CHAPTER 34

Impact of Climate-Carbon Cycle Feedbacks on Emissions Scenarios to Achieve Stabilisation

Chris D. Jones\textsuperscript{1}, Peter M. Cox\textsuperscript{2} and Chris Huntingford\textsuperscript{3}

\textsuperscript{1}Hadley Centre, Met Office, Exeter, UK
\textsuperscript{2}Centre for Ecology and Hydrology, Winfrith Technology Centre, Dorchester, Dorset, UK
\textsuperscript{3}Centre for Ecology and Hydrology, Wallingford, Oxon, UK

ABSTRACT: As atmospheric concentrations of CO\textsubscript{2} increase due to burning of fossil fuels, stabilisation scenarios are receiving increasing amounts of interest both politically and scientifically, leading to the question, ‘what emissions pathway is required to lead us to a given climate/CO\textsubscript{2} state?’ At present, about half of anthropogenic CO\textsubscript{2} emissions are absorbed naturally, but there is growing consensus that this fraction will reduce due to the action of climate change on the natural carbon cycle. Such climate-carbon cycle feedbacks will therefore influence the amount of carbon emissions required to stabilise atmospheric CO\textsubscript{2} levels.

Here we quantify the impact that climate change will have on the world’s natural carbon cycle and how this will affect the amount of CO\textsubscript{2} emissions which are permissible to achieve a stabilised climate in the future. Our simulated feedbacks between the climate and the carbon cycle imply a reduction of 21–33\% in the integrated emissions (between 2000 and 2300) for stabilisation, with higher fractional reductions necessary for higher stabilisation concentrations. Any mitigation or stabilisation policy which aims to stabilise atmospheric CO\textsubscript{2} levels must take into account climate-carbon cycle feedbacks or risk significant underestimate of the action required to achieve stabilisation.

34.1 Introduction

As atmospheric concentrations of greenhouse gases (and most notably carbon dioxide, CO\textsubscript{2}) increase due to burning of fossil fuels, there is growing recognition that this will cause major changes in climate. For some regions of the world, this may lead, ultimately, to ‘dangerous climate change’. For this reason stabilisation scenarios are receiving increasing amounts of interest both politically and scientifically. Instead of asking where a ‘business-as-usual’ increase in CO\textsubscript{2} emissions will take us, the question becomes ‘what emissions pathway is required to lead us to a given climate/CO\textsubscript{2} state?’, thereby ensuring a stable climate into the future.

At present, approximately half of anthropogenic CO\textsubscript{2} emitted is absorbed naturally, by the land surface and the oceans (Schimel et al., 1996; Jones and Cox, 2005). Without this, atmospheric CO\textsubscript{2} concentration would be far higher than the current value of approximately 375 parts per million (ppm). Projections of future rises in CO\textsubscript{2} generally assume that this natural mitigation will continue, and this is included in calculations of emission pathways required to achieve stabilisation. However, the behaviour of the natural carbon cycle is dependent on climate change itself. That is, as the climate responds to increased atmospheric greenhouse gas concentrations, these climate changes act to reduce the uptake of CO\textsubscript{2} by the terrestrial and ocean biogeochemical cycles, and lead to higher CO\textsubscript{2} levels than would otherwise be the case. We will refer to these throughout this work as ‘climate-carbon cycle feedbacks’.

There is recent modelling evidence that feedbacks between the climate system and carbon cycle will have a significant impact on future relationships between emissions and atmospheric CO\textsubscript{2} concentrations. For a prescribed scenario of CO\textsubscript{2} emissions, Cox et al. (2000) found that the natural components of the carbon cycle have, in response to future evolving climate, a reduced capability to mitigate CO\textsubscript{2} emissions and thus provide a positive feedback; in fact the land surface eventually turns into a major natural source. Friedlingstein et al. (2001) found a weaker positive feedback with the terrestrial carbon sink reduced but not becoming a source of carbon. In fact a comparison of ten coupled climate-carbon cycle models found overwhelming evidence that the feedbacks are positive: although the strength is uncertain, the impact of climate change will be to reduce both the terrestrial and oceanic carbon cycles’ ability to take up anthropogenic CO\textsubscript{2} (Friedlingstein et al., 2005). In the same way, therefore, it is likely that these positive feedbacks will reduce the magnitude of CO\textsubscript{2} emissions that lead to stabilised CO\textsubscript{2} levels.

