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Stable water isotope characterization of human and natural impacts on land-atmosphere exchanges in the Amazon Basin

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[1] Stable water isotopes have been employed as a means of challenging, validating, and improving numerical models of the Amazon Basin since the 1980s. This paper serves as an exemplar of how characterization of human and natural impacts on surface-atmosphere water exchanges could beneficially exploit stable water isotope data and simulations. Interpretations of Amazonian isotopic data and model simulations are found to be seriously hampered by (1) poor simulation of the gross water budget (e.g., lack of surface water conservation in models); (2) considerable model differences in the fate of precipitation (i.e., between reevaporation and runoff); (3) wide ranging characterization of natural causes of water isotopic fluctuations (especially El Niño and La Niña events); (4) isotopic land-atmosphere flux sensitivity to the prescription of boundary layer atmospheric water vapor isotopic depletion; and (5) significantly different characterization by current land-surface schemes of the partition of evaporation between isotopically fractionating (from lakes and rivers) and nonfractionating (transpiration) processes. Despite these obstacles, we find features in the recent isotopic record that might be derived from circulation and land-use changes. ENSO events may cause decreased depletion in the dry season, because of reduced convective precipitation, while increases in upper basin isotope depletions in the wet season may result from relatively less nonfractionating recycling because there are fewer trees. The promise for isotopic fingerprinting of near-surface continental water cycle changes depends upon fixing shortcomings in current atmospheric and land-surface models. *INDEX TERMS:* 1615 Global Change: Biogeochemical processes (4805); 1610 Global Change: Atmosphere (0315, 0325); 1833 Hydrology: Hydroclimatology; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; *KEYWORDS:* stable isotopes, Amazon, models

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1. Isotopes in the Amazon

1.1. Isotopic Measurement and Modeling in the Amazon

[2] Land use change in the Amazon Basin, the largest and most biologically diverse river system in the world, has the potential to cause significant disruption to hydrological, biogeochemical and human systems. Within the atmospheric component of the hydrologic cycle, fractionation of water molecules arises from the processes of evaporation and condensation [e.g., *Dansgaard*, 1964]. By examining the two most abundant "heavy" isotopes of water (HDO and H_2O^{18}), it is possible to diagnose the history of evaporative and condensation processes [e.g., *Ingraham and Craig*, 1986] (Figure 1a). An early review of Amazonian isotopic data, published by *Salati and Vose* [1984], was influential because its publication coincided with the first Global Climate Model (GCM) of the impact of Amazonian deforestation on climate [*Henderson-Sellers and Gornitz*, 1984]. Together, these papers underlined and disseminated the fact that the Amazon Basin recycles about half its water. Specifically, the central Amazon has a water recycling time of about 5.5 days, and during this period, about half the rainfall is reevaporated or transpired, and of this around 50% falls again as precipitation [e.g., *Matsui et al.*, 1983]. As a consequence, the average gradient in $\delta^{18}O$ going inland is only 1.5‰ per 1000 km as compared with 2.0‰ typical of other continental areas [*Rozanski et al.*, 1993].

[3] In 1991 the results of two isotopic models of Amazonian precipitation and its implications for regional hydrology and climate were published. *Gat and Matsui* [1991] employed a simple steady state 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 [*IAEA*, 2003], they interpreted a +3‰ deviation

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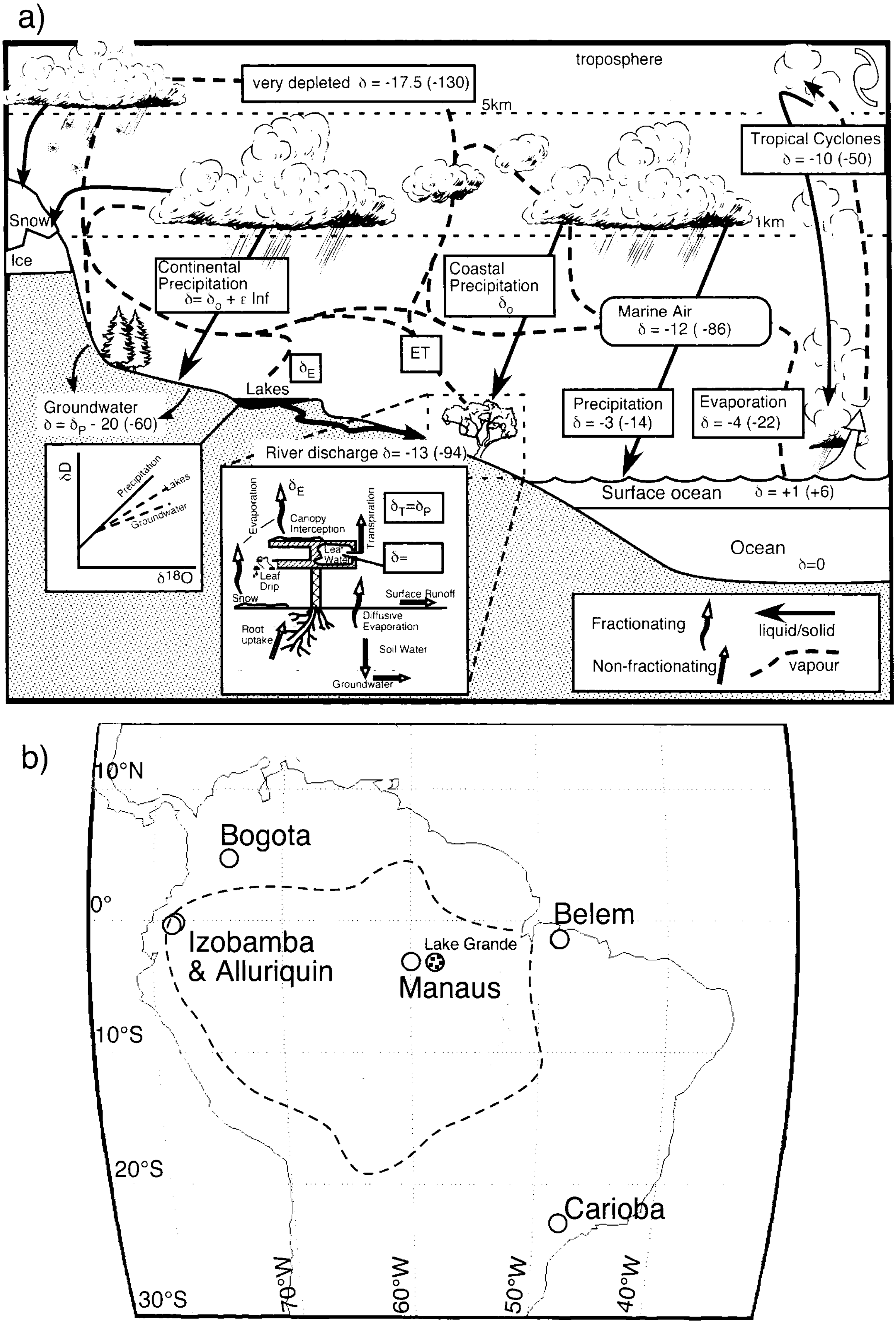

a)
troposphere
very depleted δ = -17.5 (-130)
5km
Tropical Cyclones
δ = -10 (-50)
Snow
Ice
1km
Continental Precipitation
δ= δ$_o$ + ε Inf
Coastal Precipitation
δ$_o$
Marine Air
δ = -12 (-86)
δ$_E$
ET
Lakes
Groundwater
δ = δ$_P$ - 20 (-60)
Precipitation
δ = -3 (-14)
Evaporation
δ = -4 (-22)
River discharge δ= -13 (-94)
Surface ocean δ = +1 (+6)
Ocean δ=0
δD
δ^{18}O
Precipitation
Lakes
Groundwater
Evaporation
δ$_E$
Canopy Interception
Transpiration
δ$_T$=δ$_P$
Leaf Water
δ=
Leaf Drip
Snow
Surface Runoff
Diffusive Evaporation
Root uptake
Soil Water
Groundwater
Fractionating
liquid/solid
Non-fractionating
vapour
b)
10°N
0°
10°S
20°S
30°S
70°W
60°W
50°W
40°W
Bogota
Izobamba & Alluriquin
Lake Grande
Manaus
Belem
Carioba

Figure 1

from the Meteoric Water Line as evidence that 20–40% of the recycled moisture within the basin is derived from sources such as lakes, the river or standing water, which fractionate isotopes of oxygen and hydrogen. *Victoria et al.* [1991] combined IAEA/WMO isotopic results from Belem and Manaus (Figure 1b) between 1972 and 1986 and a box/sector model of *Dall'Olio* [1976] and *Salati et al.* [1979] to show that wet season recycling is primarily by transpiration, while dry season recycling is mostly accomplished by reevaporation of precipitation intercepted on the canopy (see also *Gat* [2000], who reviews and revises this work). *Martinelli et al.* [1996] used stable isotopes to determine the sources of evaporated water in the Amazon Basin.

[4] *Henderson-Sellers et al.* [2002] detected statistically significant temporal changes (1965 to 1990) in stable water isotopic signatures in the Amazon, which they compared with the results of GCM simulations, revealing notable differences. Their analysis found no significant change in dry season isotopic characteristics despite earlier predictions that land-use change signals would be found first in the dry season. In the context of recent GCM simulations of Amazonian deforestation, *Henderson-Sellers et al.* [2002] suggested that changes observed in the isotope characteristics are more consistent with the predicted effects of greenhouse warming, possibly combined with forest removal, than with the predicted effects of deforestation alone.

[5] Although isotope-enabled GCMs (IGCMs) date back to the mid-1980s [e.g., *Joussaume et al.*, 1984; *Jouzel et al.*, 1987], there has been little application of their results to the Amazon until recently [e.g., *Hoffman et al.*, 2003]. *Vuille et al.* [2003a] analyze two IGCMs in terms of the interannual variability of $\delta^{18}O$ in precipitation over the tropical Americas including the Amazon Basin. Both *Hoffman et al.* [2003] and *Vuille et al.* [2003b] focus on the $\delta^{18}O$ in precipitation in the Andes and the way in which its variability affects interpretation of the isotope record in Andean ice cores. They conclude that the impact of ENSO events on $\delta^{18}O$ integrates many fractionating factors including precipitation amount, moisture source and temperature (see Figure 1a).

1.2. Isotopic Interpretations of Land-Atmosphere Interactions

[6] Stable water isotopes allow differentiation between transpiration (through plants) and evaporation (from water surfaces or stores). Throughout this paper, we use the term evaporation to encompass all water loss from the surface. Nonfractionating evaporation comprises transpiration (which, assuming the plant has a steady state water balance, has no net effect on the isotopic balance of soil water) and full evaporation of canopy-intercepted precipitation (which cannot fractionate if it is complete) [*Moreira et al.*, 1997]. Fractionating evaporation is therefore evaporation from water bodies (lakes and rivers). We set aside partial canopy evaporation where the remaining, enriched, water never evaporates on the grounds that this is a somewhat implausible fate [*Leopoldo*, 1981]. Delta values are given relative to the Vienna SMOW (VSMOW) standard and obtained from mixing ratios for the two stable water isotopes as:

$$\delta = \left(\frac{R}{R_{SMOW}} - 1\right)*1000. \qquad (1)$$

where R_{SMOW} is 0.0020052 for $^{18}O/^{16}O$ and 0.00015576 for D/H and the isotope ratio for particular water flux is the total isotope in the flux divided by the total water flux. Components of the surface water budgets are evaluated isotopically by determining the δ offsets (depletions or enrichments) of ^{18}O and D (^{2}H).

[7] Stable water isotopes can provide information on the sources and sinks of atmospheric moisture in the Amazon [*Hoffman et al.*, 2003] and the internal recycling of water where model validation is of increasing importance [e.g., *Townsend et al.*, 2002]. The failure of the GCM simulations reviewed by *Henderson-Sellers et al.* [2002] to correctly represent the relative seasonal importance of transpiration (nonfractionating) as compared to the fractionating evaporation seemed likely to be traceable to the land-surface parameterizations. Indeed, the land-surface schemes employed in the GCMs' simulations reviewed by *Henderson-Sellers et al.* [2002] either did not have the capability to incorporate open water bodies or, if such an option existed, it was not used in any available Amazon simulations.

[8] Specific caveats on the conclusions of *Henderson-Sellers et al.* [2002] included the following: (1) Monthly isotope data to 1990 only were available and hence analyzed; (2) the statistically significant wet season changes reported might be related to, or even exaggerated by, El Niño-Southern Oscillation (ENSO) events or other climatic variations that modify the Walker circulation and Intertropical Convergence Zone (ITCZ) position and hence affect the moisture climatology of the Amazon; (3) no information on fluxes from simulated open water as a surface type in the Amazon GCM experiments was considered; (4) the selected model sets analyzed by *Henderson-Sellers et al.* [2002] were found to be failing to correctly simulate the relative components of transpiration and reevaporated canopy interception in the Amazon dry season; and (5) no isotope tracking in the Amazon deforestation simulations was reviewed, because none was available at that time.

[9] This paper reviews all of these topics as follows: (1) The monthly data are updated to 2000 for available GNIP stations, and 1980s' daily data are reanalyzed for Belem and Manaus; (2) ENSO and other climatic variability impacts are assessed; (3) the different representation of evaporation terms in two land-surface schemes (LSM [*Bonan*, 1996] and CLM [*Dai et al.*, 2003]) (incorporating lakes explicitly) allows detailed analysis of simulated components of water recycling; (4) while isotope tracking is still not available in any Amazon deforestation simulations, an

Figure 1. (a) Schematic of the global hydrological cycle showing approximate depletions in $\delta^{18}O$ (and δD in parentheses) as a result of the various processes. Depletions increase as altitude and distance from the ocean increase and as temperature decreases. Inputs of heavy isotopes from continental nonfractionating processes (e.g., transpiration and total evaporation of canopy-intercepted water) are also shown. (b) Amazon Basin showing the location of the isotope measurements used. See color version of this figure in the HTML.

off-line simulation using a land surface scheme that includes isotope fluxes is assessed; and (5) a third IGCM's simulation of large-scale Amazonian water cycling is added to the two models reviewed by *Vuille et al.* [2003a, 2003b].

