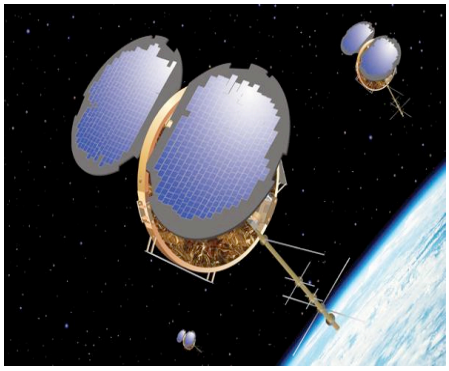
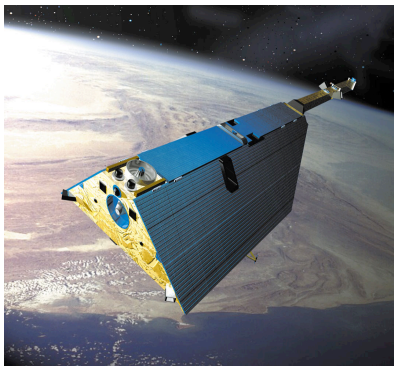


COSMIC



CHAMP

YEAR 2 ANNUAL PROJECT REPORT
NOAA GRANT NA07OAR4310224

VALIDATION AND CALIBRATION OF MSU/AMSU MEASUREMENTS AND RADIOSONDE OBSERVATIONS USING GPS RO DATA FOR IMPROVING STRATOSPHERIC AND TROPOSPHERIC TEMPERATURE TREND ANALYSIS

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1. Introduction

Accurate temperature trend estimates are crucial to monitor decadal climate variability and to understand climate change forcing mechanisms. To construct consistent climate temperature records, long-term well-calibrated satellite temperature measurements with good temporal and spatial coverage from various missions are needed. On board the National Oceanic and Atmospheric Administration (NOAA) series of polar-orbiting satellites, the Microwave Sounding Unit (MSU) and the Advanced Microwave Sounding Unit (AMSU) have also provided near all-weather temperature measurements at different atmospheric vertical layers since 1979 and 1998, respectively. Radiosondes are the only operational instruments that have provided continuous atmospheric pressure, temperature, and humidity measurements in the troposphere and lower stratosphere (~25 km) for more than three decades. However, due to on-orbit calibration drift for MSU/AMSU measurements, and measurement uncertainties associated with different types of radiosondes at different geophysical locations and seasons, it is extremely difficult to use MSU/AMSU and radiosonde observations to construct a long-term climate quality data set. Recently, the Global Positioning System (GPS) Radio Occultation (RO) technique has been proven to be a mature global observation technique and is ideally suited for climate trend detection. GPS RO produces global data coverage without the need for calibration or bias correction. In addition, because GPS RO data do not contain orbit drift errors and are not affected by on-orbit heating and cooling of the satellite components, they are very useful for identifying the MSU/AMSU time/location dependent biases for different NOAA missions.

The specific goals for this project are as followings:

- **Task 1: Using GPS RO data to help identify a set of operational radiosonde network for further climate studies.**

- **Task 2: Using GPS RO data in the stratosphere and the identified radiosondes in the troposphere as climate benchmark datasets to validate MSU and AMSU measurements to understand exactly how and why there are differences in temperature trends reported by several analysis teams using the same observation systems but different analysis methods.**

- **Task 3: Generating long-term stratospheric and tropospheric climate quality temperature datasets by reprocessing nine years of AMSU/MSU data from 2001 to 2009 and delivering this data set to NCDC.**

The work undertaken to date on these project goals is detailed in section 2 and immediate plans are detailed in section 3. Plans for next year are in section 4.

2. Progress on Proposed Studies

In this study, we propose to use MSU/AMSU measurements and radiosonde observations and GPS RO data from *Challenging Minisatellite Payload* (CHAMP) from 2002 to 2009 and FORMOSAT-3/Constellation Observing System for Meteorology, Ionosphere, and Climate mission (denoted as COSMIC hereafter) from 2006 to 2009 to construct consistent long-term stratospheric and tropospheric climate quality temperature datasets. Following tasks in year 1, **work to-date has focused on 1) continuing the preparation of GPS RO, radiosonde and MSU/AMSU data for geo-location comparisons, 2) continuing to quantify the uncertainty of GPS RO data for climate monitoring, 3) continuing to estimate the reproducibility for using GPS RO data for climate monitoring, 4) continuing the assessment of the systematic biases of global radiosonde measurements using RO data, 5) refining the methods to use GPS RO data to inter-compare and inter-calibrate MSU/AMSU data, 6) performing comparisons of COSMIC/CHAMP data with $NESDIS_{NEW}$ MSU data and $NESDIS_{OPR}$ MSU data, 7) performing comparisons of CHAMP/COSMIC, RSS, UAH TLS Trends.**

2.1 Preparation of GPS RO, Radiosonde, and MSU/AMSU Data for Geo-location Comparisons

Several new processed GPS RO data, NOAA MSU/AMSU data, MSU/AMSU climatology from RSS and UAH groups, AMSU data from NASA Aqua AMSU measurements, and temperature measurements from global radiosondes are collected. Two procedures were performed to prepare the data for further comparisons:

a. Data collection (all data we have collected, newly processed data are in blue)

We downloaded the following data from corresponding FTP and achieve sites:

- CHAMP data (from Jan. 2001 to May 2009) from UCAR CDAAC,
- COSMIC data (from June 2006 to May 2009) from UCAR CDAAC,
- GRACE data (from June 2006 to Dec. 2008) from UCAR CDAAC,
- MSU/AMSU data from NESDIS ($NESDIS_{OPR}$) for NOAA 14 (MSU), NOAA 15 (AMSU), NOAA 16 (AMSU) and NOAA 18 (AMSU) from 2002 to 2009,
- RSS V3.2 data from 2001 to 2009 from their FTP site,
- UAH V5.1 data from 2001 to 2009 from their FTP site,
- New processed $NESDIS_{NEW}$ data (processed by Dr. Cheng-Zhi Zou and NOAA team) from their related FTP sites,
- Global radiosonde data from NCAR archive, and
- ECMWF data from NCAR archive.

b. Data matching

To minimize the temporal/spatial/vertical-resolution mismatches among various datasets, we generated the following collocated data pairs:

- CHAMP-COSMIC, GRACE-COSMIC pairs (within 90 minutes, and 200 km).
- MSU/AMSU-RO pairs (within 15 minutes, and 50 km).
- RSS/UAH-RO pairs (monthly mean, 2.5×2.5 grid, we further bin each monthly mean MSU/AMSU and CHAMP 2.5 degree × 2.5 degree matched pairs into 10 degree × 10 degree grids).
- Radiosonde-RO pairs (temperature and moisture profiles obtained from radiosondes are interpolated onto RO locations within 3 hours and 200 km).
- ECMWF-RO pairs (ECMWF temperature and moisture profiles are interpolated onto RO locations within 3 hours and 200 km).
- To avoid AMSU vertical weighting function representation errors, instead of using a global fixed weighting function (WF), we apply a COSMIC/CHAMP dry temperature profile to an AMSU fast forward model from the Cooperative Institute for Meteorological Satellite Studies-CIMSS with 100 fixed pressure levels.

2.2 Continue to quantify the uncertainty of GPS RO data for climate monitoring

We continue to quantify the uncertainty of GPS RO data for climate monitoring. Here we quantify the uncertainty of GPS RO data for climate monitoring by estimating (i) the precision and (ii) long-term stability of GPS RO data.

a. Quantification of the Precision of COSMIC Data for Climate Studies

- **Using GPS RO profiles from the COSMIC mission to quantify the precision of RO data for climate research**: RO profiles from early stages of the COSMIC mission were used while the six COSMIC receivers were closely located, and were supposedly sensing GPS RO signals crossing similar atmospheric paths. Results show that the mean difference (the precision for climate research) between two receivers (FM3-FM4) in dry temperature measures 0.03 K between 0.5 km and 30 km, while near the surface, the mean difference is about 0.09 K (**Figure 1**). These differences are consistent with different latitudinal zones.
- **Comparing results from COSMIC FM3-FM4 dry temperature to theoretical prediction and understand the causes of the differences:** Not only the mean difference is important but also the uncertainty of the difference is important for climate monitoring. Although we have theoretical analysis available, the error characteristics are never examined using real data. Here we quantify the error characteristics for the COSMIC RO data from different COSMIC receivers.
- **Comparing COSMIC FM3-FM4 dry temperature at different local time**

bins

- **Quantifying the sampling error and random error of RO data by comparing COSMIC data to ECMWF profile**
- The initial results are published in **Ho, S.-P.**, M. Goldberg, Y.-H. Kuo, C.-Z Zou, W. Schreiner, Calibration of Temperature in the Lower Stratosphere from Microwave Measurements using COSMIC Radio Occultation Data: Preliminary Results, Terr. Atmos. Oceanic Sci., Vol. 20, doi: 10.3319/TAO.2007.12.06.01(F3C), 2009 (see section 2.9).
- More results found in this study are in preparation for a journal paper (**Ho, S.-P.**, Y.-H., Kuo, W. C. Schreiner, D. Hunt, C. R. Rocken, Estimates of the precision of GPS Radio Occultation for climate studies, J. Geophy. Research, 2009).

