COSMIC Program Office

Algorithm Theoretical Basis Document (ATBD)

GPS RO Temperature Climatology

1. Introduction

1.1 Purpose

The purpose of this document is to describe the algorithm submitted to the UCAR Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) Data Analysis and Archive Center (CDAAC) by Dr. Shu-peng Ben Ho/COSMIC UCAR. This algorithm produces monthly mean temperature climatology using Global Positioning System (GPS) Radio Occultation (RO) temperature profile measurements from Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC), Meteorological Operational Polar Satellite–A (Metop-A)/GRAS (GNSS Receiver for Atmospheric Sounding (launched in October 2006), and Meteorological Operational Polar Satellite–B (Metop-B)/GRAS (launched in September 2012). The intent here is to provide a guide to understanding that algorithm from a scientific perspective.

1.2 Definitions

Following is a summary of the symbols used to define the algorithm.

Atmospheric parameters:

T = *Temperature* (1)

P = *Pressure* (2)

P_w = *Vapor Pressure* (3)

N = *Refractivity* (4)

1.3 Document Maintenance

This document describes the submission, version 1.0, of the processing algorithm and resulting data. The version number will be incremented for any subsequent enhancements or revisions.

2. Observing Systems Overview

2.1 Products Generated

Monitoring and detecting the vertical structure of atmospheric temperature trends are key elements in the climate change problem. In addition, identifying the long-term change of temperature and tropopause structure (i.e., tropopause height) in the upper troposphere and lower stratosphere (UTLS) is necessary to advance reliable predictions of trends in climate or global change. The temperature monthly mean climatology (MMC) is constructed from COSMIC, Metop-A, and Metop-B reprocessed data. COSMIC2013 reprocessed data covering from June 2006 to April 2014, Metop-A/GRAS (i.e., Metop-A version 2016.0120 covering from to September 2007 to December 2015), and Metop-B/GRAS (i.e., Metop-B version 2016.0120 covering from to September 2012 to December 2015) are used to construct the RO temperature MMC. The sampling errors for each mission for each individual months are estimated by using NCEP, ERA-Interim, and MERRA reanalysis data. The mean and standard deviation of the mean sampling errors are estimated. The COSMIC, Metop-A/GRAS, and Metp-B/GRAS GPS RO MMC are calculated and binned on 5-degree latitudinal bins. The final product consists of monthly mean averages of temperature profiles from June 2006 to December 2015.

2.2 Instrument Characteristics

With all-weather coverage, and long-term stability [Anthes et al., 2008; Ho et al., 2009a,b,c], GPS RO data are very suitable and reliable for climate monitoring. Accurate RO retrievals of atmospheric variable profiles depend on the adequate calculation of the GPS excess atmospheric phase data of two L band frequencies (1575.42 MHz (L1) and 1227.6 MHz (L2)) due to signal delay and bending in the Earth's atmosphere and ionosphere (Kursinski et al., 1997; Ho et al., 2009a). These processing steps include: i) precise orbit determination (POD) and atmospheric excess phase processing, ii) bending angle calculation, iii) ionospheric correction, iv) optimal estimation of the bending angles in the stratosphere, v) calculation of refractivity by Abel inversion, vi) calculation of pressure, temperature, and geopotential height, and vii) quality control (QC). A consistent RO inversion package developed by the COSMIC Data Analysis and Archive Center (CDAAC) is applied to COSMIC, Metop-A, and Metop-B missions to derive multi-year temperature profiles. GPS RO observations are of high vertical resolution (from ~60 m near the surface to ~1.5 km at 40 km). The COSMIC, Metop-A, and Metop-B post-processed dry temperature profiles (atmPrf) downloaded from UCAR CDAAC (http://cosmic.cosmic.ucar.edu/cdaac/index.html) are used to generate the tropopause heights. The CDAAC inversion procedures are detailed in

Kuo et al., [2004], and Ho et al., [2009a,b,c, 2012]. The mean dry temperature difference between the collocated soundings of COSMIC and CHAMP is within 0.1K from 200 hPa to 20 hPa [Ho et al., 2009a; Anthes et al., 2008; Foelsche et al., 2009]. The estimated structural uncertainties for the CDAAC dry temperature from the 8 km to 30 km layer is about 0.03K with a Median Absolute Deviation of 0.43K [Ho et al., 2012].