[10] Our goal is to test the hypothesis that stable water isotopes can now, or might in the future, illuminate, and perhaps separate, the impacts of natural and human-induced variability. To do this, we evaluate reported mismatches between isotopic simulations and observations of surface-atmosphere hydrological exchanges. We choose this focus, of land-atmosphere interactions, because the surface is the locus of human activity and hence responses to climatic shifts have impacts on people here. As stable water isotopic land-surface schemes are just coming to be included in increasingly comprehensive IGCMs, this paper serves as an exemplar of how investigations of the possible causes of changing hydrology could beneficially exploit stable water isotope data and simulations. We focus on an area where isotopic characterization initiated GCM analysis of land-atmosphere interactions: the Amazon Basin, and follow a staged investigation. Section 2 evaluates isotopic characterization of surface-atmosphere water fluxes as represented by current land-surface schemes applied to the Amazon. Section 3 compares observations and simulations of large-scale hydro-climatic variations and applies isotopic analysis tools to aspects of these basin-scale evaluations. In section 4 we combine these learnings in a tentative assessment of recent isotopic perturbations in the Amazon.

2. Land-Surface Representation of Water and Isotopic Fluxes

[11] When assessing simulations of the impacts of deforestation in the Amazon, *Henderson-Sellers et al.* [2002] noted that all GCMs to that date had neglected the possible effects of the large areas of surface water there. Since then, further assessments have emphasized the extent and importance of open water areas. *Richey et al.* [2002] found that in May around 20% of the main Amazon river area is flooded. The combined effect of tributaries south of the Amazon reaching peak stage in April or May and those from the north peaking in June/July is to generate the maximum flooding in May (350,000 km^2, about 20% of the quadrant they studied). The annual mean flooded area was determined to be 250,000 km^2 [*Richey et al.*, 2002]. Flooding in neutral years was estimated by *Foley et al.* [2002] to be from 20,378 to 170,070 km^2. *Foley et al.* [2002] also examined the impact of ENSO forcing on the extremes of the flooded area finding that, while both El Niños and La Niñas enlarge the minimum area (by +2,483 and +7,049 km^2, respectively), La Niñas also increase the maximum while El Niños diminish this extent. Overall, estimates of the maximum flooded area range from ~350,000 km^2 to about half this.

[12] In this section we employ two land-surface parameterization schemes: LSM [*Bonan*, 1996] and CLM [*Dai et al.*, 2003] in off-line simulations of the Amazon [cf. *Pitman et al.*, 1999]. *Bonan et al.* [2003] report that CLM greatly differs in its representation of some components of the hydrological cycle over the Amazon. Specifically, the CLM (circles) (Figure 2) computes much larger canopy evaporation (which is fractionating if it is complete) than the two earlier versions of a closely related scheme (LSM, squares and dotted line). Here we run both CLM and LSM forced by NCEP meteorology [*National Oceanic and Atmospheric Administration-Cooperative Institute for Research in Environmental Sciences (NOAA-CIRES)*, 2003] for the AMIP II period. The version of LSM we use (ISOLSM) includes stable water isotopes [*Riley et al.*, 2002].

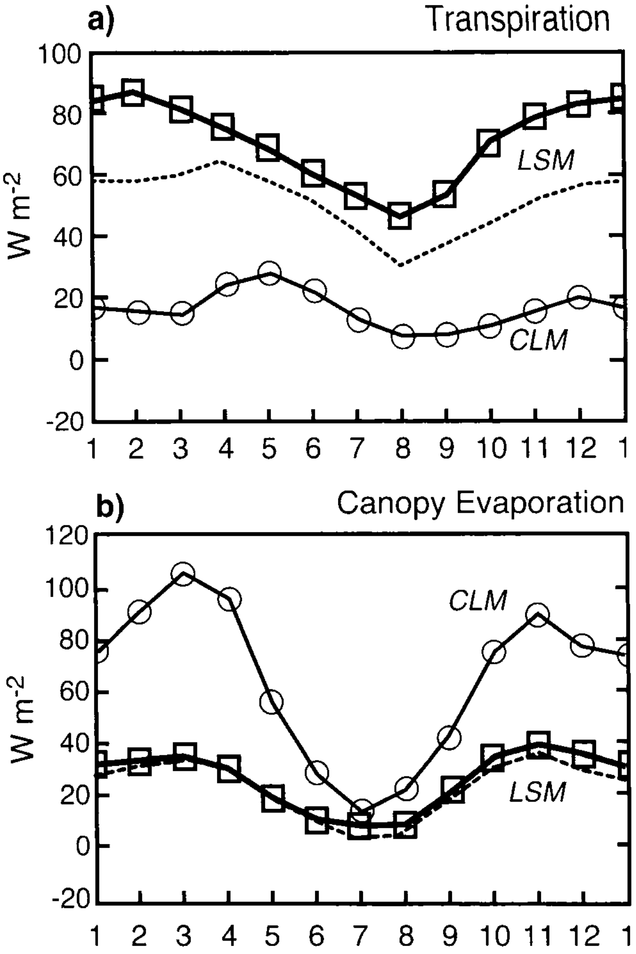


Figure 2. Two components of the evaporative flux (W m^{-2}) in the Amazon computed by two land-surface schemes (CLM and LSM) where CLM is open circles, LSM1 by open squares, and LSM2 by dotted lines for (a) transpiration and (b) canopy evaporation [after *Bonan et al.*, 2003]. The much higher canopy evaporation from CLM is combined with reduced transpiration (and ground evaporation, not shown). Overall CLM's LH is lower than those of the earlier LSMs.

2.1. Isotopic Fractionation of the Surface Water Budget

[13] *Henderson-Sellers et al.* [2002] found it was not possible to examine the *Gat and Matsui* [1991] conclusion regarding the fraction of recycled moisture from lakes directly in terms of the available GCM results. However, they found that the results of GCM simulations appeared to be at odds with the conclusions of *Victoria et al.* [1991]. The latter claimed on the basis of isotope analysis that

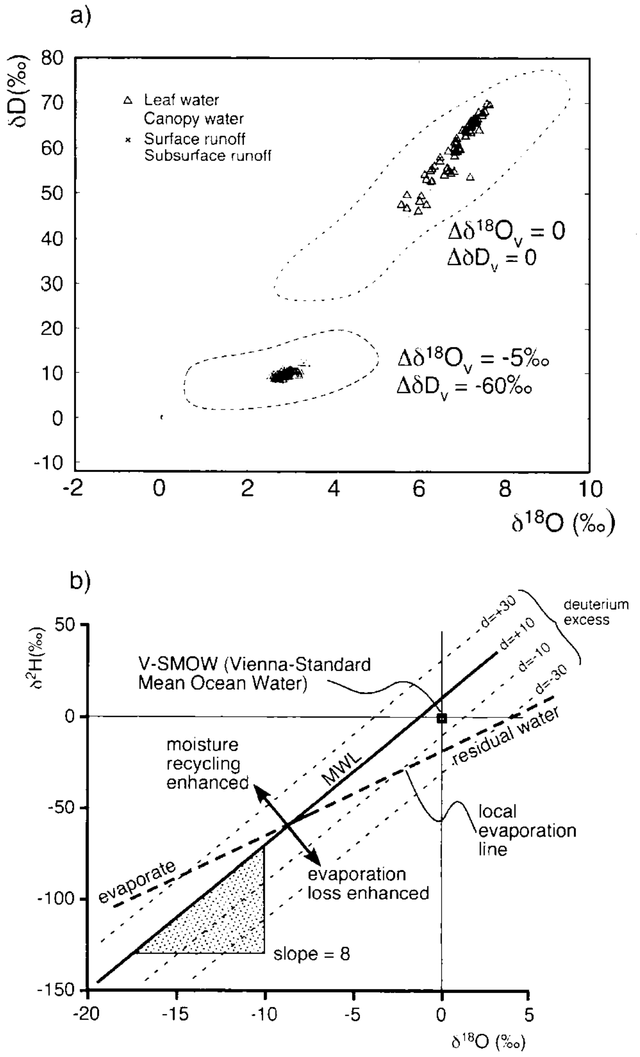


Figure 3. (a) Simulations by ISOLSM of stable water isotopic (δ^{18}O and δD) offsets for deep soil drainage (subsurface runoff), soil surface runoff, intercepted canopy water, and leaf structural water for every point and every month in two 5-year off-line simulations for the Amazon Basin. In one case the enrichment of the vapor is set to zero (i.e., equal to VSMOW), and in the second case the vapor is depleted by fixed amounts on the basis of the observations reported in Table 3b. (The depletions were calculated as representative of the basin by averaging the observed differences at Manaus between the mean vapor and mean precipitation depletions in the top and lowest deciles in Table 3b. These average differences are $\delta^{18}O = -5.1$‰ and $\delta D = -60.1$‰. Here we use $\delta^{18}O = -5$‰ and $\delta D = -60$‰.) (b) Schematic of relationships between δ^{18}O and δD for various water components of large basins in comparison with the Vienna-Standard Mean Ocean Water (V-SMOW). The slope of 8 of the global Meteoric Water Line (MWL) is contrasted with the smaller gradient of residual water remaining in lakes and rivers following local evaporation: the local evaporation line. A range of deuterium excess d values which show air mass origins and history is also illustrated (redrawn after *Froehlich et al.* [2002]). See color version of this figure in the HTML.

transpiration is the major source of recycled water in the wet season while *Henderson-Sellers et al.* [2002] found that the GCM they analyzed, NCAR CCM1, which used BATS [*Dickinson et al.*, 1986] as its land-surface scheme, simulated transpiration as being very much more significant in the forest's dry season budget of recycled water. The isotopic data analyzed by *Victoria et al.* [1991] show a deuterium excess of 14‰ in the dry season (June–November) requiring significant input of recycled water from one or more fractionating sources such as lakes and rivers [e.g., *Craig*, 1961]. The CCM1-Oz model [*McGuffie et al.*, 1988] failed to reproduce this component of the Amazon's hydrological cycle, so these results, while not absolutely contradicting the *Victoria et al.* [1991] findings of transpiration dominance in the wet season, seem to be in contention with them. CCM1-Oz was found to have the vast majority (73%) of the recycling being by transpiration in the dry season, while the isotopic data suggest this dominance actually occurs in the wet season.

[14] A second means of GCM assessment employed by *Henderson-Sellers et al.* [2002] was to utilize the results of *Gat and Matsui* [1991] regarding the relative amounts of water recycled in the Amazon from fractionating and nonfractionating sources. By comparing δ^{18}O and δD isotopic observations with results from their steady state model of the central Amazon Basin, *Gat and Matsui* [1991] deduced that 10%–20% of the input precipitation is reevaporated from fractionating sources (i.e., sources where water remains after evaporation such as lakes and rivers), 30%–40% from nonfractionating sources (e.g., transpiring plants and complete reevaporation of canopy-intercepted water), with about half of the total hydrological budget going to runoff. *Henderson-Sellers et al.* [2002] noted that these values differ from those shown in the CCM1 simulations they analyzed especially in terms of the relative proportions of water recycling and running off. This method could be used to evaluate the hydrologic budget components of GCMs especially if agreement can be achieved between the *Gat and Matsui* [1991] proportions and those of later researchers [e.g., *McGuffie et al.*, 1995; *Costa and Foley*, 2000].

[15] In this section we explore the questions of transpiration, reevaporation of canopy-intercepted water and other vegetation-water budget interactions, using two more recent variants of the NCAR land-surface scheme. These are an isotope version of the LSM [*Bonan*, 1996; *Riley et al.*, 2002] and CLM [*Bonan et al.*, 2003; *Dai et al.*, 2003], which have different vegetation water budgets (Figure 2). The stand-alone simulations here are for illustrative purposes only and are thus for periods shorter than the 17-year AMIP II predictions analyzed subsequently. *Bonan et al.* [2003] report in detail on the differences between CLM and two earlier versions of the LSM.

2.2. Isotopic Tracking With LSM

[16] *Riley et al.* [2002] describe the addition of water and carbon isotopes to a version of the NCAR land-surface model known as "LSM" [*Bonan*, 1996]. Here we employ ISOLSMv1.2.1 [*Riley et al.*, 2002] in a series of off-line simulations of the Amazon Basin's water cycling. ISOLSM is forced with NCEP reanalysis meteorology every 6 hours and the isotopic characteristics of precipitation and atmo-