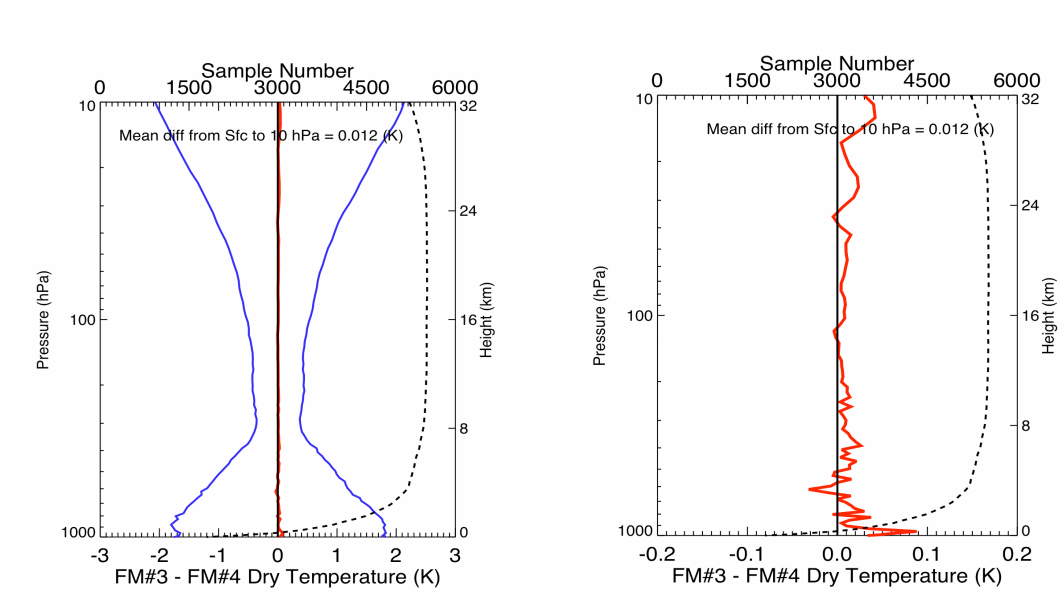

Figure 1. Panel on the left illustrates the mean and the median absolute deviation (MAD) of the dry temperature difference between two COSMIC satellites (FM3 and FM4) from 2006, day 111 through 300 where the distance between FM3-FM4 receivers is within 20 km. The dash line is MAD to its median difference (in solid line) and the dash dot line is number of FM3-FM4 profile pairs used in the comparison at various vertical levels. Panel on the right illustrates the median of the dry temperature difference between FM3-FM4 as the panel on the left but in a much smaller temperature scale in x-axis.

b. Quantifying the uncertainty of the difference between two RO missions

To use GPS RO data as a climate benchmark dataset, it is extremely important to quantify the mean difference between two RO missions to demonstrate that the quality of GPS RO data are not changed after launch.

- **Quantify the uncertainty of the difference between COSMIC (launched in 2006) and CHAMP (launched in 2000) data for climate research:** we used the latest post-processed COSMIC and CHAMP data from 2006-2008 to quantify the mean difference between these two datasets in order to demonstrate that the quality of GPS RO data will not change after launch. Results of the COSMIC and CHAMP pairs collocated within 200 km and 1.5 hours collected from September 1 2006 to July 31, 2008 show that the mean dry temperature difference between 300 hPa and 10 hPa is equal to 0.04 K (**Figure 2**).
- **Quantify the uncertainty of the difference between COSMIC and Gravity Recovery and Climate Experiment (GRACE, launched in March 2002):** similar comparison are made between COSMIC and GRACE. Results of the COSMIC and GRACE pairs collocated within 200 km and 1.5 hours collected from September 1 2006 to July 31, 2008 show that the mean dry temperature difference between 300 hPa and 10 hPa is equal to 0.035 K (**Figure 2**). This study demonstrates stability of RO data from different RO missions.
- Results found in this study are in preparation for a journal paper (**Ho, S.-P.,** Y.-H., Kuo, W. C. Schreiner, D. Hunt, C. R. Rocken, Estimates of the long stability of GPS RO data: inter-comparison of COSMIC and CHAMP results, J. Geophy. Research, 2008).

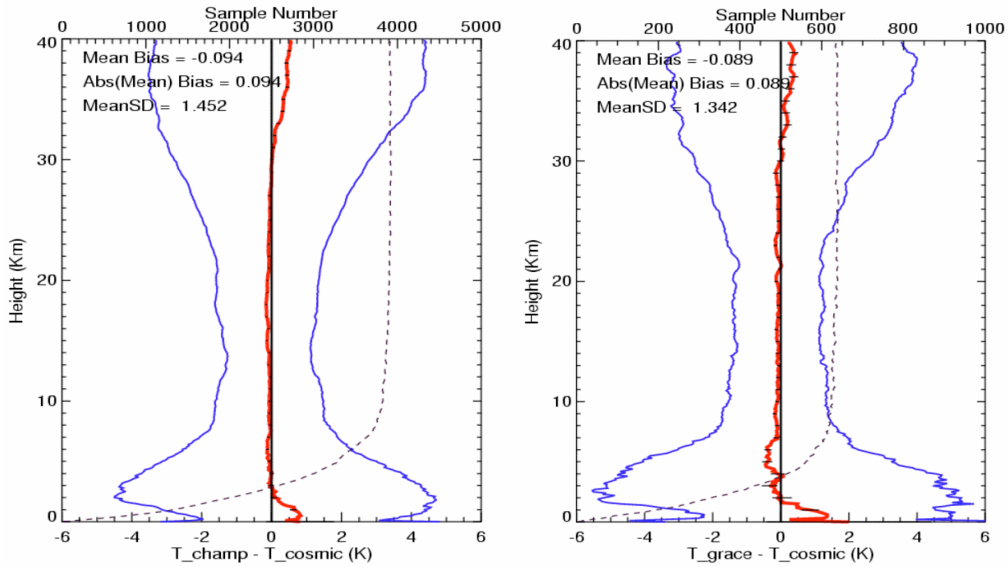

Figure 2. Panel on the left illustrates comparison statistics (mean: red; standard error of the mean: horizontal black lines superimposed on the mean; standard deviation: blue, sample number of compared soundings: dotted black line) of 4000 CHAMP and COSMIC profiles that were collocated within 200 km and 90 minutes September 1 2006 to July 31, 2008. Panel on the right illustrates comparison statistics of 600 GRACE and COSMIC profiles that were collocated within 200 km and 90 minutes September 1 2006 to July 31, 2008.

2.3 Estimates of the Reproducibility for using GPS RO Data for Climate Monitoring: Inter-comparisons of Refractivity Derived from Different Data Centers

To claim GPS RO data as a climate benchmark dataset, we need to demonstrate that inverted RO products are not dependent on retrieval algorithms.

a. Monthly mean climatology (MMC) comparison

- **Inter-comparisons of MMC of refractivity derived from different data centers:** Currently, multi-year GPS RO climate data can be obtained from the GeoForschungsZentrum Potsdam (GFZ), Potsdam, Germany, the Jet Propulsion Laboratory (JPL), Pasadena, CA, USA, the University Corporation for Atmospheric Research (UCAR), Boulder, CO, USA, and the Wegener Center of the University of Graz (WegC), Graz, Austria. To quantify the uncertainty for using GPS RO data for climate monitoring, the monthly mean CHAMP refractivity profiles from 2002 to 2006 derived from these four RO centers are compared.
- **Trend difference: Fig. 3** depicts the time series of monthly mean fractional refractivity (N) anomalies for UCAR, JPL, Weg and GFZ. The monthly mean time series of fractional refractivity anomalies are computed from the average of the N values from 8 km to 30 km. Because the differences in fractional refractivity produced by the four centers are in general unchanging with time, the uncertainty of the trend for fractional refractivity anomalies among centers is **±** 0.04%/5 yrs globally. The primary cause of the trend uncertainty is due to different quality control methods used by the four centers, which have the effect of eliminating different subsets of the entire data set, yielding different sampling errors for different centers.
- **Using NCEP data to estimate the sampling errors:** We used the National Centers for Environmental Prediction reanalysis in the same period to estimate sampling errors. After removing the sampling errors, the uncertainty of the trend for fractional refractivity anomalies among centers is between -0.03 to 0.01%/5 yrs. Thus 0.03%/5 yrs can be considered an upper bound in the processing-scheme induced uncertainty for global refractivity trend monitoring.
- Results found in this study are under review of JGR (**Ho, S.-P.**, Gottfried Kirchengast, Stephen Leory, Chris Rocken, Ying-Hwa Kuo, Jens Wickert, Tony Mannucci, Sergey Sokolvskiy, William Schreiner, Doug Hunt, Andrea Steiner, Ulrich Foelsche, and Chi Ao, 2008: Estimates of the Uncertainty for using Global Positioning System Radio Occultation Data for Climate Monitoring: Inter-comparisons of Refractivity Derived from Different Data Centers, *J. Geophys. Res.* (submitted and complete response to review).

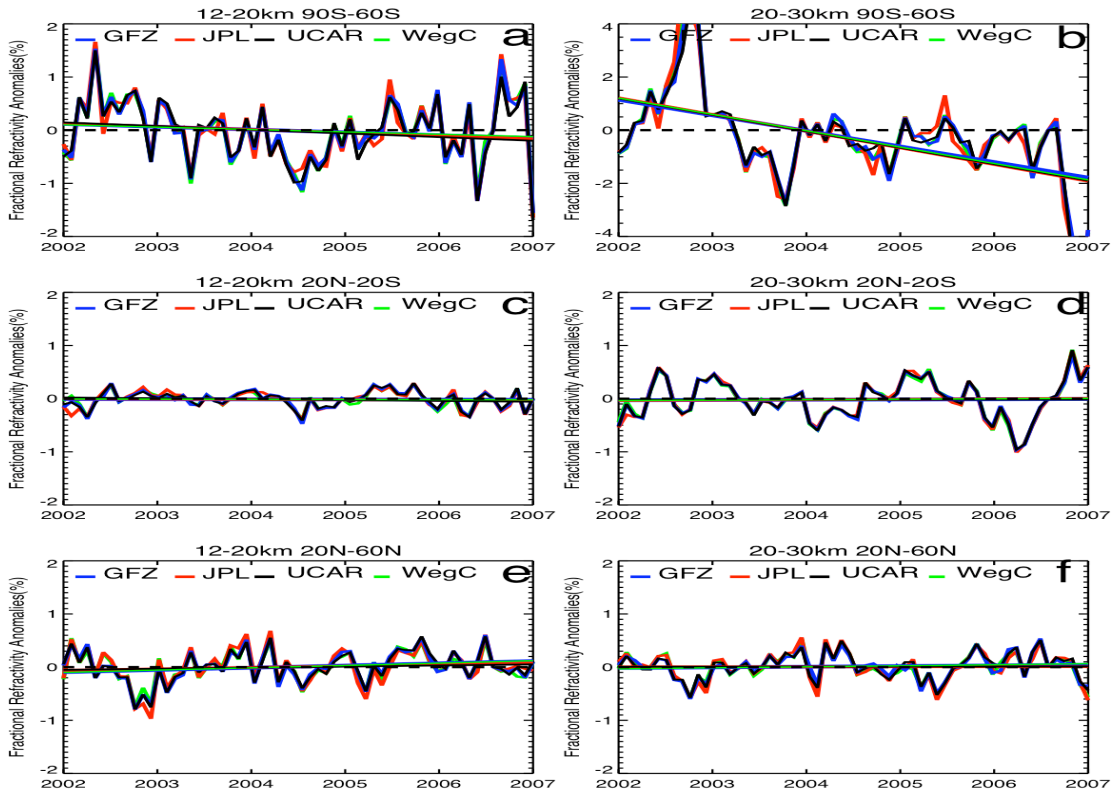

Fig. 3. The de-seasonalized fractional refractivity anomalies for each center in the 12-20 km layer for a) the 60ºS to 90ºS zone, c) the 20ºN to 20ºS zone, and e) the 20ºN to 60ºN zone, and in the 20-30 km layer for b) the 60ºS to 90ºS zone, d) the 20ºN to 20ºS zone, and f) the 20ºN to 60ºN zone. The 5-yr trend for each center is shown as well. Note that panel b has its ordinate range enlarged to +/-4% (relative to +/-2% of panels a, c-f).

