Strong carbon cycle feedbacks in a climate model with interactive CO$_2$ and sulphate aerosols

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[1] Carbon cycle feedbacks are a significant source of uncertainty in climate change projections, with the potential for strong positive feedbacks to accelerate the rate of anthropogenic global warming during the 21st century. A climate change experiment is presented which uses a General Circulation Model (GCM) in which both interactive carbon and sulphur cycles have been included for the first time, along with the natural climate forcings due to solar changes and volcanic aerosol. These extra climate forcing factors have a significant impact on both 20th century climate change and the contemporary land and ocean carbon sinks. The additional forcings act to delay by more than a decade the conversion of the land carbon sink to a source, but ultimately result in a more abrupt rate of CO$_2$ increase with the land carbon source (which reaches 7 GtC yr^{-1} by 2100) exceeding the ocean carbon sink (which saturates at 5 GtC yr^{-1} by 2100) beyond about 2080.   INDEX TERMS: 1615 Global Change: Biogeochemical processes (4805); 1620 Global Change: Climate dynamics (3309); 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 1610 Global Change: Atmosphere (0315, 0325). **Citation:** Jones, C. D., P. M. Cox, R. L. H. Essery, D. L. Roberts, and M. J. Woodage, Strong carbon cycle feedbacks in a climate model with interactive CO$_2$ and sulphate aerosols, *Geophys. Res. Lett.*, *30*(9), 1479, doi:10.1029/2003GL016867, 2003.

1. Introduction

[2] Strong positive feedbacks between climate and the carbon cycle were found in a previous study by *Cox et al.* [2000, hereinafter referred to as "Cox00"]. Increased soil respiration due to rising temperatures during the 21st century exceeded enhanced biospheric uptake due to elevated CO$_2$ levels. As a result the rate of increase of atmospheric CO$_2$, and hence the rate of climate change, were accelerated. Drying of the Amazon basin due to the climate change caused a dieback of the Amazon forest which contributed to further carbon release and extra positive feedback.

[3] However, Cox00 used just greenhouse gas (GHG) forcing. Other important forcings of climate, such as anthropogenic sulphate aerosol and ozone forcings, and also natural forcings due to changes in solar forcing and volcanic stratospheric aerosol, were not included. Other studies have found that these extra forcings are necessary to simulate the climate of the 20th century [*Stott et al.*, 2000, 2001]. In particular, anthropogenic sulphate aerosols seem to have acted to slow the rate of climate warming during the latter part of the last century.

[4] As a result of the omission of these forcing factors in Cox00, the 20th century global climate warming was overestimated by about 50%. This was cited as part of the reason for an error in the present-day CO$_2$ concentration of +20 ppmv [*Cox et al.*, 2000]. However, a legitimate doubt can also be raised based on these results; could the overestimate of the historical CO$_2$ rise be indicative of an unrealistically strong sensitivity of the carbon cycle to climate in HadCM3LC, and might this explain the strong positive feedback seen in Cox00 relative to other climate-carbon cycle simulations [*Friedlingstein et al.*, 2001]?

[5] In order to address these issues we have carried out new climate-carbon cycle projections including additional forcing factors necessary to simulate 20th century climate change. These factors have an important impact on the evolution of climate and the carbon cycle - in other words, human activity other than direct CO$_2$ emissions can have a significant effect on the carbon cycle via its impact on climate.

2. Methods

[6] The climate model used is HadCM3L - a version of HadCM3 [*Gordon et al.*, 2000], but with a slightly lower ocean resolution (2.5° × 3.75° compared with 1.25° × 1.25°) which is required due to the extra computational expense of the ocean carbon cycle model. As a result the model requires the use of flux corrections [*Johns et al.*, 1997]. The climate model is coupled to terrestrial and ocean carbon cycle models [*Cox et al.*, 2001]. The terrestrial carbon cycle model, TRIFFID [*Cox*, 2001], is a dynamic global vegetation model, which models carbon allocation between 5 competing plant functional types and also a soil carbon reservoir. The ocean carbon cycle model, HadOCC [*Palmer and Totterdell*, 2001], includes a representation of oceanic chemistry and biology. The extra climate forcings are added as in a previous study [*Johns et al.*, 2003].

[7] The forcing of the coupled system comprises:

[8] - Atmospheric CO$_2$ concentration is modelled interactively by specifying emissions from the IS92a scenario and allowing the carbon cycle model to partition these between ocean, terrestrial and atmospheric carbon pools.

[9] - Non-CO$_2$ GHGs are prescribed as in Cox00, also following the IS92a scenario.

