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Strong downdrafts preceding rapid tropopause ascent and their potential to identify cross-tropopause stratospheric intrusions

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Abstract:

The capability of measuring 3-dimensional wind and tropopause structure with relatively high time and vertical resolution makes VHF radar a potentially significant tool for studying various processes of the atmosphere. Here the potential detection of possible stratospheric intrusion events is discussed using the Beijing MST radar located at Xianghe (39.75°N, 116.96°E). During the passage of a cut-off low in late November 2014, a deep V-shaped tropopause structure, and strong downdrafts (>0.8 m/s) immediately preceding the rapid tropopause ascent (>0.2 km/h) were observed. Within the height region of the downdrafts, the 'normal' radar-tropopause layer seems to be destroyed (weakened) with the decreased echo intensity. Analysis results from global

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reanalysis and the satellite data, as well as the trajectory model have shown the clear evidence of the downward stratospheric intrusions (dry ozone-rich and depleted methane air) associated with the strong downdrafts. According to the previous studies and the present case observation, the strong downdrafts preceding rapid tropopause ascent are considered as a significant signature of stratospheric intrusions. Twenty typical cases of such strong downdrafts, occurring during various synoptic processes in different seasons, have been presented and 16 of them are exactly associated with some form of stratospheric intrusions. Four years (2012-2015) of such downdrafts are further discussed. The observations reveal that the strong downdrafts preceding the rapid tropopause ascent can be a valuable diagnostic for monitoring intrusion events, which will gain a better understanding of stratospheric intrusions in VHF radar observations.

Keywords: Stratospheric intrusions; strong downdrafts; rapid tropopause ascent; MST radar; VHF radar; cut-off low

1. Introduction

The tropopause is a stable transition zone separating the vertically stable stratified stratosphere from the active free troposphere. The stratospheric and tropospheric air are remarkably different in their chemical and dynamical characteristics. The stratosphere is dominantly high in ozone and potential vorticity (PV) content and low in water vapor (WV) and methane (CH_4) concentration, while the troposphere is just on the contrary (Holton et al., 1995). Consequently, the natural stable tropopause layer, characterized by strong gradients of trace constituents and wind speeds, plays an important role in stratosphere-troposphere exchange (STE) processes. In other words, the layer is a significant barrier for the atmospheric transport between stratosphere and troposphere (Mahlman, 1997). From a long-term point of view, the long-term seasonal variation of the tropopause height determines the seasonal variation of the flux of stratospheric air into the free troposphere (Appenzeller et al., 1996). Under the global climate warming (e.g. the continuing rise in CO_2), the tropopause variation is also a significant factor that must be considered when comes to the recovery of the stratospheric ozone (Butchart et al., 2010; Chipperfield et al., 2017). On the other hand, the short-term tropopause variability is sensitive to various meso– and small–scale atmospheric processes, during which the folding/intrusion events commonly occur. This characteristic of the tropopause change are sometimes directly used to detect the tropopause folds (e.g. Rao et al., 2008; Alexander et al., 2012, and references therein), but are less, if any, directly used to identify stratospheric intrusions. More detailed analysis of the variability of high-resolution tropopause height and of course some other

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parameters (e.g. 3-dimentional wind), and how the stratospheric air transport across the tropopause into the troposphere will help us to yield better understanding of the downward stratospheric intrusions (e.g. Sprenger et al., 2003; Leclair de Bellevue et al., 2007; Das et al., 2016).

Photochemical production within the troposphere, although, is the main source of tropospheric ozone, the influence of the downward stratospheric intrusions on the tropospheric ozone content cannot be ignored (Oltmans and Levy II, 1992; Monks, 2000; Stevenson et al., 2006). Stratospheric intrusions bring dry ozone-rich air down into the free troposphere (e.g. Stohl et al., 2000; Sørensen and Nielsen, 2001) and sometimes even deep to the surface (e.g. Gerasopoulos et al., 2006; Ding and Wang, 2006; Lefohn et al., 2011). By now, it is well established that these intrusions of stratospheric origin will significantly influence other trace gases (such as hydroxyl (OH)) in the troposphere (Holton et al., 1995). These influences then will further contribute to the change of radiative balance (Ramaswamy et al., 1992) and play an important role in the radiative forcing of global climate change (Holton et al., 1995). It is true that stratospheric intrusion events occur all over the world and in any season. However, they are highly episodic in both vertical and isentropic (horizontal) directions (Chen, 1995). Various dynamical and physical processes have been proposed to be responsible for extra-tropical intrusion events. These mainly include tropopause folds, stratospheric streamers and break-up, cut-off lows (COLs), wave breaking, and mesoscale convective activities and thunderstorms (Stohl et al., 2003).

The certain dynamical and chemical characteristics of stratospheric air allow the

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tracers, such as dry ozone-rich and high PV, to be proper indicators for the intrusions penetrating down into the troposphere. Various methods are available to detect intrusion events based on these tracers. Among them, balloon-borne ozonesonde sounding are without doubt one of the most appropriate tools, but is limited by coverage (He et al., 2011) and not possible to obtain continuous profiles with fine temporal resolution. In contrast, the satellite-borne remote sensing instruments, such as Atmospheric Infrared Sounder (AIRS), can provide nearly global coverage of various trace gases but have limitations in vertical and temporal resolution. Another method for studying transport processes is trajectory model, from which the backward trajectories can provide valuable information on the possible sources of the trace gases (e.g. Elbern et al., 1997).

By far, large-scale STE has been widely studied and is fairly well understood, but the details of small scale intrusions are still remain uncertain (Holton et al., 1995). Kumar and Uma (2009) reported that the dearth of direct vertical wind measurements in the vicinity of the tropopause may be responsible for the lack of detailed fine observations of smaller scale intrusions.

Very-High-Frequency (VHF) radars, comparing the tools mentioned above, are capable to provide 3-dimensional wind and tropopause height continuously with both high temporal and spatial resolution and can operate unmanned continuously for 24 hours per day under any weather conditions. During the past two decades, VHF radar measurements were commonly used to assist to study the stratospheric intrusions. However, it still remains uncertain in many aspects when using only the VHF radar to identify intrusion events. Complicated and changeable atmospheric processes make it

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difficult to identify the intrusion events by only radar data. The research by Hocking et al., (2007) have achieved a development in this issue. They found that the rapid ascent in radar-derived tropopause altitude (>0.2 km/h) can be a valuable diagnostic for possible stratospheric intrusions. However, it does not always work (e.g. He et al., 2011) and remains uncertain when purely using the information of radar-determined tropopause.

The central objective of the present study is to discuss the signature of downward cross-tropopause intrusions using both the measurements of tropopause height and vertical wind by the Beijing MST radar. This study is carried out mainly via a detailed case observation during the passage of a COL and other general cases associated with various atmospheric processes. Our discussion mainly focused on the potential of the MST radar data to identify possible intrusion events, which is the main point of this paper. In section 2 the datasets used in this paper are described, section 3 presents detailed results and discussion, and section 4 gives the conclusions.

2. Dataset

2.1. MST radar data and tropopause detection

The Beijing MST radar located at Xianghe, China (39.75° N, 116.96° E, 22 m above sea level) is a VHF radar operated at 50 MHz and installed in 2010 based on the first phase of Chinese Meridian Space Weather Monitoring Project (Chinese Meridian Project for short) (Wang, 2010). The radar antenna array consists of 24×24 three-element Yagi to produce an average power aperture product of 3.2×10^8 Wm^2 and maximum directive gain of 34.8 dB. It operates radiation pattern with 172 kW peak power and 3.2° half-power beam width. More detailed information of the radar system can be found in Chen et al. (2016). Routine low mode data were used for present study with 0.5 h time resolution and 1 μs coded pulse, which provides 150 m vertical resolution. Details of the low mode setup used in this study are given in Table 1.

