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Isotopes as validation tools for global climate models

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SUMMARY

Global Climate Models (GCMs) are the predominant tool with which we predict the future climate. In order that people can have confidence in such predictions, GCMs require validation. As almost every available item of meteorological data has been exploited in the construction and tuning of GCMs to date, independent validation is very difficult. This paper explores the use of isotopes as a novel and fully independent means of evaluating GCMs. The focus is the Amazon Basin which has a long history of isotope collection and analysis and also of climate modelling: both having been reported for over thirty years. Careful consideration of the results of GCM simulations of Amazonian deforestation and climate change suggests that the recent stable isotope record is more consistent with the predicted effects of greenhouse warming, possibly combined with forest removal, than with GCM predictions of the effects of deforestation alone.

1. ISOTOPES AND GCMS IN THE AMAZON

Global climate modelling and isotopic analysis in the Amazon both have histories of over thirty years (e.g. Salati *et al.*, (1) and McGuffie and Henderson-Sellers (2)) and these histories are not unconnected. For example, an important review of Amazonian isotopic and other data was published by Salati and Vose in 1984 (3). This paper was influential because its publication coincided with the first reports of a simulation using a Global Climate Model (GCM) to assess the possible impact of deforestation of the Amazon. Indeed, Salati and Vose (3) quote preliminary (1983) results from the work of Henderson-Sellers and Gornitz (4). Although the Salati and Vose (3) paper was primarily a collection of their, and others', previous work with isotopic analysis, it underlined to the newly emerging global climate modelling community that the Amazon recycles about half its water within its basin.

Important papers were published in the early 1990s on the subject of isotopic analysis of Amazonian precipitation and its implications for regional hydrology and climate. Gat and Matsui (5) employed a simple box model of the central Amazon Basin to demonstrate that some of the water recycling is from fractionating sources. Using data from the International Atomic Energy Authority/World Meteorological Organization (IAEA/WMO) global station network up to 1981, they interpreted a +3‰ deviation from the World Meteoric Line as indicative of 20-40% of the recycled moisture within the basin being derived from fractionating sources such as lakes, the river or standing water. The paper by Victoria *et al.* (6) also used IAEA/WMO data; they analysed isotopic results from Belem and Manaus over the fourteen year period from 1972 to 1986. Using the box/sector model of Dall'Olio (7) these researchers were able to employ isotopic data to show that wet season recycling is by means of transpiration while dry season recycling in the Amazon is primarily by re-evaporation of precipitation intercepted on the canopy. Since the mid 1990s, there have been relatively fewer papers on Amazonian isotopes, although Gat (8) reviews some work and reports that an updated model of the Amazon's water balance, which uses isotopic input, improves earlier predictions.

The first GCM simulation of the impact of Amazonian deforestation was published by Henderson-Sellers and Gornitz in 1984 (4). Since then, there have been a large number of similar GCM simulations. Some of the differences in the outcomes of GCM predictions are due to the imposed differences in surface albedo, surface roughness, density and mix of original and replacing vegetation, soil type and state and so on. McGuffie *et al.* (9) review the problems associated with correctly specifying climate model parameters in both control (present day) and deforested simulations and find that almost all models predict increased surface temperatures following deforestation. There is also general agreement that both precipitation and evaporation decrease but less consensus on the sign of the change in atmospheric moisture convergence (e.g. Table 1, top line). A detailed literature survey has not revealed any GCM simulations of the impact of Amazonian deforestation tested against the available isotopic data. This is partly the result of the relevant research communities' ignorance of one another. It may also be because very few GCMs have, as yet, included isotopic composition as a computed variable. Notable exceptions include work by Jouzel *et al.* (10,11) but neither of these studies include consideration of deforestation impacts.

Table 1. Stable isotopic and global climate model characterisation of climate change in the Amazon

Amazonian Deforestation Simulations (e.g. McGuffie *et al.* (9))	- decrease in precipitation - decrease in evaporation - less water recycling - ?decrease in atmospheric moisture convergence
Recent Isotopic Record (derived here)	- more water recycling in the wet season - greater relative importance of transpiration and canopy evaporation in the wet season - decrease in runoff ratio (equivalent to a decrease in atmospheric moisture convergence)
Greenhouse Impacts in Amazon (e.g. Houghton *et al.* (12))	- increase in precipitation - increase in evaporation - intensification of hydrological recycling - ?sign of atmospheric moisture convergence change unknown

The data used in this study were obtained from the Global Network for Isotopes in Precipitation database (13), jointly maintained by the World Meteorological Organization (WMO) and the International Atomic Energy Agency (IAEA) since 1961. From each Amazon station, monthly average values of temperature, humidity, precipitation, precipitation type, deuterium, oxygen-18 and tritium are available (Table 2). As part of ANSTO's ongoing research into the possible synergies between isotopic and global climate modelling studies of Amazonian deforestation, we have examined these IAEA/WMO station records in the Amazon Basin for temporal trends. We find noticeable changes in the wet season, which extends from about December to May. The continental gradient of $\delta^{18}O$, already the weakest in the world, has been further weakened over the last three decades in the wet months from December to May.

