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Low stable isotope ratios of tropical cyclone rains

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Abstract. Tropical cyclone rains have distinctly lower stable isotope ratios than rains in other tropical and summer precipitation systems, with a mean value slightly above that of water vapor near the sea surface. The isotope ratios also decrease radially inward to the eye wall, but appear to be anomalously low even near the periphery of the rain shield. These findings indicate that tropical cyclones are highly efficient precipitation systems and suggest the use of stable isotope ratios as dynamic tracers of a tropical cyclone's water and energy budgets.

Introduction

Tropical cyclones which include tropical storms and hurricanes are organized, violent storms that contrast strikingly with normal tropical weather. We present here the first surface-based measurements of isotope ratios ($^2H^1HO/^1H_2O$ and $H_2{}^{18}O/H_2{}^{16}O$) of rain in tropical cyclones. The stable isotope ratios of most rains in tropical cyclones are far lower than those in other tropical events. They generally display a decrease radially inward toward the eye wall. An earlier airborne study (Ehhalt and Östlund, 1970) of Hurricane Faith showed low isotope ratios for both rain and vapor.

Stable isotope ratios are presented here using standard δ notation [$\delta_x = (R_x / R_{SMOW} - 1) * 1000$], where R is the stable isotope ratio and SMOW is Standard Mean Ocean Water ($R_{SMOW} = .0020052$). The $\delta^{18}O$ values of almost all precipitation on Earth fall in the range, -50 to 0 per mil, with the lower values confined to the polar regions (Dansgaard, 1964). Most tropical and summer season rains fall at the high end of the range, or about -6 to 0 per mil (Dansgaard, 1964; Lawrence and White, 1991). Rains from tropical cyclones, however, almost invariably have $\delta^{18}O < -6$ per mil and therefore form a distinct population that has little overlap with the background tropical and summer rain signal.

The Observations

The comparison between oxygen isotope ratios of rains from tropical cyclones and from other storms from June through September is shown in the histogram of Fig. 1. One rain sample was collected and subjected to isotopic analysis from each of 166 storms that struck the University of Houston Coastal Center near Dickinson, Texas, about 50 km southeast of Houston from 1985 to 1992. In addition, 42 rain samples were collected in Texas from five tropical cyclones which made landfall in the western Gulf of Mexico between 1988 and 1993 (Table 1). Spatial suites of samples were collected from Hurricane Gilbert (1988) and Tropical Storm Arlene (1993), while 1 to 4 rain samples from a single location were collected from each of Tropical Storms Jerry (1989), Chantal (1989) and Allison (1989).

Fig. 1. shows that the isotope ratios of hurricane rains and of other tropical or summer rains represent two distinct populations with little overlap. The mean $\delta^{18}O$ value of the 166 rainfall events that exclude tropical cyclones is -2.9 per mil, with only 6 samples below -7 per mil. The mean $\delta^{18}O$ value of the 42 rain samples from five tropical cyclones is -9.4 per mil, with only eight samples above -7 per mil. Five of the tropical cyclone samples had $\delta^{18}O < -12$ per mil. This is close to the mean isotope ratio of water vapor along the Gulf Coast of Texas collected in Houston for 9 dates over the summer of 1990 (-12.3 ± 0.8 per mil). Such low values in precipitation are very rarely recorded near Houston even during the winter, and are much more likely to be found in snowstorms much farther to the north (Lawrence *et al.*, 1982).

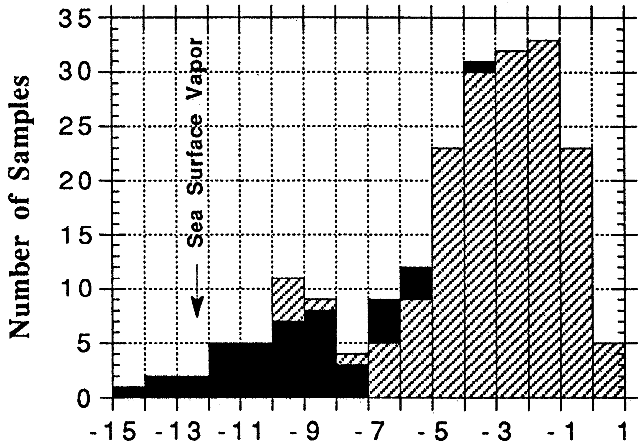

Figure 1. The distribution of $\delta^{18}O$ values of two sets of precipitation data. The first set shown in hatched design is a collection of all rain events for the summer months, June, July, August and September from 1985 to 1992 from the University of Houston Coastal Center near Dickinson about 50 kilometers southeast of Houston, Texas. The second set shown in black is a collection of precipitation samples from a hurricane and four tropical storms. The mean $\delta^{18}O$ value of vapor in Houston, Texas for 9 dates in the summer of 1990 is also shown.

