A global analysis of atmospheric refractivity anomalies using CHAMP data

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ABSTRACT

In early 2006, the US-Taiwan joint satellite mission known as the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) will launch six Low Earth Orbit (LEO) satellites. These satellites, each equipped with an advanced Global Positioning System (GPS) receiver, will use radio occultation (RO) limb sounding technology to profile the Earth's atmosphere with unprecedented accuracy and vertical resolution. The GPS RO soundings available from COSMIC will make significant contributions to global weather prediction, ionospheric research, and climate monitoring. The GPS receivers will measure the phase and amplitude. From that we can deduce the bending angles as a function of height, and obtain vertical profiles of refractivity using the Abel inversion under the local spherical symmetry assumption. To demonstrate the potential value of GPS RO data in climate research, we analyzed atmospheric refractivity obtained from GPS RO data in a recent single-satellite German mission, known as the *CHAllenging Mini Payload for Geophysical Research and Application* (CHAMP). This study examined the refractivity anomalies by altitude and latitude per season of CHAMP GPS RO data, provided by UCAR's COSMIC Data Analysis and Archive Center (CDAAC), from May 2001 through present. Refractivity anomalies across the globe were illustrated in color plots that identified any persistent anomaly patterns. A structure has been identified over the tropical stratosphere from 20-30km, which may have a possible relationship with the Quasi-Biennial Oscillation (QBO). Results show that GPS refractivity data can be used to identify specific trends between seasons as well as identify multi-year phenomenon such as QBO. This study highlights the usefulness of refractivity values from GPS RO data in climate research.

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I. INTRODUCTION

1.1 Climate

Climate change is a research topic that today is receiving a remarkable amount of attention across many different scientific disciplines. As our planet continues to change, the need to understand the effects of these changes becomes increasingly more apparent and even crucial to maintaining our way of life. Studies have shown that although a general Artic warming trend has existed for the past hundred years, the past few decades show a trend 8 times larger than the 100-year trend (Comiso 2003). Comiso's study in 2003 used satellite thermal infrared data to find that the large warming anomalies of the 1990's not only surpass those of the previous decade, but also have lengthened the melting season by 10 to 17 days. In the Antarctic, warming is not quite as pronounced due to the high elevation of the continent. However, there are still some indications from various data sources that show significant warming trends in this region as well. Even in the tropics Meehl's study in 2000 showed that the tropical tropopause is a region where models predict significant changes.

1.2 Applications

The accuracy of meteorological predictions is greatly limited by the scarcity of available data. Large data gaps exist over oceans and poles, where obtaining hourly or even daily meteorological information can be very difficult. Even continents such as South America have very few radiosonde stations and have very limited daily atmospheric soundings. Figure 1 illustrates where radiosonde stations are currently available to obtain vertical profiles; these locations are shown by the red dots. The green dots on this figure are examples of RO soundings that will be available from the upcoming Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission within a 24-h period. Immediately, one can notice that a great advantage of missions such as COSMIC will be their increased global coverage. In particular, COSMIC will provide uniform global coverage (unlike the radiosonde), which is very important for climate monitoring, as it will significantly reduce potential sampling errors due to irregular distribution of data. Assimilating this new data in the form of refractivity or bending angle into numerical weather models allows models to obtain more accurate analysis of atmospheric field variables (temperature, water vapor, and wind) closer to actual values (Kuo et al., 1997, Zuo et al., 1999, 2000).

