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Atmospheric tracers during the 2003–2004 stratospheric warming event and impact of ozone intrusions in the troposphere

Y. Liu[1], C. X. Liu[1,2], H. P. Wang[1,2], X. Tie[3], S. T. Gao[4], D. Kinnison[3], and G. Brasseur[3]

[1]Laboratory for the Middle Atmosphere and Global Environmental Observation (LAGEO), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
[2]Graduate University of the Chinese academy of Sciences, Beijing, China
[3]National Center of Atmospheric Research, Boulder, Colorado, USA
[4]Laboratory of Cloud-Precipitation Physics and Severe Storms (LACS), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

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Correspondence to: C. X. Liu (lcx@mail.iap.ac.cn)

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Abstract

We use the stratospheric/tropospheric chemical transport model MOZART-3 to study the distribution and transport of stratospheric O_3 during the exceptionally intense stratospheric sudden warming event observed in January 2004 in the Northern polar region. A comparison between observations by the MIPAS instrument on board the ENVISAT spacecraft and model simulations shows that the evolution of the polar vortex and of planetary waves during the warming event plays an important role in controlling the spatial distribution of stratospheric ozone and the downward ozone flux in the lower stratospheric and upper tropospheric regions. Compared to the situation during the winter of 2002–2003, lower ozone concentrations were transported from the polar regions (polar vortex) to mid-latitudes, leading to exceptional large areas of low ozone concentrations outside the polar vortex and "low-ozone pockets" in the middle stratosphere. The unusually long-lasting stratospheric westward winds (easterlies) during the 2003–2004 event greatly restricted the upward propagation of planetary waves, causing the weak transport of ozone-rich air originated from low latitudes to the middle polar stratosphere (10 hPa). The restricted wave activities led to a reduced downward ozone flux from the lower stratosphere (LS) to the upper troposphere (UT), especially in East Asia. Consequently, in this region during wintertime (December and January), the column ozone between 100 and 300 hPa was about 10% lower during the 2003–2004 event compared to the situation in 2002–2003.

1 Introduction

One of the most prominent phenomena observed in the winter stratosphere is the development of stratospheric sudden warming (SSW) (Scherhag, 1952). These large disturbances are the consequence of the interactions between vertically propagating planetary waves and the zonal winds (Matsuno, 1971; Holton, 1976). Planetary wave activity is best described through the Eliassen-Palm (EP) flux and its divergence

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(Edmon et al., 1980). The divergence of EP flux, which is related to the northward eddy flux of quasi-geostropic potential vorticity, provides a measure of the momentum provided by the eddies to the mean flow as a result of planetary wave breaking. When the polar vortex is disturbed by the breaking of such waves (Baldwin and Holton, 1988), filaments of high potential vorticity air are stripped off the edge of the main vortex, and are gradually mixed with the surrounding low PV air (McIntyre and Palmer, 1983, 1984).

Disturbed polar vortex and major warming events are usually associated with the negative phase of the Arctic Oscillation (AO) (Thompson and Wallace, 1998), which provides a measure of the coupling between the stratosphere and the troposphere (Baldwin and Dunkerton, 1999). In summary, the stratosphere can be regarded as a recipient of energy and waves from the underlying troposphere, and as a modulator that organizes chaotic waves forcing from below and generate feedbacks by influencing the troposphere (Baldwin et al., 2003).

The interactions between the stratosphere and troposphere do not involve only dynamical processes, but also include radiative and chemical processes. Stratospheric ozone, although dynamically dominated in the lower stratosphere, strongly affects the coupled chemical, radiative, and dynamical interactions in the upper troposphere and the lower stratosphere (UTLS). This coupling has a strong influence on temperature, circulation (Ramanathan, 1977), radiative transfer (Ramanathan et al., 1976; Ramanathan and Dickinson, 1979), and chemical concentrations (Tie and Brasseur, 1995). In addition, stratospheric ozone, which has been thought for a long time to be the major source of tropospheric ozone (Junge, 1962; Danielson, 1968), is now known to contribute globally to 20%~50% of ozone below the tropospause (Follows and Austin, 1992; Roelofs and Lelieveld, 1997; Tie and Hess, 1997; Lelieveld and Dentener, 2000).

