Comparison of CHAMP Radio Occultations with Global Model Forecasts: 2005 Hurricane Season

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ABSTRACT

GPS RO technique measures the bending of radio signals as they pass through the Earth’s atmosphere. From the vertical profile of bending angles, one can derive vertical soundings of refractivity. GPS RO soundings are of very high accuracy and very high vertical resolution, and of uniform global coverage. The availability of GPS RO soundings over the ocean provides a unique opportunity to verify model hurricane forecasts. This investigation primarily focused on the Global Forecasting System (GFS) model. To verify the GFS forecasts, the GFS outputs of temperature, pressure, and water vapor pressure were converted into refractivity. A mean absolute value of the fractional differences between the RO measured refractivity and the GFS refractivity was calculated as a measure of the error of GFS analysis and forecast. The mean absolute error of GFS forecasts was calculated for the cases with and without tropical cyclones. This study further analyzed cases with tropical cyclones and correlated the GFS output error to the errors in the predicted track and intensity. Results for all the storms for 2005, the 2005 Atlantic and East Pacific hurricane season showed consistent error in the GFS output. The analysis reveals that the GFS error was larger closer to the core of the storm when a tropical cyclone was in the vicinity. These results suggest that including RO data in the initial conditions of GFS models may improve the GFS forecast of hurricanes.
1. Introduction

In this study three global forecast models are verified against Radio Occultations (RO) measurements. The three global forecasts models that were used are the European Centre for Medium-Range Weather Forecasting (ECMWF), Global Forecasting System (GFS) model, and the Aviation-output model (AVNO). The ECMWF model uses four-dimensional variation data assimilation and a coupled ocean-atmospheric model along with a separate ocean analysis system (ECMWF product, http://www.ecmwf.int/products). The ECMWF can produce forecasts out to 10 days in advance. The GFS model can forecast out to 384 hours and in 12 hour increments (NCEP GFS Model Forecasts, http://www.nco.ncep.noaa.gov/pmb/nwprod/analysis/namer/gfs/00/model_l.shtml), but in this study only the 0 and 12-hour forecast were analyzed. The GFS global model output is used as the AVNO input values, as reported by the National Hurricane Center (NHC) website. The AVNO is a late-baroclinic model, which produces forecasts for tropical cyclone track, intensity, and structure using the hydrostatic, vorticity, divergence, thermodynamic, mass continuity, and conservation equations. It is essentially the same as GFS, except AVNO is run with short data cut-off, to allow timely (and shorter, 3-day, forecast). GFS is usually run for extended period of 16 days. (NHC Model Overview, http://www.nco.ncep.noaa.gov/pmb/changes/avn-gfs_rename.html). This study places emphasis on the verification of the GFS 12 hour and AVNO 0 hour model outputs to the available RO data.

The Stanford University Center for Radar Astronomy (SUCRA) pioneered the RO technique for the studies of planetary atmospheres in the 1960’s. Then SUCRA’s idea of RO sampling the atmospheres of other planets was later applied to earth’s atmosphere. An occultation is the refraction of radio wave passing through the atmosphere. These radio wave signals are transmitted from a Global Positioning System (GPS) satellite which is later received by a receiver onboard a Low Earth Orbit (LEO) satellite. As the earth gets in between a LEO and a GPS satellite, the GPS satellite transmits two frequencies (L1 = 1575.42 MHz & L2 = 1227.6 MHz) heading tangent to the earth’s surface. This allows measurement of the atmosphere. Specifically, as these waves travel toward earth’s surface they encounter the atmosphere which bends and refracts the waves’ signal into the LEO satellite’s antenna. This occurs because the density of earth’s atmosphere decreases with height, which makes the atmosphere act similar to a spherical lens. The LEO satellite then identifies the incoming rays and with their corresponding time of arrival, and reports these data back to a database where they are then converted into vertical profiles of the atmosphere; see figure 1 for an illustration of how these two satellites work together to produce an RO (COSMIC: CDAAC Description, http://cosmic-io.cosmic.ucar.edu/cdaac/doc/about/index.html).
Once occultation data are entered into a database then a many-step retrieval process converts the data into bending angle profile, refractivity profile, and then profiles of pressure, temperature, and water vapor pressure. The first step in this process includes using Doppler frequencies to calculate the bending angle. It should be noted that all the Doppler transform methods tend to over simplify the earth’s ellipsoid shape into a symmetrically spherical shape that can eventually lead to huge retrieval errors. This problem is compensated for by making a reference frame and creating a localized center of the earth each time an occultation is taken.