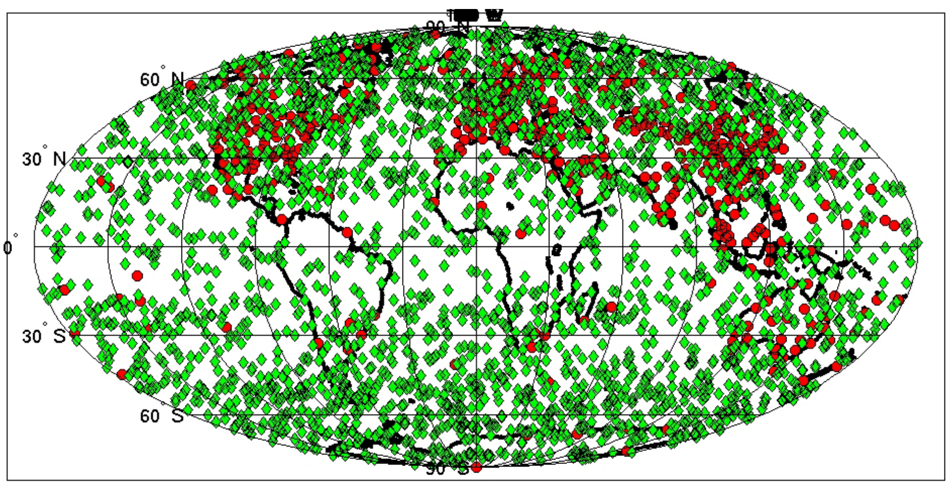

Figure 1. Locations of the current global radiosonde stations are shown in red. An example of GPS RO soundings over a 24-h period from COSMIC are shown in green. Much more data will be available over oceans and polar regions for research and operational applications.

COSMIC will also allow scientists to monitor current atmospheric conditions without the need for calibrating a variety of measuring the same variables. In addition, the GPS limb sounding technology used in COSMIC is mission independent and therefore eliminates the concern of long-term consistency with climate monitoring. As previously mentioned, areas such as the oceans and polar regions contain very few traditional radiosonde measurements; this becomes a problem when attempting to monitor climate. The uniform global distribution of COSMIC GPS RO data will allow for more robust climate studies in areas that are of particular interest.

1.2 COSMIC

When launched in spring 2006, the COSMIC mission will begin collecting vertical soundings of the Earth's atmosphere with an extent of global coverage that has never been achieved before. The COSMIC mission will consist of six Low Earth Orbit (LEO) satellites that will orbit the planet at an inclination of 72 degrees. Each LEO satellite will be equipped with a GPS receiver, a tiny ionospheric photometer (TIP), and a tri-band beacon (TBB). The GPS receiver will be the primary payload instrument with the major objective of collecting phase and amplitudes of GPS signals. The TIP and TBB are secondary payload instruments and will be used to measure nighttime electron density as well as ionospheric scintillation. Overall, COSMIC will give atmospheric scientists, in a variety of fields, access to data that has exceptional global coverage and is readily available in near real-time.

1.4 Study Objective

In this study we examined refractivity values for the entire globe by latitude bands of 2.5. Refractivity values were collected for all occultations available from CHAMP. Plots of refractivity changes for each season and each year were created to illustrate how a particular year's season compares to a seasonal average. This paper provides a method to monitor climate change in the form of refractivity to be used in future studies involving GPS RO data.

II. METHOD

2.1 GPS Introduction

Using the Global Positioning System (GPS) as a remote sensing tool is a revolutionary technique to determine atmospheric properties. This technology, known as GPS Radio Occultation (RO), can be used to obtain measurements of refractivity, temperature, pressure, electron density, and water vapor (Anthes et al. 2003). The GPS system, which contains 24 operational satellites, works in conjunction with Low Earth Orbit (LEO) satellites to capture radio signals that pass close to the Earth's atmosphere and consequently are refracted by vertical variation of density. The measurement of the bending of the radio signals transmitted by GPS can be used to determine the atmospheric refractivity (Anthes et al. 2003, Rocken et al. 2000). In order to infer other properties from atmospheric refractivity, one must first compute a Doppler shift from phase and amplitude collected by the GPS receiver and combine this information with known GPS and LEO velocities to compute a bending angle of the radio signal shown in Figure 1 (Kursinski et al. 2000, Anthes et al. 2003). Anthes et. al. 2003 show how this angle can be used in an Abel transform to obtain an index of refraction profile. From this one can relate refractivity with temperature, water vapor, and electron density to determine more specific atmospheric properties (Anthes et al. 2003).

