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Features of Ozone Mini-Hole Events over the Tibetan Plateau

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ABSTRACT

Based on TOMS total ozone data and SCIAMACHY ozone profile data, climatology of the ozone mini-hole events over the Tibetan Plateau and ozone vertical structure variations during an ozone mini-hole event in December 2003 are analyzed. The analyses show that before 1990 ozone mini-hole events only occurred in November–December of 1987 but that the number of events increases after 1990. These events only occur from October through February, with maximum occurrence frequency in December. During the event in December 2003, the decrease in total ozone of over 20% is mainly caused by the ozone loss in the upper troposphere and lower stratosphere region due to the horizontal transport of low ozone from the lower latitude subtropics and the uplift of low ozone from the lower troposphere over the Tibetan Plateau.

Key words: ozone mini-hole, Tibetan Plateau, subtropical jet, upper troposphere and lower stratosphere

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1. Introduction

After the discovery of the Antarctic ozone-hole by Farman et al. (1985), it was recognized that the ozone-hole and ozone depletion in mid- and high-latitudes are caused by heterogeneous chemistry and by anthropogenic chlorine chemistry. Ozone depletion and its effect on the climate and environment have become an international issue (WMO, 1999, 2003). The Montreal Protocol on Substances that Deplete the Ozone Layer was signed in 1987. With respect to ozone observed over China, Zhou et al. (1995) and Zou (1996) discovered the existence of an ozone valley over the Tibetan Plateau in summer, which was recognized as one of the top-10 science and technology advances in China. By analyzing the total ozone data from TOMS and ground-based observations, Bian et al. (2006) found that a large area with extremely low ozone (which is defined as total ozone below 220 DU) occurred over the Tibetan Plateau during 14–17 December, 2003.

Such transient and localized events with low total ozone have been shown to be synoptic scale regions lasting typically a few days. Low ozone events are directly associated with the passage of tropospheric weather systems (James, 1998a). Reed (1950) was the first to explain the dynamical influence on the ozone changes. Such synoptic-scale extremely low ozone events were named "ozone mini-holes" by Newman et al. (1988).

The processes leading to ozone mini-holes as a result of dynamical influence are significantly different from those in the formation of the Antarctic Ozone Hole caused by photochemical ozone destruction (Bojkov and Balis, 2001). Ozone is usually not destroyed by chemical processes during an ozone mini-hole event, but redistributed over the hemisphere by dynamical processes. In order to avoid conceptual confusion, Bojkov and Balis (2001) advocated the term "extremely low ozone event" instead of "ozone mini-hole".

Ozone mini-hole events are known to be caused mainly by dynamical processes rather than chemical processes. Iwao and Hirooka (2006) summarized three mechanisms for the formation of ozone mini-holes. First, the dynamical reduction of column ozone is due to isentropic transport of ozone poor air poleward associated with a Rossby wave breaking in the upper troposphere and the lower stratosphere and equatorward of the polar air in the middle stratosphere (Orsolini et al., 1995; James, 2000; James et al., 2002). Second, loss of air masses in isentropic layers is caused

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by the vertical uplift of isentropes in the lower and middle stratosphere over a strong tropospheric anticyclone (Petzoldt et al., 1994; Petzoldt, 1999, Hood et al., 2001). The first two mechanisms have roughly equal effects in both hemispheres. The last mechanism occurs only in the southern hemisphere, caused by the displacement or stretching of the Antarctic ozone hole toward the mid-latitudes, whereby total ozone is reduced by the equatorward transport of ozone depleted polar air throughout the stratosphere.

