ISOTOPES AS VALIDATION TOOLS FOR PREDICTIONS OF THE IMPACT OF AMAZONIAN DEFORESTATION ON CLIMATE AND REGIONAL HYDROLOGY

A. HENDERSON-SELLERS
Australian Nuclear Science and Technology Organisation,
Lucas Heights, New South Wales, Australia

K. McGUFFIE
Department of Applied Physics, University of Technology,
Sydney, New South Wales, Australia

S. CHAMBERS
Australian Nuclear Science and Technology Organisation,
Lucas Heights, New South Wales, Australia

Abstract. Isotopic analysis and modelling of the Amazon Basin have both been reported for about thirty years. Isotopic data have been used to explain important characteristics of Amazonian hydrologic cycling by means of simple models. To date there has been no attempt to use isotopic data to evaluate global climate models employed to predict the possible impacts of Amazonian deforestation. This paper reviews the history of isotopic analysis and simulations of deforestation in the Amazon and initiates isotopic evaluation of GCMs. It is shown that one widely reported simulation set gives seasonal transpiration and re-evaporated canopy interception budgets different from those derived from isotopic analysis. It is found that temporal changes (1965 to 1990) in wet season deuterium excess differences between Belem and Manaus are consistent with GCM results only if there has been a relative increase in evaporation from non-fractionating water sources over this period. We propose synergistic future interactions among the climate/hydrological modelling and isotopic analysis communities in order to improve confidence in simulations of Amazonian deforestation.

1. HISTORY OF ISOTOPE ANALYSIS FOR THE AMAZON

The simple topography of the extensive basin and the single water source, the Atlantic Ocean, makes the Amazon Basin unique as a study region of isotopic fractionation processes. Salati *et al.* [1] used one year's isotope data from precipitation and river samples and results from a sector box model to reinforce Molion's [2] conclusion that about half the Amazon Basin's water is recycled. On the basis of 13 months data (October 1972 to October 1973) they were able to identify that the gradient inland of $\delta^{18}O$ is surprisingly weak, compared to other continental areas, which shows that a proportion of the hydrologic recycling is from non-fractionating sources i.e. transpiration and canopy re-evaporation. This recycling within the Amazon Basin leads to a smaller 'continental' gradient in $\delta^{18}O$ going inland on an east to west transect with seasonally averaged gradients of only 1.5‰ per 1000 km cf. 2.0‰ in Europe [3] (Fig. 1).

In 1981, Leopoldo [4] reported values of the stable isotopes of oxygen and hydrogen as measured in samples of stemflow and throughflow at the Duke Reserve, near Manaus. Although his results were somewhat contradictory, they seem to point to isotope heterogeneity in originating air masses as the most likely source of observed differences. These results have been cited by more recent researchers (e.g. Ref. [5]) because the fate of water intercepted by the canopy is crucially important to a complete understanding of forest hydrology.

