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Seasonal variation in the stable isotopic composition of precipitation in the tropical montane forests of Monteverde, Costa Rica

Amy L. Rhodes,^{1,2} Andrew J. Guswa,^{2,3} and Silvia E. Newell¹

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[1] Climate and land use change may diminish orographic clouds over tropical montane forests, stressing biota and water resources during dry seasons. From 2003 to 2005 we measured the stable isotopic composition of precipitation and throughfall in Monteverde, Costa Rica, to distinguish convective, wet season rainfall associated with the Intertropical Convergence Zone (ITCZ) from dry season, orographic rain produced by northeasterly trade winds. While event-to-event fluctuations of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ are high, monthly samples reveal a seasonal signal that may be used to trace water through the hydrologic cycle. Deuterium excess indicates that water evaporated from land is an important flux to the region during the transitional and dry seasons when winds from the Caribbean slope dominate. Following the shift to convective rainfall at the start of the wet season, when the western equatorial winds influence the Pacific slope of Costa Rica, d excess values become depressed. Yet as the wet season progresses, d excess begins to climb. These data suggest that several months of rain are needed following an acute dry season on the northern Pacific slope before a terrestrial evaporative signal is detected in wet season precipitation. The evaporative flux may result from a wet season expansion of surface water bodies and flooding of seasonal wetlands.

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1. Introduction

[2] Tropical montane cloud forests (TMCs) are ecosystems of extraordinary biological diversity whose existence depends on frequent immersion in clouds and mist [Stadtmüller, 1987; Bruijnzeel and Proctor, 1995; Hamilton *et al.*, 1995]. Characteristically, TMCs are situated on the ridges of mountain ranges. Orographic clouds can be the sole courier of moisture to the forests for many months of the year, and the water flux from orographic clouds can be significant. Strong updrafts created by interactions between winds and topography can keep large water droplets suspended within the clouds, ultimately producing higher amounts of water than advective fogs over flat terrain [Scholl *et al.*, 2006]. As a result, orographic clouds can be accompanied by significant wind and rainfall, and survival of many cloud forest ecological communities may be dependent on this input [Pounds *et al.*, 1999; Nadkarni and Wheelwright, 2000]. Hydrologically, the occurrence of TMCs in headwater regions also makes them important recharge areas, especially during dry seasons when interception of orographic clouds by the forest canopy may be

the sole hydrologic input [Zadroga, 1981; Bruijnzeel and Proctor, 1995; Bruijnzeel, 2001].

[3] The highland TMCs of Monteverde, Costa Rica exemplify this delicate balance between hydrology and forest ecology, yet climate change may be diminishing orographic cloud water to the region. Longer mist-free intervals observed over recent decades during the dry season have been attributed to an increased base height of the orographic cloud bank, and this phenomenon may be linked to population crashes of anuran species and increased elevational ranges of many bird species [Pounds *et al.*, 1999]. Epiphyte transplant experiments showed that small elevational changes that affect dry season moisture inputs on leeward slopes result in increased mortality of epiphyte plants and radical compositional changes in forest canopy communities; the loss of epiphytes could intensify this effect by diminishing the ability of the canopy to capture and store nutrients and water [Nadkarni and Solano, 2002]. Whether reduced orographic moisture is due to an increase in sea surface temperatures [Pounds *et al.*, 1999], land surface temperatures [Still *et al.*, 1999] or deforestation of lowland areas upwind of Monteverde [Lawton *et al.*, 2001; Nair *et al.*, 2003], improved understanding of the importance of orographic precipitation is needed. In recent years, Monteverde has also grown rapidly as an important ecotourist destination, and the associated increase in population has increased demand for potable water from springs and streams sourced within the forests, particularly during the drier seasons [Rhodes *et al.*, 2006a].

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[4] This paper presents a 2-year characterization of the stable isotopic composition of precipitation in Monteverde to test whether the stable isotopes of water (^{18}O and ^2H) may be used as a method for tracing precipitation from the drier seasons through the forest water cycle. Because of variation in their condensation histories, different kinds of precipitation (e.g., orographic versus frontal systems) may be characterized by differing stable isotopic compositions [Scholl *et al.*, 2002]. Therefore precipitation at Monteverde should reveal an annual fluctuation between heavy and light stable isotopic compositions that reflects the seasonal variation between orographic precipitation during the drier seasons, which is delivered to Monteverde by northeasterly trade winds, and wet season convective rainfall associated with the migration of the Intertropical Convergence Zone [Newell, 2004; Rhodes *et al.*, 2006b]. Identification of a strong seasonal isotopic signal will establish one tool for understanding the interconnections among climate, hydrology, ecology, and water resources at Monteverde in future research.

[5] In addition to tracing the condensation history of different sources of atmospheric water vapor, stable isotopes can identify precipitation that originates from rainfall that reevaporated from terrestrial sources [Gat, 2000]. Considerable research has established the importance of recycled water in the Amazon basin [Salati *et al.*, 1979; Gat and Matsui, 1991; Martinelli *et al.*, 1996; Henderson-Sellers *et al.*, 2002], and in Costa Rica, a snapshot in time of the stable isotopic composition of Costa Rican surface waters revealed that reevaporated water was an important contributor to the terrestrial water budget [Lachniet and Patterson, 2002]. However this latter study did not include any samples close to Monteverde, and the regional contours of the stable isotope data have great uncertainty in the Monteverde region. Measuring the stable isotopic composition of precipitation will enable us to evaluate the importance of recycled water to the water budget for the Monteverde region, which has relevance to hypotheses by Lawton *et al.* [2001] and Nair *et al.* [2003], who assert that lowland deforestation is diminishing orographic cloud formation at Costa Rica's mountain tops.

2. Background: Use of Stable Isotopes in Hydrometeorology

2.1. Tracers of Condensation History

[6] During condensation, the relative abundances of ^{18}O and ^2H in cloud water are functions of the source of water vapor and, to a lesser extent, temperature. As a rain cloud evolves, the isotopic composition of precipitation can change due to progressive condensation from the surrounding vapor mass. This is known as the rain-out or "amount effect" [Dansgaard, 1964; Clark and Fritz, 1997]; continued removal of the condensed phase from the vapor mass by precipitation gradually depletes the heavy isotopes in the remaining water vapor and causes the isotopic composition of the precipitation to become lighter as the storm progresses. The rain-out process leads to precipitation at the end of a rain event with $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values that are more negative than at the onset. Though temperature at the time of condensation can affect the isotopic composition, it will not account for large differences in δ values in the tropics

[Fricke and O'Neil, 1999; Gonfiantini *et al.*, 2001]. Therefore large differences in the isotopic composition of precipitation may be used to identify the condensation mechanism of liquid water at Monteverde, as well as at other mountainous regions in tropical environments. Rainfall during Monteverde's wet season (see section 3) may form from clouds that have experienced significant rainout, yielding stable isotopic compositions that are relatively light. Conversely, orographic clouds represent an early stage condensate that forms at temperatures near the land surface, and typically they are characterized by heavy stable isotopic compositions [Ingraham and Matthews, 1988; Scholl *et al.*, 2006], although orographic rain also may evolve to lighter values through a rainout process [Scholl *et al.*, 2002].

2.2. Tracers of Recycled Water

[7] Deuterium excess (d excess) values provide a useful isotopic tracer of the source of atmospheric vapor in precipitation, where d excess is defined as $d = \delta^2\text{H} - 8 \cdot \delta^{18}\text{O}$ [Dansgaard, 1964]. When water evaporates at a relative humidity less than 100%, kinetic (or disequilibrium) fractionation leads to vapor with a higher concentration of deuterium relative to ^{18}O than would be predicted for equilibrium conditions [Martinelli *et al.*, 1996; Gat, 2000]. The excess deuterium is preserved in moisture when the vapor condenses. Thus when water initially evaporates from the ocean, initial values of deuterium excess are fixed by the relative humidity of the air mass [Merlivat and Jouzel, 1979]. The global meteoric water line has a mean d excess value of $\sim 10\text{‰}$, resulting from a single stage of evaporation from the oceans at an average relative humidity of $\sim 85\%$ [Merlivat and Jouzel, 1979; Clark and Fritz, 1997]. Subsequent cycles of evaporation will introduce proportionally more deuterium into the vapor phase, leading to precipitation with even larger d excess values. Therefore a d excess value greater than $\sim 10\text{‰}$ can indicate that the precipitation contains water either recycled (e.g., reevaporated) from the land surface or condensed from vapor that formed when relative humidity was much less than 85%.

[8] Sea surface temperatures and wind speed also can affect kinetic fractionation but only weakly [Merlivat and Jouzel, 1979]. According to the calculated model by Merlivat and Jouzel [1979] the effect of temperature on d excess is negligible at tropical temperatures ($\sim 20\text{--}30^\circ\text{C}$) when relative humidity is greater than 70%. Clark and Fritz [1997] do note, however, that sea surface temperature can have an important kinetic effect on fractionation if it creates a large humidity contrast between the ocean surface and atmosphere. Vapor condensation from ice in clouds can experience an isotopic fractionation that will increase d excess in precipitation [Gonfiantini *et al.*, 2001]. However, this effect is less likely to occur in orographic clouds that condense near the land surface than for clouds that extend several kilometers into the atmosphere [Scholl *et al.*, in press]. Deuterium excess of vapor and liquid phases does not change during equilibrium condensation of rain, although low relative humidity over continents can facilitate partial evaporation of raindrops below the cloud base, which will reduce the d excess of rain [Rozanski *et al.*, 1993]. Transpiration is a nonfractionating process [Gat and Matsui, 1991] and does not affect d excess. Similarly, complete evaporation of a liquid water body, such as intercepted water on foliage, will not affect the amount of excess deuterium in

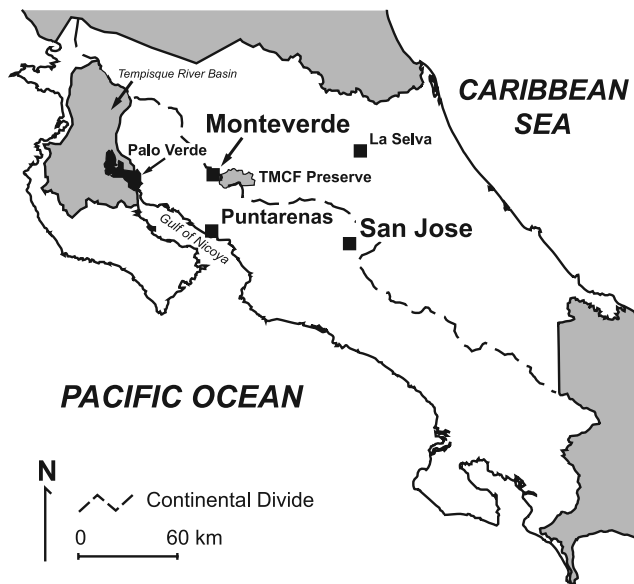


Figure 1. Location of Monteverde, Costa Rica (latitude $10^{\circ}18'N$; longitude $84^{\circ}48'W$).

resulting water vapor. Thus although many physical process can potentially affect the excess deuterium measured in precipitation, the relative humidity during evaporation as well as evaporation from terrestrial sources are likely to be the dominant influences at Monteverde.

