Satellites will address critical science priorities for quantifying ocean carbon

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The ability to routinely quantify global carbon dioxide (CO_2) absorption by the oceans has become crucial: it provides a powerful constraint for establishing global and regional carbon (C) budgets, and enables identification of the ecological impacts and risks of this uptake on the marine environment. Advances in understanding, technology, and international coordination have made it possible to measure CO_2 absorption by the oceans to a greater degree of accuracy than is possible in terrestrial landscapes. These advances, combined with new satellite-based Earth observation capabilities, increasing public availability of data, and cloud computing, provide important opportunities for addressing critical knowledge gaps. Furthermore, Earth observation in synergy with in-situ monitoring can provide the large-scale ocean monitoring that is necessary to support policies to protect ocean ecosystems at risk, and motivate societal shifts toward meeting C emissions targets; however, sustained effort will be needed.

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Climate-relevant gases, including carbon dioxide (CO_2) and oxygen (O_2), are continuously exchanged between the ocean and atmosphere, with considerable temporal and geographic variations. Collectively, ocean and terrestrial CO_2 uptake reduce the accumulation of anthropogenic CO_2 in the atmosphere and have acted as a brake on global warming. The oceans, which are the largest long-term net sink of carbon (C), have so far been responsible for the uptake of about 25% of total anthropogenic CO_2 (Le Quéré *et al*. 2018), and the magnitude of this uptake varies on seasonal, interannual, and probably decadal timescales (Watson *et al*. 2009; Wanninkhof *et al*. 2013; Gruber *et al*. 2019).

In a nutshell:

- The oceans cover >70% of the Earth's surface and are critical for food supply and maintaining global climate
- Increasing carbon dioxide (CO_2) absorption alters ocean chemistry and ecology, affecting marine ecosystems over both the short and long term
- Accurate estimates of CO_2 absorption by the world's oceans provide a powerful constraint on carbon (C) budgets, and are needed to inform policies to motivate societal shifts toward reducing C emissions
- We review recent and foreseeable advances for studying oceanic CO_2 absorption, explain why satellite-based Earth observation is key to addressing existing knowledge gaps, and discuss how global monitoring is now both possible and necessary to support policy and conservation

Concentrations of CO_2 in seawater have increased measurably over the past 35 years (Bates *et al*. 2014). This absorption (or "sink") of CO_2 into the oceans reduces atmospheric CO_2 concentrations but lowers ocean pH levels, fundamentally altering ocean chemistry (WebPanel 1) and environmental conditions for marine ecosystems (Raven *et al*. 2005). The gradual and long-term lowering of pH – termed ocean acidification – is measurable on decadal timescales, but short-term intra-annual episodic events, driven primarily by atmosphere and ocean interactions (eg upwelling of low-pH and potentially corrosive waters; Feely *et al*. 2008), can have catastrophic impacts on marine life and ecosystems. The areal extent and intensity of these events are increasing as the oceans absorb more CO_2 (Feely *et al*. 2008).

Estimates of the land C sink are usually calculated or verified by determining the differences between net anthropogenic emissions, atmospheric uptake, and ocean C uptake (Le Quéré *et al*. 2016), typically through the use of inversion modeling (eg Resplandy *et al*. 2018), or are estimated from dynamic global vegetation models (Le Quéré *et al*. 2018). Because all of these methods rely on an accurate estimate of the ocean C sink (that is, an estimate of its annual uptake, either as a major component of the calculation or as a necessary observational constraint), overlooking variations and trends in the ocean C sink can have a profound impact on the accuracy of estimates of the land C sink and the global C budget, and consequently on guidance for emissions targets.

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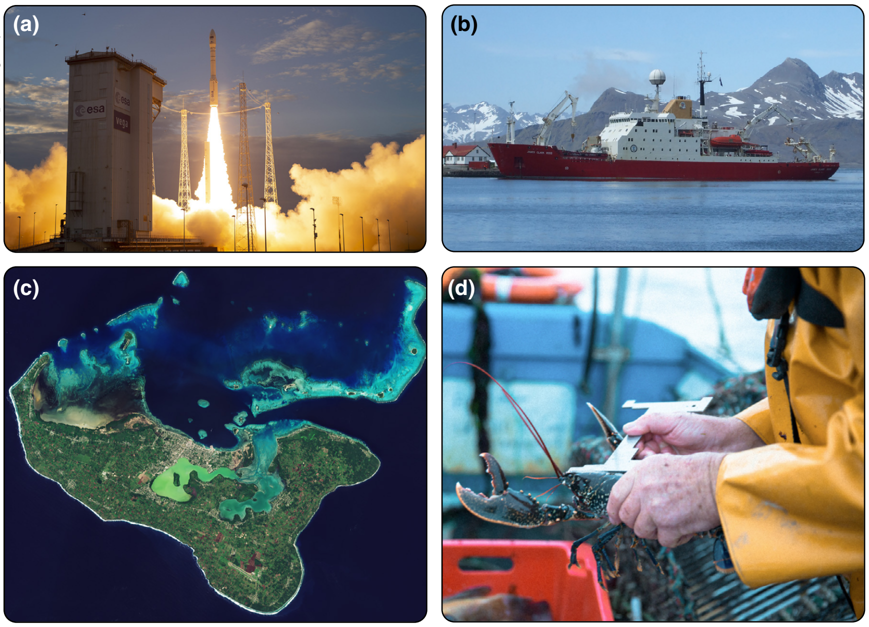

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Figure 1. (a) An environmental monitoring satellite is launched into a polar orbit. (b) Research vessels, buoys, and transport ships all routinely collect measurements for monitoring ocean atmosphere–ocean gas exchange, but some oceans are not well sampled and much of the data collection is voluntary. (c) A coral reef viewed from space; these sensitive ecosystems can be negatively impacted by episodic ocean acidification events caused by upwelling (Feely *et al.* 2008). (d) Calcifying organisms that use carbonate to build their shells, including commercially important lobsters, can be negatively affected by ocean acidification (McLean *et al.* 2018).

