7B.4

STABLE ISOTOPE RATIOS OF RAIN AND WATER VAPOR IN HURRICANES IVAN (2004) AND KATRINA (2005)

James R. Lawrence and **Sergio Sarmiento**
Department of Geosciences
University of Houston
and
Stanley David Gedzelman* and **Kwan-yin Kong**
Department of Earth and Atmospheric Sciences and NOAA CREST Center
City College of New York

1. INTRODUCTION

Ivan (2004) and Katrina (2005) are the first intense hurricanes at landfall for which stable isotope ratios (HDO:H_2O and $H_2{}^{18}O$:$H_2{}^{16}O$) of rain and water vapor were sampled from the edges through the eye or eye wall. Isotope ratios are expressed in δ terminology as the deviation of the sample from Standard Mean Ocean Water (SMOW) in parts per thousand. Thus,

$$\delta^{18}O = 1000\left[\frac{(^{18}O:^{16}O)_{sample}}{(^{18}O:^{16}O)_{SMOW}} - 1\right]$$

Because hurricanes act as fractionation chambers, isotope ratios of rain and water vapor contain much information about storm structure, evolution, and water budget. Heavy isotopes concentrate in rain and snow and are removed from the rising air. Thus, isotope ratios decrease with height. Falling rain sweeps additional heavy isotopes from vapor in the converging air of hurricanes near the surface by diffusive exchange. Lawrence et. al. (1998) showed that as a result, $\delta^{18}O$ values of rain and vapor at ground level in hurricanes and tropical storms decrease by up to 15‰ from typical tropical values (-1 to -5‰ for rain and –11 to -15‰ for vapor) at the outer edge of the rain shields to the central dense overcast. However, isotope ratios 1: increase at the inner edge of the eye wall where clouds slope outward and rain originates in the lower troposphere (Ehhalt and Östlund: 1966) and, 2: are higher to the right of the storm track when air has not passed through much rain upwind, as in Opal (1995).

Evaporation of spray and spume generated in high wind regions over open waters and/or diffusive isotope exchange between spray and the ambient vapor restore heavy isotopes to the vapor. This increases isotope ratios at ground level to the right of the storm track at landfall, where air comes from the sea (Gedzelman, et. al.: 2003, Lawrence, et. al, 2004) to abnormally high values ($\delta^{18}O$ > -8‰) before steady rains set in.

* Corresponding Author Address: Stanley David Gedzelman, Department of Earth and Atmospheric Sciences, City College of New York, New York, NY 10031, Email: sgedzelman@ccny.cuny.edu

2. RESULTS

As is shown below, $\delta^{18}O$ values of rain and water vapor samples collected along the Gulf Coast in Hurricanes Katrina and Ivan were much higher than in most other hurricanes and tropical storms. During Katrina, rain and water vapor samples were collected at 1: Slidell, LA and, 2: near Mobile AB (30.59 N, 88.18 W). $\delta^{18}O$ values deep in the storm were no more than 5‰ lower than normal (Fig 1). At both stations, $\delta^{18}O$ values remained very high until rain spread over the entire region. Prior to 1200 UTC, Mobile remained at the outer edge of widely spaced rain bands so that air below 500 m encountered little rain upwind (Fig. 2). Omega profiles from WRF model runs (not shown) indicate that most condensation occurred in the lower troposphere.