2.3. Quantification of Cloud Water to Forests

[9] In addition to research campaigns that have employed physical measurement to quantify fog interception in forests [Giambelluca *et al.*, 2004; Frumau *et al.*, 2006; Giambelluca *et al.*, 2006; Holwerda *et al.*, 2006a, 2006b; Tobón *et al.*, 2006] stable isotopes have also been used for this purpose. A detailed review by Scholl *et al.* [2006] shows that rain and fog exhibit the greatest difference in isotopic composition in arid and temperate environments where fog is generated locally. Many of these studies were able to trace fog water in leaf water, tree sap, soil, and/or groundwater, thus characterizing the importance of fog to ecology and water resources in these arid and temperate climates [Aravena *et al.*, 1989; Ingraham and Matthews, 1990; Dawson and Ehleringer, 1991; Ingraham and Matthews, 1995; Ingraham, 1998].

[10] Less is known about isotopes in tropical environments, however, and for mountains frequently immersed in raining orographic clouds, isotopic signatures of rain and fog may be indistinguishable [Scholl *et al.*, 2006]. In a Costa Rican TMC, located about ~ 6 km north of Monteverde on the windward slope of the Cordillera de Tilarán (R. Burkard *et al.* as discussed by Scholl *et al.* [2006]) observed small isotopic differences between orographic cloud water and rain collected simultaneously (mean difference in $\delta^{18}O$ ranged between $+0.4$ to -0.9 ‰), and results were inconsistent as to whether cloud water was isotopically heavier or lighter than rainfall. Similarly, simultaneous collection of orographic cloud water and rain near Pico del Este in the Caribbean National Forest of Puerto Rico showed cloud water to be isotopically enriched compared to rain for 78% of samples, and the difference in the isotopic

signal was quite small compared to the temporal variability of the weather patterns (R. Burkard and W. Eugster as discussed by Scholl *et al.* [2006]). Scholl *et al.* [2002] were able to show slightly larger distinctions between orographic cloud water and rain at a TMC in East Maui, Hawaii (cloud water was enriched by up to 3‰ in $\delta^{18}O$), and more recently, Liu *et al.* [2005] observed even greater isotopic distinctions between fog drip and rain in a seasonal tropical rain forest in China.

[11] This paper presents observed differences in the isotopic composition of dry and wet season precipitation. A distinct signal is needed to evaluate the importance of dry season orographic precipitation to the ecology and water resources of Monteverde. The difficulty of distinguishing between rain and fog in this tropical region makes the use of stable isotopes to trace cloud water through the water cycle uncertain. Our emphasis is on the entire dry season contribution, independent of deposition mechanism.

3. Site Description

3.1. Climate Patterns

[12] Monteverde (Figure 1) is located near the continental divide on the Pacific slope of the Cordillera de Tilarán, a Tertiary-aged volcanic mountain range located in north central Costa Rica, Central America. Historical weather records of precipitation measured by John Campbell and Alan Pounds from 1973–2004 at 1520 m (A. Pounds, personal communication, 2005) show a mean annual rainfall of 2677 mm, with strong seasonal variability. Climate patterns are strongly influenced by interactions between the mountains and synoptic wind systems, as well as the seasonal migration of the Intertropical Convergence Zone (ITCZ).

[13] The eastern Pacific ITCZ is a broad area of tropical convection that occurs over a pool of warm seawater [Magaña *et al.*, 1999], and it follows an annual north-south migration due to changes in solar radiation and sea surface temperatures. This phenomenon produces three seasons in Monteverde: wet, transitional, and dry (Figure 2). The wet season (May–October) begins when the ITCZ migrates north over Central America, and precipitation is dominated by intense convective events. Precipitation increases in June and peaks in September and October, with a relative minimum occurring during July and August when the ITCZ loses intensity [Clark *et al.*, 2000; Hastenrath, 2002; Muñoz *et al.*, 2002]. In Costa Rica, this period of diminished rainfall within the wet season is referred to as the “veranillo,” or little summer. Equatorial westerly winds from the Pacific Ocean appear and persist during the wet season, and Costa Rica receives more precipitation on the Pacific slope than on the Caribbean slope in September and October [Muñoz, 2002].

[14] The transitional (November–January) and dry (February–April) seasons, which we refer to collectively as the “drier” seasons, correspond to months when the ITCZ is located to the south of Costa Rica. During this time, mist and fog are generated via orographic uplift. The northeasterly trade winds force moist air from the Caribbean Sea up the Tilarán Mountains. High-elevation regions can become enshrouded in clouds and drizzle, and precipitation is produced from orographic clouds. During the dry season,

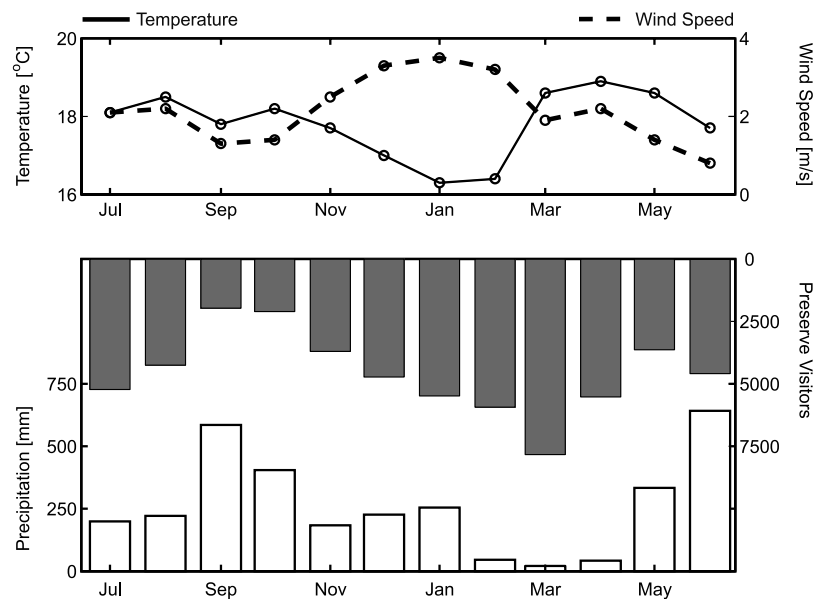


Figure 2. Annual variation in monthly average temperature, average wind speed, and total precipitation for 2004, as measured at the Monteverde Institute. Census of average number of visitors to the Monteverde Cloud Forest Preserve between 1998 and 2002 (Centro Científico Tropical, Reserva Biológica Bosque Nuboso Monteverde, personal communication, 2006) suggests that demands for water are greatest during the driest months of the year.

diminished trade winds bring less moisture over the continental divide [Clark *et al.*, 2000]. Overall, the seasonal distribution pattern of precipitation observed in Monteverde is synchronous with patterns observed elsewhere along the Pacific slope of Costa Rica, Central America, and southern Mexico [Magaña *et al.*, 1999; Hastenrath, 2002]; however, the rain shadow greatly reduces the amount of precipitation at lower elevations on the Pacific slope of Costa Rica during the drier seasons. Just down the leeward slope from the continental divide at Monteverde's Brillante Gap, Haeger and Dohrenbusch [2006] measured a 7% difference in precipitation along an elevational transect between 1450 m (2678 mm) and 1200 m (2486 mm) during the wet season. The rain shadow effect is more pronounced during the drier seasons (November–February), when downslope precipitation was reduced by 25% (1412 mm at 1450 m and 1056 mm at 1200 m). Their results also showed that distinct changes in the structure and composition of forests paralleled variations in annual precipitation. On the northern Pacific coast of Costa Rica, little to no precipitation falls during the dry season (M. Mena, Clima de Costa Rica, San José, Instituto Meteorológico Nacional, <http://www.imn.ac.cr>). In Monteverde, average monthly dry season (February–April) precipitation is 58.2 mm (A. Pounds, personal communication, 2005) whereas at Puntarenas, which is located on the Pacific coast (Figure 1) deeper within the rain shadow, average monthly dry season precipitation is 13.1 mm (World Meteorological Organization, World Weather Information Service, <http://www.worldweather.org/>).

[15] Without wind direction data for Monteverde, we do not know for an individual rain event during the wet season whether moisture comes predominately from the Atlantic or the Pacific. The seasonality of the sea surface winds that control the precipitation patterns for Costa

Rica, however, are well documented [Hastenrath and Lamb, 1977; Hastenrath, 2002; Xie *et al.*, 2005], and they provide a general picture of changes in moisture sources to Costa Rica's Pacific slope throughout the year. As illustrative examples, we use the National Aeronautics and Space Administration's Quick Scatterometer (QuikSCAT) satellite measurements of daily sea surface wind velocities [Physical Oceanography Distributed Active Archive Center, 1999] to show differences in seasonal wind directions on days that we measured significant rainfall at Monteverde (Figures 3a–3d). The influence of the Atlantic trade winds is strongest during the transitional and dry seasons, resulting in a northeasterly wind flow over the Atlantic and Pacific Oceans (Figure 3d). In contrast, Figures 3a–3c show westerly winds over the Pacific that converge with the trade winds to produce convective rainfall typical of the wet season. The strength of the trade winds can vary during the wet season [Muñoz *et al.*, 2002], perhaps altering the contribution of Atlantic-sourced moisture to wet season precipitation in Monteverde. However, unlike the drier seasons, the sea surface winds over the Pacific are consistently directed toward Costa Rica, strongly suggesting that the Pacific slope is influenced by Pacific moisture throughout the wet season. The effect of this shifting wind pattern from the dry to the wet season is reflected by the increased in rainfall at Monteverde and elsewhere on the Pacific slope.

