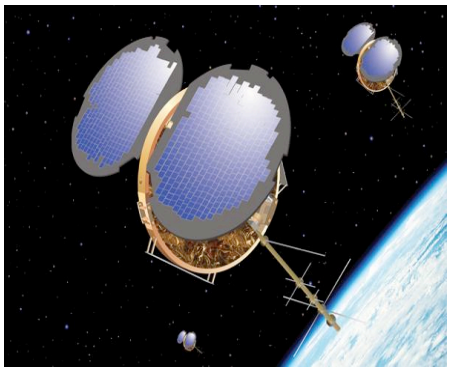
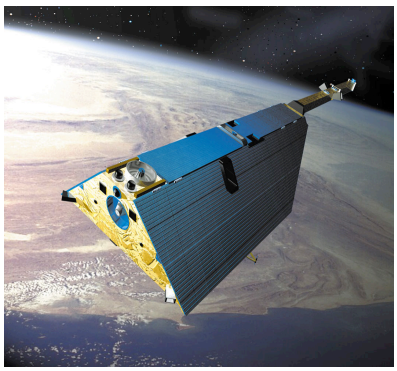


COSMIC



CHAMP

YEAR 1 Bi-ANNUAL PROJECT REPORT (from 06/01/2010 to 11/30/20100
NOAA Award number: NA10NES4400002

Construction of Consistent Microwave Sensor Temperature Records and Tropopause Height Climatology using MSU/AMSU Measurements, GPS RO Data, and Radiosonde Observations

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1. Introduction

The monitoring and detecting of the vertical structure of atmospheric temperature trends are key elements in the climate change problem. In this study, we propose to use GPS RO data to serve as climate benchmarks to vicariously calibrate MSU/AMSU measurements and use the "adjusted" MSU/AMSU data (both NOAA MSU/AMSU and NASA Aqua AMSU) to inter-calibrate other overlapped MSU/AMSU data to construct microwave sensor temperature climate data records (CDRs) from 1979 to 2012, and to use GPS RO soundings (from 2001 to 2012) to construct tropopause height climatology (as Thematic CDR–TCDR) that is consistent with changes in temperature and tropopause structure estimated by MSU/AMSU and those from radiosondes.

The specific goals for this project are as followings:

(i) Quantify the pixel-level MSU/AMSU temporal and spatial temperature anomalies using GPS RO data from 2001 to 2012 as climate benchmark datasets. This would help to define a better approach for constructing MSU/AMSU temperature records from 1979 to 2012.

(ii) To generate a long-term climate quality temperature dataset by reprocessing thirty-three years (1979-2012) of MSU/AMSU data using the SNO method. The 'adjusted' MSU/AMSU data that were calibrated by CHAMP and COSMIC (from 2001 to 2009 the previous study), and SAC-C (launched in 2000), GRACE (Gravity Recovery and Climate Experiment, launched in 2004), CHAMP (after 2009), COSMIC (after 2009), and GRAS (Metop's Global Navigation Satellite System Receiver for Atmospheric Sounding, launched in 2007) RO (this study) will serve as reference data to calibrate other overlapped MSU/AMSU data.

(iii) To use GPS RO soundings collected from multi-RO missions to construct tropopause height climatology from 2001 to 2012. High vertical resolution radiosonde data will be collected and the radiosonde-derived tropopause heights will be compared to those from RO data.

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

2. Progress on Proposed Studies

In this study, we propose to use MSU/AMSU measurements, radiosonde observations, and GPS RO data from by multiple RO missions including CHAMP, COSMIC, SAC-C, GRACE, and GRAS to serve as reference data to calibrate other overlapped MSU/AMSU data. ***Work to-date has focused on 1) Preparation of GPS RO, radiosonde, and MSU/AMSU data for geo-location comparisons, 2) Reprocessing the GPS RO from multiple RO missions using consistent inversion procedures and quantifying the reproducibility of GPS RO data for climate monitoring, 3) Quantifying of the structure***

uncertainty for using GPS RO data for climate monitoring: Inter-comparisons of RO profiles derived from different data centers, 4) Constraining Microwave Sensor Temperature Records from 2001 to 2012 Using GPS RO data and radiosonde Data, 5) Using GPS RO data to construct tropopause height climatology

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. Data collection and data matching were performed to prepare the data for further comparisons:

a. Data collection

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

- CHAMP data (from Jan. 2001 to April 2010) from UCAR CDAAC,
- COSMIC data (from June 2006 to April 2010) 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 2010,
- AMSU data from Aqua and Metop-A
- 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 $NESDIS_{NEW}$ V2.0 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 Reprocessing the RO data from multiple RO missions using consistent inversion procedures and quantifying of the reproducibility for using GPS RO Data for climate monitoring

a. Improvements to RO Data Processing

A new RO inversion package is developed. Several improvements to precise orbit determination (POD), excess atmospheric phase and neutral atmospheric inversion processes are developed:

i) With regard to POD, NCAR CDAAC improved COSMIC attitude anomalies and POD antenna phase center variations.

ii) Applying 1 or 5 s GPS clocks (instead of 30 s GPS clocks used in current CDAAC processing) in zero- and single-difference processing improves stratospheric profiles. This improvement corresponds to about a 13 % reduction in standard deviation of the differences between COSMIC and high-resolution ECMWF refractivity profiles at 30-km height. These studies will lead to more accurate satellite position/velocity and excess phase data, and all higher level products, in the next version of the CDAAC software.

iii) Improvements have also been made to the CDAAC neutral atmospheric inversion software that reduced systematic biases in the stratosphere and LT. These biases were not large (i.e. ~0.2% in stratosphere and ~1% in tropical LT) for NWP applications, but were potentially significant for climate studies when combining data from different data centers. The first improvement/fix removed a positive bias in BA and refractivity (N) between ~10-40-km altitude (up to ~0.2%).

iv) The second improvement eliminated a positive bias in bending angle (BA) and N below ~6-km (up to ~1% in tropics) by removing a non-linear sliding median filter that was used to eliminate large spikes in BA.

v) An additional improvement was optimizing the truncation of raw RO signals that are used in the inversion.

b. Continue to monitor RO climate data quality

With the new CDAAC inversion procedures, all the available RO missions including COSMIC, CHAMP, GRACE, Metop/GRAS, GRACE, SAC-C, TerraSAR-X are re-proceeded. To continue to monitor the long-term stability of RO derived parameters, we inter-compare the collocated RO data among Metop/GRAS, GRACE, SAC-C, TerraSAR-X, CHAMP, and COSMIC and other possible new RO missions.

Here we continue to quantify the differences of inverted profiles among different RO missions which were launched in different years. This is to demonstrate the long-term stability of RO data for climate monitoring.

- Collect atmospheric soundings from multi-RO missions including SAC-C, GRACE, CHAMP, COSMIC, and MetOp-A GRAS, which are all processed by UCAR: we used the latest post-processed SAC-C, GRACE, CHAMP, COSMIC, and MetOp-A GRAS data from 2001-2010 to quantify the mean difference among different RO missions in order to demonstrate that the quality of GPS RO data will not change after launch.
- Compare collocated profiles from two RO missions for similar azimuth angle, close time, close distances. Only high quality RO data are used in the comparison.
- Compare RO profiles of high signal to noise ratio (SNR) between COSMIC and MetOp-A GRAS temperature profiles.
- **Figure 1** depicted the collocated temperature comparison between CHAMP and COSMIC (Figure 1a), GRACE and COSMIC (Figure 1b), and Metop-A GRAS and COSMIC (Figure 1c). The mean temperature biases from 8 km to 30 km for these three ensembles are all less than 0.1 K.

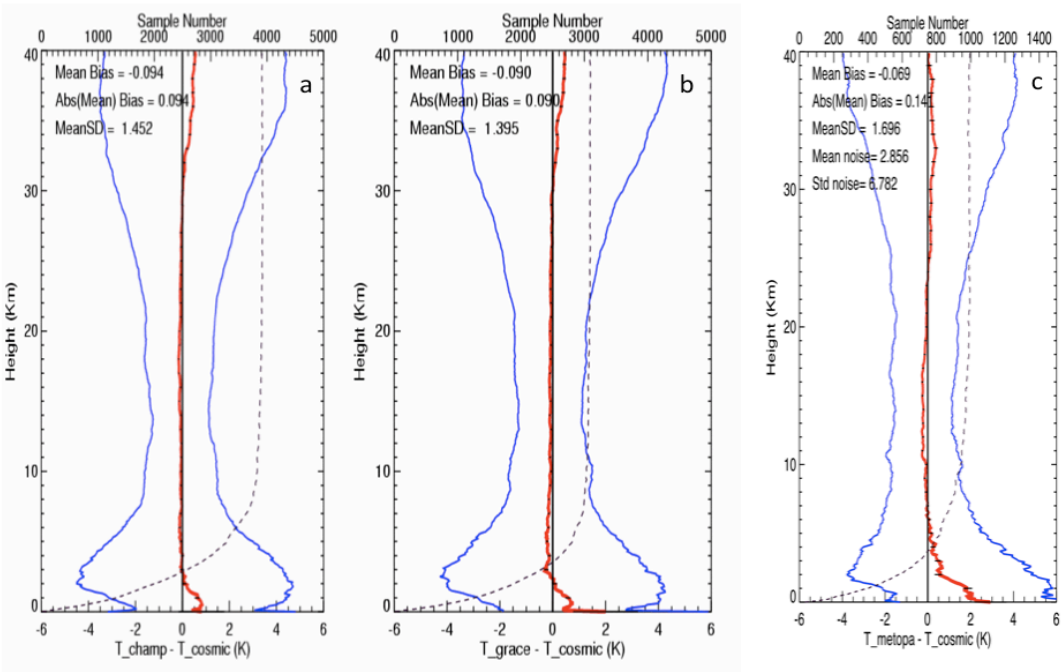


Figure 1. Temperature comparison for (a) CHAMP and COSMIC collocated ensemble, (b) GRACE and COSMIC collocated ensemble, and (c) Metop-A GRAS and COSMIC ensemble.

2.3 Quantifying the Structure Uncertainty for using GPS RO Data for Climate Monitoring: Inter-comparisons of RO Profiles Derived from Different Data Centers

Before using GPS RO data for climate monitoring, we need not only to quantify the precision and long-term stability of GPS RO data but also to quantify the dependence of errors in GPS RO-derived variables on atmospheric excess phase processing and inversion procedures. Here we aim at quantifying the structural uncertainty in GPS RO-derived vertical profiles of bending angle, refractivity, and dry temperature obtained from atmospheric excess phase processing and inversion procedures.

Currently, multi-year GPS RO climate data can be obtained from the GeoForschungsZentrum Potsdam (GFZ), Germany, the Jet Propulsion Laboratory (JPL), Pasadena, CA, USA, the University Corporation for Atmospheric Research (UCAR), Boulder, CO, USA, the Wegener Center of the University of Graz (WegC), Graz, Austria, the Danish Meteorological Institute, (DMI), Copenhagen, Denmark, and the Meteorological Division, EUMETSAT (EUM), Darmstadt, Germany. Different centers used different assumptions, initializations, and implementations in the excess phase processing and inversion procedures, which may introduce bending angle, refractivity, and dry temperature differences between centers.

Approaches:

i) To examine the suitability of GPS RO observations as a climate benchmark dataset, here we collect CHAMP data (2001 to 2008) processed by UCAR, JPL, GFZ, DMI, EUM, and Wegc.
ii) In order to match the exact the same profiles processed by different centers, we first used UCAR routines to rename the filename from individual centers so that they are consistent with the UCAR filename.
iii) Using the profile information from the filename, we match all the individual profile processed by different processing centers.

Comparison results:

- **The profile-to-profile fractional bending angle comparison between UCAR, JPL, WegC, GFZ, EUM, and DMI are compared:** Note that because different implementations of quality control have the effect of eliminating different subsets of the entire data set, the previous MMC comparisons in Ho et al. (2009c) still contain sampling errors for different centers. To quantify the structural errors of RO data processed by different centers, we conduct the profile-to-profile BA comparison. **Figure 2** shows that the mean profile-to-profile fractional bending angle difference among the six different centers are within 0.1% for the globe and for all other five latitudinal zones.