It has long been known that VHF radar reflectivity is proportional to the mean generalized refractive index gradient M, which is a function of humidity variation and static stability and given by (Ottersten, 1969) as follows

$$M = -77.6 \times 10^{-6}(p/T)(dln\theta/dz) \cdot \{1 + 15500q/T[1 - (dlnq/dz)/(2dln\theta/dz)]\} \quad (1)$$

where p is the atmospheric pressure (hPa) T is the temperature (K), θ is the potential temperature (K) and q is the specific humidity (gg^{-1}). According to the second and third terms of the equation (1): large humidity variation contributes to the echo from the lower and middle troposphere. From the first term: the radar backscatter power is proportional to the static stability, which in fact is directly proportional to the potential

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temperature gradient. The tropopause, near which a strong potential temperature gradient exists, will lead to strong radar echoes in vertical incidence, as well as large radar aspect sensitivity (as shown in Figure 1). Radiosonde data used in this paper were received from the GTS1 type digital radiosonde launched from Beijing Meteorological Observatory (39.93 ^{o}N,116.28 ^{o}E, station number 54511), which is less than 45 km to the MST radar site. The black line in Fig.1 denotes the lapse-rate tropopause (LRT) defined using the temperature lapse rate (World Meteorological Organization (WMO), 1986). Applying the characteristic (partial specular reflection) mentioned above, the tropopause can be detected and its height determined by VHF radars (Gage and Green, 1979). It has received widespread application around the world, either in middle latitudes (e.g. Hocking et al., 2007), polar regions (e.g. Alexander et al., 2012), and tropical regions (e.g. Yamamoto et al., 2003; Das et al., 2008). Here, the radar-determined tropopause (RT) height is defined as the lower edge (the height above 500 hPa with largest power gradient) of the secondary maximum backscattered echo power (shown in Figure 1a as the orange circle). This definition of RT is similar to that in the studies of Alexander et al., 2012 and Ravindrababu et al., 2014.

In the present study, the MST radar mainly provides continuous measurements of backscattered echo power, 3-D wind, and RT height with time resolution of 0.5 hour. In addition, the radar aspect sensitivity that expressed as the ratio between vertical (p_v) and oblique (p_o) beam echo power is mainly caused by the horizontally stratified anisotropic stable air and thus will be used as potential signature of stratospheric intrusions in the troposphere (e.g. Kim et al., 2001). The backscattered echo power given here is expressed as relative power in decibels (dB). In order to reduce the random noise, the profile of p_v is smoothed by a 3-point running mean in altitude. Note that the data that are heavily contaminated will be eliminated from our datasets. The data of Dec. 2015 and Sep. 2015 are excluded.

2.2. AIRS satellite data

The AIRS instrument on NASA Aqua/EOS polar orbit satellite is a 2378 channel nadir cross-track scanning infrared spectrometer. It can provide profiles of a number of trace gases, including ozone and CH_4 (Susskind et al., 2003). The footprint of these retrieval data is of 45 km by 45 km and their most sensitive region is in an altitude range of 300-600 hPa. Many studies have shown that these AIRS retrieval constituents are useful indicators for detecting stratospheric intrusions. He et al. [2011] suggested that AIRS can observe the enhanced tropospheric ozone that is of stratospheric origin. Xiong et al. [2013] reported that AIRS is capable of observing abnormal depletion in CH4 in the troposphere during intrusions. AIRS offers good latitude-longitude coverage. Here we use version 6 of the AIRS Level-3 ozone and methane retrieval products.

2.3. Meteorological reanalysis

European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis ERA-interim data are also used. After Nov. 2000 the data are based on the T511L60 version available with a 6-h temporal resolution and $3^o \times 3^o - 0.125^o \times 0.125^o$ latitude-longitude grid. The dataset from 15 isentropic and 37 pressure levels with $0.5^o \times 0.5^o$ grid are applied for present study.

2.4. HYSPLIT model

Backward (forward) trajectories in given starting locations are capable to reproduce the sources (destinations) of the air parcel that will allow us to examine the intrusions of stratospheric origin in the troposphere (e.g. Elbern et al., 1997). The Hybrid Single Particle Lagrangian Integrated Trajectory model (HYSPLIT) developed by the National Oceanic and Atmospheric Administration (NOAA)'s Air Resource Laboratory (ARL) (Rolph, 2003; Stein et al., 2016) is applied to calculate the backward and forward trajectories. The calculation method of the model is a hybrid between the Lagrangian approach and the Eulerian methodology. In this paper, Global Data Assimilation System (GDAS) datasets are adopted for driving the HYSPLIT.

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3. Results and discussion

3.1. Meteorological synoptic situation

On the morning of 29 November 2014, a 500-hPa trough developed on the western side of Lake Baikal (Western Siberia). The trough moved southeastward and extended equatorward and its bottom separated from the westerlies in the afternoon of 30 November 2014 (Fig. 2b), forming a COL near the radar site. The black stars in Figure 1 and other figures indicate the location of the radar site. On the following days, the COL system moved northeastward gradually (Fig. 2b) and finally stayed over eastern Russia near Sakhalin Island until it reconnected and merged to the westerly flow. 315 K isentropic PV patterns have shown the coarse resolution features of intrusions from the polar reservoir across the tropopause into the midlatitude troposphere. The PV streamer curved and rolled up cyclonically along the western flank of the COL (Fig.2b).

Fig. 3 shows the time series of hourly surface meteorological parameters over the Beijing station. The data are obtained from the Chinese National Meteorology Information Center and is less than 50 km from the MST radar site. As the dry-cold air invasion accompanied with the COL travelled deeply into the planetary boundary layer, it brought severe weather to the surface, including a rapid decrease in temperature and humidity, and rapid increase in surface wind and sea level pressure. The humidity decreased from ~85 to 12 percent within less than 8 hours. It is well established that the polar-type COLs have strong potential to trigger deep convection (Price and Vaughan, 1993). To examine the potential convection, maps of high quality Climate Data Record (CDR) of daily Outgoing Longwave Radiation (OLR) are displayed in Fig. 4. During the development of the COL, a local region with abnormal low OLR value was clearly observed near the radar site on 29 Nov. (Fig. 4b). The Satellite-observed cloud top temperature also showed the low values corresponding to the low OLR (figure not shown), indicating a convection may be generated near radar side on 29 Nov.. Please note that we didn't observe such low value either in OLR (Fig.4c, d) or in cloud top temperature near the radar side on 30 Nov. and 1 Dec.. The time for all the observations in this paper is showed in Universal Time (UTC) which is eight hours behind Beijing standard time (LT=UT+8).