b. The profile-to-profile comparison among data from different centers

To understand the cause of the refractivity difference between centers without concerning their sampling errors (in MMC), the profile-to-profile refractivity comparison is necessary.

- **The profile-to-profile refractivity comparison between UCAR and GFZ**: Here we compare the profile-to-profile CHAMP refractivity profile from UCAR and GFZ form Jan. to Dec. 2006. The mean profile-to-profile refractivity difference between UCAR and GFZ is less than 0.05% (**Fig. 4**) in the height between 12 km and 25 km, with a MAD less than 0.2%. We have collected CHAMP refractivity profiles derived from UCAR, GFZ, JPL, and WegC from 2002 to 2006, and will continue to use the common set of data to identify the causes of the RO profile differences between centers.
- **The common set of GFZ, UCAR, WegC, and JPL CHAMP data is collected. Further comparisons will be conducted.**

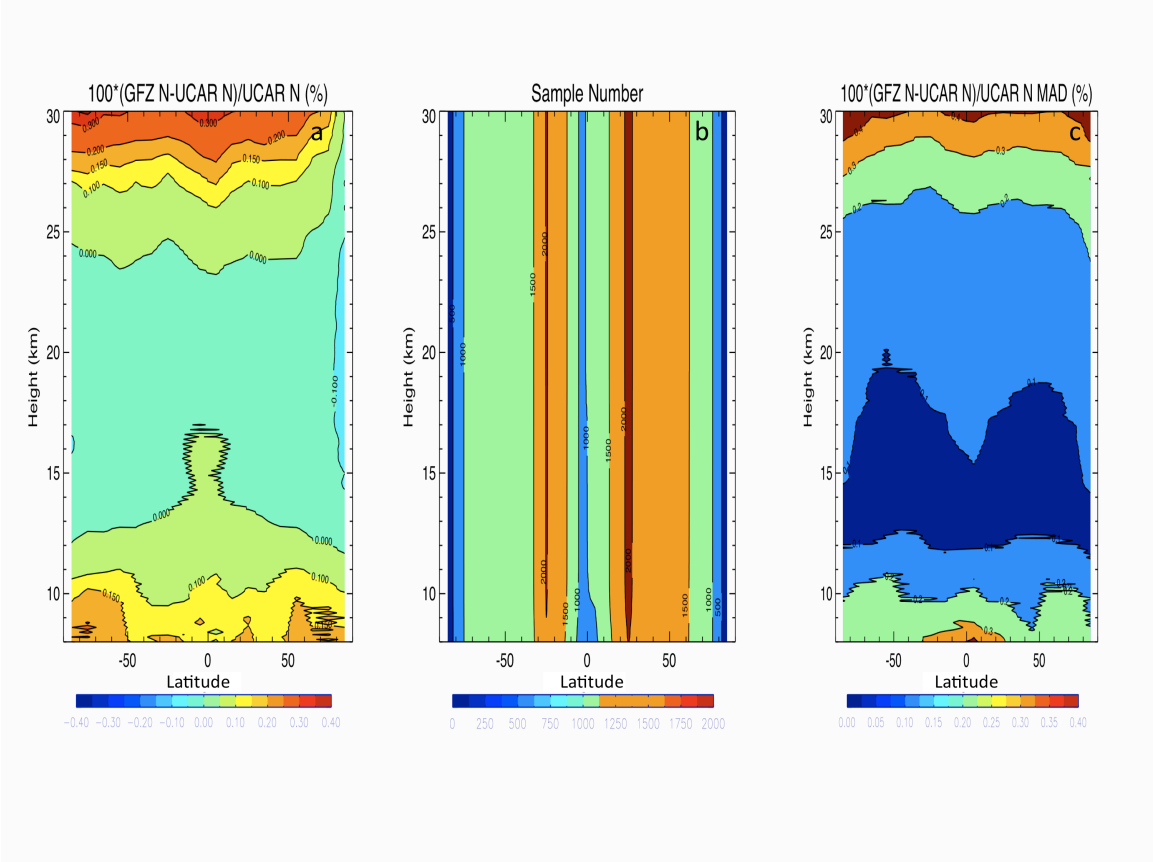

Fig. 4. The left panel illustrates the difference in the mean zonal-average refractivity (in a 5-degree bin) for profile-to-profile UCAR and GFZ fractional refractivity pairs over the period from January 2006 to December 2006. The middle panel and right panel illustrate the sample number and the median absolute deviation (MAD) in each 5-degree latitude bin, respectively.

2.4 Assessment of the Systematic Biases of Global Radiosonde Measurements using RO Data

Because the time delay of RO signal is traceable to international standards of time (SI traceability), GPS RO data, unlike radiosondes, are not affected by the changing of on-orbit extreme environments and are consistent with geographical locations. Therefore, COSMIC-derived temperature and water vapor profiles shall be useful to assess the systematic biases of global radiosonde measurements.

a. The Usefulness of COSMIC Data to Identify Temperature Biases of Different Types of Radiosonde Systems in the Upper Troposphere and Lower Stratosphere

Because the quality of COSMIC RO data are not affected by the surrounding environment (e.g., geo-location, day and night, etc.), COSMIC data are very useful to identify the possible radiative biases of radiosondes, where sensor characteristics vary considerably in times and locations for different sensor types.

- **Collecting COSMIC and global radiosonde data:** Radiosonde data used in this study are obtained from CDAAC (via NCAR mass store, DS 353.4). No radiative correction was made in this dataset. Radiosonde temperature measurements within 2 hours and 300 km of COSMIC RO soundings are used to compare to those from COSMIC.
- **Using COSMIC RO temperature to identify systematic temperature biases from different types of radiosonde: Figure 5** depicts temperature differences between COSMIC and radiosonde for MRZ, Shanghai, VIZ-B2, and Vaisala-RS92, respectively. Despite the fact that COSMIC observations have around 200 km horizontal resolution and radiosondes take point measurements, temperature profiles of each radiosonde type in general agree well with those of COSMIC from 10 km to 25 km with smaller than 0.5 K mean differences and less than 2.0 K standard deviations (**Fig. 5**). A dominant negative temperature difference (-0.3 K) between COSMIC and MRZ radiosonde occurs from 16 to 25 km while an obvious positive difference relative to COSMIC profiles is shown above 20 km for VIZ-B2 radiosonde (~0.17 K).

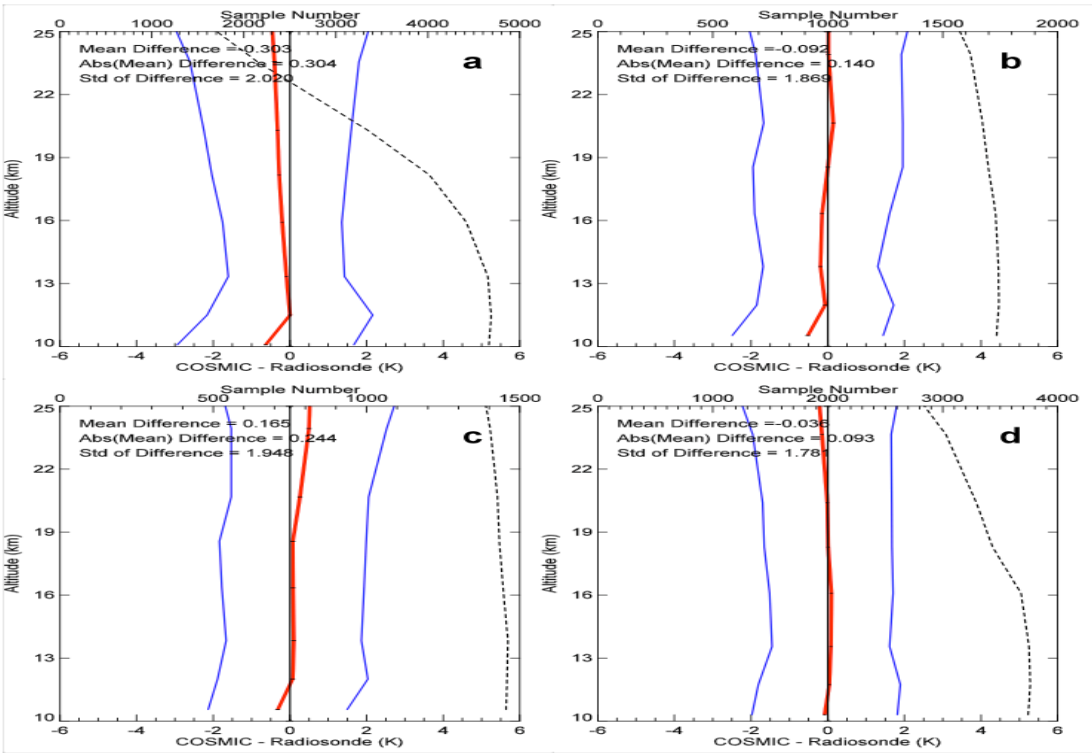

Figure 5. Comparisons of temperature between COSMIC and radiosonde for a) MRZ, b) Shanghai, c) VIZ-B2, and d) Vaisala-RS92 (the red line is the mean difference; the horizontal black lines superimposed on the mean are the standard error of the mean; the blue line is the standard deviation; the dotted line is the sample number. The top X axis shows the sample number. The same symbols are also used for the following plots).