Moisture in the troposphere also introduces complications when calculating the bending angle. Thus there are four different methods have been developed to retrieve vertical profiles of bending angle from the GPS RO raw phase and amplitude data for the troposphere: 1) back propagation which uses Kirchoff integrals, 2) sliding spectral employing Fourier analysis, 3) canonical transform which uses an integral transform, and 4) full spectrum inversion that uses one integral transform of the canonical transform. Moisture in the troposphere causes the L2 band to have strong variations in its signal, and therefore become useless for retrievals thus only the L1 band is used. The techniques developed by SUCRA compensate for the fact that electrons in the ionosphere cause a frequency delay between the signals. This is yet another necessary step in order to obtain an accurate vertical profile. To control noise in the retrieved bending angles reference profiles from climate analysis are used to make first guess estimations of the observed bending angles. When all these steps are completed, then the occultation dataset is ready to be converted into atmospheric parameters such as temperature and pressure. For more information on the specifics of the data processing that a RO undergoes is found in
Algorithms for inverting radio occultation signals in the neutral atmosphere, found in the COSMIC website.

The process of converting the corrected profiles varies depending on the characteristics of the various atmospheric layers. For the upper atmosphere where there is little moisture, the refractivity of radio signals is proportional to density. This allows pressure to be derived from the integration of the hydrostatic equation and the temperature to be derived from the equation of state. But in general a base index of refraction equation is used for the entire atmosphere (see Eq. (1)),

\[ N = (n-1) \times 10^6 = 77.6 \frac{P}{T} + 3.73 \times 10^4 \frac{P_w}{T^2} \]  

Here \( n \) is the index of refraction, \( P \) is the atmospheric pressure in hPa, \( P_w \) is the water vapor pressure in hPa, which is related to specific humidity, and \( T \) is temperature in Kelvin. Because the water vapor pressure is less than 2% at altitudes above 8-10 km we can eliminate the moist term making it valid for the upper dry atmosphere. (COSMIC: CDAAC Description, http://cosmic-io.cosmic.ucar.edu/cdaac/doc/about/index.html).

The RO that will be used to verify the forecast models were provided by the German satellite, Challenging Minisatellite Payload for Geophysical Research and Application (CHAMP), which was launched on July 15, 2000. CHAMP was the first satellite to simultaneously take high precision measurements of earth’s gravity, electromagnetic field, ionosphere, and the atmosphere, producing \( \sim 230 \) GPS RO soundings per day. Its sensors are used to characterize the state and the dynamics of the atmosphere and of the ionosphere. More than 80% of the measurements from CHAMP can be processed into vertical profiles. Their quality is good enough that approximately 50% of the profiles reach as far as the first kilometer above earth’s surface. This makes this satellite’s data vital to the scientific community (Wickert et al., 2001).

In Wickert et al, 2001, they calculate the distribution of the RO data across the world. They found that the occultation density was symmetric with respect to the equator. There were high concentrations in the polar regions (~140 occultations per \( 10^6 \)km\(^2\)) and lower distributions in the equator region (~20 occultations per \( 10^6 \)km\(^2\)), which is a 700% difference. The longitudinal distribution was mostly uniform. These authors also made comparisons of the CHAMP RO data to the ECMWF. They reported “excellent agreement” at high latitudes, but larger deviations between the model and the CHAMP data near the equator with biases of 1 to 2K in the lower troposphere. Where the temperature difference was 0.1K below 20km and <0.5K below 35km but it does not apply below 5km in elevation. Their results suggest that very few occultations will fall near hurricanes since they are most commonly observed in lower latitudes and that the profiles may be subject to temperature errors, particularly in the lower troposphere.