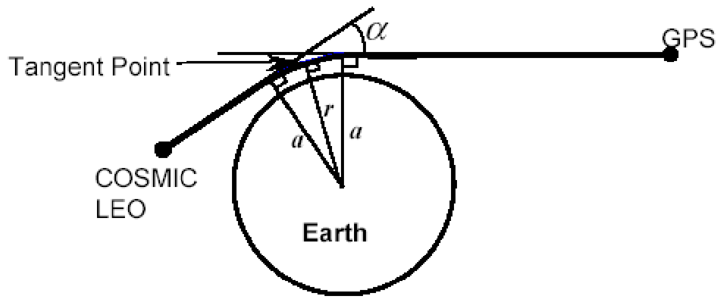

Figure 2: GPS radio signal being refracted (bent) by the Earth's atmosphere and bending angle that is obtained.

The radio occultation technique was first used in planetary exploration in the 1960s. The GPS RO capability was further demonstrated in the proof of concept mission, known as GPS Meteorology in 1995 (GPS/Met). In the past decade, several satellite missions have allowed us to enhance our understanding of GPS RO technology, and to use this knowledge to further advance the technique. The upcoming COSMIC mission builds upon previous successes and promises to provide much more data on a daily basis that will allow scientists to more easily study areas of climatology, space weather, and meteorology. COSMIC's six satellites will bring at least 3,000 GPS soundings daily across the globe when the satellites are launched in the early 2006.

However, until COSMIC data is available, this study will use CHAMP data beginning with the spring of 2001. Although other satellite data is available, this mission was optimal for this study because of its continuous record of data, which eliminates any potential problems associated with data gaps.

2.2 Data Retrieval and Analysis

The GPS RO data are collected, analyzed, and archived at the COSMIC Data Analysis and Archive Center (CDAAC) in Boulder, Colorado. CDAAC can be accessed from the COSMIC website and is open to anyone. In this study, CDAAC was accessed from a COSMIC server using customized Perl scripts. These scripts describe operations to collect soundings across the globe, to group them by latitude bands, and to calculate average statistics on the data up to a specified altitude. The outputs of these scripts are various plots designed to examine the atmospheric refractivity changes of a particular season compared to a year-long seasonal average. These plots are used in the analysis to identify trends and ultimately form conclusions and ideas for future studies.

Data analysis consisted of several steps and constraining factors:

- Vertical profiles were collected from spring 2001 until spring 2005 (dates that CHAMP data is available).
- The area sampled was the entire globe by latitude bands of 2.5.
- The data used was limited from the surface to an altitude of 30 km. Above this altitude some errors can be introduced from ionospheric effects (Kuo et al. 2004).
- Each vertical profile was divided into 500-meter layers.
- Each layer of every profile within a latitude band was averaged seasonally for each year of available data.
- A total seasonal average was also calculated for similar seasons throughout the time period (i.e winter seasonal average for all winters).
- A difference comparing one particular season to the total season average was then calculated and plotted as percent change.

The custom Perl scripts produced plots of altitude versus latitude, which showed percent refractivity changes with the above constraints. These plots were examined for trends and used to demonstrate the potential use of this method and radio occultation data in future climate studies.

