Study on Two Categories of Sudden Stratospheric Warming*

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(Received May 28, 2007)

ABSTRACT

Invoking 45-yr daily European Centre for Medium-range Weather Forecasts (ECMWF) reanalysis data, firstly all the sudden stratospheric warming (SSW) events are selected in these years, which can be classified into two categories: downward-propagating event and non-downward-propagating event. And then, based on potential vorticity distribution on isentropic surfaces (IPV), temperature field, and zonal wind field, a detailed description of the SSW occurring during the winter-spring (December and the following January, February, March) in 2000-01 and 2001-02 is given. Finally, the evolvement of polar vortex during warming process and the impact of warming on troposphere are discussed. It is found that (1) there is inter-decadal variation for stratospheric warming phenomenon; (2) the SSW event lasting from late January till early March in 2001 can propagate downward to troposphere; (3) during this SSW, there is zonal-mean easterly winds in both stratosphere and troposphere; (4) the two warming events during December 2001 and March 2002 cannot propagate downward to troposphere, while zonal easterly winds only appear in stratosphere; and (5) in the process of the two types of warming, a long and narrow high-value IPV "tongue" extends out from main polar vortex, which breaks out the gradient of IPV. Compared with the non-downward-propagating stratospheric warming case, the highest value of IPV departs farther from pole and the "tongue" is longer and narrower during the downward-propagating warming event. Pinched by anticyclone from middle latitude, the stratospheric polar vortex will displace, distort or breakdown. By contrast, the change of polar vortex is greater in the course of downward-propagating warming event. Also, troposphere circulation and polar vortex evolve in different degree, and usually both of them go with blocking, but the above evolvement in the downward-propagating warming is more distinct.

Key words: stratospheric warming, downward-propagate, non-downward-propagate, polar vortex

1. Introduction

Following the discovery of sudden stratospheric warming (SSW) phenomenon over Berlin by Scherhag (1952), it has been found at other high latitudes, and many observations have proven that it is one of the most important dynamical phenomena on large scale. Since then, the cause of SSW has been discussed from various points of view (Charney and Stern, 1962; Lindzen, 1966; McIntyre, 1972). These early theoretical studies have mainly concerned with the examination of stability property of polar night jet, but the cause of SSW is not investigated. Matsuno (1971) first explained the mechanism of SSW from dynamical viewpoint, and thought that interaction between vertical propagating stationary planetary waves and zonal meanflow may bring the SSW. Ever since Matsuno's pioneering numerical simulations, McIntyre (1982) found the prospects of understanding and forecasting stratospheric warmings. Kanzawa (1982) applied Eliassen-Palm (E-P) flux to diagnose the 1973 SSW. For the first time, Labitzke (1965) presented evidence suggesting that the development of the sudden warming closely connects to blocking in the troposphere. After that the association between stratospheric warming and tropospheric blocking was studied at different aspects (Schoeberl, 1978; Egger, 1980; Quiroz, 1986; Li et al., 1990). Manney et al. (1994) calculated PV and diabatic heating to describe two stratospheric warmings during February and March 1993. Jin and Qu (1994) found 30-60-day oscillation has a larger contribution for SSW. Hu et al. (1996)

*Supported by the climatic variation special project of China Meteorological Administration under Grant No. CCSF2007-31 and the National Natural Science Foundation of China under Grant No. 40633015.

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showed the forcing waves at tropopause have the control roles on SSW. Ma (1996) simulated the influence of the subtropical jet strength and the equatorial quasi-biennial oscillation (QBO) on the SSW, and indicated that the stronger the subtropical jet was, the faster the SSW would occur and the lower the height of warming centers would be.

In recent years, Jung et al. (2001) numerically simulated the entire evolution of the warming event during February and early March 1979. Zhou et al. (2002) and Hu and Tung (2002) studied dynamical links of the Northern Hemisphere stratosphere and troposphere, and emphasized the effect of stratospheric changes on tropospheric weather and climate. Chen and Huang (2002) also diagnosed the SSW by means of E-P flux, and indicated that the SSW is the result of anomalous planetary wave propagation along the high latitude waveguide and its interaction with meanflow. Naito et al. (2003) studied the effects of the equatorial QBO on the SSW events, showing the polar night jet is weaker and polar stratosphere is warmer in the runs with easterly "QBO wind" forcing.

In the past, the SSW events were mainly classified according to the following three principles: In view of intensity of warming, the events may be divided into strong and weak warming (Quiroz, 1986); based on evolvement of long wave, they were classed into Wave 2 type and Wave 1 type (Labitzke, 1977; Schoeberl, 1978); in the light of the location of warm high expanded to pole, there are two kinds: one is North Pacific warming, and the other is North Atlantic warming (Chou, 1985). In this study, considering the effect of SSW on troposphere, the events can be divided into downward-propagating and non-downward-propagating.

The SSW has close connection with equatorial QBO, polar vortex, blocking, and subtropical jet, and thus it has great value to research on the stratospheric warming. In this paper, all 45-yr SSW events are picked out and divided into two categories, i.e., downward-propagating stratospheric warming and non-downward-propagating stratospheric warming, and the stratospheric warming events during "winter and spring" of 2000-01 and 2001-02 are diagnosed and analysed in details as a case.

2. Data and methods

In the previous investigation of stratospheric sudden warming, the data of upper level in stratosphere are mostly retrieved from satellite data. In this study, we diagnose the SSW by using 45-yr daily European Centre for Medium-range Weather Forecasts (ECWMF) reanalysis data (from 1 September 1957 to 31 August 2002). These data are more authentic if compared with others, and have 23 levels (1000, 925, 850, 775, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10, 7, 5, 3, 2, and 1 hPa).

Because the SSW phenomena mostly occur in winter and early spring, we first calculated temperature anomalies in the polar region at different isobaric levels from 1000 to 1 hPa during winter-spring, then based on the anomalies we selected SSW phenomena. The anomalies are calculated by subtracting the 45-yr winter-spring average value from the daily temperature data, and the anomalies are normalized by their standard deviation at different levels to exclude the density effect. According to the standard deviation, the stratospheric warming events in the 45-yr winter-spring are classified into two categories. The downward-propagating stratospheric warming category is defined here as the case that a temperature anomaly is greater than 1.5 standard deviation ($\kappa \geqslant 1.5$) at middle and upper levels in stratosphere and followed under levels (from 5 to 250 hPa), and non-downward-propagating stratospheric warming category is defined as that where a temperature standard deviation is also greater than 1.5 standard deviation ($\kappa \geqslant 1.5$) above 70 hPa, but followed by a temperature anomaly smaller than 1 standard deviation at 250 hPa. Both types of stratospheric warming should persist for more than 10 days.

Zonal meanflow has direct impact on propagation of planetary wave, and the propagation plays a key role in the SSW, so the wind field has some difference between these two categories of stratospheric warming phenomena, especially zonal mean wind. The different zonal mean wind distribution is a very important signal in the process of SSW, and it is also a valuable quantity to diagnose the SSW.