In an earlier study of the assimilation of the GPS satellite data by Kuo et al. (1997), it was concluded that weather prediction models could be improved if RO data
was assimilated into forecast models. This study showed that at the 180km resolution of the Penn State/NCAR mesoscale model MM5 was capable of improving temperature and moisture structure, as a result of GPS RO data assimilation, which led to more accurate short term predictions of an extratropical cyclone. They studied an extratropical cyclone over the Northwest Atlantic Ocean on January 4 to 5, 1989. This extratropical cyclone underwent rapid cyclogenesis and reached a low central pressure of 936mb. An interesting result that came from this case study was that even though the GPS data cannot derive winds directly, once this data was assimilated into the models it produced significant improvements in forecast winds, and vorticity. Through the observing system simulation experiments (OSSE), they demonstrated that data from all the level of the atmosphere are needed to produce a significant improvement in forecasting the storm’s rapid deepening. They attempted using only GPS RO data above 3km, but doing so produced less than a 50% improvement compared to the experiment that used data at all levels.

There currently has been one published study on improving tropical cyclone forecast using GPS RO refractivity (Huang et al. 2005). This study revolved around two particular storms, Nari (September 16, 2001) and Nakri (July 7, 2002) typhoons that struck Taiwan. The main focus was using the GPS occultation data, four soundings for Nari, and five soundings for Nakri, to improve forecasts of precipitation amount, temperature, and storm tracks. They used Eq. (1), and the data from CHAMP and Satélite de Aplicaciones Científicas –C (SAC-C), the Mesoscale Model (MM5) using the three-dimensional variation data assimilation (3DVAR) in their studies.

Nari, a fairly organized and well developed tropical cyclone, moved slowly towards the south once it hit land, giving Taiwan significant rainfall, where the 24-hour accumulated maximum rainfall for that day was 570 mm at one location and 1161 mm at another location. Assimilating the occultation data and some other data to the MM5, improved the accuracy of the track forecast. The model run with the GPS data showed the slowing of this cyclone at a much earlier time than the no-GPS experiment, and improved the 24-hour accumulated precipitation forecast for the first day. A sensitivity test was conducted by removing certain occultations, and it was found that the third occultation sounding was a major factor in improving Nari’s forecast. Without this occultation the models predicted significantly less accurate forecasts, yet still better than the no-GPS run. Without the third GPS RO sounding, the track remained unchanged in the beginning, and predicted the slow down of the vortex at 36-hours, which gave a lower 24-hour accumulated precipitation total.

Nakri’s radar reflectivity demonstrated that it had strong local convection but weakly defined rainbands. Most of the rainfall was in the eastern portion of Taiwan, with a maximum of 122 mm on the first day, and 207 mm on the second day. Sensitivity test showed that the occultation soundings #4 and #5 were most important, which yielded positive moisture increments of 1 to 1.5 g kg\(^{-1}\), respectively. Even though the simulation from the models that assimilated GPS RO data did not produce any significant differences early on, it did show a southwestward flow south of Taiwan. It also showed that southwestern flow was getting stronger. The amount of precipitation accumulated on
the first day in the models showed little difference, but on the second day the MM5 model picked up a low southeast of Taiwan, which helped give a forecast of 195 mm of rain that day. The no-GPS run gave a much larger rain amount for the first 24-hours, but in both no-GPS run and GPS run the model showed a symmetrical distribution of accumulate precipitation over Taiwan.

In the conclusion the authors asserted that GPS occultation data are most effective for moisture predictions and less so for temperature and pressure. They also raised concerns about the indirect way winds are derived from the occultation data, where it is a vital component given the fact that at low latitudes the vortex of the tropical cyclone is affected by the winds.

The goal of this study is to use existing analysis methods presented in earlier studies to analyze several tropical cyclones with plenty of GPS occultations to ultimately conduct verification of the GFS and ECMWF model outputs to CHAMP RO data during a hurricane event as well as non-hurricane events. This study will also correlate the errors found in the AVNO predicted track and intensity to those of the errors found at the GFS model. These results will allow assessment as to whether or not tropical cyclone track prediction would be one of the radio occultation’s most useful applications.

2. Methodology

The accuracy of the RO method was tested by comparing them to radiosonde soundings (Kuo et al. 2005). The methods used to compare them to radiosondes are similar to those that will be used to verify the models in this study. Kuo et al. found that they are very accurate such that RO observations can evaluate the efficiencies of various types of radiosondes. With this result, it can also be said that the very high accuracy provided by the RO data made it possible to evaluate the efficiencies of global model. Kuo et al. also documented that there were huge variances between occultations below 5km. Thus this project does not focus on the 5km or below layer of the atmosphere except when doing a whole vertical profile comparison analyses.

a. Data

The analysis of CHAMP mission, (data is available from May 19, 2001 to present), was conducted at University Corporation for Atmospheric Research (UCAR) Office of Programs. Most of this data were processed and stored in a database called COSMIC Data Analysis and Archive Center (CDAAC). CDAAC’s main function is to quality control the incoming data, processing, distributing and archiving them. All the data coming into the system is sorted into tables that give temperature, moisture, geometric height, refractivity, etc.