2.3 Calculations of Refractivity Anomalies

Calculating refractivity changes involved a process of three simple calculations. After collecting the data from CDAAC, binning the occultations by 2.5 degree latitude bands, and restricting our data to 30 km, we determined a sum for all the values of refractivity for the season. This sum of all values for each band and layer of altitude was then divided by the total number of occultations to find a seasonal-year average, $\overline{N}^{YR}$. This same general method was then applied using all years for a particular season to calculate $\overline{N}^{season}$. Once these two values were determined, a simple difference was found between them. To more easily view refractivity changes, the difference between $\overline{N}^{YR}$ and $\overline{N}^{season}$ was divided by $\overline{N}^{season}$ to return a value of percent change. These percent changes were the values used in all of the plots. Equations 2a, 2b, and 2c show mathematically the procedure used to calculate refractivity changes.

$$\overline{N}^{YR} = \frac{\sum N_m}{total} \qquad \text{(eq. 2a)}$$

$$\Delta\overline{N}^{YR} = \overline{N}^{YR} - \overline{N}^{Season} \qquad \text{(eq. 2b)}$$

$$Fr(\Delta \mathrm{N}) = \frac{\Delta \overline{N}^{Season}}{\overline{N}^{Season}_{total}} \qquad \text{(eq. 2c)}$$

III. Results

The resulting calculations mentioned above from equation 2c were then illustrated in the form of a plot of altitude versus latitude by percent change of refractivity. The seasons analyzed were defined by three month intervals beginning with December as the first winter month and ending with November as the third fall month of the following year. Table 1 shows the month numbers and which season they correlated with.

Table 1. Seasonal definitions used in study

Winter	December	January	February
Spring	March	April	May
Summer	June	July	August
Fall	September	October	November

Since CHAMP's data is available since day 120 of May 2001, there were approximately four years of data which corresponds with 16 plots total (four for each season). Preliminary analyses showed that plots clearly illustrated areas where positive and negative anomalies exist. These areas had a tendency to be located in the stratospheric regions at high latitudes. An area primarily within the middle troposphere can be identified as an area of low refractivity anomalies. This tropospheric region is fairly narrow at the high latitudes and expands to a higher altitude at the equator. An example of these plots is shown in figure 3.

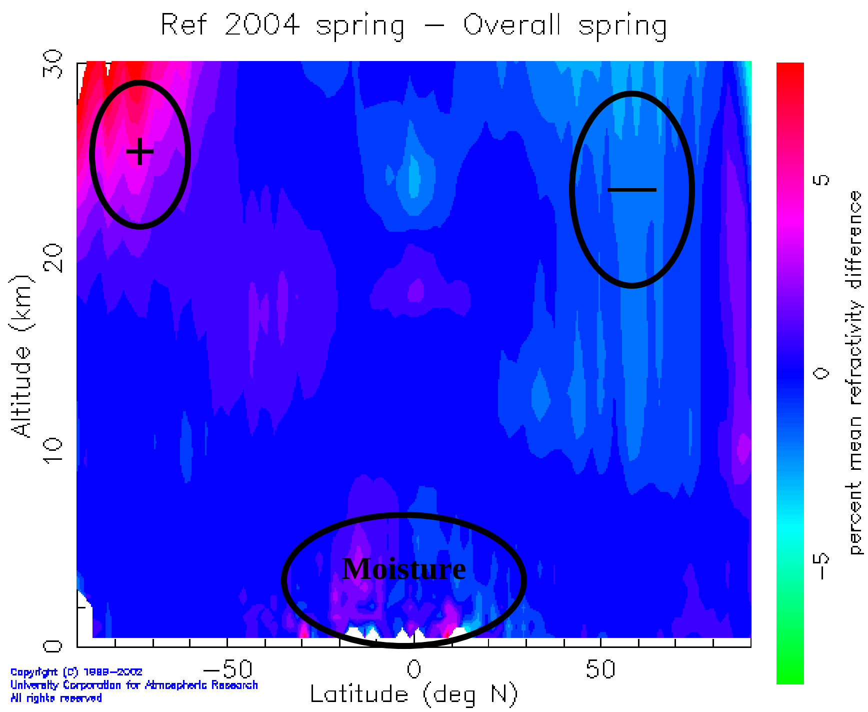

Figure 3. Example of result plot illustrating refractivity anomalies for spring 2004. The plot can be used to identify easily areas of positive and negative anomalies as drawn on the plot. An area over the low altitudes in the tropics consistently has anomalies due mostly to the nature of high moisture variability in this region.

