

## 6.3 OBSERVED INTEGRATED MOISTURE FIELDS WITHIN TROPICAL STORM SYSTEMS

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### 1. INTRODUCTION

Hurricanes, or more generally tropical cyclones, are commonly described as heat engines, using energy from warm ocean surfaces to create intense atmospheric circulations and winds. The transfer of this energy occurs primarily through the evaporation of water into the atmosphere. Observationally, there are relatively few instruments that can accurately measure water vapor in the presence of clouds and rain. Retrievals of precipitable water vapor (PW) using Global Positioning System (GPS) stations may be the most reliable way to continuously monitor column integrated water vapor. We use the Suominet network of GPS stations to investigate the variability of PW when Atlantic basin tropical storm systems make landfall. Wind speeds and minimum surface pressure data from 22 landfall events are analyzed to identify differences in storm intensity as a function of atmospheric moisture. A strong linear correlation ( $> 0.7$ ) is found linking total atmospheric moisture to storm intensity. These findings suggest that an expansion of GPS stations into the Caribbean and the Gulf of Mexico may improve the forecasting of future storms, particularly storm intensity.

### 2. HURRICANE INTENSITY FORECASTING

Atlantic basin hurricanes display a multi-decadal variability, with the current increase in intense hurricanes (greater than 2 on the Saffir-Simpson scale) beginning in 1995 (Landsea et al., 1999). It is expected that hurricane seasons will remain relatively active for at least the next 5-10 years. Advances in observational technology (such as dropsondes and

geostationary satellite observations) and numerical weather prediction have improved the forecasting of hurricane tracks, but there has been relatively little improvement in forecasting hurricane intensities. Research indicates that intensity forecasts are exceptionally sensitive to moisture observations. Hou et al. (2001) has shown an improvement in tropical forecasts when PW is assimilated from satellite microwave sensors (TRMM and SSM/I), and Kaminen (2003) has shown a direct improvement in hurricane forecasting when water vapor profiling data are assimilated. Studies such as these reinforce the role for accurate and reliable moisture data sets in tropical storm forecasts.

### 3. REMOTE SENSING OF THE ATMOSPHERE WITH GPS

Networks of ground based GPS stations are now routinely being used to estimate PW (Rocken et al., 1997; Wolfe and Gutman, 2000). The data collected from these stations are used to relate the delay of the GPS signal as it propagates through the atmosphere to the integral of water vapor density (Bevis et al., 1992; Rocken et al., 1995; Rocken et al., 1991). The delay of the signal in the zenith direction, called zenith total delay or ZTD, is equivalent to the vertical integral of atmospheric refractivity ( $N(z)$ ).

$$(1) \quad ZTD = 10^{-6} \int N(z) dz$$

Refractivity is a function of atmospheric pressure ( $p$ , [hPa]), vapor pressure ( $e_w$ , [hPa]) and temperature ( $T$ , [K]) and is approximated by equation (Smith and Weintraub, 1953).

$$(2) \quad N \approx 77.6 \left( \frac{p}{T} \right) + 3.73 \times 10^5 \left( \frac{e_w}{T^2} \right)$$

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This relationship between refractivity and atmospheric composition is considered accurate to approximately 0.5% (Bevis et al., 1994). The ZTD can be considered to be a sum of two terms; a zenith hydrostatic delay (ZHD) and a zenith wet delay (ZWD). The ZHD can be calculated and eliminated from the ZTD using a surface pressure measurement, and the assumption of hydrostatic equilibrium. The remaining ZWD can then be scaled into PW based on a simple conversion factor.

$$(3) \quad PW = \Pi \cdot ZWD$$

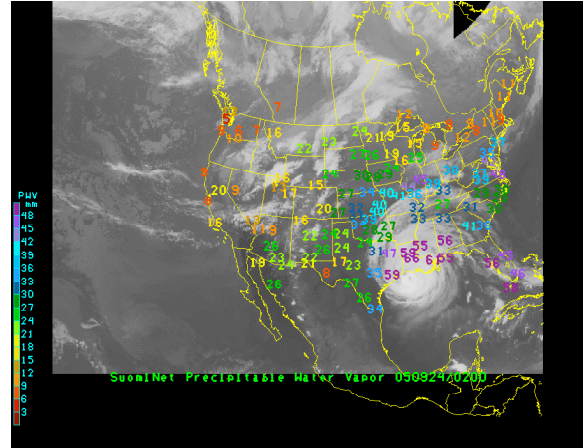
The factor  $\Pi$  is a function of the mean atmospheric temperature and is typically around 0.15 (Bevis et al., 1994). As an approximate rule of thumb, each 6.5 mm in ZWD corresponds to 1 mm in PW.

The COSMIC program at the University Corporation for Atmospheric Research (UCAR) uses data collected from various government and university agencies to estimate PW at more than 250 stations in the continental United States (Ware et al., 2000). These data have been assimilated into numerical weather prediction models; they have been used to study spatial and temporal differences in moisture fields; and to calibrate satellite and radiosonde observations.