- **Quantify the radiative effect on radiosonde temperature anomalies using COSMIC temperature profiles:** The quality of radiosonde temperature measurements varies obviously by day and night for different radiosonde sensor types. To further identify the causes of the statistically significant COSMIC and radiosonde differences for MRZ, we separate the COSMIC-radiosonde comparison for daytime and nighttime for MRZ in **Figures 6**, respectively. **Figure 6** shows an obvious warm bias for MRZ relative to COSMIC above 10 km, and the bias increases to about 1.0 K at 25 km during the day, while there is a less than 0.06 K COSMIC-MRZ temperature difference at night. Here we divide COSMIC-MRZ matches into two groups, one with solar elevation angle 0°-10° and another with solar elevation angle 10-20° since solar elevation mostly ranges from 0° to 20° during the winter over Russia. A large solar elevation angle indicates stronger direct solar heating that would potentially affect the performance of MRZ. Comparisons show that MRZ has a larger mean temperature difference (~0.9 K) relative to COSMIC for solar angle 10°-20°than that for solar angle 0°-10° (~0.62 K).

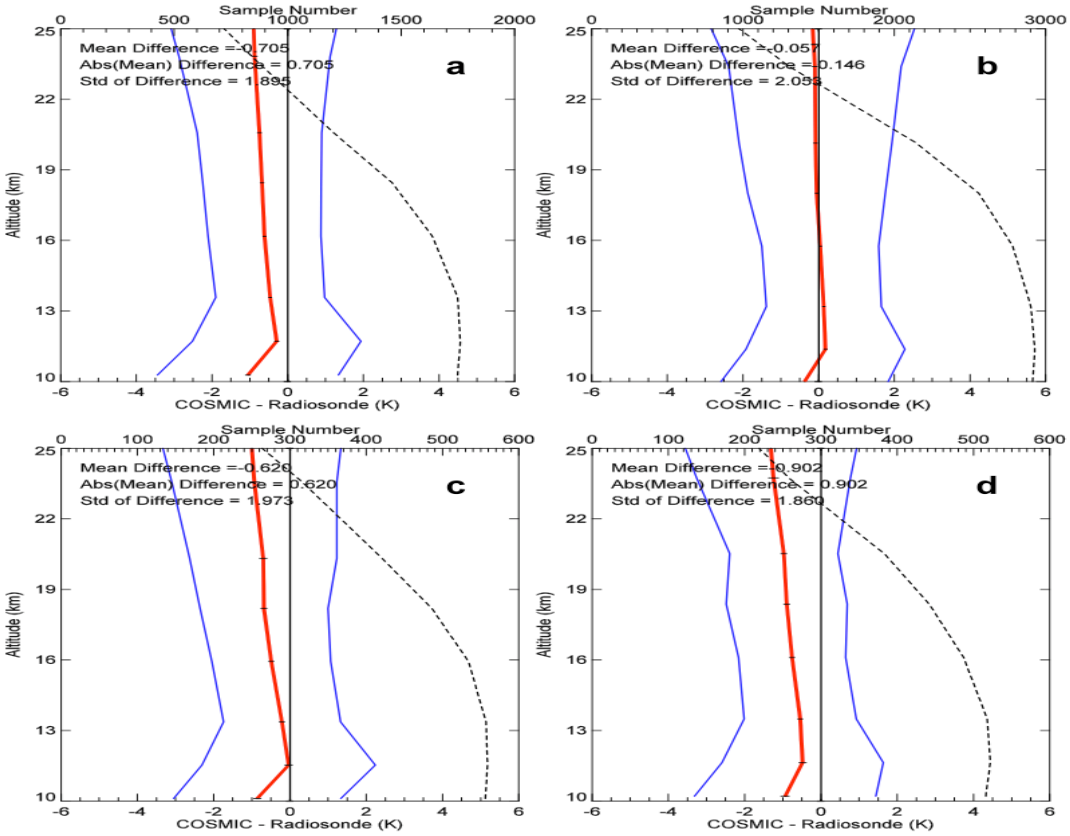

Figure 6. Temperature difference between COSMIC and MRZ radiosonde in a) day, and b) night, and c) for solar elevation angle 0°-10°, and d) for solar elevation angle 10°-20°.

- Results found in this study was submitted to GRL (Wenying He, **S.-P. Ho**, H. Chen, X. Zhou, D. Hunt, Y.-H. Kuo, Assessment of the Radiosonde Systematic Temperature Errors in the Upper Troposphere and Stratosphere using COSMIC Radio Occultation Data, *Geophy. Research Letters,* 2009 (submitted and complete response to review).
- **To further demonstrate the usefulness of GPS RO to indentify the quality of different types of radiosonde systems, CHAMP/COSMIC data from 2001 to 2009 will be used to compare to global radiosonde data.**

b. Assessing the Precision and Accuracy of COSMIC Measurements in the Lower Troposphere

With the high precision refractivity from COSMIC RO data and reasonable independent temperature profiles, we shall have highly accurate COSMIC-derived water vapor profiles.

- **Quantify the accuracy and precision of the global COSMIC refractivity and water vapor profiles in the lower troposphere:** To further validate the accuracy of COSMIC-derived water vapor, we compare the total precipitable water (PW) from COSMIC with those derived from ground-based GPS (i.e., International Global Navigation Satellite Systems–IGS) which are assumed to be not geo-location dependent. Results show that the mean global difference between IGS PW and COSMIC PW is equal to -0.2 mm with standard deviation of 2.58 mm (**Figure 7**). This result demonstrated the accuracy and precision of COSMIC-derived water vapor in the lower troposphere.

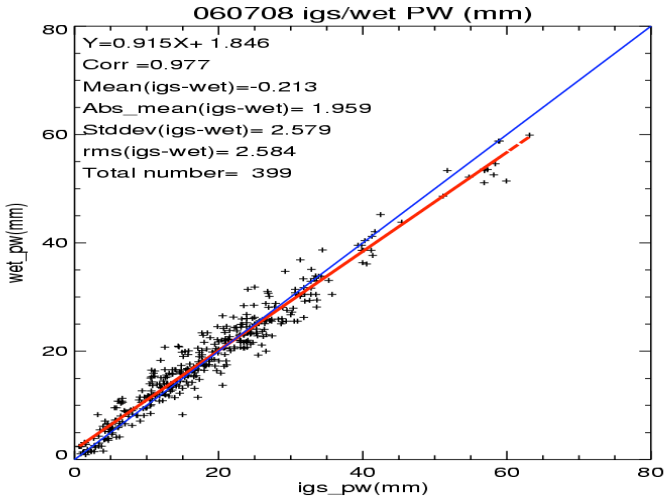

Figure 7. Global comparison of IGS PW and COSMIC PW for those IGS and COSMIC ensembles are within 100 km, 1 hour, and the height of IGS and the lowest height of COSMIC profile is within 100 m.

c. *The Usefulness of COSMIC Data to Assess the Water Vapor Biases of Different Types of Radiosonde Systems*

Because in the lower troposphere RO data are very sensitive to water vapor variation than that of temperature, the ROs yield profiles of all-weather humidity in a 200 km horizontal resolution accurate to 0.2 to 0.5 g/kg in the lower to middle troposphere. Here we use RO water vapor in the lower troposphere to assess the water vapor biases of different types of radiosonde systems.

- **Matching COSMIC water vapor profiles with those radiosonde water vapor profiles:** To assess the systematic water vapor biases measured from different types of radiosonde systems, we conducted comparisons of water vapor profiles derived from COSMIC and those profiles of radiosondes over Russia, Japan, China, and India. Radiosonde temperature measurements within 2 hours and 300 km of COSMIC RO soundings are used to compare to those from COSMIC.
- **Compare COSMIC water vapor profiles with those from ECMWF**: To quantify the accuracy of the estimated COSMIC refractivity and water vapor profiles, we also compared COSMIC profiles to those from the European Centre for Medium Range Forecasts (ECMWF) global analysis over the same geographical area of radiosondes during the same period. Results show that the quality of the RO soundings is very consistent over different geographical areas. This is evidenced by the relatively small variations in the COSMIC and ECMWF water vapor differences between geographical areas (see **Figure 8**).
- **Assess the systematic water vapor biases measured from different types of radiosonde systems using COSMIC water vapor data:** on the contrary to the RO-ECMWF water vapor comparison results, COSMIC-Radiosonde water vapor biases (in g/kg) vary considerably for different areas. There are obvious dry water vapor biases for those radiosondes from China (**Figure 8**) and India (not shown) where there are no obvious radiosonde water vapor biases from Russia and Japan. Results here demonstrate the usefulness of COSMIC-derived water vapor profiles to assess the systematic water vapor biases from different types of radiosonde systems.
- Results found in this study was submitted to GRL (**Ho, S.-P.**, Xinjia Zou, Y.-H., Kuo, 2008: Assessment of the Quality of Radiosonde in the Troposphere using GPS Radio Occultation from COSMIC, *Geophy. Research Letters* (under co-author's review, ready for submission).

