Correlating Atmospheric Water Vapor and Hurricane Development

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ABSTRACT
Research has indicated that there may be a relationship between water vapor and hurricane development; however, traditional methods of measuring water vapor lack the accuracy necessary to make direct correlations. In this study, GPS water vapor data from areas near the point of landfall of hurricanes that occurred between 2003 and 2005 were obtained and correlated to other hurricane elements such as wind speed and pressure. Findings included indications of a direct relationship between the amount of water vapor in the atmosphere and hurricane intensity. This demonstrates the need to include water vapor data in hurricane forecasting models.

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1. Introduction

a. Water Vapor and Hurricanes

The formation of hurricanes requires three conditions: warm water, water vapor, and converging winds. Converging winds cause a group of storms to rotate, increasing its intensity and emitting water vapor into the air. The energy released when this water vapor condenses to liquid water, or the latent heat of condensation, helps increase wind speeds around the storms. The storms come together and form a center point of low pressure. This center point becomes the eye of a hurricane. Water vapor continues to fuel the hurricane through condensation and the associated release of energy.

Understanding weather and climate requires understanding the distribution of water vapor [Businger, et al., 1996]. Rapid increases of the water vapor in the atmosphere typically precede thunderstorms. Decreases of water vapor are associated with passing cold fronts. Because of its role in hurricanes, water vapor may also play an important role in the modeling and forecasting of hurricanes. Accurate measurements of water vapor are needed as a result.

b. Water Vapor Measurement

There are several methods of measuring water vapor. Hygrometers are the oldest method. They are fairly simple devices, first used in 1783, and long records are available as a result. Meteorologists use modern hygrometers to take daily measurements of humidity. The current models can measure the vapor with fairly high accuracy, but they are only able to make point measurements. A hygrometer positioned on the ground can only measure the surface humidity, which can vary significantly from that of the atmosphere. They are expensive and therefore used at selective locations; data across large regions is not available.

Radiosondes are instruments carried into the atmosphere by weather balloons. They send atmospheric measurements to data centers through a radio transmitter. They are inexpensive and can be used frequently, but are disposable (one time use) and must be purchased again and again, resulting in high cost. There is a global network of radiosonde data and records that date back to the 1930s. Depending on the brand, the measurements can be very accurate in the lower troposphere, but not in the upper troposphere and stratosphere. Humidity extremes affect its accuracy.

Radiometers are instruments that measure the amount of water in a vertical column above the machine by measuring the brightness temperatures of the air. Ground-based radiometers produce high temporal resolution (expression of data through time) but poor spatial resolution (expression of data through space). Space-based radiometers produce high spatial resolution but poor temporal resolution, and they work well over oceans, but poorly over land [Rocken, et al., 1993].

Light sensors are another method of measuring water vapor. Infrared sensors such as the National Oceanic and Atmospheric Administration’s (NOAA) TIROS Operational Vertical Sounder (TOVS) measure infrared radiation emitted by the earth (www.cpc.ncep.noaa.gov). Infrared sensors are able to gather column vapor data as well as information across large areas. On the downside, they can only be used in cloud-free areas, and the vertical resolution (perception of the vertical location of the concentrations of vapor) is poor. Microwave sensors detect the microwave radiation from the earth. They produce column water vapor data over large areas in all weather conditions, and are
not affected by clouds. However, they are only useful over ice-free oceanic regions, and as with the infrared sensors, the vertical resolution is poor.

The Global Positioning System is the newest way to measure water vapor in the atmosphere. Its 99% accuracy is comparable to that of the best radiometers and radiosondes [Businger, et al., 1996]. Weather conditions do not affect its precision. GPS is remarkably able to measure water vapor during precipitation and to differentiate water vapor from clouds, water, and ice. The only real disadvantage of ground-based GPS is the difficulty in obtaining vertical resolution. However, this can be solved through the use of space-based GPS occultation methods. Another disadvantage is that currently it can only be used on land. In the future, receivers will likely be placed on buoys in large bodies of water so that water vapor measurements can be obtained over oceans and gulfs. There also clearly exists a lack of history and long-term records; GPS is not yet useful in the observation of long-term trends.

c. More on the Global Positioning System

The Global Positioning System was developed by the United States Department of Defense. It consists of twenty-four satellites that orbit the earth in twelve-hour periods. GPS receivers on the ground receive L-band radio signals from the satellites orbiting the earth. GPS signals are typically used to determine the position and velocity of an object. The signals are now being used to measure water vapor in the troposphere.

