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Statistics of the Tropopause Inversion Layer over Beijing

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ABSTRACT

High resolution radiosonde data from Beijing, China in 2002 are used to study the strong tropopause inversion layer (TIL) in the extratropical regions in eastern Asia. The analysis, based on the tropopause-based mean (TB-mean) method, shows that the TIL over Beijing has similar features as over other sites in the same latitude in Northern America. The reduced values of buoyancy frequency in 13–17 km altitude in winter-spring are attributed to the higher occurrence frequency of the secondary tropopause in this season. In the monthly mean temperature profile relative to the secondary tropopause, there also exists a TIL with somewhat enhanced static stability directly over the secondary sharp thermal tropopause, and a 4 km thickness layer with reduced values of buoyancy frequency just below the tropopause, which corresponds to the 13–17 km layer in the first TB-mean thermal profile. In the monthly mean temperature profile relative to the secondary tropopause, a TIL also exists but it is not as strong.

For individual cases, a modified definition of the TIL, focusing on the super stability and the small distance from the tropopause, is introduced. The analysis shows that the lower boundary of the newly defined TIL is about 0.42 km above the tropopause, and that it is higher in winter and lower in summer; the thickness of the TIL is larger in winter-spring.

Key words: tropopause inversion layer (TIL), eastern Asia, secondary tropopause

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1. Introduction

Recently, Birner et al. (2002) presented climatological temperature profiles relative to the tropopause based on radiosonde data over two mid-latitude sites in southern Germany with high vertical resolution. A strong mean inversion at the tropopause was uncovered; that is, temperature strongly increases with altitude in the lowermost stratosphere, which was also noted by Pan et al. (2004) based on aircraft measurements. Consequently, the buoyancy frequency squared, N^2, maximizes within this tropopause inversion layer (TIL hereafter) and the thermal tropopause is very sharp on average. The static stability parameter shows considerably enhanced values within the lowermost extratropical stratosphere compared to typical extratropical stratospheric values further aloft (Chen et al., 2005). As Birner (2006) stated, a precise knowledge of the fine-scale structure of the entire extratropical tropopause region is important for a detailed understanding of stratosphere-troposphere exchange, the radiative balance (Gettelman et al., 2004), and also for estimating the wave-driving of the middle atmosphere (to the extent that the waves, Rossby and gravity, have to propogate through the tropopause region) (Charney and Drazin, 1961; Stohl et al., 2003; Gettelman et al., 2004; Schwierz et al., 2004; Pan et al., 2006). Later, Birner (2006) analyzed the high vertical resolution climatology of the thermal structure of the extratropical tropopause region based on data from 80 U.S. radiosonde stations, and found that TIL exists throughout the investigated extratropical regions. In this study, high resolved radiosonde data from Beijing Observatory (40°N, 116°E) will be used to show whether this TIL structure exists in eastern Asia, which has the strongest winter subtropical jet in the world.

When analyzing the thickness of the TIL, Birner et al. (2002) and Birner (2006) base their conclusions on the tropopause-based (TB) averaged profiles,

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which show that temperature strongly increases just above a sharp local cold point at the tropopause, and that temperature stops increasing some distance (which assumed to be the thickness of the TIL) above the tropopause. In many individual cases in high-resolution profile datasets, however, temperature strongly increases not right above the tropopause, but some distance above the tropopause and has multi-peak structure. Furthermore, in some cases, especially in summer, temperature keeps increasing (ignoring local peaks) in the lower stratosphere, so the thickness of the TIL is hard to determine. So, a modified method to determine the TIL will be introduced and their distribution relative to the tropopause will be analyzed in this paper.

The paper is organized as follows. Section 2 describes the data set used in this study and methods that are applied. The analysis of the TB-mean thermal structure is described in section 3. Section 4 gives a modified definition of the TIL based on individual temperature profiles and analyzes the statistics of the modified TILs. Finally, section 5 summarizes the results.