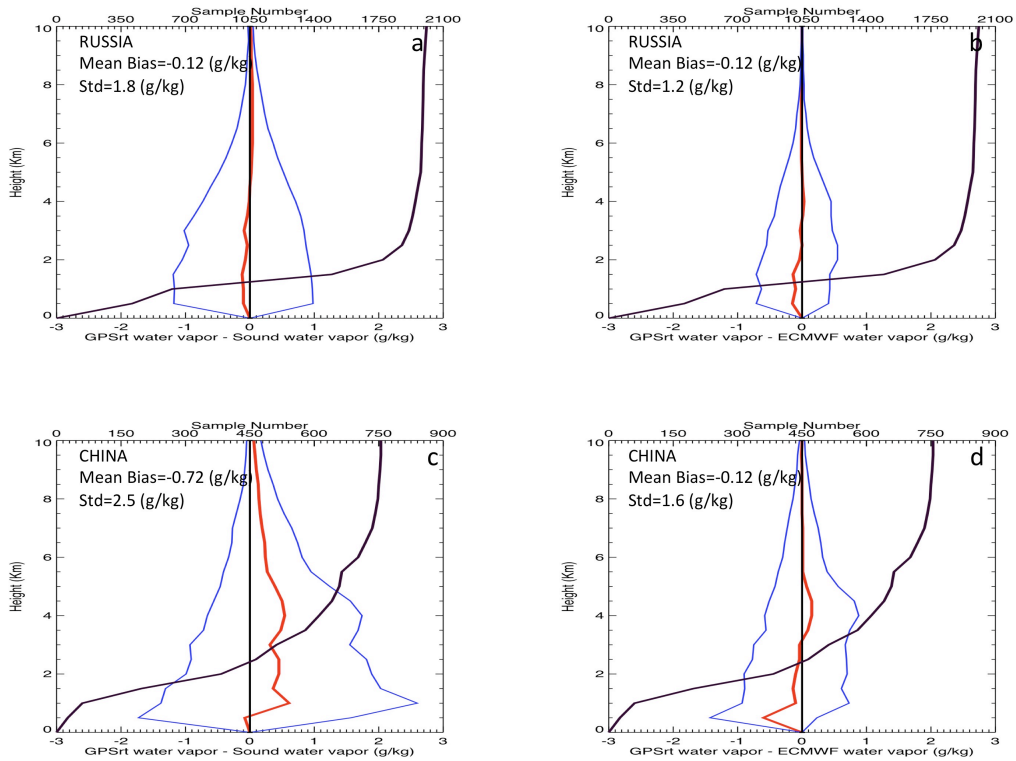

Figure 8. The comparison of COSMIC water vapor profiles with a) collocated Russian radiosondes, b) collocated ECMWF water vapor profiles near the Russian radiosondes, c) collocated China radiosondes, and d) collocated ECMWF water vapor profiles near the China radiosondes.

2.5 Continue to refine the methods to use GPS RO data to inter-compare and inter-calibrate MSU/AMSU data

We continue to refine the methods to use GPS RO data to inter-compare and inter-calibrate MSU/AMSU data.

a. The Usefulness of GPS RO to Inter-calibrate NOAA AMSU Measurements Ch8 and Ch10

To demonstrate if GPS RO data can be used to inter-calibrate not only NOAA AMSU Ch9 measurements, but also Ch8 and Ch10 measurements, we collect GPS RO-AMSU pairs within 15 minutes and 50 km and generate the calibration coefficients (slope and offset) for NOAA AMSU Ch8 and Ch10 and examine the uncertainty of the calibration coefficients. GPS RO dry temperature profiles are converted to AMSU brightness temperature using the CIMSS AMSU forward radiative transfer model.

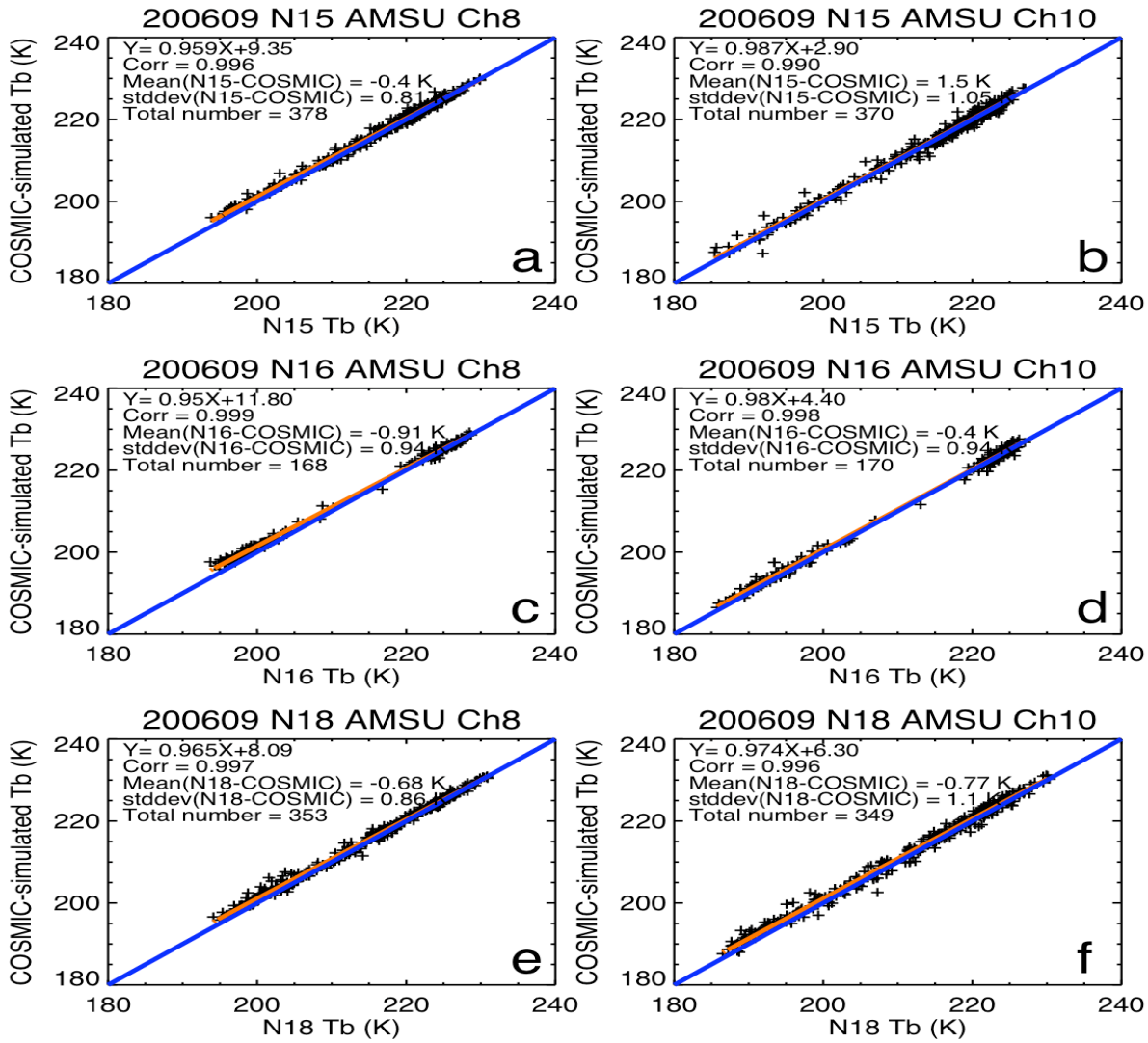

Figure 9: Comparison of (a) COSMIC-simulated AMSU Ch8 Tbs and NOAA 15 AMSU Ch8 Tbs, (b) COSMIC-simulated AMSU Ch10 Tbs and NOAA 15 AMSU Ch10 Tbs, (c) COSMIC-simulated AMSU Ch8 Tbs and NOAA 16 AMSU Ch8 Tbs, (d) COSMIC-simulated AMSU Ch10 Tbs and NOAA 16 AMSU Ch10 Tbs, (e) COSMIC-simulated AMSU Ch8 Tbs and NOAA 18 AMSU Ch8 Tbs, (f) COSMIC-simulated AMSU Ch10 Tbs and NOAA 18 AMSU Ch10 Tbs.

- **Comparison of GPS RO simulated brightness temperatures (Tbs) and AMSU Tbs**: The comparisons are made between COSMIC-simulated AMSU Ch8/Ch10 Tbs and collocated AMSU Ch8/Ch10 Tbs from N15, N16 and N18 within 15 minutes and 50 km.
- **Analysis results**: The comparisons of N15, N16, and N18 Ch8 and Ch10 Tbs, to the corresponding synthetic COSMIC Tbs are shown in **Fig. 9**. Most of COSMIC-NOAA pairs in **Fig. 9** are over polar regions where water vapor content above 500 hPa shall be negligible. Because a very

small portion of AMSU Ch8 and Ch10 WFs are covering above 10 hPa (for AMSU Ch10) and below 500 hPa (for AMSU Ch8), the effect of the uncertainty of GPS RO dry temperature below 500 hPa to the synthetic AMSU Tbs is small. The COSMIC synthetic AMSU Ch8 and Ch10 Tbs are very close to those from AMSU Tbs. The excellent agreement and small variations between AMSU Ch8 Tbs and Ch10 Tbs from N15, N16 and N18 and those from synthetic COSMIC Tbs demonstrates the potential to use COSMIC data to inter-calibrate AMSU Ch8 and Ch10 Tbs.

- Results from this study combined with other analysis are submitted and accepted by TAO (**Ho, S.-P.**, M. Goldberg, Y.-H. Kuo, C.-Z Zou, W. Schreiner, Calibration of Temperature in the Lower Stratosphere from Microwave Measurements using COSMIC Radio Occultation Data: Preliminary Results, Terr. Atmos. Oceanic Sci., Vol. 20, doi: 10.3319/TAO.2007.12.06.01(F3C), 2009)**.**

b. The Usefulness of GPS RO data to Identify the On-orbital Location/Time Dependent AMSU Biases

Different MSU/AMSU missions may contain different measurement biases, which actually vary with time and location due to on-orbit heating or cooling of the satellite component. Due to lack of an absolute reference, only relative inter-satellite biases are corrected (absolute AMSU inter-satellite biases are all smaller than that for NOAA-COSMIC pairs), which may lead to uncertainties for climate trend analysis. Here we demonstrate the usefulness of GPS RO data to inter-calibrate AMSU brightness temperatures (Tbs) by identifying the orbit-dependent biases.

