Atmospheric Research 185 (2017) 142–157

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Characteristics of the global thermal tropopause derived from multiple radio occultation measurements

Wei Li [a,*], Yun-bin Yuan [a], Yan-Ju Chai [a], Yuei-An Liou [b,c,*], Ji-kun Ou [a], Shi-ming Zhong [a]

[a] State Key Laboratory of Geodesy and Earth's Dynamics, Institute of Geodesy and Geophysics, Chinese Academy of Sciences, 340 XuDong Rd., Wuhan, Hubei Province, China
[b] Center for Space and Remote Sensing Research (CSRSR), National Central University, Chungli District, Taoyuan City, Taiwan
[c] Taiwan GIS Center (TGIC), Taipei, Taiwan

ARTICLE INFO

Article history:
Received 26 May 2015
Received in revised form 30 May 2016
Accepted 20 September 2016
Available online 21 September 2016

Keywords:
Global tropopause
Annual cycle
Interannual variation
Diurnal variation
Radio occultation
FORMOSAT-3/COSMIC

ABSTRACT

Thermal tropopause represents the region of the atmosphere where the environmental lapse rate changes from tropospheric positive to stratospheric negative. It also defines the altitude of the atmosphere beneath which significant weather perturbations occur except occasional overshooting thunderstorms in the tropical regions. Accordingly, how the temporal and spatial variability of thermal tropopause behaves is of great concern in atmospheric research and, hence, investigated in this study by using radio occultation (RO) observations obtained from seven space missions during the period from May 2001 to April 2013 (with a total of 6,075,359 occultations). While RO observations have been demonstrated to provide precise measurements of temperature profiles of the atmosphere, their results are inter-compared before further use in our analysis, showing expected high-precision observations with mean differences < 0.06 K and standard deviations < 1.6 K in the upper troposphere and lower stratosphere. Given a rather large data set of multi- space-mission RO measurements taken globally, a very detailed description of spatial structure and variability of the tropopause is revealed, and monthly mean zonal mean tropopause parameters in each 2° latitude band from 90°S to 90°N can be obtained. Many interesting features of seasonal cycle, spatial distribution, interannual variation, and diurnal variation of the thermal tropopause are observed. For examples, except for the primary minimum in January, the equatorial tropopause temperature exhibits a secondary minimum in April, possibly caused by the strongly combined wave forcing from two hemispheres; During the boreal winter over the tropics, the distribution of tropopause temperature extrema do not totally coincide with the altitude extrema spatially, and the former has a better agreement with the locations of strong tropical convection systems; Notable zonal asymmetries in interannual characteristics are observed in both tropical and extratropical regions. In both the tropics and Arctic, close correlation of the interannual variations is revealed between tropopause parameters and stratospheric temperatures in localized regions as well as zonal mean results while no such relationship is observed in the middle latitudes; and Diurnal variation of the equatorial tropopause shows warmer temperature in the morning and cooler value at midnight.

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1. Introduction

The tropopause region, which separates the turbulent mixing-dominated troposphere from the more stably stratified stratosphere, is an important part of the earth's atmospheric system. The tropopause has recently received increasing attention because it is considered to be a useful indicator for the long-term climate change (Santer et al., 2003a; Santer et al., 2003b; Sausen and Santer, 2003). A robust increase in tropopause height (decrease in tropopause pressure and temperature) during the last few decades has been discovered either in the tropics (Seidel et al., 2001) or on a global scale (Santer et al., 2003a; Seidel and Randel, 2006). The simulation study of Santer et al. (2003a) indicated that changes in tropopause parameters should be largely attributed to anthropogenic forcing. The climatology of tropopause is also crucial for the mass and energy exchange between the stratosphere and troposphere (Holton et al., 1995; Shepherd, 2002). Characteristics of the temporal and spatial structures of the tropopause parameters have been presented primarily for the tropical tropopause (Reid and Gage, 1996; Highwood and Hoskins, 1998; Seidel et al., 2001; Gettelman and Forster, 2002), while comparatively less work has been done for the polar tropopause (Highwood et al., 2000; Zängl and Hoinka, 2001). Hoinka (1998, 1999) gave a comprehensive description of global tropopause through combining the thermal (lapse-rate) with the dynamical (potential vorticity) definition of tropopause. Those climatological studies of tropopause relied mainly on radiosonde or weather reanalysis data. However, these two data sources also have obvious drawbacks, since the weather reanalysis data usually suffer from