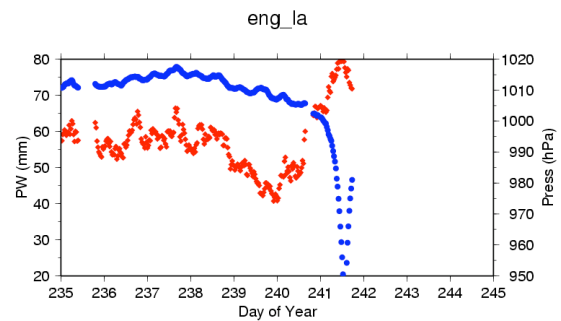
#### 4. GPS PW RETRIEVALS IN THE PRESENCE OF HURRICANES

An example of GPS PW retrievals is illustrated in Figure 1. This image shows the visible GOES image as Hurricane Rita approaches the gulf coast in 2005. The color-coded numbers plotted on the image represent the PW at individual GPS stations. This image illustrates a fundamental strength of GPS; it is generally insensitive to heavy clouds and precipitation. This makes the technology especially useful to study moisture fields in complex environments like thunderstorms and hurricanes.

A time series of PW (red) and surface pressure (blue) is shown in Figure 2 at English Turn, LA as Hurricane Katrina moved over the station. The time series end when the power and communications at the station failed. The increase in PW (by a factor of ~2) is commonly observed at stations within the general vicinity of hurricane storm systems.

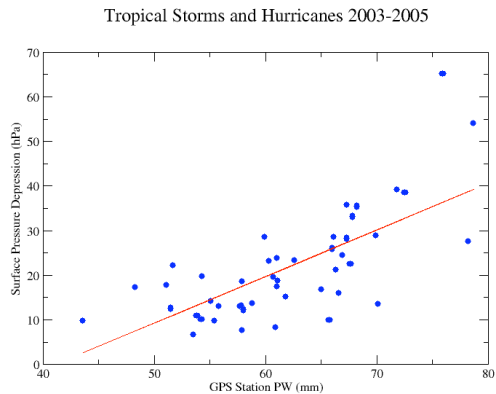


**Figure 1: Visible GOES image and color-coded PW estimates from the SuomiNet analysis on Sept 24, 2005 at 0200UTC. The official time of landfall for Hurricane Rita was 0740UTC.**



**Figure 2: Estimates of GPS PW (red) and observed surface pressure (blue) at English Turn, LA as Hurricane Katrina made landfall.**

GPS results from 2003-2005 were used to investigate the relationship between PW and tropical storm intensity. Landfall records from the National Hurricane Center ([www.nhc.noaa.gov](http://www.nhc.noaa.gov)) were used to match GPS data from stations that were within 200 km of the landfall location. Within this data set there were 22 landfall events, from 17 named storm systems, and 51 GPS stations. A scatterplot of PW and surface pressure depression is shown in Figure 3. The linear correlation of the data in this scatterplot is 0.71. This relatively high correlation shows the direct relationship between storm strength and atmospheric moisture.



**Figure 3: Scatterplot comparing GPS PW for stations within 200 km of landfall and surface pressure depression.**

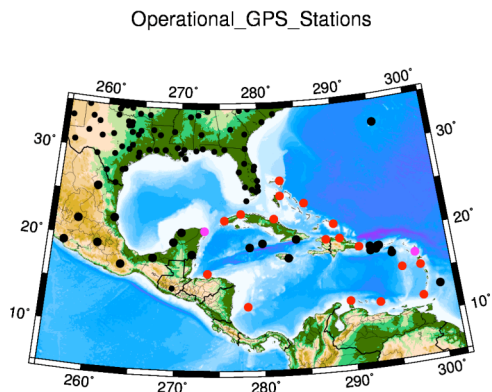
### 5. NETWORK EXPANSION INTO THE CARIBBEAN

The National Science Foundation has recently funded the COSMIC Program to install an additional 15 GPS stations in the Caribbean. The data collected from these stations will be used for two scientific applications. First, the data will be analyzed in near real-time to retrieve PW at half hour increments. Second, the positions of these stations will also help to monitor the geodetic deformation of the region to help understand the deformation of the Caribbean plate. A map of proposed station locations is shown in Figure 4. The red and purple dots represent locations where we are in contact with local researchers to host stations. The black dots represent existing station locations that will be included in the analysis. These data will be incorporated into the standard Suominet analysis and be made publicly available through the local data management (LDM) distribution system.

### 6. SUMMARY

Advances in observational technology and numerical weather prediction have advanced the forecasting skill of hurricane tracks, but intensity forecasts have shown less improvement. One possible reason is a paucity of moisture observations. GPS stations provide continuous, and all weather observations of the integral quantity PW. A comparison of GPS PW retrievals within 200km of hurricane landfall shows a significant correlation between PW and surface depression. This high correlation implies that the expansion of Suominet into the

Caribbean should improve the forecasting of hurricane strength. This network expansion will occur over the next twelve months.



**Figure 4: Map of operational GPS stations (black), and the proposed locations of new stations (red and purple) within the Gulf of Mexico and Caribbean.**

### 7. ACKNOWLEDGEMENTS

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