Potential vorticity (PV) is a synthetic quantity describing atmospheric kinetic and thermodynamic state. The use of PV, as an atmospheric diagnostic quantity, mainly bases on two principles: one is that PV is a quasi-conservative tracer of air motion along isentropic surfaces, and the other is that global PV distribution completely defines stream, with restriction of basic static stability, balance conditions, and boundary conditions (Hoskins et al., 1985). Cold west wind vortex usually inhabits pole and leads to the greater gradient of PV at middle latitudes in stratosphere during winter and spring. Upward propagation of planetary wave depends on the gradient of PV, and variation of the upward-propagation greatly influences the SSW. If the potential vorticity on isentropic surface (IPV) happens to knot or appear "surf" zone, planetary wave would break, then wave energy disperse, and lead to stratospheric warming. Therefore IPV is an important diagnostic quantity for SSW. Next, the PV on 850-K isentropic surface is given.

Firstly, potential vorticity on isobaric surface is defined as

$$PV = -g(\xi + f)\partial\theta/\partial p, \qquad (1)$$

where g is acceleration of gravity, ξ is relative vorticity on isobaric surface, f is Coriolis parameter, and $\theta = T(p_0/p)^{R/c_p}$ is potential temperature. R=287 J kg^{-1} K^{-1} and c_p=1005 J kg^{-1} K^{-1} are dry gas constant and specific heat at constant pressure, respectively. In the middle and upper stratosphere, the isentropic surfaces coincide fairly well with isobaric surfaces, and 850-K isentropic level nears 10-hPa isobaric surface, therefore the pressure of the 850-K surface may be computed through 10-30-hPa temperature, and the 850-K relative vorticity may be interpolated or extrapolated from the 7-30-hPa surface. To understand how the static stability influences IPV, the static stability $\partial\theta/\partial p$ can be expressed as

$$\frac{\partial\theta}{\partial p} = -\frac{\theta R}{p_\theta g}\left(\frac{\mathrm{d}T}{\mathrm{d}z} + \frac{g}{c_p}\right), \qquad (2)$$

where p_θ is pressure on isentropic surface.

In this paper, we suppose that $\mathrm{d}T/\mathrm{d}z$ is a constant (1°C km^{-1}) and substitute 10-hPa vorticity for 850-K vorticity. Then we can obtain PV at 850-K isentropic surface as follows

$$IPV = g(\xi_{10\mathrm{hPa}} + f)\Big(\frac{\theta R}{p_{850\mathrm{K}}g}\Big)\Big(\frac{\mathrm{d}T}{\mathrm{d}z} + \frac{g}{c_p}\Big), \qquad (3)$$

where $p_{850\mathrm{K}} = 10\mathrm{hPa}(\frac{850\mathrm{K}}{\theta_{10\mathrm{hPa}}})^\alpha$ and $\alpha = -\frac{R}{g}(\frac{\mathrm{d}T}{\mathrm{d}z} + \frac{g}{c_p})$.

3. Selecting and classifying SSW

The air temperature exists inter-annual variation to a certain extent, so there are some differences in normalized deviation of polar zonal mean temperature among each warming process. Invoking 45-yr ECWMF reanalysis data, we first compute temperature change in polar region at 10-hPa isobaric level, then calculate zonal mean temperature deviation and their standard deviation at 23 levels from 1000 to 1 hPa during 45-yr winter-spring. According to the above-mentioned criterion of classification, and making use of temperature change at 10-hPa level and the calculated standard deviation, we pick out all stratospheric warming phenomena and divide them into two categories. downward-propagating and non-downward-propagating. For example, from Figs.1a, b and 2a, b, we can find that there are two types of SSW during the winter-spring of 2000-01 and 2001-02. The changes of zonal mean temperature along 80°N at 10-hPa isobaric level (Figs.1a, b) show that there are three stratospheric warming events from 20 January to 10 March 2001, 18 December 2001 to 8 January 2002, and 10 February to 3 March 2002. In these processes, the increase of temperature reaches about 50°C during the first warming event, and the increase of temperature exceeds 50°C in the course of the second warming event. Vertical-time section of the zonal-mean temperature normalized deviation (Figs.2a, b) indicates that there is obvious variation between the first warming and the later two warming events. In first deviation section chart (Fig.2a), the normalized deviations are greater than 1.5 at both mid-upper levels in stratosphere (18 represents 10 hPa in vertical coordinates)

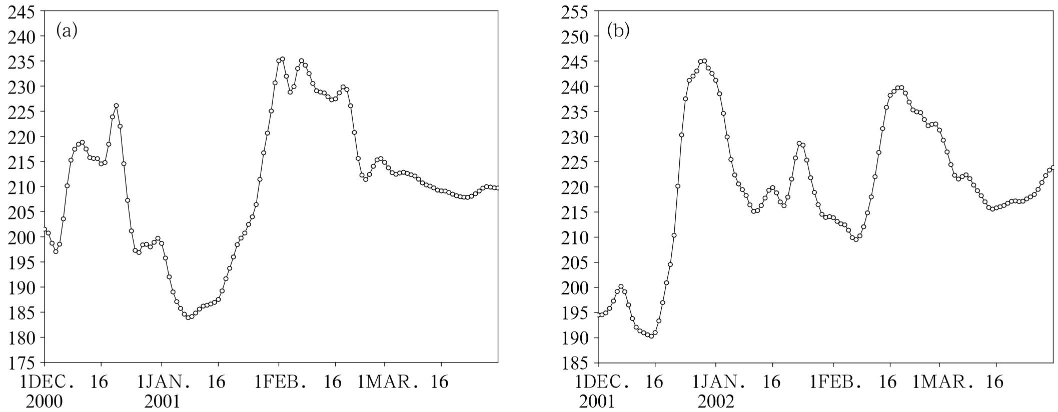

Fig.1. Zonal mean temperature along 80°N at 100 hPa from 1 December 2000 to 31 March 2001 (a), and from 1 December 2001 to 31 March 2002 (b) (Unit: K).

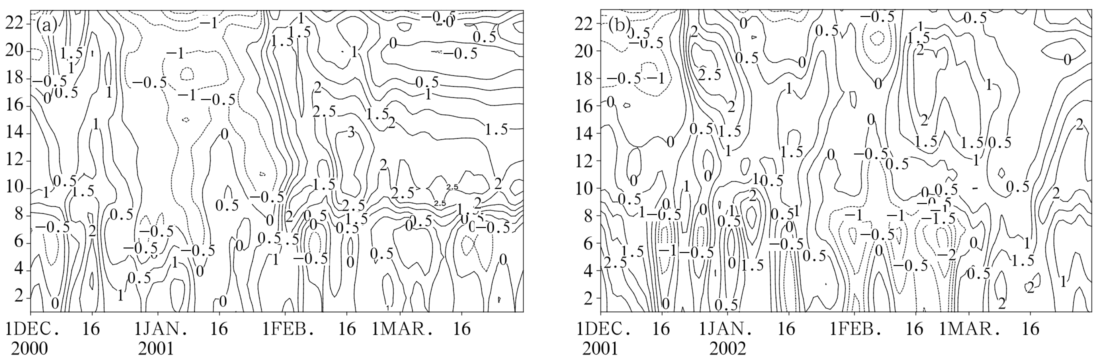

Fig.2. Altitude-time section of the standard deviation of averaged temperature along 80°N from 1 December 2000 to 31 March 2001 (a) and from 1 December 2001 to 31 March 2002 (b). The vertical coordinate 1, 2, 3,. . ., 23 represent 1000, 925, 850,. . ., 1 hPa, respectively. The same as hereafter.

and mid-upper levels in troposphere (11 denotes 200 hPa in vertical coordinates) during major warming (February 2001), so this event is a downward-propagating SSW. But the normalized deviations shown in Fig.2b exceed 1.5 only above 100 hPa (13 denotes 100 hPa in vertical coordinates) during the last two warming process, while below 100 hPa normalized deviations are smaller than 1.5, therefore the two warmings only occur in stratosphere and are called non-downward-propagating warming. In the same way, we can pick out all stratospheric warming events, divide them into two categories, and draw out Table 1.