Large scale transport and cross-tropopause exchange of ozone is dominated by the Brewer-Dobson circulation (Brewer, 1949; Dobson, 1956), which comprises a two-cell structure in the lower stratosphere, with upwelling in the tropics and subsidence at middle and high latitudes, and a single mean meridional cell from the tropics into the winter hemisphere at higher altitudes (Plumb, 2002). According to the "downward control" principle (Haynes and McIntyre, 1987; Haynes et al., 1991), this poleward "extratropical pump" is driven by irreversible deposition of angular momentum caused by the breaking of upward propagating waves, together with some other eddy dissipation effects (Holton et al., 1995). However, according to Chen (1995), the vertical flux associated with this eddy-driven diabatic circulation should be regarded as the mass flux between the overworld and the middleworld (Hoskins, 1991), rather than that between the stratosphere and troposphere. Chen (1995) also suggests that the strong downward flux across the 100 hPa level in the extratropical lower stratosphere (LS) of the northern winter (DJF) (Holton, 1990; Rosenlof and Holton, 1993) can be interpreted as the mass being transported downward from the overworld into the middleworld. Analyses of the isentropic cross-tropopause ozone transport using SAGE II observations (Wang et al., 1998) suggests that the winter buildup of ozone-rich air in the extratropical middleworld, between the isentropic surfaces of 330 K and 380 K, should be attributed primarily to the wave-driven diabatic mass circulation during fall-winter-spring seasons, rather than to transport along isentropic surfaces. At least, it appears to be strong connection between the activity of upward planetary waves and the wintertime ozone distributions (Fusco and Salby, 1999; Salby and Callaghan, 2007).

The upper troposphere and lower stratosphere region, which is a transition zone between the convectively dominated troposphere and the stably stratified stratosphere, is an important passage for the upward propagation of tropospheric waves and the exchange of chemical tracers of distinct origins. The knowledge of wave process and mass flux in the UT/LS region is critical to our understanding of the stratosphere-troposphere couplings, especially in winter. Stratospheric sudden warmings (SSW) are usually associated with significant changes in the general circulation in middle atmosphere, which induces a redistribution of the stratospheric air and trace gases (Manney et al., 1993; Manney et al., 1994). Moreover, the anomalous amplitude of upward wave activities associated with the SSW events may, to some extent, affect the vertical flux at the UT/LS region.

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After the unprecedented 2002 major stratospheric warming event that took place in Antarctica (Hoppel et al., 2003), the boreal winter has witnessed another remarkable major stratospheric warming in January 2004 (Manney et al., 2005). This event was further complicated by the occurrence of an energetic particle precipitation (EPP) event (Randall et al., 2005). In order to avoid the potential influence of this EPP event in our data analysis, only the ozone variations in the middle and lower stratosphere will be considered here. The downward ozone flux in the UT/LS region will be derived from a simulation made with a detailed chemical transport model (CTM) driven by analyzed winds and temperature.

This paper is organized in the following way. Section 2 introduces the model used in the present study, and the satellite ozone data used in our analysis. A brief description of the basic characteristics of the 2003–2004 SSW event and of another SSW that occurred during 2002–2003 boreal winter are presented in Sect. 3. The impacts of the two SSW events on the distribution of stratospheric nitrous oxide (N_2O) and ozone (O_3) are compared in Sect. 4. Section 5 analyzes the UT/LS ozone flux as derived for both winters and their effect on the upper tropospheric ozone column over East Asia. In Sect. 6, a summary of the major findings is provided.

2 Model and data description

2.1 MOZART model

In this study, we use the middle atmospheric version of the three-dimensional Model for Ozone And Related chemical Tracers, version 3 (MOZART-3), which is an extension to the middle atmosphere of its former tropospheric versions (Brasseur et al., 1998; Hauglustaine et al., 1998; Horowitz et al., 2003). This new version of MOZART (Kinnison et al., 2007) accounts for chemical processes from the Earth's surface to the lower thermosphere. This model includes not only a representation of advection, convective transport, boundary layer mixing, and dry/wet deposition, but also physical and chemical processes specific for the middle atmosphere, including vertical mixing associated with gravity wave breaking in the upper stratosphere and mesosphere, molecular diffusion of constituents above 80 km, photochemical reactions associated with halogen compounds, stratospheric heterogeneous processes involving sulfate aerosols and polar stratospheric clouds, photolysis at short wavelengths (>120 nm) and auroral contribution to the chemical budget. This extended version of MOZART is more suitable for representing chemical/physical processes in stratosphere and for quantifying ozone fluxes from the stratosphere to the troposphere (Kinnison et al., 2007). The adopted boundary conditions, including the surface emissions, the NO_x and CO emissions from aircraft and the NO_x source associated with lightning are described in previous studies (Horowitz et al., 2003; Gettelman et al., 2004; Park et al., 2004).