3.2. Forests

[16] Forests within the Monteverde area are loosely described as “cloud forests.” However, true perpetually dripping cloud forest occurs at the upper elevations of the Pacific slope from 1500 to 1850 m and from the continental divide to 1400 m on the Atlantic slope [Haber,

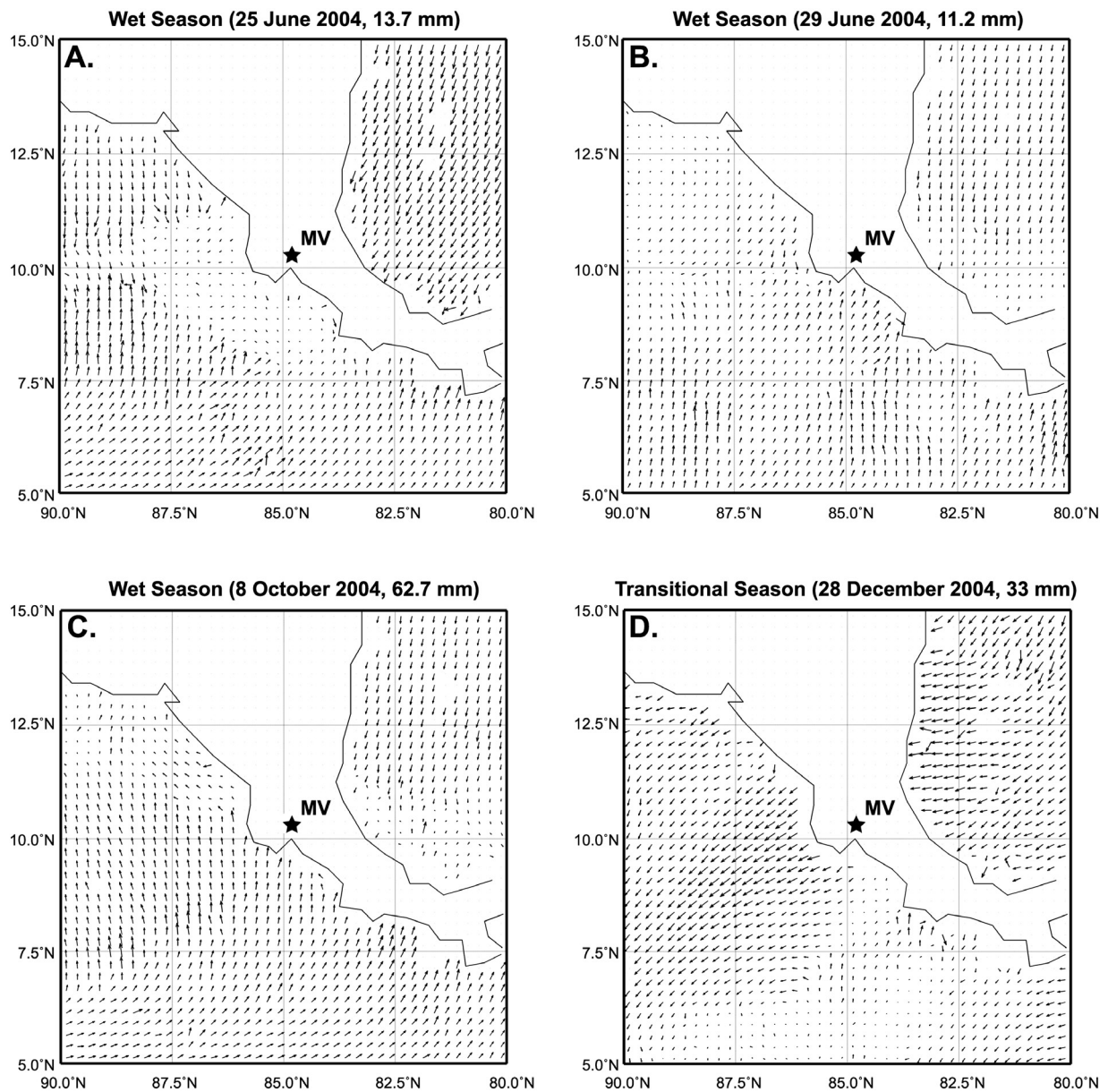


Figure 3. Illustrative examples of sea surface wind velocity vectors in the Caribbean Sea and eastern Pacific Ocean. Wind vectors indicate average daily direction and magnitude. Figures 3a–3c illustrate convergent wind flow between the trade and western equatorial winds that is typical of the wet season. Westerly equatorial winds consistently influence the Pacific slope of Costa Rica during this time, although wind velocities may vary. Figure 3d is representative of the transitional and dry seasons; sea surface winds over both the Caribbean and Pacific are oriented in an easterly direction. MV is location of Monteverde, and vectors are plotted on a 0.25° grid. Map titles list date of wind measurements by QuikSCAT satellite [Physical Oceanography Distributed Active Archive Center, 1999] and total rainfall measured at Monteverde for that date [Johnson *et al.*, 2005].

2000]. Holdridge life zone classification of cloud forests within the Monteverde Cloud Forest Preserve include lower montane wet forest and lower montane rain forest, where wind-blown mist and cloud cover are integral components of the climate. Below 1500 m on the Pacific slope, a rain shadow created by the higher peaks and ridges of the continental divide favors a transition from cloud forest to premontane wet forest [Haber, 2000]. This latter life zone consists of a seasonally dry, mostly evergreen

forest that has fewer epiphyte plants than are found at higher elevations.

3.3. Water Resources

[17] While most of the annual precipitation can be attributed to the presence of the ITCZ during the wet season, the importance of dry season orographic precipitation should not be underestimated. Despite the limited availability of water during the drier seasons, this region is home to nearly all development associated with Monteverde. Municipal

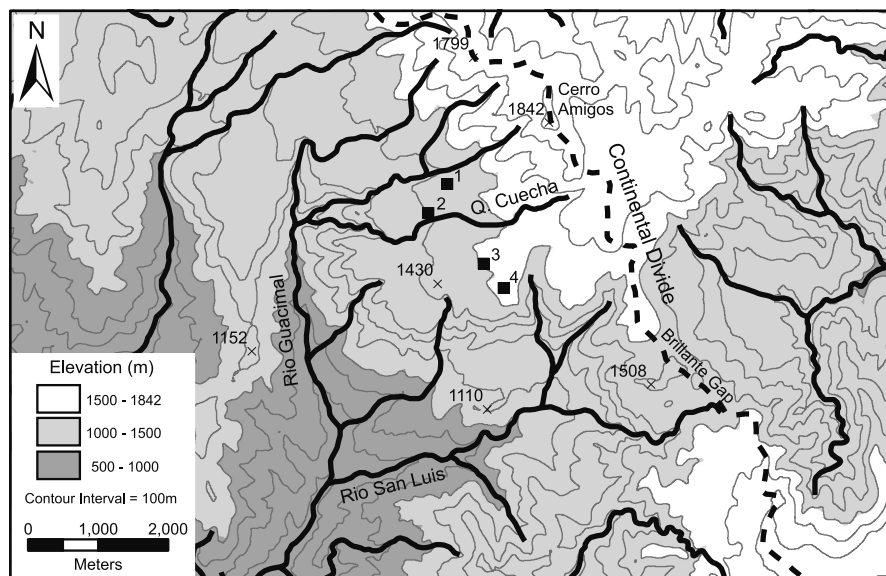


Figure 4. Digital elevation model of the Monteverde region. Sites of precipitation collection (squares) are as follows: 1, throughfall sites TF_1 and TF_3 on Monteverde Institute property; 2, Open_MVI at Monteverde Institute; 3, Campbell Farm, site of historical precipitation record initiated by John Campbell; 4, throughfall site TF_4.

water is supplied from springs and streams that respond rapidly to precipitation variability. Flow of the Quebrada Cuecha, a headwater stream of the Rio Guacimal, shows a rapid response to the onset of precipitation; base flow discharge of the Quebrada Cuecha ranges in excess of 12 mm/day in the wet season to less than 1 mm/day in the dry season. The recent boom in ecotourism has put significant stress on water resources, especially during the dry season when visitors increase in number and the overall water demands are greater (Figure 2). Water supply and water quality continue to be an important issue for the residents of Monteverde [cf. Díaz, 2005]; in question is whether diminished streamflow due to increased withdrawals will negatively impact stream ecology and water quality. Because of the potential for reduced water supply and the reality of increased demand, a better understanding of the role of orographic precipitation during the drier seasons is essential for sustaining the vibrant Monteverde region.

4. Methods

4.1. Isotopic Composition of Precipitation

[18] Samples of open precipitation and throughfall were collected over a 2-year period at four sites positioned within a 2 km² area (Figure 4). The precipitation collectors were located in close proximity to the Monteverde Cloud Forest Preserve at elevations where life zones of lower montane wet forest and premontane wet forest overlap. Sites were selected based on their proximity to two weather stations: one near the Campbell property where one of the longest records of historical weather measurements has been collected in the region [Pounds *et al.*, 1999], and the second (see section 4.2) near the Quebrada Cuecha where we also measure stream discharge. Site locations of the precipitation collectors also coordinate with complementary investigations of water quality

[Rhodes *et al.*, 2006a] and throughfall [Guswa and Rhodes, 2004] in the Rio Guacimal watershed.

[19] Between 26 June 2003 and 6 June 2004, open precipitation was collected in a 100 m² clearing within secondary forest located about 400 m upslope from the Monteverde Institute (elevation of 1460 m). Precipitation was collected using a 20-cm diameter funnel attached to a 20-L, high-density polyethylene (HDPE) bucket, which was coated with at least 1 cm of mineral oil. In January 2004 and from 10 June 2004 to 26 April 2005, we added a second open collector (site Open_MVI) on the front lawn of the Monteverde Institute (elevation of 1400 m).

