Using GPS radio occultation data in the study of tropical cyclogenesis

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ABSTRACT

Numerous studies have examined atmospheric conditions and patterns in tropical cyclogenesis. Although much has been accomplished, a complete understanding of tropical cyclogenesis is hindered by the lack of data in the regions where formation occurs. The GPS (Global Positioning System) radio occultation technique can provide valuable data in key areas. In GPS radio occultation, GPS satellites emit radio signals through the atmosphere that are received by another satellite in a low Earth orbit. Various atmospheric properties are calculated based on the alteration of the signal. This study assessed the value of GPS radio occultation data in the study of tropical cyclogenesis by examining storms of the 2002 Western North Pacific typhoon season. The signature of precursor disturbances to tropical cyclogenesis was determined by analyzing composites of data from the NCEP Aviation (AVN) analysis over four days. Similar composites of GPS radio occultation data were produced. The AVN analysis showed strong signals of precursor disturbances in the low-level wind fields and atmospheric refractivity. The GPS radio occultation data detected similarly increased refractivity values in corresponding regions, but had sizeable measurement differences with the AVN analysis. These differences were attributed to AVN analysis error due to the lack of input observational data and the high accuracy of GPS radio occultation measurements. Further comparisons showed that with the limited quantity of data currently available, GPS radio occultation by itself was not sufficient to detect precursor disturbances. It can best be used in data assimilation to improve the analysis and forecasts of tropical storms.

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1. INTRODUCTION

The formation of tropical cyclones has always been an intriguing issue in the atmospheric sciences. Numerous studies have sought to determine what causes these potentially devastating storms to develop. Over the years, scientists have identified many necessary conditions and influential weather patterns in tropical cyclogenesis, including a warm oceanic layer of sufficient depth, convergence of surface winds, conditional instability, and above-normal midtropospheric moisture (Gray 1979). Even with these findings, it is not fully understood how and why tropical cyclones form. The necessary atmospheric and oceanic conditions may be satisfied on long time scales; but they still may not be sufficient to stimulate tropical cyclogenesis. This uncertainty in prediction reflects the fact that there is no consolidated theory on hurricane formation (Ritchie and Holland 1997). More extensive research is needed to further our understanding of tropical cyclogenesis.

There are major difficulties in developing a general theory on hurricane formation, including differences in conditions between the ocean basins. Factors that influence tropical cyclogenesis in the Atlantic may not be as significant in the Pacific. Another difficulty is the lack of observational data over the long time scales and large ocean regions in which hurricanes are formed. A disturbance may be propagating for several days before it finally reaches tropical storm status. Surface observations and radiosonde soundings are only available in inhabited areas, which are sparsely distributed in the middle of the oceans. The current study addresses this problem by presenting GPS (Global Positioning System) radio occultation (RO) as a possible solution to the lack of observational data.

GPS RO is a satellite technique for observing the Earth’s atmosphere. It produces atmospheric profiles similar to radiosonde soundings by measuring the bending of radio signals transmitted by the GPS satellites with receivers on board of low-Earth orbiter (LEO) satellites. In previous work, Kuo et al. (2004) identified advantages of atmospheric data obtained by the GPS RO technique, including high vertical resolution and high accuracy in the upper troposphere. The advantage of GPS RO data that is most pertinent to the current study is its availability over uninhabited regions, such as the oceans. Other satellite data share this same advantage and have also been useful for the study of tropical cyclogenesis (Simpson et al. 1997). For example, microwave and infrared satellite sensors can provide radiance observations of cloud tops. Vector winds can be derived from satellite imageries of water vapor and cloud fields. GPS RO data, such as those to be available from the COSMIC mission, provide a beneficial addition to these traditional satellite data. This study will serve as a valuable pilot study to examine the usefulness of COSMIC GPS RO data in tropical cyclogenesis research.

COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) is an upcoming GPS RO mission. In early 2006, this joint Taiwan-U.S. project will launch six satellites into orbit for the sole purpose of monitoring the Earth’s atmosphere. It will provide ~2,500 GPS RO soundings daily uniformly distributed around the world for at least five years (Rocken et al. 2000). Previous missions include the Argentinean mission, SAC-C, and the German mission, CHAMP. SAC-C was launched in August 2001 and provided RO data until late 2002. CHAMP was launched in May 2001 and is currently still in orbit collecting RO data. The arrival of COSMIC is highly anticipated because the number of soundings will vastly exceed the quantity collected from previous GPS RO missions. Unfortunately, COSMIC data is not yet available, so this study will rely on GPS RO data from the CHAMP and SAC-C missions as a proof of concept.
The objective of this study is to assess the value of GPS RO data in the study of tropical cyclogenesis. We first identify the atmospheric conditions that serve as a signature of a low pressure center developing into the beginning stage of a tropical cyclone. Previous studies have investigated the large-scale influences and patterns of tropical cyclogenesis in the Western North Pacific, which will also serve as the area of focus in this study. Briegel and Frank (1997) used the ECMWF model analysis to find that a majority of tropical disturbances were influenced by an upper level trough as it underwent cyclogenesis. Ritchie and Holland (1999) extended this study by analyzing more storms using an Australian-developed model analysis. They identified large-scale patterns and trends associated with tropical cyclogenesis. This study uses a different model analysis, the NCEP Aviation (AVN) analysis, to determine the signature of a developing storm from data that can be directly compared to GPS RO observations. The ultimate goal is to determine how useful the GPS RO technique is in studying tropical cyclogenesis.

2. BACKGROUND

The following sections give a description of key concepts needed to understand the scope and methodology of this study.

2.a Tropical Cyclogenesis

Simpson et al. (1997) proposed that tropical cyclogenesis incorporates three distinct stages. The first stage is the establishment of the necessary thermodynamic and dynamic conditions. As mentioned earlier, the necessary thermodynamic conditions include a warm ocean layer, conditional instability, and above-normal mid-level moisture. The dynamic conditions that must be met include above-normal low-level vorticity and weak vertical wind shear. Gray (1975) hypothesized that tropical cyclogenesis occurs when these dynamic variables are met in a thermodynamically favorable environment that is adequately far from the equator. It is important to note that these conditions are necessary for tropical cyclogenesis, but they may not be sufficient.

The second and third stages of tropical cyclogenesis involve the formation and amplification of a mesoscale convective vortex (MCV). An MCV forms within a mesoscale convective system (MCS) of a pre-existing tropical disturbance. Such tropical disturbances typically contain several MCSs. This large cloud cluster is a well-known precursor to tropical cyclogenesis (Simpson et al. 1997). After the MCV is formed, it enters the third stage, amplification. This stage is marked by a deepening low pressure center and increasing convection. An MCV eventually becomes capable of rapid self-intensification if environmental conditions are still favorable (Briegel and Frank 1997). At this stage, tropical cyclogenesis is completed once the storm develops a rotation center at the surface.

2.b GPS Radio Occultation

Monitoring the Earth’s atmosphere with the GPS RO technique is a promising new tool for weather forecasting and climate models. GPS RO soundings can be taken anywhere in the world with high accuracy. In GPS RO, a GPS satellite transmits radio signals which are monitored by a LEO satellite as it sets behind the Earth. As the signal passes through the atmosphere, it is deflected due to the vertical gradient of atmospheric density. The bending angle ($\alpha$) of the signal as it varies with impact parameter ($\alpha$) are calculated from precise GPS and LEO orbit data (See Figure 1). Vertical profiles of atmospheric refractivity are then derived from these
measurements using an Abel transformation. Since refractivity is primarily a function of temperature, pressure, and water vapor, these atmospheric properties can finally be retrieved. Measurement errors are typically less than 0.5% from 5 km to 25 km altitudes (Kuo et al. 2004). Many fields of study can benefit significantly from such accurate data.

Previous studies on tropical cyclogenesis have focused more on large-scale environmental influences than on mesoscale dynamics (Ritchie and Holland 1997). Although studies of mesoscale dynamics provide valuable information on the intricate process of tropical cyclogenesis, it is difficult to obtain data with such high spatial resolution. GPS radio occultation is more of a large-scale observation due to the inherent scale of the signal’s ray path. Therefore, this study will also focus on the large-scale aspects of tropical cyclogenesis.

2.c AVN Analysis

This study uses the Aviation (AVN) model analysis to identify the signature properties of disturbances that are precursors to tropical cyclogenesis. The AVN model is run by the National Centers for Environmental Prediction (NCEP). Originally developed to aid in forecasting for aviation, the AVN model is now used for general weather forecasting. Forecasts are run four times each day, and provide valuable insight into the state of the atmosphere for up to 72 hours in the future. It is often used to forecast the motion and intensity of tropical systems. In this study, we use GPS RO observations to examine the properties of tropical cyclogenesis seen in the AVN analysis.