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Independent confirmation of anomalously low stable isotope ratios in tropical cyclones was obtained from a second data set. Precipitation samples from all storms at Mohonk Lake, New York (elev. 400 m) from May, 1977 to December, 1983 were collected and analyzed for their δD values. Of 95 summer storm samples, two came from the remnants of tropical storms. Tropical Storm Dean registered δD = -89 per mil, equal to the lowest value, while Tropical Storm David registered δD = -47 per mil, 16th lowest of the samples (Lawrence and White, 1991). In addition, three sequential rain samples collected separately at City College in New York City (elev. 75 m) during Hurricane Bob in 1991 had δD values of -79, -94 and -104. These values are below or at the lowest end of summer rain samples from Mohonk despite their lower latitude and altitude (Lawrence and White, 1991).

Table 1. Oxygen Isotope Values of Tropical Cyclones

Sample[1] No.	Latitude	Longitude	Distance[2] (km)	Amount (mm)	$\delta^{18}O$[4]
HG1	28.72	96.45	480	17	-6.0
HG2	28.41	96.53	450	72	-7.0
HG3	28.32	96.93	425	49	-6.8
HG4	28.02	97.07	400	57	-7.0
HG5	27.63	97.23	350	41	-7.0
HG6	27.58	97.76	330	67	-8.8
HG7	27.28	97.66	310	3	-8.7
HG8	26.84	97.77	260	85	-5.5
HG9	26.54	97.44	240	7	-3.9
HG10	26.07	97.21	200	90	-5.9
HG11	26.16	97.81	180	205	-9.2
HG12	26.55	98.12	225	82	-6.9
HG13	26.39	98.83	190	?	-8.6
HG14	26.90	98.58	240	109	-8.6
HG15	27.29	98.68	280	78	-8.7
HG16	26.91	99.42	220	67	-10.5
HG17	27.50	99.46	270	52	-8.7
HG18	27.88	98.61	330	52	-6.2
TSJ1	29.38	95.06	170[3]	18	-9.1
TSC1	29.38	95.06	40	97	-11.6
TSC2	29.38	95.06	80	13	-8.7
TSAL1	29.38	95.06	210	33	-9.1
TSAL2	29.38	95.06	80	93	-9.9
TSAL3	29.38	95.06	50	2	-10.8
TSAL4	29.38	95.06	30	67	-10.3
TSAR0	29.77	95.64	330	197	-8.8
TSAR1	29.15	96.35	250	47	-9.2
TSAR2	28.83	96.93	170	121	-10.5
TSAR3	28.30	97.28	120	118	-11.8
TSAR4	27.85	97.64	70	55	-12.6
TSAR5	27.29	97.80	0	24	-11.6
TSAR6	26.94	97.79	30	42	-11.8
TSAR7	26.48	97.75	60	1	-11.7
TSAR8	26.54	97.44	50	29	-12.7
TSAR2.8	28.78	97.03	180	spot	-9.7
TSAR3.3	28.19	97.38	130	spot	-7.6
TSAR4.2	27.75	97.70	50	spot	-9.5
TSAR4.8	27.43	97.85	20	spot	-9.6
TSAR6.3	26.80	97.77	50	spot	-10.9
TSAR7.1	26.48	97.75	80	spot	-14.3
TSAR8.2	26.54	97.44	50	spot	-13.7
TSAR8.1	26.54	97.44	70	spot	-13.5

1 HG=Hurricane Gilbert, TSJ=Tropical Storm Jerry, TSC=Tropical Storm Chantal, TSAL=Tropical Storm Allison, TSAR=Tropical Storm Arlene.

2 The minimum distance between the station and the storm track during the period of sampling. This gives a different meaning to spot samples and samples taken over a long time period, during which the storm may have moved a large distance.

