument, SAHFOS needs to make sure that the flight position of the CPR is not affected by the new piece of equipment:

> “There is a whole aspect of, you know, if you stick something on a CPR, what is it going to do to the CPR? So at the moment, there is actually a boat out today that is towing a CPR with a pitch and roll sensor on it. So they bolted some new piece of instrumentation on it and they have a pitch and roll sensor on it to make sure that it is not weighing it down, so if it is flying like this or going to the side. So that sort of aspect is taken into consideration. If they have a new piece of kit, how is it going to affect the flight of the CPR.” (DR0934: 23–24)

These types of experiments are a response to advancements in micro-electronics and small-scale sensor design. At the same time, on a larger scale of technological development, commercial ships have become more powerful and faster due to advancements in marine engineering. Hays (1994: 404) remarks that ‘CPRs are deployed from ships of opportunity and consequently there is no active control of towing speed’. An assessment of the effects caused by different ship speeds has been required several times throughout the survey’s history.

The ships of opportunity usually do not change their speed significantly during one route, but the average speed tends to decrease during the months of winter due to bad weather conditions and rougher seas. At the same time, the average speed of commercial ships has increased from around ten knots in the 1950s to around twenty knots today. This had a negative effect on the towing stability (Batten et al. 2003: 200–01). By 1970, the average towing speed was higher than seventeen knots, which caused more and more CPRs to destabilise and an increased number of CPRs were torn off and lost. As a consequence, stronger and more flexible steel wires with a diameter of ten instead of eight millimetres were installed from 1976 onwards (Batten et al. 2003: 199). The design of the CPR’s external body was also modified to increase towing stability: Diving planes at the front were removed and a box-shaped tails at the rear end were installed since 1977. By the end of 1980, most CPRs had been modified to feature the box-tail and the stronger wire. The removal of the diving plane had a secondary effect: It increased towing stability but also reduced the average towing depth from around ten to five metres and conversely, the length of the towing wire needed to be increased (Reid et al. 2003: 123–24, 152–53).

Experiments from 2015 on the survey's most regularly towed route between Plymouth and Roscoff suggest that higher towing speeds also cause the CPR to submerge to greater depth, with the nose pointing slightly upwards. The angle of orientation, in turn, affects the volume of water entering the internal of the CPR — a parameter that researchers want to keep unchanged for comparability of the resulting data. Experiments have shown that a pitch of twenty degrees upwards causes a seven percent decrease of water volume entering the CPR, if the CPR is oriented perfectly level (SAHFOS 2016: 19). In general, though, the effect of the towing speed on the actual depth of the CPR is still not fully understood, as the 2015 experiments showed greater depth with higher towing speeds, but earlier studies suggested a constant towing depth independent of speed (SAHFOS 2016: 19, Batten et al. 2003: 201–02).[122]

Experimental studies on the performance, technology, or design of the CPR directly scaffold the long-term continuity and commensurability of the CPR data. Developmental agents using a research infrastructure work towards increasing the confidence in the data and enable their comparison across multiple decades. The pressure to adapt is caused by external factors: the increased speed of ships, which is a parameter that the survey is unable to control. Continuity and data consistency are thus not determined solely within the researchers' controllable, institutional spaces. The weather conditions at sea as well as the tight scheduling of the commercial shipping industry are part of a setting to which the survey's data practices need to adapt by development. In some cases, a physical adjustment or assimilation is necessary, as with the design of the CPR's exterior body. This modification develops the instrument's capacities to withstand greater stress in the water. In other cases, more detailed knowledge of the technical functioning under certain conditions is internalised

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[122] Batten et al. (2003: 202) admit that the effects of different towing depths are hard to quantify; they also point out that due to the CPR being towed behind a relatively large and fast-moving vessel, the water in its track is likely well mixed and homogenised, so that differences in towing depth of a few metres are likely insignificant.

so that the gained knowledge and experience can be used in subsequent experiments as a platform for further scaffolds to develop the survey.

The silk is another external source of uncertainty that required closer examination. The silk that is used as a filter and becomes an integral part of a CPR sample is obtained in standardised rolls from a Chinese company, it is not manufactured specifically for oceanic sampling (DR0533: 9). Batten et al. (2003: 200) remark that the silk has been obtained from different suppliers throughout the survey's history. In 1996, fibre and mesh diameters of silk batches from different suppliers were compared under dry and wet conditions. Although the mesh diameters varied with different batches of silk from the same suppliers, this variability was similar between all suppliers and it was concluded that the filtering characteristics have remained relatively stable despite changing silk suppliers. Continuity with respect to the silk specifications is thus scaffolded by temporary experimental practices. Switching silk suppliers has not caused a productive resistance in a sense that the survey was required to change its supplier, to re-assess or calibrate historical data, or even modify the CPR. Yet, the knowledge that SAHFOS has gained is a development that leads to more confidence regarding the comparability of the data and the consistency of data practices.

How can experimental research be understood as scaffolds? It could be argued that a research study is not exactly a structure that is applied to an entity temporarily and afterwards discarded. I consider experimental studies as a mixture of artefact, infrastructure, and developmental agent scaffolding. Studying the effect of increased ship speed requires artefacts: sensors and instruments to measure the orientation and volume of filtered water. It also requires infrastructures: work spaces, computers, technical workshops, and resources. It further requires developmental agents who conduct the experiments, analyse results, and draw conclusions about the instrument's performance.[123]

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[123] In their categorisation of scaffolds, Caporael, Griesemer, and Wimsatt (2014a: 15) make clear that artefact scaffolding always requires agents: 'Of course, to count as artifacts, objects must be made or taken as such by agents. No agency, no artifacts.'

When experimental research acts as a scaffold for the CPR Survey, it means that an entire research capacity, including artefacts, infrastructure, and people, become a temporary component of the survey and aid its development. With respect to pitch and roll sensors that are attached to a CPR on the Plymouth-Roscoff route, two operations literally merge like a painter's scaffold and a building. And like the painter's scaffold, the experiment on the CPR maintains a different time scale than the overall plankton survey: Once a project for experimental development has run out, a specific insight has been gained, and researchers can decide whether or not modifications are necessary, the research capacity is removed from the survey and is free to operate elsewhere.[124] As Wylie (2016) has shown for archaeological research, methods of interpreting material traces of the past act as scaffolds for evidential reasoning. Wylie (2016: 204) counts 'assumptions, knowledge, and resources collectively as "scaffolding", conceptual and technical'. In a similar way, experimental studies that function as scaffolding in my case encompass conceptual and technical resources but also assumptions and the knowledge of developmental agents that may be obtained from scientific publications.

Adaptation to technological progress has played out slightly differently with regard to the microscopes inside the survey's lab. New microscope models have been introduced in 1995 and most recently in 2004. While the actual magnification of the microscope has slightly changed with different models, the size of the field of view at each stage of analysis has remained constant at least since 1958. The exact models and configurations before 1958 are unknown (Richardson et al. 2006: 35). The size of the sample area that the microscope makes visible to a taxonomist has to remain unchanged since sample analysts count the organisms they see in their field of view, as described in the previous chapter. The major innovations introduced by the new microscopes are a mobile glass stage upon which the sample is laid out and an ergonomic head which makes the sample analysis easier and more comfortable for the analyst, as Johns elaborates:

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[124] A painter's scaffold is eventually deconstructed and disappears from a building. Yet, it is not discarded but re-used to scaffold development and maintenance of other buildings.

> "To actually use [the newer microscopes] compared to this … this is horrible. When you sit down, everything is really tight, whereas these have been designed much more ergonomically and you can rest your arm on the thing here, you can move this stage. When you are analysing, you have to physically move it around like this, whereas [the newer] one, you can see there is a little wheel there to move it along, it is minimum movement." (DR0934: 5)

The newer microscopes, were custom made for the survey to "mimic" the older microscopes. Johns immediately relates this to the survey's overall ambition to keep the methodology consistent:

> "[The newest microscopes] are custom made so they kind of mimic [the old ones]. So the field of view and the magnification are all the same. The whole idea is that you keep the methodology the same. You don't want to make any mistakes with methodology, it has got to be the same. We pride ourselves on our 70-year time series, that's what we want." (DR0934: 5)

This quote is a display of how highly the methodological continuity has been valued and protected at SAHFOS. However, as the statement is related to developments in microscope technology, the continuity does not exclude occasional upgrades or the replacement of parts. Core functionality — the performance of the microscopes in the lab, but also of the silk and the CPR in the water — is the central aspect that needs to be maintained.

Similar to the introduction of GPS, the new microscopes are not directly a response to a productive resistance. The CPR Survey probably could have continued using the old models; a challenge only arises when new instruments are introduced that are less demanding to operate. In this case, the continuity of methods is scaffolded by the purchase of custom-made microscopes that mimic the old ones.

Table 6.2 summarises the challenges, scaffolds, and developments that relate to technologies used in the CPR Survey. Whereas several changes of technological context have required scaffolds in order to maintain continuity and assure commensurability of CPR data, the transition to GPS navigation seemed to be a minor challenge and is therefore omitted in the table. Due to the plankton patchiness, the “smear” between samples, and large-scale averaging, the increased precision of GPS has no effect on the data’s consistency. The transition exemplifies, however, how much the overall technological environment in which marine sciences operate has evolved in less than a hundred years, going from sun and star sights to fully automated ship identification and tracking systems. Furthermore, automated and highly accurate location data are easier to use in combination with data from additional equipment such as sea temperature or salinity. For these data, highly accurate geographical locations might be more useful than for the spatially averaged plankton distributions.

Challenge	Scaffold	Development
Adding instruments to the CPR’s exterior body	Experimental research on CPR performance	Increased certainty regarding CPR performance
Adapting to higher towing speeds	Experimental research on CPR performance	Physical modifications of the CPR’s external body and steel wire
Changing silk suppliers	Comparisons of silk batches under different conditions	Higher confidence in the consistency of silk specifications
Introduction of new microscopes	Mimicking of previous models’ functionality	Maintaining the microscopic field of view’s dimensions

Table 6.2: Challenges, scaffolds, and development of some technological aspects of the CPR Survey.

In summary, it is important to realise that the technologies of the CPR Survey are all but static, despite the long-term methodological continuity of the survey. In fact, it is the high value placed on continuity over multiple decades of historical change that requires technology to be adaptable or perhaps even "malleable" like an astronomer's digital data, as Hoeppe (2014) has argued. In some cases, maintaining methodological continuity required certain components of the CPR Survey to become the object of experimental research. This conversion is grasped by Rheinberger's (1997: 29) account of 'nontrivial interplay, intercalation, and interconversion' between epistemic things and technical objects in experimental sciences. Rheinberger (1997: 30) maintains that there can be no final distinctions between objects of scientific enquiry and the instruments that scientists use to study them. They are two extremes with 'all possible degrees of gradation' between them and 'room for all possible hybrids' (Rheinberger 1997: 30). A CPR, with sensors attached to record its behaviour under various conditions, but still regularly sampling the oceans, is a hybrid that is simultaneously research technology and the focus of research. A similar shift has been found by Shavit and Griesemer (2011: 189) in their study of the MVZ's two biodiversity surveys: The technical category of 'specimen location' became a distinctive new scientific problem 'in the face of theoretical and technological change as well as changing public priorities for science'. Likewise, in my case, the CPR technology has repeatedly become a scientific problem due to historically changing factors such as increasing ship speed, new scientific equipment, or changing silk suppliers.

6.3.2 The scientific and socio-economic context

Knowledge of the oceans, their ecosystems, as well as the processes that effect oceanic plankton has progressed substantially since the beginning of the CPR Survey. How has this progress affected the survey? The list of taxonomic entities that is used for identification of plankton organisms is a key indicator in this regard.

The microscopic analysis and the count of a specific taxonomic entity on the sample are performed with a variable degree of detail. According to Richardson et al. (2006: 37), the CPR survey records 437 different taxa in the North Atlantic. Accounting for all regions where CPRs are deployed, the number of taxonomic entities recorded is even higher, as Johns explains:

> “If you are talking about taxonomic entities, so not species, not genus, we probably count over 800. A lot of these will be to species, but for certain taxa, the calanoids, the copepods that people are very interested in, we would say ‘Not only is it genus this and species this, but it is also a male or a female or it is in a stage where it is a juvenile or it is an adult.’ So that is information that is captured as well. But only for things that people are really interested in, otherwise it just adds to the workload. […] Some of the things we are looking at, we cannot take them any further. We can only say that it is a decapod larva, which is the larva of a crab or a lobster. It would just take forever if you wanted to identify exactly to the species. So some things that we look at are quite coarse, we just stop and say ‘That is good enough. That is what we need to know.’” (DR0934: 3)

In the sample analysis, the question of interest is not always just for the quantity of a given species. The taxonomic list is designed to capture different life stages of some organisms or the abundance of several species together as a single group and not individually. For example, *Atlanta* is a genus of the phylum mollusca that consists of around twenty different species, but all of them are counted together during the zooplankton eyecount stage, recorded as the taxonomic entity *Atlanta* spp. without distinguishing on the species level. By contrast, some species are counted individually but are also recorded as part of one or more species groups, as in an example of some *Dinophysis*’ species explained further below.[125] In another example, the two copepod species *Undeuchaeta major* and *Undeuchaeta plumosa* are recorded separately, but *Undeuchaeta* specimens which are ‘identifiable to genus but not species’ level

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[125] In combination with the category counting system explained in chapter four, the individual and group counting of the same species may occasionally lead to an ‘undesirable consequence’ (Richardson et al. 2006: 37): The conversion of counted values to accepted values and to estimated abundances may result in final values for individual species which should sum up perfectly on a higher taxonomic level, but not always do so. In such cases, data users are advised to use the combined taxonomic entity rather than adding up the individual abundances themselves (Richardson et al. 2006: 37).

are counted as a separate taxonomic entity named *Undeuchaeta* spp. (Richardson et al. 2006: 52–54).

The reasons for applying different depths of analysis often lie in the specific dynamics of the ecosystem under investigation and the processes that the oceanographic community is interested in. Johns illustrates this with an example: Most of the zooplankton research of the North Atlantic and North Sea focuses on distributions of the two species *Calanus finmarchicus* and *Calanus helgolandicus*. Both species' abundances follow the seasonal cycle of phytoplankton which are eaten up by the two *Calanus* species. The seasonal cycle always features a strong spring bloom and an occasional, smaller autumn bloom. *Calanus finmarchicus* and *Calanus helgolandicus* prefer different water temperatures, so that a shift in distributions of the two may indicate a shift of temperature regimes inside the oceans. In this case, it is only important for most researchers to know whether it is one species or the other.[126] By contrast, in parts of the Pacific Ocean, an ecosystem with fundamentally different characteristics, *Neocalanus* species fill a similar role in the food chain as the two *Calanus* species do in the North Atlantic, but in an ecosystem without strong spring blooms and with constantly low phytoplankton abundances. The ecosystem and food chain are much more sensitive to small disturbances and in these cases, researchers are interested not only in species, but also in the stage of development of the organisms, whether they are juvenile or adult (DR0934: 10–11). The list of taxonomic entities is adaptable depending on what the scientific community values as important regional characteristics of a specific ecosystem.

The previous quote by Johns also hints at a relation to the socio-economic context of the survey: As the lab manager, Johns, has to keep an eye on the workload and make sure that the analyses are performed in a reasonable amount of time. The sample analysis is "the most expensive part of the entire process", says Camp (DR2901: 11). If the CPR Survey had more funding for analysis it would "happily double the amount of routes tomorrow" (DR2901: 11).

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[126] However, the CPR Survey actually distinguishes between juvenile and adult life stages of *Calanus* species.

The duration of an analysis is thus an important factor in the workflow and is determined by the methods of sub-sampling and the category system that I have described in the previous chapter, but also by the list of taxonomic entities and the level of detail that are applied in each analysis. Johns needs to find a balance between a reasonable workload for the taxonomists to avoid a growing backlog of unanalysed samples, the constraint of having a limited number of taxonomists available, and serving the interests of the scientific community.

While the sub-sampling and the category system for counting organisms have remained unchanged since the 1950s, some taxonomic entities as well as the detail of analysis have been adjusted in the course of the survey. As Richardson et al. (2006: 59) explain, 'the Survey is responsive to changes in research focus and marine management imperatives'. New taxa have been added to the survey throughout its history, which means that a new 'Taxon ID' in the CPR database is issued and taxonomists are trained to identify the new taxon. In a relatively recent example, the genus *Dinophysis* has only been identified to the genus level until 2004. Since many of *Dinophysis*' species are associated with harmful algal blooms which create toxic effects for other organisms, seven different species of *Dinophysis* have been recorded individually since then. However, the group *Dinophysis* spp. has been recorded since 1958 and also remains as a taxonomic entity by itself so that the almost 60-year time series of *Dinophysis* spp. continues (Richardson et al. 2006: 59). Similar to the additional equipment bolted on the exterior body of the CPR and the standardisation of the MECN time series, practices with a history spanning multiple decades are intended to remain untouched. If existing time-series are unaffected and the analysis remains economically feasible, a new research capacity in form of a new entity may be added.

As Bowker (2000) explains, taxonomists who record biodiversity data decide for a variety of reasons what they record, how they record, and what they do not record. These decisions are mirrored in the databases taxonomists construct and they shape our knowledge of the natural world. Histories and context such as the relations between the two *Calanus* species, the association of *Dinophysis* species with harmful algal blooms, but also SAHFOS' economic constraints are written or “folded” into biodiversity databases (Bowker 2000: 675).

Another example of a new taxonomic entity that has been added due to scientific as well as public interest are plastics (Richardson et al. 2006: 59). Even before its addition to the list of taxonomic entities, sample analysts have frequently encountered microscopic pieces of plastic on the samples. Thompson et al. (2004) have re-examined archived samples from the CPR routes between Sule Skerry and Iceland and between Aberdeen and the Shetlands. They found plastics on samples from the 1960s and their abundance has significantly increased in the following decades. In 2004, a taxonomic ID was issued and plastics have been recorded routinely since then. Richardson et al.’s (2016: 56) list of taxonomic entities of the North Atlantic lists ‘Plastics’ under ‘Miscellaneous taxa’ right between ‘*Pinus* pollen’, pollen grain of pine trees, and ‘Stellate bodies’, hairs of land plants, which are of terrestrial origin like plastics but of course biological entities. In response to the lack of quantitative data on microplastics pollution, the practice was further developed in 2016 from just recording the presence to documenting particle size, type, and abundance (SAHFOS 2017: 21). This new, non-biological taxonomic entity has been created and further developed in response to historical changes of context: increasing pollution of the seas, increased global production of synthetic fibres, as well as public and scientific interest in the matter.