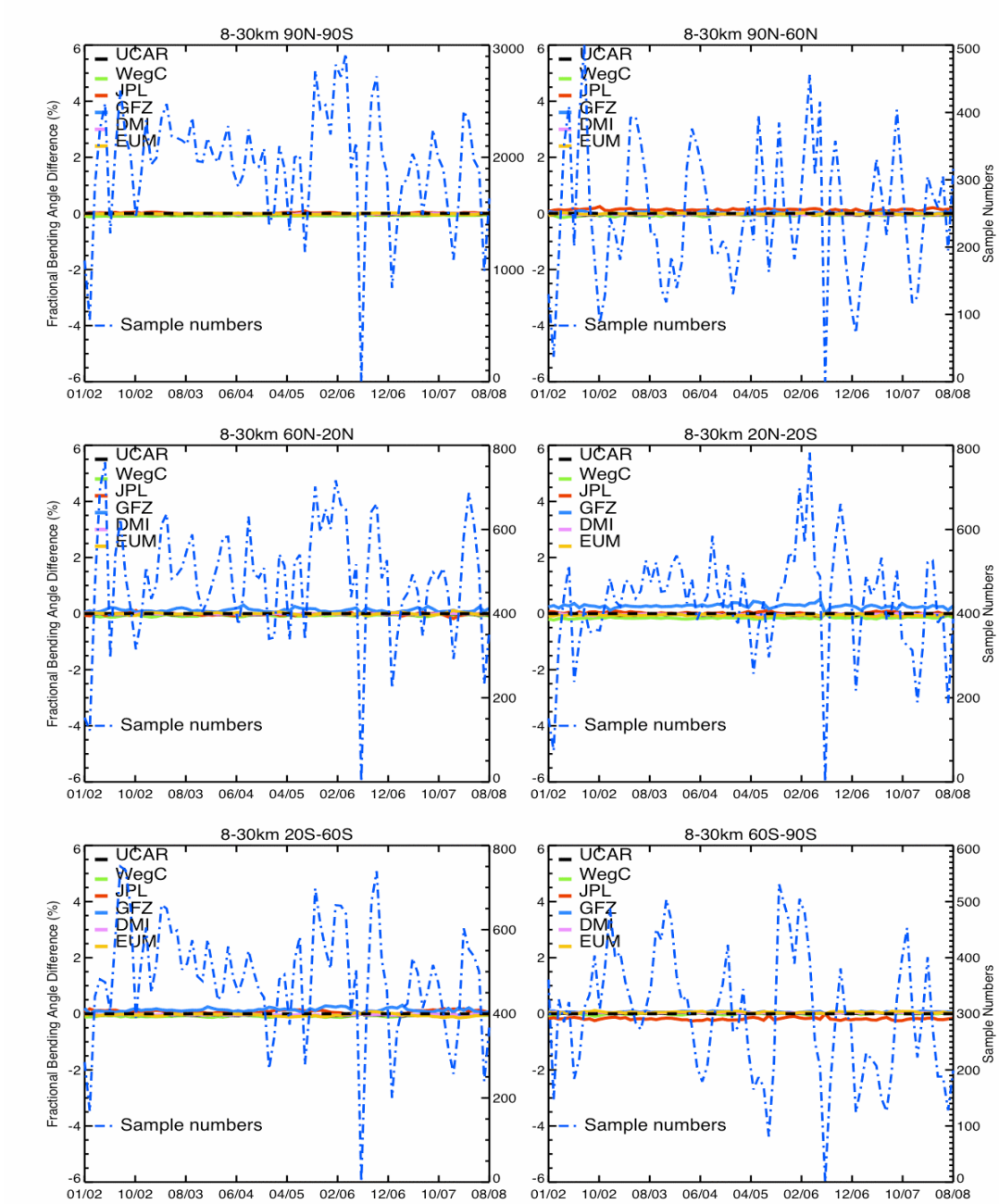


Figure 2. The time series of fractional bending angle anomalies (relative to the mean BA for all six centers) from January, 2002 to December, 2008 among six centers for the 8-30 km layer for (a) the entire globe (82.5ºN-82.5ºS, the left upper panel), b) the 82.5ºN-60ºN zone (the upper right panel), (c) the 60ºN-20ºN zone (the middle left panel), (d) the 20ºN-20ºS zone (the middle right panel), (e) the 20ºS-60ºS zone (the bottom left panel), and (f) the 60ºS-82.5ºS zone (the bottom right panel).

- **The profile-to-profile dry temperature comparison between UCAR, JPL, WegC, and GFZ are compared: Figure 3** shows that the mean profile-to-profile fractional bending angle difference among the six different centers are within 0.5 K for the globe and for all other five latitudinal zones.

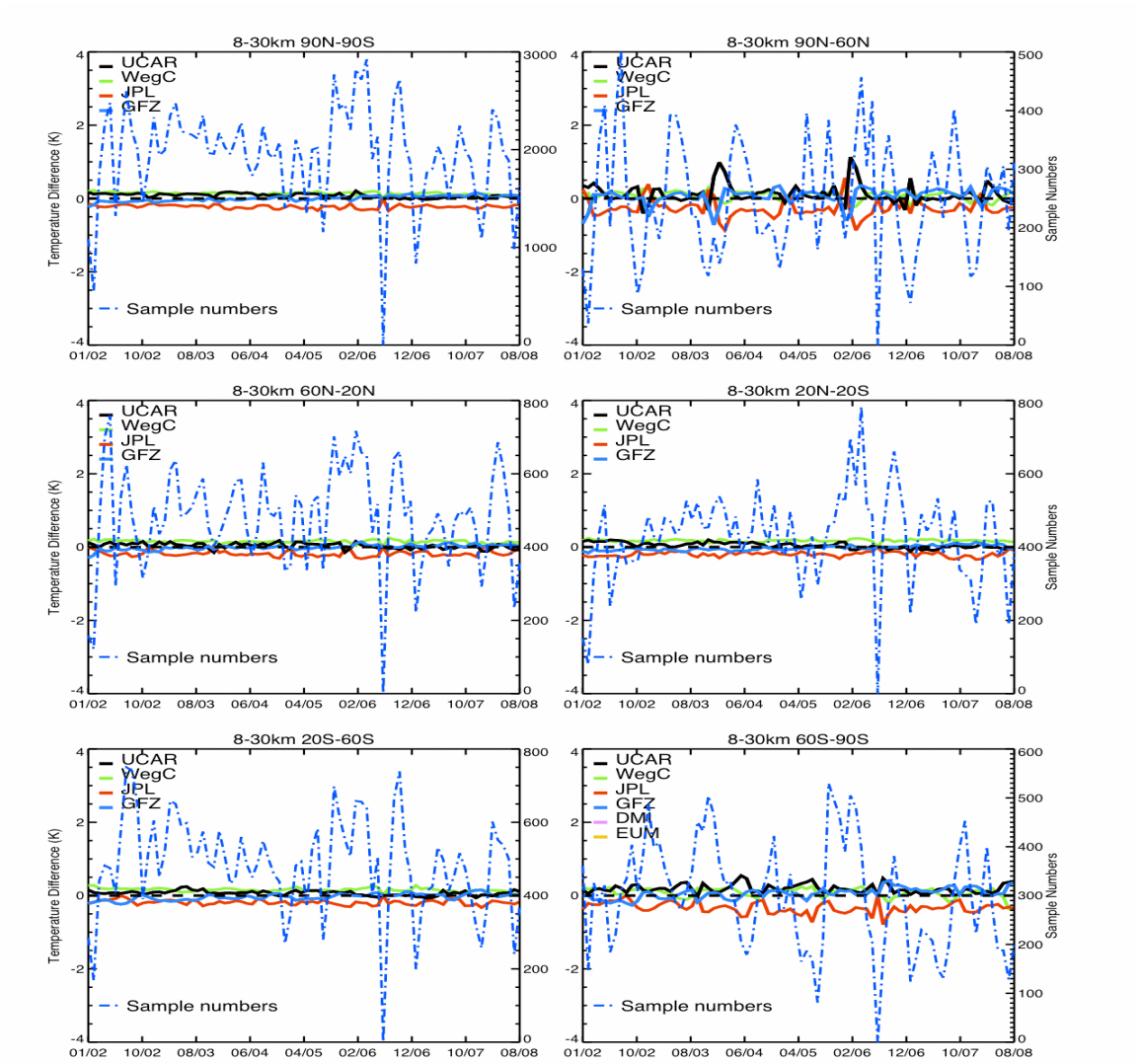


Figure 3. The time series of dry temperature anomalies (relative to the mean dry temperature from all four centers) from January, 2002 to December, 2008 among six centers for the 8-30 km layer for (a) the entire globe (82.5ºN-82.5ºS, the left upper panel), b) the 82.5ºN-60ºN zone (the upper right panel), (c) the 60ºN-20ºN zone (the middle left panel), (d) the 20ºN-20ºS zone (the middle right panel), (e) the 20ºS-60ºS zone (the bottom left panel), and (f) the 60ºS-82.5ºS zone (the bottom right panel).

2.4 Constraining Microwave Sensor Temperature Records from 2001 to 2012 Using GPS RO data and Radiosonde Data

a. Construction of the 2001 to 2010 RO calibrated TLS temperature trend

Approaches:

1) Data:
   COSMIC from 200606 to 200912
   CHAMP from 200106 to 200806
   RSS V3.2 200106-200912
   UAH V5.1 200106-200812
   SNO V2.0 200106-200912

2) Apply CHAMP and COSMIC soundings to AMSU forward model to simulate AMSU TLS

3) Match simulated GPS RO TLS to NOAA AMSU TLS within 30 minutes and 0.5 degree to find calibration coefficients for different NOAA satellites so that we can

   a. Use GPS RO data to inter-calibrate other NOAA satellite.
   b. Use the NOAA satellite measurements calibrated by GPS RO data to calibrate multi-year AMSU/MSU data and generate consistent RO and MSU/AMSU TLS climate data records.
   c. The derived TLS record is compared with the newly available TLS datasets provided by Remote Sensing Systems (RSS) and University of Alabama in Huntsville (UAH), and TLS processed by NOAA STAR (SNO method) (**Figure 4**).

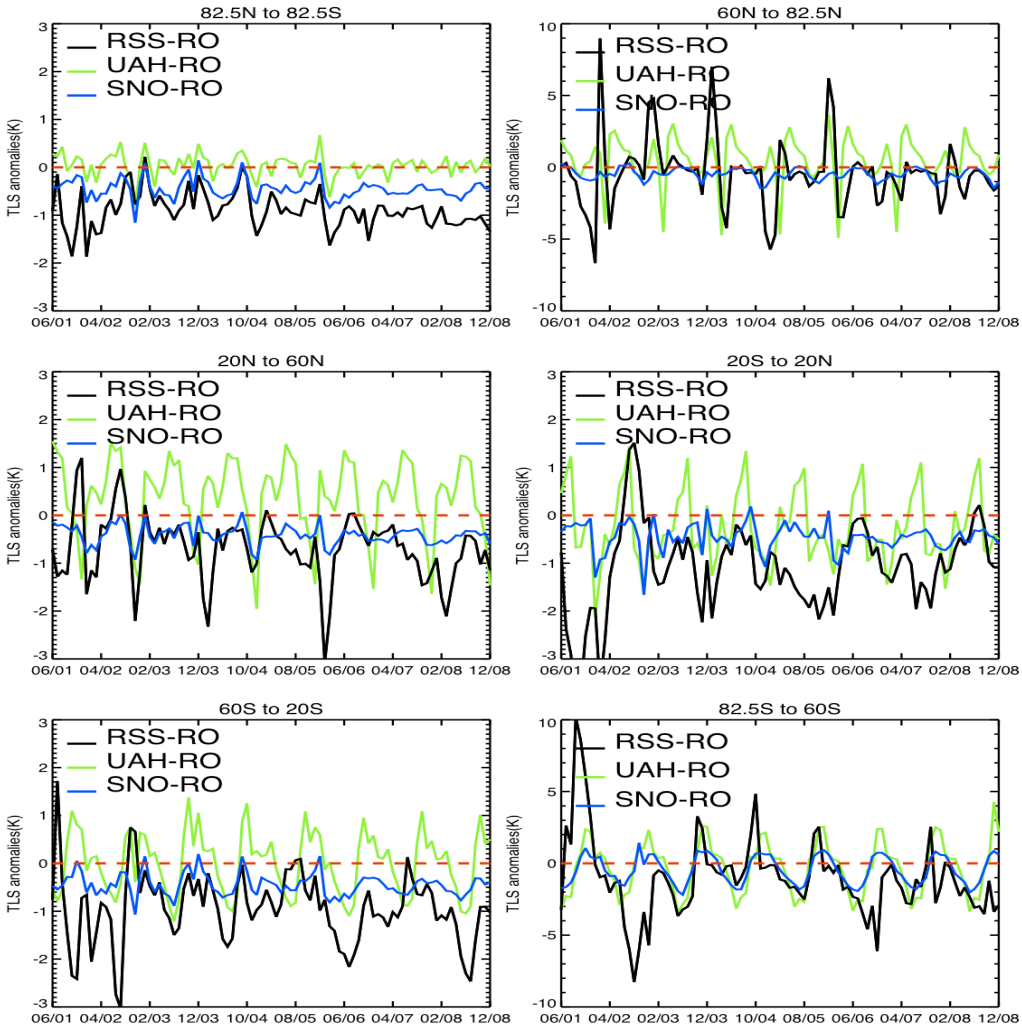


Figure. 4. The time series of TLS difference for (a) the entire globe (82.5ºN-82.5ºS, the left upper panel), b) the 82.5ºN-60ºN zone (the upper right panel), (c) the 60ºN-20ºN zone (the middle left panel), (d) the 20ºN-20ºS zone (the middle right panel), (e) the 20ºS-60ºS zone (the bottom left panel), and (f) the 60ºS-82.5ºS zone (the bottom right panel). The RO_AMSU TLS mean was subtracted on a monthly basis.

