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

Chris Jones[1], Peter Cox[2], Chris Huntingford[3]
[1] Hadley Centre, Met Office, Exeter, UK.
[2] Centre for Ecology and Hydrology, Winfrith, Dorset, DT2 8ZD, UK.
[3] Centre for Ecology and Hydrology, Wallingford, Oxon, OX10 8BB, UK.

Abstract

Climate change will affect climate-carbon cycle feedbacks such that permissible emissions to achieve stabilisation will need to be substantially lower than hereto expected. This is especially true for higher stabilisation levels with reductions to total permissible emissions of over 30%.

There is an "optimal pathway" to each stabilisation level, defined as that allowing maximum permissible emissions to reach it. Here, we demonstrate how the climate-carbon cycle feedback influences such pathways. It is found that both the climate sensitivity (to increases in greenhouse gases) and the carbon cycle sensitivity to changing climate affect the strength of the climate-carbon cycle feedback, and in turn the permissible emissions to achieve stabilisation.

1. Introduction

Stabilisation scenarios are receiving increasing amounts of interest both politically and scientifically. Instead of asking where a "business-as-usual" increase in CO_2 emissions will lead us, society is now asking what emissions pathway is required to take us to a given climate/CO_2 state. In particular, how we can avoid "dangerous climate change" and ensure a stable climate into the future?

The Earth's natural ecosystems (both on land and in the ocean) currently absorb roughly half of the anthropogenic emissions of CO_2 [1], thus buffering us from the full climate impact of our emissions. However, changes in the climate will affect this rate of absorption and hence influence the future rate of change of atmospheric CO_2. Such feedbacks between the climate system and carbon cycle will have a significant impact on the emissions which are required to stabilise atmospheric CO_2 at a given level. In particular, in the same way that positive feedbacks have been found to increase the level of climate change for a given scenario of CO_2 emissions [2,3,4], we can also state that to reach stabilised CO_2 levels, the magnitude of permissible CO_2 emissions may be significantly less than originally expected.

Here we show the impact of such climate-carbon cycle feedbacks on stabilisation emissions scenarios. In particular we examine the "WRE" stabilisation scenarios [5] and find that the predicted future climate-carbon cycle positive feedbacks reduce the total "permissible" stabilisation emissions for each stabilisation level. We also find that to reach stabilisation at any given level, there remains an optimal pathway which maximises the total permissible emissions, but this trajectory is influenced by the strength of the climate-carbon cycle feedbacks.

2. GCM results for prescribed CO_2 pathway to 550ppm.

The Hadley Centre Coupled climate-carbon cycle GCM, HadCM3LC [6], has been used to simulate the climate and carbon cycle under the WRE550 CO_2 concentration scenario (stabilisation at 550ppm: [5]). In this model experiment, the atmospheric CO_2 concentration was prescribed according to the WRE550 pathway and the resulting climate and CO_2 concentrations determine the fluxes into and out of the natural terrestrial and oceanic carbon cycle. The emission pathway to stabilisation is therefore the difference between the rate of change of atmospheric CO_2 and the modelled natural carbon fluxes and thus we infer the anthropogenic emissions required to stabilise CO_2 at the chosen level given the feedbacks between the climate and carbon cycle. The derived emissions pathway is significantly reduced as a result of the positive feedbacks which operate between the climate and carbon cycle, in particular due to a weakened or even reversed terrestrial carbon sink beyond 2050.

The impact of carbon cycle feedbacks on total cumulative emissions from 1860 through to 2300 is to reduce them significantly from 1810 to 1130 GtC (Figure 1). The dashed black line represents the amount of carbon (as CO_2) in the atmosphere. The blue and green curves show the accumulated uptake by the ocean and terrestrial biosphere respectively (negative values imply uptake). Both the oceanic and terrestrial carbon cycles absorb carbon throughout the historical period and into the early part of the 21st century. However, due to the warming climate feeding back onto these fluxes, the terrestrial biospheric carbon sink ceases by the middle of the 21st century and starts to release carbon back to the atmosphere (hence the cumulative uptake shown by the green curve starts to reduce). The oceanic sink (blue curve) persists throughout the course of the simulation, but at a decreasing rate. The anthropogenic emissions required to generate the specified CO_2 concentration are thus inferred from the difference between atmospheric carbon increase and ocean/terrestrial carbon changes (i.e. red line "= dashed black – blue – green")

