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Amazonian climate: results and future research

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Summary

Some of the results from the climate component of the Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA), which are presented in this Special Issue are summarised. Recent advances in Amazonian climate modelling are also discussed. There is a range of papers which fall into three groups: surface fluxes and boundary layer growth; convection, clouds and rainfall; and climate modelling. The new insight given by this work is discussed and an argument is made for future research to employ a wider approach to Amazonian climate modelling.

1. Introduction

Amazonia is a major source of heat and water vapour for the global atmosphere. It covers a vast area and is positioned in the tropics, where the exchange of energy between the land surface and the atmosphere is at a maximum. Changes in Amazonia are thus likely to have an impact on atmospheric circulations and the hydrological cycle, not only over South America but in other parts of the world as well. As an example, Gedney and Valdes (2000) used a Global Climate Model (GCM) to demonstrate that deforestation in Amazonia could have a significant effect on climate over the Atlantic Ocean near South West Europe. Furthermore, Amazonia plays a critical role in the global budget of carbon dioxide. It is certain that deforestation in Amazonia is one of the causes of the rising global atmospheric carbon dioxide concentration, which is expected to result in climate change. On the other hand, it is quite possible that the undisturbed forests of tropical South America are currently a sink of atmospheric carbon dioxide. Through a separate process, Cox et al. (2000) have also shown the potential for future global climate change to be accelerated by a positive feedback mechanism whereby the vegetation of Amazonia changes from being a sink of carbon, to being a source.

At present GCMs are the main tool for climate change prediction. The requirements placed on them are very broad: in the case of Amazonia, they must capture the large scale response to enriched atmospheric greenhouse gas concentrations, ensure that natural climate oscillations at the interannual or longer timescales are represented faithfully, and they must portray likely atmospheric responses to land surface changes, such as deforestation. However, to move from GCM predictions of large scale climate to an understanding of the future functioning of Amazonia implicit in such simulations, these estimates of the future have to be disaggregated to a finer spatial scale which acknowledges the variability within the region. Interannual variability and extremes are a particular concern in the prediction of South American climate because of the influence of El Niño effect. Because changes in the strength and frequency of El Niño events are likely to be the dominant factor in deciding the future climate of Amazonia, it is important that we understand how El Niño is controlling the current climatic variability. It is extreme weather that will have the dominant impact on society and ecosystems alike.

Predicting climate change requires combining the description of processes that have continental scale variation – interactions with oceans, land and major topography – with smaller scale processes ranging down in size to those describing soil and vegetation response. Fortunately these model components can be operated in isolation and therefore may be checked and calibrated against available environmental measurements. This calibration of GCM components is essential to enhance confidence in our understanding of the Earth system, make predictions of future change and, here, to interpret the role of Amazonia. Yet even now, Amazonia is still a very remote and inaccessible region with a low population. The number of climate and upper air stations is minuscule and, notwithstanding a number of well-documented experimental campaigns (e.g. Gash et al., 1996, or see the summary by Nobre et al., 2004), field data are scarce. This lack of data hinders our ability to refine climate prediction models, and was one of the main motivations which led Brazil to initiate the Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA).

The search for understanding of how Amazonia functions as a regional entity is complicated by the fact that it cannot be considered stationary. Most of Amazonia is still covered by rainforest, but this is changing as the pressure of an expanding human population and new infrastructure, such as roads, leads to deforestation and the establishment of agriculture. At the same time, Amazonia is subject to the effects of a changing global environment, mainly as a result of emissions from burning fossil fuel. This Special Issue has presented a collection of linked papers that investigate the importance of both these changes. The papers may be loosely regarded as falling into three complementary categories. The first set of papers focus on land surface behaviour and the atmospheric boundary layer. The second group addresses the complex issues of atmospheric convection, clouds and rainfall from a climatological perspective. Finally, a third group of papers present modelling results from mesoscale models, and transient GCM simulations with various model configurations.

2. Key results

2.1 Land surface and boundary layer behaviour

At the start of LBA it was not clear how rainforest responded to drought. At the regional scale it was known that moving away from the equator the average length of the dry season increases until a point is reached where the soil moisture store is insufficient to maintain rainforest transpiration throughout the year. The forest then gives way to savanna vegetation. However, while it was understood that rainforest adopts a deep rooting strategy to allow it to survive dry periods (Hodnett et al., 1996), it was not clear whether, or to what degree, the transpiration is reduced by plant physiological controls under drought conditions. Recently, Malhi et al. (2002) and Harris et al. (2003) have identified a soil moisture dependence in surface conductance that demonstrates forest previously thought to have sufficient soil moisture can exhibit a seasonal response to soil moisture stress. It is important to model this process well, because changes in the dry season partitioning of net radiation into sensible and latent heat flux (i.e. the Bowen ratio) may affect the thermodynamics and dynamics of the atmosphere over the region and hence feedback to affect the regional rainfall.