The solubility of CO_2 in seawater is highly sensitive to temperature (Woolf *et al.* 2016), which means that future warming of the upper ocean may diminish the ocean C sink. The capacity of the ocean to absorb additional CO_2 will also decline as a result of ocean acidification due to reductions in buffer capacity (Orr *et al.* 2005; WebPanel 1), and there is evidence that this is already occurring (Wanninkhof *et al.* 2013). In contrast, increased stratification and biological production could enhance the ocean C sink, while what impact the continual decline in polar ice will have remains unclear. The interplay between these counteracting processes makes future predictions challenging and warrants continued investigation.

Marine ecosystems provide food, energy, recreation, and mental and emotional well-being services to people worldwide. Future changes in the global ocean C sink may ease or strain human efforts to avoid dangerous climate change, and therefore measuring the oceanic C cycle must be a critical part of strategic and sustained long-term monitoring programs (Peters *et al.* 2017). The vastness of the world's oceans means that large-spatial-scale observations from space, combined with in-situ monitoring, are needed for identifying regions and ecosystems at risk of ocean acidification, advising emissions reductions, and evaluating progress toward the Paris Agreement and UN Framework Convention on Climate Change Sustainable Development Goals (Figure 1).

Major advances have been made over the past 5–10 years in scientific understanding (eg Wanninkhof *et al.* 2013; Woolf *et al.* 2016), instrumentation (eg WebTable 1), and international coordination (eg Bakker *et al.* 2016; Le Quéré *et al.* 2018), as well as through the exploitation of satellite-based Earth observation (eg Goddijn-Murphy *et al.* 2013; Landschützer *et al.* 2015). These advances, combined with the recent leap in Earth observation capabilities (eg Butler 2014), increased public access to satellite data, and cloud computing (eg Gorelick *et al.* 2017), provide important opportunities to fill existing knowledge gaps and enable strategic monitoring.

We explore the state-of-the-art techniques and recent breakthroughs in scientific understanding and highlight existing challenges. We then identify how Earth observation programs could enable direct observation of gas concentrations near the water surface, the processes governing its exchange, and the circulation and vertical transport of total CO_2 to further constrain the global C budget (Figure 2). We recommend the creation of a robust observational network that uses in-situ and satellite-based Earth observations to quantify the atmosphere–ocean exchange of climate-relevant gases.

Current ability to monitor ocean carbon

First, we review current scientific abilities, focusing on the advances that have been made in the past 5–10 years.

Sea-surface exchange of carbon

The solubility of gaseous CO_2 is strongly temperature dependent (Woolf *et al.* 2016); cooling waters tend to absorb atmospheric CO_2 whereas warming waters release CO_2. The in-water total CO_2 concentration can then be reduced via biological uptake by marine phytoplankton or increased via their respiration. On an annual basis, the net global pre-industrial flux of CO_2 across the atmosphere–ocean interface is thought to have been about 0.45–0.78 petagrams of C per year (Pg C yr^{-1}; Wanninkhof *et al.* 2013; Resplandy *et al.* 2018) due to net riverine C transfer from land to ocean. The post-industrial net flux is the difference between how much C is absorbed by the ocean and how much is released, each of magnitude ~90 Pg C yr^{-1}. The sum of these two terms (post-industrial net flux and pre-industrial net flux) is the anthropogenic uptake of CO_2. However, atmosphere–ocean fluxes of CO_2 cannot be measured directly over large spatial scales. The atmosphere–ocean gas exchange of CO_2 is typically calculated from the gas transfer velocity and the gaseous concentration difference at the atmosphere–ocean interface. Gas transfer velocities can be estimated in the field through bulk injection of gaseous tracers into the water column and measurement of the decline in tracer gas concentration over time. These methods provide estimates of gas transfer determined over a period of 0.5–4 days and ~100 km^2 of the ocean (eg Ho *et al.* 2011), and have shown that about 80% of the variance in gas transfer rates is explained by the wind speed (for wind speeds of 3–13 m s^{-1}). The majority of published studies therefore describe gas transfer as a function of wind speed (eg Nightingale *et al.* 2000; Schuster *et al.* 2013), although the effect of wind on transfer is indirect, acting through the generation of wind waves, near-surface turbulence, and bubbles; other controls are also known to exist (Figure 2, point 2). Fluxes can be measured directly by micro-meteorological (eddy covariance) techniques at hourly resolutions over ~1 km^2 (Butterworth and Miller 2016). The eddy covariance results have shown more variability between studies than the gas tracer results; some differences are attributable to experimental artifacts; however, other differences are due to processes that control fluxes but cannot be captured routinely by wind parameterizations (eg Butterworth and Miller 2016; Blomquist *et al.* 2017), or to region-specific complexities (eg those that occur in polar waters) (WebPanel 2). As such, scientific focus is now moving away from purely wind-based proxies for characterizing atmosphere–ocean gas exchange. Advancements in eddy covariance techniques now make it possible to collect (temporally and spatially) co-incident in-situ flux and in-situ remotely sensed measurements to improve our understanding of transfer processes, and also enable improved large-spatial-scale satellite-derived transfer. However, these opportunities have yet to be fully explored.