The first step of this research project was to find accurate best track data on tropical cyclones, which was provided by the UNISYS Weather website. These data were provided in a tabular text format, which consisted of the advisory number, latitude, longitude, time, wind, pressure, and storm status. From there, Perl scripts were composed to retrieve and analyze the UNISYS Weather website while removing
advisories with a lettered suffix, which eventually populated CDAAC with these track data sets. Then the scripts examined these newly added track data to find occultations that occurred on any $X^\circ$ by $X^\circ$ latitude-longitude box (Lat/Lon Box) from the center of a tropical cyclone, along with calculating an donut-like structure that was defined as an $X^\circ$ by $X^\circ$ minus a $Y^\circ$ by $Y^\circ$ Lat/Lon Box (see Fig. 2), occurring in a time interval, $I$. $I$ was defined as a time window three hours before and after an advisory. The Perl script also examined RO data that has already met quality control criteria for the atmprf script in CDAAC database for 2005. This atmprf script sets conditions to evaluate and flag the RO data that contains any errors, and the Perl script will thus only read the good occultations. These parameters would be considered as the domains of which the whole study is conducted upon.

![Fig. 2](image)

(a) (b)

Fig. 2: This figure illustrates the types of physical domains placed on the surface of the earth, where (a) illustrates a $20^\circ$ by $20^\circ$ Lat/Lon Box with Hurricane X having its center located at $20^\circ$N and $-40^\circ$W, and while (b) illustrates the donut like structure which is a $20^\circ$ by $20^\circ$ minus a $10^\circ$ by $10^\circ$ Lat/Lon Box for Hurricane X that has its center at $20^\circ$N and $-40^\circ$W.

A script was written to analyze the ECMWF 12-hour forecast and the GFS 0-hour and 12-hour forecasts, which are also archived in CDAAC. The hurricane AVNO 0-hour and 12-hour forecast model data was collected from the NHC ftp site. The purpose of this study was to see whether or not these model predictions (without the assimilation of GPS RO data) could accurately predict the atmospheric profiles at the occultation points around tropical cyclones. For comparison with situation when there are no hurricanes, we also performed the calculation over the exact same region, with an “imaginary” or “bogus” hurricane and its track.

This study will look at 5 different cases of Tropical Cyclones: all hurricanes from every basin for the 2005 season, 2005 Atlantic Hurricane Season, 2005 Eastern Pacific Hurricane Season, seven individual hurricanes as a group, and Hurricane Jova alone. These analyses did not include those storms that only reach their max status as a Tropical Depression, because of the lack of RO data during their short lifecycle. The seven individual storms from both the Atlantic and Eastern Pacific basins where selected by running the above scripts where five or more RO existed within a $20^\circ$ by $20^\circ$ Lat/Lon Box in a time interval $I$. After running all of these scripts, seven tropical cyclones where identified as candidates for investigation. They include Hurricanes Fernandez, Irene, Jova, Kenneth, Maria, Ophelia and Rita because each of these storms had five to six occultations within the requested fields.
There are many ways to create bogus hurricanes. The method used in this study was to subtract seven days from the actual best track data. This method was applied to all five cases such that it gave similar atmospheric conditions to which the cases with hurricanes in the vicinity thrived in. This method also provides a standard to which a case with hurricanes can be compared to normal atmospheric conditions.

b. Statistical analysis

Using CHAMP data, which has high resolution, some linear and temporal interpolation is needed to make the occultation point and the GFS and the ECMWF model outputs run on the same time, and place. Once completed some of the models’ output parameters (temperature, pressure, and water vapor pressure) are converted into refractivity values, $N$, using Eq. (1) as discussed in the Introduction. Having GPS data and GFS model outputs in refractivity values made it easier to do some statistical analysis.