[20] Throughfall was collected in secondary forest (sites TF1 and TF3; elevation of 1460 m) and in primary forest (site TF4; elevation of 1570 m). Site TF1 consisted of a 3-m-long trough constructed from one half of a 5-cm diameter PVC pipe, which emptied into a 20-cm diameter funnel, attached to a 20-L, HDPE bucket. In response to a property owner's request, in June 2004 we replaced TF1 with TF3, which we located in secondary forest at the same elevation, approximately 70 m away. TF3 consisted of a 20-cm funnel attached to a 20-L HDPE bucket. Throughfall site TF4 was initiated in June 2004 in primary forest near the Campbell farm (Figure 4). TF4 consisted of a 20-cm funnel attached to a 4-L glass bottle. All sample collectors were coated with at least 1 cm of mineral oil to prevent evaporation. Water was transferred using a 10 mL pipette to 30 mL Qorpak glass bottles with polyseal caps, and samples were refrigerated until transport to the stable isotope laboratory.

[21] In total, 118 precipitation samples and 11 replicates were collected over the study period (Table 1). The sampling interval ranged from 1 to 103 days, with a high sampling frequency (average interval is 2 days) during 28 June to 12 July 2003; 12–18 January 2004; and 5 June to 24 July 2004. Samples were collected over longer intervals at other times (average interval is 35 days). Each

Table 1. Stable Isotope and Meteorological Data for Precipitation and Throughfall Samples Collected at Monteverde, Costa Rica^a

Sample Name	Initiation Date	Collection Date	Interval, days	$\delta^{18}\text{O}$, ‰	$\delta^2\text{H}$, ‰	d Excess, ‰	Precipitation, mm	Wind, km h ⁻¹	Temperature, °C
Open ^b	6/26/2003	6/30/2003	4	-11.1	-83	6.3	—	—	—
Open ^b	6/30/2003	7/5/2003	5	-8.1	-57	7.8	—	—	—
Open ^b	7/5/2003	7/7/2003	2	-9.6	-68	9.3	—	—	—
Open ^b	7/7/2003	7/12/2003	5	-4.4	-32	3.7	—	—	—
Open	7/12/2003	7/21/2003	9	-5.4	-33	10.2	—	—	—
Open	7/21/2003	8/2/2003	12	-6.4	-46	5.2	—	—	—
Open	8/2/2003	8/15/2003	13	-3.1	-13	11.8	—	—	—
Open	8/15/2003	8/29/2003	14	-7.6	-52	8.8	—	—	—
Open	10/16/2003	11/28/2003	43	-8.7	-54	15.6	—	—	—
Open	11/28/2003	1/12/2004	45	-3.9	-14	17.2	—	—	—
Open_MVI	1/12/2004	1/14/2004	2	-1.5	5	17.0	—	—	—
Open	1/12/2004	1/14/2004	2	-1.6	5	17.8	—	—	—
Open	1/14/2004	1/15/2004	1	-1.5	8	20.0	—	—	—
Open_MVI	1/15/2004	1/18/2004	3	-1.7	6	19.6	—	—	—
Open	1/15/2004	1/18/2004	3	-1.7	5	18.6	—	—	—
Open ^{b, c}	1/18/2004	4/30/2004	103	-1.6	3	15.4	—	—	—
Open ^c	4/30/2004	6/5/2004	36	-10	-70	10.0	—	—	—
Open	6/5/2004	6/7/2004	2	-13.9	-103	8.2	—	—	—
Open_MVI	6/10/2004	6/13/2004	3	-11.6	-84	8.8	—	—	—
Open_MVI	6/13/2004	6/16/2004	3	-5.0	-34	6.0	27.94	2.2	18.9
Open_MVI	6/16/2004	6/18/2004	2	-2.4	-10	9.2	5.33	3.5	18.1
Open_MVI	6/18/2004	6/19/2004	1	-6.8	-43	11.4	2.03	2.9	18.9
Open_MVI	6/19/2004	6/21/2004	2	-12.6	-98	2.8	25.40	2.4	18.0
Open_MVI	6/21/2004	6/23/2004	2	-10.4	-77	6.2	4.06	2.6	18.8
Open_MVI	6/23/2004	6/25/2004	2	-4.0	-26	6.0	20.07	2.1	19.2
Open_MVI	6/25/2004	6/26/2004	1	-6.5	-44	8.0	13.72	3.2	17.9
Open_MVI	6/26/2004	6/28/2004	2	-1.5	-4	8.0	4.57	2.8	18.4
Open_MVI	6/28/2004	6/29/2004	1	-2.9	-17	6.2	5.59	2.7	19.3
Open_MVI	6/29/2004	6/30/2004	1	-8.3	-56	10.4	17.53	1.5	18.3
Open_MVI	6/30/2004	7/2/2004	2	-9.4	-67	8.2	13.46	3.4	17.5
Open_MVI	7/2/2004	7/3/2004	1	-1.9	-6	9.2	8.38	2.4	18.8
Open_MVI	7/3/2004	7/5/2004	2	-2.3	-9	9.4	4.57	2.3	17.8
Open_MVI	7/5/2004	7/7/2004	2	-7	-49	7.0	11.43	1.7	18.5
Open_MVI	7/7/2004	7/9/2004	2	-11.4	-87	4.2	11.18	1.7	17.4
Open_MVI	7/9/2004	7/12/2004	3	-3.8	-23	7.4	40.89	2.2	17.8
Open_MVI	7/12/2004	7/14/2004	2	-7.8	-59	3.4	5.33	2.3	17.7
Open_MVI	7/14/2004	7/16/2004	2	-5.4	-42	1.2	5.59	2.9	17.4
Open_MVI	7/16/2004	7/19/2004	3	-2.4	-16	3.2	3.81	2.1	18.6
Open_MVI	7/19/2004	7/21/2004	2	-5.9	-42	5.2	20.83	2.0	17.3
Open_MVI	7/21/2004	7/23/2004	2	-8.8	-63	7.4	25.15	2.1	18.5
Open_MVI	7/23/2004	7/24/2004	1	-8.7	-61	8.6	16.51	1.3	17.7
Open_MVI	7/24/2004	10/2/2004	70	-9.7	-67	10.6	861.82	1.8	18.2
Open_MVI	10/2/2004	10/25/2004	23	-5.3	-28	14.4	343.92	1.3	18.3
Open_MVI	10/25/2004	11/10/2004	16	-4.1	-19	13.8	173.23	1.9	17.8
Open_MVI ^d	12/11/2004	1/9/2005	29	-1.9	-4	11.2	322.58	3.4	16.7
Open_MVI ^d	1/9/2005	2/17/2005	39	-1.8	1	15.4	154.94	3.5	16.0
Open_MVI ^d	2/17/2005	3/29/2005	40	-0.8	7	13.4	48.77	2.1	18.2
Open_MVI ^d	3/29/2005	4/26/2005	28	-1.0	9	17.0	38.35	2.3	18.7
TF_1 ^b	6/26/2003	6/30/2003	4	-12.8	-94	8	—	—	—
TF_1 ^b	6/30/2003	7/5/2003	5	-7.8	-54	8	—	—	—
TF_1 ^b	7/5/2003	7/7/2003	2	-9.2	-65	8.2	—	—	—
TF_1 ^b	7/7/2003	7/12/2003	5	-4.4	-32	2.8	—	—	—
TF_1	7/12/2003	7/21/2003	9	-6.2	-41	8.6	—	—	—
TF_1	7/21/2003	8/2/2003	12	-7.8	-54	8.4	—	—	—
TF_1	8/2/2003	8/15/2003	13	-3.4	-16	11.2	—	—	—
TF_1	8/15/2003	8/29/2003	14	-7.2	-45	12.6	—	—	—
TF_1	8/29/2003	10/16/2003	48	-12.4	-82	17.2	—	—	—
TF_1 ^c	10/16/2003	11/28/2003	43	-8.4	-55	12.2	—	—	—
TF_1 ^b	11/28/2003	1/12/2004	45	-3.0	-6	18	—	—	—
TF_1	1/12/2004	1/14/2004	2	-1.5	2	14	—	—	—
TF_1	1/14/2004	1/15/2004	1	-1.8	5	19.4	—	—	—
TF_1	1/15/2004	1/18/2004	3	-1.6	5	17.8	—	—	—
TF_1 ^{b, c}	1/18/2004	4/30/2004	103	-1.6	2	14.8	—	—	—
TF_1 ^c	4/30/2004	6/5/2004	36	-11.3	-82	8.4	—	—	—
TF_1	6/5/2004	6/7/2004	2	-12.5	-91	9	—	—	—
TF_3	6/16/2004	6/18/2004	2	-2.7	-11	10.6	5.33	3.5	18.1
TF_3	6/18/2004	6/19/2004	1	-7.8	-52	10.4	2.03	2.9	18.8
TF_3	6/19/2004	6/21/2004	2	-11.8	-88	6.4	25.40	2.4	18.0
TF_3	6/21/2004	6/23/2004	2	-9.8	-72	6.4	4.06	2.7	18.8
TF_3	6/23/2004	6/25/2004	2	-4.2	-30	3.6	20.07	2.1	19.2
TF_3	6/25/2004	6/26/2004	1	-6.6	-44	8.8	13.72	3.2	17.8
TF_3	6/26/2004	6/28/2004	2	-2.3	-7	11.4	4.57	2.7	18.4
TF_3	6/28/2004	6/30/2004	2	-9.4	-65	10.2	35.05	2.1	18.8

Table 1. (continued)