The key issue here is that the upper black line shows the stabilisation emissions assumed when climatic influences on ocean and terrestrial "draw-down" of carbon are not considered (as given by [5]). It is clear that the impact of the climate-carbon cycle feedbacks is to reduce the permissible emissions (i.e. the red line is well below the dashed black line).

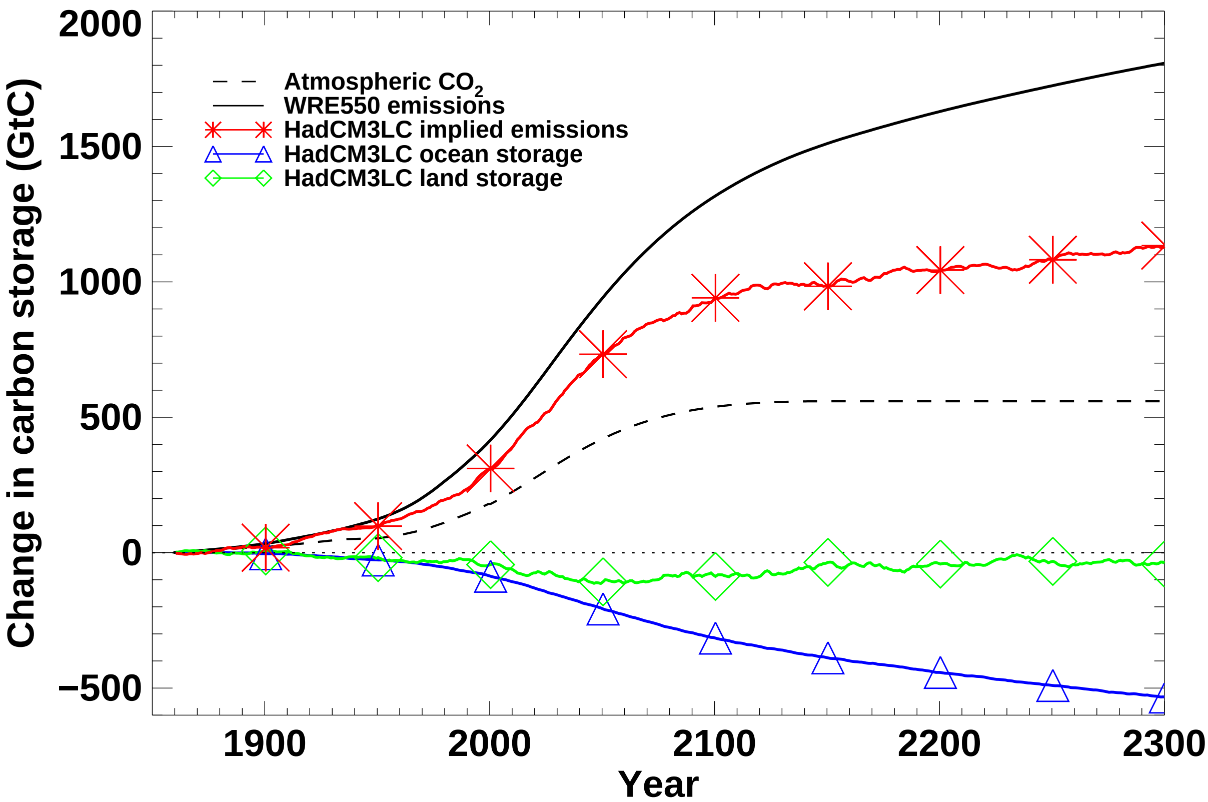

Figure 1. Cumulative changes in carbon stores for the WRE550 scenario. Anthropogenic stabilisation emissions both *with* (red line, as simulated by HadCM3LC) and *without* (black line, as in [5]) climate-carbon cycle feedback. Terrestrial carbon (green line), ocean carbon (blue line), atmospheric carbon (dashed black line).