Once the model output data have been converted to refractivity the fractional error between the models and the RO data was computed using Eq. (2):

$$\Delta N(l,n) = \frac{N_{CHAMP}(l,n) - N_{Model}(l,n)}{N_{CHAMP}(l,n)}$$

where $N_{CHAMP}$ is the CHAMP RO refractivity, $N_{Model}$ is the model’s refractivity, and $l$ and $n$ are indices for vertical level and CHAMP RO and model match, respectively. Then the absolute value was conducted on the fractional errors, where they were summed over all available levels, which was then divided by the number of levels to get the mean absolute value of the fractional errors as shown in Eq. (3):

$$\bar{|\Delta N|} = \frac{1}{N \cdot L} \sum_{e=1}^{L} \sum_{n=1}^{N} |\Delta N(l,n)|$$

With the mean fractional errors, it was decided to analyze these certain levels of the atmosphere. These levels under investigation would be the complete vertical structure (0km to 40km), 10km to 20km, 5km to 10km, 5km to 20km, and 20km to 30km, for each model output. Similar equations were used to find the mean standard deviation of the fractional errors. These numbers would then be used to compare them to their respective hurricane’s track and intensity error found in the AVNO 0 and 12-hour forecasts.

Track errors with the AVNO 0 and 12-hour forecasts were calculated by the great circle distance formula. Even though the distances are relatively small enough that errors between using the great circle distance formula and the regular distance formula are considered small, the great circle distance formula was used to maintain accuracy. Meanwhile, the intensity errors for the AVNO forecasts were calculated by taking the absolute value of the subtraction of the actual intensity from predicted intensity from the AVNO 0 hour and 12 hour forecasts. Once all these numbers were calculated, the
correlation coefficient between the mean absolute value of the fractional errors and the AVNO track and intensity error were then determined.

3. Results and Discussion

a. Differences between the errors with respect to the center of the storm

This project looked into the absolute means of the fractional errors with respect to distance from the center of the storm. The distance away from the core of the storm was calculated by plotting the errors to a $1\degree$ by $1\degree$ Lat/Lon resolution of the donut-like structure. The results from these calculations are shown in Fig. 3.

(a) All 2005 Hurricanes GFS 12h Mean

(b) All 2005 Hurricanes GFS 12h Standard Deviation

(c) Atlantic 2005 Hurricane Season GFS 12h Mean

(d) Atlantic 2005 Hurricane Season GFS 12h Standard Deviation
Fig. 3: Illustrates the mean absolute value of the fractional errors to the distance away from the center of the storm. The indigo lines illustrate the errors found with respect to the complete vertical structure of the RO, pink illustrates errors for the 10km to 20km layer of the atmosphere, lime illustrates errors for the 5km to 10km layer, sky blue illustrates errors for the 5km to 20km layer, and the red lines illustrate errors for the 20km to 30km layer.

One should expect that the absolute mean of the fractional error closer to the core of the storm should be higher than those farther away from the storm. These errors grow towards the center of the storm because near the core the atmospheric conditions are unstable and contain significant mesoscale structure and the models have a harder time predicting in these conditions. One should also expect that the standard deviation should remain the same with no preference to how far away from the core of the storm the RO data were taken. The standard deviation should not vary much because of the Law of Large Numbers. The Law of Large Numbers states that the bigger the number of RO data the more stable the standard deviation between the errors becomes.

These trends that are expected don’t seem to be reflected in this large scale analysis, because in these large scales the results are very subtle. In Fig. 3 graphs (a) and (b) contain 814 RO, (c) and (d) contain 389 RO, and (e) and (f) contain 240 RO that met the parameters of this study. As the number of RO per case drops, the pattern described by the ideas as aforesaid, are much more evident. Even though the results are fairly subtle, there is a very visible pattern that can be seen when comparing the standard deviation of the different layers. The 5km to 10km layer for the most part has the highest standard deviation, with the complete vertical structure following it as the second highest. The 5km to 20km level is the third highest, the 20km to 30km level of the atmosphere is the second lowest, and the lowest standard deviation overall is the 10km to 20km level of the atmosphere. This illustrates that the standard deviations of those atmospheric levels containing significant amount of moisture at the lower troposphere has the highest standard deviation. This may be related to two factors: First, the moisture has the highest variability in time and in space compared to other meteorological variables, and second the CHAMP used the “closed-loop” tracking technique which may be subject to higher measurement errors in the tropical boundary layer. In the COSMIC mission the open loop tracking technique will hopefully reduce the errors found in the moist troposphere.