The straightforward addition of a non-biological entity to a list of biological taxa may appear puzzling or even audacious.[127] Yet, from the CPR Survey’s perspective, it is a reasonable step to adapt to the interests and demands of science and societies. An equally important fact is that the survey utilises proven data practices that allow this move with relatively little additional efforts. A major worry about the growing pollution of the oceans with plastics concerns the uptake of microscopic plastic particles by plankton organisms. This

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[127] Note, however, that etymological origin of the term “plankton”, coming from the Greek “planktos”, meaning ‘that which is passively drifting or wandering’ (Lalli and Parsons, 1997: 3–4) does not indicate living entities explicitly. Microplastics are not biological organisms, but they are entities that passively drift with the currents just like organic plankton.

introduction of plastics into global food webs is a process that the CPR Survey seems to be predestined to study with its data practices, its research infrastructure, and the geographical and temporal scope of the CPR Survey.

However, this development of the survey has led to a new challenge, as Johns explains:

> “Over the last ten years or so there was more interest in microplastic pollution. So we started to ask the analysts if they see any. […] We have been counting microplastics as a possible indicator of pollution for about ten years. We have not really got our heads around exactly how much of that could be contamination. Because when these silks are laid out and cut, they are exposed to the air and all sorts of stuff could fall onto the silk. So it is quite difficult to say when it comes back and you look under the microscope, if it is actual pollution from the sea or if it is just a form of cloth. So we have got some ongoing work trying to get that.” (DR0934: 5)

In order to distinguish between plastic pollution of the seas and contamination, the survey needs to develop an entirely new skill. This requires specific investigation of the survey’s methods, workflow, and lab environments.

Batten et al. (2003: 204) point out that taxonomy is an ‘evolving discipline’: Since the CPR survey started, ‘new species have been discovered, and old ones have been split or even merged, as new information comes to light’ (Batten et al. 2003: 204). For example, the aforementioned genus *Calanus* has been split into *Calanus* and *Neocalanus* only in 1974. A total number of 28 changes to the ‘taxonomic resolution’ are listed in Batten et al. (2003: 205), which covers the first sixty years of the CPR survey. The majority of these are counting species separately which were only counted as part of another taxonomic entity until then and counting a taxonomic entity numerically instead of just recording it as present. Both changes are associated with an increase in taxonomic resolution (Batten et al. 2003: 203–04). Research in plankton taxonomy provides SAHFOS with a structure to build an ontology for the CPR Survey. The ontology reflects the current scientific consensus regarding the spectrum of species known to exist in the oceans, but it can also be used as an adjustable scaffold not only to create data, but to keep the survey relevant despite shifting interests of researchers and societies. As summarised in chapter three, the CPR Survey was conceived in the 1920s by Alister Hardy in the context of fisheries ecology in order to create data on zooplankton, the main food source of larval fish. Since then, the survey has developed into ‘a platform for Integrated Ocean Observing’ (SAHFOS 2017: 6), offering a wide variety of specifically processed data products which are particularly useful for the study of the oceans as part of a changing climate system and to assess anthropogenic impacts such as pollution.

Frost hints at certain pressures for traditional marine ecological practices to transform themselves and appeal to funding organisations. As he explains, the classic methods of ecology are “being slightly overlooked” and are sometimes seen as “slightly old-fashioned” (DR6427: 18). Describing the contrast to physical oceanography, Frost states:

> “When you are going for a meeting and somebody is showing how they got this ship and satellite and AUV and they have got these systems measuring how the ocean circulations change […]. That is something which your average funder and policy-maker will think ‘yeah, I can see that.’” (DR6427: 18)[128]

Whereas Frost describes an ecological survey he has participated in as follows:

> “It is people going out, I did it with PML a couple of years ago. We did the classic thing, we drove out, we dug stuff up, we put stuff in buckets, we measured stuff, we sat on the microscopes, and it is a lot harder to say that it is really, really important.” (DR6427: 18)

The “classic thing” is “a lot harder to sell”, Frost explains (DR6427: 15). The development of new capacities by deploying new instruments that widen the spectrum of potential data users is thus an activity that scaffolds the continuous

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[128] An AUV is an autonomous underwater vehicle, a robot that travels and operates without requiring input.

operation of the CPR Survey as a whole. Similar to the MECN's intentions, the CPR Survey develops a repertoire that facilitates cooperation with external researchers and attracts funding. In relation to the difficulty of funding long-term monitoring programmes, Brandner et al. (2003: 177) make clear that 'to survive for seven decades, the CPR dataset must have had some continuing utility for marine resource management or policy'.

As the previous section has shown, good audit trails and a comprehensive documentation of practices also support the continuity of long-term environmental time series. With numerous publications describing the survey's methods, extensive documentation, and internal standards of practice, the CPR Survey has managed to build an extensive written audit trail. However, crucial knowledge and plankton expertise are also preserved and passed on through the training of new sample analysts and the regular organisation of courses and workshops for internal and external scientists.[129] Still, specific expertise on local marine ecosystems, which individual researchers have gained and developed over decades, is in danger of being lost in the course of staff fluctuation and ageing of key experts. Esther Hughes, manager of DASSH, gives an example:

> "For example pycnogonids, which are little sea spiders … A lot of knowledgable marine biologists are able to put the species down to a family or a group, but they are not able to assign any sort of certainty to that record. And the guy who was the pycnogonid expert in the UK died in 2010. So we now have a lack in that expertise. That is a little bit of a problem for that group." (DR4783: 14)

Reid et al. (2003: 159) also remark that besides financial reasons, many marine environmental time-series are in danger 'because key trained staff are not being replaced'.

Some marine ecologists struggle to attract other people and funding because many of their research methods and objects of study are less "charismatic" than

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[129] In 2016, SAHFOS organised a Harmful Algae Taxonomy and Identification Workshop, a Fish Larvae Identification Workshop (SAHFOS 2017: 20–21), and three technical courses with the operations team (SAHFOS 2017: 13).

those of other oceanographic or biological research areas. Bowker (2000: 655–56) points out that the term "charismatic" has been used in biodiversity literature to describe species that attract more attention from the public, policy-makers, and funders than others:

> Many more care about the fate of the cuddly panda, the fierce tiger or indeed the frequently drunk and scratchy koala bear, than about the fate of a given species of seaweed. (Bowker 2000: 655)

Attention is also biased towards 'the exotic other' (Bowker 2000: 655), to the detriment of many leading research organisations' and funders' domestic ecosystems and species. Technologies are more or less charismatic as well, as Frost's juxtaposition of the physical oceanographers' satellites and AUVs with the marine ecologists' buckets and microscopes illustrates. Bowker (2000: 656) summarises that across all sciences, 'the activity of naming', which is the core of taxonomic and biodiversity research, 'is mundane and low status, even though it is an activity central to the development of good databases'. More charismatic species and technologies not only draw more attention from the public, policy-makers, and funders, but also attract a larger number of young researchers (Bowker 2000: 655). These kinds of feedback loops gradually reinforce the low status of taxonomic and biodiversity research and they are not controllable by the CPR Survey but rather an aspect of the context and setting in which research practices are performed. The feedback loops cause productive resistance from the perspective of marine ecologists who specialise in seaweeds, sea spiders, or a relatively uncharismatic ecosystem on a rock formation in the Western English Channel. Although oceanic plankton populations have received increased public attention due to their crucial role in the climate system, most of the research methods to study macro-scale processes remain rather "old-fashioned", like the CPR Survey's core activity that is based on mechanical sampling devices, pieces of silk, and hands-on microscopic analysis. Sukhotin and Berger (2013: 2), two marine ecologists, maintain that

> carrying out the monitoring studies is a thankless job. It is time and effort consuming and does not provide immediate scientific

> gratification. Usually, the data produced by the monitoring become valuable only when accumulated over a long period of time (sometimes decades).

The CPR Survey’s data practices are characterised by the flexibility to be responsive to the interests and attention of societies and research communities, by the ability to add charismatic entities such as microplastics to their taxonomic spectrum, and by the ability to add new instrumentation. These abilities are scaffolds that support the CPR Survey’s continuous operation. In light of numerous uncontrollable, external conditions, the survey is required to adapt and develop its scientific repertoire in order to preserve the continuity of its core activities.

Part of maintaining a data practice is maintaining the specific expertise and knowledge of the people performing the research. The expertise required for the analysis of CPR samples is quite special and passed on to new generations of sample analysts inside the lab. As the lab manager, Johns is in charge of hiring new sample analysts; he explains that it is difficult to find people who already have some sort of expertise in plankton. Johns’ description gives the impression that indeed not many young biologists are pursuing specific expertise in plankton. Therefore, Johns would be looking for people “to have some sort of knowledge of natural history, to be interested in natural history”, so that the new team member is likely to gain experience and specific expertise quickly. Johns compares this way of hiring to before he was appointed the lab manager:

> Before I was doing that, we had somebody else, who was taking people on. They just wanted people who would stay and treat it like a factory and do their work. So that is great from a work perspective, but it means that they have got no interest in the biology or the ecology of what they are looking at. So they don’t tell you if they see anything different. They don’t think ‘Actually, you know what, that is really weird at this time of the year.’ So you kind of lose that. […] One of the last ones we took on, she was interested in bats. […] So she actually has got a license to look at bats, and I was thinking ‘That’s what we want.’ You want somebody who is interested in nature, to

> say ‘Actually, this is quite unusual.’ Otherwise it becomes a bit of a conveyor belt of churning out samples.” (DR0934: 18)

A newly hired plankton taxonomist receives several months of training, which is “one to one training for most of the time with one person who leads the training”, Johns explains (DR0934: 17). In the beginning, trainees only receive samples which have already been analysed by established taxonomists so that it is possible to compare the results, Camp explains:

> “So there is quite a lot of training involved, because we have to recognise an awful lot of taxa, over five hundred different taxa. So there is a lot of training required, you are not really fully released without supervision until maybe after two years of analysis; and that is still only North Sea and North Atlantic samples. It might be some time after that until you would be looking at Pacific samples or South Atlantic, Antarctic samples, because the communities are different, there is additional training on that.” (DR2901: 8)

Analysing samples from different regions requires knowledge of the respective ecosystem and familiarity with the local organisms. A shelf filled with textbooks and other resources is kept in the lab in addition to every taxonomists’ personal notes, as Johns explains:

> “For most of the phytoplankton in that North Sea area or anywhere near the UK, most analysts here would not need to look that up. […] Some are rare things and there are a couple of things that look fairly similar, some of the zooplankton, people would look at that more often, even after years.” (DR0934: 6)

However, asked whether the skills to be a plankton taxonomist are rather learned via textbooks or from experience, Johns laughs and explains:

> “Probably most of it is informal and on-the-job stuff, yeah. Textbooks are obviously really useful, but it is not the same as looking down and actually seeing a physical specimen there.” (DR0934: 18–19)

Taylor, an experienced sample analyst, describes the interaction in the lab by which specific expertise is gained:

> “We are always looking at each other’s samples all the time. It’s not that a day goes past where you are not going to go a look at someone else’s stuff.” (DR8112: 10)

The main reason that taxonomists learn most effectively “on-the-job” is that many organisms on CPR samples do not look the same as in the images of textbooks. The organisms on the silk are “squashed” between the two silk layers and are often hit by the CPR’s steel body at considerable speeds before they get caught in the silk. The organisms hence tend to be “very, very flat”, as Johns explains (DR0934: 19). Occasionally, though, a comparison with organisms as they appear in the oceans as well as in textbooks is helpful and may adds an analyst’s expertise:

> “Guys who work in this building have got a regular sampling point right out there, the Eddystone. And they use a net to catch their zooplankton. So their zooplankton looks lovely. They are not squashed, so we also give people that to look at as well. So we can say ‘Here is the book, this is what it looks like in the book. This is what a real one looks like, it is nice. And this is what ours look like.’ So you get a nice broad understanding. You can start identify things at weird squished angles, which you would not pick out from a book.” (DR0934: 19)

The on-the-job development of capacities and preserving of expertise exemplify scaffolding by developmental agents, with interaction, cooperation, and exchanges between agents and their targets rather than just by application of an artefact or structure. These scaffolds are anything but permanent, as people in the lab are not constantly assisting each other. They may be utilised as needed, either if new analysts receive basic training, if a special expertise is going to be acquired, or if an analyst is simply in doubt about an organism’s taxonomic identity.

The majority of a plankton analyst's expertise is gained by becoming part of the group of taxonomists and by interacting and practising together with experienced taxonomists. This way of learning by practice and interaction scaffolds the maintenance of the survey by preserving the plankton- and CPR-specific expertise. Collins and Evans' (2007: 3) account of acquiring expertise as a 'social process—a matter of socialization into the practices of an expert group' is an adequate description of the training process in the CPR Survey. The skills and expertise required to identify severely deformed plankton organisms is exactly the kind of "tacit knowledge" that 'one can only gain through social immersion in groups who possess it' (Collins and Evans 2007: 6).

Challenge	Scaffold	Development
Acquiring funding for "old-fashioned" data practices on "uncharismatic" species	Flexible and adaptable list of taxonomic entities, ability to add new instruments	Development of a scientific repertoire to enhance collaboration
Staff fluctuation and ageing of key experts	Social immersion in an expert group, "on-the-job" training of new taxonomists by developmental agents	Maintaining specific marine biological expertise

Table 6.3: Challenges, scaffolds, and developments that relate to historical changes of scientific knowledge and the socio-economic context of the CPR Survey.

Table 6.3 summarises scaffolds that relate to historical changes of scientific knowledge and the socio-economic context of the CPR Survey. Whereas most of the challenges and scaffolds related to technology were specifically dealing with aspects and details of the CPR Survey, the productive resistances discussed in this section are problems faced by researchers in many disciplines: Acquiring research funding is extremely competitive so that researchers in many fields may experience a pressure to come up with innovative research projects to "sell" their science to funding agencies and to the wider public. Naturally, all scientific disciplines experience staff fluctuation and the retirement of key figures. However, ecology and biodiversity are research fields with a high diversity of practices and in some cases, an intimate relatedness to local conditions. Losing an expert of local species populations like sea spiders in the UK therefore amounts to a serious problem for the creation of continuous data related to these species.

6.4 Dynamic development underpins continuity

The empirical sections of this chapter portray the CPR Survey as a developing entity. Instead of a static tool that is applied to a natural system in strictly the same way for decades, I have encountered lively, growing, and dynamic research practices. Hacking (1983: 150) and Rheinberger (1997: 81) have characterised experimental systems as having a ‘life cycle’ and ‘a life of its own’, respectively. I suggest expanding this description to include long-standing ecological monitoring practices, even if these are characterised by strong methodological continuity.

The CPR Survey has grown and developed: Individuals who are part of the survey have gained knowledge and expertise, the purpose and scope of the survey have expanded, and new instruments have been internalised into routine research practices. Over seven decades, the survey has gained new capacities and developed a scientific repertoire, all the while it has maintained its core functionality: the “old-fashioned” mode of creating plankton data. The methodology of the survey has been maintained not despite, but because of its ability to adapt data practices to historical changes of context.

The continuity of data practices and the commensurability of data are underpinned by a variety of dynamic processes and activities, which I have discussed as scaffolds: The development of a scientific repertoire, which increases the scope of data and the potential for collaborations, scaffolds the preservation of practices in which the core functionality cannot be changed. The implementation and preservation of comprehensible audit trails amount to a scaffold that enables researchers to continue established data practices, to replicate data practices of the past, or to re-establish a practice after an extensive hiatus. Further, researchers respond to changing conditions with experiments that turn the research technology into the object of research and thereby scaffold physical modifications of the technology or increased certainty in the performance of instruments.

The data ontology, implemented as an adaptable list of taxonomic entities, provides a level of flexibility that even allows for the crossing of disciplinary boundaries by addition of non-biological and purely anthropogenic entities like plastics. Such additions or refinements may lead to new capacities that can scaffold the continuous operation of a research practice. Further, informal, social immersion of younger researchers into a group of experts scaffolds the preservation of local expertise that is often required in ecological research.

All of these scaffolding activities are integral parts of the CPR Survey and they help managing the impacts of a variety of external processes that are beyond SAHFOS's control: long-term progress in sensor technology, marine engineering and navigation; shifting interests and focus areas of scientists, science funders, policy-makers, and the public; progress in taxonomic knowledge and the discovery of new species; the progression of personal careers and biographies and the resulting personnel turnover.

The dynamics of these processes are visible in an example of an intricate interplay between the external drivers and scaffolds: In order to attract funding and continue long-term operation of the survey, new instruments are added to the CPRs. The new devices and the resulting data scaffold the continuation of the survey as a whole. However, new devices may affect the CPR's performance during a tow, so the continuity needs to be scaffolded by experimental research of the CPR's performance under different conditions.

The examples in this chapter also disclose an interaction between different scales of scaffolds and developed entities. Many developments discussed in the empirical parts of this chapter can be viewed as "small-scale": the modifications of the CPR's design based on studies of very specific components of the sampling technology, the addition of a small piece of equipment to the exterior body of the CPR, or the individual training of a junior sample analyst. This variety of small-scale developments scaffolds “large-scale” continuity: the continuous operation of the survey for multiple decades, the comparability of newly created data with historical records, and the transfer of local ecological expertise from one generation of researchers to the next.

A scientific repertoire, Ankeny and Leonelli (2016: 19) remark, makes research practices ‘relatively robust over time despite environmental and other types of changes’. Scaffolds, too, enhance the robustness of practices, but the kind of robustness that is achieved is not characterised by being unaffected by external factors and changing conditions. Robustness here consists in the ability to adapt and develop practices so that core functionalities are maintained. Griesemer, Caporael, and Wimsatt (2014: 307) explain that what biologists call robustness can be found in both biological and cultural developmental systems: the ability to ‘assimilate changes and adjust to them’. Systems with this ability ‘manifest a great deal of stability’ (Griesemer, Caporael, and Wimsatt 2014: 307). This analogy has received relatively little attention from scholars, compared to ‘the assumption that preexisting genetic predispositions explain the most important aspects of human culture’ (Griesemer, Caporael, and Wimsatt 2014: 307). My case study exemplifies the dynamic development of cultural practices that is necessary for assimilating historical changes of conditions and it contradicts an image of development that is determined by a given set of predispositions.