MOZART-3, like other off-line chemical-transport models, can be run at any reasonable time steps and spatial resolution. In this study, the adopted model configuration includes 64 Gaussian grid cells in latitude and 128 equidistant in longitude, which represents a horizontal resolution of approximately 2.8° in both latitude and longitude. The model is driven with dynamical quantities taken from the ECMWF operational analysis performed every 6 h. The simulation starts on 1 December 2003 and proceeds until 15 February 2004.

In order to highlight the specific impact of the 2003–2004 SSW event on the distribution of stratospheric ozone distribution, an experiment for another less intense warming event that took place in January 2003 is also performed. In this case, the simulation extends from 1 December 2002 to 15 February 2003. In both the experiments, the same initial conditions are used for the distribution of chemical concentrations.

2.2 MIPAS observation

MIPAS (Michelson Interferometer for Passive Atmospheric Sounding) is a limb-scanning Fourier infrared spectrometer on board the European Environmental Satellite (ENVISAT); more detailed characteristics regarding the measurements by this space-borne instrument are given by Carli et al. (2004) and Raspollini et al. (2006). The sun-synchronous polar orbit provides a global coverage with nearly 14 orbits per day at a horizontal resolution of approximately 500 km. More than 20 trace constituents are observed in the upper troposphere and in the stratosphere.

Currently, the MIPAS level-2 operational products are provided by the European Space Agency (ESA). These products include the temperature, and the concentrations of H_2O, CH_4, N_2O, O_3, HNO_3 and NO_2. In its original nominal measurement mode, MIPAS scanned the Earth limb at 17 tangent altitudes of 6, 9, . . . , 39, 42, 47, 52, 60, and 68 km. The vertical resolution is 3 km for the 13 lowermost tangent altitudes and increases to 8 km at the upper end of the limb scan. The retrieved products have been validated by Cortesi et al. (2007) and Ridolfi et al. (2007). In this study, the retrieved O_3, N_2O and temperature profiles are used and re-gridded onto 73×72 (about 2.5×5°) horizontal grid meshes.

3 The characteristics of the remarkable 2003–2004 SSW event

Manney et al. (2005) have summarized the most prominent characteristics of the 2003–2004 SSW event during the boreal winter. Their analysis shows that this event was characterized by an extraordinarily long vortex disruption in the lower and middle stratosphere, with a strong and rapid recovery of the vortex in the upper stratosphere. There is also indication that the progression of the warming from the upper to the lower stratosphere was slow.

An analysis of the MIPAS temperatures from 60° N to the North Pole shows that during the SSW event, a warming signal occurred as early as mid-December and propagated downward throughout the whole stratosphere with a rapid recovery in the upper stratosphere and an extraordinarily long persistent warming in the lower stratosphere (upper panel in Fig. 1). By contrast, the warming event observed in January 2003 was characterized by a similar winter warming near the stratopause but the warming signal remained in the upper and middle stratosphere during most of the winter. Several small and shallow downward intrusions, however, were observed after January 2003 (lower panel in Fig. 1). The major differences between the two events are highlighted by the white circles appearing in Fig. 1. During the 2003–2004 event, the zonal-mean zonal wind exhibited a prolonged reversal at high latitudes near 10 hPa between January and mid-February, while during the 2002–2003 event, the wind reversal occurred only during a few days in January 2003 (in Fig. 2).

The main differences between the two warming events can be summarized as follows: (1) The warming during the 2003–2004 winter was more pronounced in the lower stratosphere. (2) The easterly winds lasted to a considerably longer time period in the case of the 2003–2004 SSW.

4 Impacts of SSW events on stratospheric N_2O and O_3

Stratospheric warming events affect considerably the stratospheric circulation pattern as well as the mean meridional transport of chemical tracers. In order to exclusively consider the dynamical effect of the 2003–2004 SSW on the distribution of atmospheric constituents, the vertical and horizontal distributions of relatively inert nitrous oxide are compared with the distributions of ozone. Meanwhile, the same method is applied to the more "typical" 2002–2003 SSW event, so that the impacts of the two warning events on stratospheric chemistry can be differentiated.

The energetic particle precipitation event from late October and early November 2003 had important effects on upper stratospheric ozone (Randall et al., 2005). To focus our study on the SSW events, we analyze the relative ozone distribution on the 10 hPa surface. The MOZART simulation, which does not consider any EPP mechanism, is compared with the MIPAS observation.

