ABSTRACTS (PH D THESIS)

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

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The tropical tropopause at 12–19 km altitude 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). The routine radiosonde observations are mostly undertaken from continental locations, so 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. Since April 2006, the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC), working in conjunction with NSPO Taiwan and UCAR has been retrieving between 1500−2000 atmospheric profiles per day. COSMIC provides global temperature profiles with a precise vertical resolution that is comparable to radiosonde measurements. The objective of this study was to utilize COSMIC data to investigate the temperature structure and perturbations in the UTLS.

There are two fundamental GNSS-RO retrieval methods called the geometrical optics (GO), which is the time derivative of the instantaneous phase variation, and wave optics (WO) which inverts the occulted radio signal in the multipath region due to sharp gradient temperature and water vapor. The GO- and WO-based profile provides ~1.5 km and ~0.1 km vertical resolution, respectively. We conducted validation study to discuss different GNSS-RO retrievals derived from GO and WO, then studied the tropical tropopause and stratospheric GWs using WO-based temperature profiles. We processed the retrieval program at RISH, Kyoto University, adopting one of WO methods called full spectrum inversion (*rishfsi*), which was modified from the retrieval scheme at UCAR. 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.

The combined GO-based and WO-based profile occurring at a certain height is known as the transition height or sewing height. 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 examined a possible discrepancy in the statistical results of the cold point tropopause (CPT) and the lapse rate tropopause (LRT) among the three datasets, two UCAR retrievals and *rishfsi*, 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. 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. 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 tropical tropopause and stratospheric GWs.

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We investigated the structure of the tropopause 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. 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.

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.

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).

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