· Article ·

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A new method to determine the tropopause

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Abstract The tropopause has a complex structure and some interference information may exist in high-resolution global positioning system (GPS)/low earth-orbiting (LEO) radio occultation (RO) data. The position of the tropopause cannot be accurately determined using traditional cold point tropopause (CPT) and lapse rate tropopause (LRT) algorithms. In this paper, an integrative algorithm is developed to determinate tropopause parameters. The algorithm is applied to GPS/COSMIC RO data to obtain a global distribution of the height and temperature of the tropopause. This algorithm improves the utilization rate of GPS/LEO RO data by 30% compared with that from the traditional CPT method. The rationality and reliability of GPS/LEO RO data in probing the Earth's atmosphere are verified by our study of the tropopause using COSMIC data.

Keywords **tropopause, height, temperature, integrative algorithm**

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1 Introduction

In the last few decades, analysis of atmospheric variability and climate studies have refocused attention on information about the tropopause. Global positioning system (GPS) radio occultation (RO) measurements can accurately determine the temperature and height of the tropopause with high vertical resolution. The relatively high density of radio RO measurements in middle and high-latitude regions mean that the horizontal variability of the tropopause can be accurately evaluated[1].

Knowledge of the temporal and spatial structure of the tropopause, especially that of the extratropics, should allow the exchange of mass, water, and chemical constituents between the troposphere and stratosphere to be examined. As a transition layer from the convectively mixed troposphere to the stably stratified stratosphere, the tropopause region plays an important role in atmospheric system analysis. It is important that the temperature and height of the tropopause are determined with high accuracy. The transmission of water vapor and other trace constituents to the tropical tropopause affects their concentration and distribution in the stratosphere[2-3].

The tropopause marks the boundary between the troposphere and stratosphere, and one of its fundamental characteristics is that its static stability (temperature lapse rate) changes when crossing the interface. In the tropics, the tropopause is relatively high (16 km), reflecting a transition between the radiative-convective balance in the troposphere and radiative balance in the stratosphere[4]. The height of the tropopause in the extratropics is somewhat lower (8–12 km), with an equilibrium structure determined by baroclinic wave dynamics[5-6]. The extratropical tropopause is characterized by great dynamic variability, often with complex spatial structure, such as three-dimensional folds[7].

2 Data

GPS-RO provides active limb sounding measurements of the Earth's atmosphere with high vertical resolution and roughly globally uniform distribution from a climatological point of view. This technique has emerged as a promising

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approach to measure the global atmosphere. Assuming the geometric optics and local spherical symmetry of the atmosphere, the phase delay measurements can directly yield the index of refraction profile with high vertical resolution (interpolated) that varies from about 50 m in the lower troposphere to about 200–300 m in the lower stratosphere. Note that the original height resolution varies from about 500 m in the lower troposphere to about 1 km in the lower stratosphere, and the horizontal resolution is 300 km. These delays are needed to derive atmospheric profiles from refractivity, density, pressure, geopotential height, temperature, and humidity[8]. The GPS/COSMIC satellite system[9], a constellation of six low earth-orbiting (LEO) microsatellites, was put into orbit on 15 April 2006. From 21 April 2006, GPS/COSMIC constellation began to provide accurate RO global data with vertical resolution. In this paper, the COSMIC RO data collected over a three-year's period from 1 January 2007 to 31 December 2009 are used to validate the integrative algorithm mentioned in the following section.

Schneider et al.[6] thoroughly investigated the global and tropical tropopause with CHAllenging Minisatellite Payload (CHAMP) RO data. They analyzed the data obtained from May 2001 to November 2003, and found close agreement among RO measurements, radiosonde data, and European Centre for Medium-Range Weather Forecasts (ECMWF) operational analyses, with a bias of only 0.5 K in the height range of around 8−25 km (300−30 hPa). They determined the annual cycle of the temperature lapse rate, cold point tropopause temperature and height based on RO data. Staten and Reichler[10] tested the ability of the RO method to monitor the structure and long-term changes of the global tropopause. They determined the consistency and accuracy of four types of RO data. Many studies have compared radiosonde and COSMIC RO data in height profiles, and also proved their consistency. For example, Figure 1 shows the results obtained for the tropopause at Alert radiosonde station on 19 July 2006 and that at Eureka radiosonde station on 26 July 2007, and compares them with RO data[11].