Sample Name	Initiation Date	Collection Date	Interval, days	$\delta^{18}\text{O}$, ‰	$\delta^2\text{H}$, ‰	d Excess, ‰	Precipitation, mm	Wind, km h ⁻¹	Temperature, °C
TF_3	6/30/2004	7/2/2004	2	-9.3	-65	9.4	1.52	3.4	17.5
TF_3	7/2/2004	7/3/2004	1	-2.1	-6	10.8	8.64	2.5	18.7
TF_3	7/3/2004	7/7/2004	4	-6.8	-47	7.4	15.75	2.0	18.2
TF_3	7/7/2004	7/9/2004	2	-11	-82	6	11.18	1.7	17.4
TF_3	7/9/2004	7/12/2004	3	-4.1	-22	10.8	40.89	2.2	17.8
TF_3	7/12/2004	7/14/2004	2	-7.6	-56	4.8	5.84	2.3	17.7
TF_3	7/14/2004	7/16/2004	2	-6.5	-46	6	5.08	2.9	17.5
TF_3	7/16/2004	7/21/2004	5	-5.8	-39	7.4	24.64	2.2	18.2
TF_3	7/21/2004	7/23/2004	2	-8.9	-64	7.2	25.15	2.1	18.1
TF_3	7/23/2004	7/24/2004	1	-8	-56	8	16.76	1.3	17.7
TF_3	7/24/2004	10/2/2004	70	-9.8	-68	10.4	861.57	1.8	18.1
TF_3	10/2/2004	10/25/2004	23	-7.1	-44	12.8	343.92	1.3	18.3
TF_3	10/25/2004	11/9/2004	15	-6.3	-37	13.4	172.21	1.8	17.8
TF_3	11/9/2004	12/11/2004	32	-3.0	-9	15	82.80	3.0	17.6
TF_3	12/11/2004	1/9/2005	29	-2.6	-6	14.8	322.58	3.4	16.7
TF_3	2/17/2005	3/29/2005	40	-1.5	5	17	48.77	2.1	18.2
TF_3	3/29/2005	4/26/2005	28	-1.4	9	20.2	38.10	2.3	18.7
TF_4	6/11/2004	6/16/2004	5	-8.2	-57	8.6	29.46	2.2	19.5
TF_4	6/16/2004	6/18/2004	2	-3.3	-14	12.4	5.33	3.5	18.1
TF_4	6/18/2004	6/21/2004	3	-12.6	-93	7.8	27.94	2.6	18.3
TF_4	6/21/2004	6/23/2004	2	-9.9	-70	9.2	4.06	2.7	18.9
TF_4	6/23/2004	6/25/2004	2	-4.6	-28	8.8	20.07	2.0	19.2
TF_4	6/25/2004	6/26/2004	1	-7.0	-46	10	13.72	3.2	17.8
TF_4	6/26/2004	6/28/2004	2	-2.3	-7	11.4	4.57	2.7	18.4
TF_4	6/28/2004	6/30/2004	2	-7.1	-45	11.8	23.11	2.0	18.8
TF_4	6/30/2004	7/2/2004	2	-9.4	-65	10.2	13.46	3.4	17.5
TF_4	7/2/2004	7/3/2004	1	-2.5	-8	12	8.64	2.4	18.7
TF_4	7/3/2004	7/5/2004	2	-2.4	-9	10.2	4.32	2.3	17.9
TF_4	7/5/2004	7/7/2004	2	-6.6	-43	9.8	11.43	1.7	18.5
TF_4	7/7/2004	7/9/2004	2	-12.7	-93	8.6	11.18	1.7	17.5
TF_4	7/9/2004	7/12/2004	3	-4.3	-19	15.4	40.89	2.3	17.8
TF_4	7/12/2004	7/14/2004	2	-7.2	-49	8.6	5.84	2.2	17.7
TF_4	7/14/2004	7/16/2004	2	-6.3	-41	9.4	5.59	2.9	17.6
TF_4	7/16/2004	7/19/2004	3	-3.8	-21	9.4	6.10	2.1	18.5
TF_4	7/19/2004	7/21/2004	2	-6.4	-41	10.2	18.54	2.0	17.4
TF_4	7/21/2004	7/23/2004	2	-8.6	-61	7.8	25.15	2.1	18.4
TF_4	7/23/2004	7/24/2004	1	-8.4	-56	11.2	16.76	1.2	17.7
TF_4 ^c	7/24/2004	10/1/2004	69	-10.3	-69	13.4	850.90	1.8	18.1
TF_4 ^c	10/1/2004	10/26/2004	25	-6.3	-36	14.4	378.71	1.3	18.2
TF_4	10/26/2004	11/9/2004	14	-8.2	-53	12.6	146.81	1.8	17.8
TF_4	11/9/2004	12/11/2004	32	-3.4	-12	15.2	82.80	3.0	17.6
TF_4	12/11/2004	1/9/2005	29	-2.9	-6	17.2	320.80	3.4	16.7
TF_4	1/9/2005	2/17/2005	39	-2.7	-5	16.6	157.73	3.5	16.0
TF_4	2/17/2005	3/29/2005	40	-1.5	5	17	48.51	2.1	18.2
TF_4	3/29/2005	4/26/2005	28	-1.5	7	19	38.61	2.3	18.7

^aMeteorological data have been collected at the Monteverde Institute since 11 June 2004. Read 6/26/2003 as 26 June 2003.

^bAverage of two samples; maximum standard deviation = 0.07‰ ($\delta^{18}\text{O}$) and 0.7‰ ($\delta^2\text{H}$).

^cFull bucket; likely overflowed.

^dAlgal growth in bucket may have influenced results. Samples eliminated from study include Open from 26 August 2003 to 16 October 2003 (glass bottle broke in transit), Open_MVI from 10 November 2004 to 11 December 2004 (excessive algal growth in bucket), and TF_3 from 9 January 2005 to 17 February 2005 (glass bottle broke in transit).

sample represents an accumulation of rain events over the sampling interval, except for six collections, when the buckets overflowed (Table 1).

[22] Stable isotope compositions of precipitation were measured at the University of Nevada at Reno. Water- $\delta^{18}\text{O}$ analyses were performed using a Micromass MultiPrep-IsoPrime system, using the $\text{CO}_2\text{-H}_2\text{O}$ equilibration method of *Epstein and Mayeda* [1953]. Water- $\delta^2\text{H}$ analyses were performed using a Eurovector elemental analyzer-Micromass IsoPrime system, after the method of *Morrison et al.* [2001]. The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ results are reported in units of per mil (‰) relative to VSMOW. The $\delta^{18}\text{O}$ and $\delta^2\text{H}$

measurements have an uncertainty of 0.1‰ and 1‰, respectively.

4.2. Meteorology

[23] Near our precipitation sampling sites, we measured air temperature, relative humidity, solar radiation, wind speed and rainfall using a Campbell Scientific meteorological station erected on the roof of the Monteverde Institute on 11 June 2004 (elevation of 1420 m, latitude 10.31°N; longitude 84.81°W). Precipitation was measured using an 8-inch siphoning tipping bucket rain gauge, which has an accuracy of $\pm 2\%$ for rainfall intensities up to 500 mm/hr, and a data logger calculates and records 10-min total rainfall values. The rain gauge is not designed to measure

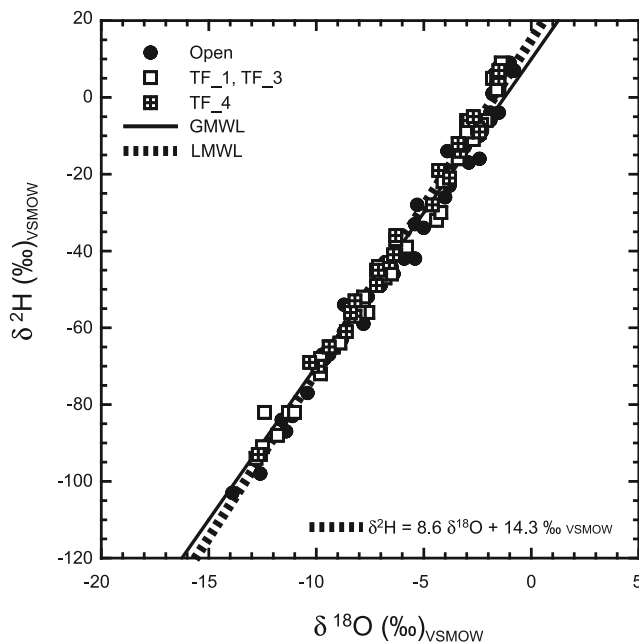


Figure 5. Isotopic composition of open precipitation and throughfall collected from June 2003 to April 2005. GMWL, global meteoric water line [Craig, 1961]; LMWL, local meteoric water line for these data.

cloud-water interception, however, and the recorded amounts may underestimate total hydrologic inputs. Johnson *et al.* [2005] and Guswa and Rhodes [2006] present a detailed description of this weather station and meteorological data through December 2005. Precipitation data presented in this paper prior to 11 June 2004 were collected by Alan Pounds in a pasture on the Campbell farm (elevation of 1520 m) near our TF4 precipitation collection site (Figure 4).

5. Results

[24] Isotope compositions for all precipitation samples (Table 1) range from -13.9 to -0.8 ‰ ($\delta^{18}\text{O}$) and -103 to $+9$ ‰ ($\delta^2\text{H}$). All samples plot near the global meteoric waterline defined by Craig [1961], and samples having the heaviest stable isotope values plot slightly above the GMWL (Figure 5). A local meteoric water line calculated as a regression of these data is $\delta^2\text{H} = 8.6 \delta^{18}\text{O} + 14.3$ ‰ (VSMOW). Simultaneous collection at the two open precipitation sites in January 2004 showed no difference beyond analytical error, suggesting that these two sites are colocated closely enough to be considered representative of precipitation near the meteorologic station at the Monteverde Institute. Differences between open precipitation and samples from TF1 collected over the same period ranged from -0.9 to $+1.4$ ‰ for $\delta^{18}\text{O}_{\text{OPEN-TF1}}$ and from -8 to $+8$ ‰ for $\delta^2\text{H}_{\text{OPEN-TF1}}$. The sign and magnitude of the Open-TF1 differences varied from sampling period to sampling period, and they showed no consistent temporal pattern. Similarly, we observed small differences in δ values for precipitation collected at Open_MVI, TF3, and TF4. The observed variability between sample sites may result from incomplete mixing of precipitation within the forest canopy, either during a storm or among different events [Saxena, 1986; Brodersen *et al.*, 2000], or it may reflect some real spatial

variation in the isotopic composition of precipitation. Collection at Open_MVI, TF3, and TF4 did not always occur over the same time interval, and intermittent algal growth in the bucket at Open_MVI may have affected its results between December 2004–April 2005 (see Table 1). Volume-weighted averages of samples from these sites show that the isotopic composition of precipitation from the drier seasons is distinct from the wet season (Table 2), and the next section elaborates on the seasonal fluctuations of the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values.

