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Stable isotope values of Costa Rican surface waters

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Abstract

Stable isotope data of surface waters from the humid tropics in general, and Costa Rica in particular, are scarce. To improve our understanding of the spatial distribution of stable isotopes in surface waters, we measured $\delta^{18}O$ and δD in river and lake ($n = 63$) and precipitation ($n = 3$) samples from Costa Rica. We also present data from the IAEA/WMO isotopes in precipitation network as context for our study. Surface water isotope values do not strongly correlate with elevation, stream head elevation, stream length, distance from Caribbean Sea, or estimated mean annual precipitation for the country as a whole. However, the data show distinct regional trends. The $\delta^{18}O$ and δD values downwind of mountain ranges are inversely related to the altitude of the ranges the air masses traverse. In the lee of the high Talamanca Range, $\delta^{18}O$ values are ~6–8‰ lower, while in the lee of the lower Tilarán Range $\delta^{18}O$ values are 2–3‰ lower than upwind sites along the Caribbean Slope. An altitude effect of −1.4‰ $\delta^{18}O$/km is present on the Pacific slope of southern Costa Rica, equivalent to a temperature effect of −0.3‰/°C. The Nicoya and Osa Peninsulas have higher values than upwind sites, suggesting input of Pacific-sourced moisture, evaporative enrichment, or decreased condensation temperatures. Elevated and increasing *d*-excess values inland along the Nicaragua Trough suggest a recycled component may be an important contributor to the water budget. These data provide preliminary stable isotope information for Costa Rica, and will benefit paleoclimatic research in the region. More detailed studies would be beneficial to our understanding of the controls on stable isotope composition of tropical waters. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Stable isotopes; Costa Rica; Surface water; Deuterium; Oxygen-18; Deuterium excess

1. Introduction

Stable isotope values of geologic deposits such as lake sediment, ice cores, and speleothems provide valuable paleoclimatic information on a wide range of timescales. Understanding climate change in tropical regions is critical for the development of valid global climate models because they export a dominant percentage of the Earth's heat budget and precipitation to higher latitudes. However, the controls on isotope values of surface waters and precipitation in tropical regions are poorly characterized. In the tropics, temperatures vary only slightly throughout the year at a given elevation. Conversely, stable isotope values may vary considerably throughout the year. Because these values are forced by condensation temperature, precipitation amount, and evaporation, one or more of these factors must vary as well (though Fricke and O'Neill (1999) suggest that stable isotope values of tropical precipitation are not significantly correlative with temperature). Few studies have focused on the variables that influence stable isotope values in the tropics (c.f. Salati et al., 1979; Longinelli

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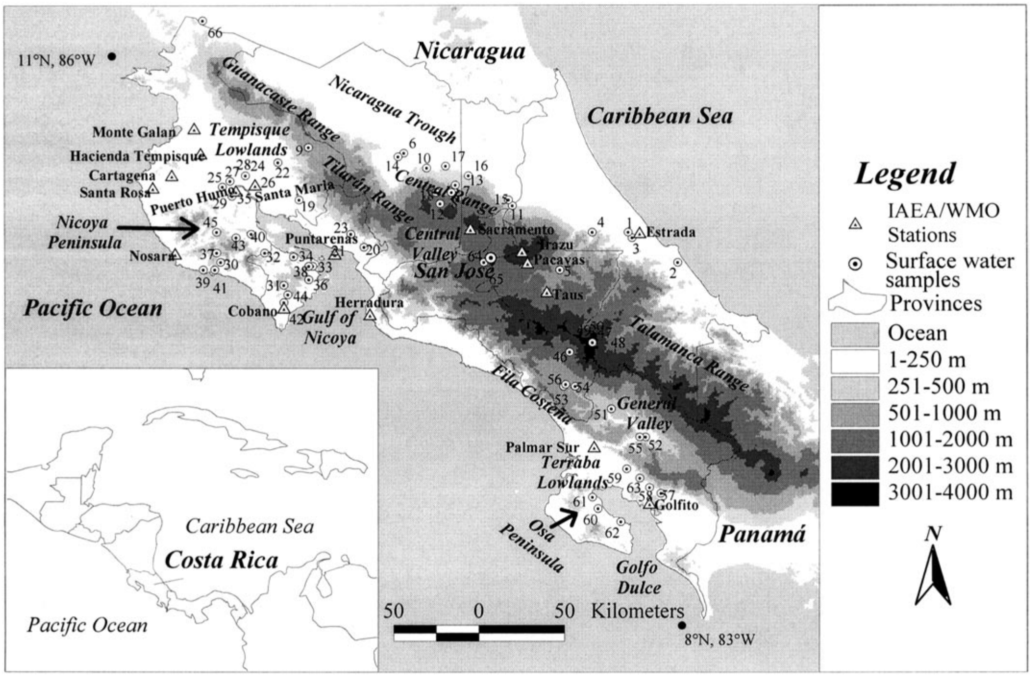

Fig. 1. Digital elevation model (in meters) of Costa Rica showing geographic locations mentioned in the text, IAEA/WMO stations (with names) and location of surface water samples (numbered). The DEM source is the USGS GTOPO30 data set US Geological Survey (1996). Note supplemental shades for low elevations. Inset is Central America and the Caribbean Basin.

and Edmond, 1983; Gat and Matsui, 1991; Araguás-Araguás et al., 1998; Njitchoua et al., 1999). As a result, our understanding of stable isotope values in tropical waters is often insufficient to interpret isotopic records preserved by sediment, carbonate, and ice core proxies.

Herein, we present a study of spatial variation in δ^{18}O and δD of surface waters and precipitation in Costa Rica (Fig. 1; Table 2). We analyzed a total of 66 river, lake, and precipitation samples for δ^{18}O and δD values. We postulate that recycled moisture in certain regions of the country is an important component of the water budget, such as noted in the Amazon basin (Salati et al., 1979), and have considered the deuterium excess (*d*-excess) in surface waters to qualitatively evaluate the significance of recycled water vapor on the hydrologic budget.

The climate of Costa Rica is dominated by the annual migration of the intertropical convergence zone (ITCZ). The 2–5 month dry season begins in January or February when the ITCZ is located near the equator, which segues to a 7–10 month wet season beginning in April or May when the ITCZ moves northward over Costa Rica. The length of the dry season varies with location; the longest dry season occurs on the Nicoya Peninsula, while the Caribbean slope has a less-pronounced and shorter dry season. Much of the country experiences a minor decrease in precipitation, when the ITCZ reaches 12°N (its northernmost position) in June and July.

Annual precipitation ranges from ~1500 mm in the dry Tempisque lowlands and Nicoya Peninsula to ~6000 mm on the Caribbean slope of the Talamanca Range and along the northern Caribbean Coast (Coen, 1983). On the Caribbean slope, mean annual precipitation (data in Bergoeing (1998)) decreases to southerly latitudes ($r^2 = 0.93$), while there is a strong and opposite trend on the Pacific coast, where precipitation increases to the south ($r^2 = 0.86$). The increase of precipitation to the south on the Pacific Coast is likely related to the orographic effect of the broad and high Talamanca Range, while northern Costa Rica consists of a lower elevation plain punctuated by isolated volcanoes less conducive to orographic distillation.