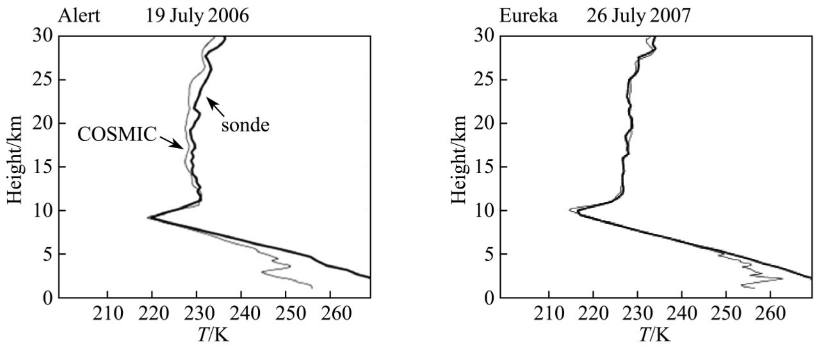

Figure 1 Comparison of COSMIC RO and radiosonde data.

The temperature profiles used in this paper were obtained from the University Corporation for Atmospheric Research (UCAR), which can be found at the following website: http://www.cosmic.ucar.edu/.

3 Determination of the tropopause

3.1 Algorithm used to determinate the tropopause

The World Meteorological Organization (WMO) has two tropopause definitions, the lapse rate tropopause (LRT) and the cold point tropopause (CPT), which are used to calculate the temperature and height of the tropopause[12].

The first definition, also called the thermal tropopause, starts from the total number of globally distributed vertical profiles, which fixes the tropopause height as the lower boundary of the layer where the temperature lapse rate is less than 2 K·km^{-1} for a depth of at least 2 km. This definition is not suitable for use in the polar regions, where several stable stratified layers could be present, or in subtropical regions, where the presence of a double tropopause (hydro and thermal tropopause) might be observed.

The second thermal definition of the tropopause is the location of the coldest point in the temperature sounding, which is called the CPT. This definition is preferred in studies of the cross-tropopause flux of water vapor in the tropics. The variation of tropopause height and temperature is caused by the topography of ground heat convection and the dynamics of the terrain. Definitions of the tropopause, such as CPT and LRT, have different mechanisms to confirm the tropopause. The tropopause defined by the LRT is the result of terrestrial heat convection and its height increases in summer and decreases in winter. In contrast, the tropopause defined by the CPT is affected by radiative heating of the stratosphere. The tropopause height defined by the CPT does not change obviously with the seasons, although it may increase slightly in winter. The height, temperature and pressure of the tropopause defined by the LRT change markedly with the seasons, whereas those defined by the CPT change only slightly. The two kinds of tropopause are consistent in summer but may differ considerably in winter. The difference between the height and temperature of the tropopause defined by the LRT and that defined by the CPT mainly arises from the complex structure of the tropopause. Double- or multi-tropopause structures can form[13].

Figure 2 shows two tropospheric temperature profiles obtained from GPS/COSMIC RO data in tropical and polar regions on 4 April 2009. Lowest points are observed in the temperature profiles. In Figure 2a, only one lowest point is apparent, whereas in Figure 2b, two points meet the definition of the CPT tropopause, so it is called a double tropopause.

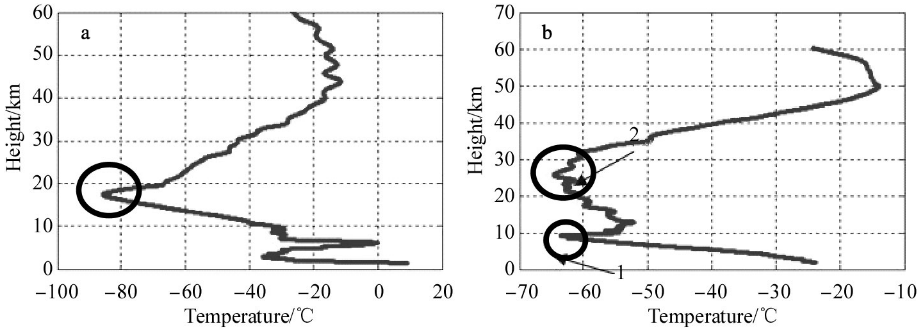

Figure 2 Temperature profile from the troposphere to the stratosphere at 127.09°E, 6.58°S (**a**) and 114.95°W, 83.58°S (**b**).

Considering the complex structure of the tropopause, we used a comprehensive definition of the CPT and LRT to determine the tropopause for GPS/LEO RO data with high resolution. Our definition is not only consistent with the traditional methods used in tropical and polar regions, but can also be easily extended to global computations. The algorithm is as follows:

1. Take the minimum temperature T_1 below 21 km as the first tropopause temperature of the coldest point in the retrieved GPS/LEO temperature profile, and the corresponding height is denoted h_1.

2. Set the smoothing temperature in a height range of 5 km as h_2 in the temperature profile.

If $T_0 < -5$℃, take the minimum temperature T_2 below 12 km in the temperature profile as the initial temperature of the coldest point, and its height is denoted h_2. This is usually applied in polar regions.

If $T_0 > -5$℃, take the minimum temperature T_2 between 12 and 21 km in the temperature profile as the initial temperature of the coldest point, and its height is h_2. This is usually applied in tropical regions.