2. Data and methodology

Radiosonde observations made by the Beijing Observatory (40°N, 116°E) on a twice daily basis at 0000 UTC and 1200 UTC in the period of December 2001 through February 2003 are used in this study. The variables such as temperature and pressure are measured by the L-band electronic method, and the wind speed is estimated by tracing radiosonde balloons by L-band meteorological radar. Measurements of temperature and pressure are archived at 1–2 s intervals, which correspond approximately to a 10-m height resolution given the approximate 5 m s^{-1} ascent rate of the balloons. The wind data are given at 60-s intervals, which correspond approximately to a 300-m height resolution. For the convenience of computation, all the variables are interpolated at 50-m intervals. The same data set has been used previously by Bian et al. (2005) to study gravity wave characteristics. In this study, only temperature data are used.

In deriving climatologies of the thermal structure around the tropopause, averages are computed by employing the tropopause-based method described by Birner et al. (2002) and Birner (2006). In this method, the tropopause itself is used as a common reference level for all temperature profiles, i.e., profiles are averaged with respect to the time-dependent tropopause level. Therefore, $\tilde{z} = z - z_{\rm TP}$ (subscript TP denotes tropopause) is used as the vertical coordinate for the TB-mean.

3. TB-mean thermal structure

First we give the annual TB-mean thermal structure in 2002 in Fig. 1a. Clearly, a TIL exists in the temperature mean profile: the mean tropopause exhibits a sharp local cold point and constitutes a very sharp interface, and just above this tropopause temperature strongly increases and N^2 jumps to 6.9×10^{-4} s^{-2} from 2.1 × 10^{-4} s^{-2} just under the tropopause. The layer with N^2 larger than 6 × 10^{-4} s^{-2} is about 200 m thick, and then N^2 decreases quickly and reaches a local minimum (∼ 4 × 10^{-4} s^{-2}) at about 15 km. The TIL has a thickness of about 2.0 km and a strength of about 3 K, which corresponds closely to the value for Reno, Nevada (40°N, 120°W) (Birner, 2006), also located at 40°N, but at a quite different longitude.

In Figs. 1b–e, the monthly TB-mean thermal structures in January, April, July, and October, 2002 are given. Despite distinct differences in the tropopause characteristics in different months, a clear TIL exists in all the months. However, the TIL shows a distinct seasonal variation in maximum values of N^2, which are a bit larger in spring-summer (7.4 × 10^{-4} s^{-2}) than in autumn-winter (6.4 × 10^{-4} s^{-2}), and in thicknesses of the TIL, which are much thicker in winter (2.5 km) than in summer (0.7 km). Compared to summer-autumn, winter-spring sees more reduced values of N^2 (less than 4 × 10^{-4} s^{-2}) in a region of 13–17 km, as pointed out by Birner (2006), who attributed this feature to the frequent existence of a secondary tropopause with rather tropical/subtropical characteristics.

The occurrence frequency of a secondary tropopause over Beijing is given in Table 1 for January, April, July, and October 2002. It is seen that the frequency is higher (∼ 70%) in winter and spring, and lower (40%–50%) in summer and autumn. Basing on GPS radio occultation temperature profiles, Randel et al. (2007) gives a similar seasonal variation of the frequency of double tropopause occurrence over this region. It seems to show that the occurrence of a sec-

Table 1. The occurrence frequency of double tropopause ($P_{\rm DTP}$: %) and buoyancy frequency squared (N^2) across the secondary tropopause (10^{-4} s^{-2}).