3.2. MST radar observations

Radar echo power, horizontal wind vector, vertical wind, and radar aspect sensitivity are plotted in Figure 5 as function of height and time during the passage of the COL. Time variation of RT (black line) and LRT (black crosses) heights are also displayed. The RT height first experienced a rapid descent, and then increased rapidly, forming a deep V-shaped structure of ~4 km depth. The vertical velocity of the RT height variation (both the rapid descent and ascent branches) reaches up to 0.28 km/h. The rapid RT variation in altitude is in fact the response of the tropopause fold below the jet stream, which will be well represented in Fig. 9a. Rapid variation in RT height remained a region with low echo power (marked by R on Fig. 5a) and low aspect sensitivity (marked by R' on Fig. 5d) where they should be normally high value within the 'normal' tropopause layer. Unlike the RT height, the radiosonde LRT altitudes are nearly constant during the COL passage. In normal conditions, RT agrees well with the LRT altitude, such as indicated by Fig. 6a. However, large differences, of order of 2.5

km (as shown in Fig.6b at 12 UT 30 Nov.), are observed between LRT and RT in altitude during the passage of the COL as expected. It is the difference in definition that contribute most to the large differences, especially under the tropopause fold conditions. It is worth noting that, in Fig.6b, although there is no clear reversion in the radiosonde temperature profile within the height of RT, the RT height exactly corresponds well to the reversion of zonal and meridional wind and potential temperature gradient. Such differences between RT and LRT heights can commonly be observed, especially during extreme synoptic situations such as cyclone (e.g. Alexander et al., 2012).

The most important observation in this detailed case experiment is the strong downdrafts (hereinafter inferred to as main downdrafts) observed immediately preceding the rapid RT ascent (Fig.5c). The radar echo power sharply weakened (dotted rectangle in Fig.5a) and the wind direction changed rapidly (Fig.5b, change from dominant southerly wind to dominant northerly jet) within the height region of the main downdrafts. As mentioned previously, abnormal low value in OLR and cloud top temperature indicates the possible occurrence of convective activity on 29 Nov., but nothing special appeared on 30 Nov. near radar site. Consequently, we preliminarily consider that the main downdrafts occurred near 07 UT 30 November might not be produced directly by convective activity. Here, the accurate origin of the main downdrafts will not be discussed in detail, and it is also beyond the scope of present study.

The research by Hocking et al. (2007) has suggested that the rapid RT ascent (>0.2 km h^{-1}) can be a valuable indicator for the occurrence of stratospheric intrusions. Here

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in this paper, the main downdrafts preceding the rapid RT ascent observed by the Beijing MST radar are thus suspected to be an important feature or response of some form of vertical stratospheric intrusions. It is indeed reasonable. Firstly, as the tropopause descends (folded downward), it will displace stratospheric air into the troposphere (e.g. Hoskins et al., 1985). Secondly, the main downdrafts will act as an effective way to weaken the tropopause by means of continuously impinges on the tropopause, through which the stratospheric air is permitted to penetrate down into the free troposphere (e.g. Hirschberg and Fritsch, 1993; Kumar, 2006). In addition, after the main downdrafts, the observed region near the upper troposphere with strong backscatter echoes (marked by Q) and especially with abnormal high aspect sensitivity (marked by Q') may also be a weak signature of the possible intrusions. In normal conditions in the upper-troposphere, they are usually low in value (such as the region marked by P and P'). As we mentioned before, the large value in radar aspect sensitivity is mainly caused by reflection from stable atmospheric layer, such as the tropopause or lower-stratosphere. When stable stratospheric air intrudes into the troposphere and without mixing with the surrounding air mass, the intrusions in the free troposphere will be reflected as abnormal large aspect sensitivity. Further direct evidence of the relevant intrusions in dynamical and chemical aspects will be demonstrated in next section, using satellite AIRS and global reanalysis data.

Someone may be interested to notice the laminar periodic downdrafts and updrafts near RT height for ~16 UT 30 Nov.-2 UT 1 Dec.. It is likely to be associated with mountain wave activity induced by northerly jet. As shown in Supplementary figure S1,

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there is relatively higher topography (~1000 m mountains) located in the north of the radar site. To examine this aspect in detail, Fig. 7b shows the wavelet spectra of the vertical wind in the lower stratosphere (at ~12.4 km, Fig. 7a). Results reveal the wave activity with a period of ~3.5 hours and amplitude of ~1.1 m s^{-1}.

3.3. Associated stratospheric intrusions

Due to the sensitivity of the AIRS retrieved ozone and CH_4 is between 300-600 hPa. Fig. 8 shows the 500 hPa distribution of AIRS observed ozone and CH_4, along with the AIRS tropopause contour (defined based on the temperature lapse-rate). The ozone distribution maps (left panels of Fig. 8) clearly show a large area with enhanced tropospheric ozone (>80 ppbv) near the radar site during the passage of the COL. Moreover, severe CH_4 depletion (<1840 ppbv) was also observed (right panels in Fig.8). These features of the ozone enhancement, CH_4 depletion, and the corresponding low tropopause altitude clearly support the evidence of vertical downward cross-tropopause stratospheric intrusions on 30 Nov..

The vertical cross-section of ECMWF PV and specific humidity at 1800 UT 30 November 2014 and the daily AIRS ozone on 30 November 2014, along with a constant latitude 40° N, is shown in Fig. 9. The corresponding vertical structure of the stratospheric intrusions (dry ozone-rich and high PV along with low tropopause) over regions near radar side is clearly seen. The specific humidity tracer displays less distinct structure as compared with the other two tracers (similar as that shown by Vérèmes et al., 2016). The cross-section of PV in Fig. 9a have demonstrated relatively finer-scale structure of the stratospheric PV intrusions (below the jet stream), which penetrated

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down deeply into ~650 hPa (~3.6 km).

3.4. Trajectory model analysis

Figure 10 shows 30h backward trajectories ending at the radar site at 18 UT 29 November (left panel) and at 18 UT 30 November (right panel). As expected, the air masses parcel transported eastward horizontally before the occurrence of main downdrafts (fig.10a). Whereas after the downdrafts, the trajectories clearly show that the tropospheric air masses over the radar site are of stratospheric origin from the western side of Lake Baikal. Trajectory results further support the evidence of stratospheric intrusions that closely related with the main downdrafts.

On the other hand, 30-h forward trajectories starting at 00 UT 30 November (left panel) and 00 UT 1 December (right panel) are shown in Fig. 11. It is interesting to note that, from Fig.11a before the passage of COL, the air parcels at 4 km transport rapidly upward (by more than 4 km within ~23 h) and northeastward to the upper-troposphere of East Siberian. This upward and poleward transportation is associated with a warm conveyor belt (dominate southerly flows) that is located ahead of the COL. It contributes to transporting the tropospheric moist and polluted air (such as aerosol) into the upper-troposphere and even the lower stratosphere (e.g. Stohl et al., 2003; Sandhya et al., 2015). After the downdrafts, forward trajectories in fig.11b demonstrate that the dry intrusion air parcels continue to be transported downward and southeastward to the boundary layer or even the surface.

3.5. Strong downdrafts preceding rapid tropopause ascent and discussion

Figure 12a shows another 20 typical cases with strong downdrafts preceding rapid RT ascent for the period Mar. 2012 and Jan. 2015 (shown placed end-to-end), and the LRT height (plotted in crosses) and the vertical velocity of the RT (plotted in orange line) is also plotted. These cases (marked by black rectangular boxes) are identified based on the following criteria: 1) the amplitude of the RT ascent should exceed 0.6 km (four range gates), 2) vertical velocities of the RT ascent excess 0.1 km/h, 3) the downdrafts occurred preceding the RT ascent should reach at least 0.5 m/s, and the height region of the downdrafts should pass through the RT layer. The criteria are put forward mainly to avoid the influence of the RT spikes. Figure 12b shows the selected 9 cases of possible intrusions by means of the backward trajectories. Results show clear evidence of possible stratospheric intrusions corresponding to the associated strong downdrafts. Their sources are mainly from West Siberia (western side of Lake Baikal), except for the case Tr5. Moreover, according to AIRS daily 500 hPa ozone distribution, almost every case in Figure 12a (except for the cases labeled as A, B, C and D in Figure 12a) were associated with some form of significant ozone enhancement, indicating intrusions of stratospheric origin (as shown in Supplementary figure S2). It is important to note that the RT excursion velocity of all the cases is not all above 0.2 km/h and some are lower than this value (e.g. case on 2 May. 2014). However, some form of stratospheric intrusions were exactly observed in such case from both the trajectory and satellite results. Therefore, the threshold of vertical velocity of the RT is set at 0.1 km/h, rather than 0.2 km/h (Hocking et al., 2007). Large differences between RT and LRT are also interesting to be noted on some occasions when the RT changes rapidly (such as the occasion near 14 Mar. 2012).