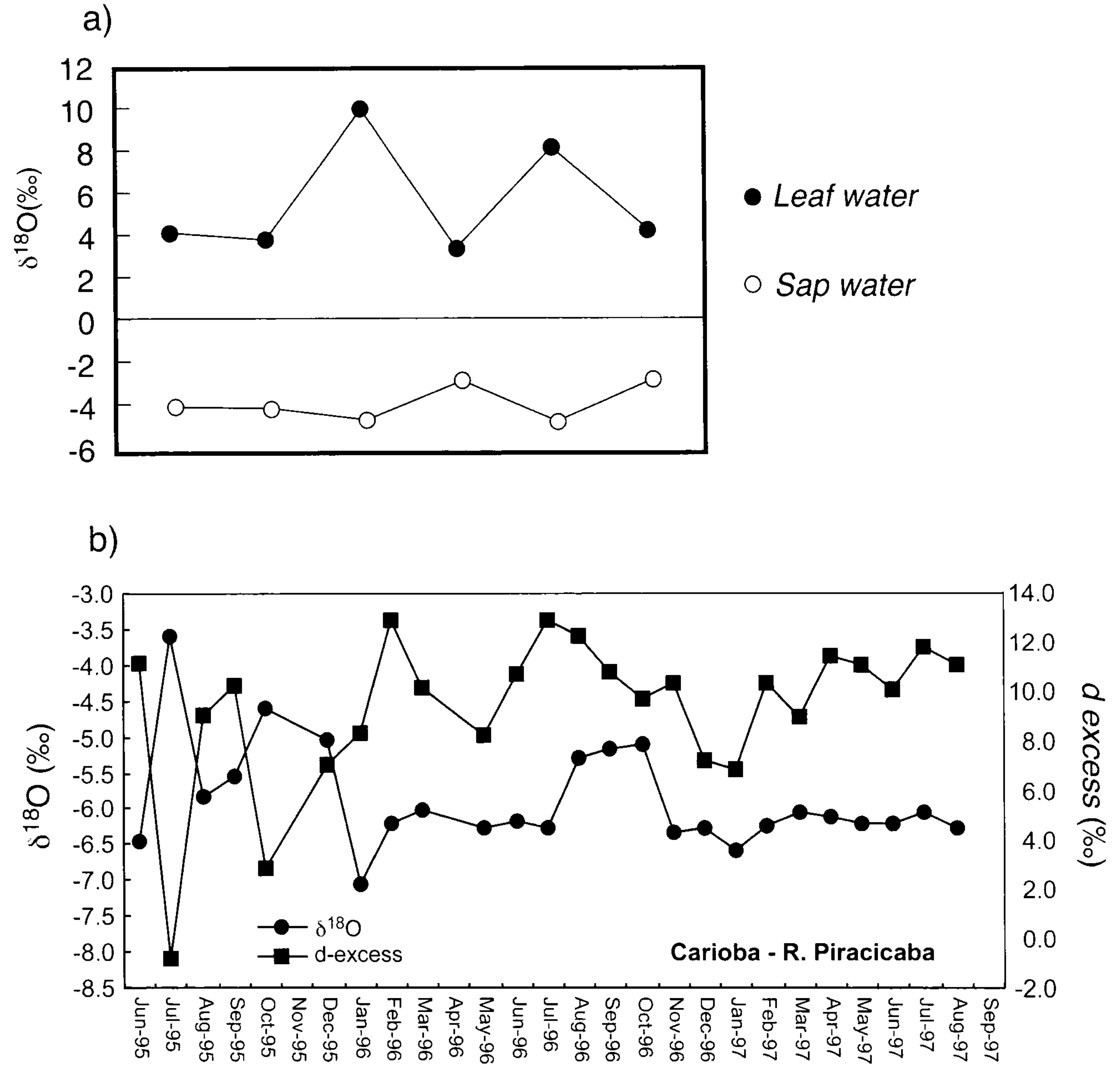


Figure 4. Selected isotopic observations from plant and river water in and near the Amazon Basin. (a) δ^{18}O values of bulk leaf water (striped) and sap water (shaded) of plants collected in the shore of Lake Grande in September of 2002. (b) δ^{18}O and d excess observations from Piracicaba River for the period June 1995 to September 1997 (both after *Martinelli* [2003]) (see Figure 1b for locations).

spheric water vapor are prescribed as VSMOW. For convenience, we analyze the terrestrial results relative to (i.e., as a difference from) these prescribed precipitation δ^{18}O and δD values. The success with which the major controls on the variability of ^{18}O and deuterium are captured by ISOLSM is evaluated in the context of the Amazon.

[17] Results presented here are based on a 5-year simulation using ISOLSM for the NCEP years 1998–2002. The δ offsets are reviewed for soil drainage (subsurface and runoff), soil surface runoff, intercepted canopy water and leaf structural water. The first two of these were chosen to allow consideration of simulation of the isotopic characterization of groundwater recharge and discharge into rivers. The latter two reservoirs are representative of the isotopic exchanges occurring at the leaf scale as represented by a "big leaf" land surface parameterization scheme and, as such, may provide insight into simulation of fractionating and nonfractionating components of the vegetation-derived surface water budgets. Two experiments were conducted: in one case, the enrichment of the vapor is set equal to VSMOW and, in the second case, the vapor is depleted by fixed amounts on the basis of the observations (see, e.g., Table 3b).

[18] For the two runoff components the basin-scale values of δ^{18}O and δD in precipitation (Figure 3a) are little affected (offsets are approximately zero), while for the two leaf water parameters there is isotopic enrichment by the land-surface scheme (i.e., the calculated offsets are all positive).

Table 1a. CLM Annually Averaged Partitioning of Surface Water Budget Components With the "Standard" Surface Types and With 20% Additional Lakes Around the Amazon River

	Standard		20% More Lakes	
	Absolute, mm d^{-1}	Percent of Precipitation	Absolute, mm d^{-1}	Percent of Precipitation
Precipitation	1.71	...	1.71	...
Evaporation	0.99	67	0.92	63
Runoff	0.73	37	0.59	26
(Total)		(104)		(89)
Canopy evaporation	0.71	45	0.47	30
Transpiration	0.07	6	0.05	4
Soil evaporation	0.21	15	0.14	10
Open water evaporation	...	...	0.26	18

The former result is expected because surface runoff and soil drainage share the isotopic characteristics of the precipitation (here VSMOW) unless there is a mechanism for enrichment or depletion. The latter result reflects the fractionation during evaporation. The vapor sensitivity study, using VSMOW and relative depletions (appropriate for the Amazon Basin) of $\Delta\delta^{18}$O of -5‰ and $\Delta\delta$D of -60‰, reveals offsets (enhancements in δs) which differ quite significantly. Figure 3a shows that the simulated delta distributions of δ^{18}O against δD for the Amazon for structural leaf water and canopy-intercepted water are extremely sensitive to the prescribed values of water vapor isotopic depletion. While enrichment in heavy water isotopes is clearly seen in the two vegetation components, the runoff parameters largely reflect the characteristics of the precipitation (i.e., offsets are near zero) for both vapor depletions. The two canopy reservoirs also show a near-linear relationship with slopes close to those of precipitation (the MWL) for vapor values set at VSMOW. However, the very different gradient for the case of isotopically depleted vapor is similar to enrichment in an evaporative environment such as a lake (Figure 3b).

[19] Figure 3a shows a tendency for the gradient to be steeper for interior (or structural) leaf water than for canopy-intercepted moisture for both vapor prescriptions. The departure of the slope of the offset leaf water isotopic values (mean gradient for VSMOW vapor is ~12.5) from the MWL (and thus the precipitation imposed δs) with a slope of ~8 indicates the importance of nonequilibrium processes in the simulated transpiration for this atmospheric water vapor prescription. Figure 3 underlines the fact that feedback between the LSS and the surrounding atmosphere is critical. Consequently, off-line experiments are very sensitive to the prescribed isotopic forcing, for which no reliable data exist on a basin or global scale. These results focus attention on the need for valid simulation of boundary layer isotopic enrichments in global atmospheric models if they are to be coupled with isotope-capable land surface schemes for meaningful investigation of vegetation effects on the isotope cycle.

[20] The site-specific and very spotty nature of isotopic data render comparisons with basin-scale "big leaf" models such as ISOLSM almost meaningless. However, it is important to demonstrate that, at the least, the depletions in Figure 3a are reasonable. Figure 4 shows plant and river water isotopic data from Brazil. Figure 4a is of δ^{18}O depletions and enrichments in sap and leaf water, respectively, collected from the Lake George shore in a short recent campaign [*Martinelli*, 2003]. The enrichments in the leaf water range up to 10‰ in good agreement with the simulations of ISOLSM. Figure 4b shows δ^{18}O and δD in river water from the Piracicaba River in Saõ Paulo state well south of the Amazon Basin (Figure 1a) between 1995 and 1997. These samples might be compared with soil water runoff values simulated by ISOLSM. In Figure 3a these are seen to be ~0‰ which are not seriously different from the river-based observations when it is recognized that the latter will have been affected by evaporative fractionation from the river itself [e.g., *Stone et al.*, 2003].

[21] ISOLSM does not include (in the implementations used here) either interaction with the host atmosphere or the explicit effect of open water. As a consequence of the latter, simulated river water, which would comprise the surface and subsurface runoff in Figure 3a, must reflect very closely the isotopic characteristics of the precipitation. In reality, however, lake and river evaporation play a role in determining the isotopic enrichment of these reservoirs. The ISOLSM mechanisms of computation of the isotopic enrichment would result in similar (and rather small) modifications to precipitation characteristics for groundwater and river input but much larger changes for vegetation-modified water components. In contrast, the very large sensitivity we have found to the prescribed vapor depletions shows that simulations of isotopic enrichment in the canopy-intercepted water and leaf structural water can differ very greatly from the prescribed precipitation. This degree of

Table 1b. CLM Partitioning of Surface Evaporative Budget Components Into Fractionating and Nonfractionating With the "Standard" Surface Types and With 20% Additional Lakes Around the Amazon River for the Annual Average, the Central Basin Wet Season (January–March), and the Dry Season (April to August)[a]

	Standard	20% More Lakes
	Percent of Evaporation	Percent of Evaporation
Annual		
Nonfractionating	7	5
Fractionating	92	95
Wet season (March–May)		
Nonfractionating	5	3
Fractionating	94	96
Dry season (August–October)		
Nonfractionating	15	11
Fractionating	84	89

[a] The location of the modeled grid point is roughly at Manaus.

Table 2a. CLM Partitioning of Surface Water Budget Components With the "Standard" Surface Types and With 20% Additional Lakes Around the Amazon River for January–March (Wet Season)

	Standard		20% More Lakes	
	Absolute, mm d^{-1}	Percent of Precipitation	Absolute, mm d^{-1}	Percent of Precipitation
Precipitation	2.28	...	2.28	...
Evaporation	1.05	46	0.95	42
Runoff	1.22	53	1.13	50
Total		99		91
Canopy evaporation	0.82	36	0.55	24
Transpiration	0.05	2	0.03	1
Soil evaporation	0.17	8	0.12	5
Open water evaporation	...	...	0.25	11

sensitivity is particularly surprising and needs careful consideration before isotope LSSs and isotope host atmospheric models are coupled.

2.3. Partitioning of Reevaporated Water in CLM

[22] A recent version of the NCAR Community Climate Model's land-surface scheme, Community Land Model (CLM), can also be operated in an off-line mode [*Bonan et al.*, 2003]. Here we use the CLM land-surface scheme to improve on the comparisons made by *Henderson-Sellers et al.* [2002] between isotope observations in the Amazon forest and simulations of the components of the surface water budget. Specifically, we have modified the percentage of open water surfaces in the region around the Amazon River itself in keeping with the data of *Richey et al.* [2002] and *Foley et al.* [2002]. Tables 1a and 1b list the comparative hydrological components when using the standard surface as compared with adding 20% more lakes. The effects of evaporation from bare soil are minimal in these tropical environments.

[23] With the standard CLM land types, the percentages are improved over CCM1-Oz (BATS) as reported by *Henderson-Sellers et al.* [2002] as follows: (1) 51% of precipitation is recycled by canopy evaporation (45%) plus transpiration (6%) annually; and (2) 15% of precipitation is recycled by soil and lake surface evaporation (Table 1a). When 20% extra lakes are added to the surface in CLM, it is found that (1) the fractionating component decreases (slightly) from 60% (45 + 15%) to 58% (30 + 10 + 18%) of precipitation; and (2) the nonfractionating component decreases as a percentage of evaporation from 7% to 5% (Table 1b).

[24] The CLM results are in stark contrast to the findings of *Victoria et al.* [1991]. In CLM, transpiration is never a large component of total evaporation, ranging from 15.7% (0.15/0.95) in the dry season to 4.7% (0.05/1.05) in the wet season (Tables 2a and 2b). Also, the addition of 20% extra lakes [e.g., *Richey et al.*, 2002] increases the input of fractionated water in the dry season (around April–August) (89% compared to 84% without lakes), which is not fully in agreement with the interpretation of the deuterium excess observations of *Victoria et al.* [1991] (Table 1b). Tables 1 and 2 show that CLM somewhat improves the overall percentages of fractionating to nonfractionating sources over those reported from BATS [*Henderson-Sellers et al.*, 2002]. The transpiration fluxes seem to be greatly underestimated by CLM (Figure 2 and *Bonan et al.* [2003]) as compared to the earlier LSM schemes. Even with extra lakes, CLM cannot capture the magnitude of the recycling of fractionated water from lakes in the dry season implied by the isotopic observations.

2.4. Summary

[25] In this section, two aspects of simulations relevant to our hypothesis regarding isotopic characterization of Amazonian land-atmosphere exchanges have been considered: the impact of additional surface water (i.e., lakes and rivers) and the inclusion of stable water isotopes in LSSs. In both investigations the LSSs have been used in an off-line (or stand alone) mode, i.e., without feedback to the atmosphere [e.g., *Chen et al.*, 1997], and for this reason we have restricted our simulations to 5-year periods, although this limits the impact of interannual variability.