b. Continue to assess the Systematic Biases of Global Radiosonde Temperature Measurements using RO Data in 2010

Because the quality of COSMIC RO data are not affected by the surrounding environment (e.g., geo-location, day and night, etc.), GPS RO 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.

- **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. Here we compare temperature profiles derived from GPS RO data of the COSMIC mission with those from four types of radiosonde systems from 10 to 25 km to assess the performance of these radiosonde systems in the upper troposphere and lower stratosphere. Results show that temperature measurements from Vaisala-RS92 and Shanghai radiosonde systems agree well with those of COSMIC with a close-to-zero mean difference. Large temperature biases are shown for MRZ and VIZ-B2 radiosonde systems relative to COSMIC, which are possibly caused by diurnal radiative effects. These biases and their possible causes are consistent with previous studies. In addition, we show that the temperature measurements from the new Chinese radiosonde system can be improved through a comparison with COSMIC measurements. Results from this study are summarized in He et al., (2009). Only radisonde temperature profiles from 2006 June to 2007 February were used.
- **Extend the comparison of GPS RO temperature profiles and radisodne comparison from 2002 to 2010**: Here we compare temperature profiles derived from GPS RO data from the COSMIC from 2006 to 2008 and CHAllenging Minisatellite Payload (CHAMP) from 2002 to 2008 with those from different types of radiosonde systems from 12 to 25 km to assess the performance of these radiosonde systems in the upper troposphere and lower stratosphere. Because GPS RO data are not affected by the temperature variation of the satellite component, we are also able to identify the radiosonde temperature biases due to possible radiative errors resulting from instrument characteristics for different types of radiosonde systems. Because of different solar absorptivity and infrared emissivity, different radiosonde sensor systems actually contain different radiative biases. **Figure 5** shows GPS RO temperature profiles are very useful to identify systematic radiative biases for different radiosonde sensor types**.**

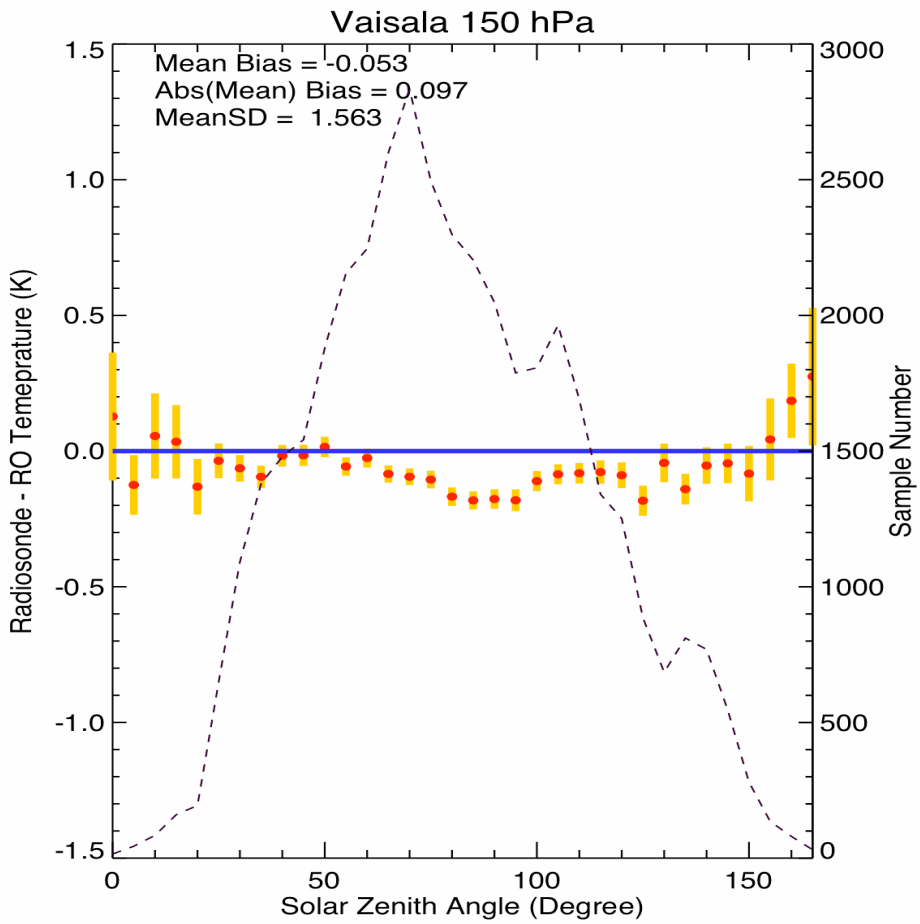


Figure 5. Temperature comparisons between COSMIC and radiosonde at 150 hPa for Vaisala-RS92 (the right panel) from 2002 to 2008. The red dot is for the mean difference, the orange line is for the standard deviation, and the dotted line is the sample number for RO and radiosonde pairs in that height.

2.5 Using GPS RO data to Construct Tropopause Height Climatology

Tropopause is defined as the transition zone between the troposphere and the stratosphere. Tropopause is in general located between the main convective outflow (~12 km) and the cold point of the temperature profile (~17 km). Changes in the structure of the tropopause may affect stratosphere-troposphere exchange, the stratospheric Brewer-Dobson circulation, and the intrusion of stratospheric moisture content. The increases in the latitudinal extent of the tropical tropopause suggests widened tropical Hadley cell. Identifying the long-term changes in temperature and tropopause structure (i.e., tropopause height) in UTLS is necessary to advance reliable predictions of trends in climate or global change. Here, we use GPS RO measurements from the multiple RO missions (COSMIC, CHAMP, GRACE, GRAS) to derive the tropopause height over the globe. The GPS RO technique can provide temperature profiles with sub-Kelvin accuracy since atmospheric excess phase, which is the basic observable of GPS RO technique, is measured with millimetric precision. Due to the high precision and vertical resolution (from ~60 m near the surface to ~1.5 km at 40 km), GPS RO data are proven suitable to detect the changes in upper troposphere and lower stratosphere (UTLS) temperature and tropopause height.

a. Computer the global tropopause heights using GPS RO dry temperature

Approach:

Here the GPS RO Lapse Rate Tropopause (LRT) is calculated using the WMO definition (WMO, 1957). The LRT is derived from COSMIC temperature profiles and is determined when the following criteria are satisfied:

(a)The lowest level between 500 mb and 70 mb at which lapse rate is less than -2°C/km is calculated.

(b) The average lapse rate between this lowest level and all higher levels within 2 km does not exceed -2 K/km.

(c) None of the levels from this lowest level up to 2 km above has lapse rate less than -2 K/km.

(d) Mean lapse rate from the layers below this lowest layer is greater than -2 K/km. This minimizes the influence of outliers in the temperature profiles.

Using this algorithm, we compute the LRT for COSMIC, CHAMP, GRACE, and GRAS.

Comparisons between temperature profiles of COSMIC RO and radiosonde soundings (in black and red, respectively) at various stations near tropical regions are shown in **Figure 6**.

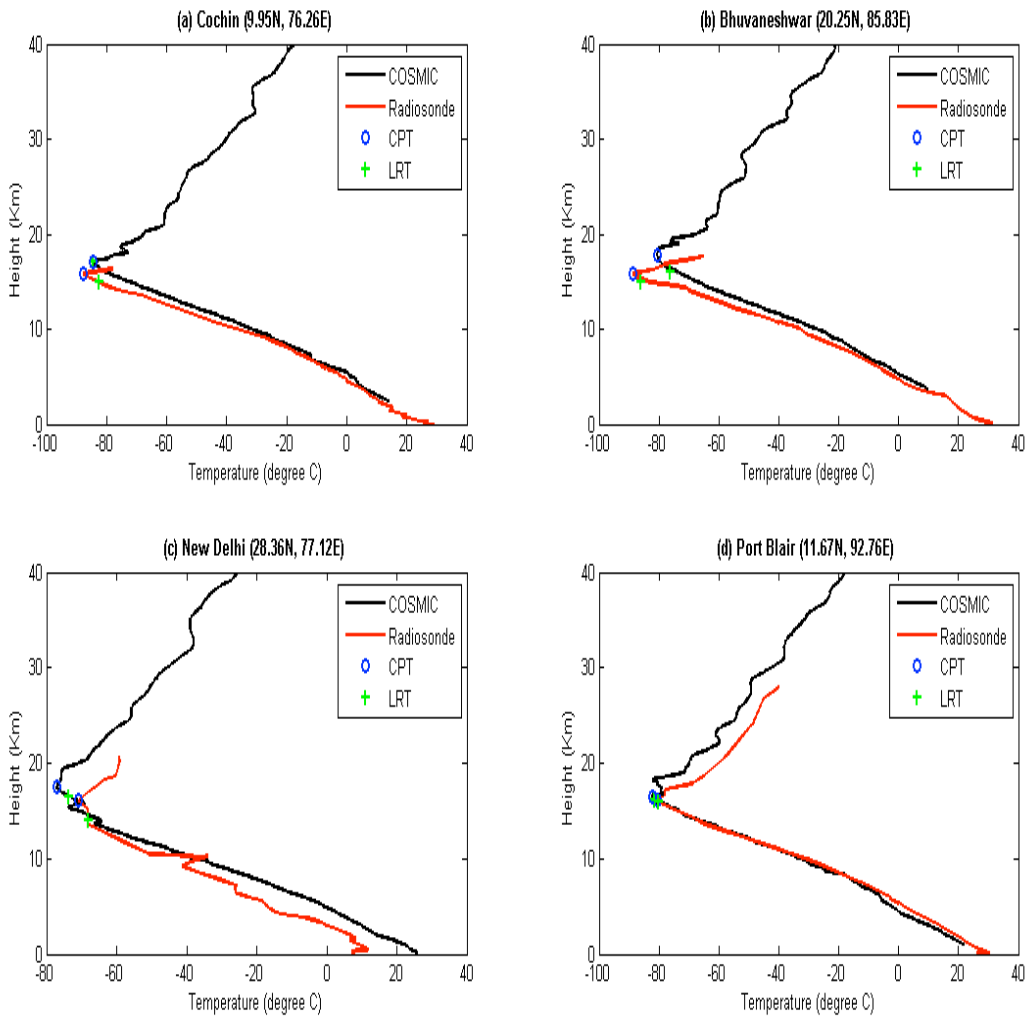


Figure 6. Comparisons between temperature profiles of COSMIC RO and radiosonde soundings (in black and red, respectively) at various stations. (a) Cochin (9.95^{o}N, 76.26^{o}E) on 13 June 2007, (b) Bhuvaneswar (20.25^{o}N, 85.83^{o}E) on 21 June 2007, (c) New Delhi (28.36^{o}N, 77.12^{o}E) on 14 January 2007, and (d) Port Blair (11.67^{o}N, 92.76^{o}E) on 29 April 2007.

b. Estimates of the Global Tropopause Height Variation

Here we use GPS RO dry temperature profiles collected from multi-RO missions (e.g., SAC-C, CHAMP, GRACE, COSMIC, GRAS), which are processed using the UCAR processing package, to construct tropopause height climatology from 2001 to 2012.