Table 1
Summary data for the IAEA/WMO stations operated in Costa Rica. For locations, see Fig. 1 (MAP, mean annual precipitation (estimated); N.A., not applicable/available)

Station	Latitude (dec. deg.)	Longitude (dec. deg.)	Elevation (m)	Dates of operation	n	Local meteoric water line	r^2	Total precipitation (mm)	Arithmetic means			Weighted means		
									δD	$\delta^{18}O$	d	δD	$\delta^{18}O$	d
Sacramento	10.10	−84.12	2260	1/90–12/90	9	$\delta D = 8.6\delta^{18}O + 14.5$	0.993	2601	−53	−7.9	10.1	−59	−8.6	9.8
Irazú	9.98	−83.85	3000	1/90–12/90	8	$\delta D = 7.8\delta^{18}O + 8.9$	0.980	N.A.	−70	−10.1	10.4	N.A	N.A.	N.A.
Pacayas	9.92	−83.82	1735	1/90–12/90	8	$\delta D = 8.4\delta^{18}O + 13.7$	0.997	1942	−52	−7.9	10.8	−52	−7.9	11.2
Estrada	10.08	−83.23	6	1/90–12/92	21	$\delta D = 7.6\delta^{18}O + 7.4$	0.943	1055	−19	−3.5	8.8	−20	−3.2	5.6
Taus	9.77	−83.72	900	1/90–12/90	8	$\delta D = 8.0\delta^{18}O + 11.1$	0.974	4256	−46	−7.1	11.3	−46	−7.2	11.6
Monte Galan	10.63	−85.57	60	1/90–12/90	8	$\delta D = 6.1\delta^{18}O - 2.7$	0.908	1185	−35	−5.4	7.8	−37	−6	11.0
Hacienda Tempisque	10.50	−85.53	22	1/90–12/91	13	$\delta D = 7.8\delta^{18}O + 5.5$	0.917	898	−35	−5.2	6.6	−42	−6.2	7.6
Cartagena	10.38	−85.68	63	1/91–12/91	7	$\delta D = 7.8\delta^{18}O + 1.9$	0.973	1010	−43	−5.7	2.9	−47	−6.3	3.4
Santa Rosa	10.32	−85.78	25	1/90–12/90	4	$\delta D = 8.2\delta^{18}O + 13.3$	0.999	992	−62	−9.2	11.1	−58	−8.6	10.8
Santa Maria	10.33	−85.25	825	1/90–12/92	18	$\delta D = 8.1\delta^{18}O + 9.1$	0.986	1601	−28	−4.5	8.8	−39	−5.9	8.2
Puerto Humo	10.30	−85.35	10	1/90–12/90	9	$\delta D = 8.6\delta^{18}O + 14.5$	0.996	1374	−42	−6.6	10.5	−41	−6.5	11.0
Nosara	9.97	−85.67	15	1/90–12/91	14	$\delta D = 8.4\delta^{18}O + 10.9$	0.925	2973	−42	−6.3	8.2	−41	−6	7.0
Puntarenas	9.97	−84.83	3	1/93–12/93	8	$\delta D = 7.9\delta^{18}O + 10.8$	0.992	1289	−41	−6.5	11.3	−55	−8.5	13.0
Cóbano	9.68	−85.10	160	1/90–12/90	8	$\delta D = 8.4\delta^{18}O + 13.6$	0.998	2400	−41	−6.5	10.8	−46	−7.1	10.8
Herradura	9.65	−84.65	3	1/90–12/90	8	$\delta D = 8.2\delta^{18}O + 12.3$	0.999	2146	−45	−7.0	11.1	−48	−7.3	10.4
Palmar Sur	8.95	−83.47	16	1/90–12/90	8	$\delta D = 8.5\delta^{18}O + 14.2$	0.990	3293	−50	−7.6	10.4	−53	−7.9	10.2
Golfito	8.65	−83.18	15	1/90–12/90	8	$\delta D = 8.1\delta^{18}O + 11.6$	0.986	2633	−45	−7.0	11.0	−45	−7	11.0
Mean									−44	−6.7	9.5	−46	−6.9	9.5
Max									−19	−3.5	11.3	−20	−3.2	13.0
Min									−70	−10.1	2.9	−59	−8.6	3.4
Median									−43	−6.6	10.4	−46	−7.1	10.6
S.D.									12	1.6	2.2	10	1.4	2.5

Table 2

Surface water stable isotope data for Costa Rica. Abbreviations: L., Lago or Laguna (lake); R., Rio (River); Q., Quebrada (stream); V., Valle (Valley). The distance from the Caribbean was measured along a NE–SW line approximating a trade wind vector

Sample site	Date	Sample #	Latitude (dec. deg.)	Longitude (dec. deg.)	Sample elevation (m)	Elevation of stream head (m)	Total stream length (km)	Distance from Caribbean (km)	MAP (m; estimated)	$\delta^{18}O$ (‰) VSMOW	δD (‰) VSMOW	*d*-Excess (‰)
R. Aguas Claras	7/29/99	1	10.05	−83.27	10	N.A.[a]	N.A.[a]	14	3.0	−4.5	−23	13.0
R. Banano	7/29/99	2	9.92	−83.03	10	1700	40.5	3	3.3	−5.2	−33	8.4
R. Chirripó Atlántica	7/29/99	3	10.08	−83.29	50	3600	85	14	2.8	−6.1	−38	11.4
R. Pacuare	7/29/99	4	10.08	−83.48	90	2700	133	27	2.9	−6.8	−41	13.3
R. Reventazón	7/29/99	5	9.88	−83.65	600	3500	123	50	4.0	−8.3	−52	14.4
R. San Carlos	7/14/99	6	10.50	−84.47	100	1500	83	94	3.0	−6.6	−32	20.2
L. Maria Aguilar	7/30/99	7	10.29	−84.20	770	770	N.A.	87	4.9	−6.8	−33	21.0
L. Hule	7/30/99	8	10.29	−84.22	750	1200	N.A.	90	4.9	−5.6	−31	14.5
L. Arenal	7/13/99	9	10.53	−84.97	540	N.A.[b]	N.A.	137	2.3	−4.5	−27	9.6
R. Aguas Zarcas	7/14/99	10	10.42	−84.35	150	2050	34	87	3.9	−6.0	−34	14.4
R. Chirripó	7/14/99	11	10.22	−83.90	250	2500	79	58	4.5	−6.7	−37	16.4
R. Desague	7/14/99	12	10.23	−84.28	1350	2350	9.5	98	4.0	−7.7	−44	17.2
R. Hule	7/14/99	13	10.33	−84.20	400	1250	15	85	4.9	−5.7	−30	15.5
R. Peñas Blancas (Tilarán)	7/14/99	14	10.48	−84.50	100	1250	54	97	3.0	−5.6	−27	18.0
R. San José	7/14/99	15	10.25	−83.92	180	800	14	56	4.5	−5.6	−30	15.0
R. Sarapiqui	7/14/99	16	10.38	−84.13	200	2100	96	78	4.7	−6.0	−30	17.6
R. Toro, lower	7/14/99	17	10.43	−84.25	200	2000	67.5	83	3.9	−7.3	−37	20.6
R. Toro, upper	7/14/99	18	10.29	−84.30	1450	2000	67.5	102	4.5	−9.0	−54	17.5
R. Abangares	7/9/99	19	10.25	−85.02	100	950	39	165	1.8	−8.0	−59	5.2
R. Barranca	7/9/99	20	10.00	−84.68	100	1900	57	148	1.8	−9.4	−57	18.3
R. Ciruelas	7/9/99	21	10.07	−84.75	100	1400	22	149	1.9	−9.4	−60	15.3
R. Corobicí	7/9/99	22	10.45	−85.13	35	1100	33	187	1.8	−4.8	−25	14.0
R. Seco (Tilarán)	7/9/99	23	10.07	−84.75	100	1100	30	149	1.9	−8.8	−56	14.4
Campos Pond	7/9/99	24	10.38	−85.30	10	20	8.5	228	1.5	−6.7	−42	11.6
P. Chamorro Marsh	7/10/99	25	10.35	−85.38	10	N.A.[b]	N.A.	234	1.5	−6.9	−48	7.4
Q. La Mula	7/10/99	26	10.38	−85.30	10	20	8.5	228	1.5	−9.0	−64	8.1
R. Tempisque	7/10/99	27	10.35	−85.38	10	1700	102	234	1.5	−6.9	−45	10.4
L. Palo Verde	7/10/99	28	10.35	−85.38	10	N.A.[b]	N.A.	230	15	−5.9	−43	4.0
L. Mata Redonda	7/12/99	29	10.32	−85.42	10	N.A.[b]	N.A.	239	1.5	−9.6	−66	11.0
R. Angostura	7/19/99	30	9.92	−85.43	75	250	6	240	2.0	−8.6	−54	15.0
R. Ario	7/20/99	31	9.80	−85.10	120	700	39	191	2.0	−8.9	−56	15.3
R. Canjel	7/20/99	32	9.97	−85.20	50	320	16	194	1.8	−8.5	−57	11.3
R. Gigante	7/19/99	33	9.90	−84.95	30	250	5.5	180	1.6	−9.2	−57	16.8
R. Gigante	1/6/00	34	9.90	−84.95	30	250	5.5	180	1.6	−9.1	−58	15.1
R. Grande	7/19/99	35	10.27	−85.37	80	300	45	204	1.5	−7.0	−44	12.2
R. Guarial	7/19/99	36	9.83	−84.97	50	180	10	179	1.8	−8.4	−53	14.0
R. Lajas	7/19/99	37	9.97	−85.45	80	400	15	240	1.9	−8.4	−54	13.9
R. Lepanto	7/19/99	38	9.95	−85.05	50	300	13	176	1.5	−8.4	−58	8.8
R. Mala Noche	7/19/99	39	9.88	−85.52	5	400	8	248	2.1	−8.5	−52	15.9
R. Morote	7/19/99	40	10.07	−85.27	50	300	45	192	1.6	−7.4	−48	11.0
R. Ora	7/19/99	41	9.88	−85.46	10	400	33	241	2.1	−8.3	−51	15.3
R. Panica	7/19/99	42	9.71	−85.10	100	200	16	197	2.2	−8.9	−59	13.0
R. Piangosta	7/19/99	43	10.05	−85.35	350	700	7	239	1.7	−8.7	−56	13.2