5.1. Seasonality of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ Values

[25] Figure 6 shows a strong temporal variation in the isotopic composition of precipitation that is consistent with variation in climate. The lightest isotopic composition, marked by the lowest $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values, occurs for samples collected during the rainiest periods of the wet season in June, September, and October, when the ITCZ is positioned directly over Costa Rica. Samples collected over short intervals during the veranillo periods of July–August 2003 and June–July 2004 (Figures 6 and 7) show a wide range of stable isotopic compositions (from -1.5 to -13.9 ‰ for $\delta^{18}\text{O}$ and from -4 to -103 ‰ for $\delta^2\text{H}$ at Open_MVI in 2004). Still, volume-weighted averages for samples collected during June and July 2004 (plotted on Figure 6) are notably lighter than samples collected during the transitional and dry seasons. During the drier seasons, orographic mist and precipitation carried by the trade winds dominate, giving rise to the heaviest measured compositions. Maximum values measured in 2003 are -1.5 ‰ ($\delta^{18}\text{O}$) and $+8$ ‰ ($\delta^2\text{H}$); and maximum values measured in 2004 are -0.8 ‰ ($\delta^{18}\text{O}$) and $+9$ ‰ ($\delta^2\text{H}$). Monthly samples show a progressive enrichment in the isotopic composition of precipitation during the drier seasons from November 2004 to April 2005. Dry season samples yield positive $\delta^2\text{H}$ values and are similar to stable isotope compositions of fog and cloud water reported elsewhere [Aravena *et al.*, 1989; Ingraham and Matthews, 1995; Dawson and Ehleringer, 1998; Ingraham, 1998; Scholl *et al.*, 2006].

5.2. Seasonality of Deuterium Excess

[26] In addition to the seasonal controls on stable isotopic composition, the precipitation data show evidence of seasonal variability in d excess (Figure 6). The lowest d excess values (<10 ‰) occur at the beginning of the wet season, but show a progressive increase up to ~ 15 ‰ as the wet season progresses. Like $\delta^{18}\text{O}$ and $\delta^2\text{H}$, d excess values continue to increase during the dry season, with highest values reaching ~ 20 ‰. Detailed sampling during the wet season in 2004 shows consistently low d excess values that are ~ 11 ‰ or less (Figure 7).

6. Discussion

6.1. Isotopic Characterization of Orographic and ITCZ Rainfall

[27] While seasonality provides a first-order separation between orographic and ITCZ-derived rainfall, greater detail regarding the hydrologic inputs may be gained through the use of stable isotopes. The isotopic composition of water (as measured through $\delta^{18}\text{O}$ and $\delta^2\text{H}$) may also be used to determine the contribution of orographic precipitation to

Table 2. Seasonal Volume-Weighted Averages for 2004–2005, Calculated With Precipitation Values Measured at the Monteverde Institute (Met_MVI)^a

Season	Dates of Integration	Sample Site	Number of Samples	$\delta^{18}\text{O}$, ‰	$\delta^2\text{H}$, ‰	d Excess, ‰	Met_MVI Precipitation, mm	Campbell Precipitation, mm
Early wet	30 Apr to 24 Jul 2004	Open_MVI	25	-9.1	-64	8.8	869.9 ^b	
Early wet	16 Jun to 24 Jul 2004	TF_3	18	-7.1	-49	8.1	265.7 ^b	
Early wet	11 Jun to 24 Jul 2004	TF_4	20	-7.2	-48	10.4	294.4 ^b	361.1
Early wet average				-7.8	-54	9.1		
Late wet	24 Jul to 10 Nov 2004	Open_MVI	3	-7.9	-51	11.9	1379.0	
Late wet	24 Jul to 9 Nov 2004	TF_3	3	-8.7	-58	11.4	1377.7	
Late wet	24 Jul to 9 Nov 2004	TF_4	3	-9.0	-58	13.6	1377.7	1287.3
Late wet average				-8.5	-56	12.3		
Total wet	30 Apr to 10 Nov 2004	Open_MVI	28	-8.4	-56	11	2249.0	
Total wet	16 Jun to 9 Nov 2004	TF_3	21	-8.4	-57	11	1643.4	
Total wet	11 Jun to 9 Nov 2004	TF_4	23	-8.7	-56	13	1672.1	1648.4
Total wet average				-8.5	-56	12		
Transitional	10 Nov 2004–17 Feb 2005	Open_MVI	3	-1.5	-2	10.5	560.3	
Transitional	9 Nov 2004–9 Jan 2005	TF_3	2	-2.7	-7	14.8	405.9	
Transitional	9 Nov 2004 to 17 Feb 2005	TF_4	3	-2.9	-7	16.7	561.3	564.1
Transitional average				-2.4	-5	14.0		
Dry	17 Feb to 26 Apr 2005	Open_MVI	2	-0.9	+8	15	87.1	
Dry	17 Feb to 26 Apr 2005	TF_3	2	-1.5	+7	18	87.1	
Dry	17 Feb to 26 Apr 2005	TF_4	2	-1.5	+6	18	87.1	88.7
Dry average				-1.3	+7	17		

^aSummation of daily rainfall measured at the Campbell Farm (Campbell) is shown for comparison.^bPrecipitation prior to 11 June 2004 was measured at the Campbell Farm; values represent a combination of data collected at Met_MVI and the Campbell Farm.

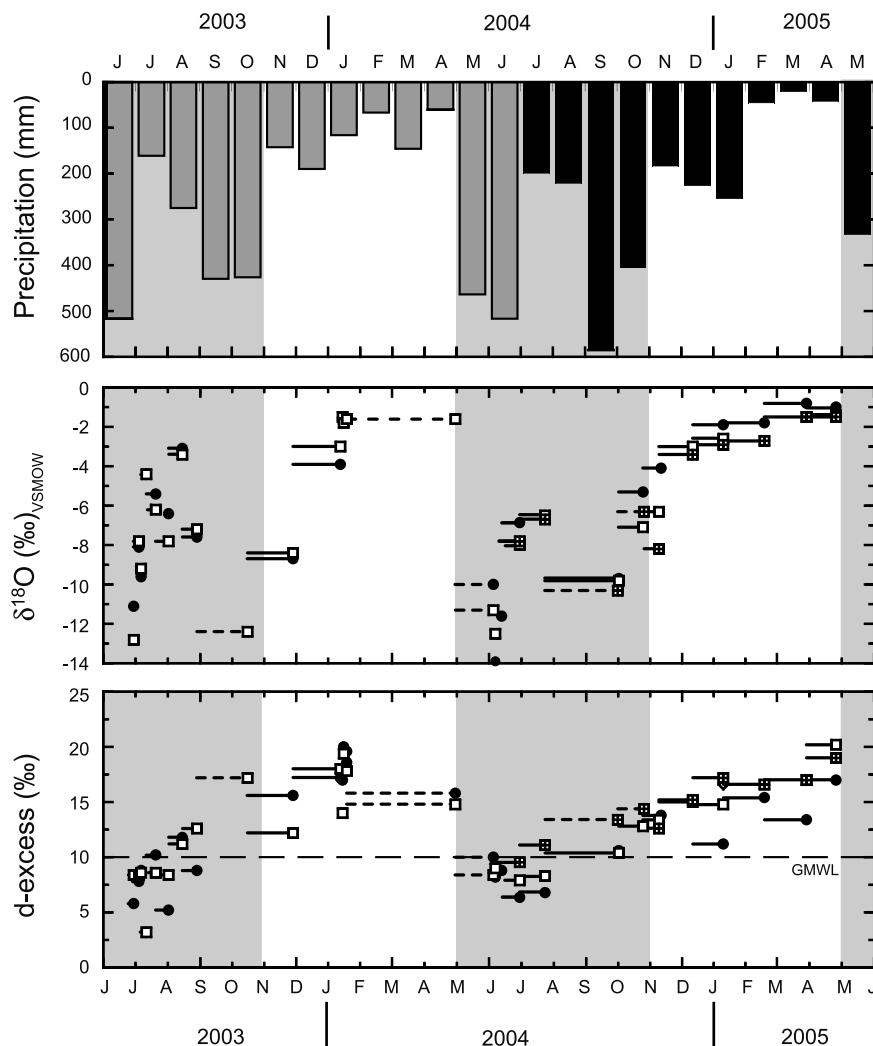


Figure 6. Seasonal variation of monthly precipitation, $\delta^{18}\text{O}$, and d excess values. Shaded areas identify wet season months. Circles denote open precipitation, open squares denote throughfall from TF_1 and TF_3, and crossed squares denote throughfall from TF_4. Symbols are plotted at the time of collection, and lines leading to the symbol show the sample interval. Samples collected from full buckets that may have overflowed are depicted with a dashed line. Points plotted for June and July 2004 represent volume-weighted averages of samples that were collected approximately every 2 days. Precision of d excess is $\pm 2\text{‰}$. Daily precipitation was measured at the Monteverde Institute (black bars) and at the Campbell Farm (gray bars).

other hydrologic fluxes within the watershed, such as plant uptake and streamflow. Our data show a distinct difference in isotopic composition between the wet and drier seasons. We measure a depletion in isotopic composition of precipitation that coincides with the seasonal occurrence of the ITCZ convective storms, particularly during the rainiest months of the year, suggesting that rainout has a stronger effect on wet season precipitation than orographic precipitation during the transitional and dry seasons. Air masses carried by the westerly equatorial winds may have long travel paths that experience episodes of precipitation prior to production of convective rainfall at Monteverde. During the transitional and dry season, however, we observe little rainout effect on the stable isotopic composition, as exhibited by the high $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values. Air masses that produce orographic precipitation condense and rain near the study area. Although orographic clouds can experience rain out

[Scholl *et al.*, 2002], the enriched stable isotopic composition that is similar to cloud water [Ingraham and Matthews, 1988] suggests that rainout does not have a strong influence on orographic rain during the drier seasons.