From Table 1, it is found that there are 20 episodes for downward-propagating and 16 episodes for non-downward-propagating stratospheric warming. The frequency of stratospheric warming phenomena was very high from evening of the 1950s to metaphase of the 1960s, and most of them were downward-propagating. It showed that winter-spring stratospheric temperature anomalies, flow anomalies occurred frequently, and also happened in troposphere during that period, which indicated that stratosphere had great effect on troposphere. But the SSW events mostly belonged to non-downward-propagating type from the late 1970s to the early 1980s, it is said that these stratospheric warmings have little impact on temperature and flow in troposphere. Then from middle to last periods of the 1980s, the SSW episodes mostly returned downward-propagating warmings, and non-downward-propagating SSW predominated again in the 1990s. All of these characteristics imply that stratospheric warming has inter-annual and inter-decadal variations, but mechanism of the

Table 1. Listing of SSW events and duration during the winter-spring of 1957-2002

Downward-propagating SSW	Duration	Non-downward-propagating SSW	Duration
23 Jan. -15 Feb. 1958	23 days	5-25 Dec. 1960	21 days
2-26 Jan. 1960	25 days	8 Feb. -10 Mar. 1972	32d ays
2 Mar. -early Apr. 1961	about 1 month	23 Dec. 1974-30 Jan. 1975	39 days
20 Jan- 20 Feb. 1963	31 days	26 Dec. 1977-6 Jan. 1978	12 days
2 Feb. -early Apr. 1964	about 2 months	17 Jan. -10 Mar. 1979	43 days
20 Dec. 1967-15 Jan. 1968	27 days	28 Jan. -15 Feb. 1981	19 days
25 Dec. 1969-5 Feb 1970	43 days	18 Jan. -16 Feb. 1982	30 days
6 Jan. -5 Feb. 1971	31 days	21 Jan. -1 Mar. 1983	40 days
7 Jan. -20 Feb. 1973	45 days	1 Mar. -early Apr. 1988	about 1 month
27 Dec. 1976-2 Feb.1977	48 days	3-25 Feb. 1990	23 days
10 Mar. -early Apr. 1978	more than 20 days	10-28 Jan. 1992	18 days
27 Feb. -29 Mar. 1980	32 days	20 Jan. -12 Feb. 1995	24 days
16 Feb. -early Apr. 41984	about 2 months	13-28 Dec. 1998	16 days
23 Dec. 1984-3 Feb. 1985	43 days	8-25 Mar. 2000	18 days
9 Mar. -early Apr. 1986	about 1 month	18 Dec. 2001-8 Jan. 2002	21 days
10 Jan. -21 Feb. 1987	43 days	10 Feb. -3 Mar. 2002	22 days
1-26 Dec. 1987	26 days		
16 Feb. -30 Mar. 1989	43 days		
20 Feb. -20 Mar. 1999	39 days		
20 Jan. -10 Mar. 2001	50 days		

variation is not clear. The variation may be related to inter-annual and inter-decadal variations of air temperature and precipitation.

4. Characteristic of SSW during winter-spring of 2000-01 and 2001-02

The gradient of temperature usually points to high latitudes due to the inhomogeneity of solar radiant energy with latitudes, but temperature field reverse in polar region during sudden stratospheric warming, the gradient of temperature is also reversal, and polar night jet rapidly weakens or breaks, so zonal easterly winds circle pole and polar vertex distort or break down.

Figures 3a and b show latitude-time section of zonal mean temperature at 10 hPa in winter-spring of 2000-01 and 2001-02. From Fig.3a, it is found that the meridional gradient of mean temperature points to mid-latitude (about 40°N) from pole in late January till late February 2001, but the gradient usually points to pole, the temperature field reverses. It indicates that polar stratospheric temperature is anomaly high in this period, while during other time the gradient becomes general, which well couple with temporal evolvements of temperature and normalized deviation shown in Figs.1a and 2a. The above analogous characteristics may be illustrated in Fig.3b, while there are twice reversals of temperature in late December 2001 to middle January 2002 and middle February to early March 2002. Additionally, the vertical-time sections

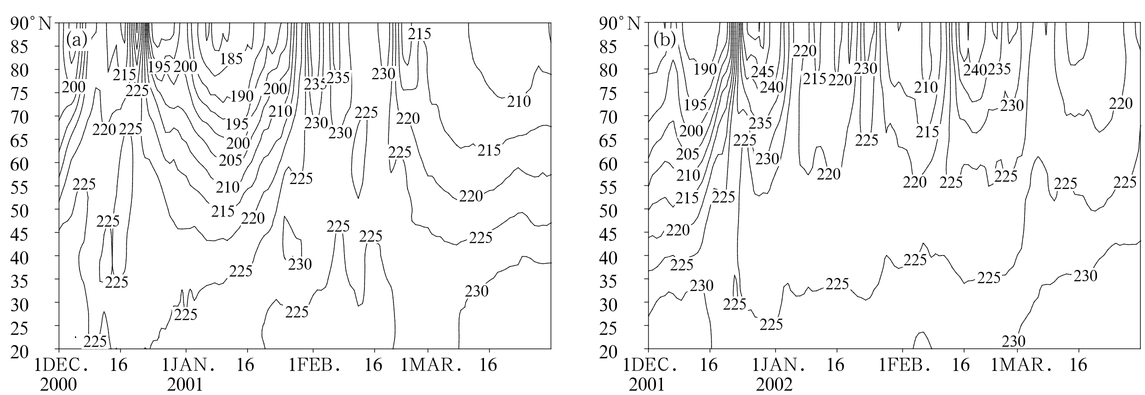

Fig.3. Latitude-time section of the zonal mean temperature at 100 hPa from 1 December 2000 to 31 March 2001 (a) and 1 December 2001 to 3 March 2002 (b) (Units: K).

of zonal mean temperature (Figs.4a, b) show that there are obvious difference in vertical structure between winter-spring stratospheric warming of 2000-01 and 2001-02. The obvious temperature positive anomaly maintains from 2 hPa slanting till 300 hPa during late January to early March 2001 (Fig.4a), which illuminates that the SSW can downward propagate to troposphere. But the biggish temperature positive anomaly only appears in stratosphere during the winter-spring of 2001-02 (Fig.4b), which indicates that these two warming events merely occur in stratosphere. That also may be commendably reflected in vertical-time section of normalized deviation of temperature (Figs.2a, b).