The IPCC Third Assessment Report (Prentice et al., 2001) briefly alludes to the impact of the carbon cycle on stabilisation emissions but does not quantify the associated magnitude of emissions reductions. Joos et al. (1999) used a ‘low order’ model to quantify the ocean carbon cycle impact but did not discuss the terrestrial behaviour. Friedlingstein et al. (2001) show how their positive feedbacks reduce the emissions required to stabilise atmospheric CO\textsubscript{2} in an idealised 4×CO\textsubscript{2} experiment.
Here we explicitly quantify the impact of climate-carbon cycle feedbacks on realistic stabilisation emissions scenarios. We do not attempt to define ‘dangerous’ in the context of dangerous climate change – this remains a political question and is discussed further throughout this book – but we do address the question of what emission profile achieves stabilisation at a particular CO₂ level. In particular we re-examine the stabilisation scenarios proposed by Wigley et al. (1996) (hereafter referred to as the ‘WRE’ scenarios), which lead to stabilised atmospheric CO₂ levels, but do not account for feedbacks in the global carbon cycle. The important conclusion of this study is that compared to the previous projections of Wigley et al. (1996), climate-carbon cycle feedbacks significantly reduce the total ‘permissible emissions’ to achieve any given stabilisation level.

### 34.2 Emission Profiles to Achieve Stabilisation

#### 34.2.1 General Circulation Model Simulations

State-of-the-art coupled atmosphere ocean general circulation models (AOGCMs), such as HadCM3 (Gordon et al., 2000), are the best tool for making predictions of future climate change over the coming centuries because of the detail with which they are able to represent the processes involved. We use a version of HadCM3 with a fully interactive carbon cycle (HadCM3LC, Cox et al., 2001). Land-atmosphere and ocean-atmosphere fluxes of carbon are modelled explicitly. Thus to make simulations of an evolving climate in response to anthropogenic emissions, we prescribe specific emission scenarios of CO₂ and the model simulates the resulting atmospheric concentrations of CO₂.

In this study, however, we calculate the emission profiles required to achieve a stabilised level of CO₂. To accomplish this, we perform simulations with prescribed profiles of atmospheric CO₂ (and non-CO₂ greenhouse gases). Throughout the simulation, the resulting climate and CO₂ state determines the carbon fluxes into and out of the natural terrestrial and oceanic carbon cycle. The ‘permissible emissions’ are therefore the difference between the rate of change of atmospheric CO₂ and the modelled natural carbon fluxes. Two GCM simulations were performed, corresponding to profiles WRE450 and WRE550 (stabilisation at 450 ppm and 550 ppm respectively; Wigley et al., 1996). The results of these predictions of emissions for the period 1860 to 2300 are presented in Figure 34.1. It is apparent that the permissible emissions calculated with HadCM3LC (red lines) are significantly reduced compared to the previous estimates of Wigley et al. (1996) (black lines). For WRE450, HadCM3LC predicts that permissible emissions are reduced by about 2–3 GtC yr⁻¹ through much of the 21st century and are still almost 1 GtC yr⁻¹ lower by 2300. For WRE550, permissible emissions are reduced by up to 5 GtC yr⁻¹ by the latter half of the 21st century and are still 1 GtC yr⁻¹ lower by 2300. This represents a significant reduction in fossil fuels that may be burnt whilst achieving climate stabilisation at CO₂ concentrations of either 450 or 550 ppm.

This comparison of HadCM3LC against the model of Wigley et al. (1996) is justified by noting that Figure 3(a) of Cox et al. (2000) shows how the coupled GCM behaves very similarly to their model in the absence of climate change. Hence we assume that the differences shown here are predominantly due to the climate feedbacks rather than the use of a different carbon cycle model.