According to the meteorological chart, the synoptic situation of those cases identified in Fig.12a are introduced. The cases occurred on 6 Mar. 2012, 13 Jun. 2012, and 31 Dec. 2012 seem to have a close relationship with the COL development; cases on 13 Mar. 2012, 5 Apr. 2012. 6 Apr. 2012, 4 Jan. 2014, and 2 May 2014, seem associated with low or high pressure systems. The remaining cases seem not associated with any significant synoptic development. However, in terms of the distribution of isentropic PV (generally at 315K in winter and 330K in summer), we found that the remaining cases occurred on 3 Aug. 2013, 3 Jan. 2014, and 3 Jan. 2015 appear to be associated with some form of stratospheric streamers and their break-up within the previous 48h. Some cases (e.g. A and B) that appear close on the same day were probably caused by the same system and not possible to examine the associated possible intrusions separately using either the reanalysis or satellite data.

In the light of present understanding, the strong downdrafts preceding the rapid RT ascent can serve as an important predictor for intrusion events, during any synoptic processes in any season. This characteristic will be of great use and play an important role in routine identification or prediction of stratospheric intrusions. Considering the duration of such downdrafts, a higher time resolution of radar observations will be more helpful. Present study have shown the duration of the majority downdrafts is generally within 1.5-3 hours. We consider, therefore, that the radar resolution should be best within 1h.

Although Hocking et al. (2007) have reported that the rapid tropopause ascent

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(>0.2 km/h) alone can be a useful diagnostic for potential intrusion events. However, using only the information of RT heights might lead to non-negligible errors, as mentioned above in introduction and according to the observations in Fig. 12. Especially on occasions when the RT ascent is between 0.1-0.2 km/h but the corresponding true intrusions were observed, all such intrusion events will be neglected (maybe ~2 per month, refer to Fig. 13a). Whereas on some occasions when the RT ascent excess 0.2 km/h, but without observing true intrusion events (e.g. He et al., 2011), these events will be misdiagnosed (maybe ~13 per month, refer to Fig. 13b). In this sense, using the unique MST radar observations of both the RT height variability and the vertical wind as complementary signature for identifying possible intrusion events is very meaningful.

Figure 13 shows four years (2012-2015) of the events with rapid RT ascent (gray bands), and the events with strong downdrafts just preceding the rapid RT ascent (black bands). The identification criteria of such strong downdrafts are similar to that mentioned above and the events are classified according to different value of vertical velocity of the ascent. Among all the events with ascent velocity between 0.1-0.2 km/h, about one-quarter (approximate 2 per month, Fig. 13a) were observed with strong downdrafts preceding them. Whereas, as for the events with the ascent velocity >0.2 km/h, the proportion is about a half (approximate 10 per month, Fig. 13b). Here, according to the results above, the occurrence of the strong downdrafts just preceding the rapid RT ascent (black bands in Fig. 13) to a large degree represents the occurrence of possible intrusions. In this way, Fig. 13 indicates that the occurrence of possible

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intrusions exhibit distinct seasonal variations, with a maximum in winter and spring minimum in summer. This is because the meso- and small-scale atmospheric processes, such as cold air outbreaks, thunderstorms, and convective activities, are more active in winter and spring. They are important sources for downward stratospheric intrusions.

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4. Conclusions

Detailed case analysis of the cross-tropopause stratospheric intrusions was carried out during a COL. Global reanalysis, satellite data, and HYSPLIT trajectories all showed consistent evidences of dry ozone-rich, high PV, and depleted CH4 air that have penetrated downward into the free troposphere. The key signature of the stratospheric intrusions in the Beijing MST radar observations is the strong downdrafts just preceding rapid RT ascent. The radar echo power decreased rapidly within the region of strong downdrafts, after which abnormal high aspect sensitivity was recorded in troposphere. Such high aspect sensitivity is served as another potential clue for the intrusions of stratospheric origin. By means of wavelet spectra analysis, the periodic perturbation with period of ~3.5 h is found in vertical wind in the lower stratosphere. This perturbation is probably related to the mountain wave activity induced by northerly jet.

Based on the criteria mentioned in section 3.5, other 20 typical cases of strong downdrafts preceding the rapid RT ascent between Mar. 2012 and Jan. 2015 were presented. These events occurred during different synoptic processes in different seasons. What counts is, almost all the cases (16 of them) are associated with some form of intrusions observed by combination of AIRS retrieved ozone and the HYSPLIT trajectory model. Our results show that the radar derived tropopause height and vertical winds are strong complementary indicators to be used to infer the occurrence of the intrusions of stratospheric origin. This will be of great use and play an important role for the routine identification or prediction of intrusion events. However, the actual origin of the observed downdrafts preceding the rapid RT ascent is not addressed in this

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paper. Further combination observational experiments need to be conducted, especially combined using ozonesonde soundings, to quantitative analyze the effectiveness of present identification criteria for possible intrusions.

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Table

Radar parameter	Value
Transmitted frequency	50 MHz
Antenna array	24 × 24 3-element Yagi
Antenna gain	33 dB
Transmitter peak power	172.8 kW
Code	16-bit complementary
No. coherent integrations	128
No. FFT points	256
No. spectral average	10
Pulse repetition period	160 µs
Half power beam width	3.2^o
Pulse length	1 µs
Range resolution	150 m
Temporal resolution	30 min
Off-zenith angle	15^o

Table 1. Operating parameters in low-mode of the Beijing MST radar.