An examination of differences between the AVN analysis data and GPS RO data is also performed in this study. It is likely that the AVN analysis has lower accuracy over the ocean due to the lack of observational data. We hypothesize that GPS RO data is more accurate than AVN analysis data for two reasons: (1) GPS RO provides actual observations rather than predictions, and (2) the measurement error for GPS RO is very small. Both AVN and the GPS RO technique provide atmospheric data with large-scale resolution. A comparison of the two datasets provides an assessment of the accuracy of the AVN analysis on its description of tropical disturbances. Furthermore, an examination of this error may demonstrate the need for accurate observational data in areas of tropical cyclogenesis.

2.d Composite Technique

Due to the limited quantity of GPS RO data, this study employs a composite technique for tropical cyclogenesis analysis similar to that used in previous studies by Briegel and Frank (1997), and Ritchie and Holland (1999). CHAMP and SAC-C were single satellites that collected ~300 occultations per day worldwide. Only a few may have been in the vicinity of a storm undergoing tropical cyclogenesis. In order to maximize the amount of GPS RO data, the composite technique combines all occultations from several storms. The same technique is performed on the AVN analysis data, and is explained in the following section.
3. DATA AND METHODOLOGY

3.a Data set

The current study focuses on the 2002 Western North Pacific typhoon season. During this year, 31 disturbances reached at least tropical depression status, with at least one storm formed in every month. The year 2002 was chosen because data from both CHAMP and SAC-C were available. The centers of circulation for every storm were obtained from the Joint Typhoon Warning Center (JTWC) best track data. The AVN analysis data were taken from archives at the National Center for Atmospheric Research (NCAR). The GPS RO data were taken from the CDAAC database of the UCAR COSMIC project office.

3.b Storm genesis and data domain

The genesis point and genesis time of each storm are defined as the location and time where each storm reached tropical depression status. This was determined by the first Tropical Cyclone Formation Alert issued by the JTWC. A rectangular domain was defined around the genesis point for each storm, with that latitude and longitude lying in the center. This domain spanned 7,260 km from west to east and 6,060 km from north to south. These distances were based on a Transverse Mercator projection of the globe centered at the genesis point. For each storm, the same domain was used for four different times: the genesis time, and 24 hours, 48 hours, and 72 hours before the genesis time. These times were labeled day 0, day -1, day -2, and day -3, respectively.

3.c Data interpolation and composite

AVN analysis data was interpolated to a common grid for each domain and time. This grid had a dimension of 121 squares by 101 squares, with each square having a projected length of 60 km. Temperature, geopotential height, wind speed and direction, and relative humidity were extracted at the 300 mb, 500 mb, and 700 mb pressure levels. Atmospheric refractivity, $N$, was calculated using the equation,

$$N \approx \frac{77.6}{T} + 3.73 \times 10^5 \frac{e}{T^2}$$

where $p$ is atmospheric pressure, $T$ is temperature, and $e$ is water vapor pressure. From this, composite grids of each data type were created for days -3 to day 0 representing average properties within the domains of all 31 storms.

GPS RO soundings that fell within each domain from both CHAMP and SAC-C were identified. These are occultations that occurred +/-3 hours from the time of each domain. The location of each occultation relative to the genesis point determined its position on the common

Figure 2. Map of genesis points of the 2002 Western North Pacific storms
composite grid. Four composite grids were made from all occultations occurring on each day. Temperature, geopotential height, and refractivity were extracted from the same pressure levels as the AVN analysis data.

3.d Data comparison and analysis
Differences were calculated between GPS RO data and the AVN analysis data corresponding to the same grid point and time. Differences in temperature, refractivity, and geopotential height were calculated and analyzed with respect to the distance from the storm and location around the storm. We also analyzed the relationship between GPS RO refractivity and the AVN vorticity fields, which were determined from the AVN wind fields.