Figure 34.2 shows how the effect of climate carbon cycle feedbacks on total cumulative emissions from 1860 to 2300 is to reduce them from 1260 to 800 GtC in the WRE450 case and from 1810 to 1130 GtC in the WRE550 case. The estimates of Wigley et al. (1996) are given as
Figure 34.2 Cumulative changes in carbon stores for (a) WRE450 scenario and (b) WRE550 scenarios. Atmospheric carbon (dashed black line), terrestrial carbon (green line), ocean carbon (blue line). Anthropogenic stabilisation emissions both with (red line, as simulated by HadCM3LC) and without (solid black line, as in Wigley et al., 1996) climate-carbon cycle feedbacks.

34.2.2 Further Stabilisation Simulations with a ‘Simple’ Model

Unfortunately, the computational cost of such GCM simulations with currently available computer power greatly restricts the possible number of simulations. Hence to examine a wide range of scenarios (from stabilisation at 450 ppm to 1000 ppm) we have extended the results from the two GCM experiments by using a ‘simple model’. This simple model has been calibrated to reproduce the results of the GCM for the original ‘business as usual’ experiment of Cox et al. (2000) and has been tested to ensure that it reproduces the results of the two GCM stabilisation experiments presented above. Description, formulation and details of the calibration of the simple model are given in Jones et al. (2003a). However, it is noted here that the simple model can capture the features of the carbon cycle as depicted in the WRE450 and WRE550 HadCM3LC simulations described above. A caveat to this is that inherent lags in the full GCM simulation are not captured as the simple model here does not simulate the rate of ocean heat uptake but rather changes instantaneously to follow the radiative forcing of the CO₂ changes. Hence there is a tendency for the simple model to slightly overestimate the strength of the terrestrial carbon sink in the early 21st century and underestimate it towards the end of the simulation. Figure 34.3 shows the success of the simple model in recreating the GCM results. For simplicity, the simple model experiments neglect all climate forcing other than from CO₂. The opposing effects of non-CO₂ greenhouse gases and sulphate aerosols are assumed to approximately cancel during the historical period, and their future impacts are not the focus of this study.
Figure 34.3 Comparison of simple model and HadCM3LC results for WRE450 (left hand column) and WRE550 (right hand column) stabilisation experiments. Simple model results (red lines) and HadCM3LC results (black lines) for global mean temperature change (top row), 'permissible' anthropogenic emissions (second row: annual GCM results in thin line, 10-year smoothed data in thick line), NEP (third row: annual GCM results in thin line, 10-year smoothed data in thick line) and ocean carbon uptake (bottom row).
The simple model also allows a decoupling of the climate and carbon-cycle response to CO₂ allowing simulations where the climate feedback on the carbon cycle is "switched off". Simulations are performed for the other stabilisation profiles considered by Wigley et al. (1996) (i.e. leading to stable atmospheric CO₂ values of 650 ppm, 750 ppm and 1000 ppm). For each of these five scenarios, experiments are performed with and without climate-carbon cycle feedbacks. The total emissions in each case are summarised in Table 34.1. Figure 34.4 shows the simulated profiles of permissible emissions for these simulations, both with climate-carbon cycle feedbacks (red lines) and without (black lines).

The results for WRE450 and WRE550 are similar to those shown previously for HadCM3LC, but differ slightly due to the CO₂-only forcing used in the simple model, which enables better simulation of the observed emissions during the historical period. The results from all the scenarios are qualitatively very similar. Each WRE scenario already requires an eventual decrease in anthropogenic emissions below present-day levels in order to stabilise CO₂ levels. But the impact of climate-carbon cycle feedbacks is to reduce the permissible emissions further. In each case the peak emissions permissible for each scenario, the level of emissions by 2300 and the total (cumulative) emissions over the period are all reduced as a result of the climate-carbon cycle feedbacks. The total cumulative emissions are reduced by 21% in the WRE450 case and 33% in the WRE1000 case, as summarised in Table 34.1 and shown in Figure 34.5. The higher the level of stabilisation, the greater the level of reduction required in the total emissions compared with the case of no climate feedbacks. This is due to the greater amount of climate change associated with the higher stabilisation levels and hence the greater reduction in the strength of the natural carbon sink. The percentage reduction appears to level off, however, asymptoting to around 34% for CO₂ levels greater than 1000 ppm.