[26] The Amazon isotopic enrichments predicted by ISOLSM are plausible: the drainage to groundwater exhibits little change from precipitation values (in agreement with Figure 4b), while the enrichments (positive offsets) in canopy-intercepted water are similar in magnitude to the depletion differences observed between precipitation and ambient atmospheric water vapor at Manaus and Belem

Table 2b. CLM Partitioning of Surface Water Budget Components With the "Standard" Surface Types and With 20% Additional Lakes Around the Amazon River for April–August (Dry Season)

	Standard		20% More Lakes	
	Absolute, mm d^{-1}	Percent of Precipitation	Absolute, mm d^{-1}	Percent of Precipitation
Precipitation	0.89		0.89	
Evaporation	0.95	107	0.93	105
Runoff	0.11	12	−0.14	−16
Total		119		89
Canopy evaporation	0.57	64	0.38	43
Transpiration	0.15	16	0.10	11
Soil evaporation	0.23	26	0.16	18
Open water evaporation	...	...	0.29	33

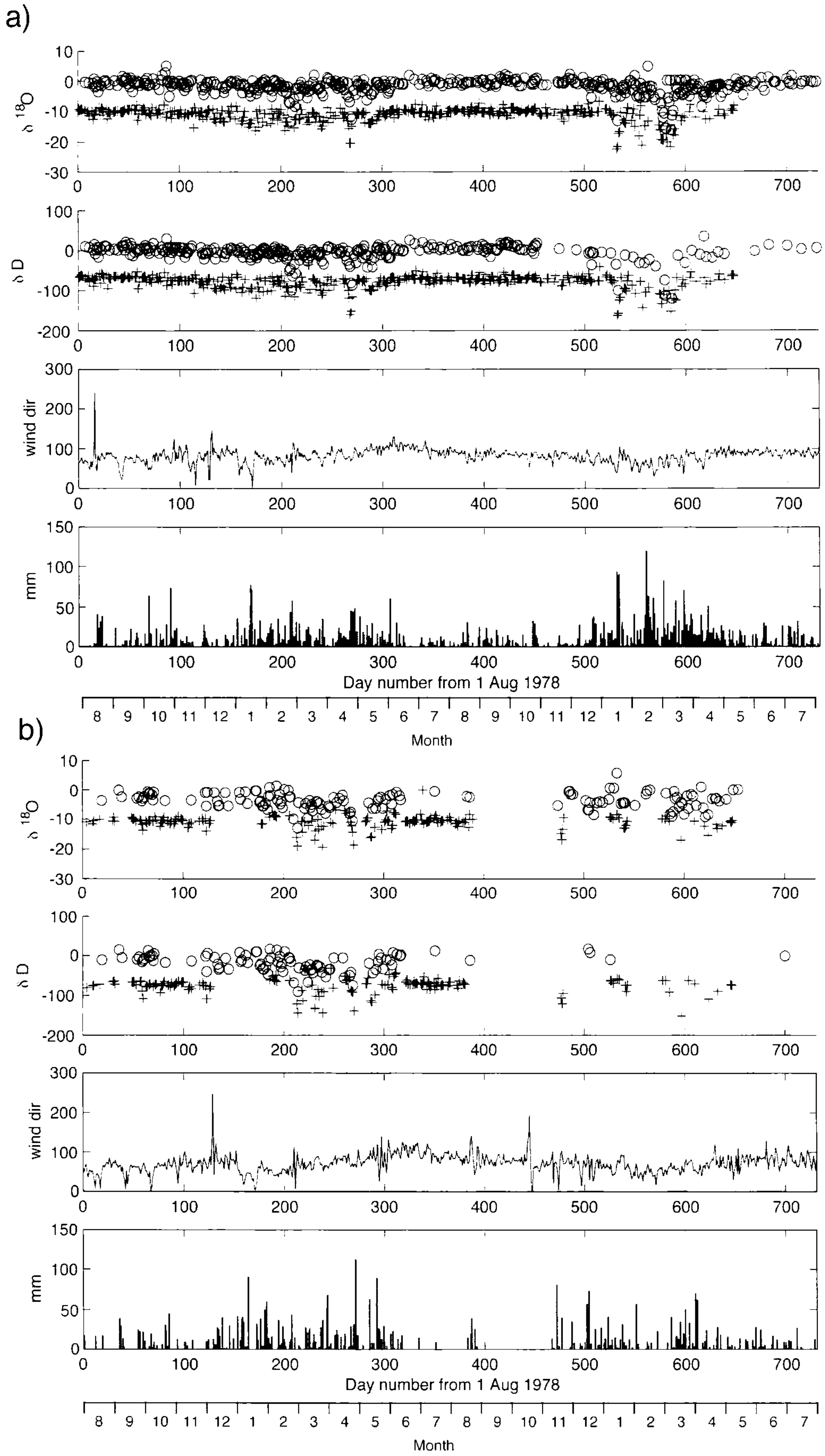

a)
δ 18O
10
0
-10
-20
-30
0
100
200
300
400
500
600
700
δ D
100
0
-100
-200
wind dir
300
200
100
mm
150
100
50
Day number from 1 Aug 1978
8
9
10
11
12
1
2
3
4
5
6
7
Month
b)
Day number from 1 Aug 1978
Month

Figure 5

(Figure 5). However, Figure 3 demonstrates that the δ^{18}O v. δD gradient of these vegetation parameter enrichments is very sensitive to the depletions prescribed in the atmospheric vapor. Without feedback to the atmosphere (i.e., a coupled isotopic land-atmosphere simulation), it is not possible to pursue the likely impact of this sensitivity, but our results suggest that valid representation of isotopic enrichments of water vapor in the atmospheric boundary layer will be critically important in coupled isotope simulations.

[27] The CLM's partition between isotopically fractionating and nonfractionating evaporation is sensitive to the addition of (a plausible) 20% open surface water. Although the CLM's representation of water recycling is better than that of BATS (used by *Henderson-Sellers et al.* [2002] in CCM1-Oz) there are still differences between the size of the simulated components of total evaporative flux and those deduced from isotopic measurements in the Amazon (Tables 1 and 2). However, as with ISOLSM, a more complete interpretation of these LSSs' sensitivities to likely Amazonian conditions is unwarranted from off-line integrations alone.

[28] This preliminary investigation of two LSSs has shown that plausible isotopic enrichments and depletion can be generated and that the partition of evaporative fluxes can be evaluated using isotopic measurements. It seems that these two results could be combined so that isotopic characterization can be employed to assess the relative impact of human-induced and natural climatic variations on large basin hydroclimates. In the next section, we review the large-scale hydro-climatic variability of the Amazon, its representation in GCMs and IGCMs and its likely impact on isotopic fluxes. Assuming that the atmospheric simulations of isotope distributions are robust, this is the second step along the path to determining whether stable water isotopes might be exploited in tracking and finger-printing climatic disturbances.

3. Amazonian Hydro-Climate Variability

[29] *Chen et al.* [2001] have described the impact of El Niño-Southern Oscillation (ENSO) on the Amazon's large-scale moisture convergence. An El Niño is drier and warmer than normal in the Amazon, while La Niñas are wetter and cooler. Amazonian temperature variations [*Foley et al.*, 2002] are quite strongly correlated with the Southern Oscillation Index (SOI): the coefficient of correlation between annual mean temperature and annual mean SOI is −0.61. Similarly, basin-wide precipitation is moderately well correlated ($r = +0.50$) with the SOI with the average El Niño precipitation being 83 mm yr^{-1} (4.0%) drier than neutral conditions, and the average La Niña 64 mm yr^{-1} (3.1%) wetter. The observed temperature changes tend to be spatially homogeneous and widely uniform throughout the basin and the year but hydrological responses (drier El Niños and wetter La Niñas) are stronger during the wet season (January–February–March) and are concentrated in the northern and southeastern portions of the basin [*Foley et al.*, 2002].

[30] However, *Botta et al.* [2002] used principal component analysis of Amazonian climate data to show that ENSO is not the major, or even the most important, mode of climate variability in the Amazon Basin. They found that ENSO explains only 21% of the total variance in annual mean precipitation and temperature and that the dominant mode of climate variability in the Amazon, which explains about 35% of the interannual variance of precipitation and 56% of the temperature variance, has a period of 24–28 years. Other proposed drivers of climate variability in Amazonia include changes to the strength of the North Atlantic high-pressure system, the position of the intertropical convergence zone (ITCZ), and wind stress and sea surface temperatures in the tropical Atlantic [e.g., *Foley et al.*, 2002]. Despite this, it seems worthwhile to try to identify, or eliminate, the possible effects of ENSO variability on isotopic measurement and simulations in the Amazon Basin.

3.1. Daily Isotope Analysis for Example "Neutral" Years

[31] Between August 1978 and July 1980, *Matsui et al.* [1983] measured daily values of δ^{18}O and δD in both precipitation and atmospheric water vapor at Belem and Manaus. These data coincide with a quiet time in ENSO terms: none of the period is rated as either a "warm" or "cool" (El Niño or La Niña) climate by the *National Oceanic and Atmospheric Administration* (*NOAA*) [2003] although the January/February/March 3 months of 1980 are noted as "W-." Notwithstanding this slight anomaly, we here designate the full period as "neutral," i.e., classified neither as El Niño nor La Niña.

[32] The expectation, in a "neutral" period such as the one selected, is that the Amazon's meteorology and hydrology will be dominated by easterly winds bringing moisture evaporated from the tropical Atlantic into the basin and upstream (Figure 5). Precipitation events will deplete these moist air masses of heavy isotopes leaving the atmospheric vapor more depleted than the rainfall and thus the inland site (Manaus) more depleted than Belem at the mouth of the river (Figure 1b).

[33] Figure 5 shows these daily isotope data (δ^{18}O and δD depletions in precipitation and atmospheric water vapor) and corresponding daily mean wind direction from NCEP reanalysis [*NOAA-CIRES*, 2003]. Easterly winds dominate at both locations, becoming more northeasterly at Manaus. Winds at Manaus exhibit a greater seasonality but, overall, the resulting climatology is dominated by winds from the east. As would be expected, vapor is more depleted than the precipitation and wet season depletions are larger (more negative) than those in the dry season. Figure 5 also shows the seasonal change in prevailing wind direction from east and northeast in the

Figure 5. Daily values of δ^{18}O and δD depletions in precipitation (circles) and water vapor (crosses) for (a) Belem and (b) Manaus from August 1978 to July 1980, together with wind direction (from 850 mbar of daily mean NCEP reanalysis for the same period) and daily precipitation amount in mm (data from *Matsui et al.* [1983] and from *NOAA-CIRES* [2003]). See color version of this figure in the HTML.

Table 3a. Numbers (n) of Daily Observations From Belem and Manaus for Atmospheric Vapor and Precipitation for the Period 1 August 1978 to 31 July 1980 of a Maximum Possible of 731 Together With Means of $\delta^{18}O$, δD, and d Excess (dxs)

	Atmospheric Vapor					Precipitation Observations				
	$\delta^{18}O$		δD			$\delta^{18}O$		δD		
	n	Mean	n	Mean	dxs	n	Mean	n	Mean	dxs
Belem	374	−10.7	355	−77.4	11.1	436	−1.9	299	−4.2	9.7
Manaus	233	−10.6	209	−75.4	12.0	198	−3.5	157	−13.8	15.3

wet season to easterly in the dry. Some indication of annual and interannual variability can be seen in the graphs, for example the wet season, between January and May, is characterized by large depletions, but the uneven data record, especially at Manaus (Table 3a), makes quantitative evaluation of either difficult. *Matsui et al.* [1983] concluded the close correspondence between events at Belem and Manaus during this ENSO-neutral period indicated the dominant role of weather systems traveling in an east to west direction during this time. At Belem, precipitation in the wet season of 1980 (days 500–600) is more depleted than that of the wet season of 1979 (days 200–300), but there is no matching difference evident at Manaus.

[34] The use of deuterium excess as a tool in the analysis of the isotopic characteristics of precipitation has been proposed since it reflects the conditions prevailing during the development of an air mass on its route to the precipitation site (Figure 1a) [*Froehlich et al.*, 2002]. Values of the d excess greater than the MWL value of 10 can be interpreted as evidence of moisture recycling during the evolution of the air mass (Figure 3b). This effect is illustrated in Table 3, which shows an increase in d excess in precipitation from Belem (9.7‰) to Manaus (15.3‰) indicative of recycling processes.

[35] The detail of the daily data offers an opportunity to examine the possible impacts of climatic excursions (e.g., due to ENSO or deforestation) on the isotopic record. Specifically, combining daily NCEP data with the observational record shown in Figure 5 allows the generation of relationships between wind speed and direction and total rainfall. Table 3b shows the "wet" and "dry" $\delta^{18}O$ and δD depletions in precipitation and vapor at both Manaus and Belem derived from the neutral period daily data. The "wet" and "dry" amounts have been generated by selecting the 10% of days with the highest precipitation and the 10% of days with the lowest precipitation at both locations. Clearly the impact of rainfall amount is large, particularly for the depletions measured in the precipitation where differences between the top 10% and lowest 10% are statistically significant except δD at Manaus.

3.2. Assessing Simulations of ENSO Variability in the Amazon Using AMIP II

[36] Our main interest is the use of isotopic data in characterizing natural and human-induced hydro-climate changes. In order to assess isotopic changes at the land surface, particularly the partition of precipitation into fractionating and nonfractionating evaporation or runoff, it is necessary to eliminate as many other variables as possible. To do this, we choose a carefully controlled experiment with a time period that encompasses both extremes of the ENSO cycle.

[37] The Atmospheric Model Intercomparison Project (AMIP) comprises two experimental phases. During the second phase (AMIP II), the experimental design remains fundamentally the same as AMIP I (i.e., commonly specified radiative forcing and ocean boundary conditions), but the simulation period has been extended by 7 years (from 1979–1988 to 1979–1995) and greater emphasis has been given to initialization/spin-up of soil moisture stores and conservation of continental surface energy and water. Also a more extensive set of land-surface variables is reported in the AGCMs' output [e.g., *Henderson-Sellers et al.*, 2003b].

[38] Of the 30 plus AGCMs participating in AMIP II, 20 have had their simulations released under the protocol of AMIP II. These AGCMs incorporate land-surface schemes (LSSs) of varied complexity ranging from the very simple "bucket" [e.g., *Manabe*, 1969] model to detailed soil-vegetation-atmosphere transfer schemes [e.g., *Costa and Foley*, 2000]. Differences among the land-surface predictions from AMIP II are being analyzed under the auspices of Diagnostic Subproject Number 12, which is focused on determining the dependence (if any) of land-surface variables (particularly latent and sensible heat fluxes) on LSS complexity [e.g., *Henderson-Sellers et al.*, 2003a; *Irannejad et al.*, 2003]. The AMIP II period (1 January 1979 through 1 March 1996) includes four El Niños (1982–1983, 1986–1987, 1991–1992, and 1994–1995) and two La Niñas (1984–1985 and 1988–1989). These climatic variations are prescribed for the participating AGCMs because sea surface temperatures (together with sea ice amounts, atmospheric composition, and solar radiative forcing) are set from observed values in the AMIP experiments [*Gates et al.*, 1999] (AMIP home page, available at http://www-pcmdi.llnl.gov/amip/amiphome.html, 2003).