4.1 The vertical distributions of zonal mean N_2O and O_3

Figures 3 to 6 compare the observed and calculated meridional cross-sections of the zonal mean N_2O and O_3 concentrations for the two successes winters under consideration. In these figures, the polar vortex is represented by the modified PV contours (solid lines). The definition of the modified PV (referenced to the 475 K potential temperature level) is provided by Lait (1994).

In Figs. 3 and 4, the observed vertical decrease in the distribution of stratospheric N_2O is represented realistically. The calculated N_2O concentrations are low inside of the polar vortex, highlighting a high correlation between the N_2O concentration and the position of the polar vortex in the middle stratosphere. Moreover, before the occurrence of the SSW, the vortices are stable throughout the middle stratosphere. For example, on 15 December 2003 (see Fig. 3a, b) and on 19 December 2002 (see Fig. 4a, b), the vortex is strong, and the N_2O concentrations are lower inside the stable vortex. A sharp horizontal gradient is observed near the edge of the vortex in both the MIPAS observations and the MOZART-3 simulation. Starting in January, the SSW events have strong impacts on the distribution of stratospheric tracers. However, the effects on the stratospheric constituents are very different in both cases. On 7 January 2004 the strength of the warming reaches a maximum: the vortex becomes unstable and starts to split. The center of the vortex is displaced from the pole, and reaches the latitude of 60° N. As a result, only a shallow trough remains in the zonal mean N_2O concentrations (Fig. 3c, d). By contrast, on 18 January 2003, even though the middle stratosphere vortex is disturbed and moves away from the pole, the vortex in the lower stratosphere remains stable and is located at the pole. As a result, the N_2O concentrations are low in the Arctic region of the lower stratosphere (see Fig. 4c, d). The intrusion of high N_2O concentrations into the polar region in the middle stratosphere occurs through the tongues of N_2O-rich air of mid-latitude origin, which is consistent with previous MLS observations (Manney et al., 1994).

The simulated distribution of the zonal mean O_3 concentration is also generally consistent with the MIPAS observations (see Figs. 5 and 6). When the vortex is stable, the ozone-rich tongue that stretches from low latitudes to higher latitudes in the middle stratosphere (from about 24 km to 40 km), remains confined outside the polar vortex (as denoted by the modified PV contours). This is the case before the SSW events on

15 December 2003 (see Fig. 5a, b) and on 19 December 2002 (see Fig. 6a, b). During the 2003–2004 SSW (e.g. on 7 January 2004) a high ozone tongue reaches the polar region as a result of the strong planetary wave disturbance. As highlighted above, in the middle of January, the split vortex shifts away from the polar region, causing a fracture of the ozone tongue just at the location of the remaining vortex (see Fig. 5c, d). During the 2002–2003 SSW event (e.g. on 18 January 2003) the intrusion of the ozone tongue is also prohibited by the remnant vortex (see Fig. 6c, d). However, when compared with the 2003–2004 warming, the observed polar ozone concentrations in the middle stratosphere are obviously higher during the 2002–2003 winter (see Figs. 5c and 6c) than during preceding winter. This can be directly attributed to the EPP event (Randall et al., 2005). However, the concentration inside the poleward ozone tongue is higher in 2002–2003 than in 2003–2004 (see Figs. 5d and 6d). This is consistent with the MOZART-3 calculation, which, however, does not account for any EPP mechanism. Thus, to some extent, these differences in ozone distributions should also result from the differences in the stratospheric dynamics between the two events. More details are provided in Sect. 5.

4.2 The horizontal distribution of N_2O and O_3 on 10 hPa

The distributions of nitrous oxide and ozone derived from MIPAS retrievals and calculated by MOZART-3 on the 10 hPa surface for the 2002–2003 and 2003–2004 warming events are shown in Figs. 7 to 10. The modified PV (MPV) contours which locate the polar vortex are also shown. Before the two major SSW events, the polar vortex and the corresponding low N_2O concentrations are located in the Arctic region with a small shift towards the North Atlantic and northern Europe. During the 2002–2003 SSW event, the polar vortex and the area with low N_2O concentrations at 10 hPa elongate after mid-January (see Fig. 8c, d). In the case of the 2003–2004 SSW event, the dynamical disturbance has significant impacts on the N_2O distribution in January. For example, on 10 January 2004 the already elongated vortex on the 10 hPa surface spilts in two parts and air mass with high N_2O concentrations originating from mid-latitudes reach the polar region (as in Fig. 7c, d). Moreover, there are differences between area of low N_2O concentrations and the location of polar vortex. The main area with low N_2O concentrations breaks into several small low concentration centers inside the remanent polar vortex. In addition, large areas of low N_2O concentrations are found outside the polar vortex. As a result, N_2O is further diluted as the warming event progresses.