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Figures

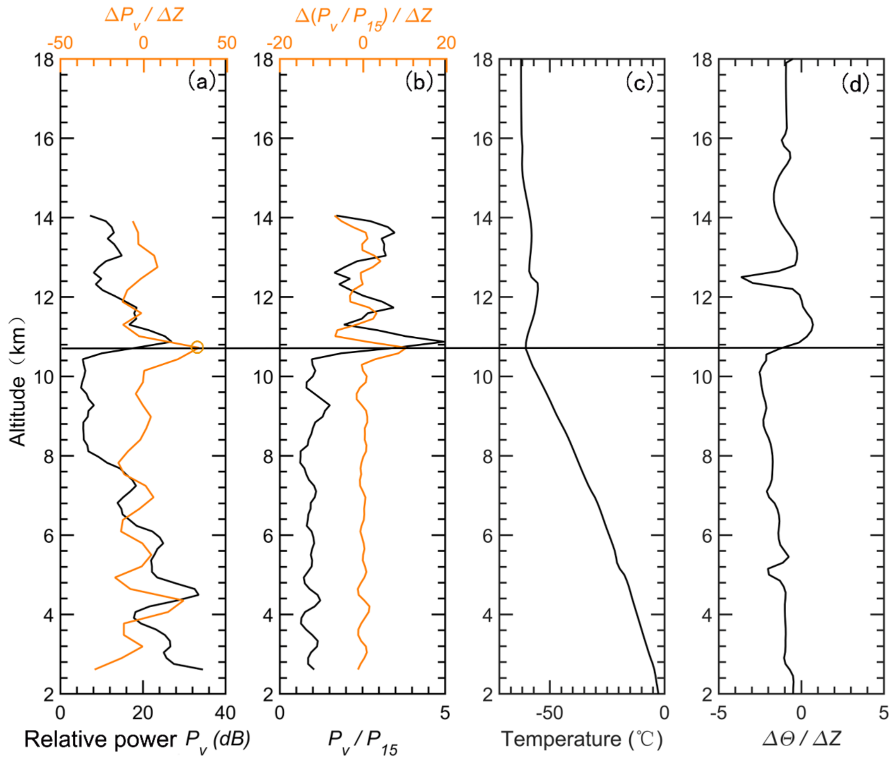

Figure 1. Example of the vertical height profiles of (a) the relative radar echo power (black line, smoothed by a 3-point running mean) along with its gradient variation (orange line), (b) the aspect sensitivity (black line, expressed as the ratio between the vertical echo power and oblique echo power) along with its gradient variation (orange line), observed on 12 UT 29 November 2014. The vertical profiles of simultaneous radiosonde observed temperature and potential temperature gradient are shown in plots (c) and (d). The black horizontal line denotes the LRT height derived from the radiosonde temperature profile. The orange circle indicates the RT height derived from the profile of the radar backscattered echo power.

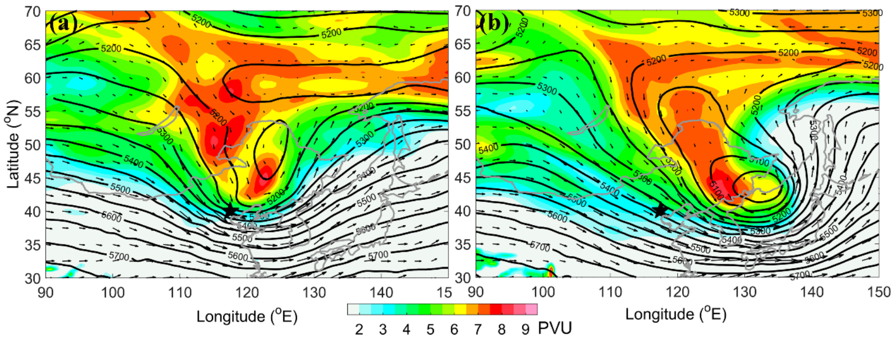

Figure 2. ECMWF derived isentropic PV map on 315 K surface (shaded above 2 pvu, 1 PVU=10^{-6} m^2 K kg^{-1} s^{-1}) and geopotential height (contoured every 50 m in solid line) along with the wind vector (arrow) at 500 hPa (~5.5 km a.s.l.) on (a) 18 UTC 30 November 2014, (b) 12 UTC 1 December 2014. The black star shows the location of Xianghe.

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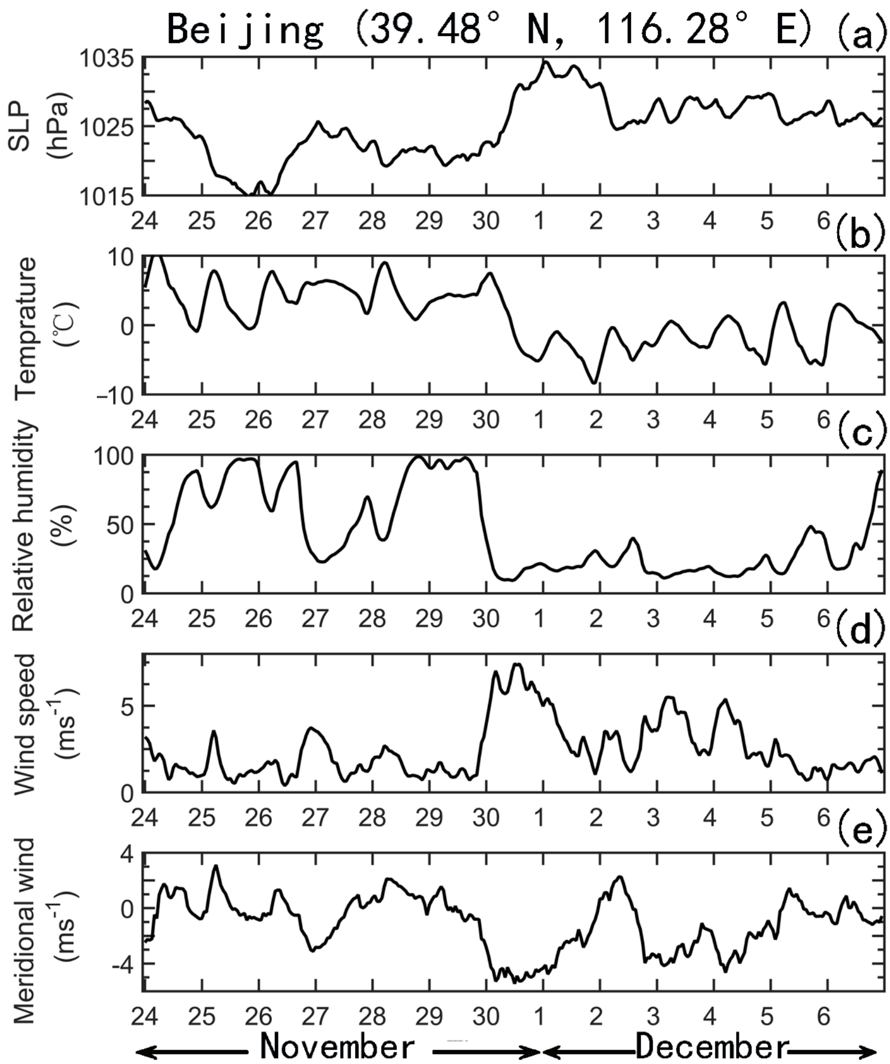

Figure 3. Time series of surface (~1.2 m above the surface) hourly meteorological measurements of (a) sea level pressure, (b) temperature, (c) relative humidity, (d) horizontal wind, and (e) meridional wind during the period 24 Nov.-6 Dec. 2014, observed over the Beijing station (39.4° N, 116.2° E, 31.3 m above sea level).

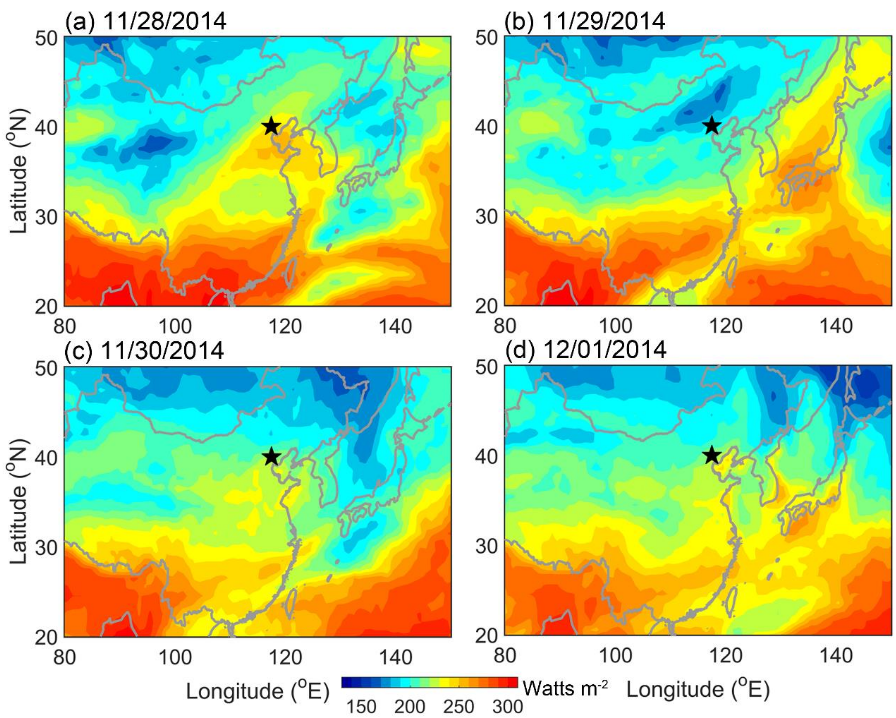

Figure 4. Contour maps of the high quality Climate Data Record (CDR) of the daily Outgoing Longwave Radiation (OLR), derived from the NOAA high-resolution infrared radiation sounder (HIRS) on (a) 28 Nov., (b) 29 Nov., (c) 30 Nov., and (d) 1 Dec. 2014. The black star shows the location of Xianghe.