- In order to quantify the uncertainty of the derived tropopause height (LRT in this case), here we also compare the UCAR CHAMP LRT time series to those CHAMP LRTs derived from DMI, GFZ, JPL and WEGC (**Figure 7**).

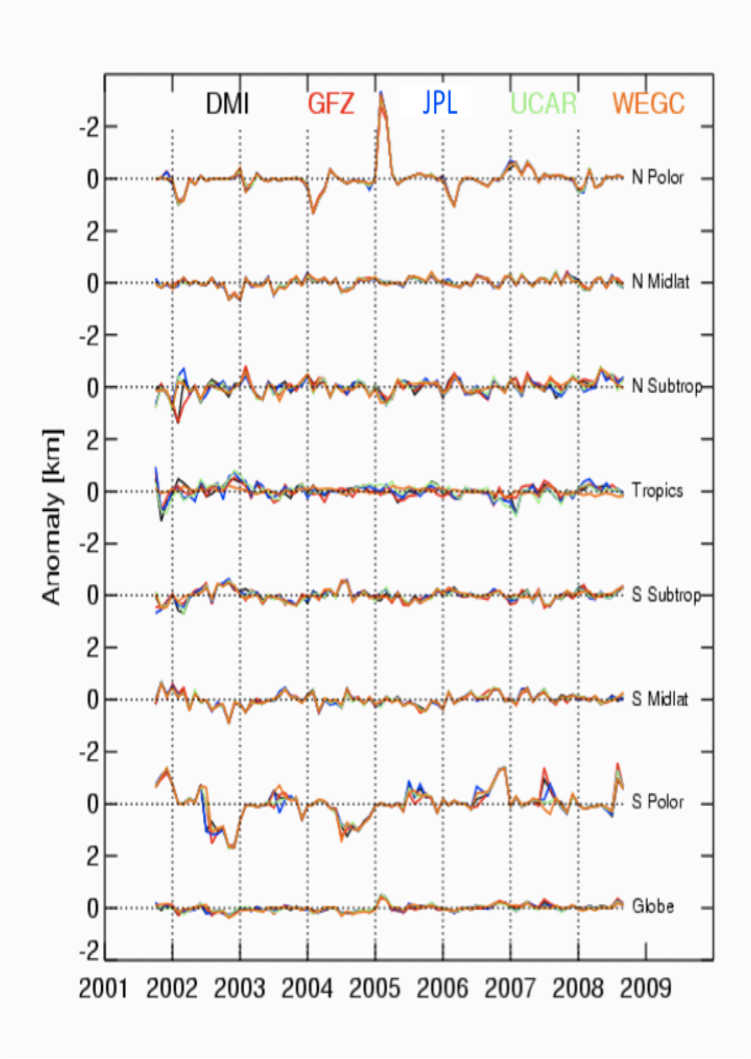


Figure 7. The LRT time series from October 2001 to October 2008 for DMI, GFZ, JPL, UCAR and WEGC for different latitudinal zones.

- The CHAMP LRT trends (meter/yr) for DMI, GFZ, JPL, UCAR and WEGC for different latitudinal zones are shown in **Figure 8**.

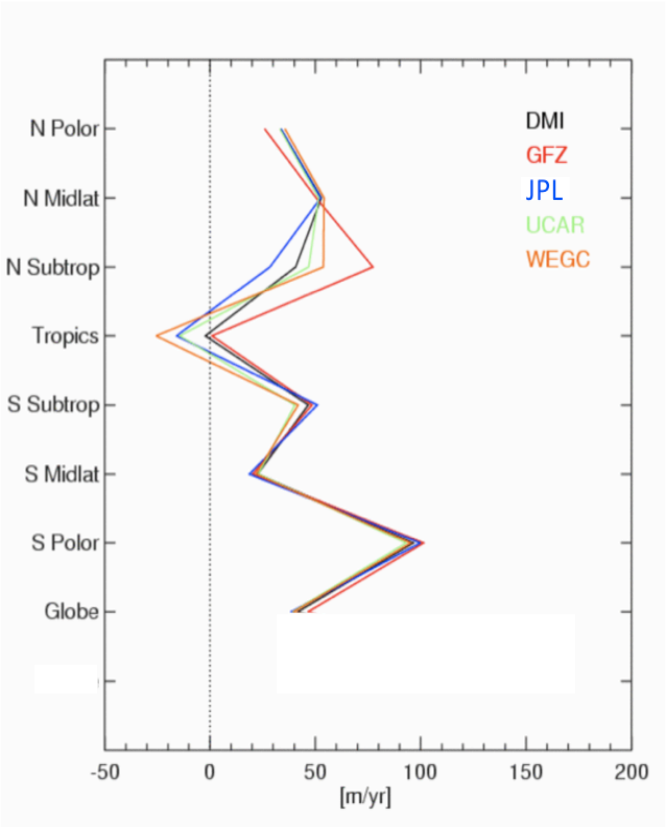


Figure 8. The LRT trends (meter/yr) from October 2001 to October 2008 for DMI, GFZ, JPL, UCAR and WEGC for different latitudinal zones.

2.6 Publications

Papers submitted or published during this period

1) Ho, S.-P., Zhou X., Kuo Y.-H., Hunt D., Wang J.-H. Global Evaluation of Radiosonde Water Vapor Systematic Biases using GPS Radio Occultation from COSMIC and ECMWF Analysis. *Remote Sensing*. 2010; 2(5):1320-1330.

2) Ho, S.-P., Ying-Hwa Kuo ,William Schreiner, Xinjia Zhou, 2010: Using SI-traceable Global Positioning System Radio Occultation Measurements for Climate Monitoring [In "States of the Climate in 2009]. *Bul. Amer. Meteor. Sci*., 91 (7), S36-S37.

3) Mears C., J. Wang, S.-P. Ho, L. Zhang, and X. Zhou, 2010: Total Column Water Vapor, [In "States of the Climate in 2009]. *Bul. Amer. Meteor. Sci*., 91 (7), S29-S31.

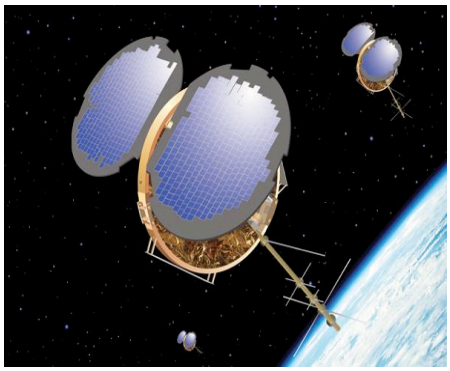
4) Shu-peng Ho, The Use of the COSMIC/FORMOSAT-3 Global Positioning System Radio Occultation Data as Global Reference Observations in Orbit and Their Applications in Meteorology, NOVA book chapter (in press).

5) Jerry Raj, Ching-Yuang Huang, S.-P. Ho, Jens Wickert, and Torsten Schmidt, Characteristics of Tropopause Height in Indian Monsoon Region Revealed by COSMIC GPS RO Data, *Geophys. Res. Lett.,* 2010 (submitted).

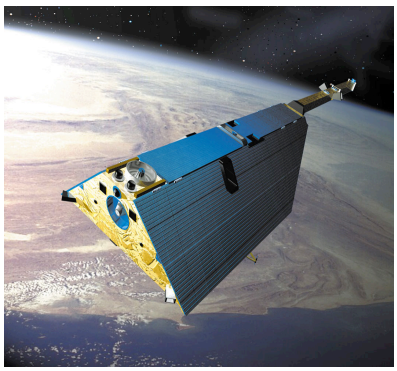
3. Immediate Plans for the Remainder of Calendar Year 2010

Immediate plans for the remainder of this calendar year (from December 2010 to June 2011) will include

1) Performing matching and comparison of GPS RO data to radiosonde data from 2009 to 2012. Statistics of ensemble in our comparisons are separated into radiosonde types and different geographical locations. A set of radiosondes whose derived refractivity fields are consistent with those from GPS RO data can then be identified.
2) Matching the all available GPS RO data including CHAMP from June 2001 and COSMIC from 2006 with MSU/AMSU data on board NOAA 14, 15, 16 and 17 from NEN_{NEW} and $NESDIS_{OPR}$, and Aqua AMSU, and identifying the spatial and temporal MSU/AMSU temperature anomalies. We will separate the RO-NEN_{NEW} comparisons for nadir and limb-corrected footprints to examine the consistency between the nadir and limb-corrected footprints.
3) Finding the statistics and calibration fits for each RO-microwave match pair for each month from 2009 to 2012.



COSMIC



CHAMP

YEAR 1 BI-ANNUAL PROJECT REPORT (from 12/01/2010 to 05/31/2011)
NOAA Award number: NA10NES4400002

Construction of Consistent Microwave Sensor Temperature Records and Tropopause Height Climatology using MSU/AMSU Measurements, GPS RO Data, and Radiosonde Observations

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1. Introduction

In this study, we propose to use temperature profiles derived from multiple Global Positioning System (GPS) Radio Occultation (RO) missions to calibrate the measurements from microwave sounders. We propose to carry out three tasks:

(i) To use GPS RO data from 2001 to 2012 as climate benchmark datasets to quantify the Microwave Sounding Unit (MSU)/Advanced Microwave Sounding Unit (AMSU) temporal and spatial temperature anomalies. Doing so would help define a better approach for constructing MSU/AMSU temperature records from 1979 to 2012;

(ii) To generate a long-term climate quality temperature dataset by reprocessing thirty-three years (1979-2012) of MSU/AMSU data. The 'adjusted' MSU/AMSU data and identified RO-consistent radiosonde data in the period of 2001 to 2009 (from the previous study) and from 2009 to 2012 will serve as reference data to calibrate other overlapped MSU/AMSU data from 1979 to 2001;

(iii) To use GPS RO soundings collected from multi-RO missions but processed using a consistent processing package to construct tropopause height climatology from 2001 to 2012 that is consistent with changes in temperature and tropopause structure estimated by radiosondes.

In this report, we summarize the continuous efforts made since the last report (submitted in December 2010) for this project. The work undertaken to date on these project goals is detailed in section 2, and related presentations and publications from June 2010 to May 2011 are listed in section 3.

2. Progress on Proposed Studies

Continued efforts since the last report have focused on: 1) Preparation of GPS RO, radiosonde, and MSU/AMSU data for geo-location comparisons, 2) Reprocessing the GPS RO from multiple RO missions using consistent inversion procedures and quantifying the reproducibility of GPS RO data for climate monitoring, 3) Quantifying the structural uncertainty for using GPS RO data for climate monitoring: intercomparison of RO profiles derived from different data centers, 4) Constraining microwave sensor temperature records using GPS RO data, 5) Continuing to assess the systematic biases of global radiosonde temperature measurements using RO Data, and 6) Using GPS RO data to construct tropopause height climatology.