Table 2. IAEA/WMO Amazon Basin isotope collection station location details and availability. The last column is the percentage of the total months of observation for which both deuterium (D) and oxygen 18 (^{18}O) observations are available.

Station	IAEA ID#	Location	Alt (mASL)	Operational	No. Months & % of total	% time for D and ^{18}O
Belem	8219100	1.43°S, 48.48°W	24	1965-1987	264	87.5%
Cayenne	8140500	4.83°N, 52.37°W	8	1962-1975	156	38.5%
Manaus	8233100	3.12°S, 60.02°W	72	1965-1990	300	52.0%
Porto Velho	8282500	8.77°S, 63.92°W	105	1965-1983	216	33.3%
Sao Gabriel	8210600	13.0°S, 67.08°W	87	1961-1990	348	26.7%
Izobamba	8404400	0.37°S, 78.55°W	3058	1968-1997	324	93.1%

In the 1960s, when the collection of isotopic data began in the Amazon Basin, monthly average values of the deuterium excess at Manaus were significantly greater than at Belem for both the wet and dry seasons. Furthermore, there was no significant difference between the mean monthly deuterium excess values from the wet to the dry season at either the coastal or interior sites. By the 1980s, the Belem mean monthly deuterium excess for both the wet and dry seasons have increased slightly compared to the values in the 1960s, but the difference is not statistically significant. In contrast, large changes are observed in the seasonal deuterium excess inside the basin at Manaus. Although the annual mean deuterium excess at Manaus in the 1980s (11.83±0.44‰) is not significantly different to that in the 1960s (12.62±0.48‰), results now show a significant difference between the wet and dry season values. In particular, the deuterium excess has decreased in the wet season and increased in the dry season. The difference in deuterium excess between Belem and Manaus is also much reduced in the wet season and Manaus' wet season value is significantly decreased in the 1980s.

Plausible explanations of the wet season deuterium excess decrease involve either more non-fractionating (e.g. transpiration) or less fractionating (e.g. lake) recycling, or both. Thus the observed temporal shift in isotope data (1960s to 1980s) requires a change in the recycling behaviour in the Amazon. These isotopic results are consistent with the GCM deforestation predictions, which show less overall transpiration only if there has been a relative decrease in the evaporation of water from lakes and other fractionating sources over this period. Table 1 summarizes the divergence among present day characterizations of Amazonian climate change as derived from (i) deforestation studies with GCMs; (ii) isotopic data; and (iii) greenhouse simulations with GCMs.

2. ISOTOPIC EVALUATION OF GCMS' SIMULATION OF THE AMAZON REGION

There are at least two methods available for isotopic evaluation of GCMs' simulation of the Amazon climate. One is to utilize the results such as those of Gat and Matsui (5) regarding the relative amounts of water recycled in the Amazon from fractionating and non-fractionating sources. They deduced by comparing deuterium and oxygen isotopic observations with results from their box model of the central Amazon Basin that of the input precipitation 10%-20% is re-evaporated from fractionating sources (e.g. lakes and rivers), 30%-40% from non-fractionating sources (e.g. transpiring plants and complete re-evaporation of canopy-intercepted water), with about half of the total hydrological budget going to runoff. These values ought to be able to can be used to evaluate GCMs. Here, this method is tested using a series of GCM experiments conducted with the USA's National Center for Atmospheric Research's Community Climate Model (CCM1-Oz) (McGuffie *et al.* (9)).

The GCM results analyzed are found to be different from those of Victoria *et al.* (6) who claimed on the basis of isotope analysis that transpiration is the major source of recycled water in the wet season. We find that at least one GCM simulates transpiration as being very much more significant in the Amazon forest's dry season budget of recycled water. Unfortunately, although the land surface scheme (BATS – the Biosphere Atmosphere Transfer Scheme) used in the CCM1-Oz simulations does permit inclusion of lakes, this option was not used in these GCM experiments. It was therefore not possible to examine the Gat and Matsui (5) conclusion regarding the fraction of recycled moisture from lakes directly.

Although these results are somewhat inconclusive, it appears that there are grounds for suspecting that a more thorough examination of the components of the Amazonian water cycle using isotopic data could both reveal inadequacies in some current climate model simulations and, hopefully, indicate how simulations by GCMs could be improved to more completely and correctly capture important moisture exchanges. This is an interesting issue because it has been shown that tropical deforestation has the potential to excite large-scale Rossby waves in the atmosphere. These waves can propagate from the source of their initiating disturbance into the middle and high latitudes of both hemispheres and, hence, prompt impacts far distant from deforestation in the Amazon (14).