Table 2 (*continued*)

Sample site	Date	Sample #	Latitude (dec. deg.)	Longitude (dec. deg.)	Sample elevation (m)	Elevation of stream head (m)	Total stream length (km)	Distance from Caribbean (km)	MAP (m; estimated)	$\delta^{18}O$ (‰) VSMOW	δD (‰) VSMOW	*d*-Excess (‰)
R. Seco (Nicoya)	7/20/99	44	9.75	−85.08	110	350	11.5	197	2.0	−9.1	−60	12.8
R. Zompopa	7/18/99	45	10.08	−85.45	160	300	5	210	1.8	−6.6	−46	6.8
R. Chirripó Pacífico	7/27/99	46	9.45	−83.60	1370	3540	25	86	3.0	−13.3	−85	20.8
L. Morrenas (CR99-132)	5/4/99	47	9.50	−83.48	3560	3800	N.A.	75	3.0	−12.2	−86	11.5
L. Morrenas	8/20/99	48	9.50	−83.48	3560	3800	N.A.	75	3.0	−13.9	−98	13.6
L. Woody	8/21/99	49	9.50	−83.48	3560	3800	N.A	75	3.0	−12.8	−86	16.0
Precipitation in V. Morrenas (06:00 h)	8/22/00	50	9.50	−83.48	3560	N.A.	N.A.	75	3.0	−14.5	−105	11.4
R. Ceibo	7/27/99	51	9.15	−83.38	250	2800	39.7	88	3.0	−8.9	−61	10.5
R. Coto Brus	7/28/99	52	9.00	−83.20	95	2200	73	92	3.0	−9.8	−66	12.9
R. General	7/27/99	53	9.27	−83.63	500	3540	108	99	3.0	−10.2	−69	12.5
R. Unión	7/27/99	54	9.27	−83.57	370	2850	24.4	95	3.0	−11.1	−77	12.1
R. Terraba	7/27/99	55	9.00	−83.23	90	3540	70.5	95	3.0	−10.4	−62	21.1
R. Peñas Blancas (VG)	7/27/99	56	9.28	−83.62	520	2500	0.2	99	5.1	−6.9	−49	6.8
R. Coto Colorado	7/28/99	57	8.70	−83.12	80	700	58.5	115	5.2	−7.9	−50	13.2
R. Esquinas	7/28/99	58	8.73	−83.18	100	270	37	116	5.2	−8.2	−50	15.6
R. Salama Nuevo	7/28/99	59	8.83	−83.30	100	300	9	114	4.5	−8.2	−51	14.7
R. Conte	7/28/99	60	8.62	−83.45	25	200	10.5	142	4.1	−7.8	−53	9.9
R. Rincon	7/28/99	61	8.68	−83.48	5	275	12.5	140	4.2	−7.8	−50	13.0
R. Tigre	7/28/99	62	8.55	−83.33	5	500	24	143	3.9	−7.9	−53	9.7
R. Piedras Blancas	7/28/99	63	8.78	−83.23	100	900	8	114	5.0	−9.4	−57	18.6
Precipitation in San Pedro (14:15 h)	10/9/99	64	9.92	−84.05	1200	N.A.	N.A.	82	2.3	−14.7	−102	15.6
Precipitation in San Pedro (19:50 h)	10/18/99	65	9.92	−84.05	1200	N.A.	N.A.	82	2.3	−15.1	−105	15.2
L. Nicaragua	7/13/99	66	11.20	−85.52	31	N.A.[b]	N.A.	250	2.50	−2.0	−9	7.0

[a] River does not appear on topographic maps.

[b] Fed by sources of numerous elevations.

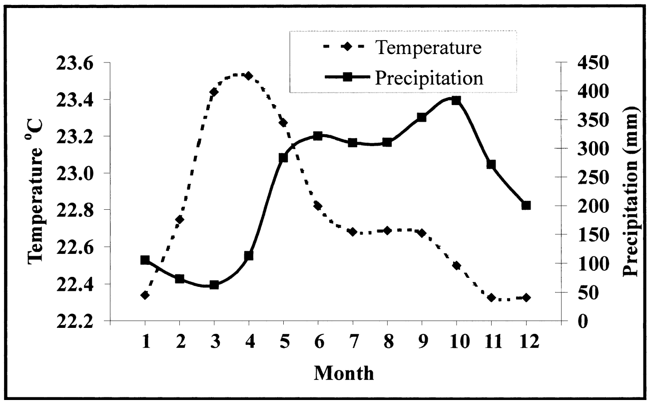

Fig. 2. Temperature and precipitation averaged from all Costa Rican weather stations. The dry season extends from January to April or May, and the wet season from May or June to December. There is regional variability that differs from the average plots.