Also, it is worth noting that the 5km to 10km layer of the verification has the most robust mean errors near the hurricanes’ core, and the higher vertical layers like the 20km to 30km mean errors aren’t as sensitive to the distance with respect to the core. It has been observed that the most accurate part of the occultation tends to reside on the 10km to 25km layer of the atmosphere (Kou et al. 2004). So it is no surprise that these results show that the most accurate part of the occultation (10km to 20km) has the lowest absolute mean (doesn’t exceed an error of 0.50%, except once) of the fractional errors and the smallest standard deviation than any of the other vertical layer of the atmosphere under consideration in this study.

b. Differences between the different models

This project looked into several different global models, mainly the GFS and the ECMWF 12-hour forecast. The following graphs chart the mean fractional error with respect to their geometric height of the atmosphere, for each to these models per case for the simple 5° by 5° and 10° by 10° Lat/Lon Box shown in Fig. 4. This project also looked into the Root Mean Square (RMS) of the vertical structure for both of these models; however these graphs aren’t shown, because they illustrate the same results.
Fig. 4: These figures illustrate the mean fractional error with respect to geometric height, where the green line represents the GFS 12-hour forecast, and the light blue line represents the ECMWF 12-hour forecast.

There are plenty of things that stand out from these graphs. The first thing is that both of these models tend to have small means fractional error in the 5km to 20km layer of the atmosphere. The mean fractional error is extremely large for the layer below the 5km, which verifies the conclusions made in Kuo et al. (2004). Another interesting point is that as the number of RO drops, the more the discrepancies between the mean fractional errors for both of these models. These results are also seen when graphing the RMS versus geometric height (not shown). With this said, further quantitative analysis was taken. Tables 1 and 2, quantify the average difference between these two models mean fractional error and RMS, respectively.

Table 1: The table enumerates the absolute mean of the mean fractional error between these two models describing the differences between the models and the difference between different resolutions of the Lat/Lon box with respect to the distance away from the core of the storm.

<table>
<thead>
<tr>
<th>Cases under investigation</th>
<th>5° by 5° Lat/Lon Box</th>
<th>10° by 10° Lat/Lon Box</th>
</tr>
</thead>
<tbody>
<tr>
<td>All 2005 Hurricanes</td>
<td>0.14%</td>
<td>0.10%</td>
</tr>
<tr>
<td>'05 Atlantic Hurricane Season</td>
<td>0.11%</td>
<td>0.09%</td>
</tr>
<tr>
<td>'05 Eastern Pacific Hurricane Season</td>
<td>0.38%</td>
<td>0.22%</td>
</tr>
</tbody>
</table>

Table 2: The table enumerates the absolute mean of the mean RMS between these two models describing the differences between the models and the difference between different resolutions of the Lat/Lon box with respect to the distance away from the core of the storm.

<table>
<thead>
<tr>
<th>Cases under investigation</th>
<th>5° by 5° Lat/Lon Box</th>
<th>10° by 10° Lat/Lon Box</th>
</tr>
</thead>
<tbody>
<tr>
<td>All 2005 Hurricanes</td>
<td>0.96%</td>
<td>0.92%</td>
</tr>
<tr>
<td>'05 Atlantic Hurricane Season</td>
<td>0.87%</td>
<td>0.89%</td>
</tr>
<tr>
<td>'05 Eastern Pacific Hurricane Season</td>
<td>0.93%</td>
<td>0.90%</td>
</tr>
</tbody>
</table>

Tables 1 and 2 illustrate that the larger the Lat/Lon Box is, for the most part, the smaller the deviation between the RMS and the absolute mean of the mean fractional error.
errors between the 12 hour forecasts of these two global models. It is important to note that the 5° by 5° Lat/Lon Box contains most of unstable atmospheric conditions, because it is near the core of the storm. Also worth noting is that the 10° by 10° Lat/Lon Box includes the 5° by 5° Lat/Lon Box unstable atmospheric conditions and RO data that is taken farther away from the core of the storm, which consist of RO data with much more stable atmospheric conditions. Since global models can predict the stable conditions better than the unstable conditions, this will help explain that the additional set of stable conditions will yield a reduction in the differences between the absolute mean of the mean fractional errors of the model in the 5km to 20km layer of the atmosphere, as shown above.