* Corresponding authors.
E-mail addresses: liwei@whigg.ac.cn (W. Li), yueian@csrsr.ncu.edu.tw (Y.-A. Liou).

http://dx.doi.org/10.1016/j.atmosres.2016.09.013
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coarse vertical resolution and radiosonde observations are sparse in the ocean and polar regions.

Recently, GPS (global positioning system) RO, which provides accurate pressure, temperature, and humidity measurements, has become a promising tool for atmospheric remote sensing (Liou et al., 2010). It is characterized by high vertical resolution, nearly uniform global sampling and long-term stability. Thus, RO temperature observations are ideally suitable for continuous identification and monitoring of the global tropopause. Initially, the thermal structure and temporal variability of the tropical tropopause were depicted by Nishida et al. (2000) and Randel et al. (2003) based on observations from GPS/MET (GPS/Meteorology), the first proof-of-concept GPS RO experiment. Then, Schmidt et al. (2004) extended their study by using a longer period of RO data from CHAMP (Challenging Minisatellite Payload). Climatological characteristics of the global tropopause were analyzed by Schmidt et al. (2005) and Kishore et al. (2006) using CHAMP and SAC-C (Satelite de Aplicaciones Cientificas-C) RO data simultaneously, while finer spatiotemporal structures are presented by Liou et al. (2010) and Son et al. (2011) using high spatial coverage RO data of FORMOSAT-3/COSMIC (Formosat Satellite-3 and Constellation Observing System for Meteorology, Ionosphere and Climate). Kumar et al. (2014) have investigated the impact of quasi-biennial oscillation (QBO) on the interannual variability of the cold point tropopause in the tropics using FORMOSAT-3/COSMIC RO data. The application of RO atmospheric profiles in long-term climate trend research was initially discussed by Foelsche et al. (2008) and Schmidt et al. (2008a), and Schmidt et al. (2008a) found a global increase of 4–7 m per year in tropopause height for the period May 2001–December 2007. In addition, Kuleshov et al. (2016) detected strong cooling in the lower stratosphere and warming in the upper troposphere for the period 2001–2008 over Antarctic, from both CHAMP RO observations and radiosonde data. In general, the tropopause parameters derived from RO soundings exhibit consistent characteristics with those from weather reanalysis or radiosonde data.

Due to the great usefulness of RO observations in operational numerical weather prediction, atmospheric structure sensing, and climate change detecting, more and more scientific research satellites are equipped with RO receiver currently, and if summed together, they are capable of providing thousands of operational soundings per day, more than the amount of global radiosonde profiles. In addition, the obvious tropopause influence on RO curves has been revealed by demonstrating sharp decreasing and next increasing of the amplitude signal amplitude with complex vertical structure of the refractivity in the troposphere (Liou et al., 2010). This study intends to conduct a comprehensive climatological study on the global tropopause from atmospheric measurements of multiple RO missions, which provide obviously higher spatiotemporal resolution than one single mission. Here, we employ data from seven missions: CHAMP, SAC-C, FORMOSAT-3/COSMIC, GRACE (Gravity Recovery and Climate Experiment), METOP/GRAS (Meteorological Operational Satellite Programme/GNSS (Global Navigation Satellite System) Receiver for Atmospheric Sounding), TerraSAR-X, and C/NOFS (Communications/Navigation Outage Forecasting System). The combination of these RO data covers the period between May 2001 and April 2013 and includes 6,075,359 atmospheric soundings. Such a large atmospheric data set derived from multiple RO missions enables description of more detailed structure and variability of the tropopause. A general structure of the tropopause is not the primary goal of present study since it has been extensively discussed before. We attempt to focus on the tropopause features that are less explored in earlier studies, such as the fine structure of seasonal cycle, interannual variation at different longitudes, diurnal variation, and so on.