If $-25℃ \leqslant T_0 \leqslant -5℃$, take the minimum temperature T_2 between 9 and 18 km in the temperature profile as the initial temperature of the coldest point and its height is h_2. This is usually applied in mid-latitude regions.

3. Determine the location of the tropopause.

If $h_1 = h_2$, the tropopause height can be finalized as $H_T = h_1 = h_2$ and the tropopause temperature is $T_T = T_1 = T_2$.

If $h_1 \neq h_2$, use the following method to determine the tropopause.

Suppose the minimum tropopause height h' is 11, 7.5 and 6 km in the tropical, mid-latitude and polar regions, respectively.

Obtain the tropopause height H_T and temperature T_T from the minimum tropopause height h' upward using the definition of the LRT.

Figure 3 provides an example of using this integrative algorithm to determine tropopause height and temperature. The left figure shows the position of the tropopause and the right gives the detailed structure near the tropopause.

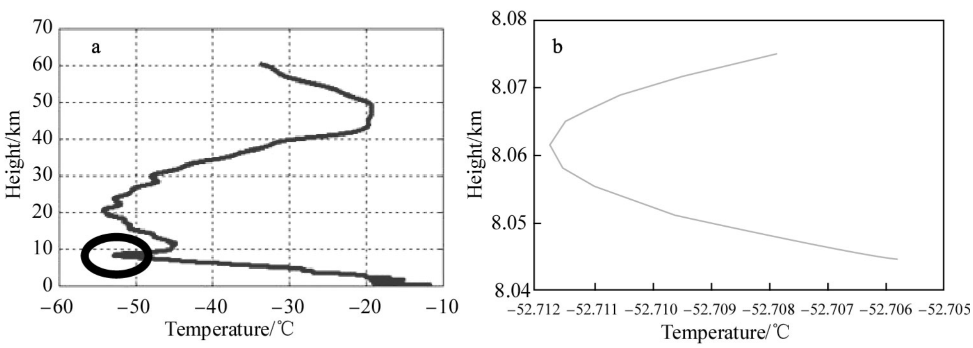

Figure 3 Determination of the tropopause at 125.63°W, 51.84°S.

3.2 Exclusion of outliers

Figure 4 shows the temperature profile of the point 45.61°S, 3.71°E. The tropopause of this profile is point p with a temperature of about −60℃ and a height of 16.12 km, which was obtained using the integrative algorithm described in Section 3.1. However, to others, the tropopause of this profile may be point q at a height of 9.87 km. Because of some large fluctuations, the inversion may stop near point q of the temperature profile. To avoid such a phenomenon, we must first smooth the tropopause height in this latitude region. We then calculate the deviation and mean error between the observed and smoothed values. Finally, we exclude outliers with an error 2.2 times greater than the mean error.

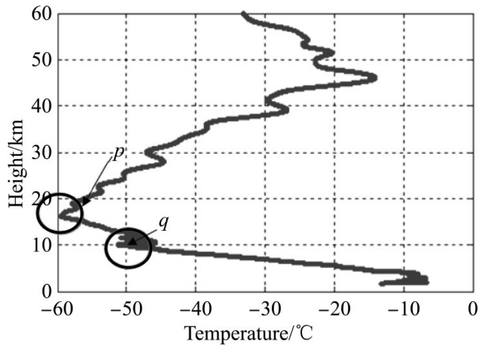

Figure 4 Temperature profile of the troposphere at 45.61°S, 3.71°E.

3.3 Smoothing the latitude of the tropopause

The height and temperature of the tropopause in different regions of the world can be obtained using the integrative algorithm introduced above in Section 3.1. Figure 5 shows the distribution of tropopause height at different latitudes on 4 April 2009 using original data from GPS/COSMIC RO. In the left panel, the blue points represent the original tropopause height observations and the red line indicates the result of the fourth curve fitting between latitude and tropopause height. The blue points in the right panel are the results excluding outliers.

The standard deviation of fitting is:

$$\delta_H = \sqrt{\frac{\sum_n (H_T - \bar{H}_T)^2}{n-5}}$$

Observations that are less than $2.2\delta_H$ are retained.

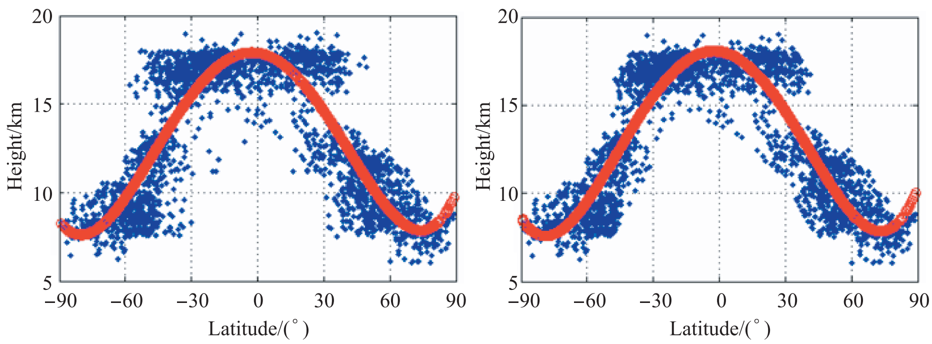

Figure 5 Distribution of tropopause height at different latitudes.