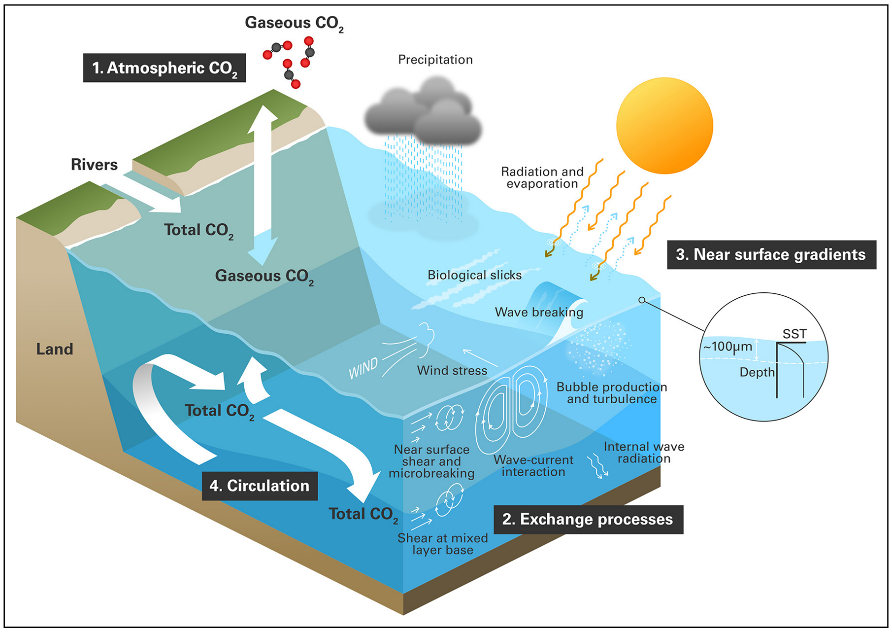

Figure 2. Conceptual and simplified view of interactions, exchange, and circulation of carbon dioxide (CO_2) within the ocean, identifying where satellite-based Earth observation is likely to play a leading role in expanding understanding and capability: (1) atmospheric measurements at the ocean surface; (2) quantifying gas, momentum, and heat atmosphere–ocean exchange processes; (3) capturing near-surface gradients in the water; and (4) measuring internal circulation and surface transport.

Ecosystem impacts

Uptake of anthropogenic CO_2 by the oceans is not without consequences. Gaseous CO_2 reacts with seawater to form carbonic acid (H_2CO_3), a process involving the release of hydrogen (H^+) ions, some of which bind with existing carbonate (CO_3^{2-}) ions to form bicarbonate (HCO_3^-). As a result, the marine uptake of anthropogenic CO_2 is causing the oceans to become more acidic (increased H^+ and HCO_3^-, decreased pH and CO_3^{2-}; WebPanel 1). Ocean acidification will profoundly affect marine organisms worldwide (Pörtner *et al.* 2015) and over time reduce the capacity of the oceans to act as a sink for additional anthropogenic CO_2 (Orr *et al.* 2005). Calcifying organisms (which need CO_3^{2-} to form their shells), including mollusks, crustaceans, corals, and some types of algae, are especially at risk, with far-reaching consequences for biodiversity, nutrient cycling, and habitat provision for socioeconomically important organisms (Brodie *et al.* 2014). However, some non-calcifying plants and microalgae are predicted to respond positively to acidification by increasing their photosynthetic and growth rates (Pörtner *et al.* 2015). The net impacts of ocean acidification on marine systems and climate are not straightforward to predict, and therefore warrant strategic and large-spatial-scale monitoring.

Upwelling – the movement of deep water to the ocean surface – is a mostly wind-driven phenomenon occurring at various scales in the global oceans. Nearshore upwelling, composed of Ekman transport and pumping (resulting from wind friction on the surface water), occurs predominantly on the eastern boundaries of the ocean basins. Upwelling brings cold, nutrient-rich water to the surface, but the low pH of these waters can disrupt the food webs, reproduction, growth, and energy balances of marine communities (O'Donnell *et al.* 2013). Consequently, episodic upwelling events can negatively affect regional ecosystems, including the Arctic, sensitive tropical reef systems, and continental shelves important for wild fisheries (Feely *et al.* 2008) and aquaculture. Wind-driven upwelling is also considered key for driving ocean interior circulation (Toggweiler and Russell 2008), which transports and (via corresponding downwelling) locks away total inorganic CO_2 (CO_{2aq} + HCO_3^- + CO_3^{2-}) for centuries. However, no direct methods currently exist to routinely monitor such global large-spatial-scale water movements, with the exception of a handful of sites (eg www.bodc.ac.uk/rapidmoc).

Instrumentation and international collaboration

Automated instruments on ships of opportunity (volunteer merchant ships), moorings, autonomous vehicles, and floats

(WebTable 1) routinely measure surface-water gaseous CO_2 with high precision and accuracy. These measurements are then assembled into global datasets (Takahashi *et al.* 2014; Bakker *et al.* 2016). The Surface Ocean CO_2 Atlas (SOCAT) in particular is an international community effort with well-documented protocols; each of its annual updates add over a million new data points, with a current data holding of 23.4 million measurements (Bakker *et al.* 2016). Concentrations of atmospheric CO_2 over the open ocean are less variable than those within the surface water. As a result, global atmospheric CO_2 is measured via 60 sustained marine boundary layer stations with weekly sampling (Conway *et al.* 1994). The individual measurements are freely available, and are also collated into the National Oceanic and Atmospheric Administration (NOAA) Greenhouse Gas Marine Boundary Layer Reference (MBLR, www.esrl.noaa.gov/gmd/ccgg/mbl/data.php). To date, all studies of the global ocean C sink utilize the zonally averaged MBLR data combined with surface-water gaseous CO_2 measurements (Panel 1; Figure 3c; eg Landschützer *et al.* 2015), but it is known that regions of meridional gradients (north–south gradients) caused by continental airflow are unlikely to be well resolved. To help assess the accuracy of the MBLR approach, atmospheric CO_2 measurements are now increasingly being collected in conjunction with the surface-water measurements. However, the sparse nature of in-situ data collection means that atmospheric concentrations in many key regions remain poorly characterized.