Temperatures vary more diurnally than seasonally. The average temperature of the warmest month does not exceed the average temperature of the coldest month by 5 °C, while the diurnal range can be up to 10 °C near sea level (Coen, 1983), and this range decreases with increasing elevation. The Pacific Coast experiences the highest temperatures with the yearly average at Puntarenas of 27.7 °C (FAO, 1985). Countrywide, average temperatures generally peak at the end of the dry season in April or May, and drop steadily during the wet season to a minimum in November, December, and January. The lowest mean annual temperature (7.6 °C) reported is at Cerro Páramo (3475 m) in the Talamanca Range (Horn, 1989) and the lowest temperature reported was −9 °C in Chirripó Park (~3600 m, Bergoeing, 1998). While snowfall is uncommon, a few occurrences have been reported on the highest peaks (Castillo-Muñoz, 1993), and hail was observed by Lachniet in Chirripó Park in late August, 1999. The lapse rate in Costa Rica was determined from radiosonde data from the San José airport to be −5.4 °C/km from the elevation of 0.9–6.0 km, a value close to the moist adiabatic rate. A summary plot of the seasonal variation in precipitation and temperature over Costa Rica is presented in Fig. 2 using combined average values for several meteorological stations across the country.

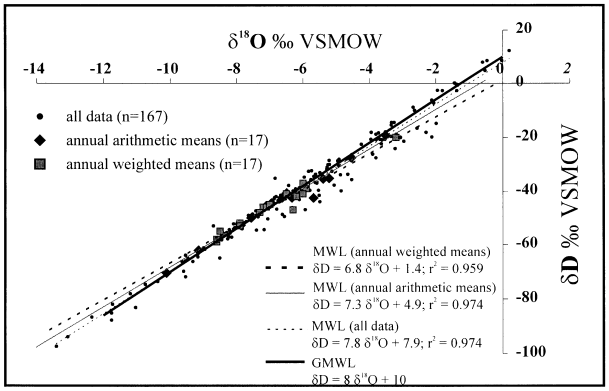

Fig. 3. Regional Costa Rican water lines from the IAEA/WMO station network. The meteoric water lines for all monthly data and annual arithmetic and precipitation-weighted means are shown in comparison with the GMWL. See text for discussion.

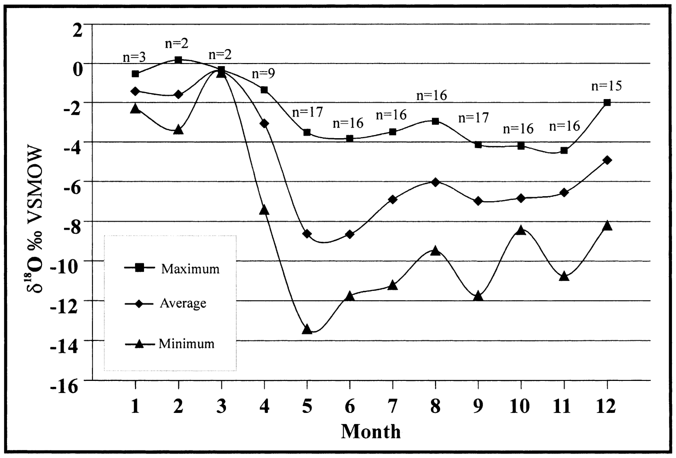

Fig. 4. Plot of monthly variation in $\delta^{18}O$ for mean of all IAEA/WMO stations in Costa Rica, along with sample size for each month. The dry season (January to April) is characterized by higher $\delta^{18}O$ values than the wet season (the remainder of the year).

2. Methods

Lake and river waters were collected in 60 ml Nalgene bottles, primarily during the wet season in July and August 1999. The limited sampling period (4 weeks) precludes extrapolation of results to assess temporal or annual mean spatial distributions. Nonetheless, the data provide a useful addition to isotope hydrology studies in the humid tropics. Due to spot sampling, the precipitation samples are not discussed in detail and are presented only for the sake of documentation. The sampling transect ran from Lake Nicaragua in the north to near the Panamanian border in the south (11.0–8.5°N and 85.5–83.0°W). Samples were recovered from elevations between sea level and 3600 m on both the Caribbean and Pacific slopes and intervening cordilleras. The sample elevation, stream length, and elevation of the stream head were estimated from 1:50,000 and 1:200,000 topographic maps (Instituto Geográfico Nacional, 1970, 1987).

$\delta^{18}O$ and δD values were determined using a Finnigan HDO-III water equilibration device directly coupled to a Finnigan MAT 252 gas ratio mass spectrometer. Results are expressed in δ notation relative to the VSMOW standard. Sample precision is $\pm 0.1‰$ for $\delta^{18}O$ and $\pm 3‰$ for δD. Water samples were analyzed for major elemental chemistry using direct-current plasma emission spectroscopy, ion chromatography, and alkalinity titration. The chemical data identified some surface waters that had volcanic and oceanic water inputs, described in the following sections.

3. Isotopes in precipitation from IAEA/WMO stations in Costa Rica

The International Atomic Energy Association/ World Meteorological organization operated 17 stations in Costa Rica as part of the Global Network for Isotopes in Precipitation (IAEA/WMO, 1998). We analyzed data from these stations to provide context for the Costa Rican surface water samples. Our aim is to provide a descriptive treatment of the data; a thorough analysis is beyond the scope of this study.

Station data are presented in Table 1, and station locations are shown in Fig. 1. Several points should be considered while evaluating isotope data from these stations. First, the stations reported $\delta^{18}O$ and δD in precipitation generally over 1 year, and at most 3 years (Estrada), in the early 1990s. The stations present only a short-term record, with the number of reported monthly means ranging from $n = 7$ to 21, with omission of precipitation amount, $\delta^{18}O$, and δD values in some months. Longer-term records are needed to evaluate 'average' conditions over the country. Second, few stations reported isotope data for the months of January to March, which corresponds to the dry season precipitation minima. Third, there is a geographic clustering of stations

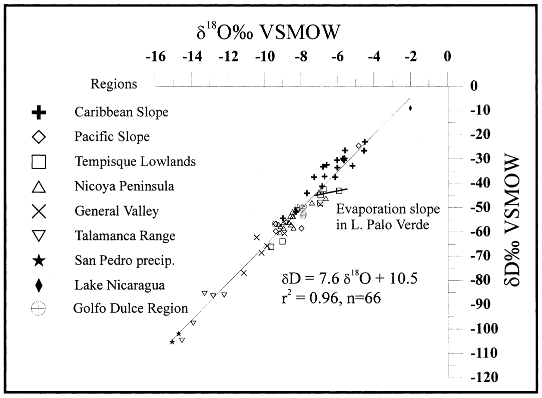

Fig. 5. Costa Rican SWL plotted by region. Sites on the Caribbean Slope tend to plot above the line, while samples from the less humid Tempisque lowlands plot below. The slope through the R. Tempisque and L. Palo Verde of 5.7 is a result of evaporative enrichment.

around the Nicoya Peninsula and Tempisque lowlands, which have a semi-arid and highly seasonal climate, and will tend to overemphasize the signal from this region. Fourth, the data coverage has significant gaps; temperature was reported for only one station (Puntarenas), and precipitation amount was not reported for all months, thus precluding a weighting procedure by precipitation amount for many months. All of these factors will result in a deviation of the calculated water line with the 'real' meteoric water line. Due to these data limitations, a thorough discussion of correlations for various climatic/physical parameters and δD and $\delta^{18}O$ is premature. Nonetheless, the stations provide valuable preliminary information on stable isotopes in precipitation in Costa Rica.