[28] Liu *et al.* [2005] observed similar results in a tropical seasonal rain forest in southwest China, where orographic fog and precipitation produced high δ values during the dry season, and the monsoonal rains of the wet season were isotopically more depleted. In the Hawaiian Islands, storm systems that progressed at sea before reaching the islands were isotopically depleted relative to precipitation that originated when warm, trade wind-driven air rose over high-relief topography [Scholl *et al.*, 2002]. Rozanski *et al.* [1993], who analyzed worldwide stable isotope data collected by the International Atomic Energy Agency/World Meteorological Organization (IAEA/WMO) network of precipitation stations, state that tropical island sites show

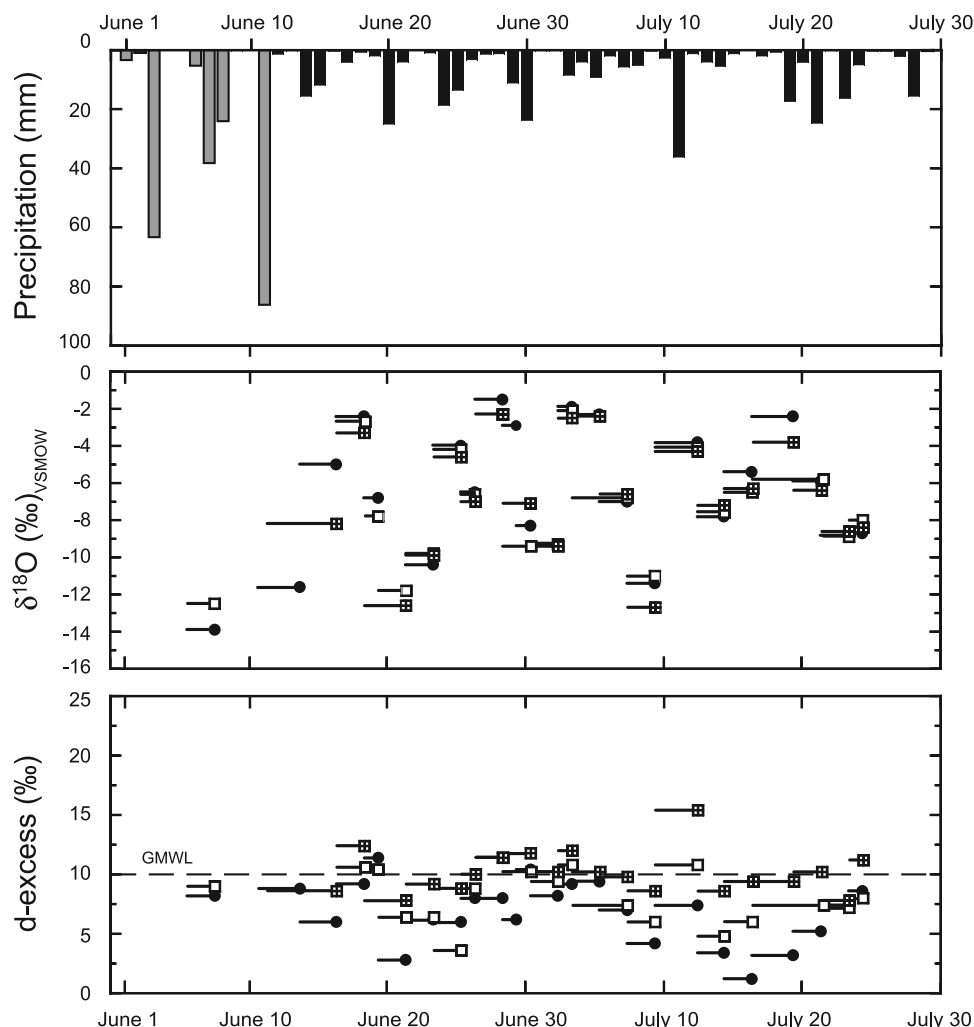


Figure 7. Detail of precipitation samples collected at short intervals during June and July 2004. Daily precipitation was measured at the Monteverde Institute (black bars) and at the Campbell Farm (gray bars).

depleted values during the rainy seasons due to greater degrees of rainout than during dry seasons. In addition, the stable isotopic composition of precipitation of tropical continental stations may be affected by changing source regions of water vapor, such as at the Izobamba station in the Amazon (0.375°S, 78.55°W) that shows depleted isotopic compositions synchronous with the arrival of the ITCZ [Rozanski *et al.*, 1993].

[29] The large variation in isotopic composition revealed by the short sampling interval during the wet season (Figure 7) suggests that the rain-out history of convective precipitation is variable, and that orographic clouds may contribute to precipitation during the wet season too. During the rainy season, a southwesterly airflow dominates on the Pacific coast of Costa Rica, and the easterly trade winds are diminished [Muñoz *et al.*, 2002]. Orographic clouds may arise from moisture carried up the Pacific slope, and we infer from the prevailing regional wind patterns (Figure 3) that wet season precipitation is derived predominately from moisture that originated at the Pacific coast. However, we cannot rule out the possibility that Monteverde may receive some orographic moisture carried from the Caribbean slope, particularly during the veranillo. During this 2–3 week

period that occurs sometime between late June–August, the ITCZ weakens and the trade winds may have a broader influence on the upper elevations of the Pacific slope, such as can be inferred from the wind vector data presented in Figure 3a. However, volume-weighted averages of the isotopic composition of precipitation, calculated for June and July 2004, show that the isotopic composition of precipitation ($\delta^{18}\text{O} = -7.1\text{‰}$; $\delta^2\text{H} = -48.2\text{‰}$; d excess = 8.4‰) is notably lighter than orographic events during the transitional and dry seasons (Table 2; mean $\delta^{18}\text{O} = -1.9\text{‰}$; $\delta^2\text{H} = +1.0\text{‰}$; d excess = 15.5‰). Thus the contribution of orographic precipitation to Monteverde during the wet season appears to be volumetrically minor.

6.2. Contribution of Recycled Water

[30] Evapotranspiration is an important process that recycles rainfall to the atmosphere. Although globally the dominant source of atmospheric water vapor forms from evaporation of the oceans, in the tropics a large proportion of the regional atmospheric water budget can consist of reevaporated rainfall derived from terrestrial sources such as lakes, streams, wetlands, or canopy interception [Gat, 2000]. Martinelli *et al.* [1996] report that evapotranspiration contributes 48 to 80% of local rainfall to the Amazon basin,

and evaporation may be responsible for up to 40% of the evapotranspiration flux [Gat and Matsui, 1991]. Large-scale deforestation may alter the evapotranspiration flux to a region's water balance, and global circulation models demonstrate that conversion of rain forest to pasture will decrease the amount of precipitation and evapotranspiration in the Amazon [Shukla *et al.*, 1990]. In Monteverde, an observed dry season thinning and lifting of the orographic cloud bank on the leeward edge of the cloud forests has been attributed to lowland deforestation on the Atlantic slope of Costa Rica [Lawton *et al.*, 2001; Nair *et al.*, 2003]. Therefore evaluating whether recycled water is an important component of precipitation at Monteverde is of considerable interest in understanding the region's water cycle.

[31] Deuterium excess values (d excess) can signal whether water evaporated from land makes an important contribution to the atmospheric water budget, and a d excess signal for reevaporated water is more convincing if relative humidity over different source areas is high and does not fluctuate greatly. Long-term climate records for different weather stations in Costa Rica (M. Mena, Clima de Costa Rica, San José, Instituto Meteorológico Nacional, <http://www.imn.ac.cr>) indicate that air masses reaching Monteverde, in fact, have traveled over land surfaces having high relative humidity. On the Caribbean slope, where annual rainfall can surpass 3500 mm, average monthly relative humidity exceeds 85% throughout the year. In the wet season, average relative humidity on the north Pacific slope, Guanacaste Province, is greater than 80% from June–August and reaches 85% during September and October. Likewise, surface air temperatures in Costa Rica vary little throughout the year. Therefore we interpret strong fluctuations in d excess of precipitation at Monteverde to result from different proportions of recycled water added to the region's atmospheric water balance. Globally, the mean d excess value for precipitation is $\sim 10\text{‰}$, resulting from a single stage of evaporation from the oceans at an average relative humidity of $\sim 85\%$ [Merlivat and Jouzel, 1979; Clark and Fritz, 1997]. We postulate that for our data, precipitation that has a d excess value notably greater than 10‰ contains a significant proportion of water evaporated from land, whereas precipitation that has a d excess value $\sim 10\text{‰}$ or less condensed from a single stage of evaporation at a relative humidity of $\sim 85\%$ or greater. Although other physical processes such as varying sea surface temperatures and wind velocities at the initial stage of evaporation from the oceans, ice formation in clouds, and partial evaporation of raindrops below the cloud base can all affect the d excess value measured in precipitation, we believe this working model, where fluctuations in d excess indicate differences in the proportion of reevaporated water in Monteverde precipitation, is reasonable because of the strong seasonal pattern observed in d excess values (Figure 6), as described below.

[32] In Monteverde, deuterium excess values are less than $\sim 10\text{‰}$ at the onset of the wet season and remain low through August. In September, d excess values steadily rise to $\sim 15\text{‰}$ and remain elevated until May. Maximum values of $\sim 20\text{‰}$ occur in January 2004 and in April 2005. These results suggest that recycled moisture is an important component of the regional water budget from October to May, but it is proportionally insignificant during the first three months of the wet season just after the onset of the

ITCZ rains when the western equatorial winds carry moisture to Costa Rica's Pacific slope. Prior to this seasonal shift in wind patterns, the orographic barrier to the trade winds, created by the cordilleras that bisect Costa Rica, produces a very strong dry season on the Pacific slope, particularly at the coast. Climate records from 1936 to 2000 show that Puntarenas, located at sea level on the coast of the Gulf of Nicoya, on average receives 4.1 mm of rain in February and 4.9 mm of rain in March, which is $\sim 0.5\%$ of the annual rainfall (<http://www.worldweather.org/>). We interpret from the d excess data that a significant reevaporated water flux from the Pacific slope is not generated until late in the wet season. This suggests that terrestrial sources of water need to become sufficiently wet before water evaporated from land contributes a measurable fraction of precipitation delivered to Monteverde. In contrast, the perpetually wet Atlantic slope of Costa Rica is analogous to the Amazon environment, where reevaporated water supplies the atmospheric vapor budget. This flux of reevaporated water from the Atlantic slope of Costa Rica is carried west to Monteverde during the transitional and dry seasons when the influence of the trade winds is greatest.

[33] The strong seasonality of changing d excess, combined with its timing and direction of change, makes this interpretation plausible. We expect that other physical processes that can cause kinetic fractionation (e.g., ice formation within clouds; evaporation of falling raindrops at the cloud base; daily differences in sea surface wind velocity and temperature), either happening in combination or independent of one another for a given event, would not produce the observed d excess signal.