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

Similar with the previous report, here we summarized the effort to collect new processed GPS RO data, NOAA MSU/AMSU data, MSU/AMSU climatology from Remote Sensing Systems (RSS) and University of Alabama in Huntsville (UAH) groups, AMSU data from NASA Aqua AMSU measurements, and temperature measurements from global radiosondes.

a. Data collection

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

- CHAMP data (from Jan. 2001 to April 2010) from UCAR CDAAC,
- COSMIC data (from June 2006 to April 2010) 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 2010,
- AMSU data from Aqua and Metop-A
- 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 $NESDIS_{NEW}$ V2.0 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 Reprocessing the RO data from multiple RO missions using consistent inversion procedures and quantifying of the reproducibility for using GPS RO Data for climate monitoring

a. Applying a consistent RO inversion algorithm to several international RO missions to derive the vertical distribution of bending angle, refractivity, temperature, and geo-potential height

A new RO inversion package is developed. Several improvements to precise orbit determination (POD) and excess atmospheric phase and neutral atmospheric inversion processes are developed. Now the consistent RO inversion algorithm is applied to several international RO missions to derive the vertical distribution of bending angle, refractivity, temperature, and geo-potential height. These RO missions include GPS/MET (from 1995 to 1997, no overlap with other RO missions), COSMIC (launched in April 2006), CHAMP (from 2001 to 2008), GRACE (launched in 2004), Satélite de Aplicaciones Científicas-C (SAC-C, launched in 2000), GNSS RO Receiver for Atmospheric Sounding (GRAS, launched in 2007), Communication/Navigation Outage Forecast System (C/NOFS, launched in 2008), and Terra Synthetic Aperture Radar (SAR) operating in the X-band (TerraSAR-X, launched in 2007).

b. Quantification of the Comparability of RO data for Climate Research

Since the instantaneous atmospheric truth profiles are not available, it is hard to quantify the absolute accuracy of GPS RO data. However, the precision of GPS RO data can be quantified by comparing closely located retrieved profiles derived from independent GPS RO missions (or among different receivers); the precision can be quantified where the GPS RO signals travel through nearly the same atmospheric paths. Here we continue to quantify the differences of inverted profiles among different RO missions whenever the newly processed RO data from different RO missions are available. We continue to conduct the following studies:

i). Quantify the Uncertainty of the Long-term Stability of GPS RO Data for Climate Monitoring by conducting profile-to-profile comparisons

To quantify not only the mean difference but also the uncertainty to the mean difference between RO missions, we continue to inter-compare the collocated RO data among CHAMP, COSMIC, SAC-C, GRACE, GRAS, C/NOFS, TerraSAR-X, and possible new RO missions beyond 2011.

ii) Documenting traceable standards for GPS RO metadata including the change of observing practices, the bending angle, phase, amplitude, and time delay of radio signals.

iii) Subsetting the data into latitude bands as well as land and ocean subsets; this will show whether this comparability is regionally dependent. We also examine differences of viewing geometry, rising/setting, thermal noise, ionospheric calibration, and orbit error among different missions.

Results show that the mean temperature biases from 8 km to 30 km between two close collocated RO missions are in general less than 0.1 K. No further results are reported.

2.3 Quantification of the Reproducibility of RO Data for Climate Monitoring

Here we quantify the structural uncertainty for using GPS RO data for climate monitoring by intercomparing RO profiles derived from different data centers (e.g., GeoForschungsZentrum Potsdam (GFZ), Germany; the Jet Propulsion Laboratory (JPL), Pasadena, CA, USA; the University Corporation for Atmospheric Research (UCAR), Boulder, CO, USA; the Wegener Center of the University of Graz (WegC), Graz, Austria; the Danish Meteorological Institute, (DMI), Copenhagen, Denmark; and the Meteorological Division, EUMETSAT (EUM), Darmstadt, Germany).

a. Reproducibility of RO Sounding Results: profile-to-profile comparisons of RO data processed by different RO centers

Here we continue to quantify the reproducibility of RO data among different RO processing centers by conducting profile-to-profile comparisons among different RO centers. Here we aim to quantify GPS RO-derived vertical profiles of bending angle, refractivity, and dry temperature obtained from atmospheric excess phase processing and inversion procedures from different RO operational centers. This is to quantify the structural uncertainty of RO parameters derived at each of the following processing steps:

a. Precise Orbit Determinations and Excess Atmospheric Phase Processing
b. Calculation of L1 and L2 Bending Angles
c. Ionospheric Correction
d. Abel Integral Upper Boundary
e. Derivation of Dry temperature
f. Derivation of geo-potential height
g. Derivation of pressure
h. Quality Control Methods

Approaches:

i) Collect CHAMP data (2001 to 2008) processed by UCAR, JPL, GFZ, DMI, EUM, and WEGC.
ii) In order to match the exact the same profiles processed by different centers, we first use UCAR routines to rename the filename from individual centers so that they are consistent with the UCAR filename.
iii) Using the profile information from the filename, we match all the individual profiles processed by different processing centers.

Comparison results:

- We compare the GPS RO-derived vertical profiles of bending angle, refractivity, and dry temperature derived by six different centers.

- **Figure1** shows the profile-to-profile bending angle comparison for JPL, UCAR, and WEGC relative to the mean bending angle profiles for all six centers. Global bending angle profiles for 2002 are used here.

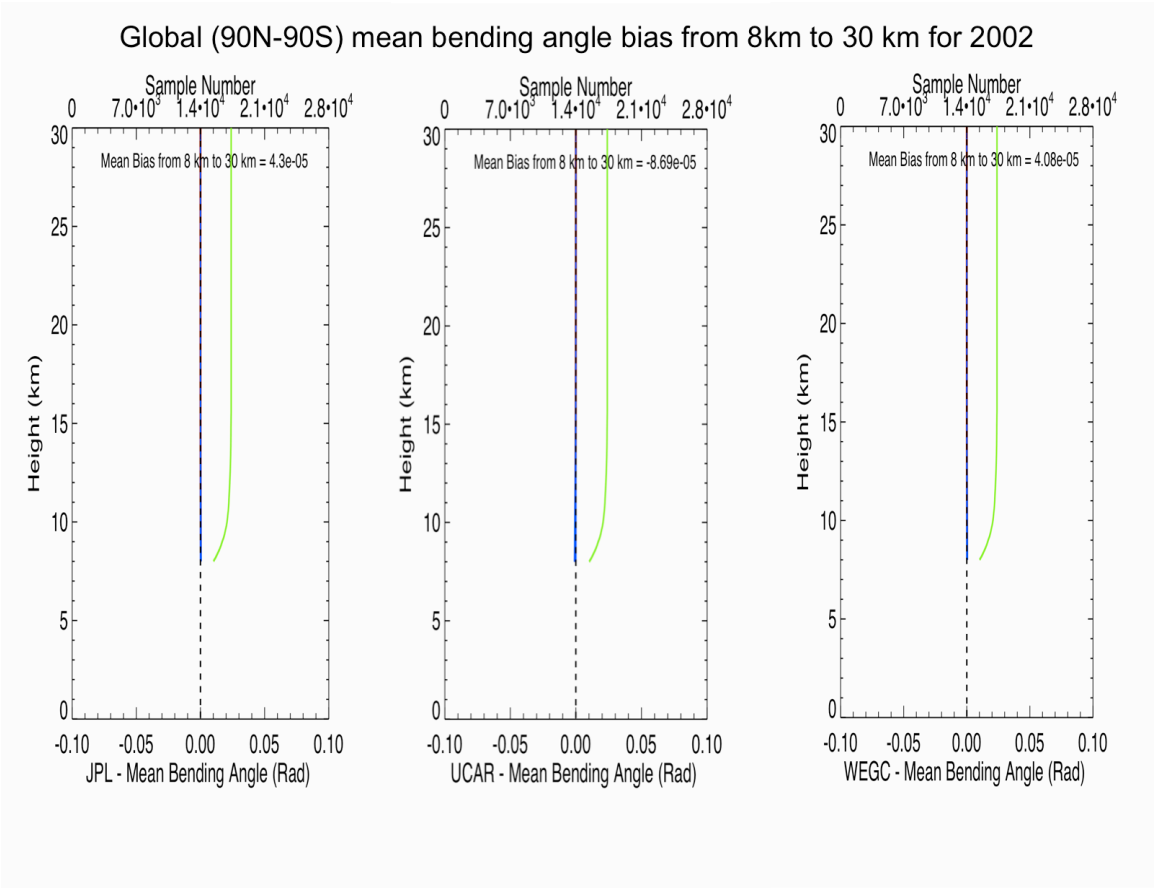

Figure1. The profile-to-profile bending angle comparison for JPL, UCAR, and WEGC relative to the mean bending angle profiles for all six centers.

- The time series of fractional refractivity anomalies are computed from the average of the refractivity (N) values from 8 km to 30 km for 90°N-90°S, 90°N-60°N, 60°N-20°N, 20°N-20°S, 20°S-60°S, 60°S-90°S zones (**Fig. 2**). The CHAMP refractivity profiles from 2002 to 2008 are used. The monthly mean fractional refractivity time series from each center are compared. Obvious systematic biases among different centers at different latitudinal zones are identified. Causes of differences are identified.
- The time series of bending angle, refractivity, dry temperature, geo-potential height, and dry pressure among all five centers (EUM is not included) are also compared.

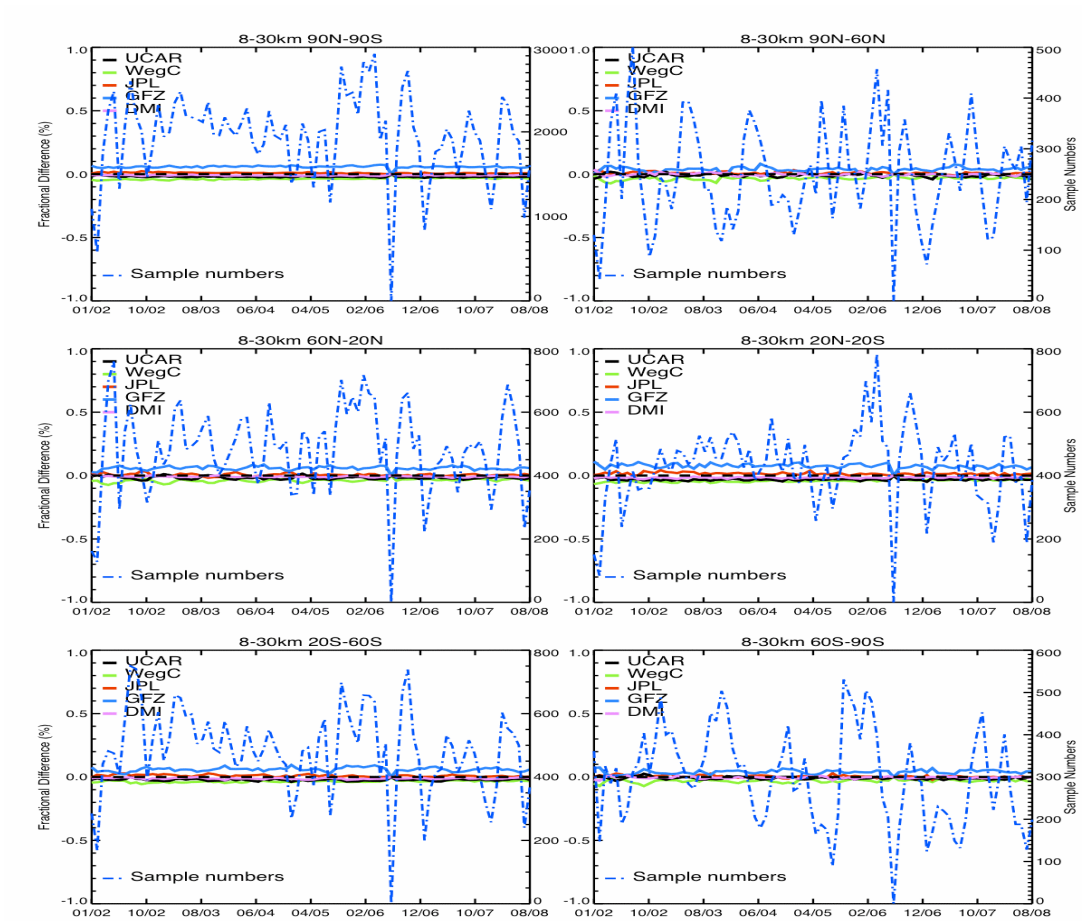

Figure 2. The time series of refractivity anomalies (relative to the mean refractivity for all five centers) from January 2002 to December 2008 among five centers for the 8-30 km layer for (a) the entire globe (82.5ºN-82.5ºS, the left upper panel), b) the 82.5ºN-60ºN zone (the upper right panel), (c) the 60ºN-20ºN zone (the middle left panel), (d) the 20ºN-20ºS zone (the middle right panel), (e) the 20ºS-60ºS zone (the bottom left panel), and (f) the 60ºS-82.5ºS zone (the bottom right panel).