Station statistics, meteoric water lines, and the annual arithmetic and precipitation-weighted means of $\delta^{18}O$, δD, and d (the d-excess, calculated by $d = \delta D - 8\delta^{18}O$; Daansgard, 1964) for each station are reported in Table 1. The annual-weighted means were calculated for the months where $\delta^{18}O$, δD, and precipitation amount were all reported. Months that did not report precipitation amount, or either $\delta^{18}O$ or δD, were omitted from the weighting procedure so that the $\delta^{18}O$ and δD values are comparable. Where an individual month (i.e. July) was reported in more than 1 year, the monthly mean was determined by weighting both months according to precipitation amount. Fig. 3 shows a plot of all data, the annual arithmetic and weighted means in $\delta^{18}O/\delta D$ space, along with best fit regressions and the global meteoric water line (GMWL). The best fit regression for all monthly data ($n = 167$; not presented in Table 1) yields a water line equation of $\delta D = 7.8\delta^{18}O + 7.9$ ($r^2 = 0.974$), which corresponds closely to the GMWL ($\delta D = 8\delta^{18}O + 10$; Craig, 1961). The best fit regressions of the arithmetic and precipitation-weighted annual means ($n = 17$) yield water lines of $\delta D = 7.3\delta^{18}O + 4.9$ ($r^2 = 0.974$) and $\delta D = 6.8\delta^{18}O + 1.4$ ($r^2 = 0.959$), respectively.

The data also reveal distinct seasonal variability. During the dry season (January to April), precipitation amount is at a minimum, and $\delta^{18}O$ values are highest, while during the wet season (the remainder of the year), $\delta^{18}O$ values are lowest (Fig. 4). The range of values is also greatest in May, which corresponds to the beginning of the rainy season and the migration of the ITCZ over Costa Rica. The small range of values in the dry season (especially January to March) likely reflects the small sample sizes resulting from small precipitation amounts. This seasonal variability is also likely to be reflected in stable isotope values of surface waters.

Despite the data limitations mentioned earlier, a few preliminary correlations can be made. Considering only the stations on the Caribbean Slope and the Central Valley (Sacramento, Irazú, Pacayas, Estrada, and Taus) which are unlikely to have undergone significant evaporative enrichment in ^{18}O, the correlation of elevation with arithmetic annual mean $\delta^{18}O$ is strong. The regression yields a $\delta^{18}O$/km slope of $-1.9‰$ ($r^2 = 0.89$), which is consistent with that observed in other locations (Rozanski et al., 1993). Utilizing the atmospheric lapse rate of -5.4 °C/km, based on radiosonde data from San José, this altitude effect corresponds to a temperature effect of $\sim -0.4‰$/°C, which is also similar to values observed elsewhere (Daansgard, 1964; Rozanski et al., 1993). Similarly, regressing δD versus $\delta^{18}O$ for these stations yields a water line of $\delta D = 7.7\delta^{18}O + 8.4$ ($n = 5$; $r^2 = 0.999$). These stations, at least, appear to reflect isotopic equilibrium conditions. The stations in the semi-arid northwest may be influenced by evaporation, and along with the Pacific Coast stations (Puntarenas, Herradura, Palmar Sur, and Golfito), may receive precipitation from a Pacific source (discussed later), thus complicating their interpretation.

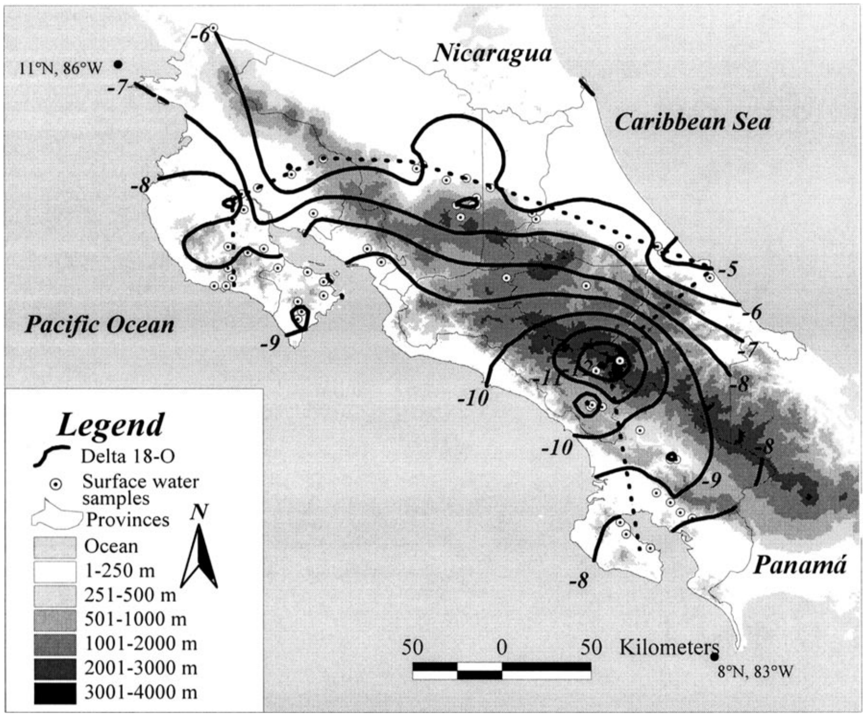

Fig. 6. Contour plot of δ^{18}O of surface waters and the generalized transects are illustrated in Figs. 7 and 8.

4. Surface water data results and discussion

The locations of the surface water samples are shown in Fig. 1, and the data are presented in Table 2. Most of the rivers we sampled occur in or near the base of mountainous areas, although some are located in coastal lowlands. Stream length varied from 0.2 to 133 km, and stream head elevation varied from near sea level to 3800 m (Table 2). Hydrologic studies assessing event and pre-event contributions to humid tropical streamflow are scarce (c.f. Elsenbeer et al., 1995a,b), and none from Costa Rica are available. Many streams contain a large proportion (~30–80%) of 'old' pre-event soil or groundwater, with the remainder being event precipitation. The relative contributions of event and pre-event water may also change temporally in the same stream. Considering this, our samples represent a mixed temporal and hydro(geo)logic signal. As a result, interpretation of these samples with respect to hydrologic processes or climate forcing is difficult. Nonetheless, the spatial coherence of the data (presented in the following sections) suggests the samples reflect real regional variations. If stochastic weather patterns only controlled the isotopic composition of surface waters, the data would be expected to show much more variability and less spatial coherence. The seasonal variability apparent in the isotopic composition of precipitation is likely to be manifested as seasonal variations in the isotopic composition of surface waters. Therefore, our data taken in July and August, reflect only a 'snapshot' and should not be used to extrapolate mean annual or seasonal conditions. For this, more detailed future studies are needed.