- **Comparison of COSMIC RO simulated brightness temperatures (Tbs) and NOAA 15, 16, and 18 AMSU Tbs at different geo-locations from July 2006 to Dec. 2008:** COSMIC RO dry temperature profiles from July 2006 to Dec. 2008 are used to compute the synthetic AMSU Ch9 Tbs. COSMIC-simulated AMSU Ch9 Tbs and collocated AMSU Ch9 Tbs from N15, N16 and N18 within 15 minutes and 50 km are compared.
- **Analysis results**: it is shown in **Fig. 10** that N18-COSMIC Tbs are in general lower during the southern hemispheric winter where N18 is under the shadow of the earth (solar zenith angle is larger than 80 degrees) and are higher in the northern hemisphere (ranges from 7 to 17 local times). Because GPS RO data are not affected by the temperature variation of the satellite component, the mean N18-COSMIC AMSU Tb biases are mainly from AMSU Tb anomalies due to the heating or cooling of the satellite component. The NOAA-COSMIC AMSU Tb biases from July 2006 to Dec. 2008 show that the variation of AMSU-COSMIC Tb biases is highly coherent with the NOAA satellite orbit change with local time. AMSU-COSMIC Tb biases are in general lower during the southern hemispheric winter in the night and higher in the northern hemisphere in the day. Because COSMIC data, unlike MSU/AMSU data, do not contain

orbit drift errors and are not affected by on-orbit heating and cooling of the satellite component, they are very useful to identify the AMSU time/location-dependent biases for different missions.

- **Exploring the possibility to use AIRS vertical temperature retrievals to quantify the accuracy of COSMIC RO temperature profiles.**
- **Comparing the NASA Aqua AMSU measurements with COSMIC/CHAMP simulated AMSAU Tbs.**

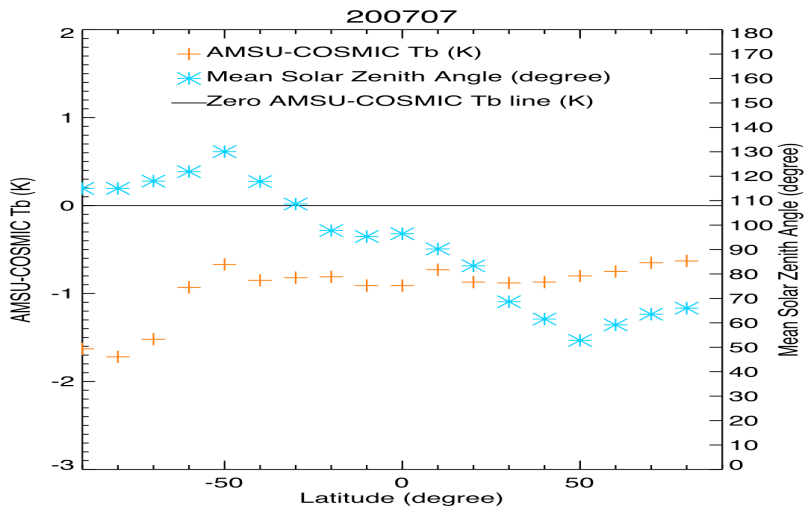

Fig. 10 Binned N18-COSMIC AMSU Ch9 Tb differences for mean solar zenith angle bin and binned latitude variation for N18 orbit.

2.6 Comparisons of COSMIC/CHAMP data with $NESDIS_{NEW}$ MSU data and $NESDIS_{OPR}$ MSU data

- **Collecting the new processed NOAA MSU $NESDIS_{NEW}$ and $NESDIS_{OPR}$ data.**
- **Performing forward calculation using CHAMP/COSMIC RO dry temperature profiles to simulate MSU Tbs.**
- **Matching COSMIC/CHAMP simulated MSU Tbs with $NESDIS_{NEW}$ and $NESDIS_{OPR}$:** To demonstrate the usefulness of RO data to identify the MSU $NESDIS_{NEW}$ Tb correction of diurnal local time drift, we compare COSMIC simulated MSU Ch4 Tbs with those from $NESDIS_{OPR}$ and $NESDIS_{NEW}$ MSU Tbs (**Figure. 11**). COSMIC data and NOAA 14 MSU data from Sep. 2006 are used. Results show that the mean $NESDIS_{OPR}$-COSMIC Tbs is equal to -0.09 K which is much smaller than that of $NESDIS_{NEW}$-COSMIC Tbs (=-1.05 K). Result here is against with what we expect (after SNO correction, the mean $NESDIS_{NEW}$–COSMIC Tb shall be smaller than that of $NESDIS_{NEW}$ –COSMIC Tb). We will closely work with Dr. Cheng-Zhi Zou and the NOAA team to further investigate this issue during the remainder of calendar year 2009.

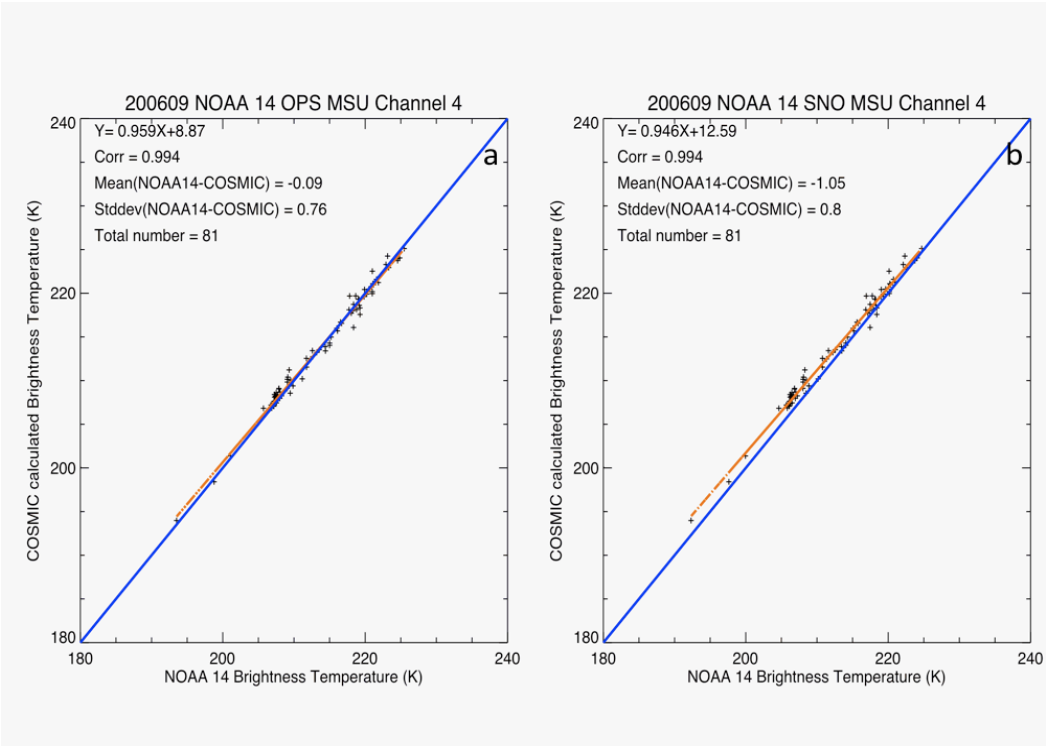

Figure 11. Comparison of COSMIC simulated MSU Ch4 Tbs with those from a) $NESDIS_{OPR}$ NOAA 14 MSU Ch4 Tbs and b) $NESDIS_{NEW}$ NOAA MSU Ch4 Tbs. COSMIC data and NOAA 14 MSU data from Sep. 2006 are used.

- **Comparing the multi-month CHAMP/COSMIC simulated MSU4/AMSU9 brightness temperatures to those of $NESDIS_{NEW}$ and $NESDIS_{OPR}$ and identifying the reason for different trends from different groups.**

2.7 Comparisons of CHAMP/COSMIC, RSS, UAH TLS Trends

Recently, Christy from the University of Alabama in Huntsville (UAH) presented climatology of tropospheric and stratospheric temperatures based on 30 years (from 1979 to 2008) of MSU/AMSU data (UAH V5.1). Mears et al., (20080 from Remote Sensing Systems (RSS) Inc. had also used the same raw MSU/AMSU measurements from 1979 to 2008 to construct a new MSU/AMSU dataset (RSS V3.2). Here we conduct comparisons of CHAMP/COSMIC, RSS, UAH TLS trends using MSU/AMSU data from June 2001 to June 2008.

- **Collecting the new processed RSS V3.2 data and UAH V5.1 data.**
- **Performing forward calculation using CHAMP/COSMIC RO dry temperature profiles to simulate AMSU TLS (AMSU Ch9 brightness temperature).**
- **Binning CHAMP/COSMIC TLS into monthly mean 2.5×2.5 grid climatology.**