Comparison of the left and right panels in Figure 5 reveals that the removed points are normal or correct. The reasons why these points are excluded may be the application of the fourth curve-fitting function, which smoothes the data, and is not optimal to fit the latitude distribution of the tropopause height curve. It is obvious that a certain thickness of the fracture zone of the tropopause exists in the latitude distribution from Figure 4.

3.4 Case Study

Taking the GPS/COSMIC RO data as an example, the total number of RO profiles obtained on 4 April 2009 was 2 495. We determined the tropopause from these profiles using our integrative algorithm, with a data detection rate of almost 100%. When using the method described in Section 3.2 to exclude outliers, the total number of profiles was 2 407 with a data detection rate of almost 96.5%, 62.4% of which were obtained directly from CPT or LRT methods, and 37.6% from the our new method to determine the tropopause. Most outliers were distributed in the mid-latitude regions, particularly in the southern hemisphere.

The distribution of the global tropopause height and temperature at different latitudes was obtained from GPS/COSMIC RO data without outliers using the nearest-grid-point interpolation method[14]. Figure 6 shows the distribution of the height and temperature of the tropopause at different latitudes in July from 2007 to 2009.

In the equatorial and low latitude regions 30°N–30°S, where the zonal change of the tropopause is steady, the mean height and mean temperature of the tropopause were about 16—18 km, and −88℃—−82℃, respectively. In the mid-latitude region, the mean height and mean temperature of the tropopause were about 10–12 km and −76℃—−70℃, respectively, while in high-latitude and polar regions, they were about 7—9 km and −56℃—−50℃, respectively. In both hemispheres, the height of the tropopause increases comparatively uniformly from higher to lower latitude. When reaching the subtropical region 20°N/S—40°N/S, it increases sharply. This phenomenon suggests that the inclination of the tropopause increases and the appearance of the tropopause fracture zone. Although we did not compare the LRT method with the integrative algorithm one, the LRT method has some limitations. For example, it cannot accurately determine the tropopause in polar and tropical regions. Our integrative algorithm can be used to determine the troposphere globally.

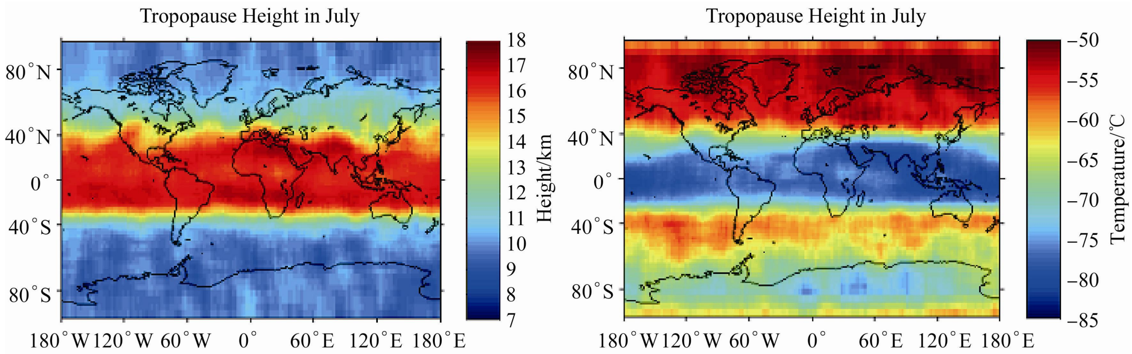

Figure 6 Distribution of the height and temperature of the tropopause at different latitudes in July from 2007 to 2009.

4 Summary

This paper presents an algorithm integrating the CPT and LRT methods, which can accurately determine the tropopause from GPS/LEO RO data. The algorithm effectively identified most of the multi- or double tropopauses from the GPS/COSMIC RO data, improving the utilization of the data and reducing error. The data detection rate is almost 100%, and the utilization rate can reach more than 95%, which is an increase of 35% compared with that from the CPT and LRT methods. This shows that the GPS/LEO RO data is of high quality and suitable to study the tropopause. The distribution of the height and temperature of the tropopause in different latitudes can reflect the global characteristics of the tropopause as well as the tropopause fracture zone. In conclusion, the developed integrative algorithm is more effective to determine the tropopause than CPT and LRT methods and can be applied to investigations of the global tropopause including its variation, periods and dependence on latitude.

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