3. Algorithm Description

3.1 Algorithm Overview

The temperature MMC is determined by the high vertical resolution COSMIC, Metop-A, and Metop-B temperature profiles. However, because the temporal and spatial resolution of Metop-A and Metop-B (one receiver) is different from those from COSMIC (6 receivers from 2006 to the current), we will need to quantify and remove the possible sampling errors before we can construct the temperature climatology. We first use reanalysis data to remove the sampling errors for Metop-A, Metop-B, and COSMIC temperature profiles. Anomaly values are then obtained by subtracting this climatology from the monthly values. The final step is to convert and combine the data into netCDF files containing the final product.

3.2 Processing Outline

In this study, we focused on construction of temperature climate data records from 2001 to 2015 using multiple RO missions. This is to generate long-term climate quality temperature monthly mean climatologies (MMCs) using dry temperature profiles from multiple RO missions in the UTLS (mainly from 8km to 30 km altitude with a vertical grid every 200 meters).

Specifically, we used the method of ''binning and averaging'' to generate the temperature MMC. Re-processed COSMIC and CHAMP temperature profiles downloaded from CDAAC are used. In this study, zonal bins of 5° latitudinal width were defined at a Mean Sea Level (MSL) altitude grid with vertical resolution of 200 meters. To reduce sampling errors in the temperature MMCs, they are all updated for each mission by subtracting estimated sampling errors (see *Ho et al.*, 2009a and 2012). The sampling errors are estimated using the ERA-Interim reanalysis data. The following procedures are used:

STEP(1) Pre-Processing: the reanalysis temperature profiles are interpolated to the times and locations of each GPS profiles for Metop-A, Metop-B, and COSMIC.

STEP(2) Removing Sampling Errors: the interpolated temperature profiles for different missions are binned to the monthly mean climatologies just as done with the original GPS temperature MMC respectively (denoted as $\overline{MMC_{Int}}$). The MMC are also generated from original reanalysis grid data (denoted as $\overline{MMC_{grid}}$). The sampling error of the MMC (MSE) is defined as

$$MSE = \overline{MMC_{Int}} - \overline{MMC_{grid}} \qquad (1).$$

The MSE estimated from ERA-Interim reanalysis are denoted as MSE_{ERA_Intrim}. The new MMC (denoted as MMC^{NEW}) for each month and mission are then defined as

$$MMC^{NEW} = \overline{MMC_{Grid}} - MSE \qquad (2)$$

The new MMC computed from MSE_{ERA_Intrim} denoted as $MMC^{NEW}_{ERA\_Intrim}$.

STEP(3) Estimating the Uncertainty of Sampling Errors: To quantify the uncertainty for MSE estimated by different reanalysis data, we compared $\overline{MMC_{Int}}$ for NCEP, ERA-Interim, and MERRA (i.e., $\overline{MMC_{Int\_NCEP}}$, $\overline{MMC_{Int\_ERA\_Interim}}$, and $\overline{MMC_{Int\_MERRA}}$, respectively) relative to the corresponding global layered temperature from 8 km to 30 km computed from RO data in Figure 1. Figure 1a depicts the $\overline{MMC_{Int\_NCEP}}$, $\overline{MMC_{Int\_ERA\_Interim}}$, and $\overline{MMC_{Int\_MERRA}}$ relative to the corresponding global layered temperature from 8 km to 30 km can vary from -1.0 K to 0.5K from June 2001 to December 2013. However, even with different $\overline{MMC_{Int\_NCEP}}$, $\overline{MMC_{Int\_ERA\_Interim}}$, and $\overline{MMC_{Int\_MERRA}}$, the estimated sampling errors (i.e., MSE_{NCEP}, MSE_{ERA_Intrim}, and MSE_{MERRA} defined in Eq. (1)) are very close among these three analyses (Figure 1b). The time series of mean temperature anomalies in the same time period for $MMC^{NEW}_{NCEP\_Intrim}$, $MMC^{NEW}_{ERA\_Intrim}$, and $MMC^{NEW}_{MERRA\_Intrim}$ are almost identical (Figure 1c). These results provide confidence in our approach for generating RO temperature MMCs. Our future plans are to i) compare newly available re-processed Metop-A, Metop-B, and COSMIC data and quantify the temperature differences from 8 km to 30 km from 2001 to the current, ii) compute the temperature sampling errors from multiple RO missions, and iii) extend the temperature MMCs from 2001 to the present by including all available RO temperature profiles, and iv) publish all MMCs on the CDAAC website. The first MMCs are expected to be published by June 2016 and will consist of reprocessed data from COSMIC and other missions. These SI-traceable RO temperature MMCs will facilitate atmospheric research by the community related to monitoring and understanding modes of atmospheric temperature variability, validation of climate models, and other studies.