[39] Figures 6a–6e shows the monthly mean surface hydrological components averaged over the Amazon Basin as simulated during AMIP. The full 17-year average is con-

Table 3b. Means and Standard Errors of $\delta^{18}O$, δD, and d Excess (dxs) for Upper and Lower Deciles of Precipitation Days for Precipitation and Water Vapor Isotopic Depletions for Belem and Manaus

	$\delta^{18}O$ Mean (S.E.), ‰	δD Mean (S.E.), ‰	dxs Mean, ‰	$\delta^{18}O$ Mean (S.E.), ‰	δD Mean (S.E.), ‰	dxs Mean, ‰
Belem						
Top decile	−13.0 (0.8)	−90.0 (6.7)	3.2	−4.3 (0.5)	−25.8 (5.2)	−1.8
Bottom decile	−11.0 (0.2)	−78.7 (2.0)	21.2	−0.6 (1.8)	4.5 (2.4)	17.2
Manaus						
Top decile	−12.0 (1.4)	−83.3 (11.4)	−2.9	−6.6 (1.2)	−21.4 (5.4)	−0.8
Bottom decile	−7.0 (1.8)	−73.3 (−7.0)	28.8	−2.2 (0.9)	−13.5 (4.9)	43.7

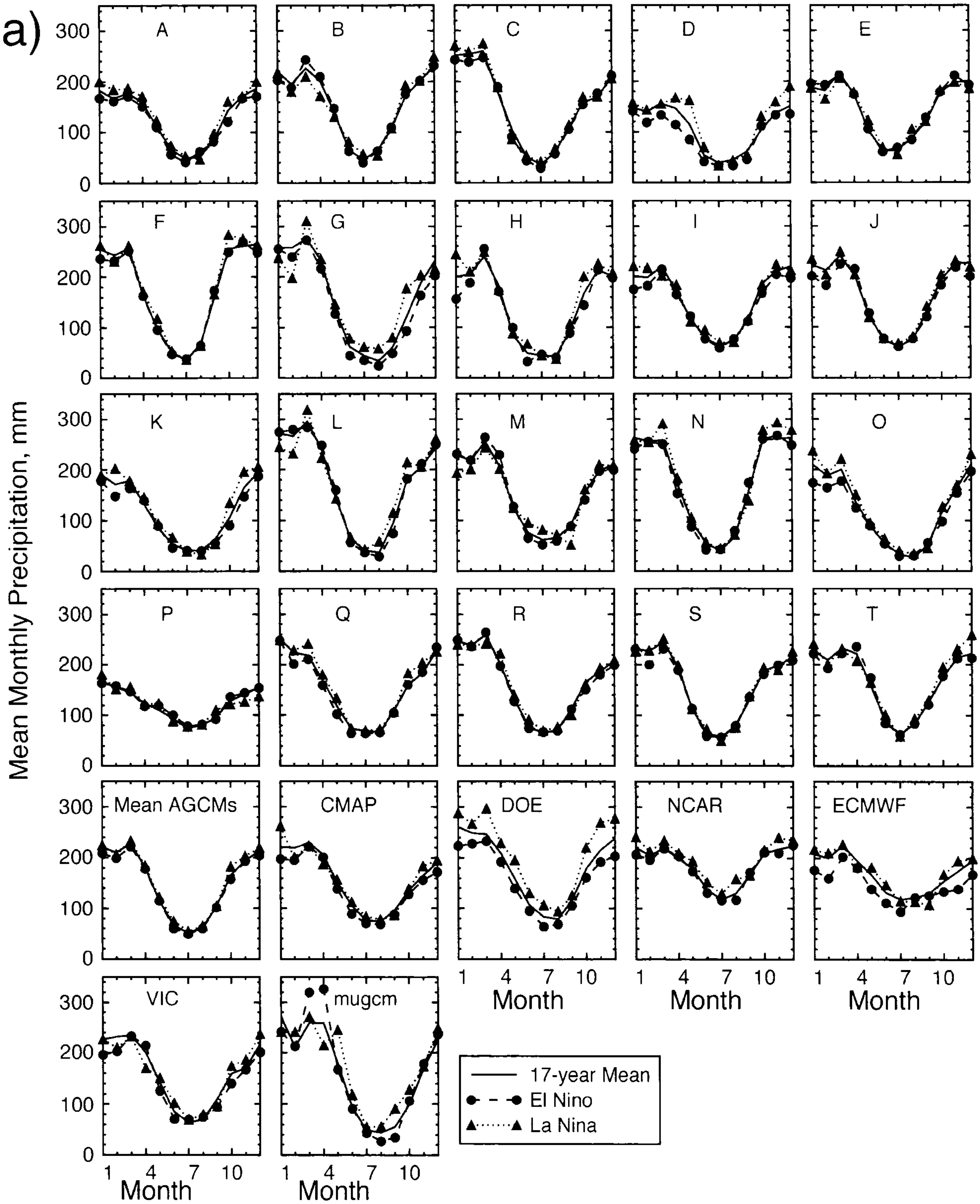


Figure 6. AMIP II monthly mean hydrology components: (a) precipitation, (b) evaporation, (c) runoff, (d) moisture convergence (*Pr* – *Ev*), and (e) evaporation ratio (*Ev*/*Pr*) for 20 AMIP models (A-T). AMIP mean, available observations, NCEP-DOE, NCEP-NCAR, ECMWF, VIC, and MUGCM. In all plots the full 17-year average is compared with El Niño and La Niña periods.

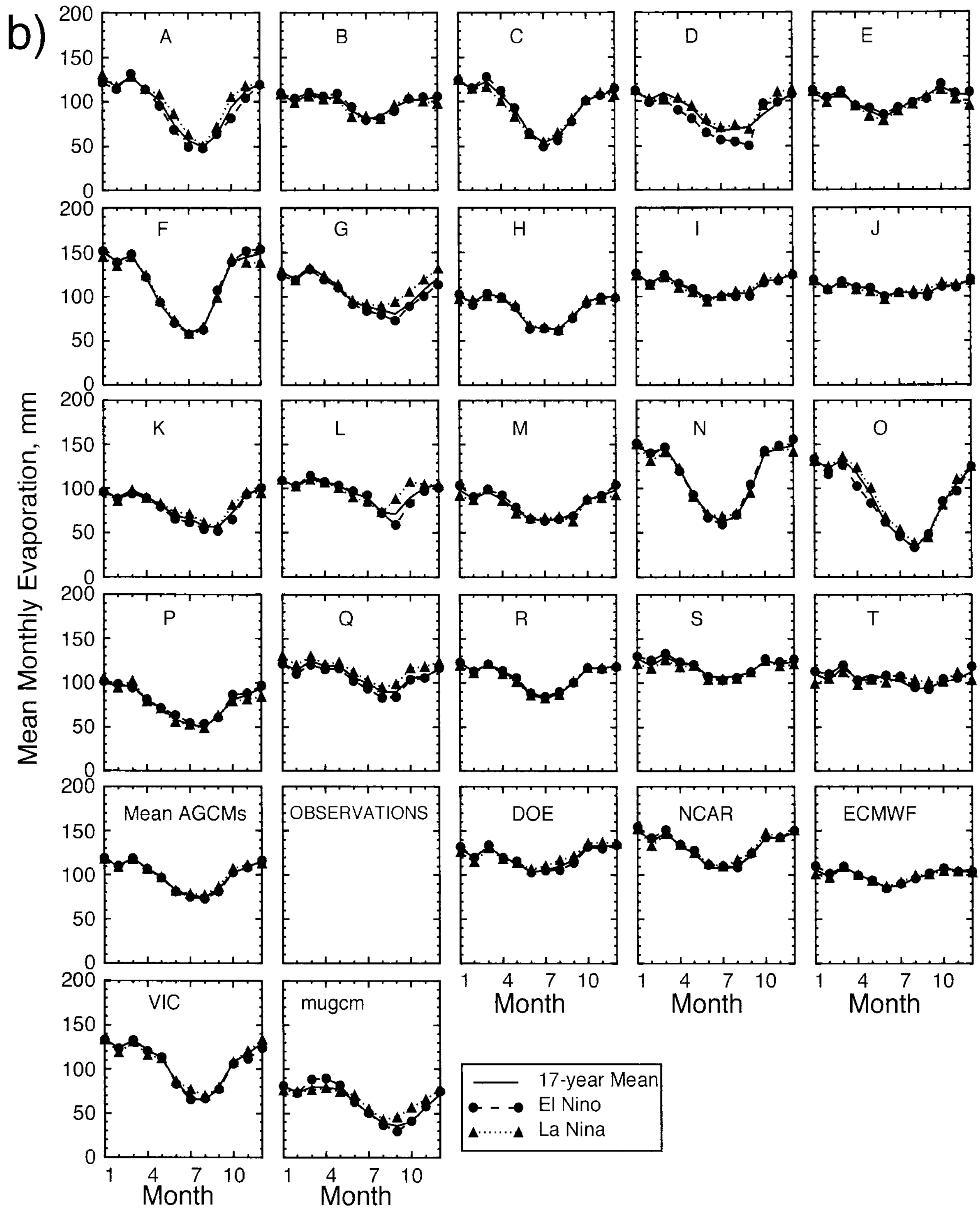
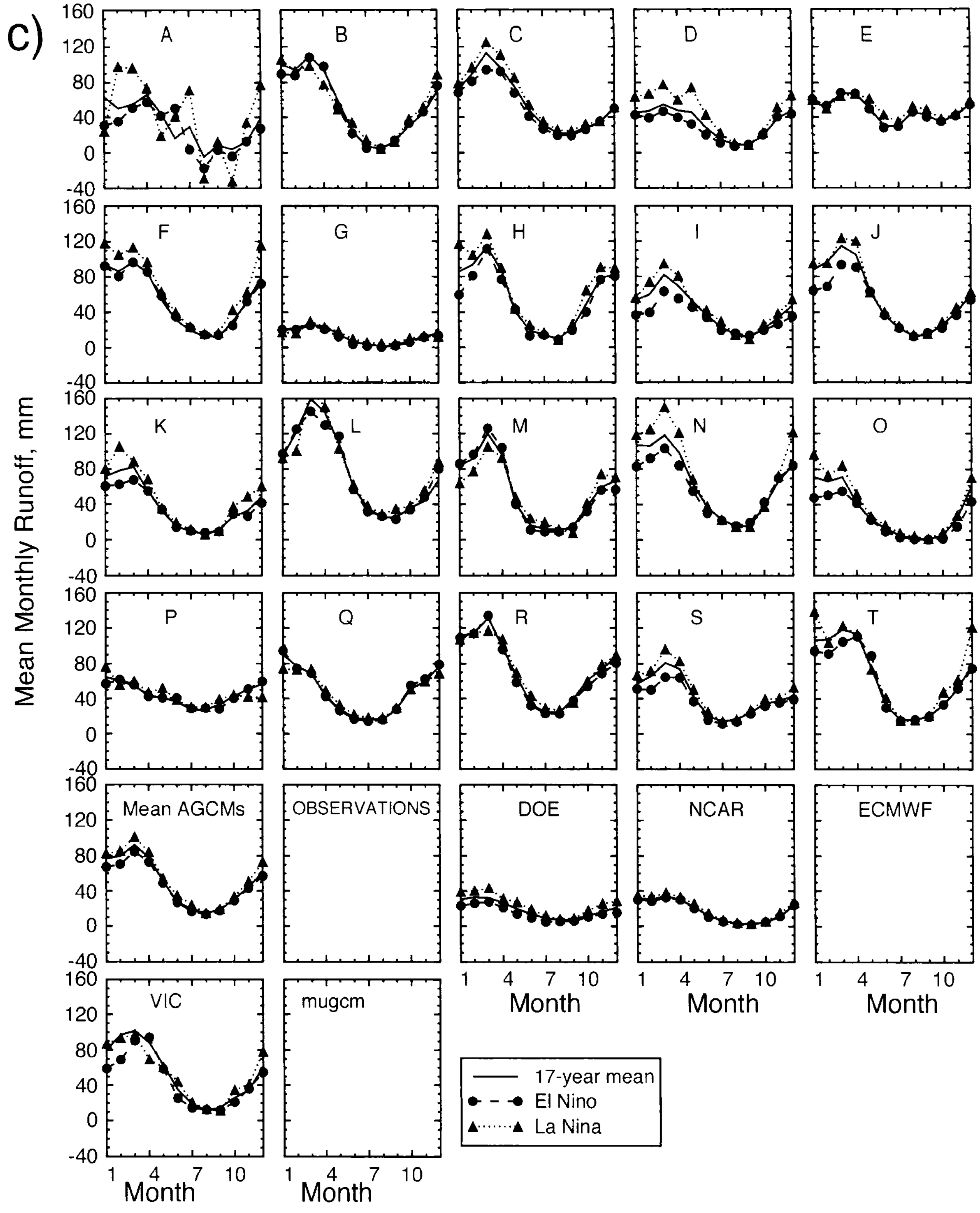


Figure 6. (continued)

trasted with the El Niño and La Niña periods as predicted by 20 AMIP II AGCMs, their mean, three reanalyses (NCEP-DOE [*Kanamitsu et al.*, 2002], NCEP-NCAR [*Kistler et al.*, 2001], and ECMWF), the VIC scheme [*Liang et al.*, 1994], and the Melbourne University AGCM (MUGCM), which is an isotope GCM [*Noone and Simmonds*, 2002]. The hydrological components are precipitation, *Pr* (Figure 6a), evaporation, *Ev* (Figure 6b), runoff, *Ro* (Figure 6c), atmospheric moisture inflow (*Pr* – *Ev*) (Figure 6d), and the evaporation ratio (*Ev*/*Pr*) (Figure 6e).