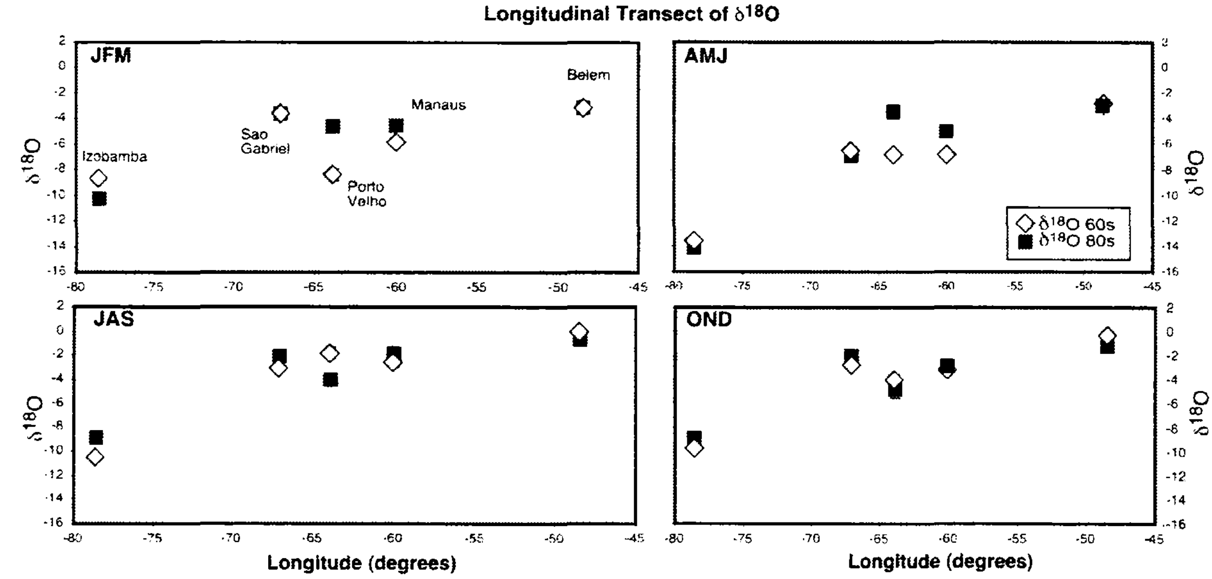

FIG. 1. Isotopic signature ($\delta^{18}O$) across a longitudinal transect of the Amazon from Belem on the coast and at the river mouth to Izobamba in the Andes for each of four seasons. The solid diamonds are the 1960s values (similar to those analyzed by [1]) while the open squares are for the 1980s.

An important review of Amazonian isotopic and other data was published by Salati and Vose in 1984 [6]. 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 [6] quote preliminary (1983) results from the work of Henderson-Sellers and Gornitz [7]. Although the Salati and Vose [6] 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 (Fig. 2(a)).

Two papers were published in 1991 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 Agency/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.* [8] 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 [9] also described in Ref. [1] 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 few reports on Amazonian isotopes. However, Gat [10] reviews some work and reports that an updated model of the Amazon's water balance, which uses isotopic input, improves earlier predictions.

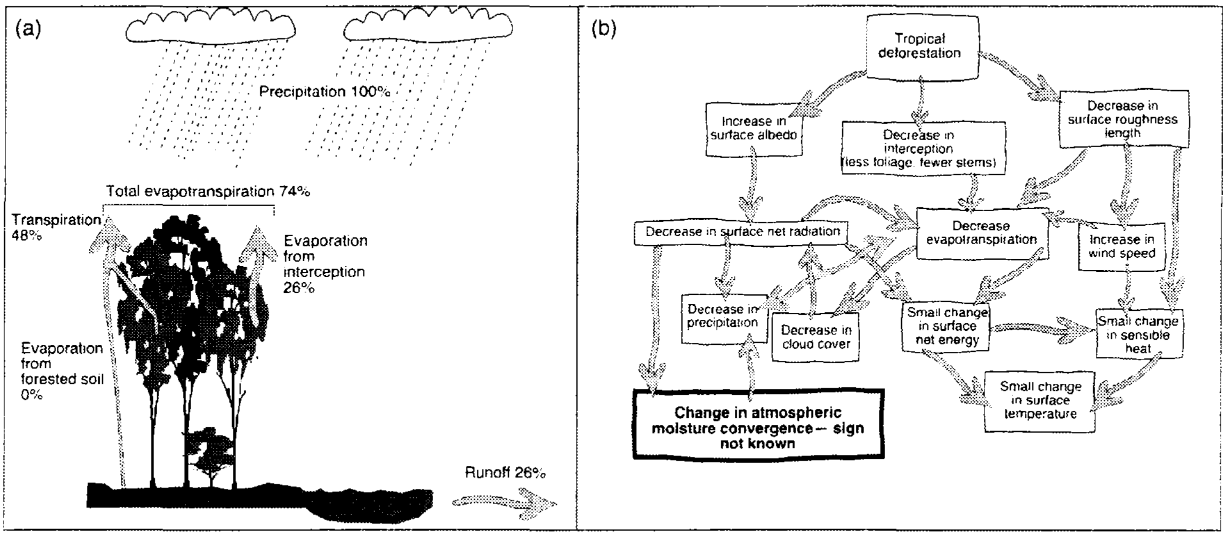

FIG. 2. (a) Schematic of the Amazonian Basin water cycle; and (b) schematic illustration of processes simulated in a global climate model (GCM) predicting changes following deforestation.