δ^{18}O values range from -2.0 to -15.1‰ and δD values range from -9 to -105‰ for Lake Nicaragua and precipitation in San Pedro (San José), respectively (Table 2). Regression of δ^{18}O and δD values yields the surface water line (SWL) for Costa Rica (Fig. 5; $\delta D = 7.6\delta^{18}O + 10.5$, $r^2 = 0.96$, $n = 66$). The data exhibit several regional trends. For example, samples from the Caribbean slope generally plot above the SWL, while samples from the more arid Tempisque

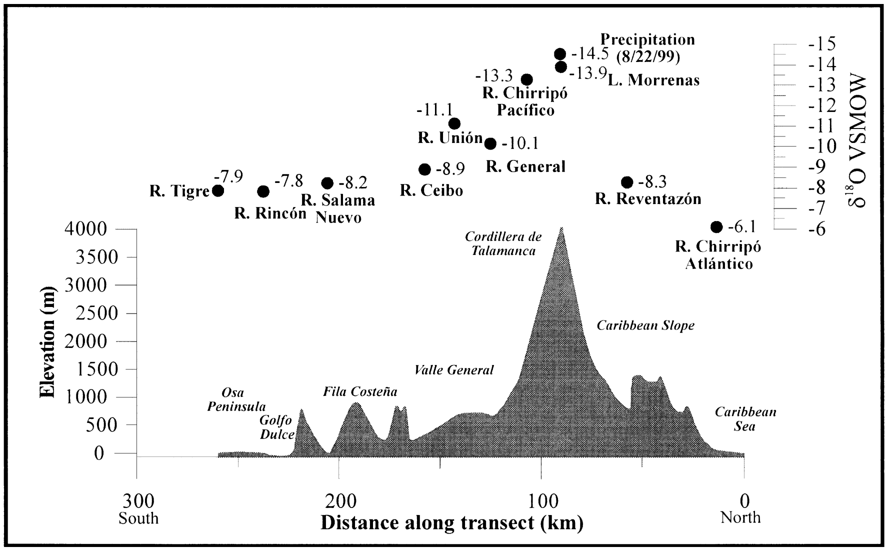

Fig. 7. Transect showing $\delta^{18}O$ values of selected surface waters across southern Costa Rica. Note the inverted $\delta^{18}O$ scale. The $\delta^{18}O$ trend mimics the topography, and surface waters decreased by 6–8‰ upon traversing the Talamanca Range.

lowlands plot below the SWL. This regional variability will be discussed in more detail later.

$\delta^{18}O$ values for the entire data set were regressed against several physical parameters. For example, the correlations against latitude ($r^2 = 0.15$), elevation of stream head ($r^2 = 0.00$), total stream length ($r^2 = 0.04$), estimated mean annual precipitation ($r^2 = 0.02$) and distance from the Caribbean Sea (the primary moisture source, $r^2 = 0.00$) were very poor. The strongest correlation is for sample altitude ($r^2 = 0.38$), with values decreasing at higher elevations due to the orographic/temperature effect. The poor correlations are likely related to the small sample size and spot sampling; further seasonal sampling may reveal improved correlations.

The poor correlations suggest that the factors affecting the $\delta^{18}O$ values of surface waters are multivariate and complex. For example, the amount of rain out of an air mass prior to reaching the sample area can be variable, resulting in variability in $\delta^{18}O$ values. Additionally, the values represent an elevation- and precipitation-weighted mean for the drainage basin upstream of the sample site, parameters that are difficult to quantify with the available data. Considering this problem, we have attempted to explain isotope values in qualitative terms in the following sections.

The regional variability in stable isotope values is most apparent when $\delta^{18}O$ values are contoured (Fig. 6). Highest values (−5 to −6‰) are found near the Caribbean Sea. $\delta^{18}O$ values from the Nicoya Peninsula and Tempisque lowlands are lower than those from the Caribbean lowlands and mountain ranges. $\delta^{18}O$ values from the Golfo Dulce Basin are higher than the upwind General Valley and Talamanca Range. Overall, the regional trends in $\delta^{18}O$ are spatially coherent. Based on the distinct regional variability, our results are discussed for southeastern and northwestern Costa Rica.

4.1. Southern Costa Rica

From NE to SW, southeastern Costa Rica consists of a narrow (~20 km) strip of Caribbean lowlands with a transition to the Talamanca Range which culminates at the isthmian divide. From there, elevations decrease abruptly to the General Valley and the Fila Costeña, and finally the Golfo Dulce region and the Osa Peninsula (Fig. 6). Much of the largely forested area along and NE of the continental divide is preserved and protected as an UNESCO International Biosphere Reserve. The General Valley and Térraba lowlands are widely cultivated, while forest is present on the Osa Peninsula.

$\delta^{18}O$ values display a strong trend along a transect

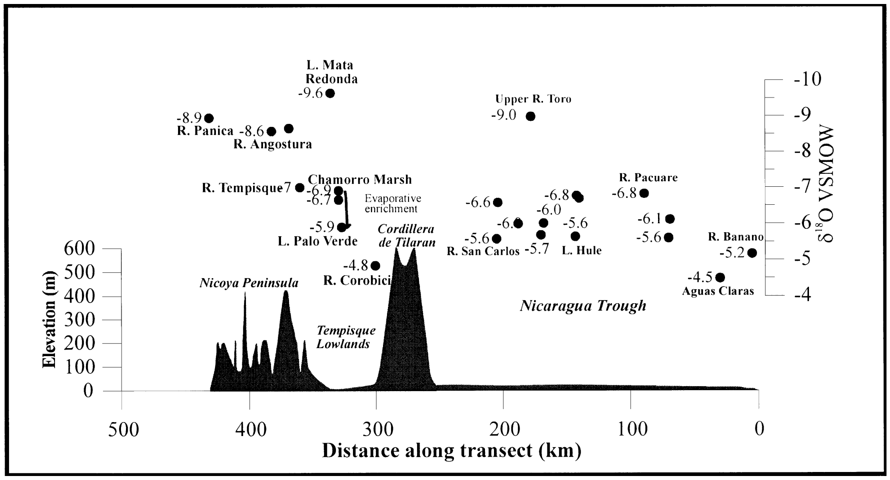

Fig. 8. Transect showing $\delta^{18}O$ values of surface waters across northern Costa Rica. Note the inverted $\delta^{18}O$ scale. Values are relatively constant along the Nicaragua Trough and become ~2–3‰ lower in the lee of the Tilarán Range. In the Tempisque Lowlands, some samples are evaporatively enriched in ^{18}O.

from the Caribbean Sea to the Pacific Ocean. The trend from the Caribbean slope and over the Talamanca Range follows the surface topography (Fig. 7). Highest $\delta^{18}O$ values ($\sim -6‰$) occur on the Caribbean lowlands, and decrease to the lowest value ($-14.5‰$ in precipitation) on the isthmian divide (3600 m). Upon traversing the Talamanca Range isotope values increase from the General Valley westward over the Osa Peninsula.

$\delta^{18}O$ values decrease by ~6–8‰ as the range is traversed relative to upwind sites. This decrease in $\delta^{18}O$ from the Caribbean slope to the isthmian divide is likely a result of orographic distillation (the effect of decreasing condensation temperature as the air mass is lifted). The higher values in the lee of the Talamanca Range may be explained by an increase in condensation temperature as air masses descend over the General Valley and/or a precipitation contribution from a Pacific source. The regression of sample elevation with $\delta^{18}O$ values on the Pacific slope yields an altitude effect of $-1.4‰$/km ($r^2 = 0.70$) which is equivalent to a temperature effect of 0.3‰/°C using the atmospheric lapse rate presented earlier. The samples over the Fila Costeña and Osa Peninsula are heavier than the upwind General Valley and Talamanca Range. These higher values may be explained by the input Pacific Ocean moisture, which has higher $\delta^{18}O$ values than the Caribbean Sea moisture that has traversed the Talamanca Range or increased condensation temperatures encountered as the air mass descends the range. An alternative hypothesis is that the higher values are a result of evaporative enrichment. However, the climate over this area is wet and humid, so we favor the first hypothesis. In support of this interpretation, the presence of the Talamanca Range serves to decrease the strength of the trade winds at surface level in its lee through establishment of a rotor (Coen, 1983), allowing Pacific-derived moisture incursions and precipitation over the Osa Peninsula and Fila Costeña.