[34] Effects of ice formation in clouds and evaporation of falling raindrops are inconsistent with the observed changes in deuterium excess at Monteverde. Orographic clouds commonly immerse the ridge tops, and their cloud base height reaches an altitude of ~ 1400 – 1700 m [Clark *et al.*, 2000] where measured air temperatures do not drop below 10°C [Johnson *et al.*, 2005; Guswa and Rhodes, 2006]. The cloud height of cumulus and cumulonimbus clouds that commonly form in Monteverde by convection associated with the ITCZ may reach altitudes of $15,000$ m [Clark *et al.*, 2000]. However, should ice form at the tops of these clouds, we would expect to observe elevated d excess in precipitation throughout the rainy season, rather than the observed decline to values that are typically less than or equal to $\sim 10\text{‰}$ in June and July (Figures 6 and 7). Additionally, evaporation of falling raindrops, which lowers d excess values [Rozanski *et al.*, 1993], would most likely occur during the dry season when relative humidity at Monteverde is lower (for example, we measured mean relative humidity values $\sim 80\%$ from January to March 2006 versus ~ 90 – 97% from July to October 2005 [Guswa and Rhodes, 2006]). Yet the dry season is when we observe the highest d excess values, making evaporative processes an unlikely cause for our measured annual variation in d excess.

[35] We also expect that variations in sea surface temperatures and velocities during the initial stage of evaporation would create random scatter in d excess. For example in a 2-year study of isotopic composition of rain in the central Amazon Basin, Matsui *et al.* [1983] observed random fluctuations around a mean d excess $\sim 10\text{‰}$ that varied from ~ 7 to 14‰ at their east coast

sample site of Belém; whereas further inland, precipitation at Manaus showed a distinct positive increase (ranging between $\sim 8\%$ minimum to $\sim 17\%$ maximum) in d excess that repeated during the winter months of both years. During the winter months, d excess at Manaus exceeded Belém, which the authors attributed to water recycling as winds carried moisture east to west across the Amazon basin [Matsui *et al.*, 1983].

[36] Our results build on those from Liu *et al.* [2005], who observed a similar seasonal fluctuation in d excess of precipitation collected at a seasonal tropical rain forest in southwest China. Deuterium excess values as high as 16 and 18‰ were observed in orographic rain and fog that occurred during the dry season, whereas values dropped to $\sim 5\%$ during a wet season generated by the Asian monsoon. Similar to our interpretation of the water cycle in Monteverde, these authors state that during the dry season, orographic rain and fog formed from air masses having a significant component of evaporated vapor mixed with water vapor already present in the atmosphere, which then condensed as it blew upslope [Liu *et al.*, 2005]. However, the amount of reevaporated water becomes proportionally insignificant during the heavy monsoonal rains, as is reflected by the low d excess values observed during the entire wet season. The environment at Monteverde differs in that the change from the dry to the wet season coincides with a change in the dominant synoptic wind system that brings moisture to Costa Rica. Similar to the results of Liu *et al.* [2005], our data suggest that the contribution of recycled water to precipitation at the onset of the rainy season is insignificant. However, as the wet season progresses into September and October, the increase in d excess indicates an increasing contribution of reevaporated water to precipitation in Monteverde. This suggests that the seasonally dry Pacific slope of Costa Rica requires several months of rain before the evaporative flux from the land surface is strong enough to affect the regional atmospheric water budget. The continued rise in d excess from the end of the wet season into the transitional and dry seasons suggests that either the evaporative flux to the atmospheric water balance continues to increase as the wet season progresses, that the proportion of reevaporated water in orographic precipitation from the Atlantic slope is greater, or that a combination of these effects is happening.

[37] An isotopic survey of river samples collected throughout Costa Rica [Lachniet and Patterson, 2002] supports our interpretation that reevaporated water is important to the regional water cycle of Costa Rica. Lachniet and Patterson [2002] observed elevated d excess values in rivers that drained the Atlantic slope, and values increased from 8.4‰ to 18‰ on an east to west transect from the Caribbean coast to the Cordillera de Tilarán. Interestingly, we note from their data that the majority of rivers draining the Pacific slope of the Cordillera de Tilarán also showed elevated d excess values ($>10\%$), despite being sampled during July when ITCZ-derived precipitation collected at Monteverde yielded d excess values $<10\%$. This discrepancy suggests that water in these rivers, which originate at high elevations but were sampled at ~ 100 m, represents recharge integrated over a long time. The accompanying $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for these river samples are consistent with the range of results observed in precipitation at

Monteverde during the wet season when convective rainfall associated with the ITCZ is the predominant source of recharge to the Pacific slope. Conversely, a low d excess value (5.2‰) was reported for a stream within a small, low-elevation catchment originating at ~ 950 m elevation on the northern Pacific slope. This low value is more consistent with a small catchment that is less likely to store a large reservoir of water from the previous rainy season. Complementary work presents an interpretation of the isotopic variability of surface waters in the Monteverde region [Guswa *et al.*, 2006].

6.3. Sources of Reevaporated Water

[38] Evaporation from the land surface is generally accepted as an important source of atmospheric water vapor in the tropics, and this supposition is supported by the widespread observance of elevated d excess values in the precipitation of many tropical environments [Salati *et al.*, 1979; Gat and Matsui, 1991; Martinelli *et al.*, 1996; Lachniet and Patterson, 2002; Liu *et al.*, 2005]. The source of the reevaporation flux in the tropics remains an unresolved question, however. Canopy interception may be a possible site for isotopic enrichment, but only if the intercepted rainfall is not entirely evaporated before the next rainfall. Isotopic studies designed to investigate this process [Martinelli *et al.*, 1996] and the composition of throughfall and stemflow (Leopoldo [1981] as reported by Gat and Matsui [1991]) were unable to identify canopy interception as an important source of reevaporated water that could produce elevated deuterium in rainfall to the Amazon. Of the possible sources of isotopic enrichment considered (canopy intercepted water, soil water, and surface water), stable isotope data support only major rivers and lakes within the Amazon as possible sites, and the surface area of these sources relative to the area of the Amazon basin appears too small to account for the entire evaporative flux [Martinelli *et al.*, 1996].

[39] We interpret the Amazon environment to be analogous to the continuously wet Atlantic slope of Costa Rica. Like investigators of the Amazon, we do not identify a specific source of reevaporated water. Yet based on the observed d excess values, the Atlantic slope appears to be an important source of reevaporated water that then is carried east to Monteverde during the drier seasons (mid-November to May) when the trade winds are strongest.

[40] We do speculate that wet season expansion of surface water bodies located on the Pacific slope of Costa Rica aids the development of elevated d excess values observed in precipitation to Monteverde from September to October. For example, the Palo Verde wetland, located in a tropical dry forest in Palo Verde National Park of northwestern Costa Rica (Figure 1), experiences large water level fluctuations between the wet and dry seasons. Approximately 95% of Palo Verde's annual rainfall (1817 mm) occurs from May through November [Jiménez R. *et al.*, 2001]. Impermeable, clay-rich surface soils trap wet season precipitation [Gallaher and Stiles, 2003], creating a seasonal freshwater lagoon that evaporates almost completely during the dry season. Lachniet and Patterson [2002] measured the stable isotopic composition of Laguna Palo Verde in July 1999 ($\delta^{18}\text{O} = -5.9\%$, $\delta^2\text{H} = -43\%$). Its comparably low d excess value (4‰) is a clear outlier relative to nearby

Pacific slope rivers (e.g., δ excess of the Tempisque River = 10.4‰), which suggests that evaporation affects the stable isotopic composition of the lagoon. This and other wetlands comprise about 20% (102,500 ha) of the Tempisque River basin [Jiménez R. *et al.*, 2001], the largest watershed in Costa Rica. Flood-prone regions cover 100,000 ha of this watershed, which can receive overflow of the Tempisque River almost annually from August to October [Jiménez R. *et al.*, 2001]. In stark contrast, the maximum dry season flow of the Tempisque River seldom surpasses 10 m³/sec [Jiménez R. *et al.*, 2001]. Therefore the annual fluctuation from drought to deluge, combined with the seasonal formation and evaporation of Laguna Palo Verde, may create the conditions required for an elevated δ excess signal to appear during the later months of the wet season, and then subsequently to disappear once the Pacific slope becomes dry.

7. Conclusions

[41] The stable isotopic composition of precipitation collected in Monteverde, Costa Rica shows strong temporal variations consistent with differences in condensation history and origin of water for rain events that occur in the wet versus transitional and dry seasons. Compositions for orographic precipitation, which dominates during the drier seasons, are consistently heavy and similar to compositions of cloud water observed in other environments. In contrast, ITCZ convective rainfall during the wet season shows wide variability on the timescale of days. When integrated over weeks or months, the water is isotopically light. Volume-weighted average δ values calculated for wet, transitional, and dry season precipitation are notably distinct, providing an isotopic signal of precipitation from the drier seasons that may be traced to vegetation and surface waters.

[42] Elevated deuterium excess values show that water evaporated from terrestrial sources is an important flux to Monteverde for about eight months of the year. The Caribbean slope, which receives high annual rainfall and is perpetually wet, is an important source of recycled water to dry season orographic precipitation at the mountain tops. Recycled water also appears to contribute an important flux of moisture from the Pacific slope during the rainiest months of Costa Rica's wet season. This recycled water signal is absent at the beginning of the wet season when the trade winds weaken and the western equatorials first bring moisture to the Pacific slope. Several months of rain are needed following an acute dry season on the northern Pacific slope before a terrestrial evaporative signal is detected. This evaporative flux to the atmospheric water vapor budget may result from a progressive, wet season expansion of surface water bodies, an accompanying increase of fresh water discharge into the Gulf of Nicoya, and flooding of seasonal wetlands. Laguna Palo Verde, which is a rain-fed wetland, may be a significant source of reevaporated water vapor to air masses that travel to Monteverde via the westerly equatorial winds.

[43] Combining the seasonal signals produced by δ and deuterium excess values can provide an effective means for tracing dry season moisture. Further work will trace these signals through the Rio Guacimal watershed and investigate how topography influences the spatial variability of orographic precipitation in the Monteverde region.

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