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Using a GCM analogue model to investigate the potential for Amazonian forest dieback

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With 3 Figures

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Summary

A combined GCM analogue model and GCM land surface representation is used to investigate the influences of climatology and land surface parameterisation on modelled Amazonian vegetation change. This modelling structure (called IMOGEN) captures the main features of the changes in surface climate as estimated by a GCM with enhanced atmospheric greenhouse gas concentrations. Advantage is taken of IMOGEN's computational speed which allows multiple simulations to be carried out to assess the robustness of the GCM results.

The timing of forest dieback is found to be sensitive to the initial "pre-industrial" climate, as well as uncertainties in the representation of land-atmosphere CO_2 exchange. Changing from a Q_{10} form for plant dark and maintanence respiration (as used in the coupled GCM runs) to a respiration proportional to maximum photosynthesis, reduces the biomass lost from Amazonia in the 21st century. Replacing the GCM control climate (which has about 25% too little rain in the annual mean over Amazonia) with an observed climatology increases the CO_2 concentration at which rainfall drops to critical levels, and thereby further delays the dieback. On the other hand, calibration of the canopy photosynthesis model against Amazonian flux data tends to lead to earlier forest dieback. Further advances are required in both GCM rainfall simulation and land-surface process representation before a clearer picture will emerge on the timing of possible Amazonian forest dieback. However, it seems likely that these advances will overall lead to projections of later forest dieback as GCM control climates become more realistic.

1. Introduction

Predictions from Version 3 of the Hadley Centre General Circulation Model (HadCM3) indicate that for enhanced atmospheric concentrations of greenhouse gases, Amazonia is likely to suffer a general reduction in rainfall and an increase in surface temperature. The atmospheric components of HadCM3 are given by Pope et al. (2000). Using surface climatologies generated from a simulation under IPCC emission scenario IS92a (Houghton et al., 1992), White et al. (1999) forced a dynamic vegetation model, HYBRID (Friend et al., 1997; Friend and White, 1999). It was found that the adjusted climate triggered dieback of the Amazonian rainforest by 2080.

Cox et al. (2000) introduced a closed representation of the carbon cycle into the Hadley Centre GCM, creating a model version called HadCM3LC. This version of the GCM includes an interactive vegetation model (called TRIFFID; see Cox, 2001), and using this coupled climate model it was found that the Amazonian rainforest was also predicted to disappear under conditions of enriched atmospheric greenhouse gas concentrations (Cox et al., 2000). Further details of

climate change predictions by HadCM3LC over Amazonia are given by Cox et al. (2004) and detailed analysis of related land-atmosphere feedbacks are given by Betts et al. (2004). Analysis of aspects of the dynamic vegetation model pertinent to dieback are given by Huntingford et al. (2000).

The GCM simulation of Cox et al. (2000) produces a significant acceleration of CO_2 increase and therefore climate change in the 21st century, due to the suppression of land carbon uptake by the projected climate change. The largest contribution to this comes from the widespread loss of soil carbon as increasing temperatures enhance rates of soil decomposition. However, the most marked regional impacts are in Amazonia where rainfall reduction and climbing temperatures make the climate unsuitable for tropical forests. The resulting forest "dieback" releases vegetation and soil carbon into the atmosphere, contributing about 11% of the projected total land carbon feedback over the 21st century (Cox et al., 2004). More importantly, such a loss of the Amazonian rainforest would represent a human-induced ecological catastrophy of unprecedented proportions (direct deforestation aside).

It is computationally too expensive to undertake coupled GCM simulations for a range of values of vegetation parameters and initial conditions. However, this is precisely what is required to assess uncertainties in predictions of large-scale land surface phenomena such as potential dieback. Huntingford and Cox (2000) developed a "GCM analogue model" that exploits propagating patterns of climatological change observed within transient GCM simulations. Patterns of change are found to be highly linear with respect to global surface temperature, which in turn is related to the history of atmospheric greenhouse gas concentrations. The resultant modelling structure is computationally fast, has common features with the GCM and can interpolate single GCM simulations to study new emission scenarios. Output is a transient estimate of surface climatology, by month and at the same spatial grid as the GCM. This output may then be used to force GCM land surface schemes.

For this study the GCM analogue model has been extended to include a closed representation of the global carbon cycle. The resultant model is driven by a prescribed scenario of global carbon emissions (along with specification of atmospheric concentrations of non-CO_2 greenhouse gases).

2. Addition of a global carbon cycle to the GCM analogue model

The original GCM analogue model (Huntingford and Cox, 2000) exploits linearities between near-surface climate and global mean land temperature change, as observed in HadCM3 for a broad range of atmospheric greenhouse concentrations. Changes in radiative forcing are calculated for given time-varying atmospheric concentrations of greenhouse gases. These are translated into changes of global land temperature through the use of a global thermal "box" model. The derived temperature values are then used to scale spatial and seasonal patterns of change, based on the linearities of HadCM3. It is these patterns of change, for a range of surface climate variables, that provide the basis of the GCM analogue model.

Here, the GCM analogue model has been modified to include the global carbon cycle. The model now incorporates land-atmosphere and ocean-atmosphere fluxes of carbon dioxide and so can predict the ability of the land and ocean to either mitigate or amplify the effects of fossil fuel burning. The carbon dioxide fluxes to and from the surface change the predictions of atmospheric carbon dioxide concentration, which in turn influences global land temperature as outlined above. The change in the global carbon cycle is described by a simple conservation equation:

$$\Delta C_{\mathrm{atm}} = \Delta C_{\mathrm{emiss}} + \Delta C_{\mathrm{land}} + \Delta C_{\mathrm{ocean}},$$

where ΔC_{atm} (GtC) is the change in atmospheric carbon since pre-industrial periods, $\Delta C_{\mathrm{emiss}}$ (GtC) is the accumulated anthropogenic emissions into the atmosphere, ΔC_{land} (GtC) is a global integration of the land-atmosphere flux and $\Delta C_{\mathrm{ocean}}$ (GtC) is a global integration of the ocean-atmosphere flux. A negative value for either of the last two quantities implies that the land or ocean has taken up carbon.

With these modifications, the GCM analogue model becomes a new climate change "impacts" assessment tool which we have called IMOGEN (Integrated Model Of Global Effects of climatic