Exploitation of satellite measurements

Remotely sensed satellite observations of sea-surface state, temperature, wind, salinity, ice, rain, and biology (WebTable 2) play critical roles in the calculation of large-spatial-scale oceanic gas fluxes, because in-situ parameterizations and sparse in-situ measurements need to be upscaled. On local scales, sea-surface temperature is a strong predictor of surface-water gaseous CO_2 values, and satellite-observed temperature is used to interpolate in time and space between these in-situ measurements. More complex methodologies are being used – including empirically based multiparameter methods and machine-learning approaches – that rely on satellite chlorophyll-*a*, sea-surface temperature, and global re-analysis datasets such as mixed layer depth (Figure 3b; eg Schuster *et al.* 2013). Finer spatial resolution remote-sensing observations have been particularly useful for studying processes and fluxes in heterogeneous areas that have commonly been omitted in global-scale flux calculations (eg within coastal oceans, upwelling zones, near the ice edge; Laruelle *et al.* 2017). A promising

Panel 1. The importance of correct temperature handling for calculating atmosphere–ocean gas fluxes

Exploiting collated datasets of carbon dioxide (CO_2) measurements

Temperature is a key controller of the water solubility of CO_2 and, as such, all CO_2 measurements from water need to be paired with their respective temperature measurement. The temperature of seawater naturally varies over time, depth, and location, and different sampling techniques and vessels will sample water from differing depths. To reduce uncertainty, observations from different sources, locations, and times should therefore be corrected to a common temperature measurement dataset at a specified depth.

Accurate atmosphere–ocean gas flux calculations

The most accurate calculation of the atmosphere–ocean CO_2 gas fluxes requires the gaseous concentrations of CO_2 to be known at the top and bottom of a very small layer of water at the surface – the mass boundary layer – that is thinner than 1 mm (Woolf *et al.* 2016). Although these concentrations cannot be measured with current technology, they can be estimated using a combination of in-situ measurements taken at a few meters' depth, satellite observations of the water temperature, and knowledge of C kinetics and interfacial dynamics. Satellite remote-sensing technologies can observe the skin (top ~10–20 μm via thermal infrared) or sub-skin (~1 mm via microwave) temperatures; the skin temperature can also be inferred from the sub-skin (or vice versa) with knowledge of the local wind conditions (Donlon *et al.* 2002). Measurements of the skin and sub-skin temperatures allow an in-situ gaseous CO_2 concentration, collected from several meters below the surface, to be recalculated to the values at the top and bottom of the mass boundary layer.

Example method

The Surface Ocean CO_2 Atlas v4 dataset (Figure 3a) was re-analyzed (Goddijn-Murphy *et al.* 2015) to a common sea-surface sub-skin dataset (Banzon *et al.* 2016) and a skin dataset (sub-skin minus 0.17°C, based on Donlon *et al.* [2002]) to determine the in-situ gaseous CO_2 concentrations at the top and bottom of the mass boundary layer (Figure 3b). A spatially and temporally complete time series of global gaseous CO_2 concentrations was then calculated using a multilinear regression technique (Schuster *et al.* 2013). Atmosphere–ocean gas fluxes were calculated using the open-source FluxEngine toolbox (Shutler *et al.* 2016), a wind-speed–based gas transfer velocity (Nightingale *et al.* 2000), a simple linear scaling of gas fluxes due to ice, and the ancillary datasets described in section 4a of Shutler *et al.* (2016) (Figure 3c). All calculations were consistent with the recommendations and guidelines of the rapid model of Woolf *et al.* (2016).

Implications of inconsistent temperature handling

The simple calculation provided in Woolf *et al.* (2016) suggests that ignoring the gaseous concentration differences across the mass boundary layer results in a 0.1–0.6 petagram C per year (Pg C yr^{-1}) underestimate (bias) in the global ocean CO_2 sink. The analysis following the example method described in this panel gives a refined estimate of this bias of 0.37–0.44 Pg C yr^{-1}, with a 16-year average of 0.41 Pg C yr^{-1}. This equates to an 18–21% underestimate of the contemporary oceanic sink of 2.1 Pg C yr^{-1} (as provided by Le Quéré *et al.* [2018]).