Figure 34.5 also shows the cumulative emissions from 2000 up to 2100 and up to 2200 (the subdivisions within the bars). For stabilisation at low levels it is clear that the majority of permissible emissions are "used up" during the 21st century: emissions after 2100 are a small fraction of the total. For stabilisation at higher levels, a greater proportion of permissible emissions are available after 2100. In other words, for the WRE profiles of CO₂ concentration, cumulative emissions up to 2100 show less variation across different stabilisation levels than do cumulative emissions after 2100, although this feature is clearly dependent on the rate at which the profiles reach the stabilisation level.

### 34.3 Discussion

The Coupled Climate-Carbon Cycle Model Intercomparison Project (C4MIP, Friedlingstein et al., 2005) has studied and compared the behaviour of the climate-carbon cycle feedback between ten coupled climate carbon cycle models. It found significant uncertainty in the strength of the feedback, but all models agreed that the feedbacks are positive and therefore in the context of CO₂ stabilisation would result in a reduction in permissible emissions.

The C4MIP analysis shows that the uncertainty is not confined to any single process, but contains significant contributions from all of these: climate sensitivity to a doubling of CO₂ (Andreae et al., 2005), sensitivity of respiration to temperature (Jones et al., 2003a), CO₂ fertilisation (Cramer et al., 2001; Adams et al., 2004), vegetation productivity sensitivity to climate (Cramer et al., 2001; Adams et al., 2004; Matthews et al., 2005) and oceanic uptake sensitivity to raised CO₂ and changed climate (Sarmiento et al., 1998; Donn et al., 2004). All of these sensitivities feature in the feedback analysis of Friedlingstein et al. (2003) and Friedlingstein et al. (2005).

HadCM3LC has the strongest feedback of the C4MIP models with a gain, roughly twice that of the mean of the ten models. Despite some of the C4MIP models clustering about a feedback strength of about half that of HadCM3LC, there is still no consensus on the magnitude of the components of the feedback, with different models producing similar feedback strengths by very different mechanisms. HadCM3LC has had aspects of the carbon cycle extensively validated against observations. It captures the large-scale terrestrial and oceanic patterns of fluxes measured by the TransCom 3 inversion study (Gurney et al., 2002), especially when all relevant climate forcings of 20th century climate are included (Jones et al., 2003b) which correct much of the overestimate of present day warming and CO₂ increase seen in Cox et al. (2000). It is also able to capture the carbon cycle sensitivity to climate variability and short-term transient changes such as those caused by ENSO (Jones et al., 2001) and the Mt. Pinatubo eruption (Jones and Cox, 2001). The atmospheric and terrestrial components of the model have
Figure 34.4 Stabilisation emissions for (a) WRE450, (b) WRE550, (c) WRE650, (d) WRE750 and (e) WRE1000 scenarios, both with (red lines) and without (black lines) climate-carbon cycle feedbacks as simulated by the simple model.
Additionally been validated over the historical period against site-specific flux tower measurements and finer scale inversion estimates (Jones and Warnier, 2004). Hence, while uncertainties remain, the ability to recreate present-day behaviour increases confidence in the predictive capability for future change. The strength of feedback presented here cannot be ruled out by observations and a simple analytical model suggests that terrestrial sink-to-source transition may be inevitable beyond some critical CO$_2$ level (Cox et al., 2005).

The historical record of temperature and CO$_2$ offers little constraint on climate sensitivity due to the uncertainty in the climate forcing (in particular of aerosols) (Gregory et al., 2002; Forest et al., 2002; Andreae et al., 2005).

It should also be noted that future carbon cycle behaviour, and hence implied permissible emissions, would be affected by other processes not yet included in our modelling. Limitation of plant growth by nitrogen or other nutrients, natural fire activity and impacts on the terrestrial carbon cycle from anthropogenic land use change are not included here.