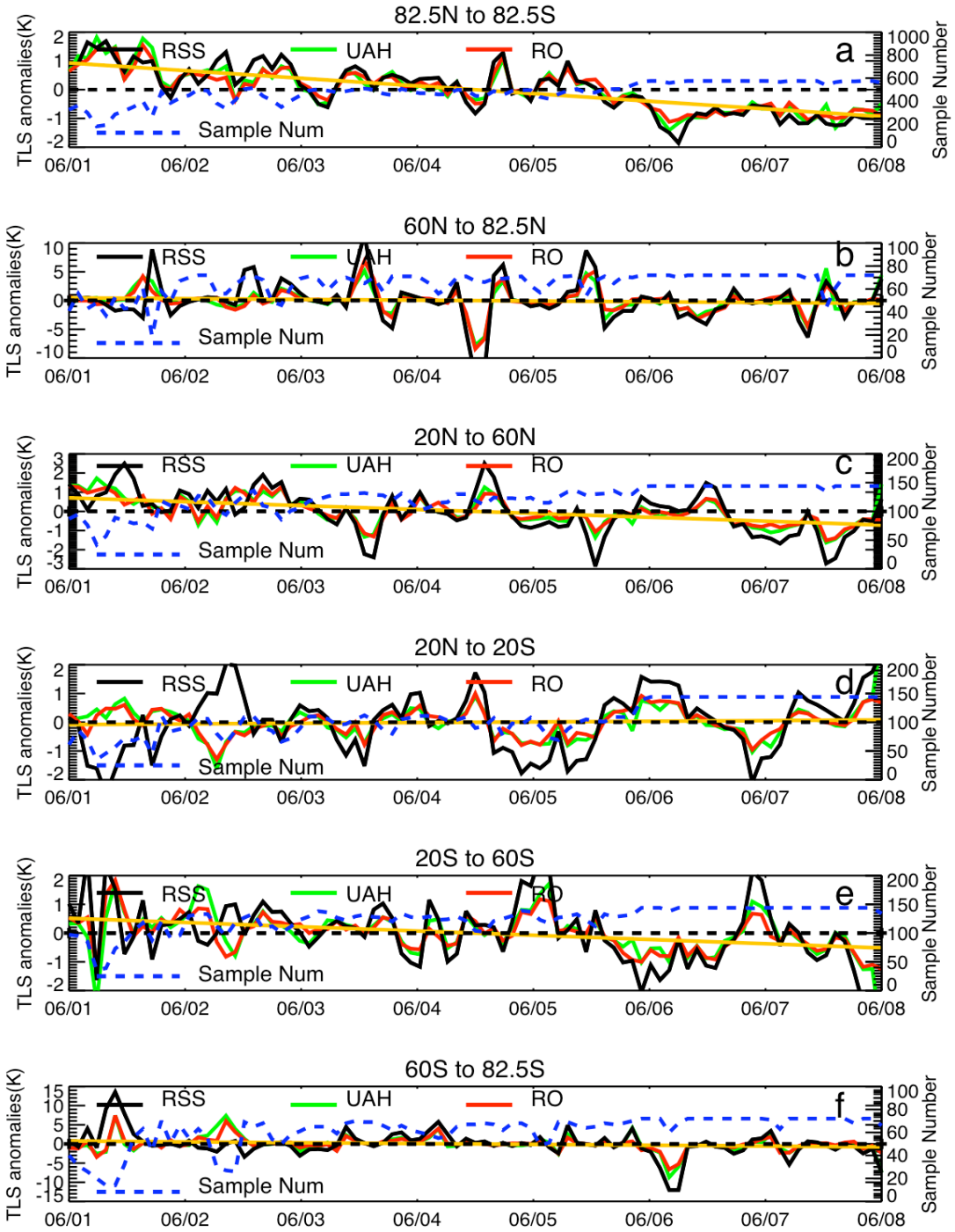

Figure 12. The de-seasonalized lower stratospheric Tb anomalies of RSS, UAH and CHAMP for (a) the global (82.5˚ N to 82.5˚ S region), (b) 60˚ N to 82.5˚ N zone, (c) 20˚ N to 60˚ N zone, (d) 20˚ N to 20˚ S zone, (e) 20˚ S to 60˚ S zone, and (f) 60˚ S to 82.5˚ S zone. The orange line indicates the mean trend for RSS. The corresponding numbers of matching pairs for each month in each latitudinal zone are in blue dash lines.

- **Further binning RSS/UAH-RO monthly mean MSU/AMSU and CHAMP 2.5 degree × 2.5 degree matched pairs into 10 degree ×10 degree grid monthly mean climatology.**
- **Performing Trend Analysis of RSS, UAH and CHAMP TLS Anomalies:** using about 8 years (96 months) of data pairs, here we examine the consistency among the $CHAMP_{TLS}$, RSS_{TLS} and UAH_{TLS} Tb anomalies. The de-seasonalized Tb anomalies of RSS_{TLS}, UAH_{TLS} and $CHAMP_{TLS}$ generated for global and five latitudinal zones are plotted in **Figure 12**. TLS anomalies are computed by subtracting the mean value for each month of the year for the period from June 2001 to June 2008 from each of the TLS time series. In general, the de-seasonalized Tb anomalies from UAH_{TLS} and RSS_{TLS} are consistent with that from $CHAMP_{TLS}$ globally (**Fig. 12a**), the trends (in K/5year) found from RSS_{TLS}, UAH_{TLS} and $CHAMP_{TLS}$ Tb anomalies, however, vary for the different latitudinal zones. RSS_{TLS}, UAH_{TLS} and $CHAMP_{TLS}$ all have cooling trends globally and in most latitude bands (**Fig. 12**). Trend of RSS data are very different from those of UAH and RO data especially in the 20˚ N to 60˚ N zone, 20˚ N to 20˚ S zone, and 20˚ S to 60˚ S zone. This is mainly due to different methods were used by RSS V5.2 to (a) calibrate shift of sensor temperature owing to on-orbit heating/cooling of satellite components and (b) remove inter-satellite calibration offsets for the different MSU/AMSU instruments (Mears et al., 2008).

2.8 Other Related Study

In addition to testing and refining the methods to use GPS RO data to inter-compare and inter-calibrate MSU/AMSU data, I have also worked with UCAR COSMIC team and inter-national RO operational centers to summarize above results and publish the results in journal papers. I have also worked with NOAA scientists, scientists in RO communities and climate communities to demonstrate the usefulness for GPS RO data for climate research. These collaborations have an influential impact on stimulating NOAA's interests in a COSMIC follow up mission (COSMIC II) and on promoting GPS RO for climate applications to the climate community. The diagram to illustrate occultation count for each month per 5 degree latitude band from 1995 to 2025 of the scenario without COSMIC II and with COSMIC II are in **Figure 13**.

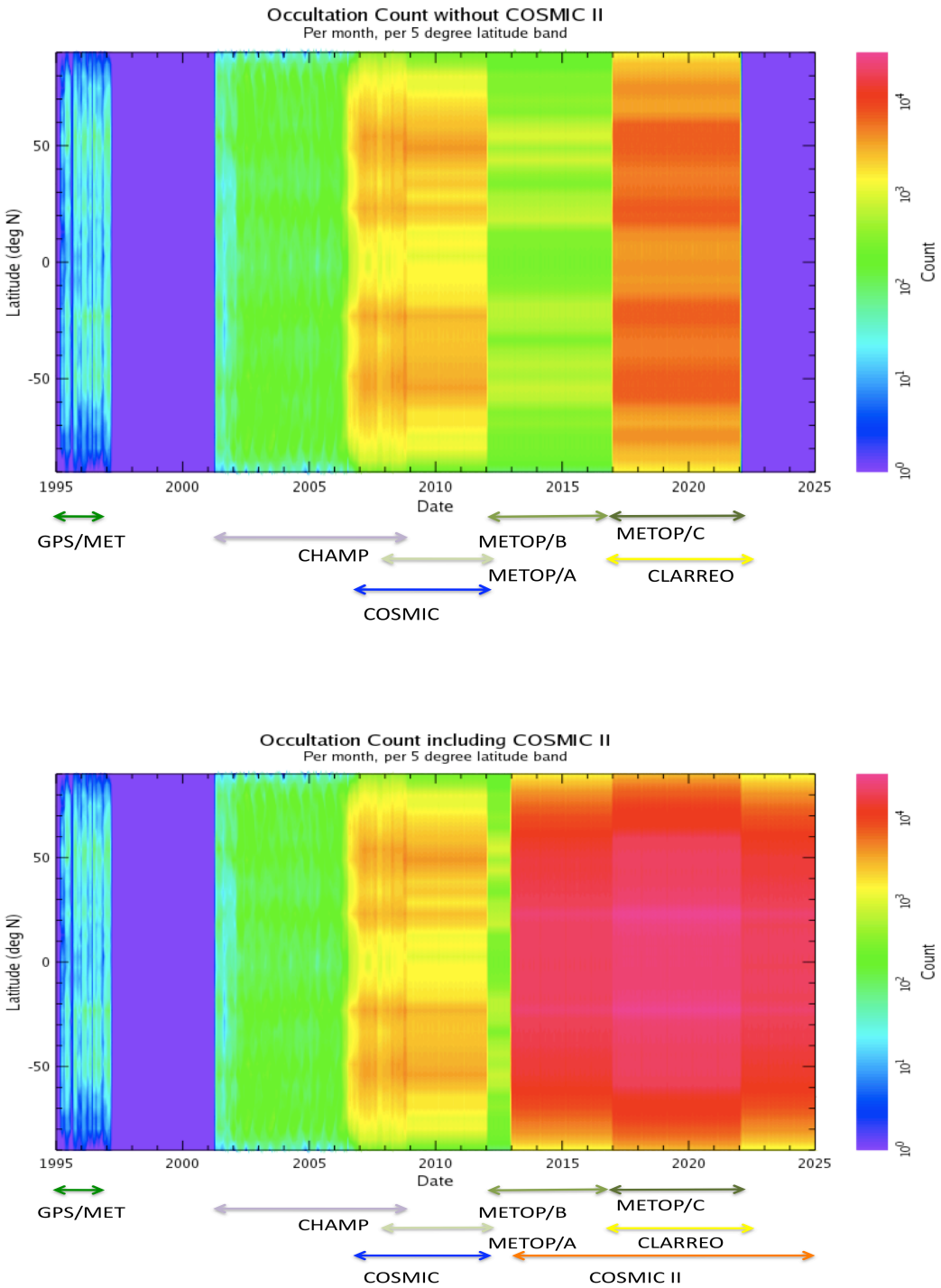

Figure 13. The occultation count for each month per 5 degree latitude band from 1995 to 2025 of the scenario without COSMIC II (upper panel) and with COSMIC II (bottom panel).