- **Figure 3** shows the time series comparison of the differences between deseasonalized fractional refractivity anomalies for each center to their mean of all centers.

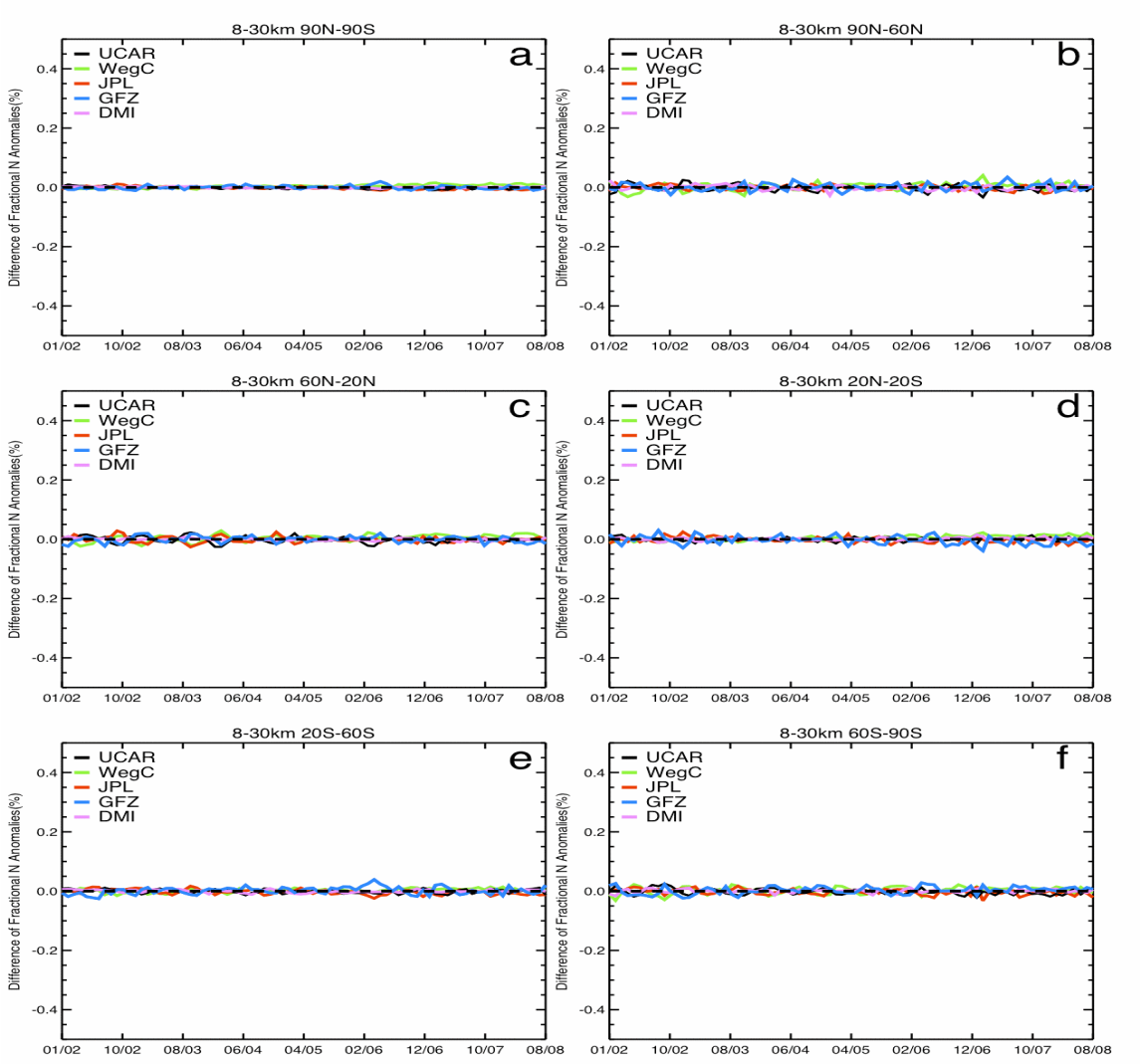

Figure 3. The differences between deseasonalized fractional refractivity anomalies for each center to their mean of all five centers (in the 8-30 km layer for (a) the entire globe (82.5ºN-82.5ºS, the left upper panel), b) the 82.5ºN-60ºN zone (the upper right panel), (c) the 60ºN-20ºN zone (the middle left panel), (d) the 20ºN-20ºS zone (the middle right panel), (e) the 20ºS-60ºS zone (the bottom left panel), and (f) the 60ºS-82.5ºS zone (the bottom right panel).

b. Comparisons of COSMIC data processed by different RO centers

We also conduct similar comparisons for COSMIC RO data derived by UCAR, JPL, and WEGC. The UCAR data and WEGC data are collected. We then collect the JPL COSMIC data and make the initial comparisons.

2.4 Calibration and Construction of Microwave Sensor Temperature Records Using GPS RO data

a. Construction of the 2001 to 2010 RO calibrated TLS temperature trend

Here we use CHAMP and COSMIC RO temperature profiles to calibrate multiple years of AMSU temperature in the lower stratosphere (TLS, AMSU channel 9) measurements from multiple satellite missions (NOAA 15, 16, 18, and 19, METOPA, and NASA Aqua). Nearly a decade of RO-calibrated AMSU TLS time series is constructed.

b. Inter-comparison of RO-AMSU TLS with other TLS datasets

The derived TLS record is compared with the newly available TLS datasets provided by RSS and UAH, and TLS processed by NOAA STAR (SNO method) since 2001 to 2010. **Figure 4** shows that the time series of the TLS anomalies of the four centers vary with different latitudinal zones. The TLS anomalies from UAH and STAR generally agree well with those from RO calibrated AMSU TLS in all latitudinal zones.

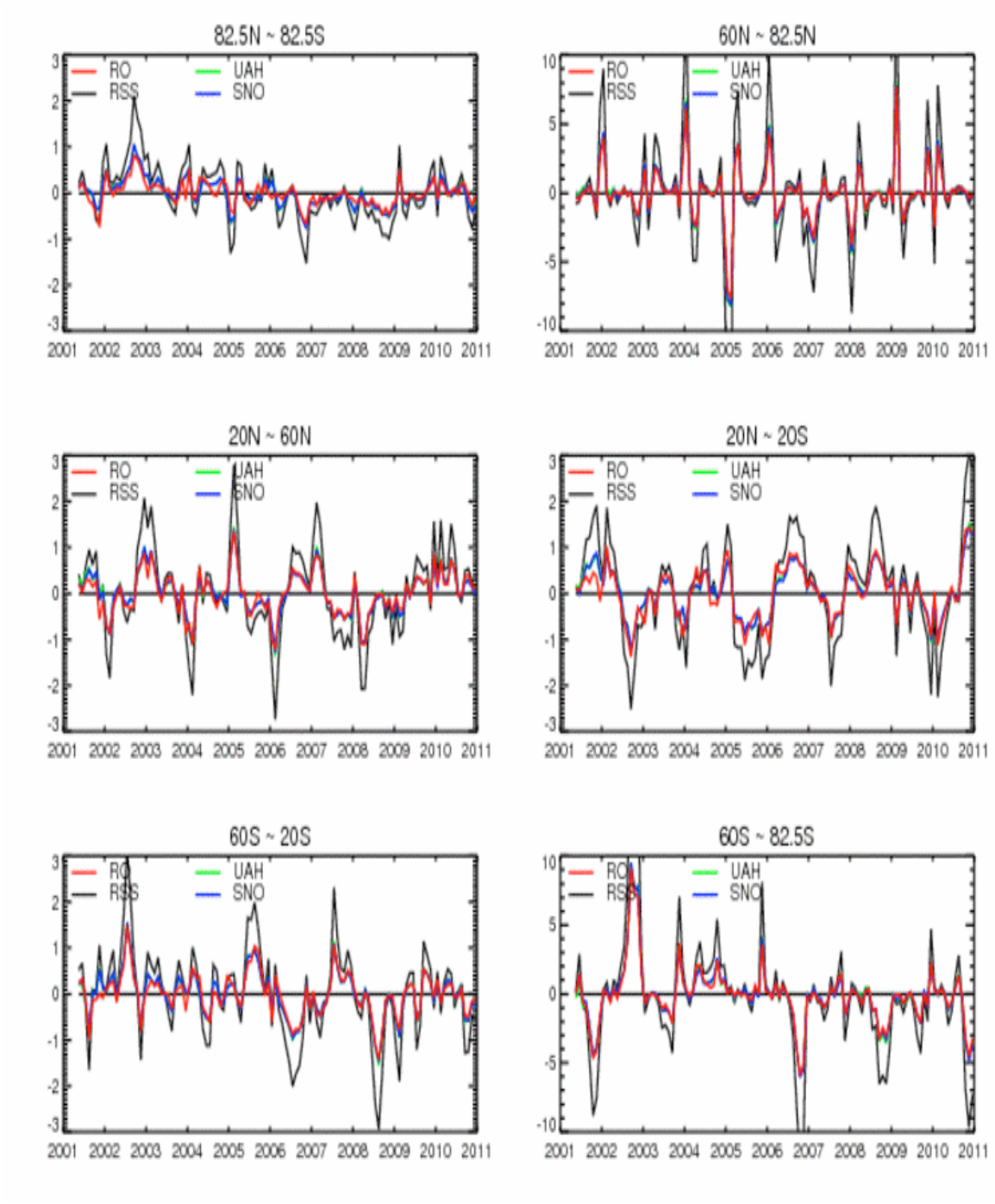

Figure 4. TLS anomalies of RSS, UAH, SNO, and RO_AMSU for (a) the entire globe (82.5ºN-82.5ºS, the left upper panel), b) the 82.5ºN-60ºN zone (the upper right panel), (c) the 60ºN-20ºN zone (the middle left panel), (d) the 20ºN-20ºS zone (the middle right panel), (e) the 20ºS-60ºS zone (the bottom left panel), and (f) the 60ºS-82.5ºS zone (the bottom right panel). The orange line indicates the mean trend for RO_AMSU.

2.5 Continue to assess the Systematic Biases of Global Radiosonde Temperature Measurements using RO Data

We continue to use GPS RO data to assess the systematic biases of the global radiosonde temperature measurements. Using RO data we can:

- **Quantify the radiative effect on radiosonde temperature anomalies using COSMIC temperature profiles;** and
- **Extend the comparison of GPS RO temperature profiles and radiosonde comparison from 2002 to 2010.**

Approaches: Globally, there are roughly 850 radiosonde stations using about fourteen different types of radiosonde systems. Different radiosonde systems have their own known observational errors. In the comparison, we use all available RO temperature profiles from multiple RO missions that occur within 2 hours and 300 km of radiosonde profiles.

Results:

- We compare temperature profiles derived from multiple years of GPS RO data from the COSMIC (from 2006 to 2010), CHAMP (from 2001 to 2008), and GRACE (from 2008 to 2010) with those from different types of radiosonde systems.

- Using RO data, we assess the systematic temperature biases from the height of 12 to 25 km for different radiosonde temperature sensors.

- **Figure 5** depicts the temperature differences between RO and Vaisala-RS92 radiosondes from 2006 to 2010. The mean temperature from the 10 km to 25 km layer is compared. Here the RO data are from 200 mb to 20 mb are compared. All RO data from multiple RO missions are consistently processed using the new CDAAC RO inversion algorithm. Radiosonde data used in this study are also obtained from CDAAC (via NCAR mass store, Date 353.4). Radiosonde temperature measurements within 2 hours and 300 km of COSMIC RO soundings are used to compare to those from RO data. Results show that Vaisala-RS92 radiosondes are very consistent with those of RO data from 10 to 25 km with a mean difference close to -0.1 K globally (**Fig. 5**).