6.5 Conclusion

Consistency of data and data practices is crucial for the recording and study of long-term changes of ocean ecosystems. This chapter shows that the commensurability of data that were created decades apart is achieved by developments of scientific practices which preserve core functionality. The continuity of data practices is not characterised by rigorously adhering to a single method that is repeated over and over again. Instead, researchers have to find and maintain a balance between on the one hand, achieving the highest possible consistency and reliability within a growing body of data and on the other hand, adapting to processes that researchers are unable to control, such as technological progress, shifting interests of research communities, the public, and funding agencies, staff fluctuation, and ageing of key experts.

Striving for continuity, but at the same time, competing for limited research funding, researchers need to develop and transform data practices. In the case of marine biodiversity and ecology, scientists are driven towards broadening the scope of their research by adding new instruments or expanding their taxonomic range to include even non-biological entities. Researchers continue their long-standing ecological time series while balancing between their valuable commitment to a legacy and openness to innovation.

I have interpreted scientific change and the development of scientific practice in terms of “scaffolding”: Artefacts, infrastructures, and developmental agents temporarily contribute to the acquisition of new capacities or to the maintenance and continuity of practices. The concept of scaffolding emphasises the dynamic character of a developmental process which is not pre-determined by a set of starting conditions, but rather plays out in response to external, historical drivers and the scientific, technological, and socio-economic conditions of research practices. With regard to the tension between change and continuity, scaffolding processes seem to reconcile what was initially perceived as an opposition: The continuity of data practices is not achieved despite changing conditions, but because of the ability to assimilate changes and adjust practices accordingly. Unlike the material continuity introduced in chapter four and the traceable series of transformations introduced in chapter five, the continuity of data practices relates only indirectly to the space in-between science and nature. Methodological continuity constitutes a lack of jumps between data of the past and data of today and thereby cuts across, somewhat perpendicularly, to the individual links between data and the natural world. These continuities and changes are interwoven in the CPR Survey’s data practices to form a flexible and yet robust layer of practices from which scientific knowledge of natural systems grows.

However, a crucial thread that is part of the setting in which the CPR Survey operates is still missing from the picture and was not mentioned in this chapter. The survey depends on collaboration with commercial ships, shipping companies, port authorities, and logistics companies to reliably deploy CPRs year after year. The next chapter is dedicated to describing cooperation with a variety of non-scientific agents, which also scaffolds the survey's reliable operation and has profound epistemological consequences.

Chapter Seven – Co-production and social continuity: How seafarers contribute to ocean sciences

Abstract: This chapter accounts for the involvement of seafarers and other non-scientific actors in the CPR Survey and in a relatively young citizen science project. In the latter, sailors are encouraged to measure a parameter related to ocean turbidity and phytoplankton biomass and submit their data with a mobile phone app to a centralised database. In both cases, ocean scientists exploit the fact that many different people frequently interact with the oceans on their own terms and that a wide range of oceanographic data can be produced by following relatively simple instructions. I argue that these collaborators actively co-produce data and knowledge of the oceans and are not passive collectors of data or samples. Non-scientists enable sampling conditions and shape the outcomes of research by using their particular skills and embodied knowledge related to their seafaring activities. Rather than being tools that are deployed by scientists in order to collect data or samples, these actors are firmly embedded in the constantly changing setting that researchers must approach in order to create knowledge. The CPR Survey's operations team continuously maintains social relationships to collaborators from a variety of professions. This social continuity between science and seafaring culture is crucial for maintaining the network of volunteers and for ensuring that the spatial and temporal regularity of sampling are sustained indefinitely. In this regard, social continuity is an indispensable component of the CPR Survey that underpins the practices' material and methodological continuity.

7.1 Introduction

In chapter three of this thesis, I have discussed the difficulty of defining oceanography or ocean sciences as a distinct scientific discipline. I settled on an understanding of ocean sciences as an engagement in the oceans and seas involving practices of sampling, observing, or recording of phenomena, the creation of data and models, or the production of knowledge from samples, records, data, or models. This understanding deliberately entails epistemic activities performed by non-scientists. Several oceanographic data practices researched for this thesis rely heavily on activities performed by seafarers and other people without scientific credentials or formal affiliation with research institutions. This chapter analyses how these crucial actors are involved in data practices and how this involvement and their individual agency enable epistemic processes in two cases of ocean science: the CPR Survey and a relatively young project named the Secchi Disk Study (SDS) which claims to be 'the world's largest marine citizen science study' (Kirby 2016).

Scholarly literature offers numerous terms for actors who are crucially involved in epistemic processes but are not scientists: Among them are "volunteers", "amateurs", "the public", or "citizen scientists".[130] Scholars have also made efforts to classify and distinguish different forms of involvement of non-scientists, in particular different modes of "citizen science", a term that has gained currency among scientists and politicians since the mid-1990s (Wiggins and Crowston 2011, Bonney et al. 2009). Many of these accounts highlight the role of non-scientists especially in the environmental sciences as a means to collecting data or samples and as a platform scientists can use or deploy to establish new sources of data. This chapter focuses primarily on the practice of collaboration and the agency of the participants, since the resulting product has already been discussed at length in the previous chapters.

I argue that non-scientists enable sampling conditions by using particular skills and embodied knowledge related to their seafaring activities. Unlike sampling tools that are deployed in order to collect data or samples in the name of science, these actors are firmly embedded in the environment that scientists intend to study. Researchers are thus required to reach out, build, and maintain long-term social relationships for a successful collaboration with seafarers. The collaborative data practices studied for this chapter entail a social continuity between the scientific domain and the seafaring culture that underpins the

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[130] Engineers or administrative staff may also be crucially involved in epistemic processes and lack scientific credentials as well, but they are usually employed by the research institution carrying out the scientific endeavour. These actors are not referred to when I use the term "non-scientists" throughout this chapter.

material and methodological continuities that I introduced in chapters four and six. In particular, my empirical research exposes the ongoing efforts that are necessary to maintain the CPR Survey's network of volunteers and to ensure that the sampling maintains its spatial and temporal regularity over multiple decades.

My view of collaboration highlights aspects that have also been emphasised in recent scholarship which conceptualises participation in scientific processes as emergent, co-productive, and always "in-the-making" (Chilvers and Kearnes 2016b). Both the scientists and the seafarers make significant epistemic contributions to the scientific process: The actual sampling of the ocean is conducted partly on the scientists' terms, as they provide instructions and equipment, and partly on the seafarers' terms, as they interpret the instructions and despatch or use the technology. By contrast, the seafarers enable sampling conditions largely on their own terms and with respect to their environment. When, where, and how the sampling can be realised depends on the participants' agency and their interaction with the seas.

The kind of collaboration discussed in this chapter can be mutually beneficial. In relation to the variety of datasets that scientists are capable of producing by themselves, the outcomes of collaborations with seafarers are unique and may fill specific niches that scientists are unable to address due to a lack of skills, knowledge, or resources. Conversely, from collaborating with scientists, the participating seafarers may identify with a global scientific effort, gain knowledge of the local environment and of scientific processes, or simply experience enjoyment while they are at sea.

The two following introductory sections focus on recent advocacy and discussions of non-scientists' participation in ocean sciences and on scholarship in on citizen scientists, amateurs, and volunteers. The empirical part focuses first on the SDS and then on the participation of commercial ships, their crews, and many other people in the CPR Survey.

7.1.1 Outsourcing data production with citizen oceanography

In 2014, a group of ocean scientists published a call to 'make a place' for citizen scientists in the oceanographic community, proposing a 'worldwide effort to empower sailors' to contribute to ocean science (Lauro et al. 2014: 2). The authors demand action that facilitates 'crowdsourcing the collection of oceanographic data' in light of the still prevalent data scarcity in ocean sciences:

> Notwithstanding satellite constellations, autonomous vehicles, and more than 300 research vessels worldwide […] we lack fundamental data relating to our oceans. (Lauro et al. 2014: 1)

As illustrated in chapter three, the enormous size of the oceans, the wide range of temporal and spatial scales of oceanic processes, and the high costs of running research vessels are the main reasons for the data scarcity. However, ocean sciences use many types of data that are relatively simple to create:

> Some of the most important types of observations require only that one be in the right place at the right time with simple instrumentation or sampling equipment. Important data can be gathered by anyone who can follow basic instructions. (Lauro et al. 2014: 2)

Among the activities non-scientists could perform are the collection of biological samples, measuring basic physical parameters such as temperature and salinity, documenting surface weather conditions, or reporting debris sightings. Simplicity of activities and contributions is the 'premise' of citizen science, explain Lauro et al. (2014: 2–3), who go on describing a basic mode of operation for citizen science in oceanography:

> Rather than dispatching scientists into the environment to collect data, scientists may instead train people who already interact with the environment to apply the scientific method to phenomena they already observe. (Lauro et al. 2014: 2)

The idea is to seize opportunities presented by people or infrastructures interacting regularly with the oceans. Seizing these opportunities means providing simple instructions and sampling equipment so that people who already interact with the oceans are able to create oceanographic data in the course of their interaction.

The primary motivation for scientists to seek collaboration with non-scientists is the lack of oceanographic data and the relatively low cost of many types of collaborations. Regarding the seafarers, ‘citizen oceanography’ can also have positive effects: It may ‘empower civilian scientists with the pride of data contribution to science’ (Lauro et al. 2014: 3). Further, claiming a benefit for both the scientists and the non-scientists, citizen oceanography is seen as an ‘incredible opportunity for outreach’, as it may enhance science education as well as public awareness (Lauro et al. 2014: 3).

Oceanographic literature offers several cases of collaboration that illustrate the ideas of Lauro et al. (2014). Brewin et al. (2015), for example, show that recreational surfers, equipped with low-cost temperature sensors, can acquire high-quality SST data all year long and may help in monitoring coastal ecosystems. Coastal zones are particularly rich in biodiversity but also particularly threatened by processes such as overfishing, climate change, and harmful eutrophication. Although these zones tend to be more accessible than the open oceans, the sampling coverage of these vulnerable areas is still insufficient (Brewin et al. 2012: 2).

Brewin et al. (2012: 1–2) conceptualise the surfers as a ‘platform to improve sampling coverage of environmental indicators in the coastal zone’ and citizen science as the ‘outsourcing of a task once performed by a set of professionals to a large network of voluntary citizens’. This outsourcing could ‘tackle costly, intractable and laborious research problems’ such as insufficient sampling coverage (Brewin et al. 2012: 2). Citizen science can promote the public understanding of science and recreational surfers are a ‘good target audience’ due to the surfing community’s strong advocacy of environmental issues and their ‘intrinsic interest in the functioning and the state of the environment’, Brewin et al. (2012: 2–3) maintain.

In another example, Schnetzer et al. (2016) review participation in the Ocean Sampling Day (OSD) 2014, which took place on 21 June 2014 and was a simultaneous sampling campaign of the oceans organised by an international group of scientists as part of an EU-funded research project on microbial biodiversity.[131] The OSD was designed to study the microbial diversity of marine surface waters worldwide on a single day with help of citizen scientists using a smart phone app to submit various oceanographic data. The submitted data showed that seventy-nine percent of the participants' sea surface temperature measurements came from locations that neither traditional in-situ measurement systems nor satellite remote sensing systems are able to cover (Schnetzer et al. 2016: 169). This figure shows that there is indeed potential for non-scientists to make contributions to epistemic processes which scientists would be unable to obtain or realise without them. Given that seafaring citizen scientists tend to make their contributions rather from or close to coastlines than from the open oceans,[132] a particular niche could be filled by these participants. Satellite remote sensing is often said to produce global oceanographic data, but land masses are a main source of interference that makes signals close to coastlines extremely difficult to interpret. Further, the ecosystems close to the coasts are particularly rich in biological diversity and require monitoring at higher granularity than the open oceans (Brewin et al. 2015: 2).

An intriguing aspect of citizen science in oceanography and other sciences is the great promise held by the combination of new technologies with citizen science. Newman et al. (2012: 298) explain that emerging technologies such as mobile phones and apps, wireless networks, and online games are 'streamlining data collection', improve data management, and may automate the quality control of the data. The 'future of citizen science will likely be inextricably linked to emerging technologies' (Newman et al. 2012: 298). The internet in particular makes the 'popularity and scope of citizen science appear almost limitless' (Tulloch et al. 2013: 128).

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[131] <https://www.microb3.eu/osd> [accessed 16 March 2017].

[132] See for example the distribution of contributions to the SDS; <http://www.playingwithdata.com/secchi-disk-project/> [accessed 17 March 2017].

Wood, Moretzsohn, and Gibeaut (2015: 16) report from a taxonomists' workshop focused on data obtained from 'non-traditional sources' in order to extend existing marine species distribution maps. They pick up the "crowdsourcing" term from Lauro et al. (2014) and conclude that citizen science and crowdsourcing could increase the amount of available data 'considerably'. New technologies are also capable of increasing the quality of scientific data created in collaborations with citizen scientists, Wood, Moretzsohn, and Gibeaut (2015: 16) argue: 'Auto-collection of geo-locations, the use of autocomplete functions and drop-down lists can substantially add to the accuracy of that data.' These examples illustrate that technological progress and collaboration with non-scientists are seen as complementary in environmental sciences. Moreover, the contributions of citizen scientists can be optimised by means of technological gadgets.

Despite alluding to positive effects for participants and society, the involvement of non-scientists in epistemic processes seems to be perceived by many scientists primarily as an additional data source from which ocean scientists could draw. The term "platform" used by Brewin et al. (2015: 1) for the non-scientific participants is a technical expression that suggests a technical understanding of the collaboration. A platform is 'a vehicle (as a satellite or aircraft) used for a particular purpose or to carry a usually specified kind of equipment'.[133] In this sense, the non-scientists function similar to satellites, Argo floats, CPRs or other sampling platforms that may be deployed as generators of samples or data if equipped with appropriate technology.[134]

Scientists are certainly not ignorant of the human nature of citizen scientists. Yet, citizen science is conceived by oceanographers primarily as a vehicle for creating more data in ways that are still improvable by means of emerging technological innovations. Non-scientists capable of volunteering are seen as an opportunity to fill niches left by existing sampling systems and to add another platform to the scientists' catalogue of sampling tools and practices.

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[133] <https://www.merriam-webster.com/dictionary/platform> [accessed 31 March 2017].

[134] In line with Hacking (1992: 48), 'data generators' can be human or non-human.

7.1.2 Contribution or co-production?

As the participation of non-scientists in epistemic process has increased in many sciences, so has the interest of scholars in the specific epistemic practices employed in citizen science projects. Some scholars have used the term “participatory turn” to describe a recent development in the relation between science and the public for which citizen science is exemplary. In particular, the participatory turn encompasses a shift from away the public merely trying to understand scientific knowledge towards members of the public participating in practices of scientific knowledge creation. The former configuration is characterised by a flow of knowledge from science to non-scientists which does seem like an adequate description of collaborative knowledge creation (Toogood 2013: 612). Chilvers and Kearnes (2016b: 31) point out that the ‘turn toward public participation’ is only one element in a broader re-configuration of the relations between science, the market, and political practices.

A challenge that any attempt at conceptualising collaborative practices faces is the number of terms that have been used to refer to non-scientists who collaborate with scientists. The term “citizen science” has gained popularity since Irwin (1995) elaborated on the complex relationships between science and the public. Besides “citizen scientists”, terms such as “non-scientists”, “volunteers”, “amateurs”, “lay people” or “lay participants”, or simply “the public” have been used to refer to non-scientific collaborators.

Some of these terms are suggestive regarding the motivations or background of non-scientists and regarding the specific form of participation. The terms “public” or “citizen”, for example, convey a sense of democratic participation and equality that gives every member of the public with an opportunity to do science. In case of ocean science, however, not every member of the public is actually in a position to participate. One needs to be a surfer to participate in the project studied by Brewin et al. (2015) and as I explain below, participants in the SDS are required to own a boat and be capable of sailing the open oceans. In these cases, certain skills are mandatory to become a citizen scientist.

By the same token, ‘the assumption that volunteers are always non-experts can be faulty’ (Wiggins and Crowston 2011). Collaborators are not always unskilled or unfamiliar with research topics and methods, as terms like “amateur” or “lay participant” might suggest. As Toogood (2013: 614) points out, the non-professional contributors to collaborative projects may pursue their activity with high seriousness over a lifetime and thereby gain exceptional expertise in their field. Wiggins and Crowston (2011) point out that ‘large-scale citizen science projects present an interesting challenge to the dominant view of scientific expertise’.

The term “amateur” might further suggest that the collaboration is not mandatory and does not involve any type of compensation or payment. Indeed, participants of a wide range of collaborative projects are neither forced to participate nor are they employed or hired by the research institution. The term “volunteers” alludes to a general willingness of the participants to sacrifice their free time and energy to a scientific endeavour without being formally compensated. However, Bruyninckx (2015: 344) has studied a counterexample and highlights the complex ‘micro-economics of data exchange’ between voluntary field collectors of natural sounds and the Cornell Library of Natural Sounds. In this case, recorded sounds submitted by participants become ‘copyrighted commodities’, which has been instrumental for expanding the sound archive.

Some scholars have shown that the backgrounds as well as the motivations of participants to collaborate may be diverse. Martin et al. (2016), who have studied the drivers and barriers of participation in a hypothetical marine citizen science project, found that for many respondents, contribution to science was a strong reason to participate, but increasing personal knowledge of marine species has also been found to be an important driver. In fact, participation might be more or less likely depending on rather contingent factors that do not apply to every member of the public: Schnetzer et al. (2016: 167) have conducted an anonymous survey with non-scientists participating in the OSD. Only twenty-eight percent of the survey respondents have stated a pre-existing interest in the oceans as a motivation to participate but forty percent stated the proximity of their home to the sea as the main reason for participating.