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[40] There is most agreement in the simulation of rainfall seasonality and atmospheric moisture convergence (at the basin level) with, arguably, least agreement in the runoff (Figure 6c) and evaporation ratio (Figure 6e). Precipitation (Figure 6a) and moisture convergence (Figure 6d), being closely related to ENSO-driven circulation changes, exhibit the largest sensitivity to ENSO forcing, with the NCEP-DOE reanalysis and the MUGCM being the most sensitive to El Niño and La Niña events. This result is not too surprising as VIC is "partitioned" from distant climatic events and the AMIP mean is an average of twenty models. However, none of the AMIP models exhibit as much

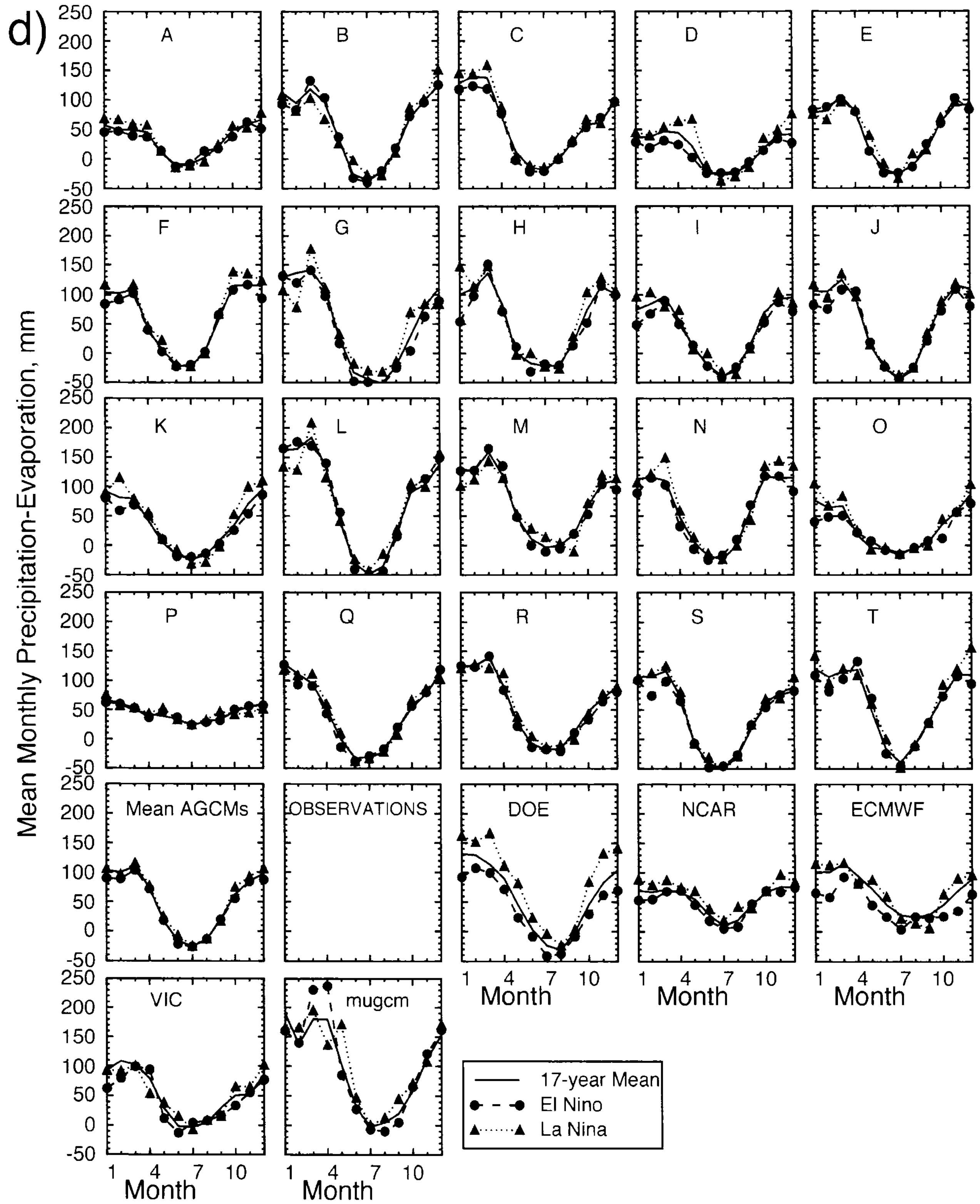

Figure 6. (continued)

sensitivity to ENSO conditions as the reanalyses: results less easily explained.

[41] The evaporative fluxes (Figure 6b) differ quite considerably with most models exhibiting very little seasonality and very little ENSO response. Some models have a significant seasonal cycle in tune with VIC. Although the MUGCM has both evaporative seasonality and sensitivity to ENSO, its values overall seem too small. The variety of runoff simulations is considerable (Figure 6c). Some models have very low seasonality of runoff (like the reanalyses), whereas others have seasonality of runoff comparable to the moisture convergence (*Pr* − *Ev*). Differences between the

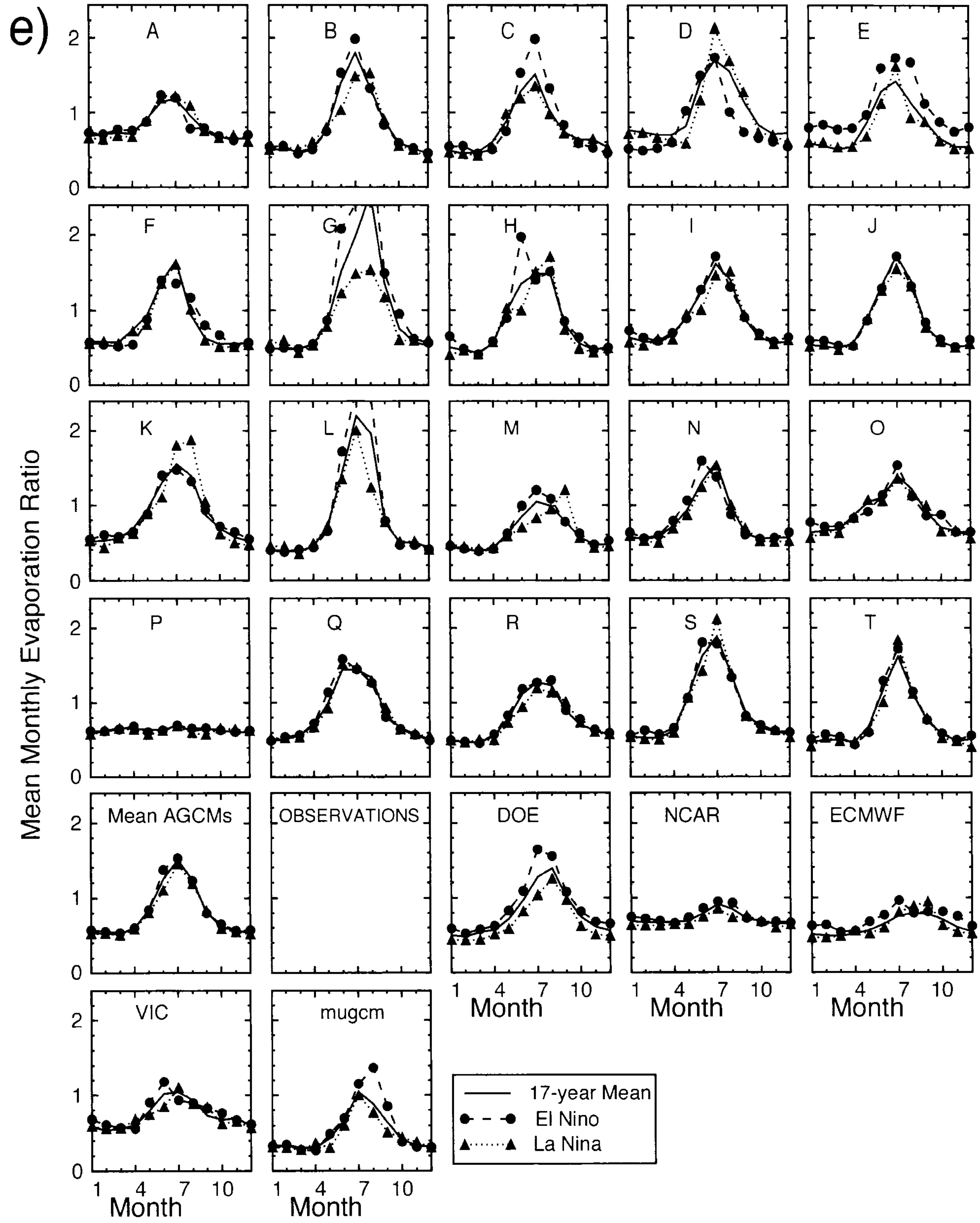

Figure 6. (continued)

seasonality of moisture convergence and runoff are indicative of moisture storage (and in extreme cases, of nonconservation of water). The evaporation ratio, shown in Figure 6e, displays the greatest intermodel differences in seasonality and in sensitivity to El Niño. Model P shows virtually no seasonality or sensitivity whereas Model L displays a large seasonality and sensitivity.

[42] The AMIP simulations do seem to capture an overall ENSO response with La Niñas being wetter (more rain in, e.g., A, D, G, and NCEP-DOE) than the average. There is

Table 4. Annual Surface Hydrologic Summaries From the AMIP II and MUGCM Models Together With a Variety of Estimates of "Truth" for the Global Land Surface (GLS) and the Amazon Basin

Source	Pr, mm d^{-1}	Ev/Pr	Ro/Pr
	GLS		
GRDC/CMAP	1.94	0.60	0.40
NCEP/DOE [*Kanamitsu et al.*, 2002]	2.40	0.79	0.45
NCEP/NCAR [*Kistler et al.*, 2001]	2.37	0.77	0.53
ECMWF [*Gibson et al.*, 1997]	2.21	0.72	...
VIC [*Nijssen et al.*, 2001]	2.07	0.67	0.33
MUGCM [*Noone and Simmonds*, 2002]	2.46	0.47	0.53
Av AMIP II	2.27	0.67	0.33
[SD AMIP II	*0.31*	*0.52*	*0.06]*
	Amazon		
GRDC/CMAP	5.00	0.39	0.61
NCEP/DOE [*Kanamitsu et al.*, 2002]	5.71	0.68	0.43
NCEP/NCAR [*Kistler et al.*, 2001]	5.93	0.71	0.39
ECMWF [*Gibson et al.*, 1997]	5.38	0.59	...
VIC [*Nijssen et al.*, 2001]	5.09	0.67	0.33
MUGCM [*Noone and Simmonds*, 2002]	5.26	0.39	0.61
Av AMIP II	4.97	0.67	0.34
[SD AMIP II	0.68	*0.07*	*0.05]*

also weak agreement with the *Foley et al.* [2002] runoff results in that some models (e.g., I, N, and S) show lower runoff during El Niños, especially in the early part of the year. There is also a large variation among these AMIP II models, which may affect their simulation of the surface hydro-climate and hence the extent to which they, and isotopically enabled versions of these GCMs, can correctly characterize surface-atmosphere water fluxes.

[43] Table 4 summarizes the annually averaged hydrological components over the Amazon from the 20 available AMIP II models together with observations of runoff (GRDC [*Fekete et al.*, 2000]) and precipitation (CMAP) from the Climate Prediction Center [*Xie and Arkin*, 1997]. As seen in Table 4, globally and in the Amazon Basin, NCEP reanalyses fail to conserve water. ECMWF [*Gibson et al.*, 1997] may also have similar problems but we were unable to assess this because we could not acquire its runoff data (NRD). VIC [*Nijssen et al.*, 2001] is seen to conserve the surface water everywhere because it is constrained by observed precipitation and tuned for large river flows. *Henderson-Sellers et al.* [2003b] argue that VIC provides a reliable surface water simulation, at least when averaged over a large area and a long period of time [see *Wood et al.*, 1998].

[44] In the Amazon, all reanalyses and AMIP models' estimated runoff ratios are smaller than observations (Table 4). Considering the relatively high available energy and dense vegetation canopy of the catchment, an observed mean runoff ratio of about 61% is arguably too high. Investigation reveals that the GRDC mean runoff over some areas of the Amazon Basin is greater than the CMAP mean precipitation (Figure 7a). Comparing GRDC with the GCPC [*Huffman et al.*, 1995] and *Legates and Willmott* [1990] precipitation climatologies provides similar results. Comparison of the mean seasonal cycles of runoff, *Ro*, and precipitation, *Pr*, for areas of $Ro \geq Pr$ (Figure 7b) shows that excess runoff in comparison to precipitation is especially large during the high precipitation period when it is expected that some of the precipitation will be stored in the soil to supply evaporation and slow drainage in the relatively drier months.

[45] The closure of the simulated land-surface water budget is a fundamental requirement for land-surface representation. Thus

$$Pr - Ev - Ro - dW/dt = 0. \tag{2}$$

Assuming that the rate of change of surface water storage with time (*t*) (i.e., *d*/*dt* of soil water, canopy water and snow and ice) is close to zero over long periods (e.g., the 17-year AMIP II simulation), the water imbalance (Wimb) can be defined as the residual of precipitation less runoff and evaporation. If this term is small, that is, less than ±0.05 mm d^{-1}, water is conserved. In Table 5 it can be seen that six of the AMIP II models (B, C, D, G, M, and R) do not conserve water at the land-surface adequately to be considered of value in hydrological assessments.

[46] The simulation of total precipitation is generally reasonable except for Model D, which has too little rainfall, as well as failing to conserve water. The partition of the incoming precipitation into evaporation or runoff is very different among the AMIP AGCMs. For example, Model A puts less than 25% of its rain into runoff while Model L has almost 45% runoff. This full AMIP range is significantly less than the 61% reported by GRDC, itself questionable [e.g., *Henderson-Sellers et al.*, 2003b]. Similarly, Model M reevaporates just over 50% of its rain while, at the opposite AMIP extreme, Model D reevaporates almost 85% and all are larger than the derived observation of 39%. As both of these fail to conserve surface water adequately, the range for AMIP models which do pass the conservation test is lower (55% to 75%).