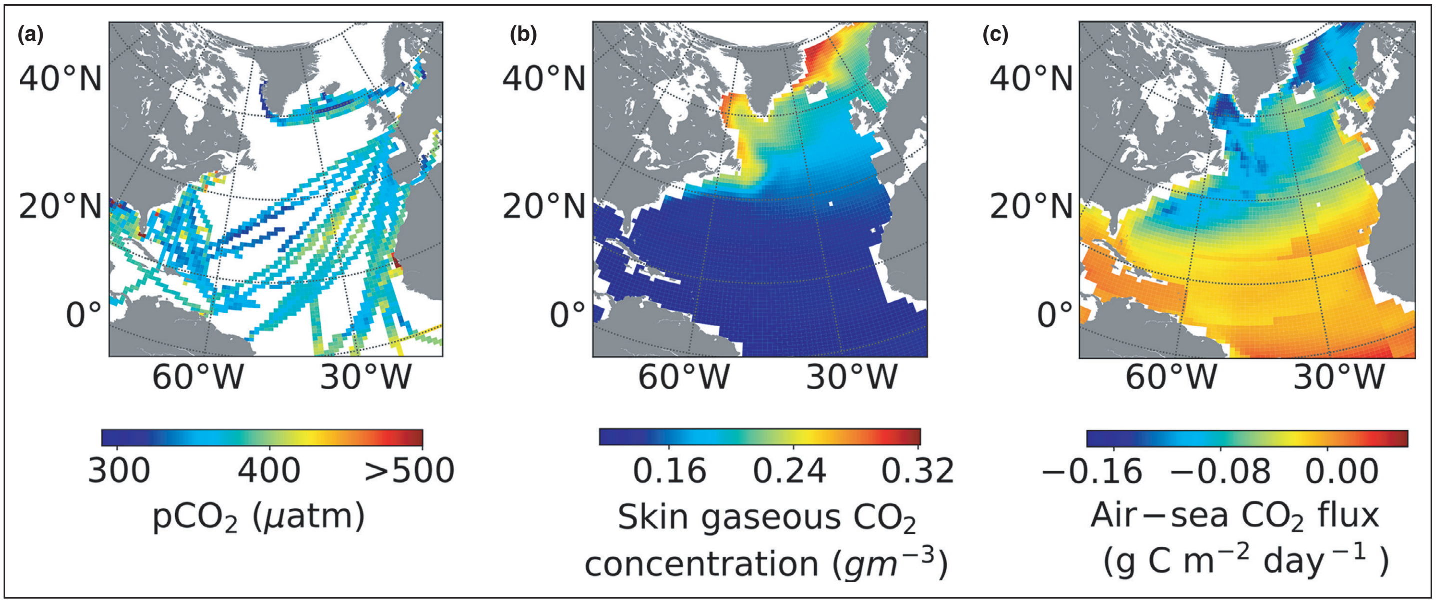

Figure 3. Examples of Earth observation data for quantifying surface ocean carbon (C) (land is gray): (a) example of an in-situ partial pressure dataset (pCO_2, the amount of gaseous CO_2 in the water) for the North Atlantic for 2010, showing sparse coverage (missing data are shown in white); (b) spatially complete gaseous CO_2 concentration at the top of the mass boundary layer, calculated using the pCO_2 data combined with Earth observation data; (c) atmosphere–ocean CO_2 gas fluxes calculated from (b) using Earth observation temperature and wind speed data. The methods for generating these data are explained in Panel 1.

method of using remotely sensed salinity levels to determine regional alkalinity has been highlighted (Land *et al*. 2015); this approach currently lacks the accuracy to assess anthropogenic change but could provide a further constraint on surface inorganic C and help elucidate the impact and progression of ocean acidification. Satellite-based biological production and sea-surface temperature data have enabled preliminary identification of the drivers of variability in the ocean CO_2 sink (Henson *et al*. 2018). Current methods for calculating gas fluxes using Earth observation techniques do not always reflect the physics of the sea surface or the available satellite instrumentation. For example, gas transfer velocities are normally calculated using wind speed as a proxy for surface exchange, though both transfer processes and microwave wavelength returns are more closely related to sea-surface roughness and exchange. Direct measurements of surface properties from space (WebTable 2) provide opportunities for moving beyond simple proxies. Some studies have already begun to investigate this potential (eg Goddijn-Murphy *et al*. 2013; Pereira *et al*. 2018) but more advances are possible.

Increased satellite capability

We are currently in the midst of a revolution in satellite technology and availability as they become fully integrated into international society. Prior to 2009, individual (agency-owned) short life span, science-focused satellites were typically launched, whereas today, multiple long-term satellite programs exist (eg Aschbacher and Milagro-Pérez 2012) and commercial operators are promoting a plethora of satellite services. Examples of commercial activity include >150 optical CubeSats already in orbit for monitoring changes on land (Butler 2014) and the planned launch of 40 passive microwave CubeSats for monitoring weather (WebTable 2). This is occurring in parallel to the emergence of routine image and pattern recognition, artificial intelligence, and commercial availability of cloud computing, meaning that non-specialists can use a laptop computer to remotely access and analyze global satellite observations. For example, Google Earth Engine (Gorelick *et al*. 2017) now provides free access and computing for scientific analysis of global satellite observation datasets. Free and open access to these satellite data permits experimentation, removes barriers for research and exploitation, and could enable long-term monitoring. Thus, all components required for strategic monitoring of ocean C absorption already exist. Spacecraft operated by international agencies, such as Europe's Sentinel missions and NOAA's polar orbiting platforms, can provide the necessary long-term monthly measurements, while commercial satellites that deliver less accurate data could provide daily observations for identifying sudden or episodic (infrequent and short-term) changes (eg upwelling). Access to commercial data could be provided through an update of the existing International Charter for "space and major disasters", which already provides free access during episodic disasters (eg flooding). This update would acknowledge the "long-term man-made climate disaster".

Satellites and remote sensing for new knowledge

Here, we identify key areas where satellite observations, in synergy with other methods, are likely to play a leading role in expanding scientific capability for studying and monitoring global ocean C (Figure 2).

Atmospheric CO_2 measurements near the water surface

Column-integrated CO_2 measurements obtained using remote-sensing instruments with an accuracy of <1 part per million (ppm) over the ocean are now possible (Connor *et al.* 2016), and the ability to distinguish between lowermost tropospheric and upper tropospheric column CO_2 measurements means that CO_2 concentrations near the ocean surface can be separated from CO_2 transported over large distances (Kulawik *et al.* 2017). These lowermost tropospheric data could be used to identify temporal and spatial biases within the MBLR approach in oceanic regions influenced by continental airflow or point sources. The accuracy of both approaches to resolve surface atmospheric CO_2 should be assessed using drone-observed or weather-balloon–observed vertical profiles (eg Corrigan *et al.* 2008).

Measuring near-surface concentrations

Satellite-based Earth observations focus on the top ~10 mm of the air–water interface and can be used to estimate near-surface vertical gaseous concentration gradients that control gas fluxes. Increased knowledge of these near-surface concentrations is critical, given that concentration differences between air and water are relatively small and so any biases within these concentrations will have large impacts on calculated fluxes. The most accurate calculation of these air and water concentrations requires the temperature to be known on either side of a ~100-μm layer at the water surface. In-situ measurements of these two concentrations in the ocean are impractical, but new work has highlighted that they can be estimated through the combination of ship measurements, satellite observations, and knowledge of chemical kinetics and dynamics of the interface (Woolf *et al.* 2016). In Panel 1, we present the first global temporal analysis using this approach, and our analysis suggests that the oceanic sink of C is 18–21% larger than current estimates. This use of satellite observation also removes the impact of unknown biases within the in-situ measurements found in the large, collated datasets that document surface gaseous CO_2. These biases, caused by different sampling conditions and equipment, were previously impossible to remove or characterize. Satellite-observed salinity data (eg Land *et al.* 2015) could be used to characterize the impact of near-surface salinity gradients on gas fluxes, which are likely to be important in regions with large river outflows and rainfall.