There is a great variety among collaborative projects regarding different modes or degrees of non-scientists' involvement in science. Several attempts to define different types of cooperation take "citizen science" projects as the overarching type of practice, which entails several modes of operation. Bonney et al. (2009) distinguish between "contributory", "collaborative", and "co-created" public participation in science. Contributory projects are defined as 'researcher-driven data-collection projects' and most projects that have received the label of "citizen science" are of this type (Bonney et al. 2009: 18). Collaborative projects also involve collection of data by non-scientists but additionally, non-scientists are involved in analysing, developing research questions, drawing conclusions, or presenting results. Co-created projects are initiated by members of the public who approach scientists to solve a specific problem or answer a specific question they are concerned with. In these cases, participants are usually active in all parts of the research process (Bonney et al. 2009: 18).

Wiggins and Crowston (2011) criticise these kinds of typologies for focusing only on the structure of participation. Their own typology, for which they have evaluated various collaborative projects, also considers explicitly formulated project goals and the degree of physical interaction of participants with the research object. Five different types of citizen science projects are distinguished by Wiggins and Crowston (2011): 'Action, Conservation, Investigation, Virtual, and Education'. Projects in which non-scientists primarily submit data during physical interaction with the environment are termed "Investigation": These projects are 'focused on scientific research goals requiring data collection from the physical environment' (Wiggins and Crowston 2011). Additional benefits for the participants such as education are secondary to the scientific motivation: 'While education is not always an explicit goal, it is frequently a strongly valued but unstated purpose' (Wiggins and Crowston 2011). The majority of investigation-type projects are in biology, meteorology, and climatology, with professional researchers or conservation organizations as project initiators who organise the project “top-down”. Projects of the type “investigation” seem very similar to the “contributory” projects of Bonney et al.’s (2009) typology.

Taking the discussion beyond exhaustive typologies, Bruyninckx (2015: 362) argues for a ‘more inclusive’ understanding of the heterogeneity of collaborative practices and for a stronger focus on the specific ‘mechanisms of engagement and commitment’. Toogood (2013: 618) emphasises the importance of how such mechanisms of engagement are framed in the first place, arguing that participation ‘cannot be reduced to processes defined by non-professionals “doing” science or taking part in particular forms of collaboration’ (Toogood 2013: 618). Practices featuring participation in biodiversity monitoring have primarily been conceived as “win-win” situations with beneficial outcomes for the researchers, who obtain more data, for the participants, who may get educated and develop their attitude and behaviour towards the environment, and for science, as collaboration is said to result in more open and publicly accountable scientific practice (Toogood 2013: 613–14). Toogood (2013: 618) urges scholars to consider more than just motivations and benefits of collaborations:

> The democratisation of participatory science in biodiversity, for example, raises questions beyond motivation and benefits. It suggests questions about the definition of public engagement, about agenda setting, about what data is gathered, about the subjectivities of those involved and, most of all, about the connections between the role of the on-the-ground volunteer scientist and decision-making processes concerning biodiversity, its protection and its future.

While this chapter does not directly respond to these open questions, sociological studies such as those offered in Chilvers and Kearnes (2016c) have moved beyond motivations and benefits by rethinking participation in a ‘relational and emergent’ sense (Chilvers and Kearnes 2016a: 5). The key point of this view is that the elements of participation such as the research target, the participants, or technological devices are not pre-determined, but held in tension through mediation and assemblage of participation. An example of this tension is a case of citizen-driven air quality monitoring in an urban area studied by Ottinger (2010), who claims that standards of measuring possess a 'double-edged' power, as they are simultaneously bridging and policing the boundary between scientists and citizens (Ottinger 2010: 266). The effectiveness and usefulness of citizen science often depend on the application of standards. At the same time, regulated standards may also be used to dismiss data created by citizens if scientists claim that the data were not produced in accordance with regulations. Measuring standards are thus capable of both “bridging” and “policing” the boundary between science and citizens (Ottinger 2010: 246-47).

Further emphasising the dynamic potential of collaborative practices, Chilvers and Kearnes (2016a: 13–14) contend that participation itself is continually being ‘made, unmade and remade’. According to this view, both assemblage and the mediation of participation proceed without central coordinating agencies or institutions and instead, the elements of participation co-produce and constitute themselves in relation to each other. As an example, Macdonald (2002), who has studied amateur birdwatching in the UK around the middle of twentieth century, found that birdwatching practices have contributed to shaping ecological, national, as well as social identities. A consequence of this shift of perspective is the inability to understand participatory practices in isolation, but rather as a practice ‘in the making’ and in relation to science and democracy (Chilvers and Kearnes 2016a: 15).

Cornwell and Campbell’s (2012) case study of sea turtle conservation involving local volunteers analyses collaboration in environmental science in terms of co-production. The collaborative monitoring of turtle nests along beaches and the joint discussion of potential nest relocations constitutes a co-production of conservation rather an application of institutionalised scientific knowledge. The participants’ local knowledge and strong emotional relationships with sea turtles play a significant role in this process of co-production.

For the analysis of my cases, “contributory” and “investigation”-type citizen science projects as well as the idea of “co-production” serve as notions that offer a conceptual lens: It is possible to consider only a collaboration’s structural mode of operation or the explicit motivations and benefits of involved actors, if possible. However, a collaborative practice can also be interpreted as co-productive in a sense that all elements of participation are held in tension and constitute each other through practising science.

7.2 The Secchi Disk Study

The goal of the SDS is to encourage seafarers such as sailors or fishermen to measure the so-called Secchi depth by lowering a plain white disk into the sea water and recording the depth at which it disappears from sight. The amount of biomass in the water affects water's optical properties and perceived clarity. The Secchi depth can be used to estimate the phytoplankton biomass in the upper ocean. Measurements are stored on the participants' mobile phones and are subsequently transmitted into a central database. The project was conceived and launched in 2013 by Richard Kirby, a marine ecologist based based in Plymouth (Seafarers, 2017). This empirical section first describes Kirby's motivation to start the project, its resources and infrastructure, before focusing on the involvement of the non-scientists.

The SDS is concerned with the phytoplankton mass in the upper oceans. Kirby explains that a controversial paper on this topic published in *Nature* in 2010 motivated him to start the project. The paper suggested that the phytoplankton mass in the world oceans had declined by forty percent since 1950 (Boyce, Lewis, and Worm 2010; Schiermeier 2010). Boyce, Lewis, and Worm (2010) had aggregated data from various sources dating back to the end of the nineteenth century to calculate long-term regional and global trends. These data included many Secchi Disk measurements, as the Secchi Disk had been the standard method of measuring phytoplankton mass since around 1865, when such a plain white disk was first used by Angelo Secchi, an Italian astronomer working at the Pontificial Gregorian University (Wernand 2010). As Kirby explains, however, Secchi Disk readings have become much less frequent since around 1950 and this decline might pose problems for the analysis of the aggregated data:

> "The hundred years broke down into two fifty year periods over which phytoplankton was measured in different ways. For the first fifty

> years, there was older technology used and around fifty years ago, with the advent of new technology, scientists switched to measuring phytoplankton in a different way. With no thought, it was just a change in technology, as all methods advance. So the old method declined in popularity and the new method took over. So when you take a hundred years you have to cross-calibrate and some scientists said that the science could be flawed, because you were measuring abundance, the amount of phytoplankton, in two different ways; and lo and behold, roughly at the point at which the methods changed the authors claimed to see a decline in abundance and perhaps your analysis is compromised." (DR5834: 1)

Indeed, the findings were quickly questioned in several sceptical replies. Scientists from various oceanographic and marine biological institutes replied jointly and cited CPR data and other long-term time series which show no similarities with the global and regional declines (McQuatters-Gollop et al. 2011). Other scientists argued that blending data generated from two different methods of sampling introduced a strong negative bias (Mackas 2011) and that the long-term decline in global biomass 'is probably an artefact of sampling methodology' (Rykaczewski and Dunne 2011: E6).

The controversy sparked by the paper in *Nature* motivated Kirby to make an attempt to 'bring back the Secchi Disk in abundance' by encouraging sailors to measure the Secchi depth and submit the data to a centralised database. The database is hosted by a Plymouth-based independent consultancy company specialised on satellite and airborne earth observation data.[135] The SDS was launched in February 2013 without any official funding, as Kirby (DR5834: 6) explains:

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[135] The company conducts 'commercially focused scientific R&D' and offers consultancy services and data in the field of earth observation. In particular, the company is specialised in water, marine, coastal, urban, and land management; <http://www.pixalytics.com/> [accessed 22 March 2017].

> “The project is run in our spare time. We fund the project out of our own pockets. We pay for the server time, we do not have any funding for it, no university funding. We do it all in our spare time.”

The project had been maintained like this for the first three and a half years until in September 2016, The Secchi Disk Foundation became registered as a charity in order to collect sponsorship and donations.[136] The study is supposed to go on indefinitely so that the project’s data will eventually be comparable to the historical records. Kirby explains that this goal could be reached after “five to ten years, … maybe longer” (DR5834: 1–3).

The Secchi Disk is a fairly simple mechanical measuring device that is not overly complicated to use: It is a plain white disk with a diameter of thirty centimetres that is connected to a tape measure at the centre and has a little weight attached to its bottom. From the beginning of the SDS, participants were encouraged to build their own Secchi Disk from a piece of plywood or a lid of an old bucket and a tape measure of at least fifty metres length (Kirby 2016: 10).[137]

To measure the Secchi depth, participants lower the disk vertically from the side of their boat into the sea water until it disappears from sight. At this point, they need to record the length of the rope below the sea surface. The participants need to subtract the distance between their hand holding the tape and the sea surface from the the total extension of the tape. The SDS primarily targets sailors and fishermen with small boats who will be standing only a few metres above sea level when measuring the Secchi depth, so that the variation of this distance will be relatively small. The participants are instructed to measure only if the following conditions are met: The Secchi Disk needs to be clean, the participants should measure only between ten o’clock in the morning and two in the afternoon, the sky should not be all cloudy, the sun should be behind the person holding the disk, and the participants should not wear sunglasses.

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[136] The Whirlwind Charitable Trust is the only sponsor mentioned on the foundation’s website at the time of writing; <http://www.secchidiskfoundation.org/> [accessed 4 April 2017].

[137] By now, participants can also purchase a Secchi Disk from the project website for £25; <http://www.secchidisk.org/> [accessed 14 March 2017].

Additionally, the Secchi Disk should only be used in places where the seabed is not visible. Participants are further advised to carefully raise and lower the disk several times at the approximate Secchi depth to increase confidence in the reading.

These instructions are downloadable from the project's website and are also integrated with illustrations into the project's smartphone application.[138] The free Secchi app allows participants to store the recorded Secchi depth on the phone. Besides providing a simple way of recording, storing, and transmitting data, the Secchi app facilitates running the project and the database, as Kirby explains:

> "With smart phones, you can collect the data and have it submitted to a database with very little effort on the side of the scientist once the project is set up and running. You are not having to input data the whole time, you are not having to manage the database; it is self-managing, essentially." (DR5834: 1–2)

The database "literally does look like an Excel spreadsheet with latitude and longitude", Kirby explains (DR5834: 2). Every Secchi depth record that is submitted by a participant is automatically added to the previously submitted data. The app also allows users to record and submit additional data such as sea temperature in case their boat is equipped with a sea temperature sensor. If the sea surface looks unusual or interesting, for example from dead remains of phytoplankton drifting as foam on top of waves, users may submit pictures or add notes. However, the main parameter of interest is the Secchi depth:

> "Whilst people are at sea, we thought, if they take the Secchi depth, they might want to do some other measurements as well. […] There are some additional things, but they don't have to do those. To submit anything, they do have to take a Secchi Disk reading. We are not interested in the temperature without the Secchi depth. The Secchi depth is the one we are interested in." (DR5834: 2)

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[138] <http://www.secchidisk.org/> [accessed 14 March 2017].

The app thus provides additional opportunities for the participants to create data even if these are not required for participation and it is rather unlikely that they will be used. The geographic location at the time of entering the Secchi depth into the app is obtained from the phone's GPS receiver. The standardised GPS formate facilitates managing the data but using GPS also increases the quality of the data, as Kirby explains:

> "With the smart phone technology you can also improve the quality of the data and the provenance of the data. You can ensure that it was collected at sea, for example, because the smart phone can obtain the GPS location. The user does not input the latitude and longitude. That is obtained from satellite, so you know at least that the person was at sea and the data is not being submitted by someone sitting in their living room in Swindon who thinks I will just have a bit of fun with the scientists' database and make up some data and spoil it. Although you cannot ensure that sailors do not make up the data, you do at least know that it was collected at sea. So if someone is going to the bother of collecting data at sea, then probably they are going to be doing it as well as they possibly can." (DR5834: 1–2)

One of Kirby's key concerns is proving that the quality of the data created and submitted by SDS participants is not inferior to data created by scientists. He feels that the quality of data created by non-scientists is often questioned by professional researchers:

> "One of the questions that are often levelled at citizen science by scientists is 'How good is the data?' Can citizens be trusted to collect scientific data? Can they do science? Or is it going to be rubbish?" (DR5834: 2)

Automation and standardisation as implemented with the GPS system is one way to assure the quality and to prevent that the dataset may be corrupted. Any data that has not been submitted from the oceans can easily be filtered. It is further beneficial that the Secchi Disk is fairly simple to use. Nevertheless, the collaboration is based on trusting that the participants perform their part as well as they can. Kirby is firmly convinced that their effort is sufficient for the data to be usable:

> “While citizens might not understand the scientific process or they might not know how to set up an experiment with regard to controls, for example, I don’t see why they should be any poorer at taking simple data measurements than a scientist. If it is explained to them how to do it properly and especially if the community taking the measurements is interested in doing so, they would do it well.” (DR5834: 3)

Encouraging seafarers to build their own Secchi Disk facilitates running the project but is also a means to get people engaged with the project and its goals. Kirby comments on the effort of building a Secchi Disk:

> “If they go to that bother, we feel that it probably means they signed up and committed to the project and are likely to do it well. That brings a bit of loyalty, I guess, and intent to do it well.” (DR5834: 3)

Regarding the data quality and the reliability of the seafarers, Kirby further explains that many historical data which are now invaluable for climatologists have been created by citizens and amateur naturalists. These data are far from being ignored by scientists on the basis of the naturalists’ reliability (DR5834: 3). The comparison with already existing data from satellites, and in particular, looking for potential differences between data made by sailors and data made by scientists, will further increase the confidence:

> “We had a look at that correlation for data collected by scientists using Secchi Disks and satellites, and data collected by sailors using Secchi Disks and satellites, and the relationships are very good. They hold up and sailors are doing it as well as scientists would do it, which is not unsurprising because Secchi Disks are a very simple thing to use. It helps to give some confidence in the data.” (DR5834: 3)

Kirby expressed the intention to produce a scientific paper in the near future to demonstrate that the participants' engagement is worthwhile and that the data can be used by scientists. The paper would also benefit the participants' understanding of the scientific and the publishing process. In 2017, *PLoS ONE* published the research article with the "Secchi Disk Seafarers" credited as the main authors. Secchi depth measurements from the first four years of the SDS were assessed by comparing them to estimated chlorophyll data obtained from satellites. As stated in the paper, the comparison demonstrates the data's 'potential usefulness for expanding the historical Secchi Disk data to understand the effects of climate change on the oceans' phytoplankton' (Seafarers 2017).

With respect to potential benefits for the participating seafarers, Kirby explains that the sailing community has responded to the SDS with "overwhelming enthusiasm" and that participants are "incredibly appreciative and almost desperate to get engaged with the sea in an environmental or scientific way" (DR5834: 4). Although the project's growth has been sporadic, with bursts of new participants following coverage of the SDS in the press or online, the project counted circa two thousand active participants roughly two years after launch (DR5834: 4).

Obviously, sailors can only measure the Secchi depth when they are out on their boat. Seasonal behaviour or preferences for going to certain regions are thus reflected in the temporal and spatial distribution of submitted data. For example, many people will not use their boats at all in the winter or they will not sail to areas known for rough weather conditions at certain times of the year (DR5834: 5). As the project's online data browser shows, a vast majority of Secchi depths have been recorded in the Northern hemisphere and only few have been recorded in the open oceans during the first four years of the study.[139]

The data created by participating seafarers are never going to be evenly distributed, neither in space nor in time, nor are they going to be distributed randomly around the globe. However, a global distribution of the data is less

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[139] <http://www.playingwithdata.com/secchi-disk-project/> [accessed 22 March 2017].

important than the long-term outlook of the project. Additionally, the SDS may support knowledge on a local scale:

> “We encourage sailors, if they are not ocean going sailors but more day sailors, to set up a sampling location that they might go to every time they go out of their harbour and sail past a particular spot. They might set up a sampling location and take the Secchi depth there, because then if they can get weekly, or two-weekly, or monthly reading. Then those will build up over the year to give an indication of local changes as well.” (DR5834: 4)

Local knowledge may be useful for short-term oriented research in coastal oceanography or fisheries as the phytoplankton underpin the entire marine food chain (DR5834: 4). Increased local knowledge of the environment is also an educational benefit which may pass on from participants to the wider community, as Kirby suggests:

> “Knowing about your local environment also will hopefully bring in a sense of local knowledge. So people who are taking part in the project will start to understand their environment, they start talking about it amongst friends, it might get into schools … Who knows where the science might end up through outreach facility. It is difficult to know where the project will go in its entirety, although there are specific goals for it.” (DR5834: 4)

Yet, the main purpose of the SDS is long-term ecological monitoring in order to build a database that allows comparison with historical data. This long-term goal poses a major challenge and a risk of failure, because the data will only become relevant if the project is sustainable and if participants measure the Secchi depth for years and decades to come. This is why the project is set up to continue indefinitely and not as a one-off event. Kirby comments on this challenge and indicates that the long-term character of his project is in tension with the attitude of many potential participants towards epistemic processes:

> “I guess one of the hurdles to overcome is people wanting immediate justification for doing something. The main question that provoked the establishment of the project requires many years of data to collect. So you have to maintain interest in that time. You are not going to say, ‘Well, I would like to participate in that project for the next ten years’. It almost has got to be a hidden agenda of the project. Although all press articles about the project say what the goal of the project is to achieve, none of them explicitly say how long that will take to do.” (DR5834: 2–3)

Kirby has a strategy for initiating and maintaining interest which includes getting the study regularly into the news and into media oriented towards the sailing community.[140] Kirby further uses social media for posting updates about the project and informative pictures and videos of plankton research.[141] Merchandise such as shirts, beanies, and flags have been available since November 2016 and an “ambassador seafarer” participating in around-the-world sailing races advocates and represents the SDS. The SDS also makes itself known by providing marina and yacht clubs with free posters and leaflets.[142]

The project has managed to reach beyond the recreational sailing community as divers, independent fishermen, as well as school children with access to boats have contributed data (Kirby 2016: 11). Upon download of the Secchi app, a unique user ID is issued and participants may enter their boat’s name and send it along with the data into the database. Participants are thereby enabled to track the data they have personally recorded online. All data are viewable on an interactive map with spatial and temporal filter functions, and with the options to enter a user ID or a boat name.[143] However, the Secchi depth data are not downloadable as a whole set. Only participants of the project who have contributed data are granted access to the database, as Kirby explains: “If

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[140] The SDS was featured on BBC News and in the sailing magazines *Cruising Helmsman*, *California Diver Magazine*, and YachtsandYachting.com.