4.2. Northern Costa Rica

Northern Costa Rica consists of several geographic zones (Fig. 1). The Caribbean slope is dominated by the lowlands of the Nicaragua Trough that are aligned from Lake Nicaragua to the Caribbean coast. These lowlands are forested in the northern coastal region while much of the remainder has been developed for agriculture. The Central Range consists of forested high elevation volcanoes (2000–3432 m), and is bordered by the Central Valley to the south that drains westward to the Gulf of Nicoya. The Guanacaste Range consists of isolated volcanic peaks (1500–2000 m) separated by lowlands (~400 m), while the Tilarán Range consists of mountains reaching

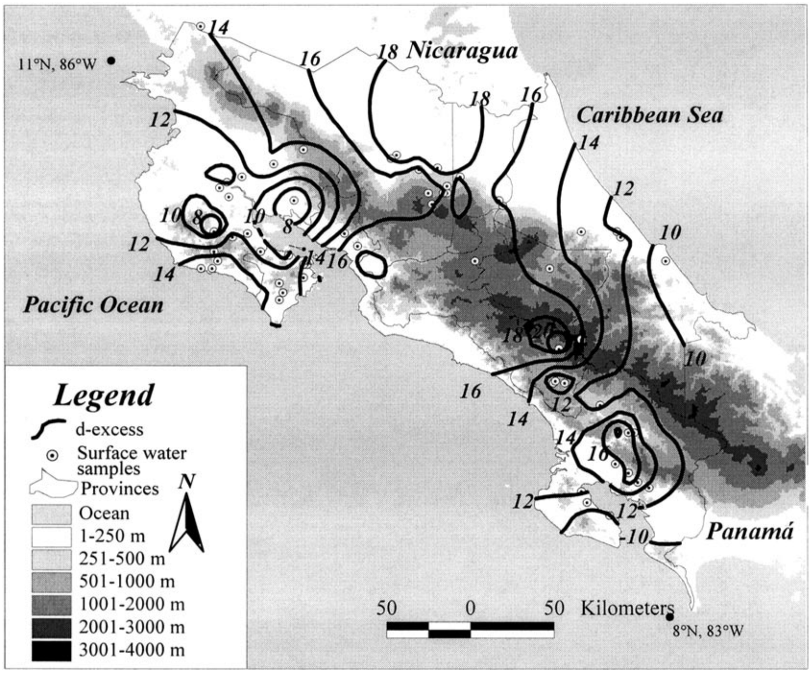

Fig. 9. Contour plot of *d*-excess for surface waters. Note increasing *d*-excess along the Nicaragua Trough from E to W. The values greater than the 10‰ typical of the GMWL suggest recycling of moisture or a cooler condensation temperature.

∼1500 m in peaks without intervening lowlands. On the SW side of the volcanic ranges, the Tempisque lowlands are bordered by the Nicoya Peninsula.

The δ^{18}O values are contoured in Fig. 6 and as a transect from the Caribbean Sea to the Pacific Ocean in Fig. 8. There does not appear to be a consistent trend in δ^{18}O values along the Nicaragua Trough inland from the Caribbean, and the values cluster around −6‰. The Rio Desague and lower Rio Toro drain runoff from the active Poás Volcano and contain elevated SO_4^{-2} concentrations, implicating volcanic water input; these samples were omitted from our statistical analysis. In the lee of the Tilarán Range δ^{18}O values decrease to ∼ − 8 or −9‰ (Barranca, Ciruelas, and Seco (Tilarán) Rivers, not shown on the transect), although Lake Arenal on the continental divide (−4.5‰) and the Corobici River in the lee of the Guanacaste Range (−4.8‰) are higher. From the isthmian divide, δ^{18}O values decrease over the Tempisque lowlands to a minimum in Lago Mata Redonda (−9.6‰ δ^{18}O), although the nearby Rio Tempisque, Lago Palo Verde, and Chamorro Marsh are heavier (−5.9 to −6.9‰ δ^{18}O). The δ^{18}O values increase to ∼−8.5‰ over the Nicoya Peninsula.

Interpreting the δ^{18}O values along the Nicoya Peninsula transect is more complicated. The lower values in the lee of the Tilarán Range suggest a depletion of 2–3‰ during the traverse of the range as a result of orographic distillation. The higher δ^{18}O values in Lago Arenal and the Corobici River suggest that they may be evaporatively enriched. The Rio Tempisque is tidally influenced near its mouth, and associated wetlands such as Laguna Palo Verde and Chamorro Marsh show elevated Na^+ and Cl^- concentrations, and higher δ^{18}O values than other local surface waters. These results are most easily explained by salt-water intrusion from the Gulf of Nicoya into the wetland. The wetlands are fed by the Rio Tempisque and possibly karstic groundwater. A linear regression of δ^{18}O and δD values for the Rio Tempisque and Laguna Palo Verde yields a slope of 5.7, suggesting that evaporative enrichment has occurred.

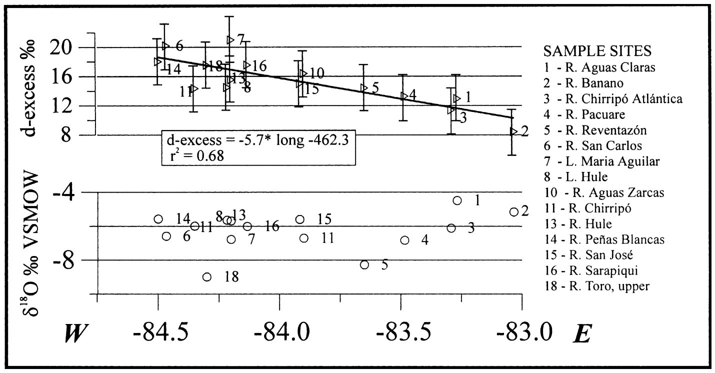

Fig. 10. Isotopic evolution along the Nicaragua Trough. The *d*-excess values increase from near the Caribbean Sea, while δ^{18}O values remain nearly constant. Error bars for *d*-excess are 3‰. The δ^{18}O values on the eastern portion of the Trough display a weak correlation with stream head elevation ($r^2 = 0.46$).

4.3. Deuterium excess

Evapotranspiration has been found to be an important component of regional water budgets. In tropical rainforests such as in the Amazon Basin, transpiration may contribute up to 80% of the water available for rainfall (c.f. Martinelli et al., 1996), but apparently does not fractionate during the process (White, 1988; Flanagan et al., 1991). However, kinetic fractionation occurs during evaporation of water bodies such as lakes and rivers under typical relative humidity (significantly <100%). Under evaporative conditions, a water body will become enriched in ^{18}O and D, generating values on a slope <8 with a *d*-excess less than the initial value. Considering conservation of mass, the resultant vapor and precipitation will have a *d*-excess value greater than the source water (Gat and Matsui, 1991; Martinelli et al., 1996). As a water volume undergoes successive evaporation and precipitation cycles, the *d*-excess will consequently increase. Thus, water that is evaporated back into the atmosphere is effectively labeled and can be traced through the water cycle. Therefore, evaluation of *d*-excess of precipitation and surface waters can provide an estimate of the relative contribution of recycled moisture. However, due to the temperature dependence of the fractionation factors for ^{18}O and D (Majoube, 1971), the *d*-excess of precipitation is also controlled by the temperature of condensation, and hence altitude of precipitation. Lower temperatures yield higher *d*-excess values, though the effect of temperature is minor (Clark and Fritz, 1997). Therefore, caution must be used in evaluating *d*-excess in precipitation and surface waters where elevation effects may be present.