These two tables also indicate that the mean absolute value of the mean fractional error difference is much smaller than the RMS between the models with respect to their Lat/Lon Box. This implies that the differences between how well these models predicted the mean conditions of the tropical atmosphere with respect to their Lat/Lon Box is much better than capturing the variability (which is represented by RMS errors) of the tropical atmosphere between the models.

c. Differences between real and bogus hurricane

To characterize the difference between the real and bogus hurricane the mean absolute value of the mean fractional error, and the mean absolute value of the standard deviation of the fractional error was taken; by summing up the donut-like structures with respect to distance away from the core of the storm by the errors to a 1° by 1° Lat/Lon resolution and dividing those numbers by the twenty, (the number of donut-like structure at the specified resolution) for each of the atmospheric levels under investigation for the GFS 12-hour plot. The results from these calculations are shown below in Table 3.

Table 3: Quantifies the differences between the mean absolute value of the mean fractional error, and the mean absolute value of the standard deviation of the fractional error for both hurricane and bogus hurricane cases. Those numbers shown in red and are italicized and demonstrate when the difference between the real minus bogus are negative.

<table>
<thead>
<tr>
<th>GFS12 hour</th>
<th>Real Mean</th>
<th>Real Standard Deviation</th>
<th>Bogus Mean</th>
<th>Bogus Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0km to 40km</td>
<td>0.003821</td>
<td>0.011299</td>
<td>0.005032</td>
<td>0.010939</td>
</tr>
<tr>
<td>10km to 20km</td>
<td>0.001641</td>
<td>0.00627</td>
<td>0.002065</td>
<td>0.005715</td>
</tr>
<tr>
<td>5km to 10km</td>
<td>0.002838</td>
<td>0.014532</td>
<td>0.004002</td>
<td>0.013419</td>
</tr>
<tr>
<td>5km to 20km</td>
<td>0.002009</td>
<td>0.009228</td>
<td>0.002787</td>
<td>0.008525</td>
</tr>
<tr>
<td>20km to 30km</td>
<td>0.003556</td>
<td>0.00731</td>
<td>0.003872</td>
<td>0.007502</td>
</tr>
<tr>
<td>0km to 40km</td>
<td>0.004258</td>
<td>0.010557</td>
<td>0.004770696</td>
<td>0.01069168</td>
</tr>
<tr>
<td>10km to 20km</td>
<td>0.001824</td>
<td>0.006035</td>
<td>0.001969315</td>
<td>0.005685947</td>
</tr>
<tr>
<td>5km to 10km</td>
<td>0.003156</td>
<td>0.012473</td>
<td>0.00374576</td>
<td>0.012012572</td>
</tr>
<tr>
<td>5km to 20km</td>
<td>0.002155</td>
<td>0.008413</td>
<td>0.002626772</td>
<td>0.007909872</td>
</tr>
<tr>
<td>20km to 30km</td>
<td>0.003426</td>
<td>0.0068</td>
<td>0.003846301</td>
<td>0.006992515</td>
</tr>
</tbody>
</table>
Table 3 demonstrates that with more data, larger storm samples, the average error at each different layer under investigation seems to be less than those for the bogus storms. One would expect that the average error for the real storms have more average error than the bogus storms. But when calculating the differences from both means in all cases, all 2005 hurricanes, the 2005 Atlantic Hurricane Season, the 2005 Eastern Pacific Hurricane Season, the seven storms under investigation as a group, and Jova, have very small differences. These differences are so small that if any outlier existed in the data sets then the differences could become positive instead of negative. However, that is not to say that it happens all the time, 90% of the time the average of the standard deviation for the bogus hurricanes is lower than the real storms. And those 10% don't differ much as already stated previously; the difference between their averages is 0.0002 the most. This again suggests that the model has about the same skill in capturing the “mean” tropical conditions with or without the hurricane. However, models have more difficulties capturing the mesoscale variabilities associated with a hurricane, particularly, in the vicinity of its core.