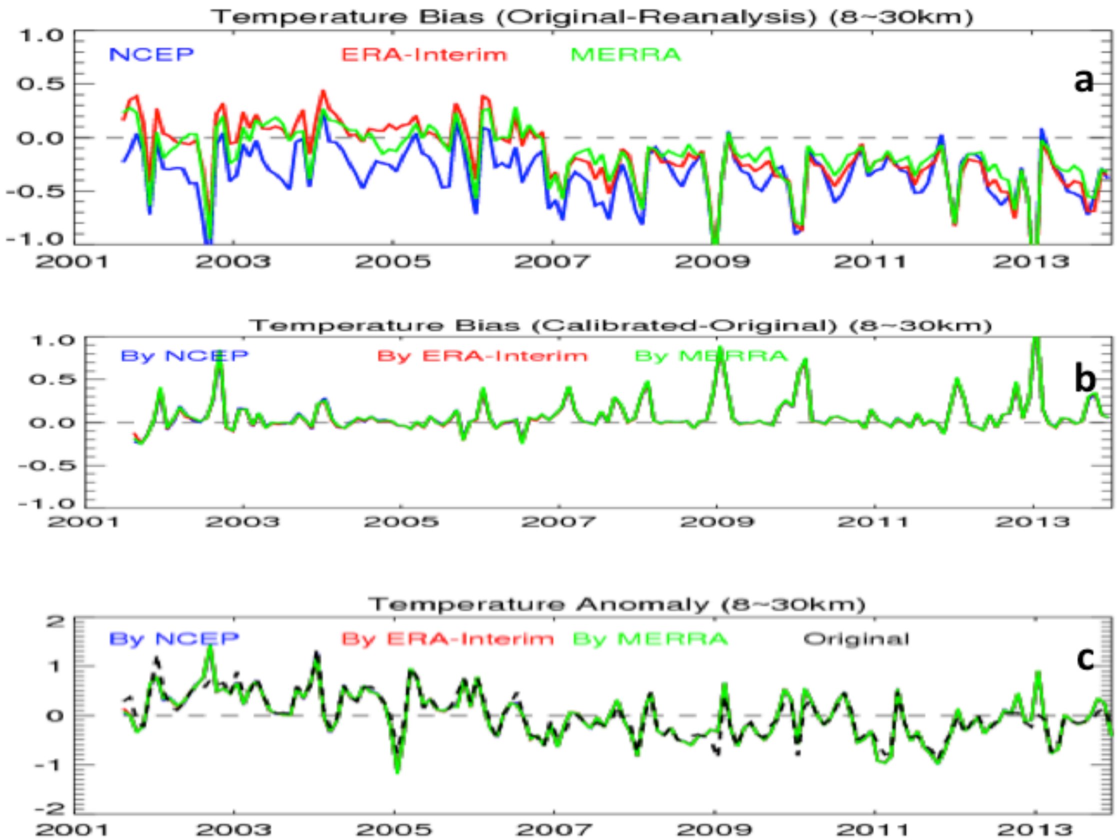

Figure 1. Time series of $\overline{MMC_{Int\_NCEP}}$, $\overline{MMC_{Int\_ERA\_Interim}}$, and $\overline{MMC_{Int\_MERRA}}$ relative to the corresponding global layered temperature from 8 km to 30 km computed from RO data, b) time series of MSE_{NCEP}, MSE_{ERA_Intrim}, and MSE_{MERRA}, c) time series anomaly for $MMC^{NEW}_{NCEP\_Intrim}$, $MMC^{NEW}_{ERA\_Intrim}$, and $MMC^{NEW}_{MERRA\_Intrim}$.

3.3 Algorithm Input

3.3.1 Primary Sensor Data

COSMIC and Metop-A, and Metop-B temperature profiles downloaded from CDAAC (http://cosmic.cosmic.ucar.edu/cdaac/index.html) are used to generate the temperature MMC.

Recently, the UCAR Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) Data Analysis and Archive Center (CDAAC) has developed an improved reprocessing package, which is used to consistently process RO data from multiple years of multiple RO missions including COSMIC (launched in April 2006) and Meteorological Operational Polar Satellite–A (Metop-A)/GRAS (GNSS Receiver for Atmospheric Sounding (launched in October 2006), and Metop-B/GRAS (launched September 2012). A sequence of processing steps is used to invert excess phase measurement to retrieve atmospheric variables including bending angle, refractivity, pressure, temperature, and geo-potential height. Comparing with the previous version, the new inversion package used improved precise orbit determination (POD) and excess phase processing algorithm, where a high-precision, multiple Global Navigation Satellite System (GNSS) data processing software (i.e., Bernese Version 5.2, Dach et al., (2015)) is applied for clock estimation and time transfer. In the reprocessing package, the POD for COSMIC and Metop-A/GRAS are implemented separately (Schrein et al., 2011). Compared to the real-time processed RO data, much improved and more completed satellite POD data are used in the reprocessed package. The re-processed COSMIC, Metop-A/GRAS, and Metop-B/GRAS data would produce more consistent and accurate RO variables than those from post-processed (periodically updated inversion packages were used) and real-time processed datasets.

3.3.2 Ancillary Data

N/A

3.3.3 Derived Data

Global temperature MMC profiles are derived from COSMIC, Metop-A, and Metop-B temperature profiles. Figure 2 depicts the latitude variations of the zonal mean temperature MMC generated with COSMIC data and tropopause height calculated by using temperature MMC. We can see that the variations of temperature lapse rates in tropics are more dramatic than those in other region. According to the definition of lapse rate tropopause height the extra-tropical region are very sensitive to the temperature bias. The large variations are found in the region between tropics and polar region.