Zonal meanflow directly affects propagation of planetary wave, which influences the evolvement of temperature, so the change of zonal mean wind is an important factor to diagnose the two categories of SSW phenomena. Here, we give a case for the stratospheric warming in winter-spring of 2000-01 and 2001-02. As shown in Figs.5a and b, the vertical-time section of zonal mean wind along 80°N has difference in vertical structure between the SSW in winter-spring of 2000-01 and 2001-02. The former section (Fig.5a) illustrates that zonal-mean easterly winds prevail both in stratosphere and troposphere during that stratospheric warming event (from late January to late February 2001). Planetary wave cannot propagate in easterly wind flow (Charney and Drazin, 1961), so after the polar wind reversed to easterly, the tropospheric wave could not propagate upward so that the heat transport was interrupted, the planetary wave breaks and its energy diffuses, where warming phenomena occur. That intuitively presents a modality of downward-propagating stratospheric warming. But the latter section in Fig.5b shows that zonal easterly winds only appear in stratosphere during the two stratospheric warming of winter-spring in 2001-02, so the planetary wave can upward propagate to tropopause and only breakdown in stratosphere. Consequently, wave energy disperses only in stratosphere where the sudden warming can take place. This

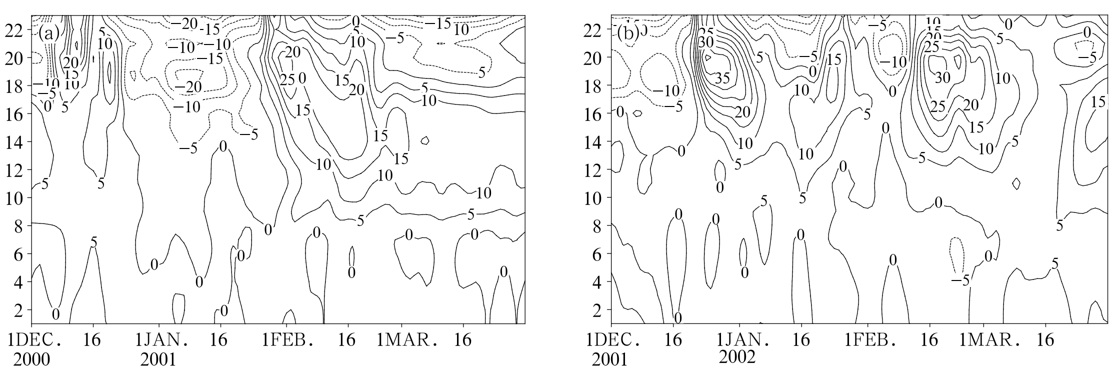

Fig.4. Altitude-time section of the deviation of averaged temperature along 80°N from 1 December 2000 to 31 March 2001(a) and from 1 December 2001 to 31 March 2002 (b) (Units: K).

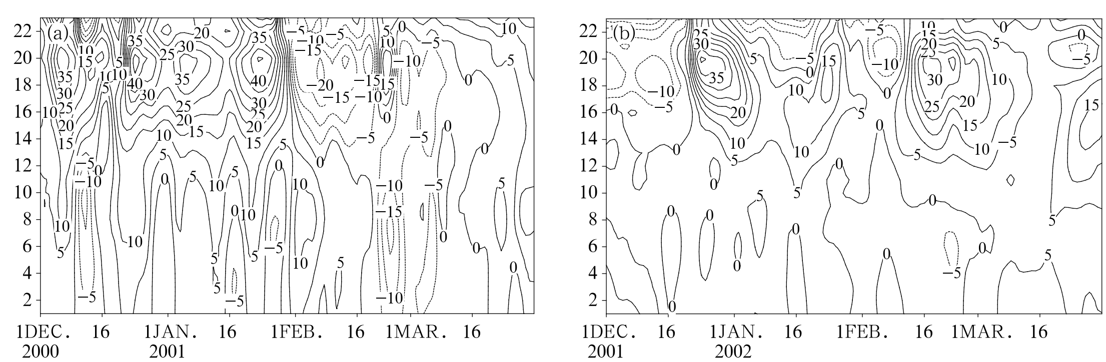

Fig.5. Altitude-time section of averaged zonal wind along 80°N from 1 December 2000 to 31 March 2001 (a) and 1 December 2001 to 31 March 2002 (b) (Units: m s^{-1}).

warming phenomenon intuitively represents a non-downward-propagating SSW. These indicate downward-propagating stratospheric warming in polar region have effect on both thermal state and dynamical state at low levels, for example, the change of zonal wind in upper troposphere (Figs.4a and 5a).

Commonly, as shown in Fig.6a, cold westerly wind vortex prevails in polar stratospheric region during winter-spring, and there is strong gradient of potential vorticity on isentropic surface in middle latitudes. Whereas in the process of downward-propagating stratospheric major warming, the IPV distribution at 850-K isentropic surface shown in Fig.6b, illustrates that a long and narrow high-value IPV "tongue" extends out from main polar vortex toward middle latitudes and mixes with low-value IPV. The Aleutian high in middle latitudes expands toward pole, which seems to swallow the gradient of IPV related to main polar vortex, and thus the gradient that maintains propagation of planet wave breaks out and the IPV "surf" zone comes into being in the region of small gradient. Consequently, planetary wave propagation breaks off with wave energy diffusing, which leads to warm in stratosphere. Furthermore, air of low-value IPV flows into polar region, with cold air sinking, and polar vortex departs from arctic pole. In order to maintain quasi-geostrophic and static balance, the temperature rises rapidly in polar region, and the SSW phenomena occur accordingly. The above IPV distribution feature of SSW illustrated in Fig.6c