[141] <https://twitter.com/SecchiApp> [accessed 16 March 2017], <https://www.facebook.com/SecchiDisk> [accessed 16 March 2017].

[142] <http://www.secchidisk.org/> [accessed 16 March 2017].

[143] <http://www.playingwithdata.com/secchi-disk-project/> [accessed 4 April 2017].

you are a citizen scientist, a sailor, and you sent in one depth or ten depths, you can ask for the whole dataset if you wish" (DR5834: 6). External scientists may request the dataset but the SDS "reserves the right to charge for it", due to the project's funding situation (DR5834: 6).

At the time of interviewing Kirby, about two and a half years after the SDS had launched, there had been no data requests by scientists. However, Kirby explains that a number of scientists from a variety of oceanographic institutions had decided to join the project as participants:

> "We have quite a lot of institutes that have joined the project and are contributing their data. But that is not to get access to the whole dataset. We have got lots of institutes which see the value in the project and see that a database for Secchi depth data is a useful thing to have. It is their second store of their data they are collecting and if they are on board of their boat and have a smart phone they can send their data off and they can see the value of making the data bigger than their individual data." (DR5834: 7)

Scientists from a variety of institutions around the world have joined the SDS,[144] not as users, but also as participants, enhancing the value of their own data and increasing the heterogeneity among the Secchi Disk seafarers.

7.3 Collaboration in the CPR Survey

In contrast to the SDS, the CPR Survey is not known as a citizen science study and does not promote itself with that label. However, this chapter is not strictly about citizen science, it is about the involvement of non-scientists in epistemic processes. The shipping crews of the commercial ships and employees of the shipping companies and ports who are involved in realising a tow are indeed non-scientists, but they are also professionals who perform activities that contribute to science while they are practising their profession at sea or at the

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[144] Kirby mentions reputable institutions such as the Swedish Institute of Marine Science, the Stazione Zoologica in Naples, and the Ifremer in France. Scientists in Chile, South Africa, and the United States have also joined the SDS (DR5834: 7).

ports. Although being part of the global shipping industry, the CPR Survey regards the participants not as business partners but as volunteers working on ships of opportunity or ‘volunteer ships’.[145] This terminology resonates with collaborative epistemic practices in environmental sciences.

My empirical account of collaboration in the CPR Survey is divided in two parts. The first covers the process of “sourcing” a ship which encompasses finding and setting up a ship for towing CPRs in close collaboration with the seafarers. The second part reconstructs the activities performed routinely by seafarers after a ship has been sourced for regular towing. This includes the handling of the CPR by the shipping crews and the way they are instructed by the CPR Survey’s operations team.

7.3.1 “Sourcing” a ship of opportunity

The CPR Survey’s website and the 2015 annual report from SAHFOS list twenty-one ships that tow CPRs on a regular basis (SAHFOS 2016).[146] Almost 250 different ships from more than thirty nations have been towing since the beginning of the survey. Ships that have been involved are of diverse sizes and purposes: ‘weather, naval, hydrographic and research ships, ferries and a wide range of other merchant ships ranging in size from ~265 to 220,000 tonnes’ (Reid et al. 2003: 119). The survey seeks to continue its established routes to assure the continuity of their existing time series. Thus, whenever a shipping company or a ship owner decides to change a ship’s schedule, a new ship that continues the route needs to be found. Seven ship changes are mentioned in the annual report for 2015, which is considered a year with ‘many ship changes’ (SAHFOS 2016: 6). Two changes are just a switching of routes between two ships of one company due to ‘fleet rotation’ by the company, but in five cases, ships that have been towing CPRs for several years had to be replaced with new ships. (SAHFOS 2016: 6). The *Green Frost*, for instance, had been towing

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[145] <https://www.sahfos.ac.uk/about-us/our-network-of-ships/> [accessed 20 March 2017].

[146] <https://www.sahfos.ac.uk/about-us/our-network-of-ships/> [accessed 20 March 2017].

between Norway's North Cape and Svalbard on the survey's most northerly route since 2008, but came off charter because the cargo would be transported by aircraft in the future (DR1960: 4, SAHFOS 2016: 6).

Finding ships to participate in the CPR Survey "is never the problem", Camp tells me; "there are lots and lots of ships and crews, who are more than happy to do it for us" (DR2901: 11). This does not mean, however, that sourcing a new ship is a small task. The survey's operations team is responsible for maintaining the network of ships. Thomas has been employed by SAHFOS for twenty years, starting as an engineer and now coordinating operations and the survey's workshop. Thomas works alongside a recently hired Ships Liaison Officer and both have professional seafaring experience aboard ships of the Royal Air Force and the Royal Navy, respectively (DR1960: 1).[147] Thomas describes his responsibilities as follows:

> "My responsibilities are to make sure that SAHFOS has a volunteer fleet that will tow for us, that anything we send to that ship will be compliant, safe, and legal, that each ship will be supported by a volunteer network at that port, by the port-handlers […]. We make sure that all the sister surveys are serviced and that any equipment that leaves this door is set up correctly, fit for purpose, and helps us keep our ninety percent success rate, which we are quite proud of." (DR1960: 2)

Sourcing a ship begins with finding a ship that regularly travels on the route in question. The approach to this depends on the desired region, since the operations team can often utilise one of their established contacts to people in the shipping sector for finding ships in areas where the survey already operates, such as the North Sea or the English Channel. Thomas keeps a multi-page list of contacts to the shipping sector which he describes as one of the survey's "most valuable company assets" (DR1960: 8).

If a new region needs to be sourced, the operations team may start with *Lloyd's List* or the internet and "you start doing your research and you make some

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[147] <https://www.sahfos.ac.uk/about-us/staff/> [accessed 29 May 2017].

phone calls", Thomas explains (DR1960: 7–8).[148] In case of a replacement for the *Green Frost*, the company owning the *Green Frost* suggested a logistics firm which knew about a ship and provided the survey's operations team with a contact to the owner of the *Norbjorn* which later took over the route (DR1960: 8). When initiating contact, Thomas explains, it is important to "try and go as high up as you can" (DR1960: 3), which means it is best to talk with a ship's owner directly to ask for permission to tow:

> "We talk to someone as high as we can in that ship's management chain and even that can be quite a convoluted thing, because you have things like owners, charterers, owner operators, management companies and you have to find the right thread to get the permissions." (DR1960: 3)

The bigger and more complex the shipping company, the harder it can be to get a hold of someone on the highest level (DR1960: 3).

It is difficult to guess what the motivations of ship owners or companies are to collaborate with the CPR Survey. Thomas explains that an owner very rarely rejects a towing request. Some ships have taken the CPR as an opportunity for social media engagement, posting photos of lowering and hauling the CPRs. The installation of a CPR on the *AAL Melbourne* for towing in the Pacific was reported on the *Shipping and Marine Events* website. The ship's Managing Director indicates that it is almost an imperative for the shipping community to collaborate with ocean scientists:

> The Sir Alister Hardy Foundation for Ocean Science is one of the world's most respected marine science organisations and its work over the past eight decades has provided an irreplaceable resource and supply of information for ocean science. We are happy to support the Foundation's work through the deployment of a plankton

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[148] *Lloyd's List* is one of the world's leading and oldest maritime and shipping news journals providing information, analysis, and knowledge for the shipping community; <https://www.lloydslist.com/ll/static/about-us/> [accessed 1 June 2017].

> recorder on the AAL Melbourne, which is certainly fulfilling her brief as a multi-purpose vessel! Fittingly, the CPR device was installed on the AAL Melbourne on 25 June, which is the International Day of Seafarer. We at AAL strongly believe that the shipping community should work together with the scientific community, including such leading organisations as SAHFOS, in order to better understand and protect the health of our oceans.[149]

Thomas explains that there is no stock answer regarding the motivations of the participants in the CPR Survey:

> "We are talking about a hundred different individuals. Some of them do it because they are told to by their boss, some of them do it because they are really enthused." (DR1960: 14)

Convincing people on the highest possible level is thus also important because owners and managers have the power to command their employees to help making the collaboration work (DR1960: 3).

As soon as the owner of a ship is convinced of the scientific importance of the survey, that towing a CPR is safe and does not interfere with the normal ship's business, the survey's operations team receives permission to set the ship up for towing. At that moment, Thomas explains, it is important to keep the momentum and get in touch with the ship as quickly as possible:

> "Once you have made that contact and they say yes and give you permission, you have got to be enthusiastic all the time. […] The worst thing you could do is, 'yeah, we give you permission' and then you don't get back to them for about three weeks." (DR1960: 8)

In this regard, Thomas benefits from personal experience in working with volunteers alongside his employment at SAHFOS. This engagement was not related to science but has taught him that "enthusiasm is infectious" and that "talking to people with respect, understanding the demands on their time and

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[149] <http://snmevents.com/aal-melbourne-installs-cpr-onboard/> [accessed 2 June 2017].

how they can fit what you want them to do alongside" is a crucial element of working successfully with volunteers (DR1960: 1). Throughout our interview, Thomas emphasises how important it is to thank the volunteers for what they do and to not take anything for granted. This attitude remains crucial even after a shipping company or owner has given permission for a tow, because permissions and goodwill are still required from a wide range of other people for the tow to be realised. The ship's Captain is just as important as the owner, Thomas explains:

> "Don't forget the Captain. The Captain of these ships are kings of their ship. So the owner may give permission, the management companies, the charterers may give permission, but if the Captain says 'No, we can't do this', it can't happen."

The operations team needs permission from the Captain to bring any equipment on board, but in order to start towing, it also needs to figure out how the ship is going to tow, as Thomas explains:

> "None of the ships we use, apart from the research ships, are designed for towing at sea. Every type of ship you can imagine, big sailing ships, oil tankers, ferries, ROROs, the list goes on … So what we have to do is work out how they are going to tow." (DR1960: 3)

Thomas and his colleagues can only work out how a ship is going to tow on a personal visit to the ship. Each ship is different and requires a unique solution, Thomas emphasises. On some ships, even a custom davit needs to be installed, a crane-like device that holds the steel wire that is attached to the CPR. Alternatively, pulleys or blocks may be installed to hold the CPR. Whether the CPR is lowered over the back or one of the sides of the ship is not really important for the scientific use of the samples. As Thomas explains, the CPRs are normally pulled towards a low-pressure area in the wake of the ship, even if they are lowered into the water from the side. In this case, the crew must be particularly careful when hauling the CPR, as it can easily smash against the ship's hull and be damaged (DR1960: 11). The most important issues when searching for a suitable spot for the davit is to be sure that it provides enough clearance over the side of the ship,[150] that operating the CPR does not interfere with the ship's normal working procedures, and most importantly, that the towing does not interfere with any of the life boats or other safety-related devices. Thomas explains:

> "We have to be really really careful not to interfere with any of the safety gear. So when you go on board you have got to be knowledgable about this." (DR1960: 4)

Thomas goes on to explain that the best way to find a solution is to get the Captain or the Chief Officer of the ship involved in the decision-making:

> "What you are trying to do is get the Captain, or the Chief Officer if he delegates it to the Chief Officer. You are trying to say 'This is a good place for the davit', but you want those words to come out of their mouth. That is the psychology. So once they think it is their idea or they are involved with the decision-making, they are far more comfortable with it." (DR1960: 4–5).

Working out how a ship is going to tow is "one of those decisions that you don't want to make wholly on your own", says Thomas (DR1960: 10). The goal is to find a solution that satisfies the participants in particular: "If the ship's officer is happy, every one is happy" (DR1960: 10).

Again, seafaring experience and knowledge of maritime culture, conventions, and hierarchies aboard ships are favourable for the operations team when it comes to joint decision-making. Camp explains that the operations team's experience of working aboard ships "has been very beneficial" for the survey, because a person like Thomas "knows what it is like at sea" and "what [the crew members] go through", which makes it "easy to convince them that it is safe and it will all be fine" (DR2901: 11). Thomas explains another of his strategies:

> "The trick is to get the bosun involved, who is like the senior non-officer guy. He is in charge of the guys, he is like the foreman on

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[150] This can be an issue if a ship has a large sponson, an outward extension on the ship's hull to increase floating stability.

> board. He will have a good working relationship with the Captain. So if you get him on board, you know you are on a winner.” (DR1960: 3)

Thomas recalls from his work with volunteers what helps him to get people enthused:

> “That is all down to people skills and a little bit of grey hair helps when you speak to people, because you have a little bit of … a sense of maturity, you know. (DR1960: 1)

Thomas remembers his visit to the *Norbjorn*, which replaced the *Green Frost* for towing to Svalbard, and how shared interests with the Captain have helped him:

> “I went to Tromsø, I went to see the Captain and I hit it off with the Captain quite well. He was a similar age, I am into sailing and he is into sailing, so we had plenty to talk about. And we did all that sort of bantering and the normal stuff.” (DR1960: 8)

Installation of the davit or blocks requires cooperation with a local engineering company that is further requested to produce a risk assessment, save working practice, and methods statement (DR1960: 8). Engineers of the “friendly engineering companies”, as Thomas likes to call them (DR1960: 6), also examine the tow point on the ship every twelve months to certify it is still fit to be operated safely (DR1960: 9). SAHFOS’ status as a registered charity sometimes helped in negotiating the price of commissions such as welding a davit onto the deck of a ship (DR1960: 8).

The final important step of sourcing a ship is figuring out what Thomas calls the “final five hundred” (DR1960: 3). The CPRs are transported from the Laboratory in Plymouth to various ports by couriers or logistics companies. With the “final five hundred”, Thomas refers to the few hundred metres between the port’s security gates and the actual ship. He explains:

> “If you go to these big terminals, the big container ports, it is amazing that our yellow box gets moved free of charge from the security gate

> to arrive at the right ship at the right time and vice versa.” (DR1960: 3)

The CPR Survey relies on people to volunteer for transporting and looking after the yellow boxes containing CPRs which “pale into insignificance when you drive them around, compared to those masses of containers” (DR1960: 10). Thomas describes the setting at one port where several of the survey’s tow routes begin:

> “That’s Seaforth Docks at Liverpool and […] it is massive. […] And these containers — you drive around here in our little blue van and it is just like container city — it is scary stuff and the forklifts are whizzing by and it is a very, very busy place.” (DR1960: 5)

In Liverpool, the operations team is helped by two heavy cargo operators to whom the yellow boxes containing CPRs are personally addressed. The heavy cargo operators have made sure that SAHFOS as a charity is not charged for the transportation of the boxes inside the port’s security gates. They look after the boxes and delegate a forklift driver to bring them to the desired ship at the right time. Upon each visit to Liverpool, the operations team brings flowers or chocolate as a sign of gratitude for the cooperation (DR1960: 5). According to Thomas, the two heavy cargo operators deserve “a medal for citizen science, […] because they really do make it work for us up in Liverpool” (DR1960: 9).

The arrangements regarding the exact whereabouts of the yellow box at the ports are made when the operations team and the volunteers walk through the final five hundred, as Thomas explains:

> “Before we leave that port, it is actually walking back the final five hundred. ‘Okay, we can leave it here? […] Is it okay if the boxes get left here?’ ‘Yeah, that’s no problem.’ And actually, the boxes in Liverpool, when they come off the ship, it works like a well-oiled machine there. The forklift driver now detects these yellow boxes because they are quite easy to identify and they leave them by the

> public toilet in the docks. So all this world-class science, the meeting place is at the back of the public toilets." (DR1960: 8–9)

Thomas clarifies that there is a unique story like the one of Seaforth Docks for each port from which the survey operates. Every port, whether in the UK, across Europe, or on a different continent, has its own characteristics and features a group of people with whom the operations team is usually on first-name terms and keeps social relationships (DR1960: 5). Thomas emphasises that the CPR Survey does not take any of the cooperation for granted and that it is a circular chain of interactions that can break at any point:

> "What we are actually doing is managing this big volunteer army, or navy because we are seaborne. And we have got the ship's agents, we have got the owners, we have got the charterers, we have got stevedores, ship managers, forklift operators, terminal managers, heavy cargo operators, shipping line admin staff, friendly engineering companies, shore side fitters, and then of course the crew and all the chain of command on board. And it is a constant thing. If we go back to Liverpool, […] we have got the heavy cargo operators, who are on first-name terms with our friendly engineering company, who all know the terminal manager. So what I am trying to say is, if you upset that relationship with one, you have upset it with all three. So if that link, if that circle, is broken, it is broken." (DR1960: 6)

Thomas says that the team's success rate in sourcing ships is "good", but if a link to a specific company or ship gets actually broken, it is extremely difficult to get these people back into cooperating (DR1960: 7). Thomas remembers that SAHFOS happened to be rejected once after sending a person to source a ship in an overseas port who was more "scientific-based" than the members of the operations team:

> "He didn't take into account the safety gear aboard the ship and it got all out of hand and we were told to leave. And once that is gone, it is very difficult to get back into that company." (DR1960: 7)

Thomas describes the operations team as “the portal between the real world and the science world” and the team’s job often comes down to “managing scientists’ expectations” (DR1960: 7). SAHFOS has been running training courses for scientists who want to use a CPR or start their own CPR Survey. At these courses, Thomas feels that the scientists’ “number one aim is to collect plankton data in a specific area”. The operations team meets them with their own “working ethos”: “Our number one aim: ‘Don’t injure or kill anyone. Don’t lose the equipment. Collect the data.’ That’s our working ethos down here” (DR1960: 15–16).