The negative difference between the bogus and the hurricane events happens at random places (regard of the number of hurricanes), but 50% of those events happen in the 20km to 30km, which is the most prone area for error in the GFS 12-hour forecasts. This occurs because the model has huge errors and standard deviations in that layer because that is the upper domain of the GFS model. In reality, it is evident that the average standard deviation of the errors between the model and the RO data is lower for bogus storms than in hurricane situations. One would expect to see that the cases with a hurricane would vary a lot and thus, the 12-hour forecast will tend to have greater errors, which is captured by the standard deviation.
d. Correlations between GFS and AVNO errors

Correlations can quantify how well two sets of data are well connected to each other. Two data sets with a positive correlation means that as one variable increases the other does too, but a correlation of negative one suggests that as one variable increases the other decreases, and a correlation of zero means that there is no relationship between the two sets of data. One major point to keep in mind is that correlation might lead to a cause but it doesn’t tell one what it is on its own course. Correlations were calculated on AVNO hurricane track and intensity errors to the GFS mean fractional error for each atmospheric layer under investigation. None of the correlations showed promising results because the correlations that were calculated mostly were somewhere close to zero. This could be because the number of storms that the errors were computed for was small, only seven, which is not a significant amount of samples for generating sound statistics. So there could be a correlation, but to find that out future work must be conducted, to incorporate more storms, maybe then some high correlations may be found.

Even though 95% of the correlations were close to zero, there were some significant and promising numbers. There was a correlation of 0.941951 between the 0-hour AVNO intensity standard deviation of the fractional error and the fractional error between the 0-hour GFS model in a 5° by 5° Lat/Lon box, at the 10km to 20km layer of the atmosphere. There was a correlation of 0.74129 between the 12-hour AVNO intensity standard deviation of the fractional error and the fractional error between the 12-hour GFS model in a 5° by 5° Lat/Lon box, at the 10km to 20km layer of the atmosphere. The reason for such high correlations is because the GFS is the same as AVNO. Since these two models are essentially the same analyses, one would expect high correlations.

Also there are high correlations in the 20km to 30km layer of the atmosphere to the mean intensity error for the 0 hour and 12 hour AVNO forecasts, with correlations of 0.67, 0.74, and 0.87, but these correlations don’t hold any significance. The reason why they do not hold any significance is because that layer of the atmosphere shows constant error in the GFS model in every case, in every storm, in every time interval \( I \), to the occultation being that this is the maximum atmospheric layer that the GFS model analyzed. Usually the models’ maximum atmospheric layers are never predicted correctly such that huge error that were correlated to the AVNO 0-hour and 12-hour predictions errors were not valid.

4. Conclusion

The goal of this study was to provide insight as to whether or not the addition of RO data into global and hurricane models might suggest improvements in the forecasts of tropical systems. The first thing that was analyzed was the characterization of error in the GFS model with respect to the distance from the center of the storm. The results showed that the error in the models grew as one got closer to the core of the storm. However, with large number of storms the results were fairly subtle, but the 5km to 10km layer of the atmosphere had the most robust error near the hurricane’s core, as oppose to the higher vertical layers like the 20km to 30km that aren’t as sensitive. Then goal of this study shifted to conducting verification of the GFS and ECMWF model outputs to
CHAMP RO data during hurricane events. The conclusions drawn from this verification were that the farther from the core of the hurricane one is, the variability between the models decreases, and that the mean fractional error was less than the mean RMS. After the verification process between the models, the GFS 12-hour forecast mean fractional error and the mean standard deviation were tested against the corresponding real hurricane and bogus hurricane. This showed that the mean standard deviations of the bogus storms were lower than those of real storms. Finally, correlations were conducted on the errors found in the AVNO model to the fractional error in the GFS model. These correlations suggest that for future work it may be wise to have more storms to get a statistically robust reading of the correlations between the GFS and AVNO errors. But there were still some high positive correlations with intensity errors between the two models in the 10km to 20km layer in the GFS 0 and 12-hour forecast model on a 5º by 5º Lat/Lon Box. Hopefully, the inclusion of these RO data into global weather forecast models will help allay the errors found near the center of the storm, improve the variations between the different global models, show that the bogus storms have a lower fractional error than the real hurricane case, lower the correlations between the errors found in the center of the storm to the errors found in the track and intensity forecasts due to the addition of these RO data around the storm to ultimately help improve the track and intensity forecast for future storms.

REFERENCES


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