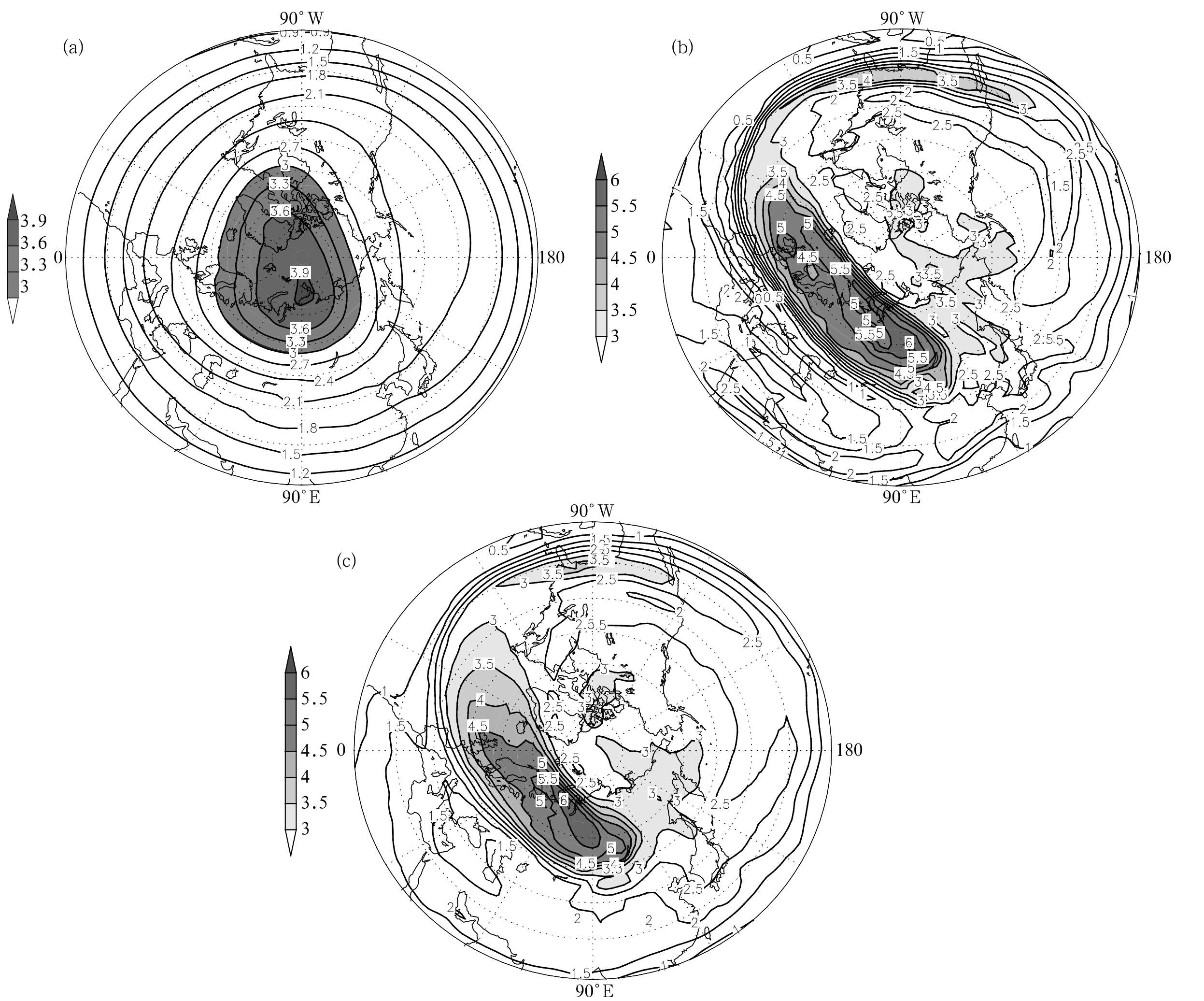

Fig.6. Potential vorticity field (20°-90°N) at 850-K isentropic surface, average of December-March from 1958 to 2001 (a), 11 February 2001 (b), and 31 December 2001 (c) (Unit: 10^{-4}km^2 kg^{-1}s^{-1}).

(31 December 2001) also reflected in the non-downward-propagating stratospheric warming event during the winter-spring of 2001-02. Compared with the downward-propagating stratospheric warming, the highest value of IPV is more near the pole, and the "tongue" is shorter than that during non-downward-propagating warming. That is one of important differences between the two categories of SSW.

5. Evolvement of polar vortex during warming events and impact at lower level

In the process of the SSW, the geopotential field in stratosphere becomes anomalous, and the most obvious change is the distortion or split of polar vortex. Therefore, the under levels circulation transforms in different degree, especially for blocking anomaly in middle latitudes and anomalous trough over North America and East Asia. But the evolution of polar vortex and mid-latitude circulation have difference between the two categories of stratospheric warming event. A detailed description for the development of polar vortex and mid-latitude circulation in stratosphere during the winter-spring SSW of 2000-01 and 2001-02 is given below.

To illustrate the development of polar vortex in stratosphere, Figs.7a-f show the change of geopotential field at 10 hPa during stratospheric warming from late January to March 2001. At the beginning of positive temperature anomaly in stratosphere, the large vortex around pole and the Aleutian high in middle latitudes are very clear in geopotential field on 24 January (Fig.7a), which is the so-called "Wave 1" type, and this status lasts to 29 January (Fig.7b). With the warming proceeding, the Aleutian high starts extending toward high latitudes and squeezes polar vortex, so the polar vortex distorts (usually becomes longer and narrower) and the center of vortex begins to depart from pole on 3 February (Fig.7c). Then with the high continually expanding and intruding polar vortex (Figs.7d, e), on 18 February (Fig.7f), the high completely pushes the Arctic low off pole and splits the polar vortex into two large cyclones in mid-high latitudes which correspond to the trough over North America and East Asia, accordingly, atmospheric circulation field in the Northern Hemisphere presents the so-called "Wave 2" type. These are important systems impacting the weather during winter-spring in the Northern Hemisphere. This is a recent example for the development of polar vortex during a downward propagating warming phenomenon, in the next, the evolution of polar vortex in the process of non-downward-propagating type will be analysed.

Figures 8a-d show the evolution of geopotential field at 10 hPa during stratospheric warming from late December 2001 to early January 2002. Before stratosphere atmosphere began to warm, as shown in Fig.8a, polar vortex is very strong, and center of the vortex is below 282×10^3 m^2 s^{-2} on 15 December 2001. At the beginning of warming in stratosphere, the large polar vortex and the high in middle latitudes are obvious on 20 December (Fig.8b), and the status persisted for several days. The high enlarged and pushed the polar vortex, and the intensity of polar vortex is 286×10^3 m^2 s^{-2} on 26 December (Fig.8c). With the warming continuing, the polar vortex became longer and narrower and the center departed from the pole to Iceland on 1 January 2002 (Fig.8d), and the center geopotential reached 288×10^3 m^2 s^{-2}. As a whole, the change of geopotential fields, especially the change of polar vortex in this event was not stronger than that in course of the downward-propagating warming shown in Fig.7. The high in middle latitudes only pushed the Arctic low and the polar vortex only distorted and moved southward a little, which cannot lead to polar vortex breakdown, and in the whole warming event the circulation field in the Northern Hemisphere presents "Wave 1" type. This is a significant difference between the two categories of stratospheric warming events. During the two warmings, geopotential fields may evolve similarly at 50 hPa, but the changes are not greater than that at 10 hPa (figures omitted).

As a result of the strong interaction between stratosphere and troposphere, especially in the period of SSW, the development of tropospheric blocking may markedly destroy polar vortex in low stratosphere. Quiroz (1986) and Li et al. (1990) studied the association between stratospheric warming and tropospheric blocking from different aspects. The evolution of geopotential fields and polar vortex and geopotential height in lower levels during the categories of SSW in winter-spring of 2000-01 and 2001-02 are discussed infra.