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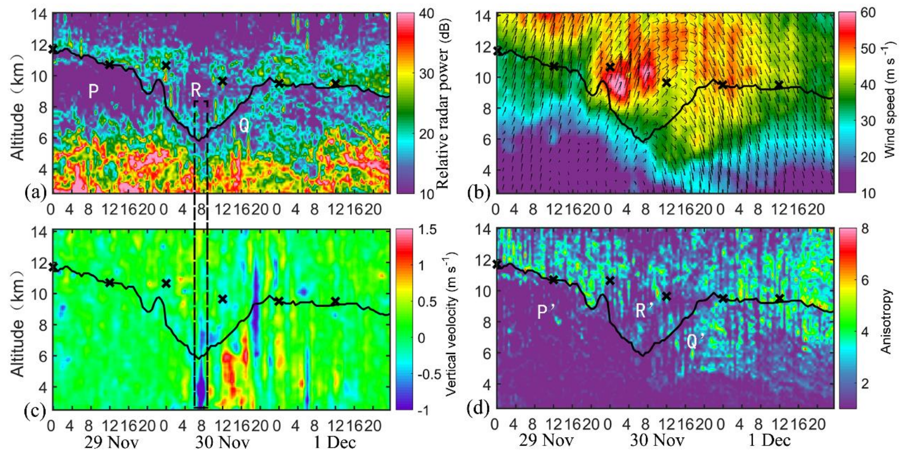

Figure 5. Altitude-time section of (a) the radar backscattered echo power in zenith direction, (b) the horizontal wind speed along with wind vector, of which the up and down arrows represent north and south respectively, and left-right is west-east, (c) the vertical velocity, and (d) the aspect sensitivity, observed by the Beijing MST radar from 29 November to 1 December 2014. The black curve shows the radar-determined tropopause, as defined in section 2.1. The dotted rectangle highlights the strong downdrafts immediately preceding the rapid tropopause ascent. The positions of the LRT tropopause heights, derived from the nearly simultaneous collocated GPS radiosonde temperature profile, are marked by crosses.

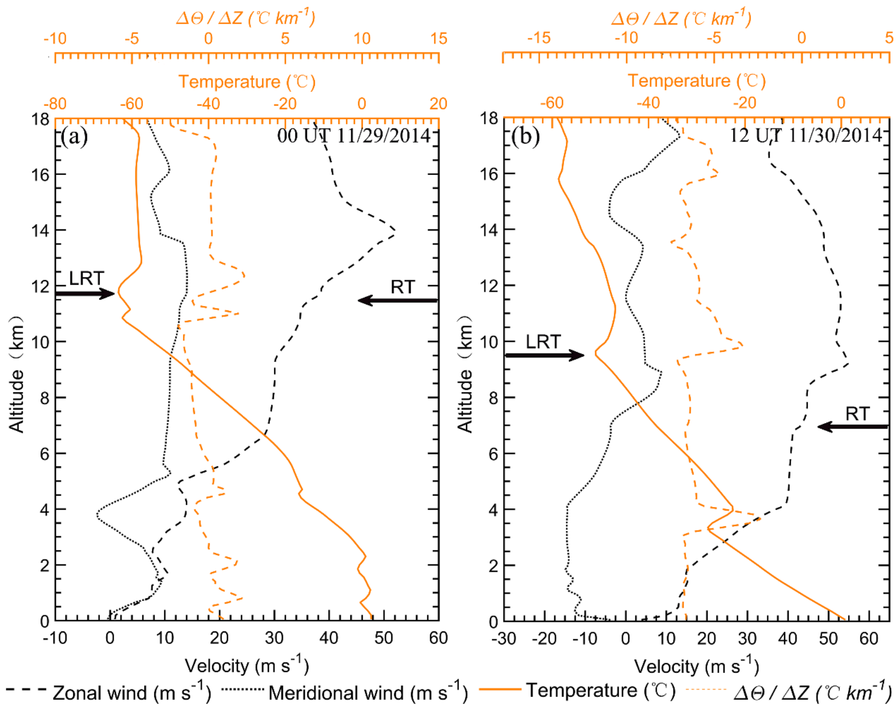

Figure 6. Vertical profiles of zonal wind, meridional wind, temperature, and potential temperature gradient derived from the GPS radiosonde measurements, at (a) 0000 UTC 29 November 2014 and (b) 1200 UTC 30 November 2014. The bold arrows on the left and right side of each panel indicate the radiosonde derived LRT tropopause and radar-derived tropopause height, respectively.

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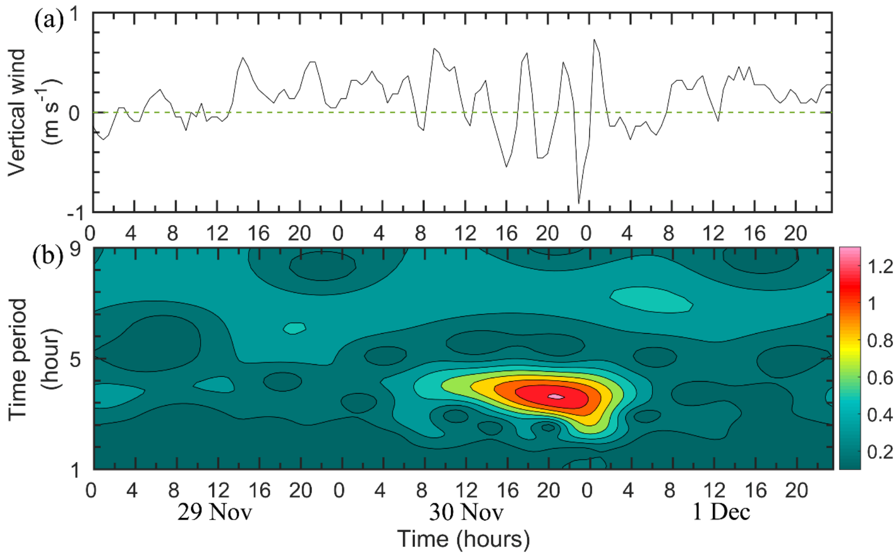