[10] - The direct effect of anthropogenic sulphate aerosol is included using an improved version of the interactive sulphur cycle scheme [*Johns et al.*, 2003], using historic anthropogenic sulphur dioxide emissions and 21st Century anthropogenic emissions according to the SRES A2 scenario [*Nakićenović et al.*, 2000]. Dry deposition is calcu-

lated separately for each of the 5 vegetation types in each gridbox, using CO_2-dependent canopy resistance values calculated by the MOSES-2 land-surface scheme [*Cox et al.*, 1998].

[11] - The first indirect effect of anthropogenic sulphate (the "albedo effect") is included using a non-interactive method in which cloud albedo perturbations are imposed based on output from a set of preliminary sulphur cycle runs [*Johns et al.*, 2003].

[12] - The second indirect sulphate effect (the "lifetime effect") has been estimated to be significantly smaller [*Jones et al.*, 2001a], and is excluded for simplicity.

[13] - Tropospheric and stratospheric ozone changes are prescribed, based on the latest results from the atmospheric chemistry model, STOCHEM [*Stevenson et al.*, 2000].

[14] - Solar forcing to present day is taken from the reconstruction of solar irradiances [*Lean et al.*, 1995], and is kept constant (equal to the mean of the last 11 years) after 2000.

[15] - Climate forcing due to volcanic eruptions is represented by specifying the stratospheric aerosol distribution [*Sato et al.*, 1993] up to present day, and assuming it is zero thereafter.

3. Results

3.1. Historical

[16] The results of this all-forcings experiment (hereafter referred to as "ALL") show that this model is capable of recreating the observed temperature record of the 20th century. Figure 1a shows modelled and observed changes in global mean temperature up to 2000. Observations are from the UEA-MOHSST dataset [*Parker et al.*, 1995]. The early century warming, mid century plateau and late century warming are all present in the model simulation. The total warming by present day is much closer to the observed value than that simulated in Cox00. The simulated CO_2 rise in ALL also matches observations more closely than Cox00 (see Figure 1b). This demonstrates that about half of the present-day overestimate of CO_2 in Cox00 was due to the omission of climate forcings other than GHGs.

[17] There is still a slight overestimate of CO_2 by present day in ALL, but this may be due to an overestimate of net land-use emissions in the standard IS92a scenario. *Schimel et al.* [1996] suggest that land use change emissions may be about 70% of those used in IS92a, consistent with the suggestion that northern forest regrowth produced a net land-use sink of 0.5 GtC yr^{-1} during the 1990s. A further experiment, ALL70, was performed using land use change CO_2 emissions reduced to 70% of the values specified in IS92a. Figure 1b shows that this simulation closely matches the historical CO_2 rise. The land carbon balance is determined by competition between CO_2 fertilisation and increased respiration as the climate warms [*Cramer et al.*, 2001]. The cooling effect of the additional forcings in ALL amplifies the historical land carbon sink by suppressing the rate at which the climate warms. This is only partially offset by reduced ocean uptake (due to a reduced rate of CO_2 increase).

3.2. Contemporary

[18] A more complete representation of the climate system and its forcing factors is required to improve the simulation of contemporary climate [*Stott et al.*, 2000,
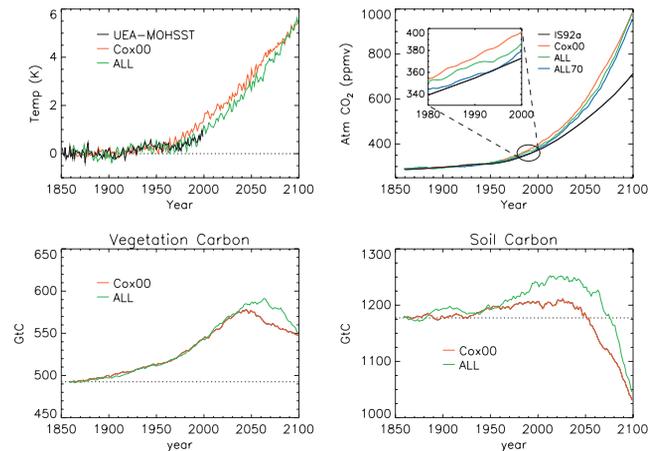

Figure 1. Modelled historical and future changes of climate and the carbon cycle from simulations including non-greenhouse gas forcing (green lines, from ALL) and excluding non-greenhouse gas forcing (red lines, from Cox00). (a) Global temperature increase compared to observations (black line), (b) Change in atmospheric CO_2 compared to standard IS92a concentrations (black line) and the ALL70 simulation (blue line), (c) vegetation carbon store, (d) soil carbon store.

2001], but the impact on carbon sinks has not previously been considered. The size of the present day terrestrial carbon sink is significantly affected by the climatic impact of anthropogenic sulphate aerosol. Without this forcing, the terrestrial biosphere would be a much weaker sink [*Cox et al.*, 2000].