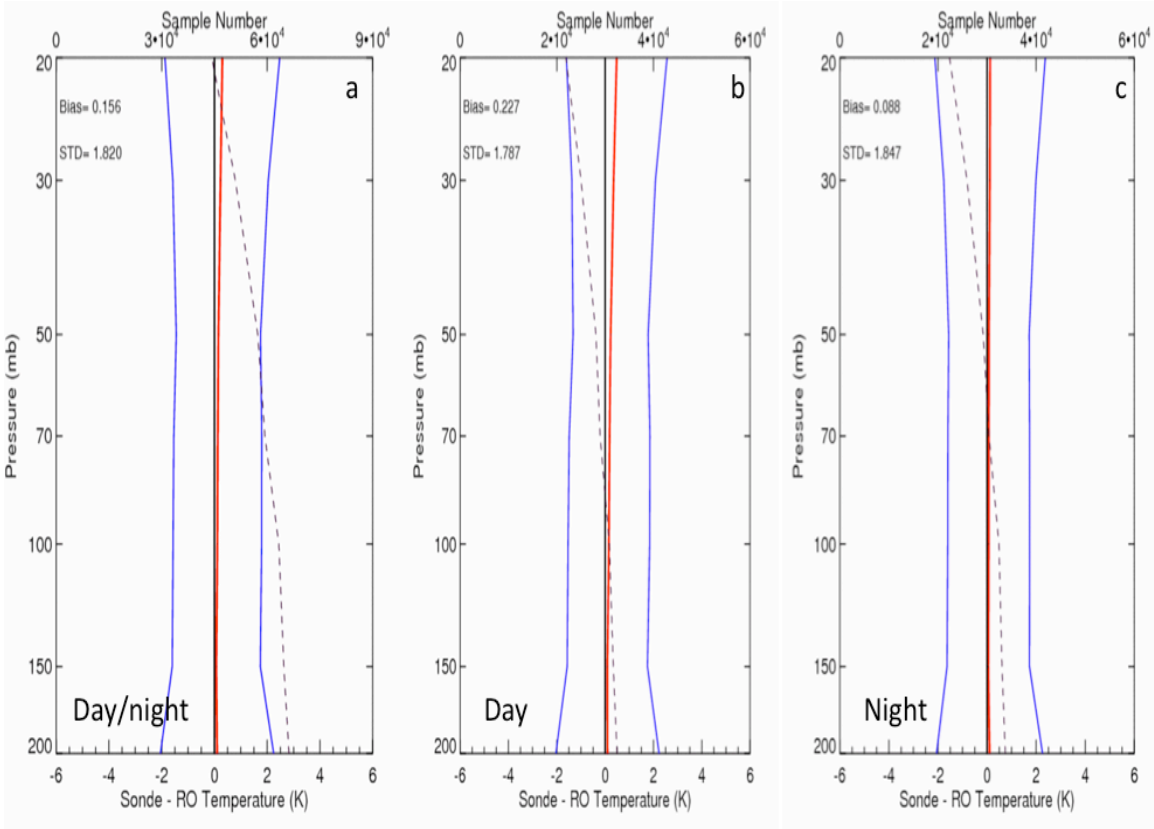

Figure 5. Temperature difference between RO data (COSMIC, CHAMP, and GRACE from 2006 to 2010) and Vaisala-RS92 radiosondes during a) both day and night, b) day, and c) night.

2.6 Using GPS RO data to Construct Tropopause Height Climatology

We continue to compute the global tropopause heights using GPS RO dry temperature and to construct tropopause height climatology from 2001 to 2010.

Approach:

Here the GPS RO Lapse Rate Tropopause (LRT) is calculated using the WMO definition (WMO, 1957). The LRT is derived from COSMIC temperature profiles and is determined when the following criteria are satisfied:

(a)The lowest level between 500 mb and 70 mb at which the lapse rate is less than -2°C/km is calculated;

(b) The average lapse rate between this lowest level and all higher levels within 2 km does not exceed -2 K/km;

(c) None of the levels from this lowest level up to 2 km above have a lapse rate of less than -2 K/km;

(d) Mean lapse rate from the layers below this lowest layer is greater than -2 K/km. This minimizes the influence of outliers in the temperature profiles.

Using this algorithm, we compute the LRT for COSMIC, CHAMP, GRACE, and GRAS. We also apply this algorithm to define LRT from CHAMP RO data processed from DMI, GFZ, JPL, UCAR and WEGC.

Results:

- We compute the global LRT using UCAR COSMIC, CHAMP, GRACE, and GRAS data and construct the Tropopause Height Climatology.
- We compute the LRT for DMI, GFZ, JPL, UCAR and WEGC, and quantify the uncertainty of the derived tropopause height.
- **Figure 6** depicts the mean tropopause height climatology and the monthly anomalies relative to the mean climatology.
- **Figure 7** depicts UCAR CHAMP LRT time series to those CHAMP LRTs derived from DMI, GFZ, JPL and WEGC.
- The LRT trends (meter/yr) from October 2001 to October 2008 for DMI, GFZ, JPL, UCAR and WEGC for different latitudinal zones is shown in **Figure 8**.
- Investigate how the QBO (Quasi-biannual oscillation) will affect the global tropopause climatology (see **Figure 9**).

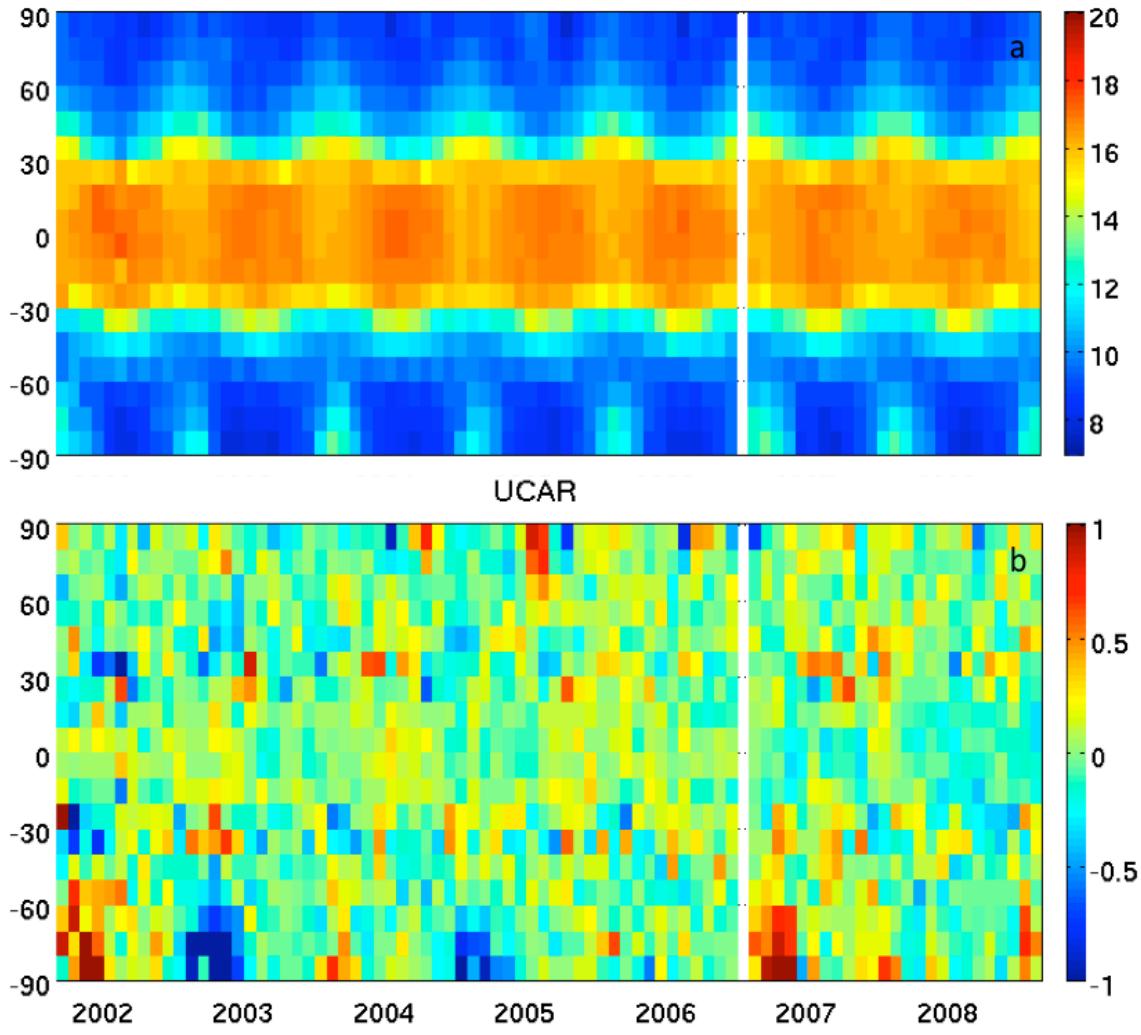

Figure 6. a) the mean tropopause height climatology (in km) generated by using CHAMP data from June 2001 to August 2008, and b) the corresponding monthly tropopause height anomalies (in km).

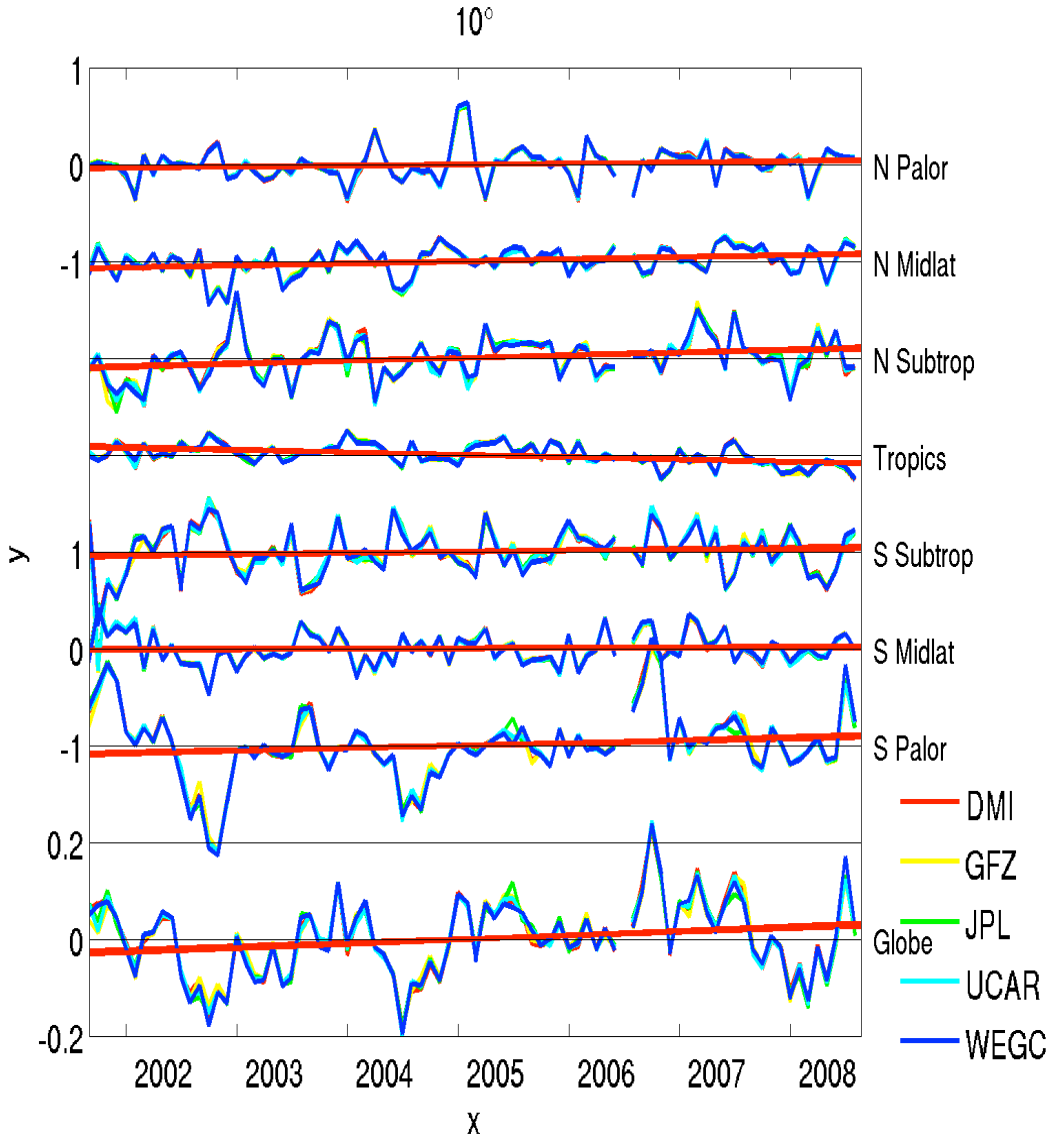

Figure 7. The LRT time series from October 2001 to October 2008 for DMI, GFZ, JPL, UCAR and WEGC for different latitudinal zones.