Figures 9 and 10 show that the O_3 concentration on the 10 hPa surface is characterized by an evolution that is similar to that of N_2O. There are, however, differences in the behavior of the two chemical compounds: there is, for example, a low ozone center located over the North Pacific and/or North America, referred to as a "low-ozone pocket" by Manney et al. (1995). This feature is observed in the middle stratospheric anticyclone during both SSW events, and is explained by the dynamical isolation of air masses at high latitudes over time periods that are long enough for local photochemical equilibrium to be approached (Morris et al., 1998). These "low-ozone pockets" are most prominent during the 2003–2004 event (see Figs. 9a, b and 10a, b), which suggests that the strength of the stratospheric anticyclone was largest during the 2003–2004 winter. After the dissipation of the SSW disturbance, the "low-ozone pockets" are distorted by the intrusion of low-latitude air (see Figs. 9c, d and 10c, d).

As shown by the different figures, there is general consistency between the observed and simulated distributions of N_2O and O_3 concentrations. However, there are also differences in the magnitude of the concentrations of both compounds, which is attributed primarily to the fact that the initial conditions used in the MOZART model simulations did not result from an assimilation of satellite data.

5 Impacts of SSW on the UT/LS ozone flux over East Asia

As indicated above, SSW events have important impacts on ozone concentrations in the lower stratosphere. As a result, the mass exchange between the upper troposphere (UT) and the lower stratosphere (LS) could be affected by the intensity of the SSW with consequences for upper tropospheric ozone. In the following section, we analyze the ozone flux in the UT/LS region, with emphasis on the intrusion of stratospheric ozone in East Asia. The economical development in East Asia is very rapid, and results in significant perturbation on ozone concentrations. As a result, study the ozone flux in the UTLS region provides a better understanding for ozone budget in East Asia.

In order to compare the cross-tropopause exchange of 2003–2004 and 2002–2003 SSW, we first multiply the daily average vertical wind velocity (in Pa/s) by the ozone concentration (in ppmv) derived by MOZART-3 at 100 hPa. The resulting vertical ozone averaged fluxes for three periods (15 December to 4 January (period-1), 5 January to 25 January (period-2), and 26 January to 15 February (period-3)) on 100 hPa level are considered for this comparison.

There are similarities between the two events. For example, the patterns of the downward ozone fluxes at 100 hPa (see Fig. 11) are generally the same: the maximum centers of the downward ozone flux in the Northern Hemisphere are located in the Baikal area (East Asia) throughout the boreal winter for both years. This suggests that the intrusion of ozone from the stratosphere to the troposphere in East Asia contributed substantially to the global ozone budget during these two SSW winters. However, there are also marked differences between the two SSW events. During the 2003–2004 winter, the downward ozone flux over East Asia was weaker and shifted slightly to the south compared to the situation in 2002–2003. The southward shift may be associated with a more pronounced southward extension of the East Asia trough during the 2003–2004 winter, resulting in the lower downward ozone flux in 2003–2004 winter.

Previous studies show that the eddy heat flux is directly proportional to the wave activity that propagates from the troposphere into the stratosphere, and can be a proxy to represent the intensity of the Brewer-Dobson circulation (Fusco and Salby, 1999; Newman and Nash, 2000). The 21-day averaged zonal-mean eddy heat fluxes from period-1 to period-3 are also analyzed to evaluate the wave activity during the two SSW events. The results show that throughout the 2002–2003 winter the westerlies were favorable conditions for the persistent upward propagation of planetary waves (see Fig. 12a, c, e). By contrast, the 2003–2004 winter was characterized by an extraordinarily strong wave activity during period-1 that lead to a remarkable warming (see Fig. 12b). This event was followed by an abrupt decline in the wave amplitude during periods-2 and 3 (see Fig. 12d, f). This evolution of the winter dynamics was closely related to the emergence and persistence of easterly winds at high latitudes, which restricted the upward propagation of the tropospheric planetary wave, even though the waves at the 100 hPa geopotential height were still active. Table 1 provides quantitative values of the area-averaged (30–65° N, 80–180° E) eddy heat flux in East Asia at 100 hPa for both winters. The average value of the heat flux during the 2003–2004 SSW event (27 K*m/s) is approximately 70% larger than during the 2002–2003 event (16 K*m/s) for period-1. After the emergence of easterly winds at high latitudes, the average heat flux during the 2003–2004 event was reduced by nearly 20% (from 27 to 22 K*m/s) during periods 2 and 3. Meanwhile, the heat flux during the 2002–2003 event was characterized by 50% increase (from 16 to 24 K*m/s) during the same period of time, which thus surpasses the value of the heat flux at the same period during the 2003–2004 event. The reduced eddy heat flux and the limited propagation of planetary waves tends to weaken the so-called "extratropical pump" process (Holton et al., 1995), which produces the Brewer-Dobson circulation in the middle atmosphere. As a consequence, less ozone was transported poleward (see Figs. 5c, d and 6c, d) and downward into the extratropical troposphere region, which may have reduced the wintertime buildup of ozone in the middleworld (Wang et al., 1998).