[19] ALL and ALL70 have a much improved simulation of contemporary carbon sinks than Cox00. Figure 2 shows the mean land and ocean carbon sinks from the simulations alongside the latest estimates from the inversion of atmospheric CO_2 measurements [*Gurney et al.*, 2002]. In each case the sinks are averages over the post-Pinatubo period 1992–1996, with the land sink including contributions from net land-use change. In all three model runs the ocean carbon sinks are within the uncertainty estimates on the inversions studies, but ALL (green bars) and ALL70 (blue bars) show remarkable agreement. The slower rate of increase of atmospheric CO_2 which results from the extra climate forcings reduces the ocean uptake globally by about a quarter.

[20] The additional forcings have an even more marked effect on the net land carbon sink (including prescribed land-use change). The modelled global land is a significant carbon sink for the 1992–1996 period, where before it was a small carbon source. The rate of rise of atmospheric CO_2 slowed in the 1990s. The reason for this is mostly associated with the climatic effects of the Pinatubo volcanic eruption which enhanced terrestrial uptake by cooling the northern and tropical lands [*Jones and Cox*, 2001b; *Lucht et al.*, 2002]. ALL and ALL70 simulate this slowing, as can be seen in the inset of Figure 1, whereas Cox00, without volcanic forcing, does not. The global land carbon sink appears to be slightly overestimated in ALL and ALL70, but this discrepancy is well within the range of the high variability in land-atmosphere carbon exchange [*Jones et al.*, 2001b]. The underestimate of a Northern sink and
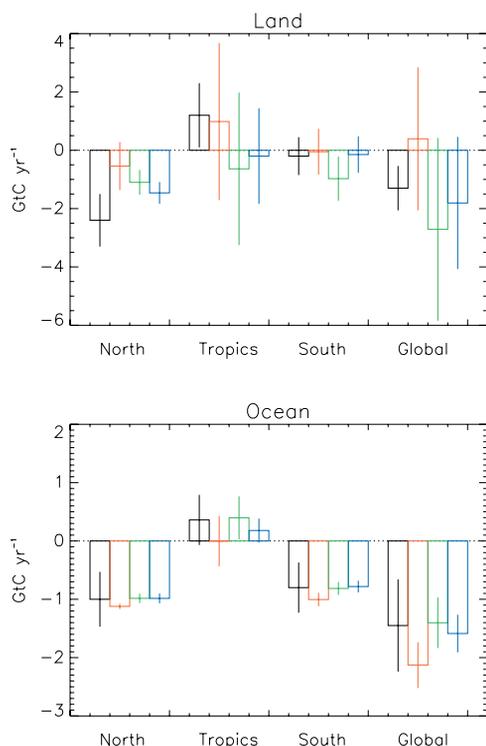
Figure 2. Impact of non-greenhouse gas forcing on the simulation of carbon sinks for the post-Pinatubo period (1992–1996). The units are GtC yr^{-1}, positive values denote a source of CO_2 to the atmosphere. (a) over land, (b) over ocean. Estimates from inversion of atmospheric CO_2 measurements [*Gurney et al.*, 2002] (black bars), are compared to 3 model simulations; Cox00 (red bars), ALL (green bars) and ALL70 (blue bars). The observation and model error bars in the figure form a useful comparison although they do not represent exactly the same type of uncertainty. The error bars on the observed quantities represent an estimate of observational error, whereas model error bars are based on the simulated interannual variability.

overestimate of a tropical sink are consistent with an underestimate of land-use emission in the tropics [*Fearnside*, 2000], balancing an underestimate of forest regrowth in the north [*Read et al.*, 2001].

[21] The increased terrestrial uptake is largely a result of the cooling associated with the extra forcings in ALL, which suppresses the increased soil respiration caused by the global warming, although there is also a contribution from a delay of the Amazon dieback in ALL. Figure 3 shows the impact on global temperature and vegetation and soil carbon stores of the extra climate forcings by the year 2000. The cooling is mainly located over the northern hemisphere industrialised areas [*Johns et al.*, 2003], which produce the majority of anthropogenic sulphur emissions.

3.3. Future

[22] As can be seen in Figure 1b, the rate of rise of CO_2 in ALL increases rapidly above that in the IS92a concentration scenario beyond 2000. The mechanisms for this positive feedback, similar to Cox00, are loss of soil carbon due to enhanced soil respiration as the climate warms and dieback of the Amazon forest due to regional rainfall

reduction. By 2100 the CO_2 concentration is 980 ppmv. The terrestrial biosphere undergoes a transition from being a net sink of carbon to become a net source in about 2040, a decade later than was the case without the extra climate forcings. The slower rate of rise of CO_2 during the 20th century in ALL is compensated by a more rapid rate of rise in the latter part of the 21st century, as anthropogenic sulphate emissions decline. As a result, global temperature in ALL increases more abruptly during the 21st century (Figure 1a).