3.1 Seasonal Comparisons

A further analysis compared similar seasons between the northern and southern hemispheres. A first glance at the plots of refractivity anomalies may spark one to question whether or not there is substance to this data and wonder if the anomalies are completely random. By comparing similar seasons from both hemispheres it can be shown that there is a consistent pattern of anomalies between seasons regardless of which portion of the globe is in reference. Figure 4 shows two plots where seasons are labeled based on the respective seasons that correspond with the calendar in that particular hemisphere. When shown side-by-side, one can clearly see that there is a mirror image effect between the two matching seasons. This provides evidence to conclude that the refractivity anomalies shown in the result plots are showing true anomalies which are not random and show consistent structure in time.

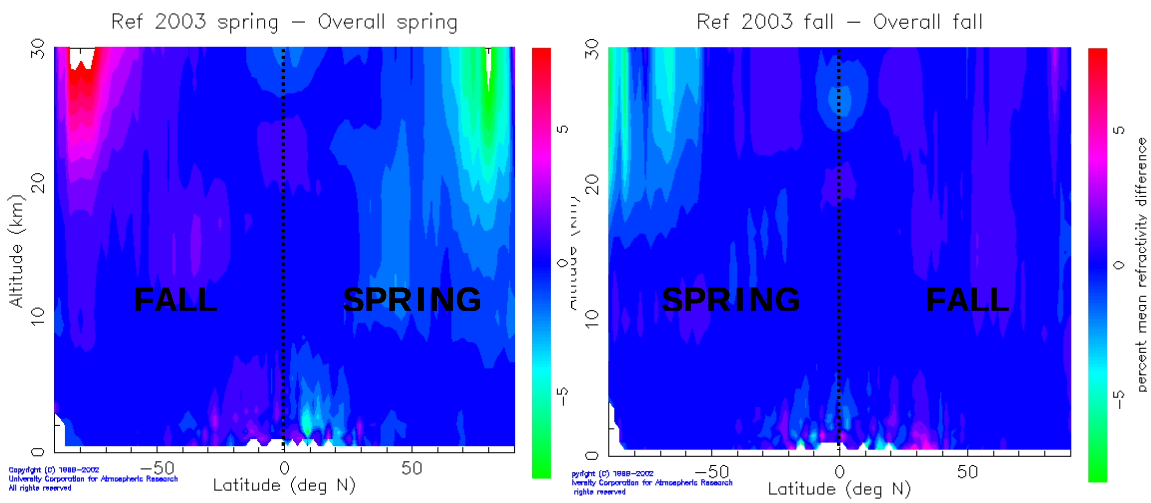

Figure 4. A seasonal comparison shows the consistency of refractivity anomalies between opposite hemispheres but same seasons.

3.2 Quasi-Biennial Oscillation (QBO)

An unexpected discovery from the refractivity anomalies was the realization of a possible relationship with the QBO. QBO is a wind phenomenon that takes place in the tropical stratosphere. Within this region the prominent winds shift from westerlies to easterlies on an average period of about 28 months. QBO is characterized by an area of predominately westerly winds at an altitude slightly higher than a separate area of easterly winds. As the normal period progresses the westerly winds propagate from the upper portion of the stratosphere to a lower altitude to eventually replace the easterly winds below. This entire process occurs on average between altitudes of 20-30 kilometers. This shift in wind direction has been shown to have a possible effect on the number and intensity of tropical cyclones which develop in the tropics (Baldwin 2001).

In our plots of global refractivity anomalies, we found that a coupled structure of positive and negative anomalies existed over the tropical stratosphere between 20 and 30 kilometers. This coupling can be best explained by QBO since this is the same type of structure of wind direction between westerlies and easterlies over the same exact region. It is likely the different wind directions bring air over the region of different temperatures which cause the refractivity values to have abrupt differences. A plot illustrating this structure is shown in figure 5.