This paper is organized as follows. Section 2 describes the RO data used in the study and the algorithms for identifying tropopause. In Section 3, an intercomparison of temperatures from different RO missions is conducted. Section 4 analyzes the climatology of global tropopause, including the seasonal cycle, spatial distribution, interannual variation, and diurnal variation. Finally, the summary of this study is given in Section 5.

2. Data and methods

An overview of the seven RO missions used in our study is shown in Table 1, in which information about their launch times, current statuses and the mission agencies are presented. In Table 1, each individual mission is assigned a short label and it will appear in the figures and tables of this paper instead of the original long mission name. Since only occultations from METOP-A satellite are used in this study, METOP/GRAS is labeled as METOPA.

The CHAMP measurements have generated the first long-term GPS RO data set (for about 8 years), and they also contributed to the preparation of several subsequent satellite missions with GPS RO capability (Wickert et al., 2001, 2004a, 2004b; Liou et al., 2005; Liou and Pavelyev, 2006; Schmidt et al., 2008a), e.g., SAC-C, GRACE, and FORMOSAT-3/COSMIC. The SAC-C mission was the first to implement and test the open-loop signal tracking on board and dramatically enhanced the RO sensing quality in the lower troposphere (Sokolovskiy et al., 2006). The RO measurements aboard GRACE were activated several years after the launch of the twin GRACE satellites, and they were based on the same type of BlackJack RO receiver as CHAMP and SAC-C (Wickert et al., 2005). The FORMOSAT-3/COSMIC mission incorporates six spacecraft, and provides typically ~1800 soundings per day, about an order of magnitude higher than the CHAMP, SAC-C, and GRACE missions (Liou et al., 2007; Fong et al., 2008a, 2008b, 2009; Anthes et al., 2008). The METOP/GRAS mission employed a new generation of instruments, which can perform both close-loop and raw-sampling modes (also known as open-loop) with frequencies at 50 Hz and 1000 Hz, respectively (von Engeln et al., 2008). The TerraSAR-X satellite is part of a twin-satellite project (TerraSAR-X/TanDEM-X), and equipped with an integrated GPS and occultation receiver (Wickert et al., 2008). More details on these RO missions are available from other references (Hajj et al., 2002, 2004; Schreiner et al., 2007, 2011; Wickert et al., 2009a, 2009b; von Engeln et al., 2011).

The COSMIC Data Analysis and Archive Center (CDAAC) processes raw RO measurements into atmospheric profiles and distributes RO products from level 0 to level 3 both in near real time and a few months after real time (Schreiner et al., 2003). It also provides re-processed data products 1–2 years later with highest quality in both accuracy and consistency, which significantly benefits climate researches. In this study, the level–2 wetPrf data of all the seven RO missions produced by the CDAAC are downloaded and used to investigate the tropopause characteristics.

The wetPrf data are generated through one-dimensional variational analysis using ECMWF (European Center for Medium-Range Weather Forecasts) low resolution analysis data and include atmospheric

Table 1
Overview of the seven RO missions used in this study.

Mission	Agency	Launch time	Status	Label
CHAMP	DLR	Jul. 2000	Completed	CHAMP
SAC-C	CONAE	Nov. 2000	Operational	SACC
FORMOSAT-3/COSMIC	NSPO, NOAA, UCAR	Apr. 2006	Operational	COSMIC
GRACE	NASA, DLR	Mar. 2002	Operational	GRACE
METOP/GRAS	EUMETSAT, ESA	Oct. 2006	Operational	METOPA
TerraSAR-X	DLR	Jun. 2007	Operational	TSX
C/NOFS	USAF STP	Apr. 2008	Operational	CNOFS

DLR: German Aerospace Center; CONAE: Comisión Nacional de Actividades Espaciales (Argentina); NSPO: National Space Program Office (Taiwan); NOAA: National Oceanic and Atmospheric Administration (U.S.); UCAR: University Corporation for Atmospheric Research (U.S.); NASA: National Aeronautics and Space Administration (U.S.); EUMETSAT: European Organization for the Exploitation of Meteorological Satellites; ESA: European Space Agency; USAF STP: United States Air Force Space Test Program.

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