This impact of the climate-carbon cycle feedback on permissible annual emissions is shown in figure 2. Although both curves show the same qualitative behaviour of a peak in emissions in the first half of the 21st century, followed by a large reduction over the following decades, the climate-carbon cycle feedbacks act to reduce the levels of emissions required to reach 550ppm. The emissions are reduced by up to 5GtC yr^{-1} by the latter half of the 21st century and are still 1 GtC yr^{-1} lower by 2300.

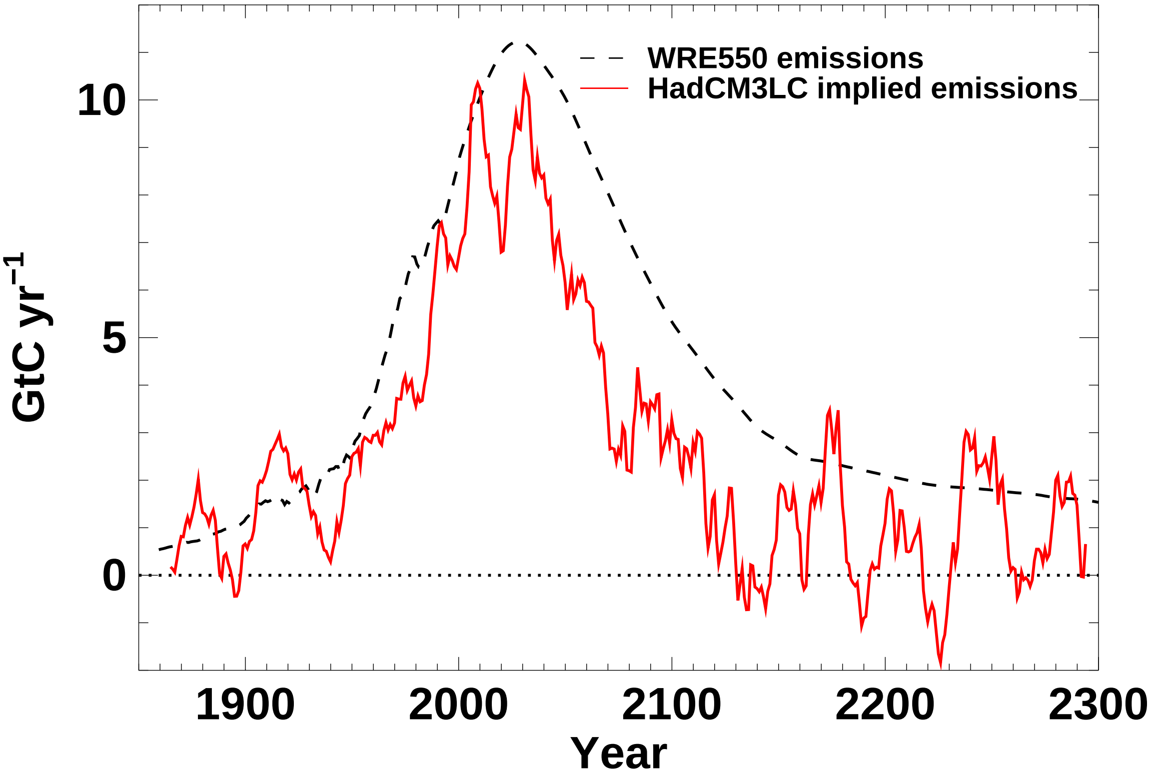

Figure 2. Annual stabilisation emissions for the WRE550 scenario, both *with* (red lines, as simulated by HadCM3LC) and *without* (black lines, as in [5]) climate-carbon cycle feedback. Internal variability in the GCM causes interannual variability in the red curve which is not present in the simple model used to produce the black curve, but this does not change the conclusions about the long term results.