Ozone mini-holes occur frequently in the middle and high latitudes in both hemispheres (James, 1998b), and exhibit a strong annual cycle peaking in late winter. In a statistical study, James (1998a) analyzed a 14-year occurrence of mini-hole days in the Northern Hemisphere, which are counted when the ozone is 70 DU less than the average. James (1998a) showed that mini-holes are at a maximum during December–February and occur along a broad circumpolar band centered roughly between 50°N and 65°N, and are associated with storm-tracks. Mini-holes are twice as frequent over the Northern Atlantic/European sector than over the Northern Pacific/Northern American sector. Later, James (1998b) compared the climatology of ozone mini-holes in both hemispheres and found that mini-hole events are far less frequent over the southern hemisphere mid-latitudes than in the northern hemisphere, and that the occurrence frequencies of mini-holes in the high latitudes of the southern hemisphere are quite different from that in other regions. This suggests that the great Antarctic ozone hole has a significant impact on mini-hole occurrence during the southern spring since it provides an extra source of depleted ozone not generally available over the northern hemisphere. By using Dobson data (before 1979) and Total Ozone Mapping Spectrometer (TOMS) data, Bojkov and Balis (2001) analyzed the characteristics of episodes with extremely low ozone values in the northern middle latitudes during 1957–2000. They used a modified criteria to count ozone mini-hole events, and found similar distribution features.

Although ozone mini-holes and their formation have been studied by many scientists throughout the world (Newman et al., 1988; McCormack and Hood, 1997; James, 1998a; James, 1998b; Allaart et al., 2000; Bojkov and Balis, 2001; Orsolini and Limpasuvan, 2001; Teitelbaum et al., 2001), attention has been directed to mid-latitude regions, while no studies have been conducted over the Tibetan Plateau.

In this study we will investigate the climatology of ozone mini-hole events over the Tibetan Plateau and investigate ozone vertical structure during one event in December 2003. Section 2 will introduce the data used in this study, section 3 will give the climatology of ozone mini-holes over the Tibetan Plateau, and section 4 will show the variation of ozone profiles during the event in December 2003. Finally, conclusions will be presented in section 5.

2. Data

Daily level 3 total column ozone data at a resolution of 1°(lat)×1.25°(lon) (version 8) from TOMS (from November 1978 through March 1993) and the Earth Probe (from August 1996 through December 2001) satellites are discussed by Wellemeyer et al. (2004) and are available via the TOMS homepage (http://toms.gsfc.nasa.gov). Total ozone data since 2002 are not used for trend analysis due to calibration issues (Bian et al., 2005; http://jwocky.gsfc.nasa.gov/news/news.html#aug15).

Scanning Imaging Absorption Spectrometer for Atmospheric CHartographY (SCIAMACHY) level 2 ozone profiles (v1.0) provided by the Institute of Environmental Physics, University of Bremen, are also used in our study, and available from the http://www.iup.physik.uni-bremen.de/scia-arc/ website. A detailed description of the SCIAMACHY retrieval method can be found in von Savigny et al. (2003).

3. Climatology of ozone mini-holes over the Tibetan Plateau

An ozone mini-hole event over the Tibetan Plateau is defined in this study as a case when the area with total ozone is less than 220 DU within the region bounded by 25°–40°N and 75°–105°E in an area larger than 400 000 km^2. According to these criteria, 13 events are found from November 1978 through December 2001, which are listed in Table 1 with their durations, minimum value of total ozone, the center location, and the area of each event. It can be seen that there are only four events before 1990, which happened in November–December 1987, an unusual winter. The other nine events took place after 1990.

During this period, the largest event happened during 9–12 December 1987, when the minimum value is only 194 DU, and the low total ozone area exceeds 1 800 000 km^2. From the total ozone distribution on 12 December (see Fig. 1), we can see that the region with values less than 220 DU exists over the Tibetan Plateau. Figure 2 gives the wind field at 200 hPa and the tropopause pressure distribution on 12 December, and shows that the subtropical westerly jet is very strong, it bends northward over the Tibetan Plateau, and that the Plateau is covered with a high