Table 2 shows the increment of the area-averaged column ozone between 100 and 300 hPa in East Asia for both winters. During period-1, the storage of the ozone column is larger by 10 DU in the early winter of 2003–2004 compared to the situation in 2002–2003. This difference is related to the considerably stronger heat flux observed during the 2003–2004 event. After the emergence of stratospheric easterly winds, the wave activity during the 2003–2004 event declinedand the storage of ozone in the middleworld changed. For example, the averaged increment of column ozone was reduced by 80% (from 15 to 3 DU) during periods 2 and 3, which was equivalent to that calculated during the 2002–2003 event (3 DU). As on a regional scale, the magnitude of the ozone flux is not perfectly proportional to the eddy heat flux (since the storage of ozone is also associated with other factors such as the horizontal advection of UT/LS ozone), the column ozone did not increase as much as the eddy heat flux during periods 2 and 3 of the 2002–2003 event.

The average column ozone (between 100 and 300 hPa) during the 2003–2004 winter (December and January) over East Asia was approximately 10% lower than during the 2002–2003 winter.

6 Conclusions

This study analyzes the intense stratospheric sudden warming event that took place in the northern hemisphere during the winter of 2003–2004, and compared the behavior of nitrous oxide and ozone during this period with the situation resulting from the major warming of 2002–2003. The present study shows that both events had significant effects on the stratospheric dynamics and on the distribution of chemical tracers. Observations by ENVISAT/MIPAS and the chemical transport model MOZART-3 were used intensively in this study. The MOZART-3 simulations for the two winters provide distributions of ozone during the SSW events that are consistent with the ENVISAT/MIPAS observations. The observations and simulations indicate that:

1. Both major Arctic SSW events (2002–2003 and 2003–2004) have caused the weakening and distortion of the stratospheric polar vortex. The SSW of 2003–2004 had, however, a much more pronounced effect on the disturbance of the polar vortex, especially in the lower stratosphere. In addition, the extraordinarily long vortex disruption in the middle and lower stratosphere during the 2003–2004 event, which has caused the long-lasting wind reversal in the Arctic, has reduced the eddy heat flux and the upward propagation of planetary waves in the extratropical stratosphere. The restricted wave activity explains the rapid recovery of the upper stratospheric polar vortex and its exceptional stability during February and March 2004 (Manney et al., 2005).

2. The distributions of nitrous oxide and ozone in the middle stratosphere bear some resemblances. They are both dynamically dominated, and affected by the isolation of the polar vortex, when the vortex is stable. The so-called "low-ozone-pockets", which have been observed, are also found in the model simulations. After the occurrence of both SSW events, the polar vortex that contains low N_2O and O_3 concentrations is displaced from the pole. Meanwhile, tongues of low-latitude air with high N_2O and O_3 concentrations extend into the Arctic region. With the weakening of the polar vortices during warming events, the enhanced exchanges across the vortices edge lead to a large area of low N_2O and O_3 concentrations outside the distorted vortices. Compared with the 2002–2003 event, the SSW of 2003–2004 results in enhanced dilution of low N_2O and O_3 concentrations outside the polar vortex. The presence of "low-ozone pockets" is also more prominent during the 2003–2004 SSW winter. Moreover, the transport of O_3 and N_2O-rich air masses from the tropics is less pronounced during the 2003–2004 event due to the restricted planetary wave activity during this long-lasting warming event.

3. Planetary wave activity, especially during SSW events, facilitates the downward transport of ozone in the extratropical UT/LS region. However, during the 2003–2004 SSW event, the long-lasting easterly winds at high latitudes reduced the intrusion of ozone-rich masses from the lower stratosphere (LS) and the upper troposphere (UT), especially in East Asia. As a result, the ozone column between 100 and 300 hPa over East Asia was 10% lower during the 2003–2004 SSW than during the 2002–2003 winter.