Further uncertainty arises because future anthropogenic emissions will come from a combination of fossil fuel burning and land use change. In deriving our permissible emissions consistent with the modelled carbon fluxes we do not differentiate between their possible sources. However, fossil fuel burning is associated with SO$_2$ release and other particulate pollution, which may exert a negative radiative forcing, although this is expected to reduce in future as a result of clean-air technology. Land use change exerts its own biogeochemical forcing of climate through changes to albedo, surface roughness and hydrology (Betts, 2000; Betts et al., 2004; Sitch et al., 2005). Although it has yet to be resolved whether this biogeochemical forcing is sufficient to counter the biogeochemical forcing from CO$_2$ release (Brovkin et al., 1999; Matthews et al., 2003) it is likely to be substantial.

The non-uniqueness of stabilisation pathways will be considered in a future study, as there are many CO$_2$ profiles, and associated emissions, to stabilise at a given level. However, initial analysis indicates that the cumulative emissions to stabilise by different pathways were relatively insensitive to the chosen pathway. Cumulative emissions are the balance between accumulated CO$_2$ in the atmosphere and the change in the terrestrial and oceanic carbon storage. Generally, in the long-term these are more dependent on the final state than the pathway to achieve it, although this may not be strictly true in extreme cases if rapid rates of climate change, or 'overshoot' and subsequent recovery, caused the climate system to cross some irreversible thresholds such as Amazonie dieback (Cox et al., 2000, 2004) or a sudden drop in ocean carbon uptake due to THC collapse (Joos et al., 1999). The economic implications, however, of different routes to stabilisation may be important. Small reductions in the short term may increase the need for more rapid, and potentially much more expensive, reductions in the future (Meinshaven). The very long-term limit which permissible emissions approach is determined by the persistent natural sinks (Prentice et al., 2001) such as transport of anthropogenic carbon to the deep ocean. Over periods much longer than our simulations even this will diminish, leaving only much smaller sink terms such as accumulation in peatlands or carbonate compensation in the ocean. Hence we would expect the lines in figure 34.1 to decrease to just a couple of tenths of GtC yr$^{-1}$ over millennial timescales.

### 34.4 Conclusions

In this study we have attempted to quantify the impact climate change will have on the world's natural carbon cycle and how this will affect the amount of CO$_2$ emissions which are permissible to achieve a stabilised climate in the future. We use a climate model able to explicitly simulate interactions between the climate and carbon cycle and find that climate-carbon cycle feedbacks significantly reduce the permissible emissions for stabilisation of atmospheric CO$_2$ concentration. Feedbacks consistent with the Hadley Centre climate-carbon cycle GCM imply a reduction of 21--33% in the integrated emissions (between 2000 and 2300) for stabilisation, with higher fractional reductions necessary for higher stabilisation concentrations.

We recognise that uncertainties in climate model formulations (including their climate sensitivity and ecosystem response to climate change) mean that there are significant uncertainties in any projection of emissions profile required to achieve stabilisation. Further, we note that HadCM3LC has the largest climate-carbon cycle feedback strength of all of the C4MIP models although it validates well against available observations. However all such models exhibit some degree of positive feedback,
and hence in the context of stabilisation scenarios all would imply some further reduction in permissible emissions. The uncertainty in these results is thus in the amount of reduction of permissible emissions rather than in the fact that some reduction will be required as a result of climate change.

We conclude, therefore, that any mitigation or stabilisation policy which aims to prevent ‘dangerous’ climate change through stabilisation of atmospheric CO₂ levels must take into account climate-carbon cycle feedbacks and their associated uncertainty. Failure to do so may lead to a significant underestimate of the action required to achieve stabilisation.

Acknowledgements

This work was supported by the UK DEFRA Climate Prediction Programme under contract PESC 7/12/37, and the UK Natural Environment Research Council.

REFERENCES


Cox, P. M., C. Huntingford, and C. D. Jones, Conditions for Sink-to-Source transitions and runaway feedbacks from the land carbon-cycle, 2005, This Volume.


Meinshausen, M. What does a 2°C Target Mean for Greenhouse Gas Concentrations? A Brief Analysis Based on Multi-Gas Emission Pathways and Several Climate Sensitivity Uncertainty Estimates, this volume.