7.3.2 Monthly towing and handling of CPRs

When sourcing a ship, a towing schedule needs to be worked out together with the ship. Naturally, the schedule for each ship depends on the schedules and business plans of the respective owner or shipping company. The operations team can thus plan and foresee the sampling dates and times only to a certain degree and short-term changes may occur. The CPR Survey manages to schedule one tow per month on most of its routes, but it is not possible to stipulate whether a sample will be taken during the day or at night. Day or night sampling has a profound impact on the types of organisms that will be retained by the silk. Some plankton species migrate vertically in the water in a daily cycle, as senior taxonomist Taylor explains:

> “We can see when things are in the night and when they are in the day. There are certain species that are night-time. […] It is called diel migration when they move up the column at night time. So in the night time you can get completely different species than in the daytime.” (DR8112: 8)

The *Pharos SG* completed six tows for more than two thousand nautical miles in 2015 in the South Atlantic Ocean (SAHFOS 2016: 13). The ship is a special case when it comes to scheduling tows, as Thomas explains:

> "This is the *Pharos SG* […] that tows for us from Falklands to South Georgia. It is a fisheries protection vessel, so they do it on their normal transits out to their patrol area and we are less able to request times because of the nature of its job, you know. It will have to go off and do patrolling work. They don't publicise that because obviously people they are trying to catch would go somewhere else." (DR1960: 4)

For each scheduled tow, the operations team sends out a tow request via email to the ship's Captain with a copy addressed to the Chief Officer who is running the ship's day-to-day business. Thomas emphasises here, too, that "you have got to get the language correct" (DR1960: 6). The letter is a polite request but English is often not the first language of the recipients, so it "cannot be too waffly, otherwise it gets lost" (DR1960: 6). The following is the wording from a letter for the Brittany Ferries ship *Armorique*, requesting a tow between Roscoff and Plymouth:

> Dear Commandant, Second Capitaine and Crew of ARMORIQUE,
>
> **We ask please that we can place Plankton recorder 192 on board the Armorique Tuesday 22nd September prior to your 22:00 departure.**
>
> May we take our blue van aboard to the stern mooring deck to do this, please?
>
> If this is agreeable:
>
> **On Wednesday 23rd Sept please tow plankton recorder 192 north bound, once only on the sailing from Roscoff to Plymouth.**[151]

Depending on the port, additional people whose cooperation is required will be notified for each upcoming tow. In a setting like Liverpool's Seaforth docks,

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[151] I received a copy of this request following one of my interviews (DR2901). Emphasis in original. It seems that for this tow, the operations team planned to come aboard with their van in order to bring the CPR aboard personally.

these are the terminal managers and heavy cargo operators who are involved in transporting and overseeing the CPR box inside the port's security areas.

For the transportation from Plymouth to the respective port, the operations team further needs to make sure that all the documentation is correct, especially if the CPR is going to a port outside of the UK. Thomas calls this aspect of his job "another part of our skill set, if you like. It is how to talk to customs people, how to make sure the customs documentation is correct the first time" (DR1960: 16). This can be more work depending on additional equipment being attached to the CPR, which may contain lithium ion batteries or specific chemicals. Thomas continues:

> "We will make sure that all the paperwork is right for the transport companies. And the goal is to get all that transport documentation right the first time, then there isn't a glitch. If there is a glitch in it, it holds things up. If it holds things up, you are screwed, because the ship won't wait for you." (DR1960: 17)

The logistics and the "well-oiled machine" (DR1960: 8) that brings yellow boxes to the right ship at the right time and back to Plymouth are running quite well. Thomas can remember only one instance where a yellow box got lost in the logistics chain. The box was loaded onto the wrong ship by a courier company, but as the ship subsequently sunk together with the CPR, there was no attempt at getting it back. Yet, Thomas keeps a tracking list of the location of each CPR at any one time and is prepared to "track [a CPR] down with a fever of a bloodhound, if you like, to keep on top of it" (DR1960: 16).

The tow request sent out to the Captain contains the desired date and location of the tow and in case of the exemplary letter to the *Armorique*, brief instructions to the crew about the handling of the CPR:

> The 90kgs recorder is lifted up by the winch drum then the wire paid out until the yellow tow mark settles in the sea. This gives the correct tow depth of 6 to 10 metres at your 19 knots.

> **Please avoid landing the tail on the bulwark**. After towing please place the recorder upright on the deck.[152]

As explained in chapter five, the towing speed and depth are important for the CPR's internal sampling mechanism and for the sample analysis. A steel wire marked for a certain speed is thus selected by the operations team and put into the yellow box with the CPR in order to have the CPR float at the right depth.

Together with the tow request, the Captain or Chief Officer also receive a tow log which they are requested to fill in during the tow.[153] The tow logs are usually filled in by whoever is the officer on the bridge during the tow. The logs are completed either on the computer or by hand and returned via email or printed and put into the yellow box with the CPR (DR1960: 13). Besides the name of the ship, its master, the route, the writer of the log and his or her rank, the log contains the internal cassette's number and information on the ship's position, which is to be logged by the officer at hourly intervals and if the ship changes course by more than five degrees. The log provides additional space for any other information or remarks regarding sea state or weather conditions that the officer might want to record (DR2901: 5).

As explained in chapter five, errors on the tow log are problematic to locate a tow geographically. In such cases, Thomas may have to reach out to the ship to clarify the ship's actual track:

> "If they forgot to put in an altered course and there is an island in between, it looks like we are collecting plankton up the High Street. So that is an obvious one and we would address that and get the accurate data back." (DR1960: 13)

Each ship of opportunity is provided with a twenty-page "Ship's Briefing Book" by which contains some background information on the purpose of the CPR Survey, how the recorders work, and what happens with the samples after they

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[152] Emphasis in original.

[153] I received a copy of an empty tow log after one of my interviews (DR2901).

return to Plymouth.[154] Most importantly, the briefing book contains a method statement and risk assessment regarding operation of the CPR by a ship's crew. The task of deploying and hauling a CPR is "relatively simple" and "relatively straightforward" (DR2901: 4) says Camp. The crew members are instructed to use, if possible, the ship's winch for lifting the CPR out of the yellow box. The steel wire that comes with the CPR has a yellow mark that needs to float on the sea surface.

The briefing book clarifies that 'deploying the CPR will not interfere with the normal ship's business' (DR1960). This means that the ship does not stop or slow down for the deployment or hauling of the CPR. The book further emphasises that the safety of the crew members is the "number one priority" during the tow. In case of rough weather that makes operating on deck unsafe, the CPR should not be deployed or hauled. Also, if fog or other circumstances require the ship to sail slower than five knots, the CPR should be hauled, as the CPR mechanism is not designed for towing speeds in that range.

The briefing book further contains instructions for changing the CPR's internal cassette, which is requested from crew members on some of the survey's longer routes. In these cases, the yellow box contains an additional case with a prepared internal. Crew members may also be asked to add extra preservative to the internal's storage tank after a tow has been completed. This is to make sure that the samples return in the best possible conditions, especially if the CPRs need to be shipped long ways from overseas ports. To add more formalin solution, crew members have to carefully remove the internal from the CPR body, open the tank lid, and empty a bottle with extra preservative into the chamber holding the silk roll (DR1960).

The crews are usually not instructed in these tasks directly by the operations team, as only the Captain or Chief Officer and the bosun are present when the ship is sourced. The briefing book is thus very clear and shows photographs for each step. It would hardly be possible to instruct all crew members directly, because almost every ship has at least two crews, as Thomas explains:

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[154] I have received an electronic version of the briefing book at one of my interview visits (DR1960).

> "There is always a watering down and that is just a fact of life. And every ship almost will have an A crew and a B crew, and certainly the officers are so many months on and so many months off. You are only going to see one on that initial visit. So that is why this has to be well detailed." (DR1960: 12)

Thomas further explains that the personal communication via email is also kept up to maintain the relationships and be able to solve any concerns or questions quickly. However, the operations team occasionally travels to the ships for what Thomas calls "good will visits" (DR1960: 9). A team member tries to visit each ship at least once every three years to express gratitude and to keep the crew up to date. Camp says that the survey's representative "would chat to them and check if there have been any updates or new information they need" (DR2901: 4). On these visits, the operations team also brings little presents like a box of chocolates and is determined to "never turn down hospitality", as Thomas explains, even if that means being invited to multiple meals in the course of one morning (DR1960: 15).

Neither the shipping companies nor ship owners are paid for towing CPRs. However, £60 per tow are awarded directly to the bosun and the crew. Camp says "it is only like either beer money, or maybe for their television fund, or whatever else they might want to spend it on" (DR2901: 11). Thomas tells me that one ship decided to save the money all up and take the crew on a skiing trip at the end of the year. Each ship is an individual case, even when it comes to transferring the £60 for the crew, as Thomas explains:

> "There is no one answer to [how the money is transferred]. Some shipping companies would not even accept it. They would donate to charity. For some, once you have made the offer, it is very important to them, depending on the parts of the world and the nationality of the crews it is more important or less important. Some want it every time, so you pay every month. Some will set it up with their shore side admin staff, so they send us an invoice every quarter, or every six months, and they do it that way to keep the admin down." (DR1960: 6)

I could not research the specific motivations of shipping companies and ships of opportunity for collaborating with the CPR Survey. The above quote indicates, however, that the motivations to collaborate might be as diverse and culturally shaped as the ways in which the companies and ships handle the small monetary compensation.

Thomas says that the good will visits, as well as the initial visits for sourcing a ship, are a fun part of his job, although they "can be really late night working" with "a lot of hanging around, if you like" (DR1960: 10). The trips to various ports and ships are crucial to maintain the network of volunteer ships, even if a visit may not be very long:

> "You go and see people and I am always conscious that I am taking up their time. So I will be 'Thank you very much for the work you do. You want to come out for lunch with us?' 'No I am a bit busy today.' 'Okay mate, if you are ever down in Plymouth, come and look us up.' And then you get out of his way. […] But that short conversation, it will be a little bit longer than that, is invaluable." (DR1960: 10)

Maintaining social relationships, visiting various ports, ships, and people, and finding unique solutions for each ship make the job of the operations and workshop team quite diverse. Additionally, the team runs training courses, writes tow schedules, it maintains, repairs, and prepares CPRs for deployment, and supports the sister CPR surveys around the world. Thomas explains:

> "That is one of the reasons I stayed here for twenty years, because even though you think running the CPR Survey is much of the same … There is so much variation, to be honest." (DR1960: 2)

The variation in Thomas' job reflects the previous chapters' finding regarding the dynamics of long-term practices: The CPR Survey is not repetitious, but permanently adjusts to changing conditions. The conditions set by the shipping sector and maritime culture were left out of chapter six, but have a profound influence on the ways in which the CPR Survey is conducted.

7.4 The agency and epistemic contributions of non-scientists

My description of the involvement of non-scientists in the SDS and the CPR Survey has revealed a variety of relationships and interactions between scientists, staff of scientific institutions, and non-scientists. In my analysis, I first compare some of the characteristics of the two cases and discuss them as “contributory” or “investigation” type projects. I call this a “mechanistic” understanding of participation in order to emphasise the role of participants as deployable tools for the collection of objects or data which are subsequently analysed by scientists. I then provide strong arguments for an alternative view that is intended to emphasise the individual agency of volunteer participants in collaborative scientific projects.

7.4.1 Non-scientists as a platform for data collection?

The two cases presented in this chapter have several aspects in common: For a start, both are rooted in specific research problems and were conceived and designed by scientists. The CPR Survey was initiated by a fisheries ecologist and has expanded over decades into a multi-purpose measuring platform to address the research interests of scientists and alleviate data scarcity. The idea for the SDS arose in response to a controversy regarding the comparability of data obtained by different sampling methods and multiple decades apart. Both projects were initiated and are managed by scientists or scientific institutions and can thus be regarded as structured “top down”. Further, in both cases the participants need to follow tight instructions for the projects to be successful. These instructions are not designed or developed in cooperation with the participants.

A way to understand this type of participation is what I call a “mechanistic” view of collaborative practice: The participants appear to be the executing component of a sampling system or machinery. Once acquired, set up with equipment, and instructed, they follow instructions like a programmed device, albeit with slightly different tasks. In the SDS, participants perform sampling, quantification, data creation, and activate transmission to a central database, while the metadata for each measurement are produced automatically via GPS reading. In the CPR Survey, participants handle the sampling device, provide for the transportation of the device in certain areas like a “well-oiled machine” (DR1960: 8), begin and end the sampling process, and record metadata in prepared sheets. The scientific product of the SDS is a quantity that becomes part of a growing dataset which scientists can analyse. In the CPR study, the product is a material object that is analysed by scientists under microscopes. The participants’ epistemic contribution appears to amount to the production of objects or data while the interpretation happens elsewhere. The projects share these characteristics with “contributory” or “investigation” type projects specified by Bonney et al. (2009) and Wiggins and Crowston (2011) who emphasise the role of participants as data collectors for projects structured and managed “top down”. The mechanistic view of participation is based on an understanding of participants’ involvement in a technical sense. They serve as an observation or sampling platform that can be deployed by scientists to produce or collect data or samples which scientists subsequently analyse and interpret. The term “platform” used by Brewin et al. (2015: 1) to refer to collaborative projects fits well with this mechanistic understanding of participation.

One could argue that the silk rolls and the transmitted Secchi depth data are the primary outputs of the respective collaborative practices. From the scientists’ perspective and with respect to the respective epistemic process they certainly are the most relevant result. The silk rolls and Secchi depth data have neither integrated nor contain any personal or local knowledge of the participants, in contrast to the sea turtle monitoring case studied Cornwell and Campbell (2012) where the volunteers’ local knowledge of the beaches is crucial for decisions taken by the scientists. In my cases, data or the objects that become interesting for the scientists are not derived directly from the participants’ personal knowledge or experience related to their local environment. This does not mean that local knowledge is unimportant, as the CPR Survey clearly demonstrates: As each ship and each port has unique characteristics and calls for unique solutions, local knowledge of these places and their characteristics is crucial. Yet, this knowledge is not what the scientists are interested in. The lack of contributed personal or local knowledge to the actual object of interest may be regarded as another argument for a mechanistic view of participation in which the participants only need to function well enough to collect usable data or samples for the scientists.

Another argument could be made in relation to the educational benefit for the participants. Besides limited background information on plankton and the research processes provided through the Secchi app and the CPR Survey's briefing book, education of participants is not formally embedded in the two projects. The participation might increase environmental awareness and make non-scientists familiar with scientific equipment, but the overall educational dimension of collaboration in science is an empirical question that is difficult to assess and goes beyond the purpose of this study.[155] Yet, resonating with the division of labour in data-intensive sciences, it appears that seafarers assume the role of data producers or sample producers, while the actual knowledge inferred from data or sample analysis is generated and stays within the scientific domain.

The mechanistic view of seafarers and volunteers as a platform for data collection situates the SDS and the CPR Survey closely to collaborative practices of the environmental sciences which have been described as primarily contributory or investigative. In these, the participants function as collectors of materials or data and as a platform scientists can utilise for their epistemic purposes. Lacking individual agency, the participants are instructed and directed "from the top" and perform their tasks solely on the scientists' terms.

7.4.2 Enabling sampling conditions on the participants' terms

In the previous section, I applied an interpretive lens that slightly overreaches. In light of my empirical research and in contrast to the mechanistic view of participation, I argue for a view that recognises and highlights the individual

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[155] An ethnographic study by Crall et al. (2013) shows how difficult it is to measure the science education effect, despite registering a 'modest change in knowledge and attitudes' among participants of an invasive species citizen project (Crall et al. 2013: 1).

agency and epistemic contributions of the seafarers and volunteers. This view is grounded in the discovery of strong social dimensions in my case studies. These are most evident in the CPR Survey, where personal communication, an understanding of maritime culture, regular good will visits, and signs of gratitude through small gifts are required to be able to conduct the survey at all. Even if the communication happens electronically via email and not face-to-face, the communication remains personally addressed and on first name terms. While these almost intimate terms cannot be found in the SDS, much of the project's regular activities appeal to the social side of participation. The project is active on social media, sells merchandise, and has involved an ambassador in order to build a global movement in support of plankton science that seafarers can identify with. The fact that collaborations between human beings feature a social dimension may sound like a truism. However, the significance of this dimension and the reliance on trust between scientists and non-scientists for a successful cooperation in both cases can hardly be overstated and strongly contradict with the view of participants as mechanical collectors who merely follow instructions.

Whereas local knowledge of the participants is not integrated into the objects resulting from the collaboration, the significance of local knowledge and its social aspects in the CPR Survey cannot be denied. To figure out how a tow may be realised, local knowledge of individual ships and port sites is required and generated together by the operations team and various participants. This joint generation and exchange of knowledge, concluded by joint decision-making, is where non-scientists make crucial individual contributions that enable the sampling process. These contributions are not material samples or data, but personal arrangements, local knowledge, and practical solutions, which enable the creation of samples in the first place.

Another contribution by the non-scientists becomes visible when considering knowledge as either propositional or embodied:[156] While propositional knowledge of the oceans or specific regions of the sea plays a minor role, the

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[156] Propositional knowledge is here understood as “knowledge-that”, referring to knowing that a proposition is true. Embodied knowledge is understood as “knowledge-how”, referring to knowing how to do something (Fantl 2016).

participants make use of their embodied knowledge related to seafaring when interacting with the sea and when performing their volunteer task for the scientific project. They manage to navigate their vessels on the oceans and are capable of handling heavy steel devices like the CPR routinely. They do this in unique settings either on their personal ships or on container ships and ferries which have been customised for towing CPRs. Non-scientists thus contribute to science their very specific embodied knowledge related to seafaring, which encompasses skills and knowledge that the majority of citizens and the public, and probably most ocean scientists, lack.

The motivations of the participants have not been studied empirically for this project but the scientists I have interviewed insinuated that most participants take pleasure in sampling, as it may come as a welcome relief from daily routines aboard ships. Additionally, many seafarers have a passionate relationship to the sea and experience a lifelong connectedness to it. This connection is expressed in recreational sailing or surfing but may also originate in a profession as fisherman or aboard commercial ships. Cornwell and Campbell (2012: 112) explain in relation to their case of co-productive sea turtle conservation that ‘an emotional bond’ between participants and the research target underpins the participants’ goals and agency. Such relationships may serve as motivation and likely affect the effort of volunteers to perform the sampling as well as they can.