Direct measurements of multiple surface-exchange processes

Brightness temperature (radiance quantity of microwave energy leaving a surface) observations from passive microwave sensors provide a fundamental climate data record and can be used to infer rain, wind speed, sea state, foam, dielectric constant, salinity, and temperature (WebTable 2). The actual energy received by the sensor is a function of time and the surface area observed. This means that passive microwave measurements contain the signature of key processes controlling surface exchange (Figure 2, point 2), including the expansion and contraction of the surface ocean due to density changes and sea state, and therefore offer a unique and largely untapped resource for direct observations of multiple exchange processes. In-situ measurements of dissipation and emissivity coupled with measurements of gas exchange and eddy covariance fluxes should be used to identify robust, physically based relationships for describing gas exchange. Initial work should focus on the ~30-year global archive of passive microwave observations (WebTable 2) and SOCAT data. Due to the dynamic nature of the ocean, the large differences in time and space between field measurements and satellite observations will need to be accounted for.

Atmosphere–ocean fluxes of momentum, heat, and gas are interrelated but are typically studied in isolation. The wide range of current space observations offers the first solution for a more holistic and consistent approach to observing multiple exchange processes and properties. Gas exchange could be studied through the mean square slope to estimate surface expansion, wave breaking distributions, and wave energy dissipation. Combining momentum and heat flux methods in this way has already provided new knowledge in open ocean surface drag and heat process studies (Kudryavtsev *et al.* 2014), both of which are important for gas exchange. Such a holistic approach is likely to improve our understanding of how competing processes interact to influence gas exchange in polar waters (WebPanel 2). However, the study of compound events will require new satellite capabilities (eg concurrent high-resolution salinity, temperature, and wind–wave–current interactions).

Measuring internal ocean circulation and surface transport

The processes driving upwelling are well understood; information on the geographical location, the Earth's rotation, and local wind conditions is therefore sufficient to calculate Ekman flows. Knowledge of these properties has been applied to wind re-analysis data to infer the reason for changes in ocean C uptake in the Southern Ocean (Landschützer *et al.* 2015) but its application to satellite observations has yet to be fully exploited (Figure 4). The use of this theory in conjunction with satellite observations would constitute the first method for quantifying and monitoring large-spatial-scale three-dimensional transport of momentum, heat, total CO_2, and nutrients at critical locations. This would provide important constraints on global water mass budgets and global circulation, as well as providing the ability to characterize ecosystem health and identify regions most at risk from episodic acidification events. Daily passive microwave wind observations have been available since 1987, but new CubeSats will provide sub-daily observations of wind conditions (WebTable 2). This will make

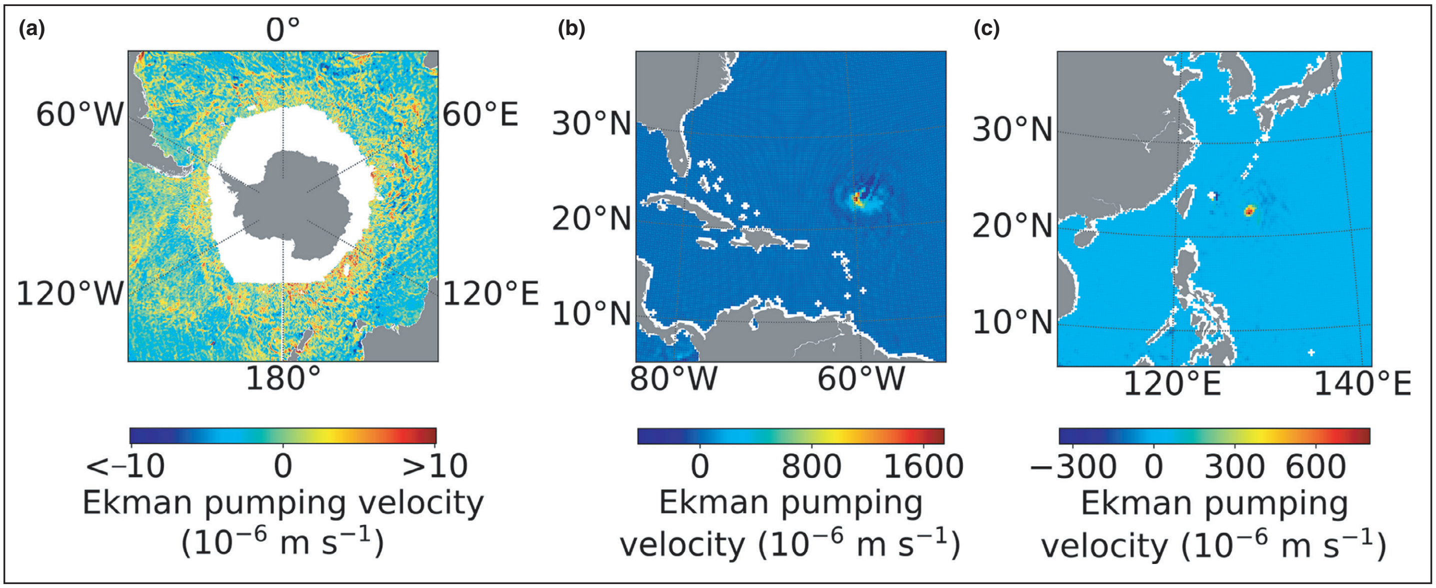

Figure 4. Examples of Earth observation data for quantifying total CO_2 transport (land is gray): (a) Earth observation-derived Ekman pumping in the Southern Ocean during the whole of September 2010 (sea ice is shown in white); and (b) Ekman pumping by Hurricane Igor in the Atlantic on 17 Sep 2010 and (c) by Typhoon Fanapi in the Pacific on 17 Sep 2010. These data were provided by the European Space Agency and were created using the methods described within Quilfen *et al.* (2016).