651

652 **Figure 7.** (a) Radar derived vertical velocity variations with time and (b) wavelet
653 spectra analysis of the vertical velocity at ~12.4 km in the lower stratosphere.
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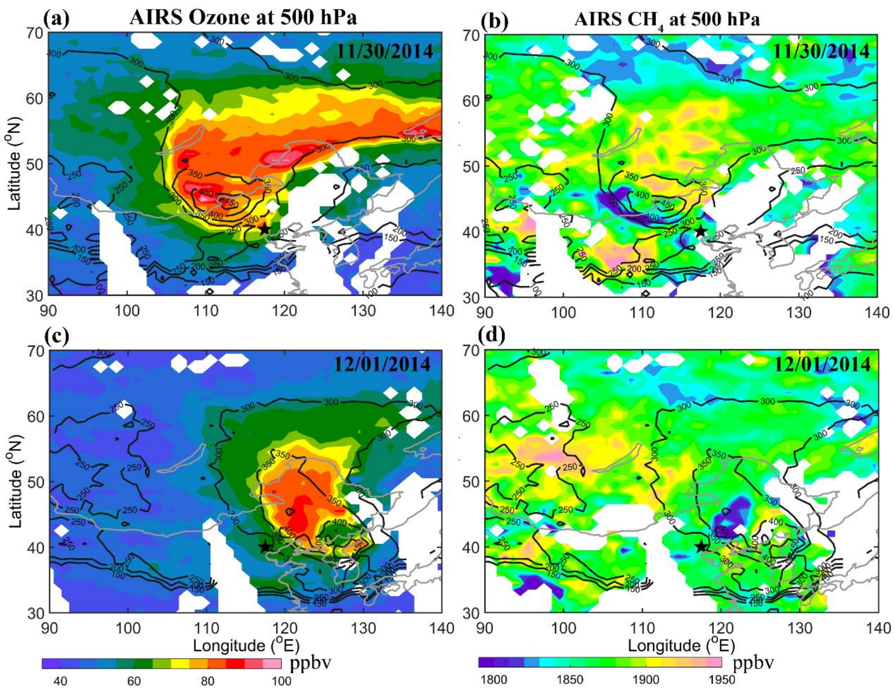

Figure 8. 500 hPa Ozone (left panels) and methane CH_4 (right panels) distribution along with the tropopause height contour, derived from the AIRS satellite observations. The top and bottom plots show the data of 30 Nov. 2014 and 1 Dec. 2014, respectively. The black star indicates the location of Xianghe.

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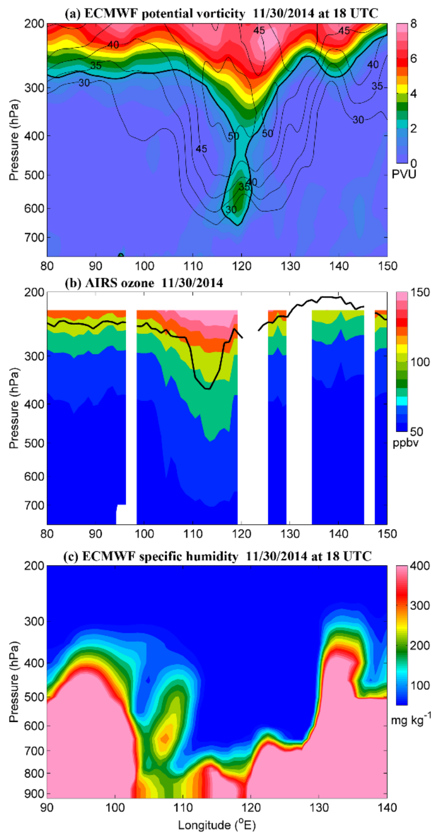

Figure 9. Longitude-pressure cross section of (a) ECMWF PV (colors, in pvu) along with horizontal wind contour (thin black line, m/s) at 18 UTC on 30 Nov. 2014, (b) AIRS ozone mixing ratio (colors, in ppbv) along with tropopause height (black line) on 30 Nov. 2014, and (c) ECMWF specific humidity (colors, in mg kg^{-1}) at 18 UTC on 30 Nov. 2014, at a constant latitude 40° N (nearest grid point in the latitude of Xianghe). The bold line in (a) marks the isotropic line of PV at 2 pvu.

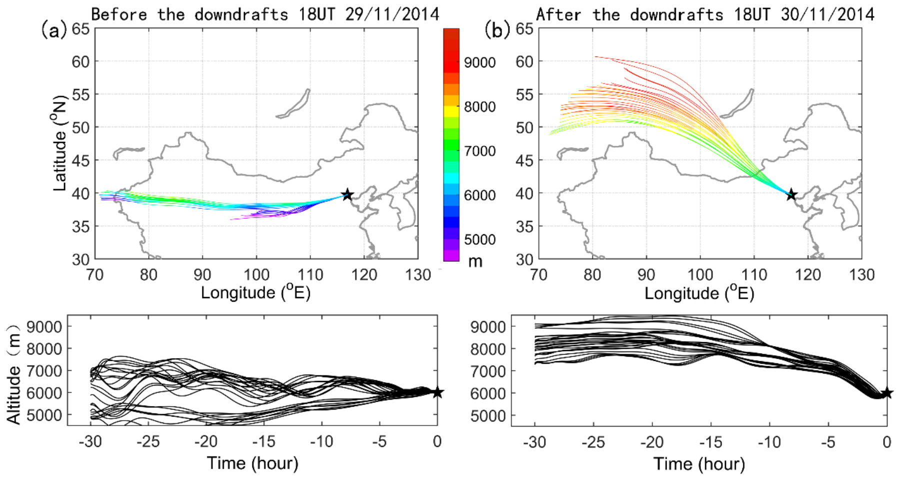

Figure 10. Illustration of 30 h three-dimensional backward trajectories ending at Xianghe using National Oceanic Atmospheric Administration (NOAA) HYSPLIT model: (a) before the main downdrafts at 18 UT on 29 November 2014, and (b) after the main downdrafts at 18 UT on 30 November 2014. The HYSPLIT ensemble consists of 27 trajectories. Upper plots show the horizontal projection of the trajectories, and the lower plots show the corresponding time-height vertical displacement of the trajectories.

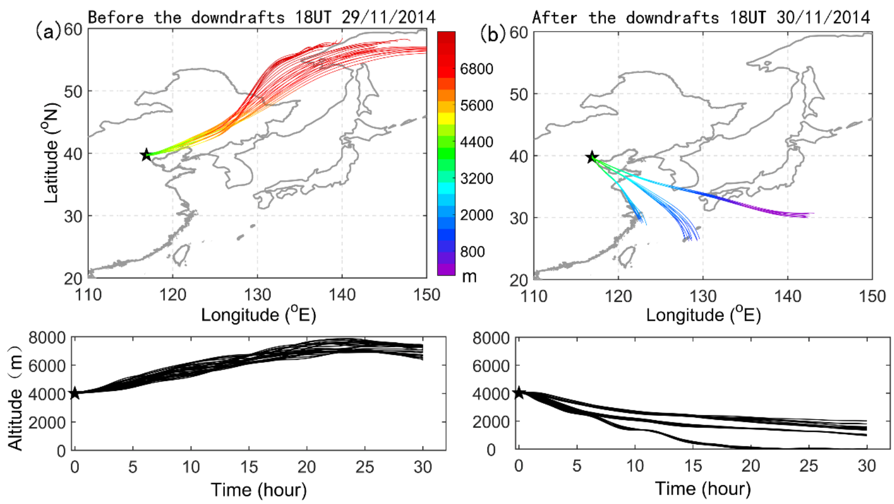

Figure 11. Same as Fig.10 but for three-dimensional forward trajectories starting at Xianghe: (a) before the main downdrafts at 00 UT on 30 November 2014, and (b) after the main downdrafts at 00 UT on 1 December 2014.