2.9 Publications and presentations

a. Refereed publications

1) Anthes, R. A., P. Bernhardt, Y. Chen, L. Cucurull, K. Dymond, D. Ector, S. Healy, **S.-P. Ho**, D. Hunt, Y.-H. Kuo, H. Liu, K. Manning, C. McCormick, T. Meehan, W. Randel, C. R. Rocken, W. Schreiner, S. Sokolovskiy, S. Syndergaard, D. Thompson, K. Trenberth, T.-K. Wee, Z. Zeng, The COSMIC/FORMOSAT-3 Mission: Early Results, submitted to *Bul. Amer. Meteor. Sci.* **89**, No.3, 313-333, 2008.
2) **Ho, S.-P.**, M. Goldberg, Y.-H. Kuo, C.-Z Zou, W. Schreiner, Calibration of Temperature in the Lower Stratosphere from Microwave Measurements using COSMIC Radio Occultation Data: Preliminary Results, Terr. Atmos. Oceanic Sci., Vol. 20, doi: 10.3319/TAO.2007.12.06.01(F3C), 2009.
3) **Ho, S.-P.**, Wenying He, Y.-H. Kuo, Construction of Consistent Temperature Records in the Lower Stratosphere using Global Positioning System Radio Occultation Data and Microwave Sounding Measurements, A.K. Steiner et al. (Eds.), Springer Berlin Heidelberg, 2009, in press.
4) **Ho, S.-P.**, Gottfried Kirchengast, Stephen Leory, Chris Rocken, Ying-Hwa Kuo, Jens Wickert, Tony Mannucci, Sergey Sokolvskiy, William Schreiner, Doug Hunt, Andrea Steiner, Ulrich Foelsche, and Chi Ao, 2008: Estimates of the Uncertainty for using Global Positioning System Radio Occultation Data for Climate Monitoring: Inter-comparisons of Refractivity Derived from Different Data Centers, *J. Geophys. Res.* (submitted and complete response to review).
5) Wenying He, **S.-P. Ho**, H. Chen, X. Zhou, D. Hunt, Y.-H. Kuo, Assessment of the Radiosonde Systematic Temperature Errors in the Upper Troposphere and Stratosphere using COSMIC Radio Occultation Data, *Geophy. Research Letters,* 2009 (submitted and complete response to review).
6) **Ho, S.-P.**, Xinjia Zou, Y.-H., Kuo, 2008: Assessment of the Quality of Radiosonde in the Troposphere using GPS Radio Occultation from COSMIC, *Geophy. Research Letters* (under co-author's review, ready for submission).

b. Scientific presentations

7) **Ho, S.-P.**, Applications of COSMIC RO to Climate Studies, NRC-CES meeting, Boulder, CO, Sep.22-23, 2008 (invited talk).
8) **Ho, S.-P.**, Comparability and reproducibility of RO data, Workshop on the Applications of GPS Radio Occultation to Climate, NCAR Foothills Laboratory, Building #1 Atrium Conference Room 3450 Mitchell Lane, Boulder, CO 80301 March 17-18, 2008 (invited talk).
9) Rocken C., S. Sokolovskiy, B. Schreiner, D. Hunt, **S.-P. Ho**, B. Kuo, U. Foelsche, Climate Monitoring with Radio Occultation Data: systematic error sources, Workshop on the Applications of GPS Radio Occultation to Climate, NCAR Foothills Laboratory, Building #1 Atrium Conference Room 3450 Mitchell Lane, Boulder, CO 80301 March 17-18, 2008.
10) Sokolovskiy S., C.Rocken, W.Schreiner, D.Hunt, **S.-P. Ho**, Y.-H.Kuo, S. Syndergaard, U.Foelsche, Climate Monitoring with Radio Occultation Data: Effects and magnitudes of some specific errors of GPS RO data and assumptions used in their processing, NCAR Foothills Laboratory, Building #1 Atrium Conference Room 3450 Mitchell Lane, Boulder, CO 80301 March 17-18, 2008.

11) **Ho, S.-P.**, Ying-Hwa Kuo, Wenying He, Doug Hunt, Chris Rocken, William Schreiner, and Sergey Sokolovskiy, Global Comparisons of Water Vapor Profiles in the Lower Troposphere from COSMIC Radio Occultation, in situ Observations, and ECMWF Analysis, 4th Asian Space Conference, Taipei, Taiwan, 1-3, October, 2008.
12) **Ho, S.-P.**, Ying-Hwa Kuo, Doug Hunt, Chris Rocken, William Schreiner, and Sergey Sokolovskiy, and Jens Wickert, Anthony J. Mannucci, Quantitative Estimation of the Reproducibility of GPS RO Data for Climate Research, 4th Asian Space Conference, Taipei, Taiwan, 1-3, October, 2008.
13) **Ho, S.-P.**, COSMIC Weather, Climate, and Space Initiatives – Important Fabrics for the NCAR Strategic Plan, UOP director meeting, Nov. 14, 2008, Boulder CO.
14) Mannucci, A. J., C. O. Ao, T. K. Meehan, B. A. Iijima, Bill Schreiner, Chris Rocken, Sergey Sokolovskiy, **Shu-Peng Ho**, Doug Hunt, SI Traceability Applied To GPS Radio Occultation, CLARREO Workshop, October 21-23, 2008, Washington, D.C.
15) Wenying He and **Shu-peng Ho**, Comparisons of Refractivity, Temperature, and Water Vapor derived from COSMIC GPS Occultations with *in situ* Measurements and Global Weather Analysis, COSMIC seminar, Aug. 20, 2008, Boulder CO.
16) **Ho, S.-P.**, Ying-Hwa Kuo, Wenying He, Doug Hunt, Chris Rocken, William Schreiner, and Sergey Sokolovskiy, Global Comparisons of Atmospheric Soundings in the Lower Troposphere from COSMIC Radio Occultation, Radiosonde, and ECMWF Analysis, AMS Annual meeting, Phoenix, AZ, 2009, Jan. 11-15.
17) **Ho, S.-P.**, Gottfried Kirchengast, Stephen Leroy, Jens Wickert, Tony Mannucci, Andrea Steiner, Ying-Hwa Kuo, Chris Rocken, Doug Hunt, William Schreiner, and Sergey Sokolovskiy, Estimating the Uncertainty of using GPS Radio Occultation Data for Climate Monitoring: Inter-comparison of CHAMP Refractivity Climate Records 2002-2006 from Different Data Centers, AMS Annual meeting, Phoenix, AZ, 2009, Jan. 11-15.
18) **Ho, S.-P.**, Applications of COSMIC RO to Climate Studies, COSMIC Climate meeting in AMS Annual meeting, Phoenix, AZ, 2009, Jan. 11-15 (invited).
19) **Ho, S.-P.**, D. P. Edwards, J. C. Gille, M. Luo, G. Osterman, S. Kulawik, and H. Worden, Global TES CO validation using MOPITT CO data, TES Science team meeting, Boulder CO, January, 23-25, 2009.
20) **Ho, S.-P.**, G. Kirchengast, S. Leroy, J. Wickert, A. J. Mannucci, A. Steiner, Y-H Kuo, C. Rocken, D. Hunt, W. Schreiner, S. Sokolovskiy, Quantitative Estimation of the Reproducibility of GPS RO Data for Climate monitoring: Inter-comparison of CHAMP Refractivity Climate Records 2002-2006 from Different Data Centers, European Geosciences Union annual meeting, Vienna, Austria, April 20-24, 2009.
21) **Ho, S.-P.**, Y-H Kuo, W He, D. Hunt, C. Rocken, W. Schreiner, and S. Sokolovskiy, Assessment of the Quality of Radiosonde Temperature and Water Vapor Measurements using GPS Radio Occultation from COSMIC, European Geosciences Union annual meeting, Vienna, Austria, April 20-24, 2009.
22) **Ho, S.-P.**, Y.-H. Kuo, D. Hunt, C. Rocken, W. Schreiner, S. Sokolovskiy, R. A. Anthes, and K. E. Trenberth, Applications of COSMIC Radio Occultation for Climate Monitoring, 2008 NOAA ESRL GLOBAL MONITORING ANNUAL CONFERENCE, May 14 and May 15, 2009, Boulder, CO.
23) **Ho, S.-P.**, et al., White paper for NCAR 5-year strategic plan: COSMIC – Providing GPS Atmospheric Remote Sensing Observations to Support NCAR's Missions in Weather, Climate and Ionosphere, Dec. 2008.

24) FORMAST-3 Evaluation Report and Follow-on Mission Plan, NSPO-PPT-004, 2009.

c. Others

25) Organizer of the AMS COSMIC-NOAA climate Meeting, Jan. 13. Phoenix, AZ, 2009.
26) Co-chair of the AMS COSMIC-NOAA climate Meeting, Jan. 13. Phoenix, AZ, 2009.
27) Committee of COSMIC 2009 International Workshop.
28) Coordinator and chair of the UCAR/COSMIC Seminar Series.
29) Interact with NOAA scientists and scientists from international RO community on several special issues related to use GPS RO data for climate researches. In charge of organizing related responses from UCAR and RO community to NOAA scientists.
30) Many above presentations, published/submitted manuscripts can be found in http://www.cosmic.ucar.edu/~spho/

3. Immediate Plans for the Remainder of Calendar Year 2009

Since I have completed the **Preparation of GPS RO, Radiosonde data, and MSU/AMSUMOPITT data for Geo-location Comparisons** and **Testing and refining the methods to use GPS RO data to inter-compare and inter-calibrate MSU/AMSU data** are completed, immediate plans for the remainder of this calendar year (from May to August 2009) will include **1) preparation of manuscripts described above, and 2) using GPS RO data to validate MSU/AMSU data from NESDIS$_{NEW}$ and NESDIS$_{OPR}$.**

a. Preparation of manuscripts

Preparation of manuscripts detailing:

- Comparability of data from different COSMIC satellites (Section 2.2.a)
- Comparability of CHAMP and COSMIC GPS satellite systems (Section 2.2.b)
- Reproducibility of GPS RO products (profile-to-profile ensemble) processed using different inversion procedures (Section 2.3.b)
- The usefulness of GPS RO to indentify the quality of different types of radiosonde systems using CHAMP/COSMIC data from 2001 to 2009 (Section 2.4.a)

b. Using GPS RO data to validate MSU/AMSU data from NESDIS$_{NEW}$ and NESDIS$_{OPR}$

In addition to the work described in Section 2.6, we will also continue:

- Performing forward calculation using GPS RO dry temperature profiles and using the calculated brightness temperatures to validate MSU/AMSU data from NESDIS$_{NEW}$ and NESDIS$_{OPR}$.

- Work with Dr. Cheng-Zhi Zou and the NOAA team to further investigate this issue listed in Section 2.6.
- Preparation of a manuscript detailing the method and results for the GPS RO and $NESDIS_{NEW}$ and $NESDIS_{OPR}$ comparisons.

4. Plans for the Calendar Year 2010

In 2010, we plan to continue to use GPS RO data to validate and calibrate MSU/AMSU measurements and radiosonde observations and focus on the specific goal 3 for this project as mentioned in section 1.