4. RESULTS AND DISCUSSION

4.a AVN analysis data
The AVN analysis data detected signals of a precursor disturbance most noticeably in the low-level wind field and refractivity. Figure 3 is a plot of the composite AVN wind field at the 700 mb pressure level from days -3 to 0. At day -3, a small cyclonic circulation lies southeast of the domain’s center. In the following days, the winds begin to strengthen as the cyclone becomes better organized. The storm moves northwestward until it arrives at the genesis point (center of domain) on day 0. Figure 4 is a plot of the composite AVN refractivity at the 700 mb pressure level for days -3 to 0. At day -3, higher refractivity values are seen in the same location of the storm seen in the day -3 wind field. This large area of high refractivity increases in strength and similarly moves to the northwest toward the genesis point in the following days. The locations of increased signals in both fields overlap for all days. As refractivity is a function of pressure, temperature, and moisture, further investigation showed that these large areas of increased refractivity are most reflective of the increased mid-level moisture. This large area of increased specific humidity is seen in Figure 5. The location and propagation of
these atmospheric conditions is indicative of a precursor disturbance to tropical cyclogenesis. The geopotential height and temperature fields showed a weak signal of the storm.

4.b GPS Radio Occultation data

The GPS RO data detected similar increases in refractivity values in the areas of the propagating precursor disturbance as seen in the AVN analysis data. Figure 6 is a plot of the composite GPS RO refractivity at the 700 mb pressure level for days -3 to 0. These plots do not look as smooth as the composite AVN plots for a few reasons. First, the occultations are scattered irregularly throughout the domain as opposed to having data regularly at every grid point. Therefore, the contours are reflective of the data locations as well as the data values.
Second, the occultation data are actual measurements from certain times and locations as opposed to averages of 31 data values. There is more variability farther from the storm because two adjacent occultations may be reflective of different and separate weather influences. But with these limitations, these plots still prove useful if one focuses on the location of the precursor disturbance that was demonstrated in the AVN analysis data. At day -3, there is an area of increased refractivity southeast of the domain’s center. With the exception of day -2, this area is seen to propagate northwestward toward the genesis point. This area is most likely due to the presence of the precursor disturbance. It is possible that the storm became lost between occultation soundings at day -2, so the signal was not as clear.

### 4.c Refractivity comparison

Despite the similarities in refractivity relative to location, there were many differences in data values between GPS RO and AVN analysis. Tables 1 and 2 present the average differences between GPS RO and AVN analysis refractivity values and their standard deviations at the different days and pressure levels. These data demonstrate that refractivity differences are larger and more scattered at the lower levels. At the 700 mb level, the AVN refractivity was on average...
larger than the GPS RO refractivity. A temporal trend is seen in the increasing differences at the 500 mb level. Also, the difference deviation for the 700 mb level becomes larger as the genesis time, day 0, approaches. There is a possibility that the higher AVN refractivity compared with the GPS RO is a reflection of “negative N bias” (Rocken et al. 1997) in the GPS RO retrieval in the tropical lower troposphere. However, the higher GPS RO refractivity at 500 mb clearly indicates that the AVN has a dry bias in terms of mid-level moisture. Figures 7 and 8 show the percent refractivity differences as a function of distance from the genesis point for all days at the 500 and 700 mb pressure levels. All of the plots show a similar scatter

Table 1. Average difference between GPS radio occultation and AVN refractivity, GPS-AVN (N units)

<table>
<thead>
<tr>
<th></th>
<th>day -3</th>
<th>day -2</th>
<th>day -1</th>
<th>day 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 mb</td>
<td>0.02705</td>
<td>-0.0338</td>
<td>0.13016</td>
<td>0.08753</td>
</tr>
<tr>
<td>500 mb</td>
<td>0.6177</td>
<td>0.78421</td>
<td>0.96099</td>
<td>1.37228</td>
</tr>
<tr>
<td>700 mb</td>
<td>-2.5822</td>
<td>-1.9343</td>
<td>-0.9115</td>
<td>-1.8255</td>
</tr>
</tbody>
</table>

Table 2. Standard deviation of refractivity differences

<table>
<thead>
<tr>
<th></th>
<th>day -3</th>
<th>day -2</th>
<th>day -1</th>
<th>day 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 mb</td>
<td>0.52984</td>
<td>0.70297</td>
<td>0.80487</td>
<td>0.66133</td>
</tr>
<tr>
<td>500 mb</td>
<td>3.60907</td>
<td>3.83801</td>
<td>3.1826</td>
<td>4.07339</td>
</tr>
<tr>
<td>700 mb</td>
<td>6.07842</td>
<td>6.40126</td>
<td>6.85634</td>
<td>7.11565</td>
</tr>
</tbody>
</table>