Noting nearly constant δ^{18}O values inland from the Atlantic Ocean, and significant *d*-excess in yearly average precipitation in the Amazon Basin of up to 15.8‰, Salati et al. (1979) and Gat and Matsui (1991) suggested that much of the water was fractionated during evaporation then re-precipitated. An increase of 3‰ in the *d*-excess of precipitation at Manaus was interpreted to reflect a 20–40% contribution of fractionated moisture to the evapotranspiration flux in the Amazon Basin (Gat and Matsui, 1991). A similar effect has been identified in tropical Africa (Njitchoua et al., 1999), and downwind of Lake Michigan (Machavaram and Krishnamurthy, 1995). Identifying the sources of evaporated waters in tropical rainforests has been difficult (Martinelli et al., 1996), though likely sources of re-evaporated water include rivers, lakes, floodplains, soil moisture, and canopy interception. Fractionation of canopy interception-derived moisture will only occur if steady state has not been reached; i.e. a portion of the volume has been removed from evaporative conditions by some mechanism, such as rain-wash into the soil zone. To evaluate if recycled moisture could be an important component of the water budget in Costa Rica, we calculated *d*-excess for our samples by the equation $d = \delta D - 8\delta^{18}O$ (Daansgard, 1964). From the results contoured in Fig. 9, and presented in Table 2, it is apparent that nearly all of the surface water samples have a *d*-excess greater than the +10‰ typical of the GMWL. High *d*-excess values are found along the Nicaragua Trough on the Caribbean slope, and are plotted as a function of longitude along with δ^{18}O values in Fig. 10. These data show a linear increase ($r^2 = 0.68$) in the *d*-excess from the Caribbean coast inland with a gradient of 0.076‰/km. Lago Arenal has a considerably lower *d*-excess (9.6‰) than nearby water bodies (~16‰). The Nicoya Peninsula also demonstrates a trend to increasing *d*-excess from NE to SW with the lowest values near the more arid Tempisque lowlands (Fig. 9).

Elevated *d*-excess values may reflect either an evaporative flux component to the surface waters or decrease in condensation temperature. Most of the streams head in mountainous regions along the isthmian divide, but there is no correlation between *d*-excess and stream head elevation ($r^2 = 0.12$) or δ^{18}O ($r^2 = 0.13$) along this transect or in other regions. Additionally, the elevation of the divide decreases inland along the transect (Fig. 9), while the *d*-excess values increase, contrary to what would be expected if an altitude effect controlled *d*-excess values in the surface waters. This suggests that an altitude effect is not the dominant control on the *d*-excess values of our waters. Alternatively, the increase in *d*-excess along the transect is most easily explained by a contribution of a fractionated (evaporated) moisture flux along the transect. Therefore, we believe that the high *d*-excess values of surface waters suggest a significant amount of moisture along the Nicaragua Trough is recycled via evaporation and re-precipitation.

The linear increase in *d*-excess inland along the Nicaragua Trough suggests that evaporation/re-precipitation cycles occur repeatedly along the storm track. We postulate that the recycling may occur on a diurnal basis, with evaporation occurring during the morning hours following radiatively forced convection and precipitation during the afternoon and night. Further data are needed to substantiate the processes controlling moisture recycling in humid tropical environments. The low *d*-excess value of Lago Arenal suggests that the lake has undergone evaporation (supported also by heavy δ^{18}O and δD values discussed earlier) and is likely a source for recycled moisture for downwind areas. No other water bodies along the transect (Fig. 10; with the exception of the Rio Banano) have low *d*-excess values, suggesting that they are not sources of recycled moisture. Considering this, the source of recycled moisture along the Nicaragua Trough may come from evaporated soil moisture and/or water on plant surfaces, though we are not able to determine this with the available data. The trend on the Nicoya Peninsula may also reflect recycling of moisture evaporated over the Tempisque lowlands and precipitated over the Nicoya Peninsula.

The mix of ages and sources for the surface water and the large (3‰) analytical uncertainty for δD preclude calculations of the percent contribution of recycled moisture to the surface waters in our study. The use of previously developed models for calculation of the percent contribution of recycled moisture from free body evaporation are likely not applicable to tropical rainforests (Dawson and Ehleringer, 1998). As such, further investigations of monthly and yearly *d*-excess values in precipitation at stations along the transect are necessary to define quantitatively the percent contribution of fractionated recycled moisture to the region's water budget.

d-Excess trends have important implications for the water budget in Costa Rica. Most of the water bodies were sampled on the agricultural lowlands, but originate on the flanks of forested volcanic peaks. However, it is unclear with the available data whether the moisture recycling is occurring on the forested peaks or on the agricultural lands, and the signal likely represents a mixed source. If evaporation of soil water and water on leaf surfaces in forested areas is an important contributor to recycled water in the area, further deforestation may alter the evaporative flux component of the water budget.

5. Summary

Based on our sample data, we are able to characterize geographical variations in stable isotope values of surface waters in Costa Rica. We measured considerable variation in stable isotope values in surface waters, from −2.0 to −15.1‰ δ^{18}O and −9 to −105‰ δD. Correlation coefficients of δ^{18}O in surface waters against latitude, longitude, and various physical parameters such as sample elevation and distance from the Caribbean Sea are weak. However, several geographic trends emerge from the data, with heaviest values near the Caribbean Sea, and lowest values in the lee of the highest mountain ranges. Moisture recycling may be a significant component of the hydrological budget along the Nicaragua Trough. The decrease in δ^{18}O values in the lee of mountain ranges are proportional to the elevation of the ranges. In the lee of the Talamanca Range where the continental divide reaches elevations >3000 m, δ^{18}O values decrease by ~6–8‰ relative to upwind sites. A decrease in δ^{18}O values in the lee of the Tilarán Range (~1500 m-high volcanoes) is ~2–3‰. Surface waters on the Osa Peninsula are higher relative to the upwind areas, suggesting the input of Pacific-sourced moisture, a decrease in condensation temperatures, or perhaps evaporative enrichment.

The surface water isotope data presented here will benefit hydrologic and paleoclimatic studies in the region. The spatial and temporal trends of δ^{18}O and δD in tropical waters have several important implications for interpreting paleoclimate proxy records such as marl, gastropods, ostracods, and cellulose in lake sediment cores, and speleothems and ice cores. Proxy records may record changes in the value of the source water, in our case the Caribbean Sea and Pacific Ocean, or varying contributions of one versus the other. Because rainout of an air mass is an important control on the values of precipitation and surface waters, variations in a proxy may record the fluctuations in the strength of convection. Departures from the value of the source precipitation may arise during evaporative enrichment, which may vary as a function of climate forcing such as a decrease in convection or relative humidity, or an increase in wind speed and insolation. Mixing and isotopic homogenization of individual precipitation events will occur in groundwater reservoirs, such as feed the growth of speleothems in cave systems. As a result, cave deposits and sediment cores in groundwater-fed lakes may record changes in the average climate state. Additionally, variations through time of the *d*-excess parameter may be recorded in proxy records, and could provide insight into ancient water cycles and water recycling. Further research is needed to evaluate the controls on the spatial and temporal stable isotope values of precipitation, surface, and groundwaters in the humid tropics, to aid in the interpretation of paleoclimate proxy records.

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