When a signal is sent from a GPS satellite to a receiver, it theoretically travels at the speed of light. Based on the distance between the receiver and the satellite, the time of the signal travel can be calculated. The real time of travel is actually slower, and this difference is due to several factors. The accepted speed of light is the speed of light in a vacuum; however, the atmosphere is not a vacuum. Water vapor in the troposphere, among other matter, delays the arrival of the signal. In contrast to other molecules in the atmosphere, the composition of water bends the radio signal and delays it even more than the sole obstruction of the signal’s path [Businger, et al., 1996]. This delay of the signal, or “wet delay,” is proportional to the water vapor along its path and can be used to determine the integrated amount of water vapor in the atmosphere.

d. Previous Research

Previous research has paired water vapor data with hurricane development, but GPS was not used. NASA developed a program called the LIDAR Atmospheric Sensing Experiment (LASE) to take vertical profiles of the atmosphere using Laser Infrared Detection and Ranging (LIDAR). The Differential Absorption LIDAR (DIAL) instrument uses the profiles to determine the amount of water vapor in the atmosphere. The system has accuracy of 94% in the troposphere. LASE water vapor data were used in 2001 to model and predict the behavior of hurricanes Erin, Humberto, and Gabrielle. Models and predictions not using the water vapor data were also developed for use as a control. After the hurricanes, both models were compared to the actual intensities and tracks. Typical track error in three-day forecasts is 200 kilometers. The predictions made from the model that included water vapor data reduced track error by 100 km. There was also nearly a 25% improvement in predicted intensity error [Kamineni, et al., 2003], which is on average 20 miles per hour.
Because LASE uses infrared light, it is ineffective in the presence of cloud cover. The water vapor data from LASE was incomplete as a result [Kamineni, et al., 2003]. The models may have been more accurate in track and intensity predictions had the gaps in the data been filled. GPS possesses the capability to do just that. There are no limitations in the areas that GPS can measure. Better water vapor data will allow scientists to further investigate the relationships between water vapor and hurricanes.

e. Summer Research

This summer’s research was a preliminary step in that investigation. Water vapor data from areas near hurricane landfalls that occurred between 2003 and 2005 were used to make correlations between water vapor and the elements of hurricanes, such as wind speed and pressure. Hurricane elements were also explored with their position relative to the storm eye (north, south, east, and west).

2. Methods

a. Obtaining Data

This research was conducted in the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) division of the University Corporation for Atmospheric Research (UCAR). The COSMIC division maintains a national network of GPS stations called SuomiNet. SuomiNet is funded by the National Science Foundation with the goal of providing real time, atmospheric data. It provides data from numerous locations at frequent time intervals, yielding high spatial and temporal resolution.

Data pertaining to hurricanes that reached land between 2003 and 2005 were obtained from the National Hurricane Center (www.nhc.noaa.gov). Collected data included the hurricane name, date and time, latitude and longitude coordinates, wind speed, and pressure of each hurricane at landfall. SuomiNet, NOAA’s Forecast Systems Lab, the US Coast Guard, the Army Corps of Engineers, the USDOT, and the state DOT’s of the Gulf and Atlantic coastal states, archived and distributed by the National Geodetic Survey through the CORS program and by UNAVCO, were used to match the dates and times of landfall to available atmospheric data. Hurricane landfalls were matched with available water vapor data within 30 minutes and a 200-kilometer radius of the storm using a PERL (Practical Extraction and Report Language) program written by John Braun of COSMIC.

b. Making Comparisons

The amount of integrated water vapor was compared to the wind speed (intensity) of the hurricane so that trends in this relationship could be observed. Comparisons using storms of all wind speeds as well as only those with wind speeds above 70 miles per hour were made since a storm must have a minimum wind speed of 74 mph to be classified as a hurricane. This was a way of comparing the behavior of all tropical cyclones to that of just the hurricanes. The water vapor was also compared to the pressure of the hurricane eye. Both pressure and wind speed are used to classify hurricane intensity.

Although only water vapor readings within 200 kilometers of the storms were used, there was reason to believe that the distance between the station and hurricane would affect comparisons. Water vapor was evaluated as a function of distance from the
hurricane eye to explore this variability. To account for any inconsistency, water vapor was compared to the atmospheric pressure at the station. There was no visible way to remove the variability in distance from the wind speed measurements.

Data concerning the intensity behavior of the storm was then collected. A storm intensifies as its pressure decreases, and each storm was classified according to its behavior. If the point that the hurricane reached land was its point of lowest pressure (greatest intensity), it was categorized as a -2. The hurricane was assigned a value of -1 if the intensity of the hurricane decreased after hitting land. If the intensity remained the same for at least an hour, it was classified with a value of 0. It was assigned to a category 1 if the storm intensified. These values were used to numerically compare the intensity behavior of a hurricane upon hitting land to the water vapor in the atmosphere at that time.

There was also an interest in the composition of the hurricane elements (pressure, water vapor, etc.) with respect to the storm eye. There were questions concerning any trends that may occur based on the position of the GPS station with respect to the storm eye. One question, for example, is whether the pressure is typically lowest in a particular section of the hurricane eye. The eye of hurricane was divided into quadrants (northeast, northwest, southeast, and southwest), and additional modifications to the PERL program determined in which quadrant of the hurricane eye the GPS station was located.