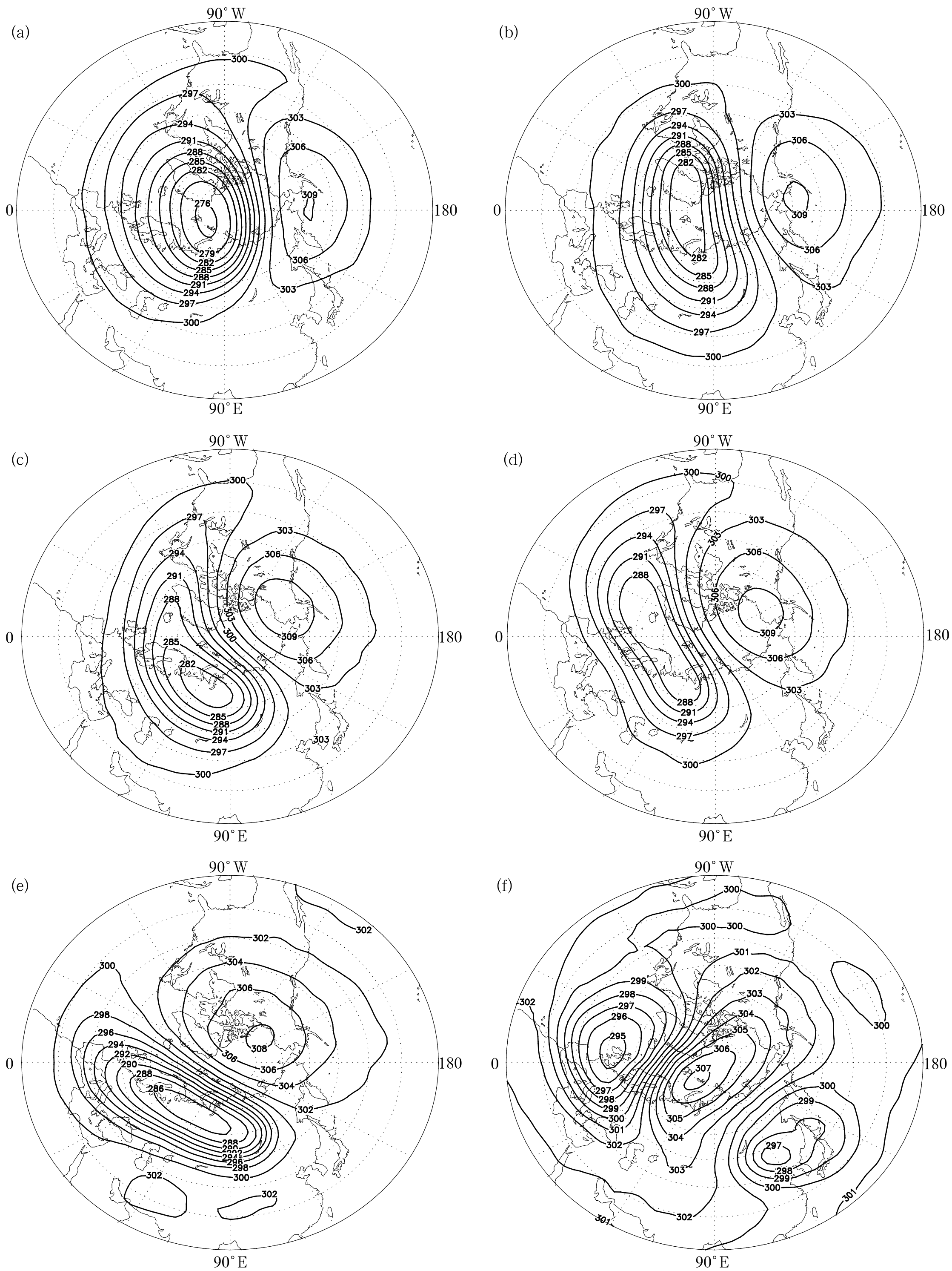

Fig.7. Geopotential (20°-90°N) at 10 hPa on 24 (a), 29 (b) January, 3 (c), 8 (d), 13 (e), and 18 (f) February 2001 (Unit: 10^3 m^2 s^{-2}).

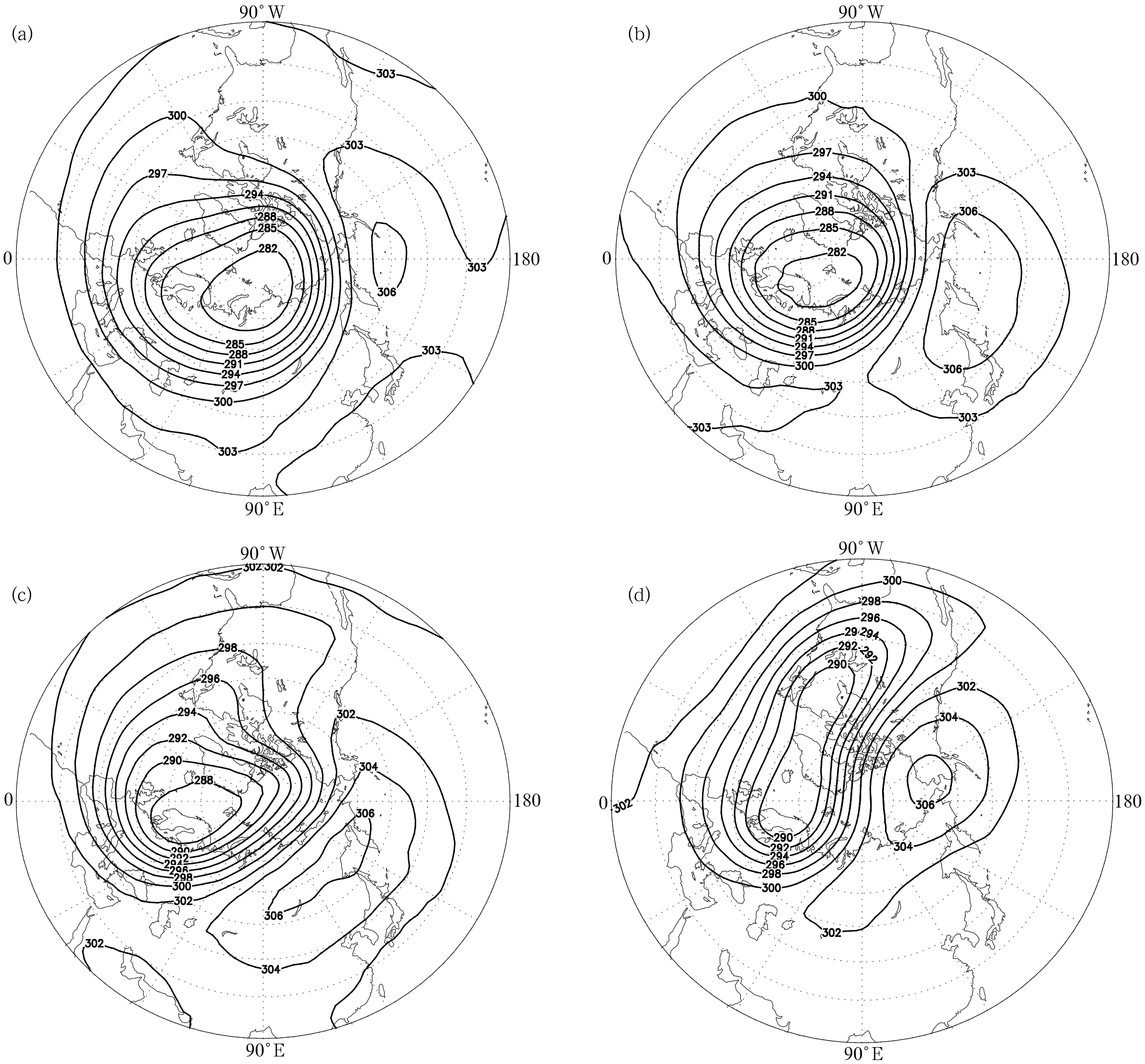

Fig.8. As in Fig.7, but for 15 (a), 20 (b), 26 (c) December 2001, and 1 January 2002 (d).