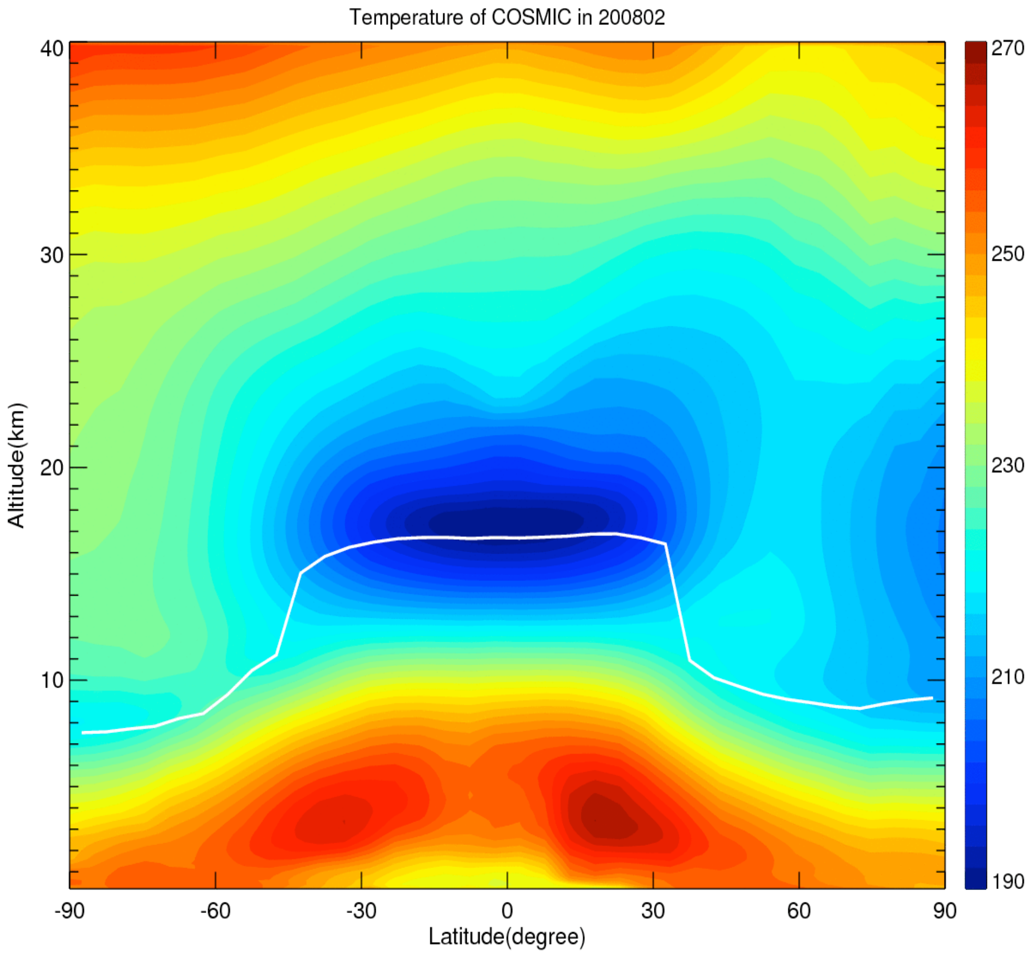

Figure 2. Mean monthly mean climatology (MMC) temperature of COSMIC in February 2008. The white line show the tropopause height calculated by the temperature profiles.

3.3.4 Forward Models

N/A

3.4 Theoretical Description

3.4.1 Physical and Mathematical Description

Raw RO observations and precise positions and velocities of GPS and LEO satellites, can be used to derive atmospheric refractivity profiles, which are a function of atmospheric temperature and moisture profile (Kuo et al., 2004; Ho et al., 2009a). In a neutral atmosphere, the refractivity (N) is related to the pressure (P), the temperature (T) and the partial pressure of water vapor (P_W) by the following equation (Bean and Dutton, 1966):

$$N = 77.6\frac{P}{T} + 3.73\times10^{5}\frac{P_W}{T^2} \quad (1)$$

The so-called "dry temperature" is obtained by neglecting the water vapor term in equation (1). Above the upper troposphere where moisture is negligible, the dry temperature and the actual temperatures are nearly equal. Because the fundamental observable for the GPS RO technique is of high precision and stability that can be traced to the SI unit of second, RO data do not contain mission-dependent biases.

3.4.2 Data Merging Strategy

Monthly gridded values (MMC) for both Metop-A, Metop-B, and COSMIC data are calculated by binning and averaging pixel level data.

3.4.3 Numerical Strategy

N/A

3.4.4 Calculations

The calculations primarily consist of binning, averaging, and linear fitting of data points.

3.4.5 Look-Up Table Description

N/A

3.4.6 Parameterization

N/A

3.4.7 Algorithm Output

The algorithm results consist of a set of netCDF files, one for each month over the time interval from June 2006 through December 2015. Each file contains the combined monthly binned temperature profiles for 5-degree latitudinal bins (in meter). Also contained in the files are the number of RO observations for each latitudinal bins and the month, year. Each of the MMC files uses less than 50Kb.

If the sampling numbers for each bin are less than 50, we assign -9999 for that bin for the derived temperature, estimated sampling errors for that temperature profile and standard deviation of the temperature field.

4. References

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