2. EVALUATION OF GCMS' SIMULATION OF AMAZONIA USING ISOTOPIC DATA

As mentioned above, the first global climate model (GCM) simulation of the impact of Amazonian deforestation was published by Henderson-Sellers and Gornitz in 1984. Since then, there have been rather a large number of simulations (Table I). McGuffie *et al.* [11] review the problems associated with correctly specifying climate model parameters in both control (present day) and deforested simulations. Some of the differences in the outcomes of predictions in Table I 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 (Fig. 2(b)). Almost all models predict increased surface temperatures (ΔT) 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 (Table I).

As far as we are aware, no GCM simulations of the impact of Amazonian deforestation have yet been tested against the available isotopic data. This is partly the result, we suspect, of the relevant research communities' ignorance of one another. It is also because very few GCMs have, as yet, included isotopic composition as a computed variable. Notable exceptions include work by Jouzel *et al.* [33,34] but neither of these studies include consideration of deforestation impacts. The wide dispersion in the results shown in Table I indicate that GCM evaluation by any available means can only be beneficial.

One means of assessing GCM performance in this area is to utilize the results 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 can be used to evaluate GCMs.

Table I. Annually-averaged regional changes predicted in response to Amazon tropical deforestation for surface temperature, T, precipitation, P, evaporation, E, and moisture convergence from various GCM studies since 1984 (N/A means the information is not available)

Study	Albedo change	Roughness change	ΔT (°C)	ΔP (mm)	ΔE (mm)	Moisture convergence change
Henderson-Sellers and Gornitz [7]	0.11/0.19	2.0/0.09	0	-220	-164	+
Dickinson and Henderson-Sellers [12]	0.12/0.19	2.00/0.05	+3.0	0	-200	+
Lean and Warrilow [13]	0.136/0.188	0.79/0.04	+2.4	-490	-310	-
Nobre *et al.* [14]	0.13/0.20	2.65/0.08	+2.5	-643	-496	-
Dickinson and Kennedy [15]	0.12/0.19	2.00/0.05	+0.6	-511	-256	-
Mylne and Rowntree [16]	0.135/0.200	No change	-0.1	-335	-176	-
Dirmeyer [17]	+0.03	2.65/0.08	N/A	+33	-146	+
Lean and Rowntree [18]	0.136/0.188	0.79/0.04	+2.1	-296	-201	-
Henderson-Sellers *et al.* [19]	0.12/0.19	2.0/0.2	+0.6	-588	-232	-
Pitman *et al.* [20]	0.12/0.19	2.00/0.05	+0.7	-603	-207	-
Manzi [21]	0.13/0.20	2.00/0.06	+1.3	-15	-113	+
Polcher and Laval [22]	0.098/0.177	2.30/0.06	+3.8	+394	-985	-
Polcher and Laval [23]	0.135/0.216	2.30/0.06	-0.1	-186	-128	-
Sud *et al.* [24]	0.092/0.142	2.65/0.08	+2.0	-540	-445	-
McGuffie *et al.* [25]	0.12/0.19	2.0/0.2	+0.3	-437	-231	-
Manzi and Planton [26]	0.13/0.20	2.00/0.06	-0.5	-146	-113	-
Zhang *et al.* [27]	0.12/0.19	2.0/0.2	+0.3	-402	-222	-
Lean and Rowntree [28]	0.13/0.18	2.10/0.03	+2.3	-157	-296	+
Hahman and Dickinson [29]	0.12/0.19	2.00/0.05	+1.0	-363	-149	-
Zhang *et al.* [30]	0.15/0.21	1.1/0.1	+0.9	+445	+248	+
Costa & Foley [31]	0.135/0.173	0.151/0.05	+1.4	-266	-223	-
Zhang *et al.* [32]	0.12/0.19	2.0/0.2	+0.3	-403	-221	-

McGuffie *et al.* [11] report on a series of GCM experiments conducted using the USA's National Center for Atmospheric Research's Community Climate Model (CCM1-Oz). Fig. 3 illustrates the components of the Amazonian water budget derived from these CCM1-Oz simulations for the annual and two 3-month seasonal means. While the amount of water recycled via transpiration does not vary all that greatly through the year, its percentage contribution to the total ranges from 38% in the wet season to 73% in the dry season.