In the end, the PERL program was modified to produce an array containing the hurricane name, the GPS station name, the distance between the station and the hurricane eye at landfall, the location of the station with respect to the eye (northeast, southwest, etc.), the atmospheric pressure at the station, the water vapor reading, the minimum pressure and wind speed of the hurricane, and the behavior of the hurricane after landfall. Only one reading per station was used for each hurricane.

c. Processing Data

The primary comparison methods used include scatter plots with linear trend lines, and correlation coefficients. The trend line uses a simple y vs. x plot to compute a linear equation for the behavior of the values. The trend line is calculated using the method of least squares, a method of finding the best-fitting straight line through a set of points.

A correlation coefficient determines how closely related two sets of numerical values are using the equation:

\[
\text{correlation} = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sqrt{\sum(x - \bar{x})^2 \sum(y - \bar{y})^2}}
\]

The correlation coefficient equals a number between -1 and 1. If the correlation is positive, two sets of values are directly related; as x increases, so does y. If the correlation is 0, there is no relationship between x and y. If the correlation is negative, the values are inversely related; as x increases, y decreases. A greater absolute value of the correlation indicates a stronger relationship between the two sets of values.

3. Results and Discussion

Data were available for 16 tropical cyclones, 11 of which were hurricanes (wind speeds of 70 mph or more). Because some hurricanes hit land more than once, this
amounts to 21 cyclone landfalls, 15 of them hurricanes. Using one observation from each GPS station with available data within 200 kilometers of landfall, 44 readings were produced for tropical cyclones. For hurricanes, 27 readings were produced.

*a. Trends in Intensity and Water Vapor*

The left side of Figure 1 is a scatter plot of the tropical cyclone wind speeds along with corresponding GPS readings of water vapor. The right side is the scatter plot for hurricanes. Both graphs show the tendency for cyclone wind speed and intensity to rise as water vapor in surrounding areas increases.

**Figure 1.** Trend lines of cyclone wind speed vs. water vapor for all cyclones and hurricanes, respectively.

Wind speed and pressure are both used to determine the intensity of hurricanes. For all tropical storms, they have a correlation coefficient of -0.951. For hurricanes, the coefficient is -0.917. In Figure 2, the pressure of the hurricane is plotted against the corresponding GPS measurements of water vapor. The slope of the trend line is negative because of the inverse relationship between hurricane intensity and pressure. As the water vapor increases, the pressure decreases and the intensity increases, implying the same trend as the previous figure.

**Figure 2.** Trend lines of cyclone pressure vs. water vapor for all cyclones and hurricanes, respectively.
The GPS stations used to gather water vapor data are all located within 200 km of the tropical cyclone eyes, but the distance between the GPS water vapor measurement and the wind speed and pressure measurements from the tropical cyclones used in the above graphs was a concern. The atmospheric data from GPS stations does not contain the wind speed at the station, but it includes the atmospheric pressure at the station. To account for water vapor variability dependent on the distance between the station and the hurricane eye, the station pressure was plotted against the water vapor measurement from the same station. The graphs for tropical cyclones and hurricanes are shown in Figure 3. The results again express a relationship between hurricane intensity and atmospheric water vapor.

![Station Pressure vs. Water Vapor](Cyclones)

![Station Pressure vs. Water Vapor](Hurricanes)

**Figure 3.** Trend lines of atmospheric pressure vs. water vapor for all cyclones and hurricanes, respectively.

*b. Correlations Between Intensity and Water Vapor*

The correlation coefficients for the data from the previous graphs follow. The absolute values of the correlation coefficients decrease between tropical cyclones and hurricanes when distance is not factored out of the wind speed and pressure measurements. When water vapor is correlated to the pressure at the same location, the correlation increases for hurricanes. This is a good indication that tropical cyclones with higher wind speeds are more sensitive to the error in water vapor measurement due to the variability in distance.

Table 1 shows correlation coefficients for water vapor and several tropical cyclone elements, including hurricane wind speed and pressure, and the atmospheric pressure at the GPS station. When making comparisons between the correlation coefficients for all cyclones versus only hurricanes, the hurricane wind speed coefficient decreases significantly more than the hurricane pressure coefficient. The hurricane wind speed coefficient decreases in correlation by more than 0.2. The hurricane pressure decreases by about 0.1, almost half. This may indicate the stability of pressure trends across all types of tropical cyclones.

The correlation coefficient for water vapor and distance from the hurricane eye is -0.215 for all tropical cyclones. The low correlation is likely due to varying humidity across the area of land studied.
### Table 1. Correlation coefficients for water vapor and cyclone intensity.