This isotope-GCM "missing link" is a second method of GCM evaluation using isotopes which warrants further detailed study. One possibility is that the temporal isotopic records are illustrative of the impact of Amazonian deforestation. At present, the available GCM studies are unable to demonstrate or deny the validity of this conclusion. Another possibility that deserves some consideration is that the disturbances in the isotopic record over time have not been caused solely by forest removal. Although the regional extent of deforestation in the Amazon is great, there are other effects which may also be contributing to the observed temporal shifts in the isotopic signatures. These could include both the direct and indirect effects of greenhouse gas increases.

There have been very few GCM studies so far which have attempted to assess the impact of deforestation and greenhouse gas increases in the Amazon. The paper by Henderson-Sellers *et al.* (15) was not focussed on deforestation but did consider plant physiological responses to increased atmospheric CO_2 levels which includes stomatal closure. Costa and Foley's (16) study is a much more sophisticated evaluation of the independent and combined effects of stomatal closure in response to an enriched CO_2 atmosphere, deforestation and greenhouse warming. Zhang *et al.* (17) consider the latter two effects but not the plant physiological responses. The challenge for future use of isotopic signatures for GCM evaluation is to know which of these representations most closely fit "present-day" isotopic measurements.

An outstanding disagreement among GCM representations of the impact of Amazonian deforestation is the sign of the change in moisture convergence (e.g. Table 1). The challenges associated with predicting this are illustrated in (14) which shows the changes in the vertically-integrated water flux across the north, south, east and west boundaries of the Amazon Basin as derived from one set of GCM simulations of deforestation. In this paper, the possibility of determining at least the sign of this important change is examined by reverting to the isotopically-derived central basin box model of Gat and Matsui (5). Since the total runoff equals the atmospheric moisture convergence, changes in either indicate a change in the other. We have employed values of parameters derived by Gat and Matsui (5) and investigated the effects of modelling runoff larger and smaller than their values. Our results suggest that it is necessary to decrease the runoff fraction by 10% in order to match the changed isotopic signature at Manaus between the periods 1965-75 and 1980-90. This result is consistent with the majority of GCM simulations.

3. IMPORTANCE OF FUTURE USE OF ISOTOPES IN EVALUATING GLOBAL CLIMATE MODELS

In this paper, we show that results derived from isotopic data from the IAEA/WMO network can be compared with outputs from GCMs. We find that water recycling in the central Amazon has changed over the last thirty years, significantly so in the wet season. While some GCM results may be consistent with this conclusion, the selected GCM results analyzed here fail to simulate the relative components of transpiration and re-evaporated canopy interception for the complementary dry season correctly. The failure by the CCM1-Oz simulations to represent the relative seasonal importance of transpiration (non-fractionating) as compared to the fractionating evaporation seems likely to be traceable to the land-surface parameterization scheme: BATS. This land-surface scheme does have an option to incorporate open water bodies but this was not employed. Furthermore, a literature review indicates no other GCM simulation of the Amazon involving open lakes and river surfaces as a source of recycling water in the basin. The isotopic data show this to be an important omission and indicate the need to include water surfaces in land-surface parameterization, at least for the Amazon, in the future.

Our results suggest that further detailed analysis and extension to the very large number of GCMs already claiming to predict the impacts of Amazonian deforestation. At a minimum, it is recommended that all future GCM predictions of the climatic and hydrological impacts of Amazonian deforestation be evaluated against all the available isotopic data. Additionally, it might be valuable for current assessments of the performance of land-surface schemes in atmospheric models include an evaluation of small land-locked water bodies as sources of atmospheric moisture (e.g. Irannejad *et al.* (18)). A new intercomparison of climate model simulations of Amazonian hydrology might also be possible, perhaps under the auspices of the Atmospheric Model Intercomparison Project II (e.g. Phillips *et al.* (19)). There is potential to explore isotopic modification by Amazonian deforestation by utilizing state of the art land surface schemes combined with one of the current 'isotope' GCMs (e.g. Hoffman *et al.* (20)). Such an examination would fit into the suite of land-surface intercomparisons organized by the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) (e.g. Henderson-Sellers *et al.* (21); Schlosser *et al.* (22)). Data from the isotopic archive for Amazonia could be offered through the GLASS (Global Land Atmosphere System Study) of GEWEX to form the basis of a new stand-alone and coupled (to an isotope-tracking GCM) pair of intercomparison and validation experimental simulations.

It can be concluded that the great need for new validation data for GCMs, and the obvious and beneficial synergy derivable from the use of isotopes for this task suggest that new observational programmes, such as the Large Scale Biosphere Atmosphere Experiment in Amazonia (LBA), embrace isotopic studies (e.g. Vörösmarty *et al.* (23)). Simulation validation and model improvement opportunities include: (a) regional to basin-scale moisture convergence estimates; (b) evaluation of model partitioning among transpiration, free evaporation and canopy evaporation; and (c) detection and attribution of the impacts of forest change and greenhouse gas increases. We strongly recommend joint investigation of the Amazon by isotope experts and climate modellers

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