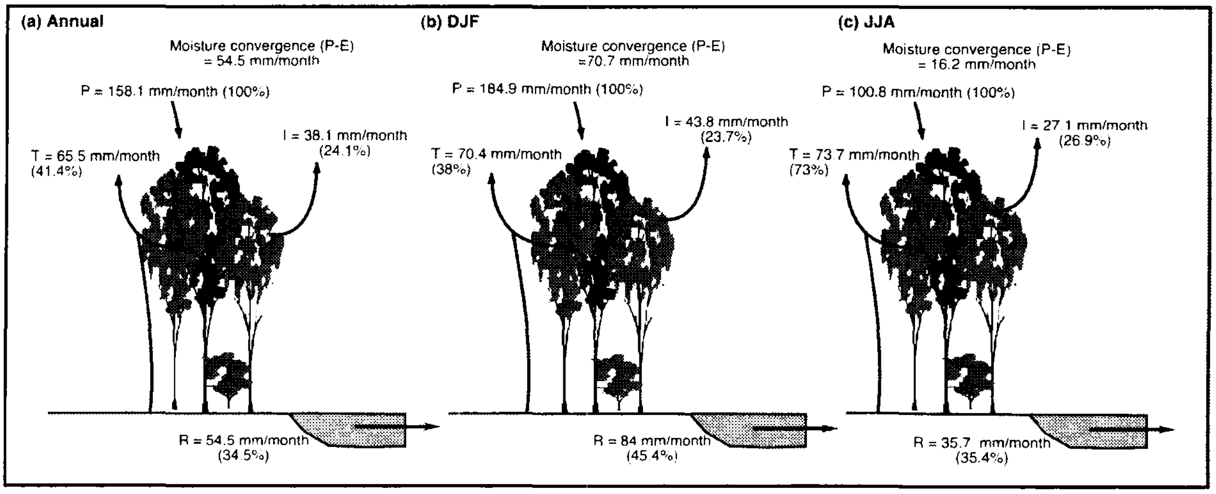

FIG. 3. One GCM (CCM1-Oz) simulation of the water budget of the Amazon for (a) annual means, (b) wet season (DJF) and (c) dry season (JJA) all given in mm month^{-1} and as percentages of the total precipitation.

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 is therefore not possible to examine the Gat and Matsui [5] conclusion regarding the fraction of recycled moisture from lakes directly in terms of this GCM. However, the results in Fig. 3 are in contrast with those of Victoria *et al.* [8]. The latter claimed on the basis of isotope analysis that transpiration is the major source of recycled water in the wet season while Fig. 3(c) shows that at least one GCM simulates transpiration as being very much more significant in the Amazon forest's dry season budget of recycled water.

Thus 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 current simulations and, hopefully, indicate how simulations by GCMs could be improved to more completely and correctly capture the moisture exchanges. This is an important 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 [35].

3. RECENT ISOTOPIC ANALYSIS IN THE AMAZON

The data used in this study were obtained from the Global Network for Isotopes in Precipitation database [36], 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. As part of our investigation of 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 (e.g. Fig. 4). 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 (Fig. 1).