3. Simple model

Experiments with HadCM3LC are very computationally expensive to perform (the stabilisation simulations shown above typically take several months on the Met Office's supercomputer). Hence to examine a wide range of scenarios (from stabilisation at 450ppm through to 1000ppm) we use a "simple model" [7] which captures climate feedbacks on the carbon cycle. The "simple model" has been calibrated to reproduce the results of the GCM under the IS92a emissions scenario and has been tested independently to ensure that it reproduces the results of the GCM stabilisation experiments.

The 5 WRE scenarios (450, 550, 650, 750 and 1000) were run with the simple model both with and without carbon cycle feedbacks. The results from all the scenarios are qualitatively very similar (analogous in functional form to a "smoothed" version of the red curve of Figure 2). Each WRE stabilisation scenario already implies a marked decrease in anthropogenic emissions by the end of the 21st century in order to stabilise CO_2 levels, but the impact of the climate-carbon cycle feedbacks is to reduce the permissible emissions further. In each case the peak emissions permissible for each scenario occurs sooner and at a lower level as a result of the feedback. The level of emissions by 2300 and the total emissions over the period are similarly reduced by the consideration of the climate-carbon cycle feedback.

The impact of the climate-carbon cycle feedback on the total permissible emissions from years 2000 to 2300 and for a range of stabilisation levels is shown in Figure 3. The total cumulative emissions are reduced by 21% in the WRE450 case and 33% in the WRE1000 case. It is interesting to note that the higher the level of stabilisation, the greater the reduction in the total emissions. 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 3 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. It is interesting to note, therefore, that although stabilisation at 550 rather than 1000 ppm implies an increase in atmospheric carbon content of just 380 GtC (from the present day) compared with about 1330 GtC for the 1000 ppm case (just 29% of the CO_2 increase in the atmosphere), the permissible emissions for the WRE550 scenario up to 2100 are 68% (with feedbacks and 66% without feedbacks) of those for the WRE1000 scenario. In other words, providing the particular trajectories used to reach stabilisation are those given by WRE, not all of the eventual reduction in emissions required to achieve 550 rather than 1000 needs to be achieved in the 21st century.