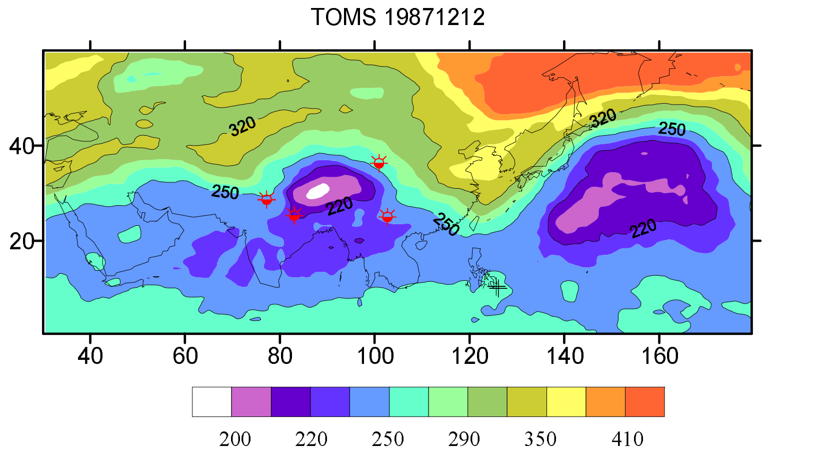

Fig. 1. The distribution of TOMS total ozone (DU) on 12 December 1987.

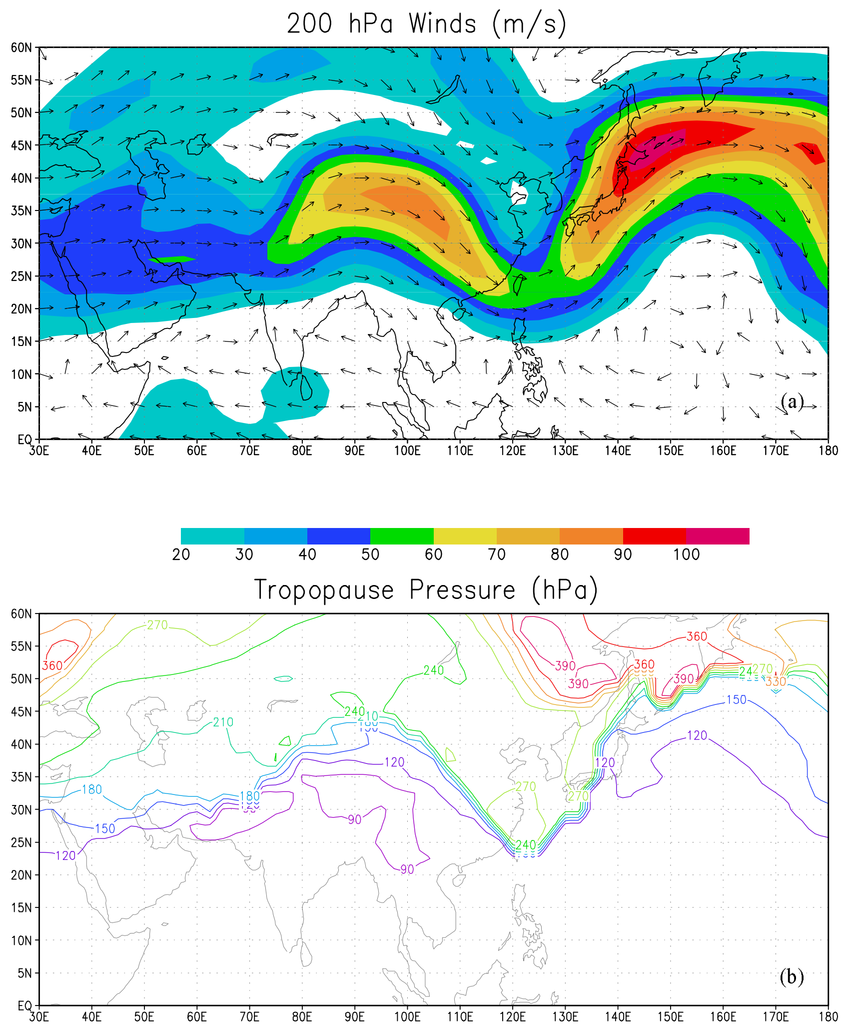

Fig. 2. (a) The wind field at 200 hPa and (b) tropopause pressure (hPa) from NCEP/NCAR reanalysis data on 12 December 1987 (Kalnay et al., 1996).

Table 1. List of ozone mini-hole events over the Tibetan Plateau during 1978–2001.