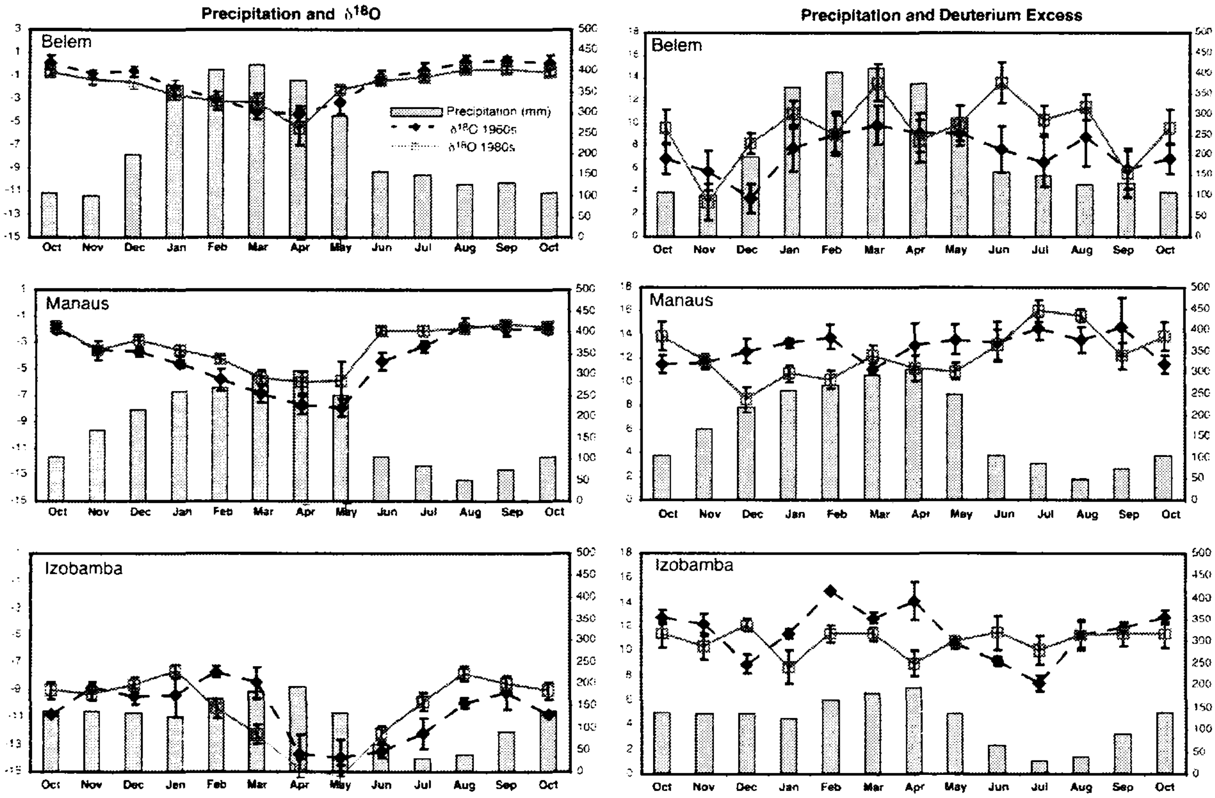

FIG. 4. Monthly mean values of $\delta^{18}O$ and deuterium excess at Belem, Manaus and Izobamba for the 1960s and the 1980s running from October to October. Mean monthly precipitation (mm) for the whole period is also shown as a histogram.

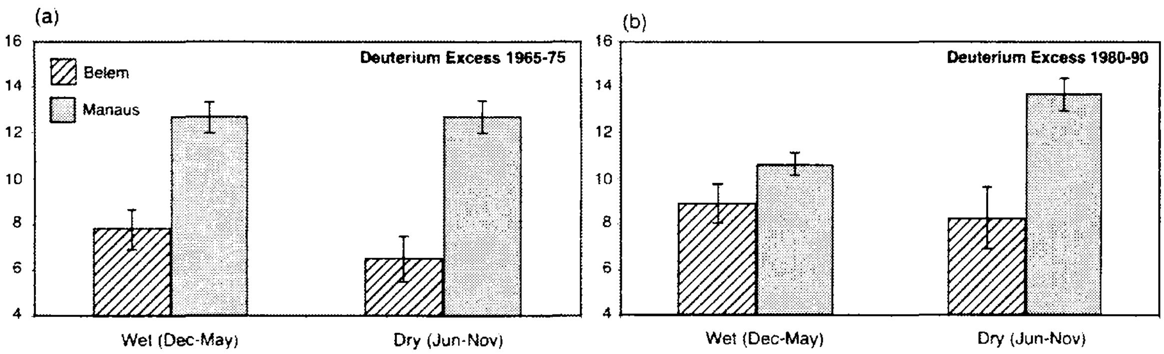

FIG. 5. Wet (Dec-May) and dry (Jun-Nov) half-year deuterium excess comparisons for Manaus and Belem at (a) the earliest decade of IAEA/WMO data (1965-1975) and (b) the most recent decade (1980-1990). Error bars show ±1 standard error.