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Table 1. Area-averaged 30°–65° N, 80°–180° E) eddy heat flux for East Asia calculated flux on the 100 hPa isobaric surface (K*m/s): the first column represents the average for period-1 (15 December–4 January); the second column is the average for period 2 and 3 (5 January–15 February).

	$[v'T']_{\text{former}}$	$[v'T']_{\text{latter}}$
2002–2003	16	24
2003–2004	27	22

Table 2. Increment of East Asia area-averaged (30°–65° N, 80°–180° E) column ozone (DU) derived between 100 and 300 hPa for different periods: the first column corresponds to the increment from period-0 (1–14 December) to period-1 (15 December–4 January); the second column is the increment from period-1 (15 December–4 January) to period-2 and period-3 (5 January–15 February).

	$\Delta[O_3]_{former}$	$\Delta[O_3]_{latter}$
2002–2003	5	3
2003–2004	15	3

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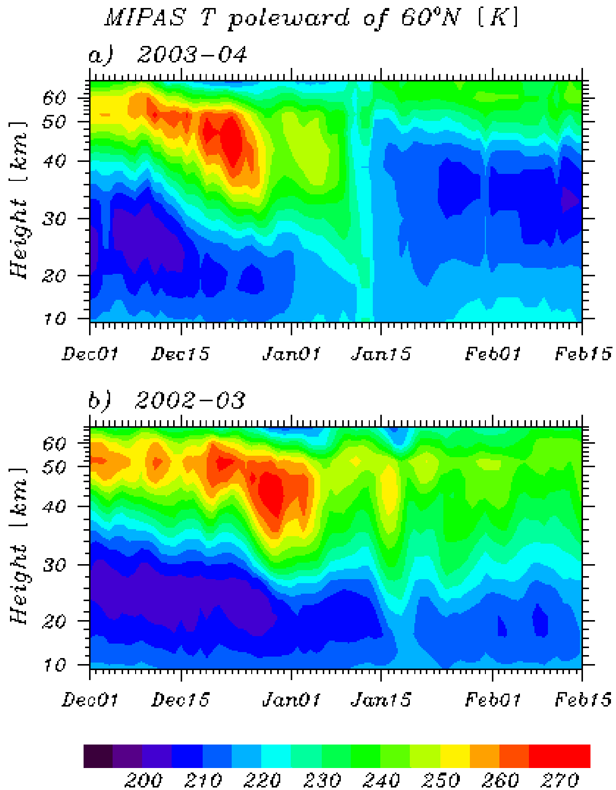

Fig. 1. Time evolution of MIPAS temperature (K) averaged from 60° N to the North Pole: **(a)** from 1 December 2003 to 15 February 2004 (upper panel); **(b)** from 1 December 2002 to 15 February 2003 (lower panel). The interval of the temperature contour lines is 4 K.

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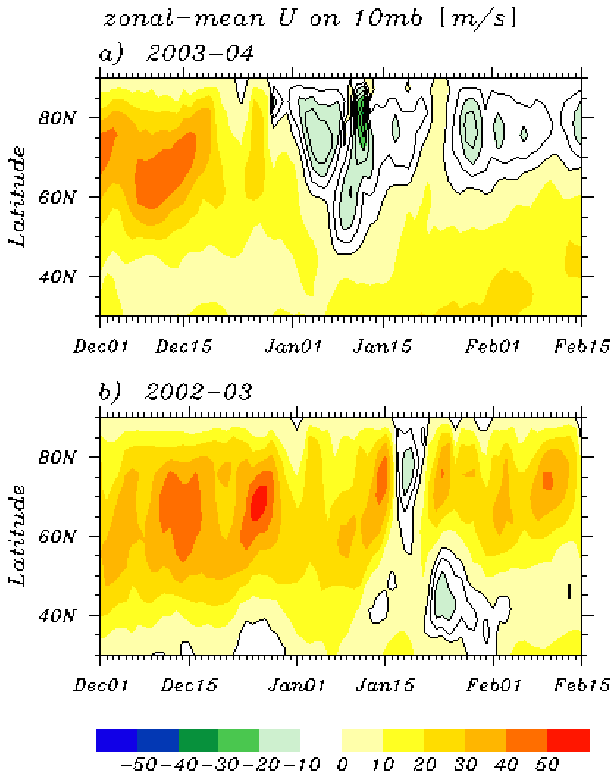

Fig. 2. Time evolution of the zonal-mean zonal wind at 10 hPa provided by ECMWF: **(a)** from 1 December 2003 to 15 February 2004; **(b)** from 1 December 2002 to 15 February 2003. Solid contour lines represent easterly winds. The interval of the wind contour lines is 10 m s^{-1}.