	Month			
	JAN 02	APR 02	JUL 02	OCT 02
$P_{\rm DTP}$	71	73	39	52
N^2(TP–50)	2.13	2.20	2.18	2.19
N^2(TP)	3.77	3.60	3.94	3.72
N^2(TP+50)	5.46	5.44	6.11	5.76
ΔN^2	3.33	3.24	3.93	3.57

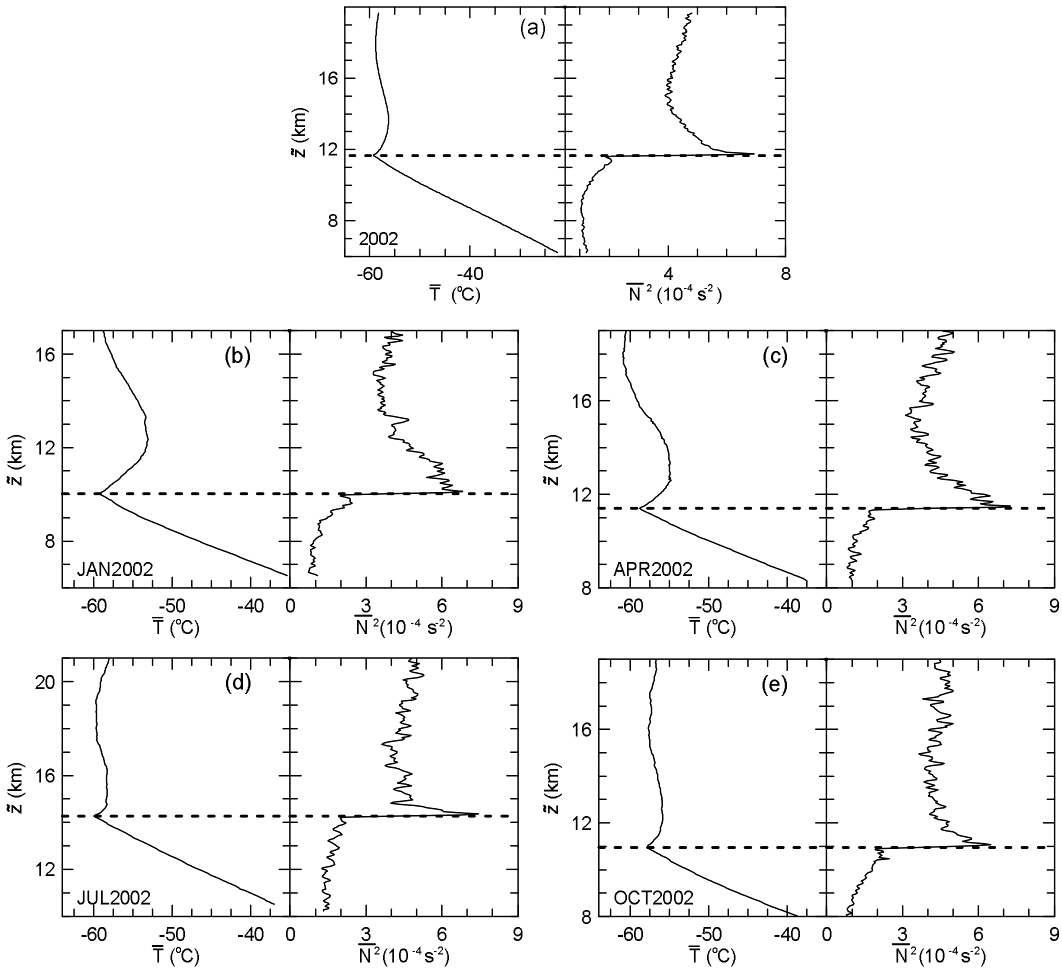

Fig. 1. (a) Annual and monthly TB-mean temperature (left) and buoyancy frequency squared (right) in (b) January, (c) April, (d) July, and (e) October, 2002. The mean tropopause levels are denoted as horizontal heavy dashed lines.

ondary tropopause has good relation to the reduced values of N^2 in a region of 13–17 km over Beijing. More frequent secondary tropopauses correspond to the further reduced values of N^2 in winter and spring.