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 (Fig. 5(a)). 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 (Fig. 5(b)). 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 (Fig. 6) only if there has been a relative decrease in the evaporation of water from lakes and other fractionating sources over this period.

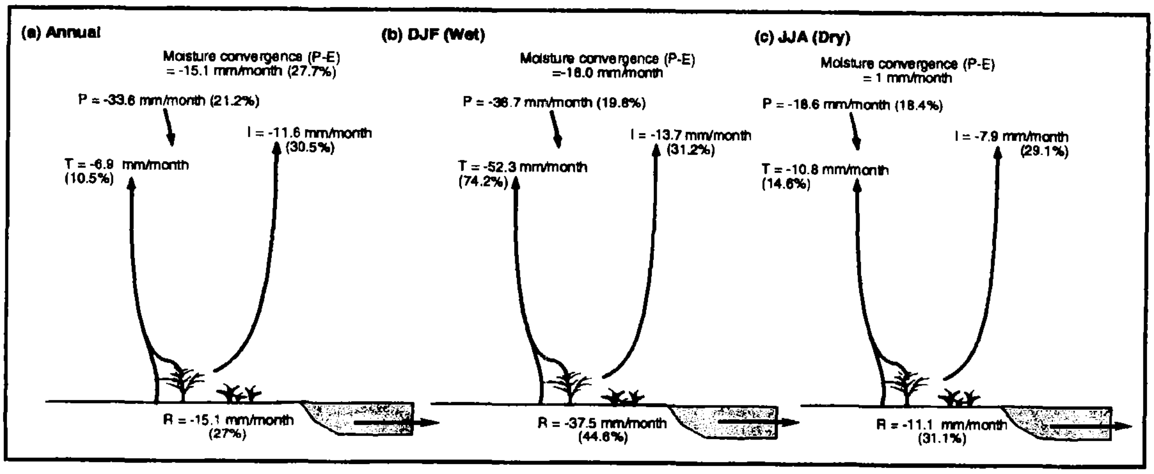

FIG. 6. Changes simulated by CCM1-Oz to the Amazon water budget following deforestation. Differences and percentages are all from the forested case in Fig. 3 for the same periods.

This isotope-GCM "missing link" 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.

4. RECENT GCM STUDIES OF THE AMAZON

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. Table II lists the imposed changes and predicted outcomes for the three available studies. The paper by Henderson-Sellers *et al.* [37] 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 [31] 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.* [32] 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.

Table II. Annually-averaged regional response to Amazon tropical deforestation for surface temperature, T, precipitation, P, evaporation, E, and moisture convergence from recent GCM studies which have included the effects of greenhouse gas increases. (N/A means information is not available)

Study	Albedo change	Roughness change	ΔT (°C)	ΔP (mm)	ΔE (mm)	Moisture convergence change
Henderson-Sellers *et al.* [37]) Doubled stomatal resistance and warming no deforestation	No change	No change	+	N/A	-	+
Costa & Foley [31] Doubled CO_2 & deforestation with plant physiological response	0.135/0.173	0.151/0.05	+3.5	-153	-146	-
Zhang *et al.* [32] Doubled CO_2 & deforestation	0.12/0.19	2.0/0.2	+0.4	-424	-215	-

Tables I and II emphasize an outstanding disagreement among GCM representations of the impact of Amazonian deforestation: the sign of the change in moisture convergence (Fig. 2(b)). The challenges associated with predicting this are illustrated in [35] 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. We have examined the possibility of determining at least the sign of this important change 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 (larger number of) GCMs in Tables I and II that find a decrease in moisture convergence.

5. FUTURE USE OF ISOTOPES IN EVALUATING MODELS OF THE AMAZON'S CLIMATE AND HYDROLOGY AND THE POSSIBLE IMPACTS OF DEFORESTATION

Isotopic analysis and modelling studies relating to the Amazon date back to the early 1970s and estimates of the likely impacts of deforestation begin around 1984. Results from isotopic research have influenced climate and hydrological modelling but the two communities have rarely worked closely. The potential importance of the impact of Amazonian deforestation to distant locations has been suggested recently. Such results increase the importance of using all available data in the evaluation and, hopefully, validation of global climate models used to predict these impacts.