3 Maps showed that rain fell at Galveston and Jerry approached closer after the announced sampling period.

4 The precision of repeated analyses of a laboratory isotope standard is better then ± 0.1 per mil.

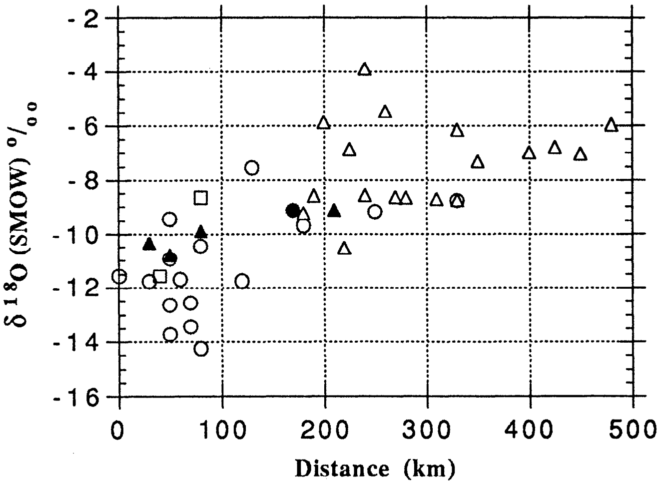

Figure 2. The oxygen isotope values of precipitation from Hurricane Gilbert (open triangle) and Tropical Storms Allison (filled triangle), Chantal (open box), Jerry (filled circle) and Arlene (open circle) plotted as a function of the closet approach of the storm to the collection site during the sampling period.

The stable isotope ratios of rains from tropical cyclones in Texas decreased radially inward as seen in Fig. 2 where the $\delta^{18}O$ ratio of all 42 tropical cyclone samples is plotted as a function of minimum distance from locus of the storm track. Below average values for summer rains occurred near the outer periphery of the rain shield. From there they decreased radially to extremely low values near the eye wall. Any sample taken within 100 kilometers of the storm center invariably had a $\delta^{18}O$ value less than -8.7 per mil.

The inward decrease of isotope ratios emerged clearly despite large variance in the data and despite the existence of considerable heterogeneity in the sampling (Table 1). For example, much of the 110 mm of rain from the two samples from Tropical Storm Chantal fell from the eye wall cloud near the storm center or an inner rain band while the rain from Tropical Storm Jerry fell in an outer rain band and at a mean distance considerably greater than the minimum distance. In addition for Tropical Storm Arlene, there were eight spot samples lasting only two minutes apiece ($\delta^{18}O$ = -11.1 ± 2.5 $^{o}/_{oo}$) , while all other samples represent total accumulations from the entire storm ($\delta^{18}O$ = -11.2 ± 1.4 $^{o}/_{oo}$). The greater variance in the spot samples may be a result of variations due to transient convective elements. Ehhalt and Östlund (1970) documented the existence of mesoscale structure of isotope ratios within Hurricane Faith. They found much lower isotope ratios in the rain and vapor just outside the core of the rain bands and the eye wall cloud than in the surrounding regions of light rain.

Our data do not provide a sufficiently detailed picture to extract other definitive relations between tropical cyclone structure and its stable isotope ratios. Rain in the eye wall clouds could not be distinguished from rain in showers or rain bands on the basis of their $\delta^{18}O$ values. Cloud top height was so variable, particularly in Tropical Storm Arlene, that it could not be simply related to isotope ratio. No consistent relation between isotope ratio and storm intensity was de-

