Characteristics of tropical tropopause and stratospheric gravity waves analyzed using high resolution temperature profiles from GNSS radio occultation

Abstract

Noersomadi

Chapter 1 General introduction

The tropopause functions as a boundary between the upper troposphere and lower stratosphere (UTLS), typically at altitudes of 10−30 km. Various coupling processes occur across this region which influence mixing between the troposphere and stratosphere, primarily through the activity of atmospheric gravity waves (GWs). In particular, understanding the behavior of the tropical tropopause layer at 12–19 km altitude is important for comprehending the mixing and transport of tropospheric minor constituents. A sharp increase in stability at the tropopause acts to enhance the amplitudes of atmospheric gravity waves. On the other hand, the level of wave activity considerably modifies temperature profiles near the tropopause.

Many observational studies have been conducted to investigate the dynamics and radiative processes occurring in the UTLS, using both ground-based measurements and satellite data from direct and remote-sensing techniques. A radiosonde is considered a standard direct measurement instrument for wind velocity, pressure, humidity and temperature and has a good height resolution (about 100 m or better). Since routine radiosonde observations are mostly undertaken from continental locations, they are not sufficient for describing the global distribution of meso-scale atmospheric perturbations.

Global Navigation Satellite System – radio occultation (GNSS-RO) refers to limb soundings of radio waves transmitted by navigation satellites passing through the Earth's ionosphere and atmosphere, which arrive at an onboard GNSS receiver. The technique provides global temperature profiles with a precise vertical resolution that is comparable to radiosonde measurements. GNSS-RO data provide a unique opportunity to investigate the global characteristics of meso-scale temperature perturbations. The objective of this study was to utilize GNSS-RO data to investigate the temperature structure and perturbations in the UTLS. Earlier studies commonly used GNSS-RO with a vertical resolution of approximately 1−2 km in the UTLS. Using GNSS-RO profiles with a vertical resolution of approximately

0.1−0.2 km, we focused on detailed temperature-stability profiles in the region of the tropical tropopause and temperature fluctuations caused by GWs in the lower stratosphere.

Chapter 2 GNSS radio occultation

We introduced the basic principle of the GNSS-RO measurement technique in Chapter 1. Occultation occurs whenever a GNSS satellite rises or sets and the ray path from its transmitter traverses the Earth's atmospheric limb to the receiver. The occultation provides useful atmospheric data. On 3 April 1995 the first RO mission, named Global Positioning Satellite Meteorology (GPS/MET), launched a small low Earth orbit (LEO) satellite (*MicroLab 1)* equipped with a GPS receiver.

The GPS/MET mission led to subsequent missions, including the Challenging Minisatellite Payload (CHAMP) and satellite de Aplicaciones Cientificas-C (SAC-C) in 2001, and Gravity Recovery And Climate Experiment (GRACE) in 2002. Since April 2006, the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC), working in conjunction with National Space Organization (NSPO) Taiwan and the University Corporation for Atmospheric Research (UCAR), has been retrieving between 1500−2000 atmospheric profiles per day. The European Organization for Meteorological Satellites (EUMETSAT) released a series of three polar-orbiting Metop satellites to form a component of their polar system. Satellites Metop-A, Metop-B and Metop-C were launched on 19 October 2006, 17 September 2012, and 7 November 2018, respectively. The success of COSMIC initiated a follow-on, COSMIC-2, led by U.S. agencies and NSPO Taiwan. It is expected that COSMIC-2 will provide a significant number of atmospheric profiles (~10,000 per day).

Chapter 3 Retrieval of atmospheric profiles from GNSS-RO

We reviewed the geometrical optics (GO) and wave optics (WO) methods for retrieving a temperature profile from GNSS-RO measurements. In general, the GNSS-RO atmospheric profiles were retrieved by combining (sewing) GO-based and WO-based profiles. The vertical resolution of the GO retrieval is limited at ~1.5 km due to the Fresnel diffraction effect, but vertical resolution can be as good as ~0.1 km using the WO retrieval method. In addition, we reviewed one of the WO methods, called the full spectrum inversion (FSI), which has the advantage of low computational cost. FSI shows that the arrival times of the instantaneous frequencies can be approximated as the derivatives of the phase of the conjugated Fourier spectrum. Consequently, FSI provides a very high vertical resolution profile.

We processed the retrieval program at Research Institute for Sustainable Humanosphere (RISH), Kyoto University, adopting FSI (*rishfsi*), which was modified from the retrieval scheme at the COSMIC Data Analysis and Archive Center (CDAAC) of UCAR, with intensive support from the CDAAC team. We obtained a good vertical resolution (about 100 m near the tropopause) of temperature profiles for altitudes of up to 30 km. The upper limit of the *rishfsi* datasets is ~28 km.

Chapter 4 Statistical difference between the three retrievals of GNSS-RO results

The combined GO-based and WO-based profile occurring at a certain height is known as the transition height or sewing height. CDAAC/UCAR retrieved two sets of dry atmosphere temperatures (*T*) from COSMIC, which are called atmPrf2010 and atmPrf2013. In atmPrf2010, the sewing height varies between 10 and 20 km, but it is fixed at 20 km for atmPrf2013. The height resolution of atmPrf2010 depends on the sewing height, while the *T* profiles of atmPrf2013 are smoothed over 500 m. We investigated the statistical difference of GNSS-RO retrievals derived from the three different methods, which are the two UCAR retrievals and the *rishfsi* dataset. We aimed to examine a possible discrepancy in the statistical results of the cold point tropopause (CPT) and the lapse rate tropopause (LRT) among the three datasets, in addition to comparing them with radiosonde data from the CINDY DYNAMO 2011 campaign for October 2011 to March 2012.