In this paper, we have shown 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 GCM results may be consistent with this conclusion, they are not, so far, correctly simulating the relative components of transpiration and re-evaporated canopy interception for the complementary dry season. These results warrant further detailed analysis and extension to the very large number of GCMs already predicting the impacts of Amazonian deforestation.

Furthermore, 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. Ref. 38]). Finally, the great need for new validation data for GCMs, and the obvious and beneficial synergy, seems to demand that new observational programmes, such as the Large Scale Biosphere Atmosphere Experiment in Amazonia (LBA), embrace isotopic studies as a potentially very valuable tool for model validation. Ideas include: (a) moisture convergence estimates; (b) partitioning among transpiration, free evaporation and canopy evaporation; and (c) detection of the impacts of forest change and greenhouse signals.

REFERENCES

[1] SALATI, E., et al., Recycling of water in the Amazon Basin: An isotopic study, Wat. Res. Res. **15**(5): (1979) 1250-1258.

[2] MOLION, L.C.B., A climatonomic study of the energy and moisture fluxes of the Amazonas basin with considerations of deforestation effects, PhD. Thesis, Univ. of Wis., Madison (1975).

[3] ROZANSKI, K., et al., Isotopic patterns in modern global precipitation, Climate Change in Continental Isotopic Records. Geophysical Monographs **78**: (1993) 1-36.

[4] LEOPOLDO, R.R., Aspetos hidrologicos at florista amazonica denga na regiao de Manaus, PhD thesis, University National Estado San Paolo, Botucato SP Brasil (1981).

[5] GAT, J.R., MATSUI, E., Atmospheric water balance in the Amazon Basin: an isotopic evapotranspiration model, J. Geophys. Res. **96**(D7): (1991) 13,179-13,188.

[6] SALATI, E. VOSE, P.B., Amazon Basin: a system in equilibrium, Science **225**: (1984) 129-137.

[7] HENDERSON-SELLERS, A., GORNITZ, V., Possible climatic impacts of land cover transformations, with particular emphasis on tropical deforestation, Clim. Change **6**: (1984) 231-258.

[8] VICTORIA, R.L., et al., Mechanisms of water recycling in the Amazon Basin: Isotopic insights, Ambio **20**(8): (1991) 384-387.