In this volume Harris et al. (2004) use data from the two forest sites near Manaus, to test the performance of a set of default GCM land-surface model parameter values. The results highlight deficiencies in the modelled response of canopy conductance to solar radiation, which lead to overestimated Bowen ratios and underestimated daytime carbon dioxide uptake. Calibrating stomatal and soil parameters in the model against the Manaus carbon dioxide and water vapour flux data improved simulation of the Bowen ratio, and the diurnal cycles of carbon dioxide uptake and energy fluxes. The latter are important for initiating modelled convection in GCMs and driving the regional circulation. It was only possible to simulate the mean measured Bowen ratios at both the forest sites when revised soil parameter values were used. These revised parameters reflect the low soil water holding capacity found around Manaus which limits dry season transpiration. While the modelled net carbon balance remained approximately neutral before and after calibration (increased daytime photosynthesis is compensated by increased night-time autotrophic respiration), the reduced plant available water would affect the model's functioning under future climate change, where central Amazonia is likely to become drier and warmer (Cox et al., 2004).

The design of LBA consolidates the trend away from data collection in short measurement campaigns to collecting continuous data over periods of a year or longer. Von Randow et al. (2004) have analysed the data from the LBA sites in Rondônia, which have a long record of fluxes from both forest and pasture. Particularly for the forest, the eddy covariance measurements of the energy fluxes suffer from the systematic undermeasurement relative to the net radiation which typically bedevils measurements of this type. Energy closure at the forest site was still no better than 84 per cent, despite following the recommendations of Finnigan et al. (2002), for long averaging and coordinate rotation times, and of Gash and Dolman (2003), and van der Molen et al. (2004), for angle-of-attack dependent sonic anemometer calibration. Nevertheless there is still much insight to be gained from the data and von Randow et al. use the comparative measurements of the radiation balance, the heat, water vapour and carbon dioxide fluxes, and the soil moisture to study the different functioning of the two vegetation types and how this varies with season. The pasture and forest behave very differently, especially in the dry season where the shallow roots of the grass result in lower evaporation. Both photosynthesis and respiration are relatively lower in the pasture compared to the forest, but the respiration more so. This leads to the important result that the pasture is a relatively stronger sink of CO_2 than the forest. A more comprehensive carbon analysis is needed to include the effect of animal grazing, nevertheless this study emphasises the need for experiments with coupled models which include carbon feedback and are driven by realistic scenarios of vegetation land *use* change (i.e. conversion of forest to pasture), as well as land *cover* change (i.e. rainforest giving way to savanna vegetation) resulting from changed climate.

The differences in behaviour between the forest and pasture are consistent with the seasonal differences in growth of the atmospheric boundary layer over the same surfaces. During the dry season at the LBA Rondônia sites, Fisch et al. (2004) observed greater boundary layer growth over the pasture than over the forest, with the boundary layer over the pasture being typically 1650 m, compared to 1000 m over the forest. However, during the wet season the boundary layer heights for both biomes were around 1000 m. This phenomenon was reproduced by Fisch et al. in a 2-dimensional simulation using a mesoscale model. Because the boundary layer connects the surface to the free atmosphere above, it is a vehicle through which changes in surface properties can be translated into changes in convection and cloud formation. It is thus important that the boundary layer is correctly modelled. The data presented by Fisch et al. are benchmark measurements against which model performance should be assessed.

2.2 Convection, clouds and rainfall

The papers by Fu and Li (2004), Machado et al. (2004) and Marengo (2004) investigate the climate of Amazonia for the present and recent past. Their analyses make use of satellite data and operational weather centres' reanalysis products – essential in such a data-poor region – to study convection and rainfall variability, covering intraseasonal to decadal time scales. Their results show the importance of both the remote (sea surface temperature anomalies in tropical oceans) and local (changes in land surface characteristics, soil wetness) factors in creating variability in rainfall, the hydrological balance characterised by accumulated rainfall, and the dates of the onset of the rainy or dry seasons, across the whole of the Amazon basin.