In order to show how the existence of a secondary tropopause influences the thermal structure, a monthly mean temperature profile relative to the secondary tropopause for April 2002 is given in Fig. 2. In this mean profile, the secondary tropopause, located at an altitude of 16.5 km, also exhibits a sharp local cold point and constitutes a very sharp interface. A TIL exists just above this tropopause, and N^2 jumps from 2.2×10^{-4} s^{-2} just under the tropopause to 5.4×10^{-4} s^{-2}, a bit smaller than that above the tropopause in the first TB-mean profile. The layer with N^2 less than 4×10^{-4} s^{-2} just under the secondary tropopause ranges from ~12.5 km to ~16.5 km, which corresponds to the reduced values of N^2 in the region of 13–17 km in the first TB-mean profile.

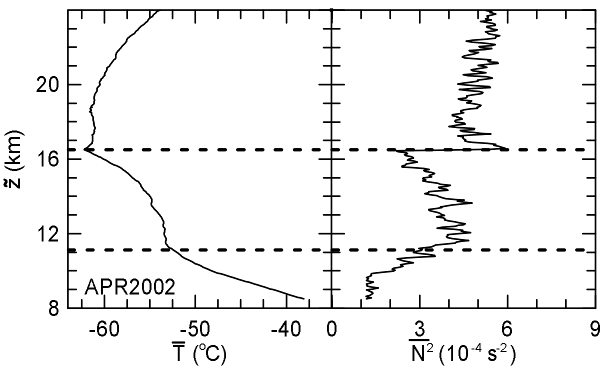

Fig. 2. Monthly secondary TB-mean temperature (left) and buoyancy frequency squared (right) in April, 2002. The heavy dashed horizontal lines show two thermal tropopauses.

It should also be noted that the thermal structure and the static stability profiles above the secondary tropo-

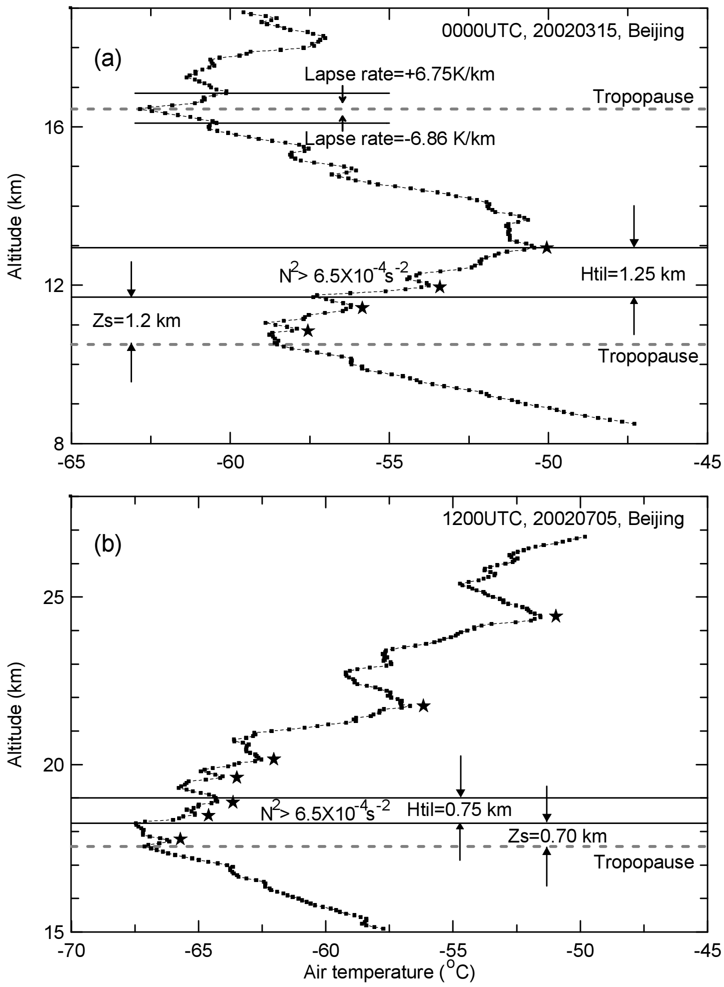

Fig. 3. Two examples illustrating the modified definition of the TIL. The horizontal grey dashed-lines give the altitude of thermal tropopause, and the symbol "★" indicates some of the local maximum temperature heights. In (a), there are two tropopauses, and the TIL defined by Birner et al. (2002) does not begin right above the first tropopause. There is no TIL as defined by Birner et al. (2002) in (b).