[47] The startlingly large range in simulated water partitioning shown in Table 5 suggests that characterization of hydro-climatic changes using stable isotopes, or indeed by any other means, will be very difficult if not impossible for a number of these GCMs in the Amazon. Indeed, the analysis performed here shows that in the Amazon Basin a few of the AMIP II AGCMs and well used reanalyses fail to close the surface water budget to within an acceptable margin of ±0.05 mm d^{-1}. Since isotopic analysis involves tracking hydrological fluxes and reservoirs several orders of

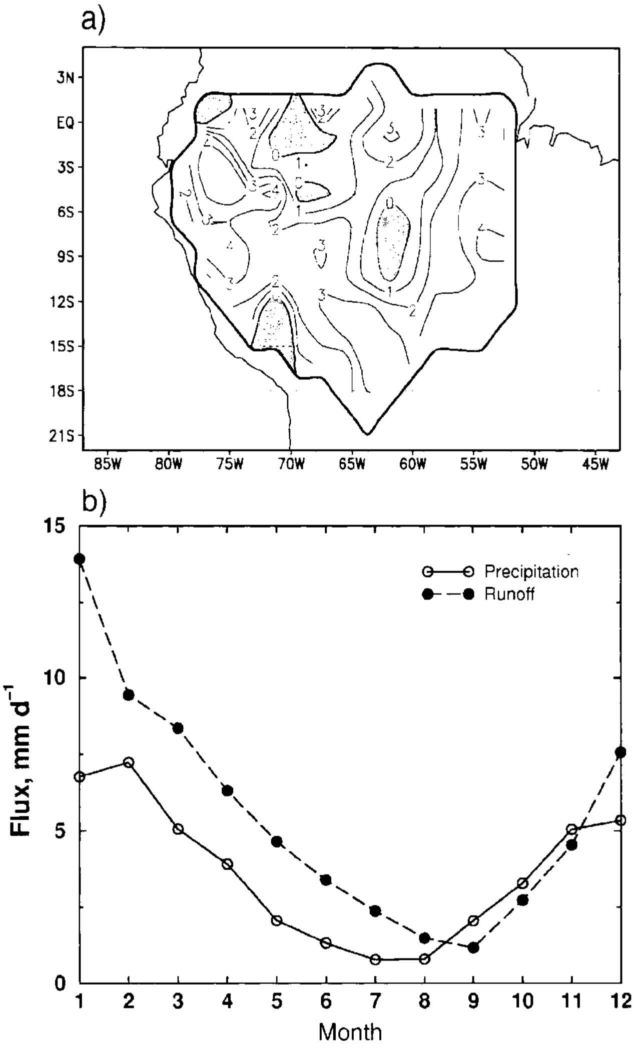

Figure 7. (a) Geographical distribution of the observed mean *Pr* − *Ro* (mm d^{-1}) in the Amazon (*Ro* > *Pr* in the shaded area) and (b) the mean seasonal cycle of *Pr* and *Ro* (mm d^{-1}) for one grid square in the shaded area. All data are drawn from global observational sets of runoff (GRDC [*Fekete et al.*, 2000]) and the CMAP precipitation from the Climate Prediction Center [*Xie and Arkin*, 1997].

magnitude smaller than those in traditional hydrological models, very much more benefit can be gained by dealing with water budget closure in the gross hydrology before proceeding to address isotopic fractionation processes.

[48] Among the models that do not close the water balance, some have not followed the AMIP protocol for reporting values of the required variables [e.g., *Henderson-Sellers et al.*, 2003b]. Despite the emphasis in the AMIP II protocol, soil water initialization is still a problem in major hydrological regions such as the Amazon. Problems concerning the lack of reliable global observations for evaluating land-surface simulations persist. The nonclosure of the surface water budget and very different evaporation ratios from observations suggests that reanalyses are not appropriate tools for evaluating simulated surface water budget components. Furthermore, the GRDC runoff data set is found to be problematic in the Amazon and is not consistent with global precipitation data sets. Owing to constrained atmospheric forcing, off-line land-surface schemes, such as VIC, close the surface water balance and simulate evaporation ratios better than any reanalyses, but in some regions runoff ratios are very different from observations although these themselves may be questionable [*Henderson-Sellers et al.*, 2004].

3.3. Summary

[49] In this section, simulations of Amazonian basin-scale hydro-climate variability have been examined over the AMIP II period and observations reviewed in the context of detailed daily observations of stable water isotopes in precipitation and near-surface vapour. As isotopic depletions are a strong function of precipitation amount but exhibit weaker relationships to wind speed and direction (Figure 5), isotopic characterization and model interpretation will be incorrect if precipitation is inadequately predicted either seasonally or under climatic variations such as ENSO-driven circulation shifts (see Figures 6a–6e and Table 4).

[50] Despite limitations in observations, which make absolute determination of correctness difficult (e.g., Table 4 and Figure 7), some global model simulations are found to be too poor to be of value (Table 5) for isotopic application and interpretation. Overall, ENSO forcing causes responses in many of the AMIP II models, the MUGCM, VIC and the reanalyses (Figures 6a–6e). These sensitivities are almost always small relative to the seasonal cycle and generally in the expected directions, i.e., the models' simulated sensitivities agree with the observed impacts of El Niño/La Niña events. The isotope AGCM (MUGCM) performs fairly well but tends to exhibit more variability than the AMIP AGCMs and the three reanalyses.

[51] Although it is true that, even if a simulated climate differs widely from reality, isotopic simulations can be appropriate to this model-simulated climate, such isotopic characterization would be of little use for assessment of the causes of land-atmosphere exchange mechanisms: the goal of this paper. This section has demonstrated the need for valid hydrological simulations prior to any investigation of isotopic hydrological exchanges.

4. GNIP Data Analyses and Interpretation

4.1. GNIP Data From Recent Decades

[52] Stable isotopic data in rainfall have been collected by the IAEA/WMO in the Amazon Basin since 1961 [e.g., *Rozanski et al.*, 1993] as part of a global monitoring program over 550 stations. Sadly, from this total, less than half have records appropriate for interannual analysis, and only a very small fraction are still operational. Of the six or seven stations that have been established within the general area of the Amazon Basin (Figure 1b), the most recently reporting (to 2001) stations are Izobamba and Bogota as compared with Belem, Manaus, and many other Brazilian stations which provided data until the end of the 1980s (Table 6a).

[53] Although the AMIP II period includes three El Niños and two La Niñas, the availability of Amazon GNIP data does not coincide very well with the later of these events. To

Table 5. Annually Averaged Water Budget Components for the Amazon Basin From 20 AMIP II AGCMs[a]

AMIP AGCM	Precip., mm d^{-1}	Wimb., mm d^{-1}	*Ev/Pr*	*Ro/Pr*
Observations	4.98	0.0	0.39	0.61
A	4.25	0.02	0.75	0.25
E	4.86	−0.02	0.68	0.32
F	5.80	−0.02	0.65	0.35
H	4.73	−0.04	0.60	0.41
I	5.10	0.01	0.73	0.27
J	5.47	0.00	0.66	0.34
K	3.91	−0.04	0.68	0.33
L	5.73	0.02	0.55	0.44
N	5.91	−0.02	0.64	0.36
O	4.06	−0.01	0.74	0.26
P	4.03	0.00	0.63	0.37
Q	5.14	−0.02	0.70	0.31
S	5.35	0.05	0.73	0.26
T	5.56	0.00	0.62	0.38
Water imbalance unacceptable below here				
B	5.11	***0.08***	0.63	0.35
C	5.06	***0.07***	0.62	0.37
D	3.55	***−0.55***	0.84	0.31
G	5.22	***−0.08***	0.67	0.34
M	5.18	***0.68***	0.52	0.35
R	5.40	***−0.49***	0.65	0.44

[a] Water imbalance (Wimb) is determined to be unsatisfactory if it exceeds ±0.05 mm d^{-1}. These cases are highlighted by boldface and italics.

obtain adequate data for analysis, one earlier La Niña (1973–1975) was included, and the last event of each type in the AMIP II period was set aside. Table 6b lists the number of months for which δ^{18}O and δD data are both available at Manaus and Izobamba.

[54] Despite the relative sparseness of the data in Table 6b, the differences in depletions are remarkable (Figure 8). Specifically, the δ^{18}O and δD measurements follow one another very closely in the mean (average of all months available, see Table 6a); in El Niños (about 20 months' data); and in La Niñas (between 22 and 33 months' data, see Table 6b). At Manaus, El Niños cause a very noticeable reduction in depletions from April to August (dry season), while La Niñas enhance the mean dry season depletions. For the other months of the year, El Niño tends to reduce the depletions as seen at Manaus. δ^{18}O and δD depletions track closely and clear separations occur between ENSO and "normal" conditions especially in the dry season. The opposite effect is seen at Izobamba in May when El Niños increase the depletion in both isotopes. Near the Pacific coast of South America, El Niños are characterized by increased precipitation, largely derived from Pacific-sourced moisture which is not affected by the Amazon [*Hoffman et al.*, 2003] (Figure 8c).

[55] Figure 9a compares basin-wide averages of δ^{18}O and deuterium excess for the 17 years of the AMIP II period from MUGCM together with the observed values for Manaus and Izobamba. For δ^{18}O the model lies between the two sets of station data, with a very similar seasonal pattern. For the deuterium excess, however, the MUGCM basin averaging leads to values close to the MWL (see Figure 3b), while data for Manaus show evidence for increased recycling in the middle of the year. Figures 9b and 9c are for the El Niños and La Niñas listed in Table 6b. The δ^{18}O values are rather similar to the means (Figure 9a), except that Manaus data and the MUGCM simulations show a little more depletion during La Niñas. In the deuterium excess seasonal cycle, however, there are clear differences between El Niño and La Niña years for MUGCM, with much larger values of d excess in August–September of El Niño years, indicating more recycling at these times.

[56] Analyses for Izobamba and Bogota show upper Amazon Basin isotopic depletions altering recently (i.e., into the 1990s and 2000s, Figures 10a and 10b). Enhanced depletions in wet months tend to be statistically significant at both locations. At Izobamba the larger depletions have recently become still greater, while smaller depletions have tended to diminish (Figure 10a). As century-long analysis of ice core isotopes from the Andes indicate significant interdecadal variability [*Hoffman et al.*, 2003], care needs to be exercised in attempting to draw conclusions from recent decadal-only contrasts. However, the recent enhanced depletion is interesting because it contrasts with *Henderson-Sellers et al.*'s [2002] finding of decreasing depletions at Manaus between the 1960s and the 1980s. One possible interpretation could be that in recent decades the impact of deforestation [e.g., *Fearnside*, 1993] is affecting water recycling which is the result of canopy interception and reevaporation of that water. Alternatively, increases in the areal extent of open water [*Foley et al.*, 2002] might have decreased the relative importance of reinsertion of heavy isotopes into the basin hydrological system. Finally, there are known to have been changes in the large-scale circulation of both the atmosphere and the oceans between these two periods [e.g., *Vuille et al.*, 2003a, 2003b] which may have affected the source or isotopic history of precipitation and/or flooding extent and persistence.

[57] Seasonal amplitude in isotopic depletions in the upper part of the Amazon Basin has increased over the last 25 years (Figures 10e and 10f). At Izobamba the dry season depletions have decreased, and the wet season depletions increased. At Bogota (where precipitation is influenced by

Table 6a. IAEA/WMO Amazon Basin Isotope Collection Station Location Details and Availability[a]

Station	Location	Alt., m asl	Operational Period	Number of Data Months	Percent Time for D and ^{18}O
Belem	1.43°S, 48.48°W	24	1965–1987	264	87.5%
Manaus	3.12°S, 60.02°W	72	1965–1990	300	52.0%
Izobamba	0.37°S, 78.55°W	3058	1968–date, i.e., 2001-	324	93.1%
(Alluriquin)	(0.2°S, 78.38°W)	(850)	(1992–1996)	(24)	(93%)
Bogota	4.7°N, 74.13°W	2547	1971–date, i.e., 2001-	213	95%

[a] 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.

the Amazon for only part of the year), the wet season depletions have also increased, while the dry season shows no change. It is possible that the seasonal change in δ^{18}O and δD signatures between the 1970s/1980s and 1990s/2000s may indicate the impact of deforestation (vegetation removal prompting less recycling and less reinsertion of heavy isotopes into the basin hydrological system) or greater river water and flooded areas in the central basin might have altered the balance between fractionating (evaporation from open water) and nonfractionating (full canopy and transpiration). This latter proposition could possibly be probed further using d excess observations and simulations. Although Figures 10c and 10d show no d excess differences at times when δ^{18}O depletions change, the integrating impact of ENSO events on Andean isotopes demonstrated by *Hoffman et al.* [2003] and *Vuille et al.* [2003b] might be smoothing anticipated signals.

4.2. Using Isotopes to Evaluate Amazonian Hydro-Climatic Changes

[58] There is considerable interest in the use of isotopic information as a novel data source for model evaluation [e.g., *Gibson et al.*, 2002]. The purpose of this paper is as an exemplar of how investigations of changing hydrology could possibly exploit stable water isotope data and isotopic model simulations. It focuses on an area where isotopic characterization initiated GCM analysis of land-atmosphere interactions: the Amazon Basin.

[59] We have shown in section 2 that two LSSs (CLM and ISOLSM) exhibit significant sensitivities in their simulation of gross and isotopic surface hydrology when addition is made of 20% open water and with a realistic depletion in the ambient atmospheric water vapor. It is likely that isotope-enabled LSSs would result in similar, if not greater, disagreement on the relative importance of fractionating and nonfractionating processes [e.g., *Chen et al.*, 1997].

[60] In section 3 we illustrated the great variety in the performance of AGCMs in simulating the water budget of the Amazon Basin. As *Vuille et al.* [2003a] argue that ENSO events effectively integrate many factors affecting the isotopic character of South American precipitation, our results demonstrate that, without a better consensus among state-of-the-art AGCMs and reanalyses on the nature of this major basin's hydrology, the addition of isotope tracing is unlikely to reveal much that is unambiguous about changes to the system.

[61] In this section, observations of isotopic depletions in Amazonian precipitation have been compared with simulations by an isotope AGCM and analyzed for possible recent trends. We find that recent upper basin isotope measurements show a tendency toward more depletion, possibly because there is less or changed water recycling (Figure 10). There is more depletion in the wet season arguably because relatively less nonfractionating recycling occurs (i.e., less transpiration and full canopy evaporation and/or relatively more evaporation from open water areas). The recent increased seasonality at Izobamba (Figures 10e and 10f) could therefore be due to (1) relative changes between fractionating as compared to nonfractionating evaporation (a plausible conclusion if lake and open water areas have changed); (2) less water recycling (a possible result of deforestation); or (3) circulation changes.

[62] *Henderson-Sellers et al.* [2002] proposed that their observed isotopic changes might be due to greenhouse intensification of the hydrological cycle masking any land-use change impact. Alternative explanations for their null result, including that isotope data to 1990 only were available and the statistically significant wet season changes reported might be related to ENSO events or other climatic variations that modify the regional circulation and hence affect the gross and isotopic hydrology of the Amazon, have all been shown here to have merit. On the other hand, it has also been demonstrated that numerical models (both atmospheric and land-surface) that cannot reproduce gross water budgets correctly cannot add value to isotopic interpretations.

[63] There is certainly potential to explore isotopic modification in the Amazon by utilizing state-of-the-art isotopically enabled land surface schemes combined with plausible "isotope" GCMs [*Noone and Simmonds*, 2002; *Hoffman et al.*, 2003; *Vuille et al.*, 2003a, 2003b]. The challenge is to choose problems appropriate to this new tool and to validate gross water predictions before interpreting isotopic simulations.