Comparison between the three GNSS-RO retrievals showed that the mean difference of temperature in UTLS between atmPrf2010 and atmPrf2013 is almost zero, while the results of *rishfsi* were colder (warmer) than the UCAR retrievals below (above) the tropopause. Small discrepancies between the three GNSS-RO retrievals seem to be caused by the difference in vertical resolution and/or the difference in the background atmospheric models used for the ionospheric calibration. Throughout the CINDY-DYNAMO period, we found 134 radiosonde soundings that coincided with GNSS-RO within ±3 hours and they were collocated within 200 km from GNSS-RO. The *rishfsi* is consistent with radiosonde readings below LRT, while both atmPrf2013 and atmPrf2010 show a positive bias of 0.2 K. The negative bias of 1.0–1.5 K in the lower stratosphere could be attributed to the spatial and temporal variations by the atmospheric gravity waves. *T* at CPT of the *rishfsi* data is colder, while that of the UCAR profiles is warmer than the radiosonde soundings, within ±0.4 K. The vertical wavenumber spectral density of the temperature gradient, $\partial T/\partial z$, is in good agreement between the *rishfsi* and the radiosonde measurements for the short wavelength range (< 0.5 km).

Further, we continued our study by utilizing the *rishfsi* dataset to investigate two scientific subjects, which are presented in following two chapters.

Chapter 5 Analysis of the static stability and the tropical tropopause inversion layer

We studied the structure of the tropopause using the *rishfsi* dataset for the period January 2007 to December 2016. We investigated the global distribution of static stability (N^2) and the characteristics of the tropopause inversion layer in the tropics, where a large change in temperature gradient occurs associated with sharp variations of N^2. We showed the variations of the mean N^2 profiles in conventional height coordinates, as well as in coordinates relative to both the LRT and the CPT. When the N^2 profiles are averaged relative to CPT height, there is a very thin (<1 km) layer with average maximum N^2 in the range 11.0–12.0 × 10^{-4} s^{-2}. The mean of the tropopause sharpness, defined as the difference between the maximum N^2 and minimum N^2 within ±1 km of the CPT, is (10.5 ± 3.7) × 10^{-4} s^{-2}.

We focused on the variation of tropopause sharpness in two longitude regions, 90°–150°E (Maritime Continent; MC) and 170°–230°E (Pacific Ocean; PO), which have different land–sea distributions. The sharpness anomaly was out-of-phase with the outgoing longwave radiation (OLR) anomaly in both the MC and PO. The correlation between the sharpness anomaly over MC and PO and the sea surface temperature (SST) Niño 3.4 index was –0.66 and +0.88, respectively. This means that during La Niña (SST Nino 3.4 < –0.5 K) in the MC, and El Niño (SST Nino 3.4 > +0.5 K) in the PO, warmer SSTs in the MC and PO produce more active deep convection that tends to force the air upwards to the tropopause layer causing an increase the temperature gradient. The intra-seasonal variation in the sharpness anomaly during slow and fast episodes of the Madden–Julian oscillation demonstrates that eastward propagation of a positive sharpness anomaly is associated with deep convection. This suggests that convective activity in the tropics is a major control on variations in tropopause sharpness at intra-seasonal to interannual timescales.

Chapter 6 Global vertical wavenumber spectrum in the lower stratosphere

We studied the characteristics of temperature perturbations in the stratosphere at 20–27 km altitude caused by the atmospheric GWs. This altitude range does not include a sharp jump in the background N^2 near the tropopause, and it was reasonably stable regardless of season and latitude. We analyzed the vertical wavenumber spectra of GWs with vertical wavelengths ranging from 0.5 to 3.5 km, and we integrated the (total) potential energy E_p^T. Another integration of the spectra from 0.5 to 1.75 km was defined as E_p^S for short vertical wavelength GWs, which was not studied with the conventional GO retrievals. We also estimated the logarithmic spectral slope (*p)* for the saturated portion of spectra with a linear regression fitting from 0.5 to 1.75 km.

Latitude and time variations in the spectral parameters were investigated in two longitudinal regions: (a) 90–150°E, where the topography was more complicated, and (b) 170–230°E, which is dominated by oceans. We compared E_p^T, E_p^S, and *p*, with the mean zonal winds (*U*) and OLR. We also investigated the ratio $E_p^S : E_p^T$ and discussed that the generation source of E_p^S, E_p^T and *p* clearly showed an annual cycle, with maximum values in winter at 30–50°N in region (a), and 50–70°N in region (b), which was related to topography. At 30–50°N in region (b), E_p^T and *p* exhibited some irregular variations in addition to an annual cycle. In the southern hemisphere, we also found an annual oscillation in E_p^T and *p*, but it showed a time lag of about 2 months relative to *U*. Characteristics of E_p^T and *p* in the tropical region seem to be related to convective activity. The ratio of E_p^T to the theoretical model value, assuming saturated GWs, became larger in the equatorial region and over mountainous regions.

Chapter 7 Summary and conclusions

We have demonstrated the advantages of high vertical resolution temperature profiles, retrieved from GNSS-RO using *rishfsi,* for understanding the global characteristics of UTLS. We investigated the characteristics of the stability profile of the tropical tropopause, and studied the behavior of the very thin enhanced layer within it. We also analyzed the wave energy of stratospheric GWs with vertical wavelengths from several kilometers to as short as approximately 500 m, which were not captured with the conventional GO retrieval of GNSS-RO data. As evidenced, the *rishfsi* dataset with superior vertical resolution (~0.1 km) is useful for studying meso-scale temperature perturbations in the UTLS. Therefore, we encourage the international scientific community to utilize the *rishfsi* dataset, which is now freely available on the inter-university upper atmosphere global observation network (IUGONET) system, the metadata database of the Japanese inter-university research program (www.iugonet.org).