No.	Year	Duration	Minimum (DU)	Latitude, Longitude	Area (10^4 km^2)
1	1987	29 Nov–01 Dec (3 d)	205	32°N, 89°E	133
2	1987	05 Dec–08 Dec (4 d)	210	29°N, 91°E	105
3	1987	09 Dec–12 Dec (4 d)	194	34°N, 86°E	189
4	1987	21 Dec–23 Dec (3 d)	210	30°N, 85°E	80
5	1993	02 Jan (1 d)	212	32°N, 87°E	47
6	1993	08 Feb–10 Feb (3 d)	205	35°N, 77°E	65
7	1996	17 Dec (1 d)	205	29°N, 93°E	41
8	1998	16 Nov (1 d)	206	28°N, 91°E	47
9	1998	19 Nov–23 Nov (5 d)	204	28°N, 99°E	97
10	1999	23 Jan–25 Jan (3 d)	205	28°N, 90°E	105
11	1999	19 Feb–20 Feb (2 d)	207	33°N, 95°E	77
12	2000	30 Oct (1 d)	208	35°N, 79°E	63
13	2001	18 Dec–20 Dec (3 d)	200	30°N, 84°E	45

Table 2. Occurrence frequency of ozone mini-hole events during 1978–2001 in different seasons.

Month	Total No.	No. with duration > 1 d	No. with area > 700 000 km^2
Oct	1	0	0
Nov	3	2	2
Dec	5	4	3
Jan	2	1	1
Feb	2	2	1
Sum	13	9	7

tropopause at a pressure lower than 120 hPa. The dynamical structure during this event is similar to that in the event of December 2003 (Bian et al., 2006).

Table 2 summarizes the occurrence frequency of ozone mini-hole events over the Tibetan Plateau during 1978–2001 in different seasons. It is apparent that all the events happen during October to February, with a maximum rate of occurrence in December. Table 2 also gives the number of events with durations longer than 1 day, or with area larger than 700 000 km^2.

4. Ozone vertical structure during December 2003

We next investigate how the vertical ozone distribution changes during an ozone mini-hole event. To achieve this goal, we analyze the largest mini-hole event during 14–17 December 2003 (Bian et al., 2006) as an example. Figure 3a presents ozone number density profiles at two latitudes (20°N and 35°N) along 90°E on 10 (pre-event) and 16 (in-event) December. On 10 December, the ozone density at both latitudes is at a maximum at 24 km at 20°N and 21 km at 35°N and exceeds 4.7×10^{12} cm^{-3}. In contrast to this structure, the maximum ozone density on 16 December is at 26 km and has a smaller value of $\sim4.3\times10^{12}$ cm^{-3}