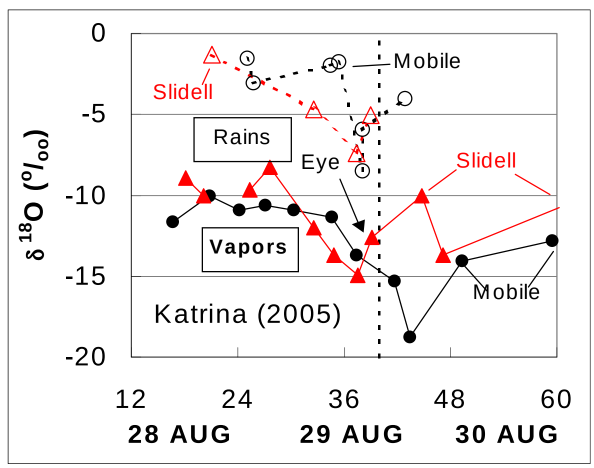

Figure 1. $\delta^{18}O$ values of rain (light curves and hollow symbols) and vapor at Slidell LA (triangles) and near Mobile, AB (circles) during Hurricane Katrina. The vertical line at 1600 UTC on 29 Aug shows the time Katrina passed between the stations at 30.5 N, 89.6 W.

At 1855 UTC, after Katrina moved inland a final rain shower had $\delta^{18}O$ = -4.0‰. This was far above isotopic equilibrium with the vapor sample collected over the next hour ($\delta^{18}O$ = -18.5‰). The low vapor value is consistent with the back trajectory, which had circled the storm and passed through much rain, but only significant evaporation of the falling rain can account for its anomalously high $\delta^{18}O$ value.

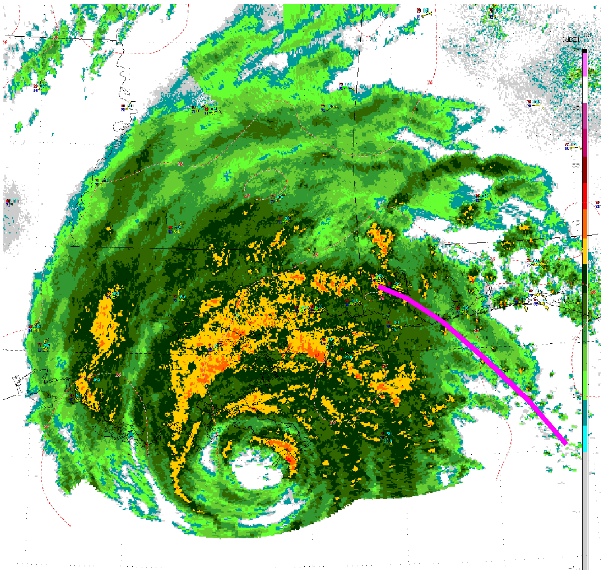

Fig. 2. WSR88 image of Katrina at 0950 UTC 29 AUG 2005. Back trajectory (purple line) from NOAA ARL HYSPLIT ending at 500 m near Mobile encountered little rain upwind.

At Slidell, $\delta^{18}O$ values were quite high until about 0400 UTC on the 29th, when rain overspread the region. Two vapor samples with very high $\delta^{18}O$ occurred during strong NE winds (with gusts to 27 knots) both prior to and during a break in the rain. Spray may have been generated in the swamps a short distance to the NE. But even after heavy rains set in, $\delta^{18}O$ values never fell much and began increasing about 2 to 3 h prior to passage of the eye, where vapor had a typical value outside hurricanes ($\delta^{18}O$ = -12.6‰). Hurricane force SE winds from the Gulf indicate that spray lifted $\delta^{18}O$ values during the height of the storm.

In Hurricane Ivan, $\delta^{18}O$ values of whole storm rains on the Gulf Coast (Fig. 3) were, as in Opal (1995) higher east of the storm track where winds came from the sea and air encountered less rain, but more spray.

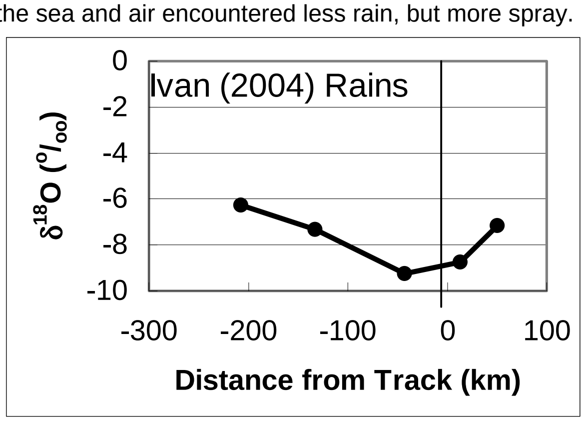

Figure 3. $\delta^{18}O$ values of whole-storm rains across Hurricane Ivan's (2004) track (vertical line) at 30.5 N.