it possible to study how conditions at intense frontal regions affect gas exchange, as fronts themselves can greatly increase turbulence, which drives gas exchange (D'Asaro *et al.* 2011). Future satellite missions will expand these capabilities; the recently proposed Sea surface KInematics Multi-scale monitoring (SKIM; Ardhuin *et al.* 2018) and the Surface Water and Ocean Topography (SWOT; eg Oubanas *et al.* 2018) satellites will, by observing wind–wave–current interactions, enable the first direct spatial measurements of surface and vertical water transport. These satellites will provide the first measurements of vertical overturning (large-scale three-dimensional circulation) within equatorial regions and ocean basins (eg the Southern Ocean), as well as frontal turbulence and water movements within the marginal ice zone, across heterogeneous continental shelf boundaries and large river outflows.

Conclusions

Monitoring ocean C is crucial for identifying ecosystems most at risk of ocean acidification, closing the global C budget, informing policies to meet emissions targets, and tracking progress toward the goals of the historic Paris Climate Agreement developed by the 21st Conference of the Parties (COP21). Routine monitoring of the global oceans is now possible, but resources and impetus are required to help initiate long-term global ocean monitoring. Only satellites can provide the large-spatial-scale observations needed to efficiently and economically monitor the vast oceans, and these must now be used in synergy with in-situ observations. Such synergetic approaches are already leading to groundbreaking discoveries about the processes controlling gas fluxes. Our ability to observe the oceans and their ecosystems is increasing, and these advances, along with routine monitoring, will provide opportunities to fill existing knowledge gaps.

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References

Ardhuin F, Aksenov Y, Benetazzo A, *et al.* 2018. Measuring currents, ice drift, and waves from space: the Sea surface KInematics Multiscale monitoring (SKIM) concept. *Ocean Sci* **14**: 337–54.

Aschbacher J and Milagro-Pérez MP. 2012. The European Earth Monitoring (GMES) programme: status and perspectives. *Remote Sens Environ* **120**: 3–8.

Bakker DCE, Pfeil B, Landa CS, *et al*. 2016. A multi-decade record of high-quality fCO_2 data in version 3 of the Surface Ocean CO_2 Atlas (SOCAT). *Earth Syst Sci Data* **8**: 383–413.

Banzon V, Smith TM, Mike Chin T, *et al*. 2016. A long-term record of blended satellite and in situ sea-surface temperature for climate monitoring, modeling and environmental studies. *Earth Syst Sci Data* **8**: 165–76.

Bates N, Astor Y, Church M, *et al*. 2014. A time-series view of changing ocean chemistry due to ocean uptake of anthropogenic CO_2 and ocean acidification. *Oceanography* **27**: 126–41.

Blomquist BW, Brumer SE, Fairall CW, *et al*. 2017. Wind speed and sea state dependencies of air–sea gas transfer: results from the high wind speed gas exchange study (HiWinGS). *J Geophys Res-Oceans* **122**: 8034–62.

Brodie J, Williamson CJ, Smale DA, *et al*. 2014. The future of the northeast Atlantic benthic flora in a high CO_2 world. *Ecol Evol* **4**: 2787–98.

Butler D. 2014. Many eyes on Earth. *Nature* **505**: 143–44.

Butterworth BJ and Miller SD. 2016. Air–sea exchange of carbon dioxide in the Southern Ocean and Antarctic marginal ice zone. *Geophys Res Lett* **43**: 7223–30.

Connor B, Bösch H, McDuffie J, *et al*. 2016. Quantification of uncertainties in OCO-2 measurements of XCO_2: simulations and linear error analysis. *Atmos Meas Tech* **9**: 5227–38.

Conway TJ, Tans PP, Waterman LS, *et al*. 1994. Evidence for interannual variability of the carbon cycle from the National Oceanic and Atmospheric Administration/Climate Monitoring and Diagnostics Laboratory Global Air Sampling Network. *J Geophys Res* **99**: 22831.

Corrigan CE, Roberts GC, Ramana MV, *et al*. 2008. Capturing vertical profiles of aerosols and black carbon over the Indian Ocean using autonomous unmanned aerial vehicles. *Atmos Chem Phys* **8**: 737–47.

D'Asaro E, Lee C, Rainville L, *et al*. 2011. Enhanced turbulence and energy dissipation at ocean fronts. *Science* **332**: 318–22.

Donlon CJ, Minnett PJ, Gentemann C, *et al*. 2002. Toward improved validation of satellite sea surface skin temperature measurements for climate research. *J Climate* **15**: 353–69.

Feely RA, Sabine CL, Hernandez-Ayon JM, *et al*. 2008. Evidence for upwelling of corrosive "acidified" water onto the continental shelf. *Science* **320**: 1490–92.

Goddijn-Murphy LM, Woolf DK, Land PE, *et al*. 2015. The OceanFlux Greenhouse Gases methodology for deriving a sea surface climatology of CO_2 fugacity in support of air–sea gas flux studies. *Ocean Sci* **11**: 519–41.

Goddijn-Murphy L, Woolf DK, Chapron B, and Queffeulou P. 2013. Improvements to estimating the air–sea gas transfer velocity by using dual-frequency, altimeter backscatter. *Remote Sens Environ* **139**: 1–5.

Gorelick N, Hancher M, Dixon M, *et al*. 2017. Google Earth Engine: planetary-scale geospatial analysis for everyone. *Remote Sens Environ* **202**: 18–27.