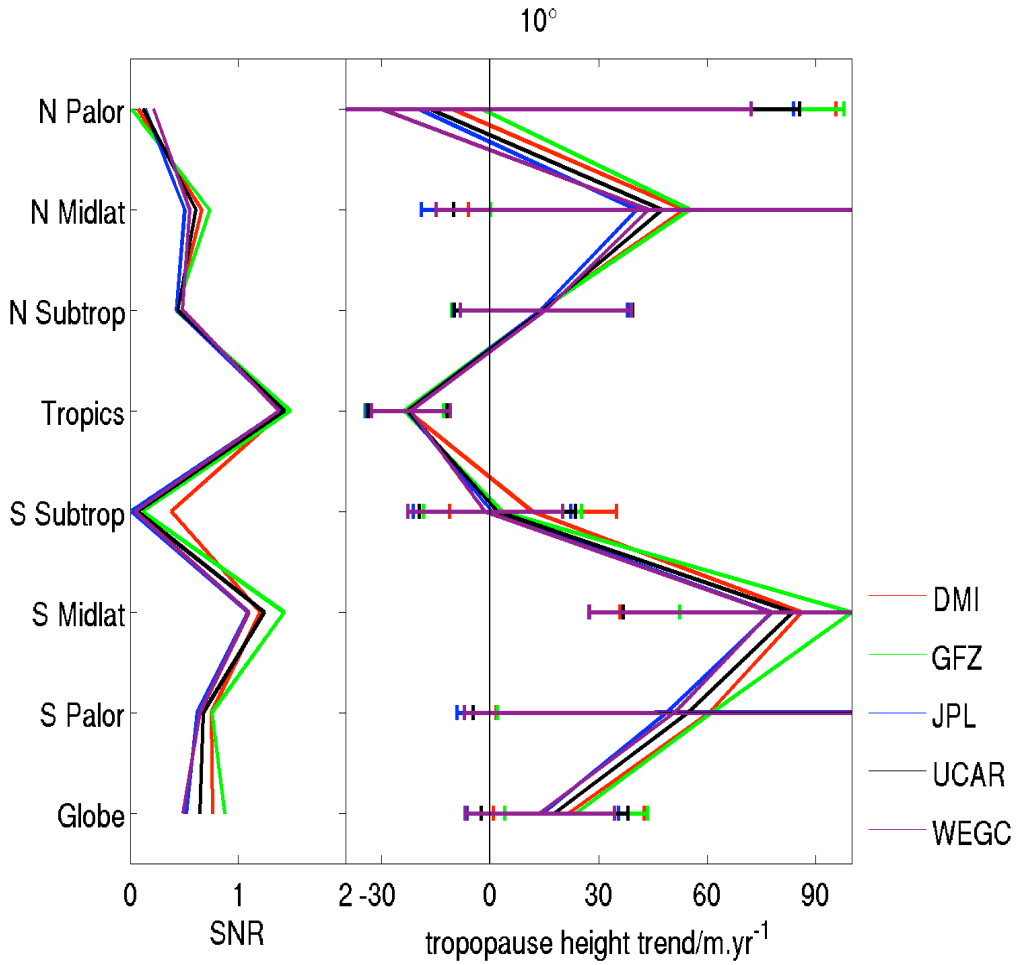

Figure 8. The LRT trends (meter/yr) from October 2001 to October 2008 for DMI, GFZ, JPL, UCAR and WEGC for different latitudinal zones.

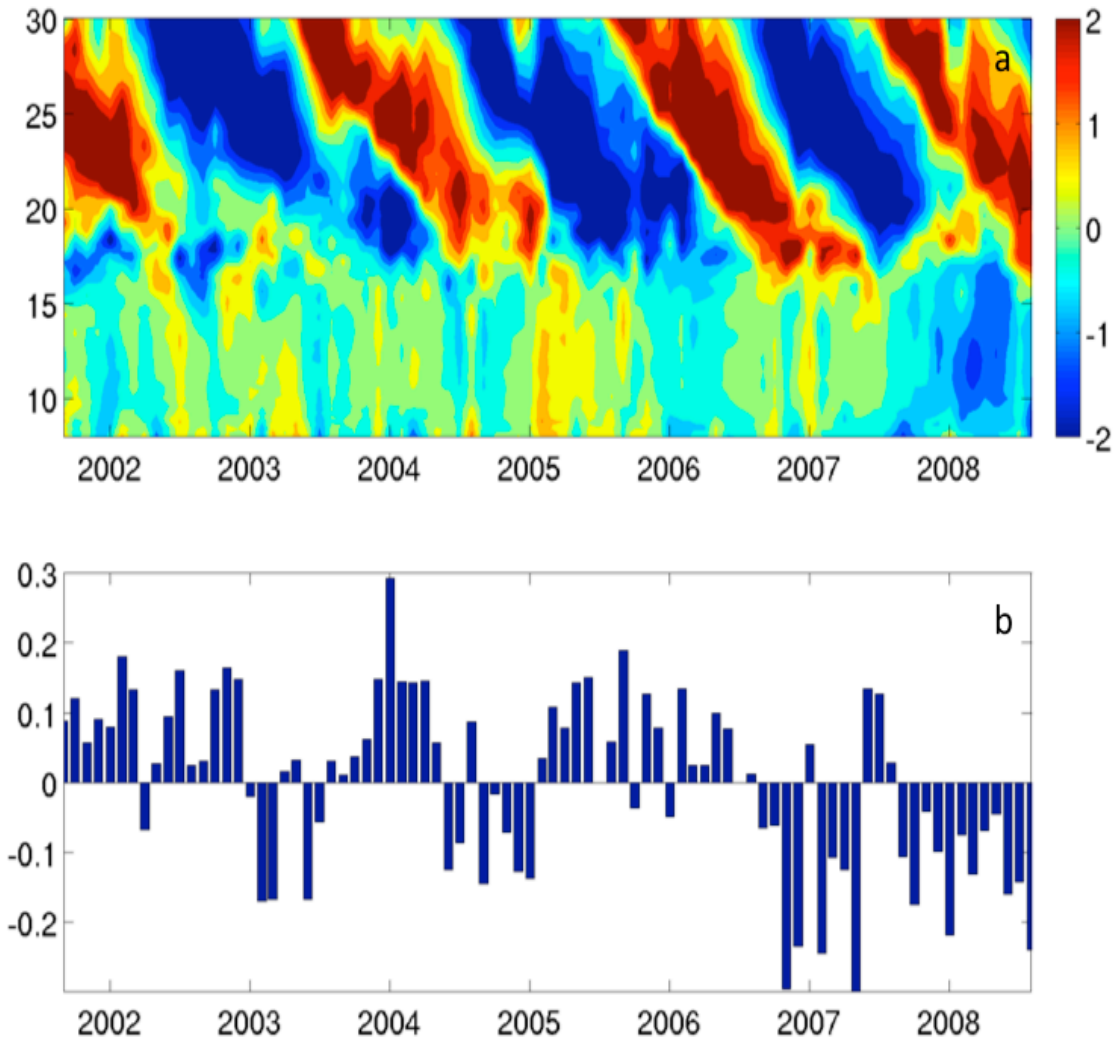

Figure 9. a) the time series of temperature anomalies (in K) from 8 km to 30 km in height and from 10 degree N to 10 degree S that are constructed by using UCAR CHAMP data, and b) the corresponding time series of the trend of tropopause height (in km/year) also computed by using UCAR CHAMP data.

3. Presentations and Publications

Related presentations and publications from June 2010 to May 2011 are listed:

1) **Ho S.-P.**, X. Zhou, Y.-H. Kuo, D. Hunt, and C.-Z. Zou, 2010: Construction of a Consistent Microwave Sensor Temperature Record in the Lower Stratosphere Using Global Positioning System Radio Occultation Data and Microwave Sounding Measurements. Presentation, joint 2010 CWB Weather Analysis and Forecasting and COAA 5th International Ocean-Atmosphere Conference, Center Weather Bureau, Taipei, Taiwan.

2) **Ho, S.-P.**, X. Zhou, Y.-H. Kuo, and D. Hunt, 2010: Climate Calibration Observatory in Orbit: Calibration and Validation of Measurements of AMSU and AIRS using Global Positioning System Radio Occultation Observations. Presentation, OPAC-4, Graz, Austria.

3) Steiner, A. K., S.-P. Ho, D. Hunt , G. Kirchengast, A. J. Mannucci, B. Scherllin-Pirscher, H. Gleisner , A. von Engeln , T. Schmidt C. Ao , S. S. Leroy , U. Foelsche , Y-H. Kuo , E. R. Kursinski, K. B. Lauritsen , S. Syndergaard , C. Marquardt , C. Rocken , W. Schreiner , S. Sokolovskiy, J. Wickert W.and Coauthors, 2010: Uncertainty of the CHAMP Climate Record from Different Data Centers. Presentation, OPAC-4, Graz, Austria.

4) Callaghan, P. F., **S.-P. Ho**, T. Yunck, B. D. Wilson, and G. Manipon, 2011: Evaluation of AIRS V5 Temperature Profiles Using Matched Retrievals From COSMIC and ECMWF Analyses. Presentation, 91st American Meteorological Society Annual Meeting, Seattle, WA, USA.

5) Steiner, A. K., **S-P. Ho**, D. Hunt, G. Kirchengast, A. J. Mannucci, B. Scherllin-Pirscher, H. Gleisner, A. von Engeln , T. Schmidt C. Ao , S. S. Leroy , U. Foelsche , Y-H. Kuo , E. R. Kursinski, K. B. Lauritsen , S. Syndergaard , C. Marquardt, C. Rocken, W. Schreiner, S. Sokolovskiy, J. Wickert W.and Coauthors, 2011: Uncertainty of the CHAMP Climate Record from Different Data Centers. Presentation, the 5th FORMOSAT-3/COSMIC Data Users Workshop & ICGPSRO 2011, Taipei, Taiwan.

6) **Ho, S.-P.**, Y.-H. Kuo, X.-J. Zhou, and P. Callaghan, 2011: Long Term Assessment of Radiosonde Temperature Systematic Biases using COSMIC, CHAMP, and GRACE from 2001 to 2010. Presentation, the 5th FORMOSAT-3/COSMIC Data Users Workshop & ICGPSRO 2011, Taipei, Taiwan.

7) **Ho, S.-P.**, Y.-H. Kuo, X.-J. Zhou, and P. Callaghan, 2011: The Use of the COSMIC/FORMOSAT-3 Global Positioning System Radio

Occultation Data as Global Reference Observations in Orbit and Their Applications in Meteorology. *Horizons in Earth Science Research, Vol. 5*, B. Veress and J. Szigehty, Eds., NOVA Publishers (invited).

8) **Ho, S.-P.**, X. Zhou, Y.-H. Kuo, D. Hunt, and J.-H. Wang, 2010: Global Evaluation of Radiosonde Water Vapor Systematic Biases using GPS Radio Occultation from COSMIC and ECMWF Analysis. *Remote Sensing*, 2(5), 1320-1330.

9) **Ho, S.-P.**, Y.-H. Kuo ,W. Schreiner, and X. Zhou, 2010: Using SI-traceable Global Positioning System Radio Occultation Measurements for Climate Monitoring [In "States of the Climate in 2009]. *Bul. Amer. Meteor. Sci*., 91 (7), S36-S37 (invited).

10) Mears C., J. Wang, **S.-P. Ho**, L. Zhang, and X. Zhou, 2010: Total Column Water Vapor, [In "States of the Climate in 2009]. *Bul. Amer. Meteor. Sci*., 91 (7), S29-S31 (invited).

11) Mears C., J. Wang, **S.-P. Ho**, L. Zhang, and X. Zhou, 2011: Total Column Water Vapor, [In "States of the Climate in 2010]. *Bul. Amer. Meteor. Sci.,* in press (invited).

12) **Ho, S.-P**., IPCC AR5 report, a section of "Inter-comparison of RO data with other climate temperature data record" (invited).