<table>
<thead>
<tr>
<th>Tropical Cyclones</th>
<th>Element 1</th>
<th>Element 2</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water Vapor</td>
<td>Cyclone Wind Speed</td>
<td>0.525088577</td>
</tr>
<tr>
<td></td>
<td>Water Vapor</td>
<td>Cyclone Pressure</td>
<td>-0.61433036</td>
</tr>
<tr>
<td></td>
<td>Water Vapor</td>
<td>GPS Station Pressure</td>
<td>-0.70969988</td>
</tr>
<tr>
<td>Hurricanes</td>
<td>Water Vapor</td>
<td>Hurricane Wind Speed</td>
<td>0.310012293</td>
</tr>
<tr>
<td></td>
<td>Water Vapor</td>
<td>Hurricane Pressure</td>
<td>-0.494962631</td>
</tr>
<tr>
<td></td>
<td>Water Vapor</td>
<td>GPS Station Pressure</td>
<td>-0.764814074</td>
</tr>
</tbody>
</table>

**c. Counts of Intensity Behavior**

Histographs of tropical cyclone intensity behavior are given in Figure 4. Of the 21 landfalls, only one storm increased in intensity after reaching land. This storm was Hurricane Katrina upon reaching Florida. This area had a water vapor reading of 82.2 mm, the highest water vapor reading available for all of the tropical cyclones that occurred between 2003 and 2005. In general, tropical cyclones decrease in intensity upon hitting land. There is not nearly as much atmospheric water vapor over land as there is over large bodies of water. The water vapor, acting as a fuel source, is depleted and the intensity of the cyclones decreases and dissipates, further supporting the connection between water vapor and hurricane behavior.

**d. Characteristics of Hurricane Eye Quadrants**

Multiple GPS station readings for tropical cyclones allowed observation of the distribution of hurricane elements based on the position of the station relative to the storm. Data were available from three of the four quadrants of the tropical storm
Hermine of 2004 (Table 2). The water vapor and pressure measurements from each of the stations are unique. Despite the varying distance of each station from the hurricane eye, the readings support the idea of the heterogeneity of the hurricane eye. The pressure reading provided by the station 27 kilometers away from the eye in the northeast quadrant has a pressure reading of 1009.1; however, the pressure 133 kilometers away from the eye in the northwest quadrant is much lower, 997.8. The intensity is considerably lower in the northeast quadrant, even closer to the storm.

<table>
<thead>
<tr>
<th>Quadrant of Storm Eye</th>
<th>Distance from Storm Eye (km)</th>
<th>Pressure (hPa)</th>
<th>Water Vapor (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE</td>
<td>27</td>
<td>1009.1</td>
<td>53.8</td>
</tr>
<tr>
<td>NW</td>
<td>133</td>
<td>997.8</td>
<td>51.7</td>
</tr>
<tr>
<td>SW</td>
<td>197</td>
<td>1007.4</td>
<td>51.5</td>
</tr>
</tbody>
</table>

Table 2. Atmospheric data available from stations located in three quadrants of one storm.

Finally, Table 3 shows the correlation between the water vapor and station pressure for measurements of water vapor taken in the four quadrants of the eye. All of the correlation coefficients are unique, maintaining the idea that the eye is not uniform. Measurements of water vapor from GPS stations in the southeast corner of the tropical cyclone eye are highly correlated to hurricane intensity. These measurements may be very helpful in forecasting and modeling intensity. In addition, water vapor measurements taken in the northeast quadrant of the tropical cyclone eye are not as highly correlated. These measurements would likely not be as useful in forecasts.

<table>
<thead>
<tr>
<th>Quadrant</th>
<th>Tropical Cyclones</th>
<th>Hurricanes</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE</td>
<td>-0.522211157</td>
<td>-0.754572433</td>
</tr>
<tr>
<td>NW</td>
<td>-0.731261288</td>
<td>-0.895368278</td>
</tr>
<tr>
<td>SE</td>
<td>-0.91448125</td>
<td>-0.838038555</td>
</tr>
<tr>
<td>SW</td>
<td>-0.713349646</td>
<td>-0.705403456</td>
</tr>
</tbody>
</table>

Table 3. Correlation coefficients of station pressure and water vapor in different quadrants of the tropical cyclone eye.

4. Conclusion

Better understanding of water vapor and its role in hurricane development may be the missing link in knowledge of these storms. More information would likely aid in improving models and forecasts. In this study, correlation between hurricane intensity and atmospheric water vapor was investigated. The pressure and water vapor near hurricane landfall clearly showed an inverse relationship, suggesting that hurricane intensity increases with water vapor in the atmosphere. Future research includes further investigation of the distribution of elements in the hurricane eye, examination of the wind speed at GPS stations and its correlation to water vapor, and water vapor data available immediately before and in closer proximity to hurricane landfall.
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