Table 6b. El Niño and La Niña Periods Analyzed From GNIP Stations Together With the Number of Months of Measurements of Both δ^{18}O and δD

Period	Manaus	Izobamba
El Niño		
July 1982 to June 1983	10	9
July 1986 to June 1987	10	0
July 1991 to June 1992	0	11
La Niña		
July 1973 to June 1975[a]	23	21
July 1984 to June 1985	10	1

[a] Note that the first La Niña event is not in the AMIP II period but was included because the GNIP coverage of the La Niñas in AMIP is poor.

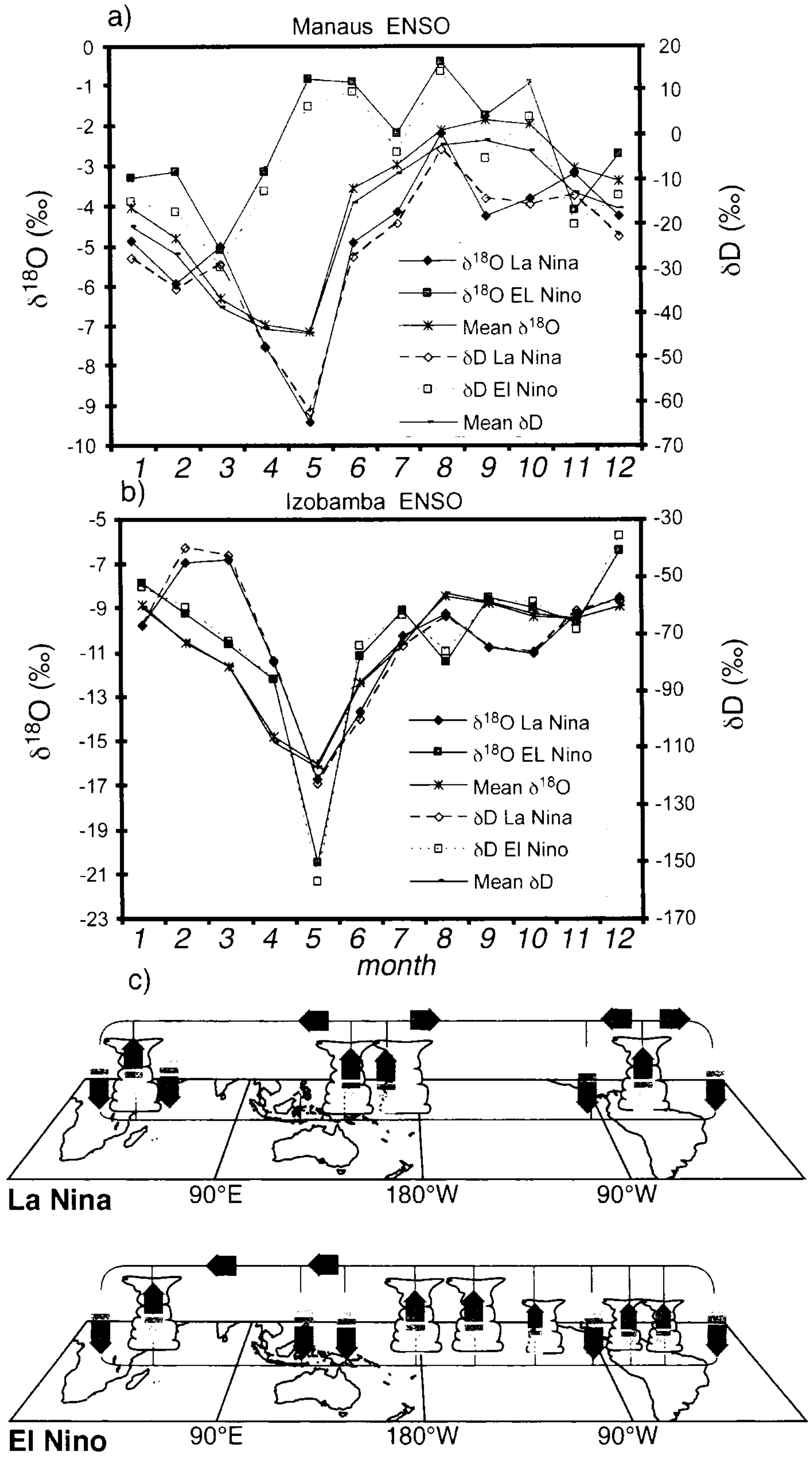

Figure 8. El Niño and La Niña $\delta^{18}O$ and δD depletions from GNIP observations at (a) Manaus and (b) Izobamba for all years (mean, see Table 6a; El Niño, 20 months; and La Niña, 20–30 months, see Table 6b). (c) Changes to the Walker Circulation during La Niña (above average precipitation, upper panel) and El Niño (lower panel) periods when convection shifts to the central Pacific, reducing precipitation in the Amazon (modified from *Foley et al.* [2002]). See color version of this figure in the HTML.

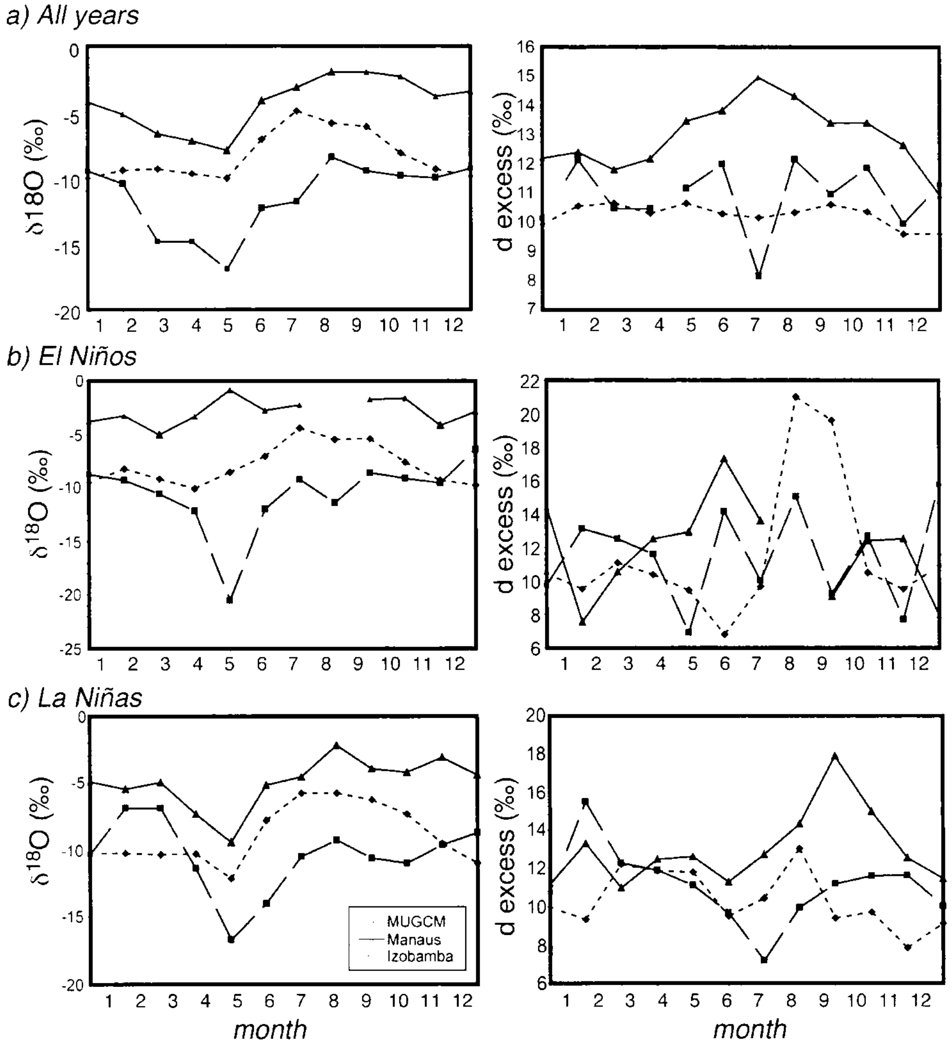

Figure 9. (a) Seasonal cycle of precipitation-weighted δ^{18}O (‰) and deuterium excess for all 17 years of the AMIP II period for MUGCM together with GNIP-derived values for Manaus and Izobamba from all available years. (b) As Figure 9a, except for El Niños. (c) As Figure 9a, except for La Niñas (ENSO periods listed in Table 6b give rise to a data gap in August at Manaus for El Niños).

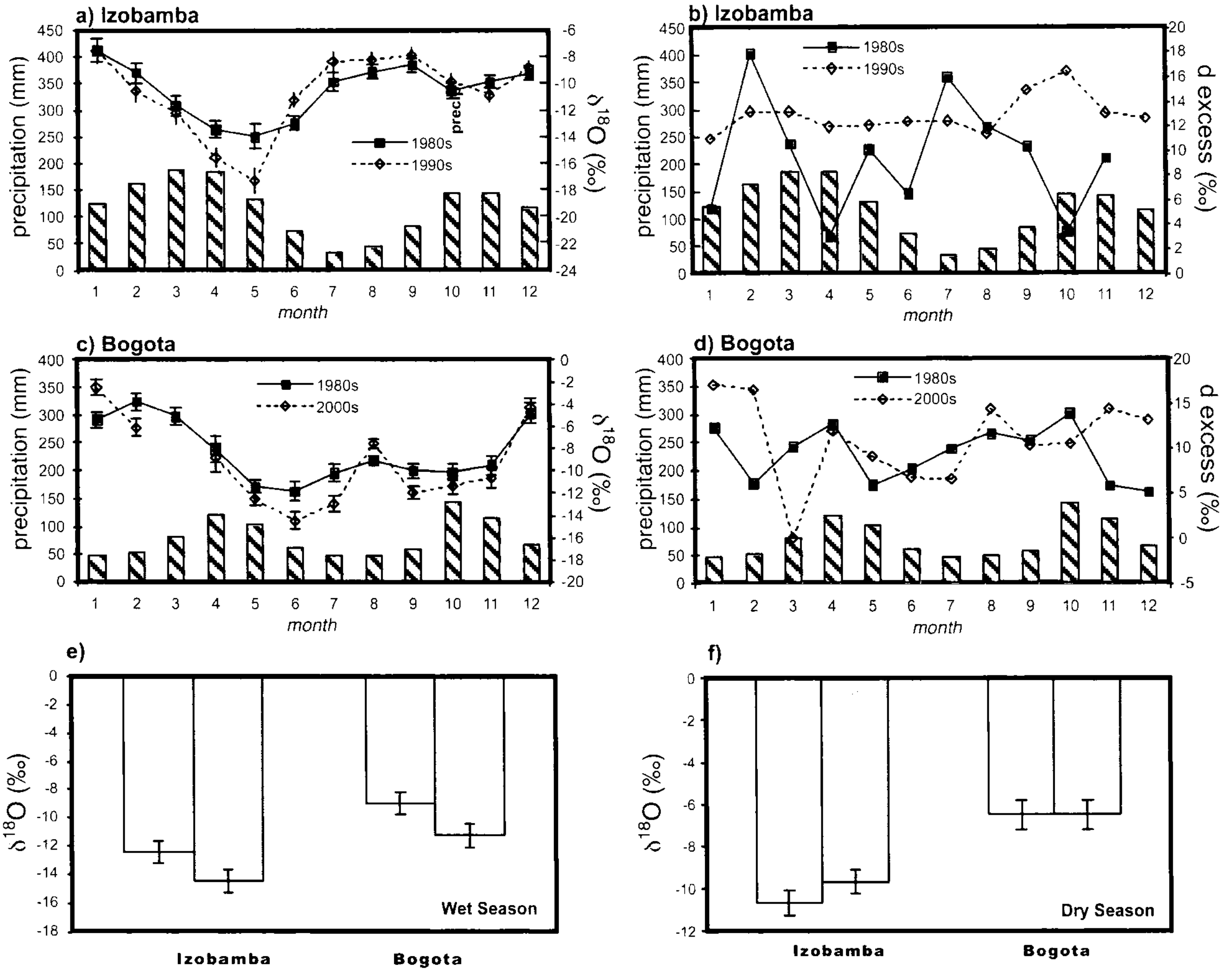

Figure 10. Monthly mean precipitation (mm) and values of $\delta^{18}O$ in precipitation at (a) Izobamba for the 1980s as compared to 1990s and (b) Bogota for the 1980s and 2000s. Error bars are ±1 SE. (c) and (d) As Figures 10a and 10b, except for d excess. (e) Four-monthly wet season averages of $\delta^{18}O$ between the two bidecadal periods (1970s plus 1980s) as compared to (1990s plus 2000s) at Izobamba (February–May) and Bogota (April/May and October/November). (f) As Figure 10e, except for dry seasons (June–September) at Izobamba and (January/February and July/August) at Bogota. Full period standard errors show the statistical significance.

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Stable water isotope characterization of human and natural impacts on land-atmosphere exchanges in the Amazon Basin

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Abstract

Stable water isotopes have been employed as a means of challenging, validating, and improving numerical models of the Amazon Basin since the 1980s. This paper serves as an exemplar of how characterization of human and natural impacts on surface-atmosphere water exchanges could beneficially exploit stable water isotope data and simulations. Interpretations of Amazonian isotopic data and model simulations are found to be seriously hampered by (1) poor simulation of the gross water budget (e.g., lack of surface water conservation in models); (2) considerable model differences in the fate of precipitation (i.e., between reevaporation and runoff); (3) wide ranging characterization of natural causes of water isotopic fluctuations (especially El Niño and La Niña events); (4) isotopic land-atmosphere flux sensitivity to the prescription of boundary layer atmospheric water vapor isotopic depletion; and (5) significantly different characterization by current land-surface schemes of the partition of evaporation between isotopically fractionating (from lakes and rivers) and nonfractionating (transpiration) processes. Despite these obstacles, we find features in the recent isotopic record that might be derived from circulation and land-use changes. ENSO events may cause decreased depletion in the dry season, because of reduced convective precipitation, while increases in upper basin isotope depletions in the wet season may result from relatively less nonfractionating recycling because there are fewer trees. The promise for isotopic fingerprinting of near-surface continental water cycle changes depends upon fixing shortcomings in current atmospheric and land-surface models.

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