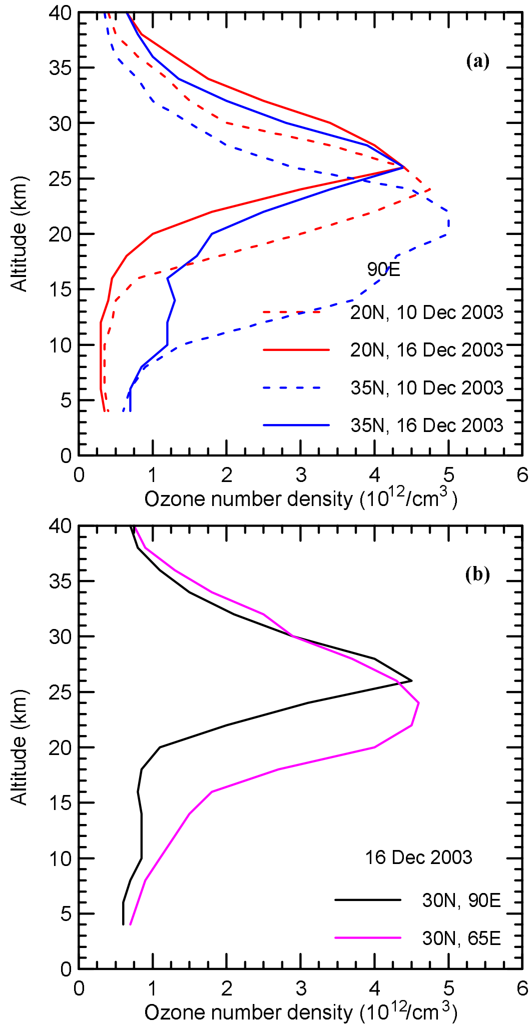

Fig. 3. Ozone profiles during 10–16 December 2003. (a) Comparison between 10 and 16 December ozone profiles at two latitudes (20°N and 35°N) along 90°E; (b) comparison between ozone profiles at two longitudes (65°E and 90°E) along 30°N on 16 December.

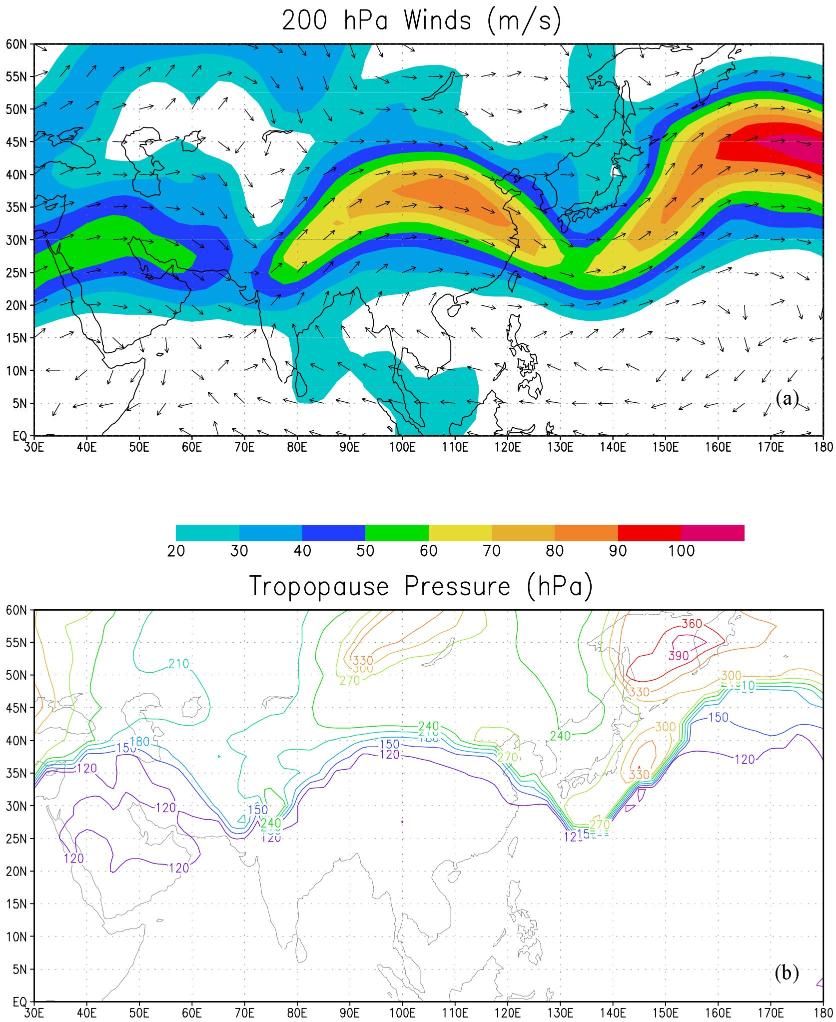

Fig. 4. Same as Fig. 2, but for 16 December 2003.