During Ivan, vapor and rain samples were collected at Pensacola, FL (30.30 N, 87.22 W), 4 km west of Pensacola Bay. As Ivan approached, $\delta^{18}O$ values of rain decreased almost monotonically, while vapor $\delta^{18}O$ values oscillated widely between –6‰ and –13.5‰ for reasons we cannot explain. After 1200 UTC on the 15th ENE winds increasing from 20 knots to hurricane force were fast enough to generate spray over the Bay.

A second suite of rain samples was collected on a track from Macon to Calhoun, GA. There, more than 300 km inland, rain washed out any impact from spray. $\delta^{18}O$ values were high at the outer edge of the rain shield (as is typical) but fell to –12.7‰ near the center of circulation (4‰ below the lowest value at Pensacola) and remained below –10‰ despite shallow, light rains as the center of circulation passed by early on the 17th.

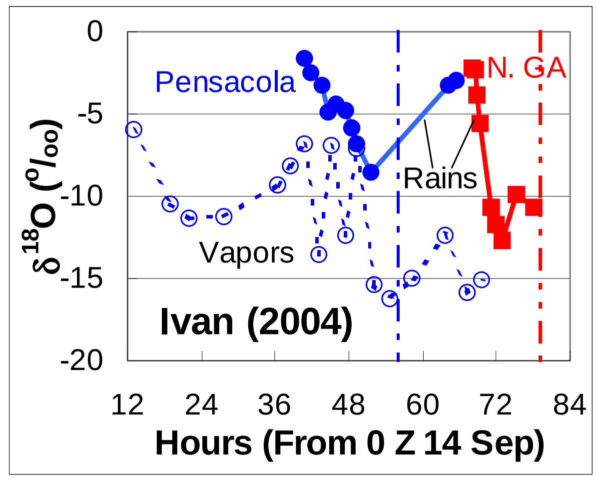

Figure 4. $\delta^{18}O$ values of vapor (hollow circles) and rain (solid circles) at Pensacola, FL (blue 30.50 N 87.22 W) and of rain in north Georgia (red squares) in Hurricane Ivan. Vertical lines show when Ivan passed north of the stations.

We conclude that the small depletion of ^{18}O of rain and vapor along the Gulf Coast when air came off the sea surface during Hurricanes Katrina and Ivan imply sea spray as a major source of water for hurricanes.

ACKNOWLEDGEMENTS

This research was supported by grants from NOAA CREST, PSC CUNY, the Texas HEC Board, and EIH.

REFERENCES

Ehhalt, D., and H. Östlund, Deuterium in Hurricane Faith, 1966: Preliminary results. *J. Geophys. Res*. **75**, 2323-2327, 1970.

Gedzelman, S., J. Lawrence, J. Gamache, M. Black, E. Hindman, R. Black, J. Dunion, H. Willoughby, and X. Zhang, 2003: Probing hurricanes with stable isotopes of rain and water vapor. *Mon. Wea. Rev.*, **131**, 1111-1127.

Lawrence, J., S. Gedzelman, X Zhang, and R. Arnold, 1998: Stable isotope ratios of rain and vapor in 1995 hurricanes. *J. Geophys. Res.*, **103**, 11381-11400.

Lawrence, J., S. Gedzelman, D. Dexheimer, H. Cho, G. Carrie, R. Gasparini, C. Anderson, K. Bowman, and M. Bigerstaff, 2004: Stable isotopic composition of water vapor in the tropics. J. Geophys Res. 109, D06115.