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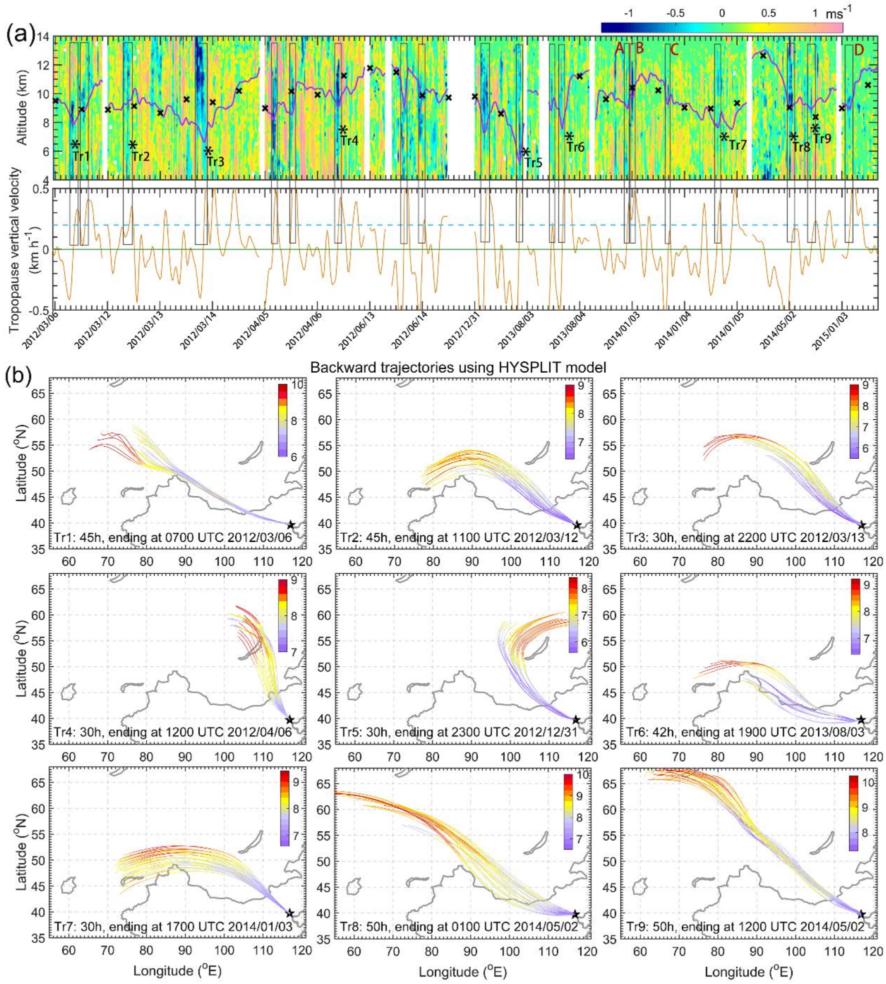

Figure 12. (a) Height-time section of several episodic observations of the radar-derived vertical wind (colors in m/s) along with RT height (purple bold line) and LRT height (bold crosses), between Mar. 2012 and Jan. 2015. The corresponding vertical velocity of the RT (orange line) is plotted in the lower panel of (a), dotted blue line indicates the value of 0.2 km/h. Dates for the observations are displayed as year/month/day. Black rectangular boxes represent the strong downdraughts (absolute value ⩾ 0.5 m/s) observed just preceding rapid tropopause ascent (>0.1 km h^{-1}). Symbol '*' labeled as

Tr1-Tr9 indicates the ending point of the corresponding trajectories in Fig.12b. (b) Results of backward trajectories (colors in km) of the typical 9 selecting cases from Fig.12a, providing the signature and source of possible stratospheric intrusions.

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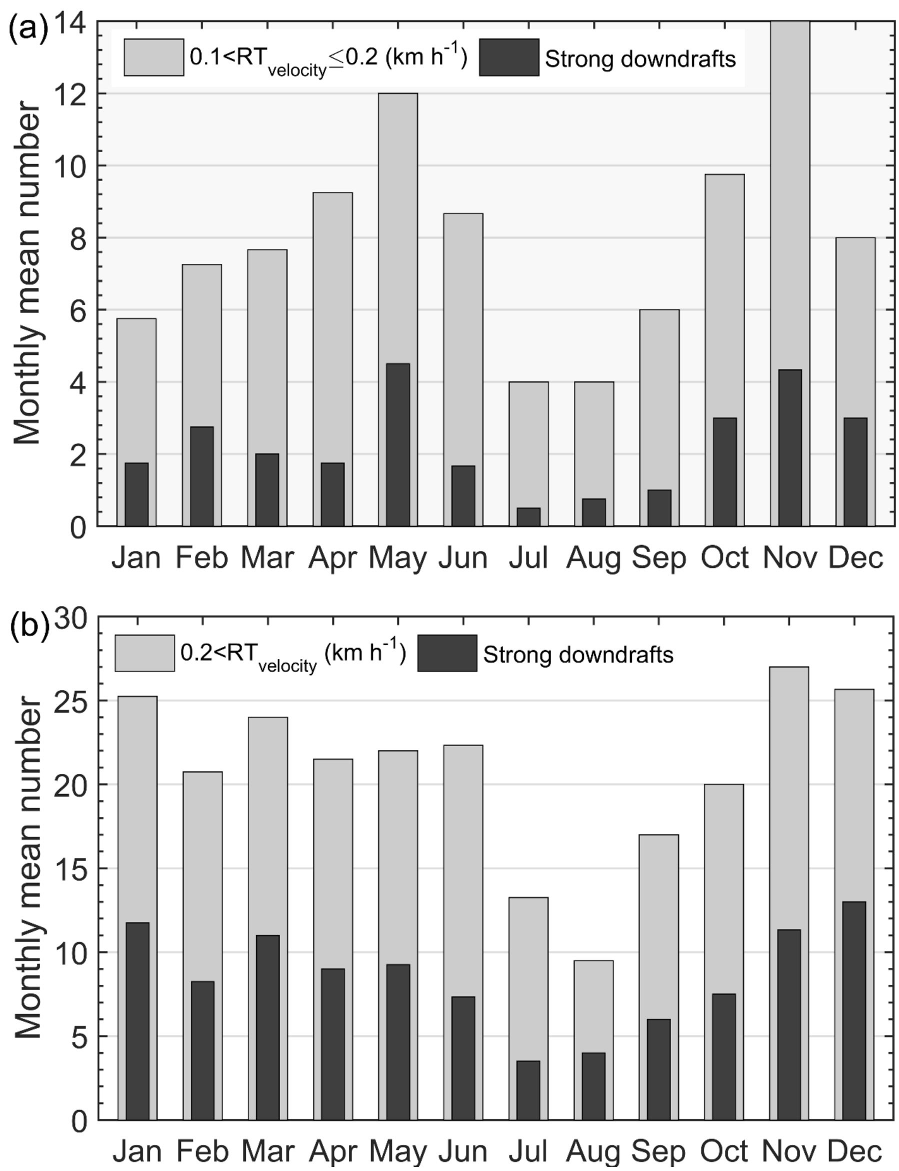

Figure 13. Four years (2012-2015) of radar-determined monthly mean number of rapid tropopause ascent (gray bands) and the corresponding strong downdrafts just preceding the rapid tropopause ascent (black bands). (a) Gray bands: with the ascent by at least 0.6 km and the excursion velocity is between 0.1-0.2 km h^{-1}; black bands: except for the criteria of gray bands, strong downdrafts occurred preceding the rapid RT ascent

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must exceed 0.5 m s^{-1} and pass through the RT layer. (b) Same as (a) but for the occasions when the ascent velocity is larger than 0.2 km h^{-1}. According to the study here, the black bands in the histogram well represent the occurrence of possible stratospheric intrusions.