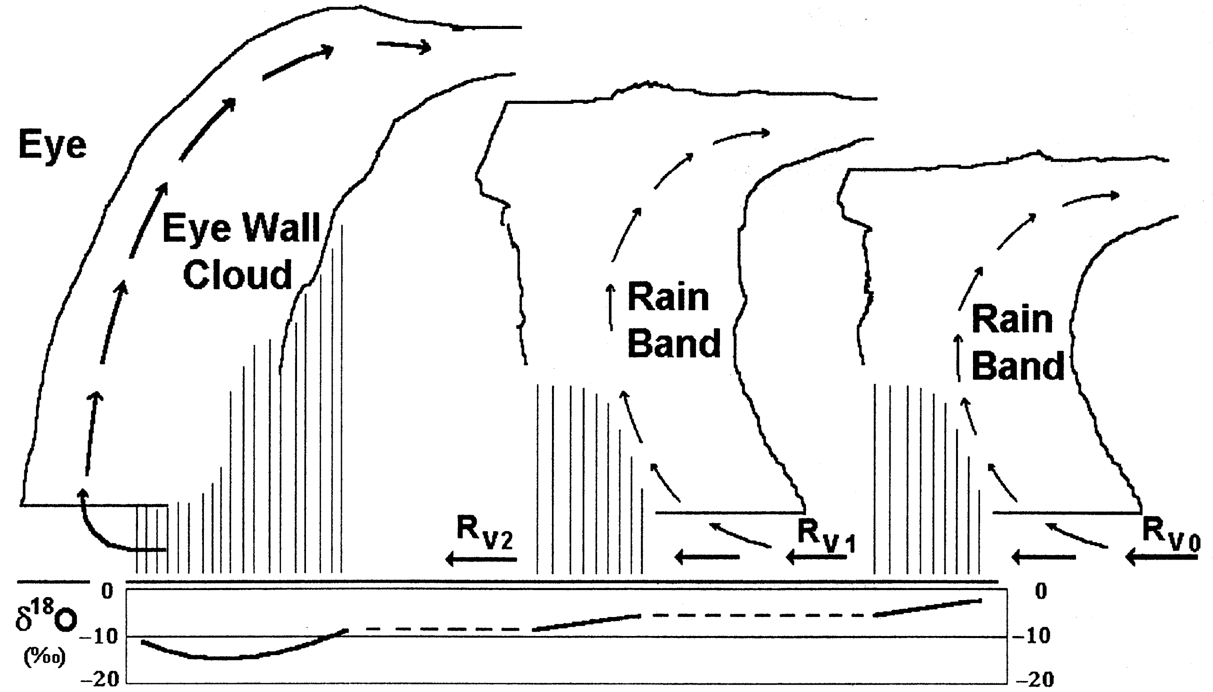

Figure 3. A schematic diagram based on a computer model (Gedzelman and Arnold, 1994) modified to simulate oxygen isotope ratios in hurricanes. Note that the model simulates oxygen isotope ratios of vapor and rain which decrease radially inward. The spatial relationship for the vapor is $R_{V2} < R_{V1} < R_{V0}$. The $\delta^{18}O$ value of the rain is shown at the bottom. The model does not, however, explain low isotope ratios near the periphery of the rain shield.

tected, perhaps because none of the storms was a major hurricane at peak strength. Only Gilbert represented a strong hurricane, but by the time it made landfall along the northeast coast of Mexico, it was the rapidly dissipating remnants of a once great storm. Furthermore, the storm's most intense and continuous rain fell farther to the south in Mexico where no samples were collected.

All samples from Gilbert came from outer rain bands more than 180 km from the storm center. One station registered $\delta^{18}O$ = -3.9 per mil, the highest of all 42 tropical storm and hurricane rain samples despite being located only 240 km from the storm track. This station experienced only an isolated light shower (7 mm). By overlaying a trajectory of the air passing beneath that shower on radar charts, it was apparent that the air had not previously encountered any other showers. Thus, despite the station's rather small distance from the storm track, it was effectively located at the extreme outer edge of the storm's precipitation shield where isotope ratios tend to be highest.

Principles of Stable Isotope Meteorology of Tropical Cyclones

The patterns and values of stable isotope ratios of precipitation and water vapor in a number of different storm systems have been explained by applying the basic physical laws governing isotope separation to the particular meteorological situations (Dansgaard, 1953; Federer *et al.*, 1982; Gedzelman and Lawrence, 1982; Gedzelman *et al.*, 1989; Gedzelman and Lawrence, 1990). By extending these principles to the generic structure of tropical cyclones both the low mean value and the radially inward decrease of stable isotope ratios of tropical cyclone rains can also be explained.

Stable isotope ratios of precipitation and water vapor are governed by fractionation during phase change and by diffusive isotope exchange between rain and vapor. Heavy isotopes have lower saturation vapor pressures and also evaporate more slowly than normal water. As a result, the heavy isotopes are less concentrated in vapor than in the sea water from which they derive. Condensation in an air parcel further reduces the isotope ratio of the remaining vapor by preferentially removing the heavy isotopes as snow or rain. Isotope ratios of vapor and condensate therefore both decrease sharply with height (Dansgaard, 1953, 1954; Ehhalt and Östlund, 1970; Ehhalt et al., 1980; Taylor, 1984).