Gruber N, Landschützer P, and Lovenduski NS. 2019. The variable Southern Ocean carbon sink. *Annu Rev Mar Sci* **11**: 159–86.

Henson SA, Humphreys MP, Land PE, *et al*. 2018. Controls on open-ocean North Atlantic ΔpCO_2 at seasonal and interannual timescales are different. *Geophys Res Lett* **45**: 9067–76.

Ho DT, Wanninkhof R, Schlosser P, *et al*. 2011. Toward a universal relationship between wind speed and gas exchange: gas transfer velocities measured with $^3He/SF_6$ during the Southern Ocean gas exchange experiment. *J Geophys Res-Oceans* **116**: C00F04.

Kudryavtsev V, Chapron B, and Makin V. 2014. Impact of wind waves on the air–sea fluxes: a coupled model. *J Geophys Res-Oceans* **119**: 1217–36.

Kulawik SS, O'Dell C, Payne VH, *et al*. 2017. Lower-tropospheric CO_2 from near-infrared ACOS-GOSAT observations. *Atmos Chem Phys* **17**: 5407–38.

Land PE, Shutler JD, Findlay HS, *et al*. 2015. Salinity from space unlocks satellite-based assessment of ocean acidification. *Environ Sci Technol* **49**: 1987–94.

Landschützer P, Gruber N, Haumann FA, *et al*. 2015. The reinvigoration of the Southern Ocean carbon sink. *Science* **349**: 1221–24.

Laruelle GG, Landschützer P, Gruber N, *et al*. 2017. Global high-resolution monthly pCO_2 climatology for the coastal ocean derived from neural network interpolation. *Biogeosciences* **14**: 4545–61.

Le Quéré C, Andrew RM, Canadell JG, *et al*. 2016. Global carbon budget 2016. *Earth Syst Sci Data* **8**: 605–49.

Le Quéré C, Andrew RM, Friedlingstein P, *et al*. 2018. Global carbon budget 2017. *Earth Syst Sci Data* **10**: 405–48.

McLean EL, Katenka NV, and Seibel BA. 2018. Decreased growth and increased shell disease in early benthic phase *Homarus americanus* in response to elevated CO_2. *Mar Ecol-Prog Ser* **596**: 113–26.

Nightingale PD, Malin G, Law CS, *et al*. 2000. In situ evaluation of air–sea gas exchange parameterizations using novel conservative and volatile tracers. *Global Biogeochem Cy* **14**: 373–87.

O'Donnell MJ, George MN, and Carrington E. 2013. Mussel byssus attachment weakened by ocean acidification. *Nat Clim Change* **3**: 587–90.

Orr JC, Fabry VJ, Aumont O, *et al*. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature* **437**: 681–86.

Oubanas H, Gejadze I, Malaterre PO, and Mercier F. 2018. River discharge estimation from synthetic SWOT-type observations using variational data assimilation and the full Saint-Venant hydraulic model. *J Hydrol* **559**: 638–47.

Pereira R, Ashton I, Sabbaghzadeh B, *et al*. 2018. Reduced air–sea CO_2 exchange in the Atlantic Ocean due to biological surfactants. *Nat Geosci* **11**: 492–96.

Peters GP, Le Quéré C, Andrew RM, *et al*. 2017. Towards real-time verification of CO_2 emissions. *Nat Clim Change* **7**: 848–50.

Pörtner HO, Karl DM, Boyd PW, *et al*. 2015. Ocean systems. In: Climate change 2014 impacts, adaptation and vulnerability: part A: global and sectoral aspects. Working Group II Contribution to the IPCC Fifth Assessment Report. Cambridge, UK: Cambridge University Press.

Quilfen Y, Chapron B, and Girard-Ardhuin F. 2016. Annex 3 – remote sensing derived estimates of upwelling. In: Shutler J, Land P, Ardhuin F, *et al*. Pathfinders OA final report. www.pathfinders-oceanacidification.org. Viewed 8 Jul 2019.

Raven JA, Caldeira K, Elderfield H, *et al*. 2005. Ocean acidification due to increasing atmospheric carbon dioxide. London, UK: The Royal Society. Policy document 12/05.

Resplandy L, Keeling RF, Rödenbeck C, *et al*. 2018. Revision of global carbon fluxes based on a reassessment of oceanic and riverine carbon transport. *Nat Geosci* **11**: 504–09.

Schuster U, McKinley GA, Bates N, *et al*. 2013. An assessment of the Atlantic and Arctic sea–air CO_2 fluxes, 1990–2009. *Biogeosciences* **10**: 607–27.

Shutler JD, Land PE, Piolle JF, *et al*. 2016. FluxEngine: a flexible processing system for calculating atmosphere–ocean carbon dioxide gas fluxes and climatologies. *J Atmos Ocean Tech* **33**: 741–56.

Takahashi T, Sutherland SC, Chipman DW, *et al*. 2014. Climatological distributions of pH, pCO_2, total CO_2, alkalinity, and $CaCO_3$ saturation in the global surface ocean, and temporal changes at selected locations. *Mar Chem* **164**: 95–125.

Toggweiler JR and Russell J. 2008. Ocean circulation in a warming climate. *Nature* **451**: 286–88.

Wanninkhof R, Park GH, Takahashi T, *et al*. 2013. Global ocean carbon uptake: magnitude, variability and trends. *Biogeosciences* **10**: 1983–2000.

Watson AJ, Schuster U, Bakker DCE, *et al*. 2009. Tracking the variable North Atlantic sink for atmospheric CO_2. *Science* **326**: 1391–93.

Woolf DK, Land PE, Shutler JD, *et al*. 2016. On the calculation of air–sea fluxes of CO_2 in the presence of temperature and salinity gradients. *J Geophys Res-Oceans* **121**: 1229–48.

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