Figure 7. Percent difference in refractivity values at 500 mb

Figure 8. Percent difference in refractivity values at 700 mb
of significant normalized differences. The measurement error for GPS RO at the 500 mb level is less than 0.5%. Since Figure 7 shows that differences with AVN analysis data are much larger than 0.5%, it is likely that the AVN refractivity is in error. The same conclusion can be translated to the 700 mb level. At this level, the GPS RO measurement error is 3-4% over the tropics (Kuo et al. 2004). Although Figure 8 shows that many AVN refractivity values come within this error, some do not. Furthermore, with the knowledge of the AVN error at 500 mb, it is best to conclude that the GPS radio occultation measurements are also more accurate at the 700 mb level. Since refractivity is most reflective of moisture in the atmosphere, these refractivity differences suggest errors in the AVN moisture fields, particularly at 500 mb.

![Vorticity from AVN analysis data for day 0 at 700 mb](image1)

**Figure 9. Vorticity from AVN analysis data for day 0 at 700 mb**

![GPS RO refractivity vs. AVN vorticity at 700 mb](image2)

**Figure 10. Scatter plot of GPS radio occultation refractivity vs. AVN vorticity at 700 mb for all days**

**4.d  Refractivity vs. vorticity**

Figure 9 is a plot of the composite AVN vorticity at the 700 mb level on day 0. This strong vorticity signal is reflective of the increased wind strength and rotation at the genesis point and time of the precursor storm. Since increased refractivity was seen as a signal of the precursor storm, large areas occurred in the same locations of strong vorticity. If GPS radio occultation were able to detect precursor storms based on refractivity alone, it would correlate well with the vorticity seen by AVN. Figure 10 presents this comparison at the 700 mb pressure level for all days. In this plot, there is no clear correlation as the data points are evenly distributed about the zero vorticity line. Since refractivity, again, reflects moisture, this plot demonstrates that areas of higher humidity occur in both cyclonic and anticyclonic wind patterns. The same was seen at the 300 mb and 500 mb pressure levels.
5. CONCLUSIONS AND FUTURE WORK

This research assessed the value of GPS RO data in the study of tropical cyclogenesis. The assessment began by examining the atmospheric properties in GPS RO data that were seen as signals of precursor storms to tropical cyclogenesis in AVN analysis data. Comparisons were made between the two data sets by examining their differences and relationships. The AVN analysis successfully detected signals of precursor disturbances in the 700 mb wind and atmospheric refractivity fields. Above-normal vorticity was seen in the increased wind speed and rotation at low levels. The AVN wind field demonstrated the need for low-level vorticity in tropical cyclogenesis. Since refractivity is a reflection of moisture in the atmosphere, the AVN analysis also demonstrated the need for above-normal mid-level moisture through its increased regions of refractivity. These regions were always coincident with the precursor disturbance.

The GPS RO data observed increased refractivity in regions of precursor disturbances as seen in the AVN analysis. But the same observations were also made in many other areas. There was very little correlation between the AVN vorticity and available GPS refractivity data. With a limited number of soundings, GPS RO from CHAMP and SAC-C was not sufficient by itself to detect precursor disturbances. The GPS RO data did reveal the error in moisture fields from the AVN analysis. The 500 mb moisture in the AVN analysis appears to be underestimated for precursor disturbances. Forecasting models traditionally have difficulty in accurately estimating the atmospheric moisture. Refractivity from GPS radio occultation data can be used through data assimilation to improve the moisture fields of model analyses, especially in uninhabited areas. Improved weather analyses and simulations will enhance the understanding of tropical cyclogenesis, and improve the forecasts of tropical storms.

There are several possibilities to expand this work and the general study of tropical cyclogenesis. This study focused only on tropical storms occurring in one year and in one ocean basin. An analysis of more years and ocean basins can provide new conclusions on the value of GPS RO in the study of tropical cyclogenesis. The study can also be expanded by analyzing tropical disturbances that do not develop into tropical depressions. Comparing these storms with those that do further develop can present distinguishable characteristics that will better explain tropical cyclogenesis. Lastly, future studies will use GPS RO data from COSMIC. COSMIC will provide significantly more data, with an increased concentration of soundings in areas pertinent to studies on tropical cyclogenesis. This new source of data could further improve forecasting models, and stimulate the development of a theory on hurricane formation.

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