To illustrate the development of polar vortex in troposphere, Figs.9a-f show the changes of geopotential fields at 200 hPa during winter-spring of 2000-01. Before the stratosphere began to warm, there was only one center of polar vortex in geopotential field on 24 January (Fig.9a), and the center (its geopotential was below 106×10^3 m^2 s^{-2}) located near 85°N. This is usually so-called "circumpolar type" polar vortex. After the beginning of positive anomaly for temperature in stratospheric polar region, the polar vortex split into two centers on 1 February (Fig.9b). One center is located in North Asia, the other is situated over Canada, which may be so-called "dipole types". Here, the North Pacific high and the North Atlantic high existed in middle latitudes, and the circulation presents "Wave 2" type. With stratospheric warming downward-propagating continuously, polar vortex still behaved "dipole type" on 8 February (Fig.9c), and the only change was the evolution of centers. Hereafter, Alaska high gradually strengthened and blocking developed. As shown in Fig.9d, polar vortex further broke up on 14 February: the center in North Asia distorted largely, almost split into two centers at 200 hPa, and the three centers of vortex nearly appeared in the Northern Hemisphere. With the warming development, three centers entirely emerged on 22 February (Fig.9e), which may be called "multipolar type" polar vortex. The three centers are respectively located in

Northeast Asia, North America, and North Siberia, and the intensity also weakened to 108×10^3 m^2 s^{-2}. After several days there were four different centers of polar vortex on 28 February (Fig.9f).

Moreover, before stratospheric atmosphere remarkably warmed, the blocking occurred at 500 hPa

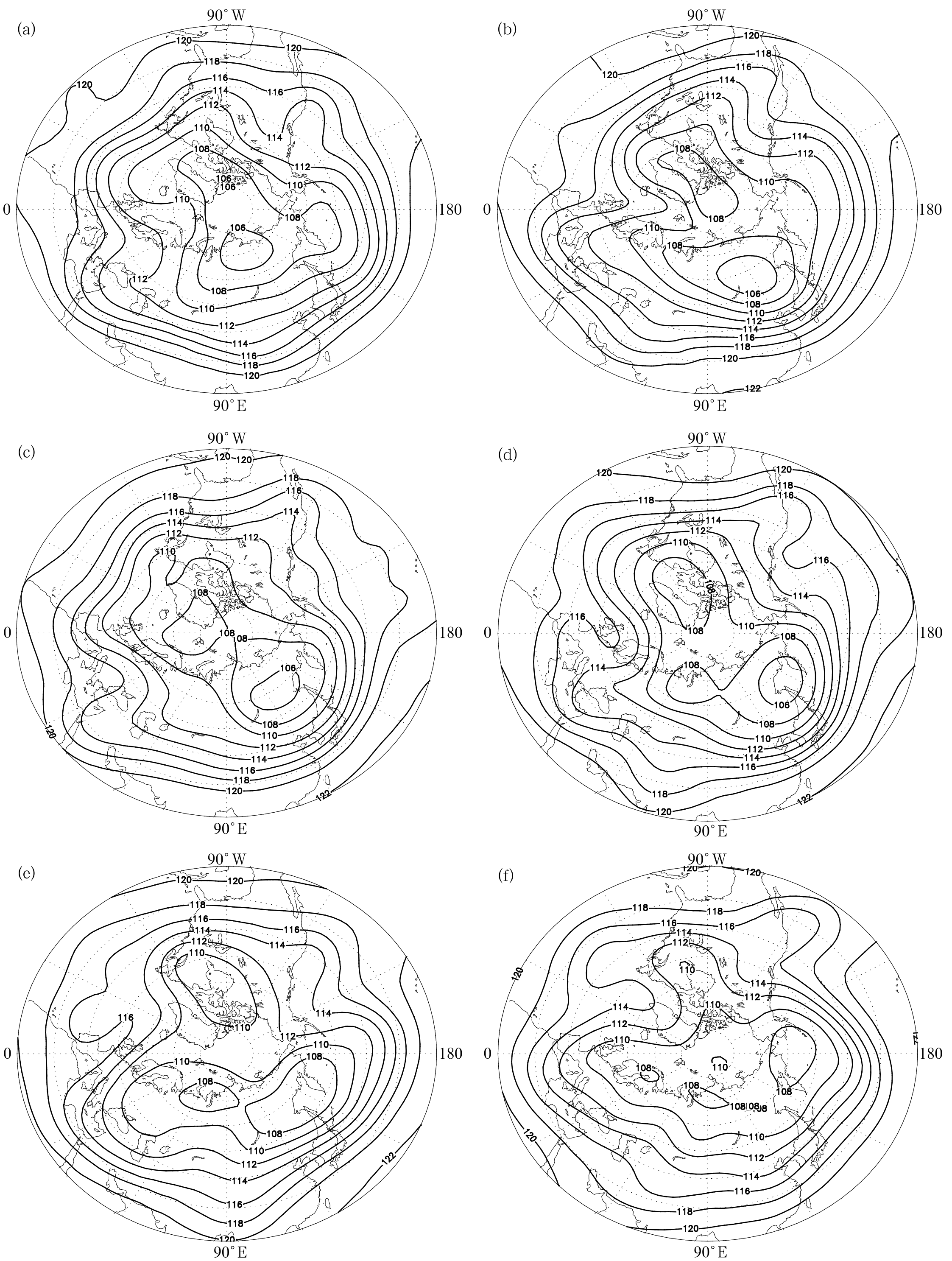

Fig.9. Geopotential (20°-90°N) at 200 hPa on 24 January (a), 1 (b), 8 (c), 14 (d), 22 (e), and 28 (f) February 2001 (Unit: 10^3 m^2 s^{-2}).

(figure omitted), which agrees with the statistical relation between blocking in troposphere and warming in stratosphere (Quiroz, 1986). The circulation and polar vortex at 500 hPa change to a great extent during the SSW, and usually both of them go with high or blocking in latitudes intruding into high latitudes and polar vortex shifting or breaking.

From the above evolvement of geopotential fields, it is found that the circulation and polar vortex anomalies at 10 hPa take place behind the anomalies at 200 and 500 hPa, which means stratosphere may indicate troposphere, and it is one of the most important characters in downward-propagating stratospheric warming. The above view agrees with some recent scientists' (Baldwin et al., 2003). Troposphere influences stratosphere mainly through atmospheric waves that propagate upward, and the stratosphere organizes this chaotic wave forcing from below to create long-lived changes in the stratospheric circulation. These stratospheric changes can feed back to affect weather and climate in the troposphere (Baldwin et al., 2003). Baldwin and Dunkerton (2001) suggested that stratospheric harbingers may be used as a predictor of tropospheric weather regimes, and show that large variations in the stratospheric circulation, appearing first above 50 km, descend to the lowermost stratosphere and are followed by anomalous tropospheric weather regimes.

The changes of circulation in troposphere during the non-downward-propagating stratospheric warming from late December 2001 to early January 2002 (Figs.10a-f) were weaker than that during downward warming (Figs.9a-f), but the geopotential fields and polar vortex at 200 hPa undergo changing in different degree. For example, before warming, a blocking persisted anomaly near Britannia and polar vortex appeared "circumpolar type" or "eccentricity type" at 200 hPa around 13 December (Fig.10a). Polar vortex was very strong, whose center low was under 106×10^3 m^2 s^{-2}. After stratospheric warming beginning, polar vortex distorted a little, and its center moved to New Siberia Isle on 19 December (Fig.10b). With warming continuing, the Atlantic high extended northward and the polar vortex became long and narrow, even "dipole type" polar vortex appeared around 22 December (Fig.10c), and the two centers located near New Siberia Isle and west of Newland Island. As a result of the high in mid-high latitudes expanding and moving, the intensity of polar vortex declined on 27 December (Fig.10b), and the center geopotential reached 108×10^3 m^2 s^{-2}. Along with non-downward propagating warming, polar vortex distorted and moved remarkably and became weaker, longer, and narrower on 3 January 2002 (Fig.10e). After the end of warming (8 January, shown in Fig.10f), the intensity of polar vortex returned 106×10^3 m^2 s^{-2}. Thus it can be seen that during the whole non-downward-propagating stratospheric warming, the polar vortex at 200 hPa only distorts, moves, and sometimes splits infirmly, and no anomalous circulation system emerges. The degree of circulation anomaly is weaker than that in downward-propagating warming events. Before the non-downward propagating stratospheric warming began, the blocking also persisted anomaly at 500 hPa (figure omitted), which also manifested the close association between tropospheric blocking and the SSW.