Understanding the functioning of convective processes and associated rainmaking processes is an essential prerequisite to obtaining a complete description of how Amazonia functions today. Machado et al. (2004) combine four long time series of simultaneous surface meteorological and radiosonde measurements with satellite data, to characterise the development of cloud over Amazonia, and to reveal the role of convection, and its interactions with the large scale circulation patterns and associated forcing.

At a longer time scale, the transitions between dry and wet seasons and the associated interactions with the hydrological cycle are critical climatic features. Fu and Li (2004) demonstrate the importance of land surface feedbacks in the timing of dry–wet season transition for Amazonia. The transition is enhanced and induced earlier following higher than average rainfall amounts during the dry season. This earlier "triggering" of rainfall by surface contributions adding to wet season moisture convergence illustrates the potential impact of land use change on wet season duration as a possible mechanism through which deforestation could produce large scale change.

Marengo (2004) discusses climate variability in the Amazon basin at interannual and longer time scales, and considers the influence of El Niño in year-to-year rainfall variability. The importance of the remote tropical forcing in Amazonian rainfall suggested by this paper complements the findings of Fu and Li (2004) on the impact of the land surface on the hydrological cycle and moisture transport in Amazonia. To characterize interannual and interdecadal variations for the present climate, Marengo (2004) undertakes a full investigation of long-term records of raingauge (point and gridded) measurements. Variations in regional rainfall at an inter-annual timescale are particularly prominent in northern Amazonia due to El Niño Southern Oscillation and this variability has been affected by decadal scale variations, especially observed changes in the mid-1940s and 1970s that were reflected in regime shift in rainfall all across the basin.

These papers add significantly to our understanding of interannual variability and the timing of rainfall events. If this current climate behaviour can be reproduced by climate models we gain confidence in our ability to predict the future. The prediction of year to year variation in rainfall is especially important, because it is not the average change but the extremes that will have the largest effect on ecosystems. It is essential that climate modelling captures these extremely dry years (or combinations of extremely dry years) for current and future atmospheric greenhouse gas concentrations.

2.3 Insights from modelling

The River Tapajós is some 20 km wide at its confluence with the Amazon, comparable with the length scale of boundary layer generation processes, and Silva Dias et al. (2004) show that these rivers are of sufficient size to affect local climate by the generation of river breezes. The combination of field measurements and a mesoscale model provides a powerful demonstration that the process occurs and emphasises the point that Amazonia is not uniform; the forest is often interspersed with large areas of water. In the case studied here, the mesoscale circulations associated with the river breeze phenomenon were strong enough to reverse the trade wind and resulted in anomalous cloud formations.

This theme is continued in the model experiment of Gandu et al. (2004). These authors used a nested mesoscale model to study the effect of deforestation on the climate of eastern Amazonia. Comparison of the output from the control run, with a forested landscape, with the same area after deforestation demonstrated the complexity and non-uniformity of local features and feedbacks. Topography, large rivers and the proximity to the coastline all influence the degree to which deforestation affects the new modelled climate. This study emphasises that Amazonia should not be expected to respond to environmental change as a single uniform plane. Just as the region is a complex mixture of land and water, with soil, topography and the driving climate all varying, so the local impacts of change will also vary. This paper points the way to the future modelling studies, which are needed to investigate the local scale impacts in response to both deforestation and global climate change induced by increased greenhouse gas concentration.

When photosynthesis and respiration models are coupled to a dynamic vegetation model and introduced into a GCM, it is possible to estimate the influence of the land surface in mitigating or amplifying the effects of increased atmospheric CO_2 concentration. In one simulation with such a coupled model Cox et al. (2000) made the startling prediction that under the IS92a ''business as usual'' emission scenario, the climate over South America would change to such a degree that the rainforest would become unsustainable, with significant ''dieback'' occurring from around 2050 onwards. A positive, global feedback was then predicted to occur as the loss of carbon by the rainforest through respiration enhanced atmospheric CO_2 concentration, thereby amplifying the effects of global warming.