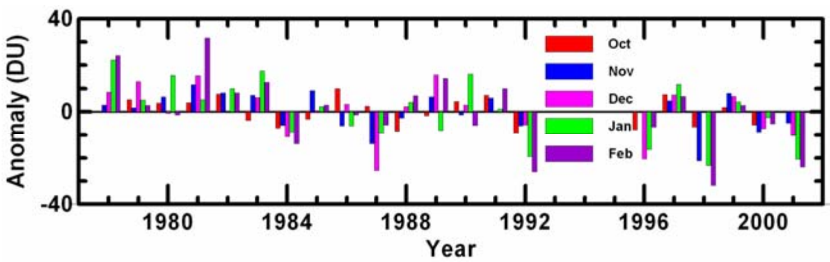

Fig. 5. Regional mean total ozone anomalies (28.5°–34.5°N, 80.625°–99.375°E) in different months during 1978–2001.

at both latitudes, and the ozone density decreases dramatically in the range of 15–26 km (at 20°N), especially in the altitude range of 10–25 km (at 35°N). This vertical structure contributes to the large decrease of total ozone over the Tibetan Plateau during the event (Bian et al., 2006). On 16 December the ozone density peaks at 26 km over the Tibetan Plateau (30°N, 90°E), but has another peak at a lower level of 23 km at 65°E at the same latitude (Fig. 3b), so the ozone density in the range of 12–26 km has a much smaller value over the Tibetan Plateau at 90°E than at 65°E at the same latitude.

As pointed by Bian et al. (2006), the subtropical westerly jet over the Tibetan Plateau is directed northeastward during this ozone mini-hole event, increasing from the southwest to the northeast sector of the plateau, then bending southeastward (see Fig. 4a). The jet is directed northward and reaches nearly 40°N, and correspondingly, the tropopause over the Tibetan Plateau is raised upward above the 120 hPa level, as shown in Fig. 4b. The wind field and the tropopause pressure distribution on 16 December 2003 are similar to those on 12 December 1987 (see Fig. 2).

From the dynamical structure discussed above, the ozone density decrease in the upper troposphere and lower stratosphere region (12–25 km) over the Tibetan Plateau during this event seems to be caused by both horizontal transport and vertical motion. The horizontal transport associated with a Rossby wave breaking around the tropopause brings low ozone air from the lower latitude subtropics to the Tibetan Plateau, and the vertical uplift of isentropes in the lower and middle stratosphere over a strong tropospheric anticyclone causes loss of air masses in isentropic layers as summarized by Iwao and Hirooka (2006).

5. Summary and discussion

TOMS total ozone data in the discussion above are used to analyze the climatology of ozone mini-hole events over the Tibetan Plateau, and SCIAMACHY ozone profile data are used to study the variations of the vertical ozone distribution during an ozone mini-hole event in December 2003. Based on the TOMS data from November 1978 through April 1993, and August 1996 through December 2001, analyses show that there are 13 ozone mini-hole events during this period. Four of the events occur before 1990 (i.e., in November–December 1987) and the other nine events occur after 1990. Analyses also show that the ozone mini-hole events over the Tibetan Plateau only occur from October through February, with a maximum occurrence frequency in December.

During the ozone mini-hole event over the Tibetan Plateau in December 2003 (Bian et al., 2006), the ozone density is found to decrease mainly in the upper troposphere and lower stratosphere. During this event, a strong anticyclone controls the Tibetan Plateau meteorology in the upper troposphere and the tropopause is lifted to a pressure less than 120 hPa. The total ozone loss seems to be due to the horizontal transport of low ozone air from the lower latitude subtropics and also due to the uplift of low ozone air from the lower troposphere over the Tibetan Plateau.

Why is the occurrence of ozone mini-hole events over the Tibetan Plateau quite different before and after 1990? From the list of mini-hole events, it is seen that these events occurred in 6 winters, 1987–88, 1992–93, 1996–97, 1998–99, 2000–01, and 2001–02 (see Table 1). Figure 5 presents regional mean total ozone anomalies over the Tibetan Plateau (28.5°–34.5°N, 80.625°–99.375°E) in the winter months (October–February) during 1978–2001, and shows that there are seven winters with negative anomalies in nearly all winter months, i.e. 1984–85, 1987–88, 1992–93, 1996–97, 1998–99, 2000–01, and 2001–02. Except for 1984–85, ozone mini-hole events occurred in other negative-anomaly winters. This seems to suggest that there is a correlation between the occurrence of an ozone moni-hole and total ozone during October–February.

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