According to the above analysis, it is known that troposphere circulation and polar vortex evolve in different degree during the two categories of stratospheric warming, and usually both of them go with blocking, but the above evolution in the downward-propagating warming is more distinct.

6. Conclusions and discussions

In this study, firstly, invoking 45-yr daily ECMWF reanalysis data, the SSW are newly defined, and all the SSW events in 45-yr are picked out and divided into the above two categories: downward and non-downward propagating stratospheric warming. Then, by virtue of IPV, temperature fields, and zonal wind fields, a detailed description of the SSW occurring during the winter-spring of 2000-01 and 2001-02 is given. Finally, the evolution of polar vortex and circulation in the course of stratospheric warming and the impact of warming on troposphere are discussed. It is found that:

1) There are inter-annual and inter-decadal variations during stratospheric warming events. The frequency of downward-propagating SSW is very high from evening in the 1950s to metaphase in the 1960s, but the SSW events mostly belong to non-downward-propagating category from anaphase in the 1970s

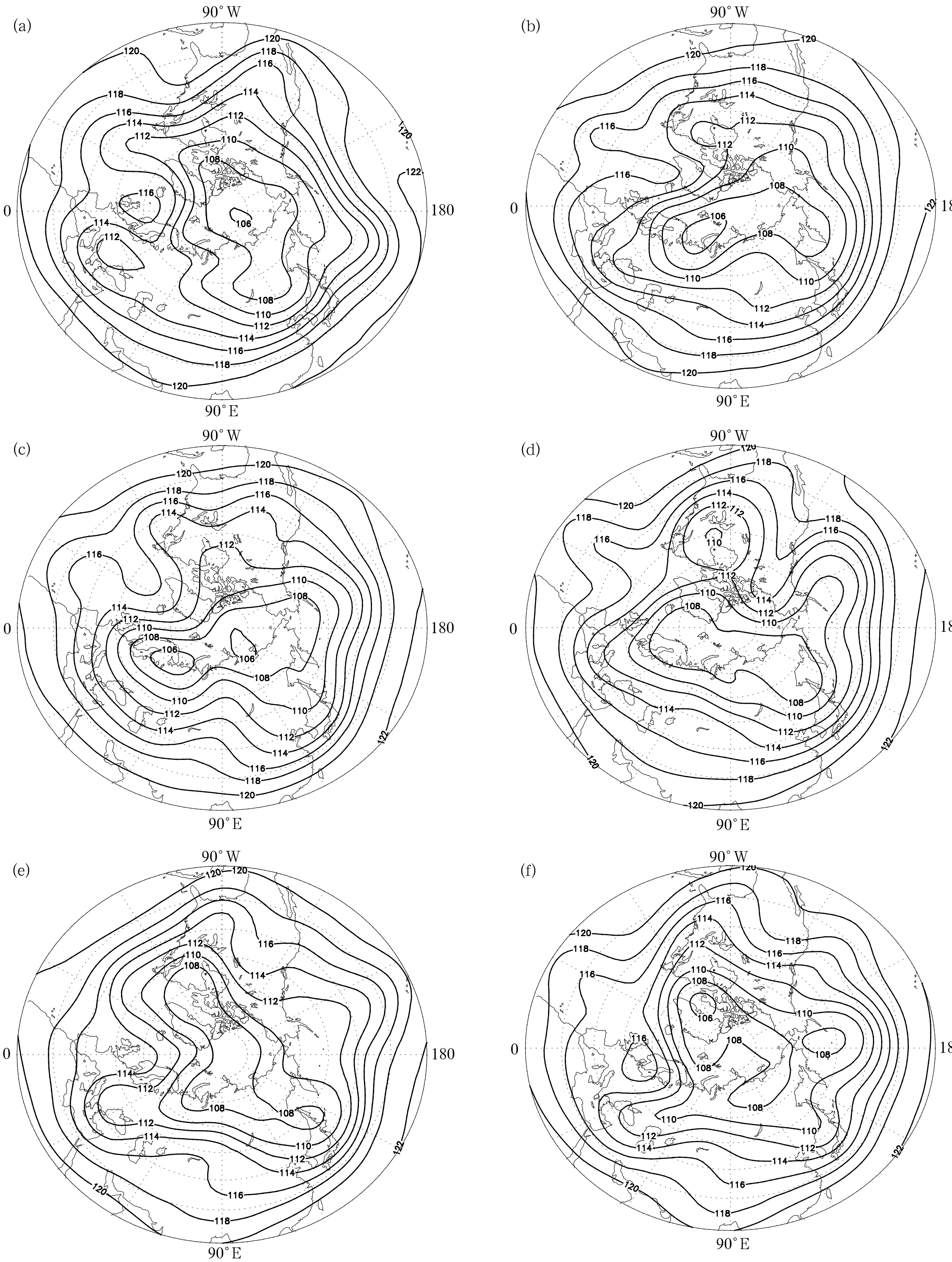

Fig.10. Geopotential (20°-90°N) at 200 hPa on 13 (a), 19 (b), 22 (c), 27 (d) December 2001, 3 February (e), and 8 (f) January 2002 (Unit: 10^3 m^2 s^{-2}).

to early stages in the 1980s. From middle to late 1990s, the SSW episodes mostly returned downward-propagating type, while non-downward-propagating category predominated in the 1990s.

2) The SSW event occurring from late January to early March in 2001 can propagate downward to troposphere, and there are zonal-mean easterly winds in both stratosphere and troposphere during this stratospheric warming event. But the two warming phenomena during December 2001 and March 2002 cannot propagate downward to troposphere, and zonal easterly winds only appear in stratosphere. In the process of warming, a long and narrow high-value IPV "tongue" extends out from main polar vortex and the Aleutian high in middle latitudes expand toward pole, which breaks the gradient of IPV. Thus, planetary wave breakup and its energy is diffused, which leads to warm in stratosphere. Compared with the non-downward-propagating stratospheric warming events, the highest value of IPV departs farther from pole and the "tongue" is longer and narrower during the downward-propagating warmings.

3) During the SSW, pinched by anticyclone, stratospheric polar vortex will shift, distort or split. By contrast, the change of polar vortex is greater in the course of downward-propagating warming. Also, tropospheric polar vortex also evolves in different degree, and usually both of them go with blocking, but the evolvement in the process of downward-propagating warming event is more prominent.

The mechanism of interaction between SSW and QBO, blocking, subtropical jet, etc. is not clear. In addition, the exchange between stratosphere and troposphere have important influence on SSW. All these problems may be researched further in future. It is also important to simulate SSW and the interaction between SSW and the other systems and to forecast SSW and its effect.

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