The findings of Cox et al. (2000) are important and warrant a more comprehensive analysis than was possible previously. In this Special Issue Cox et al. (2004) provide a more detailed description of their earlier dieback result with an emphasis on the predicted reduction in rainfall and increase in temperature, and the associated connections with the emergence of more persistent El Niño-like patterns in Sea Surface Temperatures. Although the prediction of more frequent El Niño-like SST patterns is common to many GCMs; not all GCMs translate this into reduced rainfall over Amazonia. However, observed connections between SST patterns and rainfall for current climate are reproduced by the Hadley Centre GCM (Cox et al., 2004), indicating the predicted interplay between ocean temperature and Amazonian rainfall is realistic. Betts et al. (2004) analyse the two feedbacks that occur as the rainforest suffers dieback – the global feedback outlined above of plant and soil respiration accelerating global warming, and the regional feedback whereby the loss of forest cover reduces evaporation and the recycling of rainfall across the basin. This latter feedback aggravates the greenhouse gas induced reduction in Amazonian rainfall.

Although Global Circulation Models are our best available tool to understand and predict climate change, model runs are time consuming and even using the fastest available computers, a simulation from the pre-industrial period to the end of the 21st Century requires several months before the results are available for analysis. In addition, full climate models can be difficult to modify and operate. Yet many of the issues creating uncertainty in the future response of Amazonia are associated with possible changes in the land surface response, and there is a need to test the sensitivity of the predictions to the land surface parameterizations. This situation can be resolved by using the Huntingford and Cox (2000) ''GCM analogue model'', which is an efficient method of capturing the salient features of changes in surface climatology expected for prescribed increases in atmospheric greenhouse gas concentrations. Here, this tool has been extended by Huntingford et al. (2004) by coupling to the GCM land surface scheme, and including an interactive carbon cycle. This allows assessment of both ecosystem response and the associated feedbacks on atmospheric CO_2 concentration for a range of model parameter values and configurations. The set of analogue model runs presented by Huntingford et al. reveal that the GCM results are highly sensitive to the specification of the land surface parameters and the initial climatology. The analogue model can be initialised either with observed climatology, or the GCM's prediction of current climate. This is a powerful capability which has been used to demonstrate the degree to which the predicted timing of forest dieback depends on the GCM estimate of the rainfall over Amazonia for the present climatology. If, as it does, the GCM under-estimates current rainfall, then forest dieback will occur earlier in the GCM prediction than should be expected in reality. On the other hand, implementation of the new surface parameters derived by Harris et al. (2004) indicates that the onset of dieback could occur earlier than the decade of the 2050s suggested by the analysis of Cox et al. (2000).

3. A perspective on future climate research

The overall motivation behind LBA is to create the components of scientific understanding of processes at the local level so that they can be pieced together to give knowledge and understanding of how Amazonia functions as a region. With this understanding, assessments of how the region may function in the future have more credibility. Ideally, policymakers will use these predictions to guide decisions so that the region will adapt and develop in ways that mitigate, rather than exacerbate, the effects of global climate change; while keeping the ecosystems ability to provide the environmental services for current and future generations of Amazonian inhabitants.

Physical Climate is just one of several components that make up LBA and the climate-focussed papers presented in this Special Issue are therefore reporting only a small fraction of the work in LBA. However, taken together, they show that the objectives of LBA are achievable. It can be seen that we now have a growing understanding of:

i. the behaviour of surface fluxes under conditions of water stress and data that can be used to calibrate models,
ii. boundary layer development, clouds and rainfall, and datasets against which GCM estimates of current climate can be checked
iii. the role of mesoscale land surface features in defining climate
iv. the regional scale interaction between Amazonia and the large scale atmospheric and oceanic circulations and,
v. the role of Amazonia in the global carbon cycle, and the potential large-scale changes in regional vegetation due to global warming-induced climate change.

The objective should now be to use fine scale GCMs, or nested Regional Climate Models (RCMs) over South America. These models should have realistic fine scale representations of large rivers, coastlines and topography, but also accurate, current land cover and realistic descriptions of the future, based on possible scenarios of future land use. Sets of RCM/GCM modelling experiments need to be designed to show the combined effects of climate change induced by fossil fuel burning and by deforestation, for a set of development and emission scenarios. These experiments need to be analysed to predict not just the average climate, but equally changes in the frequency of the extremes.

Article 2 of the UNFCCC: states that greenhouse gas levels should be stabilised at a level that "would prevent dangerous anthropogenic interference with the climate system" and that this "should be achieved in a time-frame sufficient to allow ecosystems to adapt naturally ...". We need to know what this means for the ecosystem of Amazonia. Specifically, we need to know what this means in terms of critical thresholds in the response of the rainforest to a time-evolving climate forced by fossil fuel emissions, in combination with a suite of potential deforestation scenarios.

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