pause look somewhat similar to those in the first TB-mean profile in July 2002, which seems to imply that there may be some relevance between them and further research should be done to explain this similarity. Table 1 gives N^2 across the secondary tropopause in January, April, July, and October 2002. In all the months, N^2 drops from $> 5.5 \times 10^{-4}$ s^{-2} just over the tropopause to $\sim 2.2 \times 10^{-4}$ s^{-2} just under the tropopause.

4. Seasonal distribution of the TIL

As mentioned in section 1, the above analysis of the thickness of the TIL is based on the TB averaged profiles, which show that temperature strongly increases just above a sharp local cold point tropopause, and that temperature stops increasing some distance (which is assumed to be the thickness of the TIL) above the tropopause. In many individual cases, however, temperature does not strongly increase right above the tropopause. Such an example is given in Fig. 3a, in which temperature still decreases just above the tropopause, and strongly increases only several hundreds meters above. Figure 4 gives the monthly distribution of the buoyancy frequency squared, N^2, in the layer of 100 m above the tropopause in 2002. In about 25%–50% of the cases in all the seasons, N^2 is less than 5×10^{-4} s^{-2}. That is to say, the TIL in individual cases seems to have some different features against TB-mean thermal structure, which has the TIL right over the tropopause.

Another feature in individual cases is that tempera-

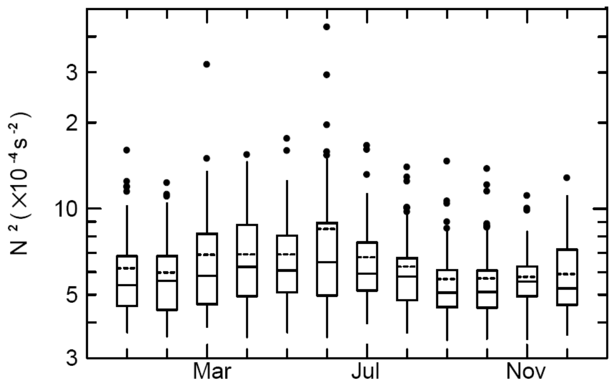

Fig. 4. Box-plot of the monthly distribution of the buoyancy frequency squared in the layer of 100 m above the tropopause in 2002. Dashed lines are monthly averages, and solid lines and boxes mark the median, upper and lower quartiles. The point whose distance from the upper or lower quartile is 1.5 times larger than the range between both quartiles is defined as outlier, which is marked by black dot.

ture has multiple peaks in the profile; two examples are given in Figs. 3a–b. Such a thermal oscillation with height is considered to be related to the inertial gravity waves, and is used to analyze the feature of gravity waves (Allen and Vincent, 1995; Wang et al., 2003; Bian et al., 2005). In such cases, a few inversion layers can be defined according to various vertical scales. Furthermore, in some cases especially in summer, temperature keeps increasing (ignoring local peaks) in the lower stratosphere, as shown in Fig. 3b, and the TIL is hard to determine.

So, an effective and objective method to define the TIL must be introduced. In this study, TIL is defined as a layer, whose lower boundary is less than 1.5 km above the tropopause, and has a mean value of $N^2 > 6.5 \times 10^{-4}$ s^{-2} and the largest height range. Defined as such, the enhanced value of N^2 in the TIL and the very short distance from the tropopause are considered to be two key points. Strictly speaking, the TIL as defined above is a super-stable layer just above the tropopause. This is the most critical point in the study of the TIL. In Fig. 3, the distance from the lower boundary ($H_{\rm S}$) of the TIL to the tropopause ($H_{\rm TP}$) is denoted as $Z_{\rm S} = H_{\rm S} - H_{\rm TP}$, which is 1.2 km and 0.7 km for these two examples; the thickness of the TIL is given as HTIL. Based on this definition, the TIL is determined for all the individual temperature profiles in 2002, and these are then are analyzed.