[23] The primary driver of the more rapid change in ALL is the reducing anthropogenic sulphate emissions projected for the second half of the 21st century, which imply a reducing aerosol cooling of the climate system (i.e. a net warming). The reducing emissions are only partially offset by suppressed dry deposition due to CO_2-induced stomatal closure and, to a lesser extent, changes in vegetation distribution.

[24] The accelerated temperature increase in ALL is amplified by positive climate-carbon cycle feedbacks. Cox00 has a smaller and shorter-lived increase in land carbon storage, Figures 1c and 1d, while ALL accumulates more carbon (especially in the soil) for longer before
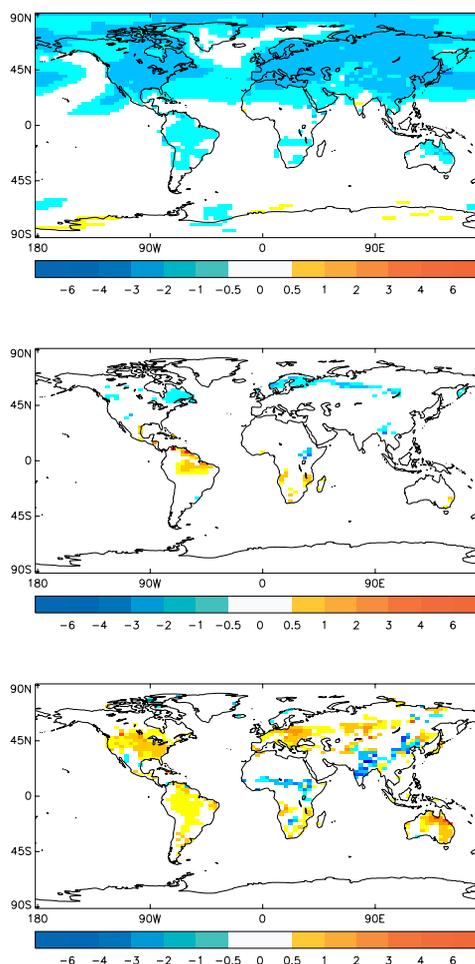
Figure 3. Impact of non-greenhouse gas forcing on the simulation of the current climate and land carbon state, calculated as the mean differences between ALL and Cox00 for 1970–2000. (a) Surface air temperature (K), (b) vegetation carbon (kg C m^{-2}), (c) soil carbon (kg C m^{-2}).

decreasing more rapidly. Despite slightly lower (but more rapidly increasing) temperatures in ALL, which act to lower the *specific* soil respiration rate, the absolute soil respiration rate is higher by about 1.2 GtC yr^{-1} due to a larger soil carbon reservoir.

[25] As in Cox00, these results are subject to uncertainties associated with the sensitivity of regional climates to CO_2 increase (e.g. the extent of Amazon rainfall reduction), and ecophysiological responses to climate, CO_2 and other environmental changes (e.g. neglected nitrogen deposition effects). Work is underway to reduce these uncertainties by, for example, using observed carbon cycle variability to constrain key internal model parameters such as the sensitivity of soil respiration to temperature [*Jones and Cox*, 2001a; *Jones et al.*, 2003].

4. Conclusions

[26] For the first time, both interactive carbon and sulphur cycles have been incorporated in a GCM climate change projection with a full set of natural and anthropogenic climate forcing factors. This more complete treatment of the Earth system has been found to improve the simulation of historical climate change. We have also found these extra forcings to have a significant impact on the carbon cycle. The overestimate of present day CO_2 in a previous climate-carbon cycle model [*Cox et al.*, 2000] has therefore been shown to be due in large part to the omission of these important additional forcing factors. The direct and indirect cooling effects of sulphate aerosols play a key role, suppressing the rate of warming due to greenhouse gases, and thereby increasing historical carbon accumulation by delaying the negative impacts of climate change on the land carbon cycle.

[27] However, this effect is only transient. Anthropogenic sulphate emissions are expected to reduce strongly throughout the 21st century, leading to a reducing negative forcing (i.e. a net warming) from sulphate aerosols. Future climate change is therefore projected to be more rapid when these additional factors are included, fuelled partly by more abrupt carbon cycle feedbacks as the additional carbon accumulated in the soils during the historical period is released to the atmosphere. By 2100 strong positive feedbacks between climate and the carbon cycle have accelerated the rate of global warming and CO_2 increase.

[28] This work indicates that strong positive carbon cycle feedbacks in the future are consistent with the historical record provided non-greenhouse gas forcing factors are taken into account. These additional climate forcings are doubly important, since these both directly determine key aspects of climate change and its consequences, and also indirectly influence climate change through their impact on the future trajectory of atmospheric CO_2.

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