Falling rain becomes enriched in the heavy isotope as it falls as a result of evaporation and diffusive isotope exchange with isotopically heavier vapor near the ground (Miyake, et. al., 1968). This process ensures that most rain reaches the ground with higher isotope ratios than the initial rain at cloud base. But this exchange process also lowers the isotope ratio of the ambient vapor near the ground with time, which in turn leads to a temporal decrease of isotope ratios of rain during a storm. This is one example of the so called amount effect, in which isotope ratios of rain are negatively correlated with total rainfall amounts (Dansgaard, 1964).

In relatively long-lived storm systems such as tropical cyclones, the total mass of rain produced far outweighs the mass of vapor in the storm at any time so that the mean isotope ratio of the rain depends on the condensation efficiency and therefore on the thickness of the clouds. Because many fully developed tropical cyclones have clouds whose tops reach 15 km, most vapor condenses, and the mean $\delta^{18}O$ value of the rain should approach that of the source vapor. Vapor collected in the summer of 1990 in Houston which was derived from the surface waters of the Gulf of Mexico had a $\delta^{18}O$ value equal to -12.3 per mil. A recent study by Samsury and Zipser (1995) indicates the presence of substantial convergence from

900 to 600 mb in many rain bands. This would mean a more elevated vapor source with a $\delta^{18}O$ value lower than -12.3 per mil because of the normal vertical gradient of isotope ratios (Ehhalt and Östlund, 1970; Ehhalt et al., 1980). Given these facts it is not surprising that stable isotope ratios in tropical cyclones are low.

We have developed a hypothesis for the inward decrease of isotope ratios of rain in tropical cyclones that is based on recycling of water. As the air in the atmospheric boundary layer passes beneath each rain band, falling hydrometeors evaporate and undergo diffusive isotopic exchange with surrounding vapor reducing its isotope ratio. For a series of rain bands in a tropical cyclone this process results in a sequential lowering of isotope ratios of both vapor and rain. A simplistic picture of this process is shown in Fig. 3 in which the rain bands are drawn using the dynamics of air flow described by Anthes (1982). A similar lowering of isotope ratios would also be produced using the model of Powell (1990a, 1990b) in which rain bands produce a mixture of convective and stratiform precipitation. This model differs in that a significant portion of the rain falls radially outward from the rain band. The recycling process in this instance more closely matches that that shown for the eyewall in Fig. 3.

Summary and Conclusions

Rain samples collected during five hurricanes or tropical storms that made landfall on or near Texas possess anomalously low stable isotope ratios which decrease radially inward to values below that typical of the vapor near sea level. We attribute the low mean value of the isotope ratio to the storm's high condensation efficiency. We hypothesize that evaporation and diffusive isotope exchange between inflowing vapor and falling rain from rain bands lead to the inward decrease of isotope ratios. This recycling of water appears to be significant compared to evaporation from and isotopic exchange with the sea surface.

These observations and conclusions treat only the gross properties of isotope ratios in tropical cyclones and need to be investigated in much greater detail. We remain puzzled by a number of features such as the low isotope ratios even in storms such as Arlene, which exhibited little coherent structure, and also by the low isotope ratios quite near the outer fringe of the tropical cyclones' rain shields. We have not begun to treat the potentially important effects of mesoscale variability, asymmetry, unsteady storm development and motion, changes of source waters upon landfall, and the effects of microphysical sorting of liquid and solid hydrometeors. Our existing data sets also fall far short of what is needed for a fuller understanding. As a result, we have begun a program to obtain detailed temporal and geographical records of the isotope ratios for individual tropical cyclones, which includes isotope data above ground level and for the vapor entering the storm.

The potential payoffs of monitoring and understanding the isotope ratios of rain and water vapor in tropical cyclones are considerable. Because isotope ratios are so low, increased tropical cyclone activity in the geologic past might be detectable by undertaking oxygen isotope studies of ancient cave deposits or fresh water fossils. For the subtropics and possibly the middle latitudes the isotope ratio of rain from tropical cyclones represents a natural isotopic spike into the soil water/ground water system which could be utilized by hydrologists. Finally, isotopes may provide a much needed handle for evaluating a tropical cyclone's water budget by providing information about data sparse regions such as the inner regions of the tropical cyclone near the sea surface and in the upper-level stratiform clouds.

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