1. INTRODUCTION

Ivan (2004) and Katrina (2005) are the first intense hurricanes at landfall for which stable isotope ratios (HDO:H2O and H218O:H216O) 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,

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

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, δ18O 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 (Ehnhart 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 when air has not passed through much rain upwind, as in Opal (1995).

As is shown below, δ18O 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). δ18O values deep in the storm were no more than 5‰ lower than normal (Fig 1). At both stations, δ18O 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.** δ18O 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 δ18O = -4.0‰. This was far above isotopic equilibrium with the vapor sample collected over the next hour (δ18O = -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 δ18O value.
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.

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 $-6.5\%$ 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.

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.

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REFERENCES