The distributions of $Z_{\rm S}$ are given in Fig. 5a. Only a small percentage of individual cases show the super-stable TIL existing just above the tropopause as in the TB-mean profile, and at least 50 percent of the lower boundaries are 250 m above the tropopause. The lower boundary levels of the TILs are higher in winter (0.48 km) than in summer (0.33 km) relative to the tropopause. The annual average of the monthly median values of $Z_{\rm S}$ is about 0.41 km in 2002.

The thickness of the super-stable TIL has a distribution as shown in Fig. 5b. HTIL has a clearly seasonal character, larger in winter-spring (0.72 km), and smaller in summer-autumn (0.42 km), which is consistent with those shown in Fig. 1. The annual mean of the monthly median values of HTIL is about 0.57 km. Although these values for the TIL are much less than the values for the TIL in the TB-mean profile (2.0 km for annual mean, 2.5 km in winter, and 0.70 km in summer) in section 3, they are significantly larger than 0.2 km for the layer with $N^2 > 6 \times 10^{-4}$ s^{-2}.

5. Conclusions

In this study, the strong tropopause inversion layer over eastern Asia is analyzed by using the high resolution radiosonde measurements over Beijing. The tropopause-based mean analysis shows that there exists a TIL over Beijing, which has an annual mean

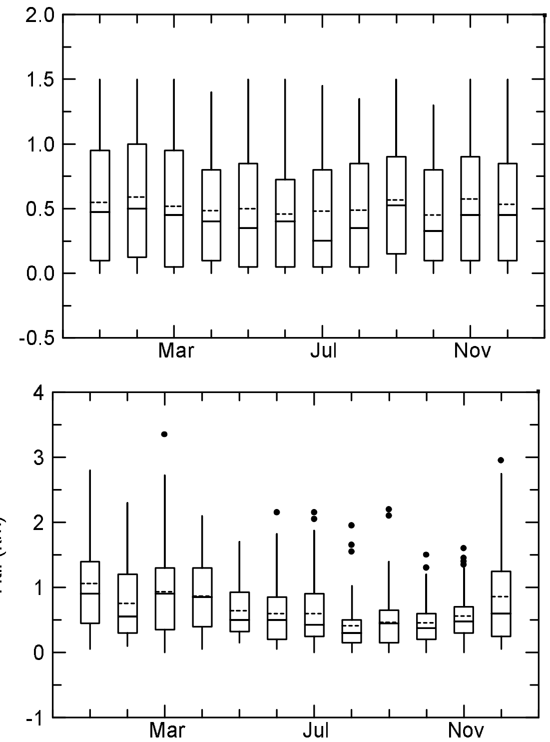

Fig. 5. Box-plot of the monthly distribution of the distance of the lower boundary relative to the tropopause height ($Z_{\rm S}$) and the thickness of the super-stable TIL (HTIL) in 2002. The symbols and lines are the same as Fig. 4.

thickness of about 2.0 km and a strength of about 3.0 K, and that it is much thicker in winter than in summer. This analysis gives evidence in eastern Asia to support the result of Birner et al. (2002).

By analyzing the thermal structure based on the secondary tropopause-based mean profile, it is found that the layer with greatly reduced values of buoyancy frequency in the 13–17 km altitude range in winter-spring is related to the higher occurrence frequency of the secondary tropopause in this season.

The TIL above is based on the TB-mean thermal profile. In individual cases, however, the TIL does not always exist directly above the tropopause. So, a modified definition of the TIL is introduced, with focus on the super static stability and the small distance from the tropopause. The statistical analysis shows that the lower boundary of the newly defined TIL is about 0.42 km in average above the tropopause, and has seasonal variation (higher in winter and lower in summer). The thickness of the TIL also varies with season. It is thicker in winter-spring, which seems to be related to the more frequent occurrence of the secondary tropopause in winter-spring.

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