Both the SDS and the CPR Survey show that human agency introduces certain degrees of unpredictability and an inability to fully control the sampling. This also speaks against a mechanistic view of participation in which tasks are performed reliably in the exact same way each and every time.[157] In the SDS, due to the seasonal behaviour and regional preferences of the participants, the scientists cannot plan or predict when and where participants will measure the Secchi depth. Sailors and fishermen decide when they want to go where based on numerous variables and even if a seafarer is out on the oceans at the right

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[157] Machines are certainly not exempt from making mistakes or being imprecise but I am thinking here of machines used in mass production of goods on industrial scales which requires the repeated performance of tasks with very little or no variation at all.

time of the day, weather conditions, other activities on board, or personal mood might prevent a participant from sampling or cause him or her to forget about it. In the CPR Survey, deployments are pre-arranged and communicated between the operations team and the ships of opportunity, but the ship's normal business always takes priority. A ship of opportunity will not wait for a CPR or may not even disclose its schedule, as in case of the *Pharos SG*. Additionally, there can always be unplanned course alterations, rough weather that may slow down a ship or obstruct sampling altogether. The CPR Survey can neither control if sampling happens at day or at night, which affects the outcome of the sampling significantly. Moreover, CPRs can only be towed in regions frequented regularly by commercial ships. In both the CPR Survey and the SDS, the spatial and temporal distribution of the sampling is far from random or homogeneous: The distribution depends on the agency of the sailors, fishermen, divers, and commercial shipping companies, as well as on environmental and economical factors. I thus argue that the individual agency of participants is fundamental for making sampling possible and that the volunteers' embeddedness in their environment shapes how, when, and where sampling may be performed.

To be clear, the unpredictability and limited control in both cases do not make this practice illegitimate or less scientific than any non-collaborative scientific endeavours. Nothing indicates in the SDS that the sailors perform the sampling worse or less reliably than scientists. Potential mistakes and variation in the consistency of performing a task are normal for non-scientists as well as for scientists. Both projects have implemented or experiment with the implementation of functions such as automated GPS reading to lower the risk of errors. These developments reflect the belief that new technologies may play an important role in participatory practices with respect to the quality of the outcome.

Yet, many tasks are still performed without the possibility to control what the participants are doing exactly and under which conditions. In case of the SDS, it is not possible to know how consistent the participants are in judging when exactly they lose sight of the disk, which may also depend on the participants' vision, their ability to distinguish colours or whether or not they remember to remove their sunglasses. Both of my cases mainly rely on trusting that the participants follow the instructions faithfully as well as they can and that they perform their task well enough so that the data and samples are usable. This is one reason why building trust through social relationships is so important; the relationships also function as feedback loops through which issues and questions can be resolved so that the sampling can be performed more consistently. On the one hand, individual agency is a source of the “watering down” when it comes to instructing people to follow a certain method. As Thomas remarked, the watering down is a “fact of life” which happens in any scientific and non-scientific context (DR1960: 12). On the other hand, individual agency is the source of embodied knowledge, local expertise, social relationships and trust, which are crucial in the two cases studied for this chapter.

Individual agency implies individual relations to a local context which constitute an embeddedness of the participants in their environment. This embeddedness entails their specific relations to certain regions of the oceans, their nationalities, their passion for the seas or its organisms, as well as seasonal and economical fluctuations of their interaction with the research target. The activities performed by recreational and professional seafarers, as well as by employees of ports and shipping companies, are always subordinate to their regular duties and to their profession’s structure and hierarchies. The volunteers remain firmly embedded in their local context, even while performing an activity that is part of a research process. Neither SDS nor CPR Survey participants are likely to take their boats or commercial ships and sail the seas just to measure the Secchi depth or tow a CPR through the ocean. It may sound trivial but the fact that the volunteers only sample when interacting with the oceans anyway reflects their embeddedness in their local environment.

Rather than “collecting” objects or data, I characterise the contribution of the volunteers as the “enabling of sampling conditions” and as an epistemic activity in its own right. Sampling of the oceans is only possible because of the fact that seafarers are out on the oceans on a more or less regular basis. My research illustrates how the enabling is achieved: As I have discussed here, much of this epistemic activity is rooted in the individual agency of the participants who scientists or staff of scientific institutions need to get involved with. Rather than being sampling tools that are deployed and function in the name of science, the seafarers are part of the setting or the environment that scientists need to reach out to in order to create knowledge. I discussed in chapter three that ocean scientists are required to reach out and explore the oceans. Surfers, seafarers, and the shipping sector are inextricable part of this environment. Considering the seafarers as part of the setting is not to degrade them or assign them a passive role in the epistemic process but to emphasises their embeddedness in the local context to which any scientific activity is subordinate. The CPR Survey needs employees with seafaring experience and certain “people skills” in order to approach the maritime world and culture and make the collaboration successful. The operations team frequently embarks on field expeditions into this world to explore, establish, and maintain unique solutions for each ship and port, not to despatch participants as parts of a standardised collecting machinery.

The enabling of sampling conditions happens on the participants’ terms because their specific embeddedness determines when, where, and how sampling is made possible. By contrast, the sampling itself is performed partly on the scientists’ terms, because scientists conceive the collaboration and provide the instructions and equipment, and partly on the participants’ terms, because they are the ones who interpret and follow the instructions. Their individual agency introduces natural variability and unpredictability into the sampling process.

My view of collaboration between scientists and non-scientists resonates with the co-productive view of participation as an “emergent” practice (Chilvers and Kearnes 2016a). Several crucial elements of collaborative practice are not determined solely by either of the involved groups of actors. Both the scientific products and any non-scientific outcome emerge in jointly delineated but unpredictable ways. Their emergence may be likened to the integration of materials at the intersections between sampling technology and the natural world that I conceptualised as material integration in chapter four. Samples, data, and the various ways in which they may figure in epistemic processes constitute the scientific products of collaboration. The non-scientific outcomes encompass local knowledge, personal relationships, educational benefits for society, or pleasure. The identities of those who are involved in the collaborative practices are shaped by all of these outcomes — the seafarers' by the outcomes I have described as non-scientific, the scientists' primarily but not exclusively by the scientific products.

7.5 Conclusion

The involvement of people without scientific credentials or affiliations in epistemic processes, in particular in the environmental sciences, has often been thought and conceptualised as that of collectors of materials or data which scientists can analyse. This understanding suggests a picture of participants in such projects as mechanical parts or extensions of a sampling system that is conceived, directed, and despatched by scientists. My empirical study of practices in ocean sciences suggests a contrasting view that is grounded in an understanding of science as a social endeavour. This understanding is firmly substantiated by this chapter's empirical accounts of collaborative practices in ocean sciences.

My view accounts for the non-scientists' individual agency and their epistemological contribution in the enabling of sampling conditions on their own terms. The contribution manifests itself to a lesser extent in propositional knowledge but rather in using embodied knowledge and skills related to seafaring, local knowledge of ports and ships, and the application of scientific equipment. When volunteers participate in science, they remain embedded in their local context and in their roles as recreational or professional seafarers. The outcomes of collaborations are not pre-determined by scientists by virtue of designing equipment, methodologies, and research questions. Instead of merely collecting and supplying science with materials or data, volunteers and scientists co-produce scientific products such as samples and data as well as outcomes related to the non-scientific domain which have the potential to shape the identities of every individual involved.

In both cases that I have studied, a layer of social relationships and correspondence is required to maintain the network of volunteers and to ensure that the sampling maintains its spatial and temporal regularity over multiple decades. In case of the CPR Survey, the social continuity is an indispensable part of these data practices and underpins the practices' material and methodological continuity. Similar to the methodological continuity discussed in the previous chapter and the material interactions discussed in chapter four, a variety of factors and changing conditions are beyond the researcher's control but decisively shape the actual outcomes of collaborations.

Chapter Eight – Conclusion: Continuities, change, and agency in oceanographic data practices

This thesis set out to study the genesis of oceanographic data in an empirical case study of scientific practices, their conditions, and their outcomes. The four empirical chapters that are based on ethnographic interviews and visits of research sites converge towards a complex picture of activities, people, and processes that constitute dynamic changes and continuities in-between a natural system and science. This assemblage extends to various domains beyond the control and the traditional boundaries of scientific institutions.

Chapter four highlighted a variety of physical interactions between the sampling technology and the oceanic ecosystem and reveals how these processes beyond the scientists' grasp shape the characteristics of the research samples. While chapter five focused on the manipulation of samples and the implications of certain counting procedures that are involved in creating data in the lab, chapter six exposed how external conditions and historical change influence the practices of sampling and data creation. Chapter seven discussed how scientific and maritime cultures meet in research collaborations in which the agencies of both scientists and non-scientists contribute to the research outcome.

In my introduction, I created room for a philosophical account of the practices, processes, and people in-between science and the natural world. This conceptual space gradually filled in the course of this thesis with material, methodological, and social continuities, but also with series of traceable transformations performed on newly generated scientific data. I have shown how these continuities interweave: The material continuity that connects data and samples with the ocean ecosystems is crossed by methodological continuity between newly generated data and data of the past. Both of these continuities are underpinned by the social continuities between the scientific and the maritime world. Within this layer of practices and people, traceable journeys of data from hand-written records to digital databases and beyond are securely embedded. Like the silk that is used for sampling, the data practices of the CPR Survey are flexible, but strong enough not to distort too much or come apart. The survey assimilates historical changes of context, technological innovations, shifting interests of scientists, funders, and the public, and a host of uncertainties and foibles due to the survey's material sampling and semi-quantitative counting procedures. By virtue of these continuities and their flexibility, the survey's data practices are consistent and have generated continuously for multiple decades a consistent body of meaningful data relating to a natural system as vast and inaccessible as the ocean's ecosystems. This is how continuity, an absence of jumps, and change, an alteration of a thing in time, coexist in scientific practices and mesh in a generative way.

A key to this picture emerged in chapter six, where it became clear in relation to Caporael, Griesemer, and Wimsatt's (2014a) scaffolding framework that development and maintenance are two sides of the same coin. One cannot exist without the other in certain cultural practices, including scientific enterprises with relatively long timelines, as my thesis has revealed. The material, methodological, and social continuities neither constitute an absence of change nor relate to nostalgia or traditionalism. They are the result of dynamic activity, change, and innovation.

This integrated picture drawn from my thesis' main chapters converges with existing philosophical and sociological scholarship by demonstrating that research practices are performed in specific technological, historical, and socio-economic settings. My thesis spells out what that means: Neither are scientists able to freely design their research practices nor are they in a position to independently decide on the context and content of their research. As explained in chapter seven, the CPR Survey has to accommodate and actively reach out to the seafaring culture, maritime conventions, and the shipping business. The cooperation with volunteers constitutes a co-production in which both sides perform epistemic activities on their own terms. In chapter six, I explained how the survey accommodates the interests of other researchers, funding agencies, and the public by expanding their scientific repertoire and modifying their data ontology. The chapter also discussed how the survey is forced to react to technological progress and innovations by conducting experimental research and at times even modifying the designs of research instruments. This shows that the agency of researchers in creating knowledge of a natural system like the oceans is limited and constrained by a variety of external factors and processes that can be unpredictable. A good example of this is how funding for long-standing marine ecological practices was phased down in the 1980s, yet not much later, climate change made these rather “old-fashioned”, manual practices highly relevant again and pushed researchers towards developing a shared scientific repertoire.

Another quite obvious example of the researcher’s limited agency in the data practices I have researched is the fact that scientists hand over the control of research technologies and the entire sampling procedure to non-scientific actors, as explained in chapters four and seven. This is a significant fact considering the epistemological implications of the material integration that takes place during sampling. After all, the silk samples that result from material integration and continuity are the foundation of the CPR Survey’s entire research programme. As in other examples of data-intensive science, this is an instance of collaborative knowledge production and division of labour in which epistemologically relevant actions and agency are spread among many different actors, including scientists and a variety of non-scientists.

It seems that the laboratory, where in my case taxonomists create the plankton data by microscopic analysis, is the environment where scientists can fully exert their agency. As explained in chapter five, the sample analysis and data creation are a series of intended and largely controlled changes or transformations that gradually expand the scope of data. However, even in this setting, constraints are ubiquitous: Taxonomists have to deal with the result of a material integration that can be surprising or difficult to analyse. The identification of species can only be performed to certain levels of detail due to the flow of returning samples and the limited capacities of the lab. Further, the sample analysts rely on instruments and lists of taxonomic entities that set limits to the scope and depth of the analysis. Most importantly, these limits are deeply entrenched due to the legacy of the survey and the high value of methodological continuity.

Limited agency does not mean passivity. To the contrary, my account of oceanographic data in the making emphasises the interventionist character of data practices. The data of the CPR Survey, as well as the material samples, are the result of formation processes that are induced by intentional intervention: by reaching out to actors that already frequent the object of study, by lowering sampling devices into the ocean, and by applying microscopic analysis practices, semi-quantitative counting procedures, and spatial and temporal averaging. Tracking these interventions in the course of making scientific data reinforces the notion of artificiality that I introduced in chapter one. In this view, data are not collected. The view of data as a resource from which scientists can collect items effortlessly is a partial perspective centred on databases that are already filled with data. As I argued in chapter seven, even the seafarers who volunteer to create data contribute their skills and knowledge and engage in co-producing novel research objects together with scientists rather than "collecting nature" (Strasser 2012a) only by using research instruments.

The notion of "collecting" data is not the only concept that my thesis puts into a critical perspective. Chapters four and five contribute to a deeper philosophical understanding of materiality and scientific representation. My account of sampling in chapter four exemplifies materiality as an ongoing process — a duality of integration and continuity — that results in an effect of physical boundaries and tangibility that is maintained and traceable in order to be useful for the creation of data. The attribution "material" indicates more than just an ontological state. It encompasses, as Woolgar and Lezaun (2013: 326) have pointed out, an "upshot" of certain practices. In these practices and in the materiality they constitute, I locate the epistemic value of samples.

Today's primacy of data, which is often reflected in scholarship on data-centric sciences and tends to take the global availability of data in digital databases as a starting point, might obscure the material origins and the genesis of data. In particular, conceiving data as direct representations of natural phenomena bypasses the material practices and the actual reason for the data's epistemic value. Chapter five argues for a view of scientific representing that unties data from natural phenomena and makes room for a context-dependent conception of data and representation. My account emphasises the intentionality of representing which is often aimed at increasing the scope of data by making them computable, comparable, and integrable with already existing representations. In this view, masses of data aggregated in digital databases are anything but pure and uninterpreted representations of real-world phenomena. Digital data are objects that are forged intentionally in specific ways in order to fit with already existing standards and views of the world.

My thesis' re-framing of materiality and representing points to philosophical issues that have not disappeared in the course of the data-centric reconfigurations of research practices. As I suggested in my introduction, how to observe, represent, and understand the natural world are still fundamental questions in all environmental sciences. The ways in which ocean scientists in my case study create samples and useful scientific data reinforces Bogen and Woodward's (1988) argument that scientists cannot observe natural phenomena in a straightforward sense. The ecosystems of the world's oceans are unobservable to humans, but researchers have developed ways of implementing and sustaining material, methodological, and social continuities in order to create objects that researchers can use as starting points for scientific reasoning.

The question if data will eventually represent real-world systems or not relates — as almost everything else in philosophy of science (Chakravartty 2017) — to debates about scientific realism. Books could be filled with philosophical discussions on the realism of the phenomena and processes that oceanographers describe and explain with their data. To say that the oceans' ecosystems are unobservable would probably irritate many ocean scientists who might spend entire careers trying to record data relating to the oceans. To a marine ecologist, a bucket of sea floor mud and organisms under a microscope are certainly real. On the basis of my thesis, and in relation to Hacking's (1983) realism about practices of intervention and manipulation, I can only suggest that the reality of the oceans is manifest in the material practices of the ocean scientists, regardless of the relation between the outcome of these practices and the real-world system. In the picture outlined above, the material, methodological, and social continuities that interweave in the layer between science and the world are real. They consist of interactions with the oceans, research instruments, and people. Scientific knowledge and human understanding of the natural world grows by sustaining and developing these continuities that are the reality of oceanographic practices.

In my main case study, the CPR Survey, the material, methodological, and social dimensions of data practices are particularly pronounced: The survey's various manual practices, the individual handling and storage of samples, the mechanical functioning of the plankton recorder, and the close relationships to seafarers expose the continuities of the survey's data practices. In many other oceanographic practices, especially those with high levels of automation, these practices and relations might be hidden in black boxes, obscured by high-volume technologies and autonomously working systems. I do not claim that my thesis' picture of the genesis of oceanographic data reflects the entirety of oceanographic research practices. Yet, the practices in my case study exemplify the data scarcity, data-centrism, collaborative research, and the ties with maritime culture that I found characteristic of ocean sciences in chapter three.

However, a specific terminology and self-perception associated with exploration and discovery seems to be at odds with my account of data practices that emphasises the creation of novel objects upon intervention and interaction. Sociological and historical research could shed more light on this question. My own research suggests that scientists are less free to explore and discover, but rather bound in the context of their research where they balance the constraints related to continuities and change. Yet, I have argued that oceanographers are required to actively reach out beyond the scientific domain and induce various interactions between materials and people. Figuring out the material details of the sampling and finding ways to make huge container ships tow sampling devices requires active exploration not of the natural world, but of research settings involving marine organisms, technologies, and people.

Even in doing a detailed local case study of research practices, my thesis reached certain limits. These, however, offer some promising research opportunities. As this thesis is about the genesis of oceanographic data, I have hardly considered concrete use cases of CPR data. In relation to the portability of data and Leonelli's (2016) notion of data journeys, finding out how and in which research contexts the plankton data are used for scientific reasoning would be an obvious way to follow up my research. How and why some data are integrated or compared with certain other data becomes easier to understand with knowledge of the data's genesis, of their semi-quantitative nature, and their respective relations to real-world systems and material samples. Additionally, the notion of continuities, which underpin the creation and transformations of data as they are moved between different contexts, could add an interesting perspective on data journeys and further illuminate what factors facilitate or impede such journeys.