[9] DALL'OLIO, A., A composicao isotopica das precipitacoes do Brasil: modelos isotermicos e a influencia de evapo-transpiracao na Bacia amazonica, MS thesis, University of Sao Paolo, Piracicaba, Brasil (1976).
[10] GAT, J.R., Atmospheric water balance – the isotopic perspective, Hydrological Processes **14**: (2000) 1357-1369.
[11] MCGUFFIE, K., et al., Modelling climatic impacts of future rainforest destruction, in B.K. Maloney (eds), Human Activities and the Tropical Rainforest, Kluwer, Netherlands (1998) 169-193.
[12] DICKINSON, R.E., HENDERSON-SELLERS, A., Modelling tropical deforestation: a study of GCM land surface parameterisations. Quarterly Journal of the Royal Meteorological Society **114**: (1988) 439–462.
[13] LEAN, J., WARRILOW, D.A., Simulation of the regional climatic impact of Amazon deforestation, Nature **342**: (1989) 411–413.
[14] NOBRE, C.A., et al., Amazonian deforestation and regional climatic change. Journal of Climate **4**: (1991) 957–988.
[15] DICKINSON, R.E., KENNEDY, P.J., Impacts on regional climate of Amazon deforestation. Geophysical Research Letters **19**: (1992) 1947–1950.
[16] MYLNE, M.F., ROWNTREE, P.R., Modelling the effects of albedo change associated with tropical deforestation, Climatic Change **21**: (1992) 317-343.
[17] DIRMEYER, P.A., GCM studies of the influence of vegetation on the general circulation: the role of albedo in modulating climate change, unpublished PhD thesis, Department of Meteorology, University of Maryland (1992).
[18] LEAN, J., ROWNTREE, P.R., A GCM simulation of the impacts of Amazonian deforestation on climate using an improved canopy representation. Climate Research Technical Note No26, Hadley Centre for Climate Prediction and Research, Meteorological Office, Bracknell, UK (1992).
[19] HENDERSON-SELLERS, A., et al., Tropical deforestation: modelling local to regional-scale climate change. Journal of Geophysical Research **98**: (1993) 7289–7315.
[20] PITMAN, A.J., et al., Assessing climate model sensitivity to prescribed deforested landscapes, International Journal of Climatology **13**: (1993) 879–898.
[21] MANZI, AO, Introduction d'un schema des transfert sol-vegetation-atmosphere duns un modèle de circulation general et application a la deforestation Amazonienne, PhD Thesis, Université Paul Sabatier, Toulouse (1993).
[22] POLCHER, J., LAVAL, C., The impact of African and Amazonian deforestation on tropical climate. Journal of Hydrology **155**: (1994) 389–405.
[23] POLCHER, J., LAVAL, C., A statistical study of the regional impact of deforestation on climate in the LMD GCM. Climate Dynamics **10**: (1994) 205-219.
[24] SUD. Y.C., et al., Biogeophysical effects of a tropical deforestation scenario: a GCM simulation study. Journal of Climate **9**: (1996) 3225–3247.
[25] MCGUFFIE, K., et al., Global climate sensitivity to tropical deforestation, Global and Planetary Change **10**: (1995) 97–128.
[26] MANZI, O., PLANTON, S., Calibration of a GCM using ABRACOS and ARME data and simulation of Amazonian deforestation, Amazonian Deforestation and Climate (eds. J.H.C. Gash, et al.), John Wiley and Sons (1996) 505-530.
[27] ZHANG, H., et al., Impacts of tropical deforestation .1. Process analysis of local climatic change. Journal of Climate **9**: (1996) 1497-1517.
[28] LEAN, J., ROWNTREE, P.R., Understanding the sensitivity of a GCM simulation of Amazonian deforestation to the specification of vegetation and soil characteristics. Journal of Climate **10**: (1997) 1216-1235.

[29] HAHMANN, A.N., DICKINSON, R.E., RCCM2-BATS model over Tropical South America: Applications to tropical deforestation. Journal of Climate **10**: (1997) 1944–1964.

[30] ZHANG, H., et al., Uncertainties in GCM evaluations of tropical deforestation: a comparison of two model simulations, in W. Howe and A. Henderson-Sellers (eds), Assessing Climate Change: results from the Model Evaluation Consortium for Climate Assessment, Gordon and Breach, Sydney, Australia (1997) 323-355.

[31] COSTA, M.H., FOLEY, J.A., Combined effects of deforestation and doubled atmospheric CO_2 concentrations on the climate of Amazonia, Journal of Climate **13**: (2000) 18-34.

[32] ZHANG, H., et al., The compounding effects of tropical deforestation and greenhouse warming, Clim. Change (2001) in press.

[33] JOUZEL, J., et al., Simulations of the HDO and $H_2{}^{18}O$ atmospheric cycles using the NASA GISS general circulation model: sensitivity experiments for present-day conditions, J. Geophys. Res. **96**(D4): (1991) 7495-7507.

[34] JOUZEL, J., et al., Water isotopes in precipitation: data/model comparison for present-day and past climates, Quaternary Science Reviews **19**: (2000) 363-379.

[35] ZHANG, H., et al., Impacts of tropical deforestation II: the role of large-scale dynamics, J. Clim. **9**: (1996) 2498-2521.

[36] IAEA/WMO, Global Network for Isotopes in Precipitation. The GNIP Database. Release 3,Oct. 1999 (1999) URL: http://www.iaea.org/programs/ri/gnip/gnipmain.htm

[37] HENDERSON-SELLERS, A., et al., Sensitivity of global climate model simulations to increased stomatal resistance and CO_2 increases, J. Clim. **8** (7): (1995) 1738-1756.

[38] HOFFMANN, G., et al., Stable isotopes in atmospheric general circulation models, Hydrological Processes **14**: (2000) 1385-1406.