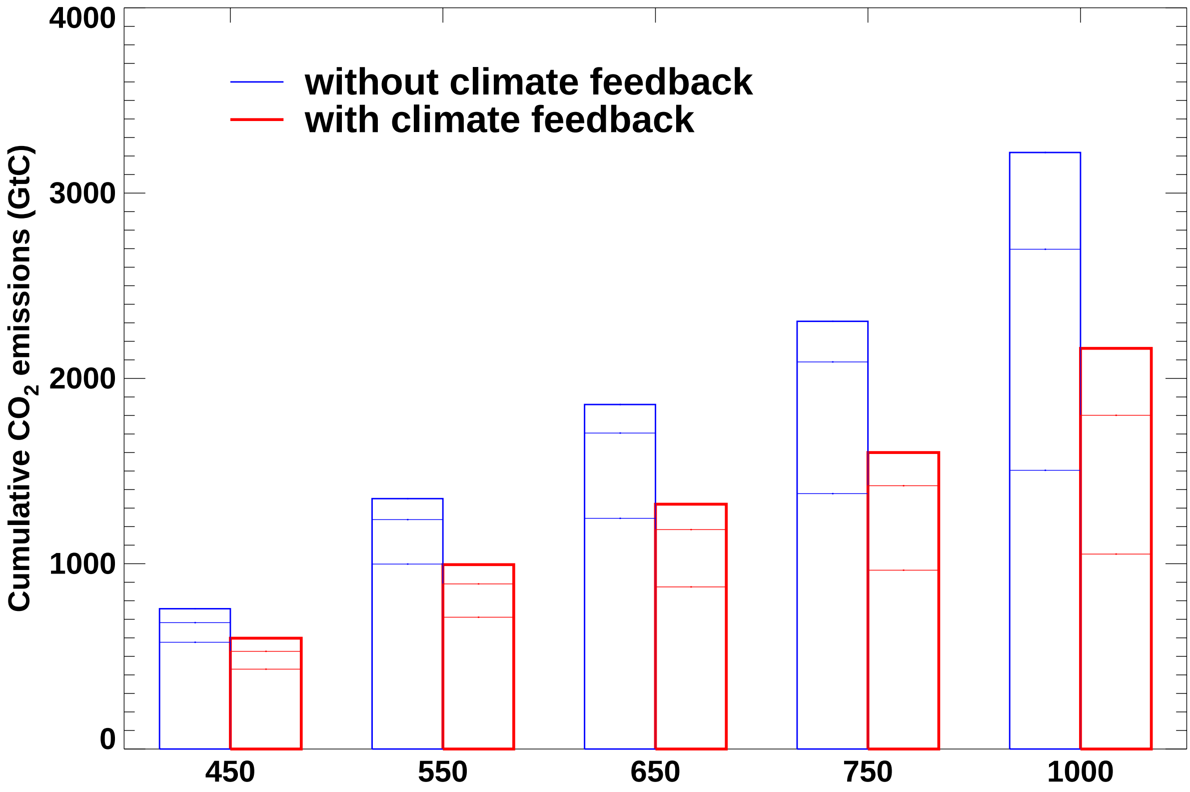

Figure 3. Cumulative emissions totals from 2000 to 2300 for the 5 WRE stabilisation scenarios, both *with* (red histogram) and *without* (blue histogram) the climate-carbon cycle feedback. The lower and upper subdivisions within the bars show the cumulative emissions up to 2100 and up to 2200 respectively.

4. Addressing uncertainty

Modelling studies of the climate-carbon cycle feedback have shown that there is large uncertainty in the strength of the feedback [2,3,4,8], although all agree that the feedback is positive, thereby leading to some degree of reduction in permissible emissions compared to previous understanding. Here we use the "simple model" to investigate the key parameters which determine the strength of the climate-carbon cycle feedback, and determine how these translate into ranges of uncertainty for required reduction in emissions to achieve climate stabilisation.

Here, we consider two key uncertainties. These correspond firstly to the "climate sensitivity", which is the amount of warming expected for a given CO_2 level and secondly the "sensitivity of the carbon cycle to climate change". The modelling and understanding of both of these effects requires the balance between multiple factors, all of which include uncertainties which are difficult to eliminate through comparison with the 20th Century data record. For example, climate sensitivity is not well known, largely due to uncertainty in the climate forcing during the 20th century (in particular, uncertainty in the magnitude of the cooling effect of sulphate aerosols) [9,10,11,12]. Both high climate sensitivity and strong aerosol cooling, and weak climate sensitivity and weak aerosol cooling are consistent with the observed record of 20th century warming. However, they imply very different futures of the climate system for future change. Similarly, the sensitivity of the carbon cycle to changes in climate is not well constrained – relatively low uptake of CO_2 by the biosphere and a weak sensitivity of decomposition to temperature, or vigorous uptake and highly temperature sensitive decomposition are both consistent with the observed rate of CO_2 growth. Again, the different ends of the spectrum imply very different responses of the natural carbon cycle to future climates. We have used the simple model to investigate the impact of these uncertainties on the permissible emissions. Greater climate sensitivity and greater sensitivity of decomposition to warming both lead to stronger climate-carbon cycle feedbacks and hence greater reductions in permissible emissions.

The “simple model” allows easy investigation of climate-carbon cycle feedbacks on the major result by WRE, whereby emissions required to stabilise at a particular level are dependent on the rate at which that level is approached. WRE show that in the case of no climate-carbon cycle feedbacks, a quicker approach to stabilisation allows for more uptake by the natural carbon cycle and hence slightly greater permissible emissions. However, when climate-carbon cycle feedbacks are considered, this may no longer be the case because the faster rate of warming (which would be associated with the faster rate of approach to stabilisation) means that the terrestrial carbon sink may cease earlier. Thus the “optimal” stabilisation pathway may require a greater initial reduction in emissions and slower approach to stabilisation. We believe the determination of the “optimal” pathway to stabilisation depends on the strength of the climate-carbon cycle feedbacks and are currently relating this to feedback strength within the expected bounds of uncertainty discussed above.

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