The CPR Survey is also an intriguing case for empirical research with respect to the ability or inability to automate epistemic processes. I was not able to discuss the potential to automate practices of the CPR Survey within this thesis, although I talked about this topic with some of my interviewees. Leonelli (2014b) expresses scepticism regarding the ability to fully automate epistemic processes, in particular with respect to data analysis and scientific discovery. Ribes and Jackson (2013) emphasise that automated data technologies tend to obscure the care and labour by humans that are required to build and sustain functioning data infrastructures. My case study exemplifies how important personal experience, local expertise, social relations, and manual, hands-on practices are in the creation of scientific data. It seems unlikely that any of these capacities could be replaced by robots in the foreseeable future. Yet, as other data-intensive sciences, ocean sciences embrace highly automated, remote technologies (Lehman 2017). My case indicates that some ocean scientists are actually caught in a tension between manual practices with a historical and methodological legacy and the pressure to use new technologies and produce more data at lower costs. In this scenario, new technologies complement rather than replace long-standing practices.

Another promising avenue for further philosophical research relates to the way that the CPR Survey has incorporated microplastics into its taxonomic identification practice. As already suggested in chapter six, this inclusion of a non-biological entity in the survey's list of taxonomic entities can be seen as a bold move. Yet, it is reasonable from the perspective of the survey's data practices and illustrates how anthropogenic impacts on natural systems become inscribed in scientists' ontologies and thereby shape our understanding of the world. Oceanographers, climatologists, and researchers of biodiversity already know that their scientific objects are subject to anthropogenic change. For ocean scientists, distinguishing between natural and anthropogenic processes has become a recurring challenge. Yet, the role and practices of environmental sciences while truly "natural" systems and entities continue to disappear require more philosophical thinking. My case study demonstrates how difficult it is for scientists to grasp an entity like the ocean ecosystem or any features thereof in a way that allows scientific reasoning. More often than researchers and philosophers of science might think, scientists actually deal with integrated entities or hybrids — deformed organisms fused with silk in a constellation that formed in a container ship's turbulent wake, or a plankton organism that has incorporated a tiny piece of tyre rubber. Like Griesemer (2014), philosophers need to discuss the objects that scientists regard as individuals or hybrids and how these objects guide researchers' practices and their understanding of the world. The empirical study of research practices and materiality can disclose these entities' complex formation processes and the motivations for scientists to adopt certain perspectives.

Building on my emphasis on material integration and continuity, a promising follow-up project from this thesis would be an empirical study even more explicitly dedicated to materiality in data-intensive sciences. Given the variety of material objects that are part of epistemic processes in today's sciences, it is not certain if the notions of material integration and continuity could apply to other research settings in a similar way. This question has to be answered by more empirical research. As Morgan (2014) points out, knowledge related to local contexts travels from local to local before it might become generalised. The implications of material interactions at different stages of the epistemic process are spelled out in my thesis in relation to only one specific research setting. Further case studies could also evaluate if implications of materiality are overlooked in scholarship on data-intensive sciences that focuses primarily on digital databases and not on the genesis of scientific data.

Besides specifying the notion of materiality, my research has shifted the focus to materialisation processes, to the efforts required to maintain and trace them, and to the epistemic value of material continuity. My thesis demonstrates the benefits of tracking the genesis and transformations of research objects in time, as things that seem stable quite often change or assimilate changes in their environment. This line of thought could be linked to process ontology, a metaphysical stance dating back to ancient philosophers that is put forward today by philosophers of science to argue for a metaphysical view that assumes processes instead of substances or things as the basic building blocks of reality (Seibt 2017). An analysis of processes requires the tracking of materialisation and stabilising processes not unlike what I have attempted in this thesis.

Finally, this thesis could serve as a platform for more collaborations and deeper mutual understanding between philosophers of science and oceanographers. The oceans crucially influence the most basic conditions for life on our planet and philosophers of science should be interested in research practices related to these still “alien” (Helmreich 2009) and widely unknown habitats for myriads of creatures. From a distance, ocean sciences may appear uncomplicated regarding the relation between science and the world. Knowing about marine organisms and tracking their development make a generally intelligible, perfectly legitimate, and graspable research enterprise that only seems to require somebody to go out there and take stock on a regular basis. Drawing on my research, it turns out that oceanographers have a lot to say about the challenges and balancing acts that lead to the generation of meaningful scientific data and knowledge of our environment. The kind of empirical research carried out for this thesis opens these experiences and narratives for productive rethinking and refinement of a variety of philosophical concepts.

Appendices

Appendix A: Criteria for selecting fieldwork sites

Criteria for selecting fieldwork, DATA_SCIENCE

Key question for us: given characteristics of field of interest, which characteristics of databases and data do we want to focus on? What makes for most interesting comparators?

Characteristics of field

Practical criteria

- Location of project coordination
- Ease of access
- Geographical locations of users and donors
- Degree of complexity
- History (how far back does it stretch, how easy is it to reconstruct, how rich for our purposes?)
- Success to date (measured in users, reputation, relation to journals and learned societies, and/or financial support)

Characteristics of database

- Field (by self-description)
- Covered sub-disciplines
- Aim/purpose/scope
- Prospective users (academics/government/others)
- Prospective data donors
- Relation to specific projects
- Methods used to collect and mine data
- Software used
- Statistical and visualisation tools used
- Location of data storage
- International involvement
- Sponsorship (private/public, national/international, consortium)
- UK involvement
- Languages involved
- Timescale

Characteristics of data involved

- Types of data and meta-data
- Types of research covered
- Types of ontologies
- Variety of parameters considered
- Geographic coverage of data
- Timescale of data
- Material form of data (format)

Appendix B: Interview questions

Interview Protocol – Data Users

Theme	Keywords	Questions
Personal history	biography, type of work, research interests disciplinary affiliations, research communities specific projects: with whom, funded by whom, to do what, with which materials	What is your background? Where are you affiliated? What research community do you belong to? What are your research interests? What type of work do you do? How did you get to your current position and interests? What are the kinds of people you work with and what are their roles? What projects are you working on? Who are the funders? What are the aims of the project? Who are you working with? What materials/things are you working on?

Practices of data handling	types of data produced/used instruments/IT/materials of data **production**/storage/**analysis**/modelling strategies of data storage strategies of data dissemination (if any)	What types of data do you work with? What instruments/IT/methods/protocols do you use to produce data? What are the materials in your scientific research and are you working with any kinds of specimens specifically? How do you store the data? How do you disseminate the data? What instruments/IT do you use to disseminate the data? Do you prefer working with specific kinds (types, formats) of data? How do you choose if several sources provide similar or the same data (if there are such cases)? Can you explain your methods/protocols/instruments/models for data analysis? Do you handle data differently when you collected it yourself compared to data you obtained from other sources? Do you keep a lot of data on your work or personal computers? If yes, why and which data? If no, why not?

		Can you recall specific cases where you reused data many times for different purposes? Did the reuse cause specific kinds of problems? Were the data easily transferable or did this require a lot of additional work?
Experience with database use	databases of interest examples of using databases for data dissemination examples of consulting databases for further research examples of successful data re-use and failure to re-use meta-data	What sources of data do you use? Where do you look when you are interested in finding out what data are available on a given topic? Which databases are you interested in? Have you used databases for disseminating data? Why/ why not? (if yes) Why did you choose these databases? What problems/issues did you encounter? What databases have you consulted for further research? Why did you choose these databases? For what purposes? Have you re-used data? Where were the data originally from? What did you have to do in order to re-use data? Was it harder to work with re-used data? Do you handle/store data that you sourced elsewhere differently from the data that you produced yourself?

		What were the key meta-data (and/or features) that made work with database X possible? Have you ever failed to access or re-use data? Why? What are the most urgent features or improvements you would like to see to database X or Y and why? Would those changes impact the adoption of the database by the community or yourself? Are you aware of citizen science and crowdsourcing efforts? What do you think of them?
Disciplinary and social context		How have data production and dissemination methods changed since you have entered your field? Can you name significant technological or methodological innovations? Can you name typical or recurring problems your field faces in work with data? Are there particular challenges? How could issues perhaps be improved or overcome? Do you see changes in funding agencies, industrial partners and/or research institutions with regard to data?

		How is open access to data being discussed in your field? Can you name examples of successful open access implementation? Do you know of commercial initiatives/services that have emerged because of the possibilities offered by data sharing, re-use, open data? How are relationships with peers in the field? How competitive is the field's culture? Describe research ethos in the fields of interest. How global are the research communities in your field? How big/global are the field's professional organizations? Small and local or big and global conferences?
Meaning of term data		What do you mean by data? What do your colleagues mean by data? What are the prerequisites for you to consider something to be data for research? Do data need to be computable?

Appendix C: Ethics consent form

GUIDE INFORMATION/CONSENT FORM FOR INTERVIEWS

Title of Research Project: **The Epistemology of Data-Intensive Science**

Sabina Leonelli, Principal Investigator; Niccolo Tempini, Research Fellow; Gregor Halfmann, PhD Student

The purpose of the research is to systematically analyze whether and how the epistemology of science is changing in the digital age, through a comparative study of data-intensive research practices and their results across scientific areas. In order to document the practices surrounding the production, dissemination and use of data, recorded interviews are being conducted with relevant scientists and practitioners. The interviews will inform publications intended for academic audiences. More information can be found on the project website http://www.datastudies.eu .

What is involved in participating: you will be invited to describe your everyday research practices and will be asked questions focused on your experiences with data handling, dissemination and interpretation. You will also be asked about the databases used in that work. The scheduling and length of the interview will be at your own convenience. Typically interviews last between one and two hours, however you may choose to have a shorter interview, or offer a in-depth account of your everyday work. The interview will be conducted at a mutually agreeable location, or over the phone.

Participation is entirely voluntary: You are free to decline to answer any question and to end the interview at any point. For a month after the interview, you may choose to withdraw from the study; simply contact the researchers to say so, and they will immediately destroy your contributions.

Recordings and data: Recording interviews is a practical and common data collection technique, but if you are uncomfortable with it, we can conduct the interview without audio recording. The interview materials will be de-identified, labeled with a pseudonym, stored on a password-protected computer, and kept in accordance with the Data Protection Act for ten years and then destroyed. Other than the research team, the only person with temporary access to the recordings will be a professional transcriber, conditional to signing a confidentiality agreement.

Confidentiality: The information you share with us will be kept confidential and will be attributed to you only with your permission. While in our work we will refer to the project or institutional context you belong to, the information will be used and reported in anonymous form, with the aim to make direct identification of yourself impossible. We will also ask you whether you are happy for us to make the eventual interview transcript available as open access research data. This is optional and disconnected from the question of anonymity. You can choose to be identifiable and at the same time for the transcripts not to be shared, or conversely, to not be identifiable but for anonymised versions of the transcripts to be made available. In any case, your contact details will be kept separately from your interview data.

Use of non-confidential data in future related projects: Upon completion of this project, researchers may keep non-confidential interview data for use in related research projects. At the end of any related research project, the data will be destroyed, unless you opted for making the interview transcript available online.

Risks and benefits: Based upon the information available to us, we believe that there are no special risks nor benefits associated to your participation in our research. If you choose to be named and/or have your contributions identifiable, the potential risks and benefits depend on your circumstances.

Research findings: You may request a copy of publications resulting from this study from the researchers.

Independence of project: The work is funded by the European Research Council via Starting Grant DATA_SCIENCE. The researchers involved have no conflict of interest relating to the subject matter, the individuals or the institutions involved in the research. This project was reviewed by the Exeter University Research Ethics Board, which provided clearance from February 2015 to December 2018.

Contact details: For further information about the research or your interview data, please contact Professor Sabina Leonelli, Department of Sociology and Philosophy, Exeter University, Devon UK. Email: s.leonelli@exeter.ac.uk . If you have concerns/questions about the research you would like to discuss with someone else at the University, please contact Professor John Dupre, j.a.dupre@exeter.ac.uk .

Your signature below serves to signify that you agree to participate in this study.

Participant's consent: I have read the above information and I choose to participate in an interview for research towards "The Epistemology of Data-Intensive Science".

I agree to be audio-recorded: Yes ____ No ____

Name of participant: ____

Signature of participant: ___________________________ Date:_______________

Signature of researcher: ___________________________ Date: ______________

[2 copies to be signed by both interviewee and researcher, one kept by each]

To be completed after the interview, only if desired by the participant:

I, , give permission to be identified and have my contributions attributed to me. Yes ____ No ____

I agree for the interview transcripts to be edited and shared as open access research data. Yes ____ No ____

Signature of participant: ___________________________ Date:_________________

Signature of researcher: ___________________________ Date: _________________

Appendix D: Data re-use and archiving agreement

INTERVIEW RE-USE/ARCHIVING AGREEMENT FOR

Project: The Epistemology of Data-Intensive Science

This agreement is entered into by ____________________________________, interviewee, and the research team of the project, which consists of Sabina Leonelli, Niccolo Tempini and Gregor Halfmann. Both parties enter into this agreement in order to facilitate the future use of the interview conducted on this date, ______________________________, for research, historical, and educational purposes.

A member of the research team conducted this interview as part of a research project on the practices underlying data handling and dissemination across scientific fields. The purpose of this agreement is so the transcripts from the interview can be shared with other researchers and the public. This agreement would allow the transcripts of the interview to be made accessible on a website created for the project, and/or deposited at an archive or other repository. It would also permit future uses of the transcript such as presentations, web sites, publications, audiovisual works, public exhibits, online venues, and other media deemed appropriate. The transcripts will be shared in edited format. This is to maintain the original meaning and tone of your words while at the same time omitting fillers, grammatical errors and rough expressions, with the aim of improving readability and reporting. Also, the research team will never use information from your interview that may lead to the identification of somebody else.

Interviewee:

1. Consented to voluntarily participate in this interview.

2. Authorizes the research team to record, transcribe, and edit the interview, and to use and re-use the interview transcript in whole or in part. The original recording will never be disseminated further than the research team.

3. Understands that the research team shall have no obligation to use the interview, and may dispose of the transcript if no suitable archive or repository is found.

4. Has no expectation of financial compensation for participation in this project.

5. Agrees to give and assign all rights, title, and interest, including copyright, of whatever kind from this information and interview to the research team and, if a suitable archive or historical repository at which to deposit the project's transcripts is found, to that archive or repository.

6. Understands that even if a suitable archive or repository is found, in the future, the archive or repository may dispose of part or all of the transcripts.

Date of interview: _________________________

Full Name of Interviewee (print) Full Name of Interviewer (print)

Signature Signature

Address Address

City Province Postal Code City
Province Postal Code

Date Date

Glossary

AIS: Automatic Identification System for marine entities
Argo: The International Argo Project, coordinates a global array of autonomous temperature and salinity profiling floats
AUV: autonomous underwater vehicle, a robot that travels and operates without requiring input
BODC: British Oceanographic Data Centre, Liverpool
CoML: Census of Marine Life, 2000s
CPR: Continuous Plankton Recorder
CTD: measurement unit with conductivity, temperature, and depth sensors
DAC: Data Assembly Centres, introduced with WOCE
DASSH: Data Archive for Seabed Species and Habitats, Plymouth
Defra: UK Department of Environment, Food, and Rural Affairs
EGU: European Geosciences Union
GACS: Global Alliance of CPR Surveys
GEOSS: Global Earth Observing System of Systems
GEOTRACES: An international study of marine biogeochemical cycles of trace elements and their isotopes
GODAE: Global Ocean Data Assimilation Experiment
GOOS: Global Ocean Observing System, oceanographic component of GEOSS
GPS: Global Positioning System
IAS: American Institute of Advanced Study
ICES: International Council for the Exploration of the Sea
ICSU: International Council for Science
IDOE: International Decade of Ocean Exploration, 1970s
IGY: International Geophysical Year 1957–58
IMO: International Maritime Organisation
IOC: Intergovernmental Oceanographic Commission, UNESCO
IPY: International Polar Year 2007–08
MBA: Marine Biological Association of the UK, Plymouth

MECN: Marine Environmental Change Network, an effort to coordinate and sustain the practices of long-term marine ecological monitoring programmes in the UK

MODE: Mid-Ocean Dynamics Experiment, 1970s

MVZ: Museum of Vertebrate Zoology in Berkeley, CA

NCAR: United States National Center for Atmospheric Research

NERC: National Environmental Research Council of the UK

NMBL: National Marine Biological Library, Plymouth

NOAA: United States National Oceanic and Atmospheric Administration

NOC: National Oceanography Centre, Southampton

NODC: United States National Oceanographic Data Centre

NSF: United States National Science Foundation

OBIS: Ocean Biogeographic Information System

OED: Oxford English Dictionary

OSD: Ocean Sampling Day 2014, EU-funded citizen science project

PCI: phytoplankton colour index, a four-category scale for assessment of a CPR sample’s colour

phytoplankton: microscopic single-celled plants, protists, or bacteria drifting in the upper ocean; consume carbon dioxide by photosynthesis; foundation of the aquatic food web

PML: Plymouth Marine Laboratory

ROV: remotely operated vehicle, a multi-sensor submersible navigated from ships

SAHFOS: Sir Alister Hardy Foundation for Ocean Science, Plymouth, conducted the CPR Survey between 1990 and 2018

SAR: synthetic aperture radar, a technique that increases the resolution of earth observing satellites

SCOR: Scientific Committee on Oceanic Research

SDS: Secchi Disk Study, citizen science project based in Plymouth

Secchi Disk: a plain white disk lowered into the water from ships to measure sea water turbidity

ship of opportunity: commercial ships that voluntarily contribute to the production of scientific data

SSH: sea surface height

SST: sea surface temperature

STS: science and technology studies or science, technology, and society

TSG: thermosalinograph, an instrument measuring temperature and salinity mounted on ships of opportunity and research vessels

UNEP: United Nations Environment Programme

WCRP: World Climate Research Programme

WDC: World Data Centres, introduced with the IGY

WMO: World Meteorological Organisation

WOCE: World Ocean Circulation Experiment, 1990s

WoRMS: World Register of Marine Species

XBT: expendable bathythermograph, temperature probe dropped from ships

zooplankton: animals living near the surface of the sea that drift with the currents, although some are weak swimmers; includes larvae of many fish species; a key component of the marine food web

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