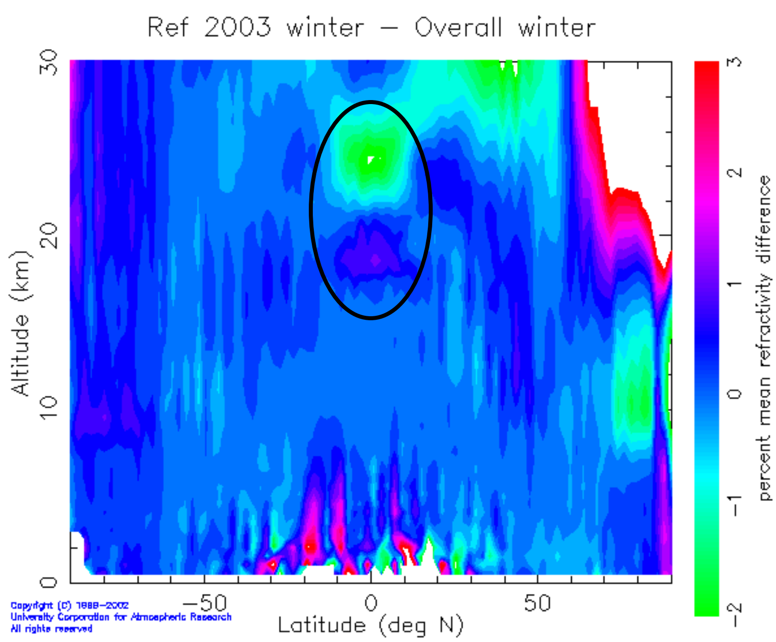

Figure 5. Plot of refractivity anomalies showing a coupling of positive and negative values which is best explained by effects of QBO.

IV. Conclusions

4.1 Possible Error Sources

Although a great deal of valuable information appears to be available using plots of global refractivity anomalies, we must be careful to keep in mind even the smallest of possible error sources. Kuo et al 2004 showed that there are some errors generally above 25km related to ionospheric effects and the use of climatology to reduce this noise. These errors are generally small, but could cause problems with small percent average differences as used in this study. The use of a neutral atmosphere may not be a good assumption when averaging and differencing over a period of years. However, Adame 2004 showed in a study of average refractivity over a period of a year for the Antarctic region, that standard deviations are generally quite small, less then 5%. This shows that although refractivity values over smaller averages are valid, more must be done to determine the validity due to ionospheric effects of these averages over a longer time period.

4.2 Future Work

Perhaps the most interesting conclusion from this study is the possible relationship with the Quasi-Biennial Oscillation. This area of research is fairly unexplored and the introduction of GPS remote sensing to this field could help answer many involved scientific questions. Understanding QBO better using this method of global refractivity anomalies could very well make a significant impact on climate studies of the stratosphere.

In addition, more work must be done to understand the exact error that propagates into yearly averages of refractivity. This percent error must be calculated before any confirmation of a QBO relationship can be made. It must be proven, without any significant doubt, that these refractivity anomaly values are very real and justified.

4.3 Summary and Conclusions

Although exact calculations have not been completed to determine the exact error possibly associated with ionospheric effects, the patterns are clearly defined in these refractivity plots. The patterns are consistent between seasons as shown in a comparison of fall and spring months in the southern and northern hemispheres. The method allows scientist to create plots which clearly show areas of positive and negative anomalies. And lastly, a consistent structure of positive and negative anomaly coupling can best be explained by the effects of QBO.

This method promises to provide valuable information to atmospheric scientists across a variety of fields, in particular, those studying climatology of the tropical stratosphere. The method also gives value to the use of radio occultations in atmospheric science. The future launch of more satellites to collect more GPS soundings will only contribute more to the accuracy and capabilities of methods such as the one used in this study.

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