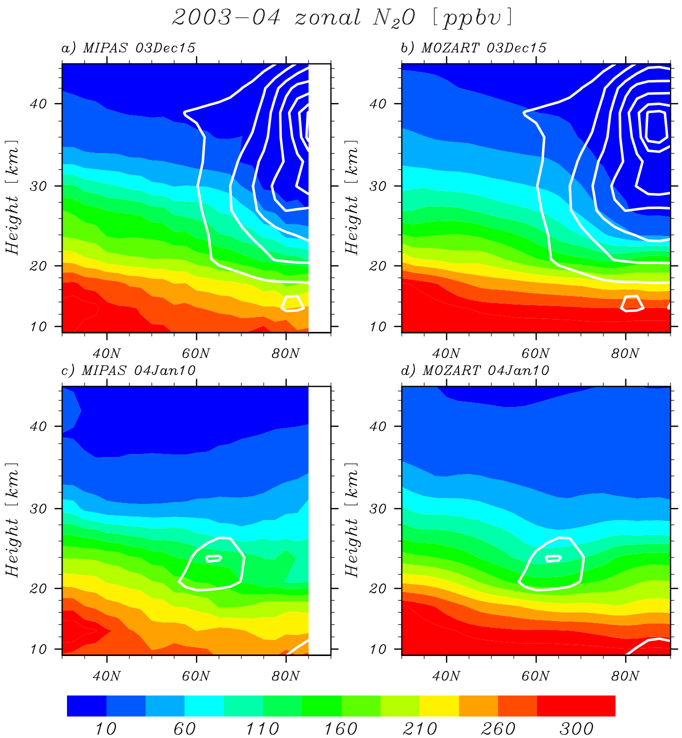

Fig. 3. Meridional cross-section of the zonal mean N_2O mixing ratio (ppbv) poleward of 30° N before and after the 2003–2004 SSW: **(a)** MIPAS N_2O on 15 December 2003; **(b)** MOZART N_2O on 15 December 2003; **(c)** MIPAS N_2O on 7 January 2004; **(d)** MOZART N_2O on 7 January 2004. The MPV contours larger than 35 MPVU are also shown by the solid lines with intervals of 10 MPVU [1 MPVU corresponds to $1 \times 10–6\,m\,2\,s^{-1}\,K\,kg^{-1}$].

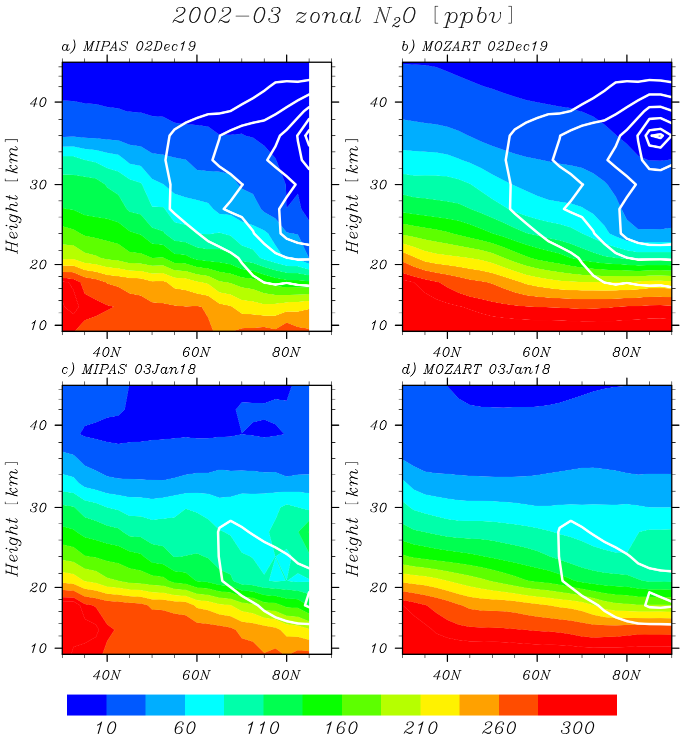

Fig. 4. Meridional cross-section of the zonal mean N_2O mixing ratio (ppbv) poleward of 30° N before and after the 2002–2003 SSW: **(a)** MIPAS N_2O on 19 December 2002; **(b)** MOZART N_2O on 19 December 2002; **(c)** MIPAS N_2O on 18 January 2003; **(d)** MOZART N_2O on 18 January 2003. The MPV contours larger than 35 MPVU are also shown by the solid lines with intervals of 10 MPVU.

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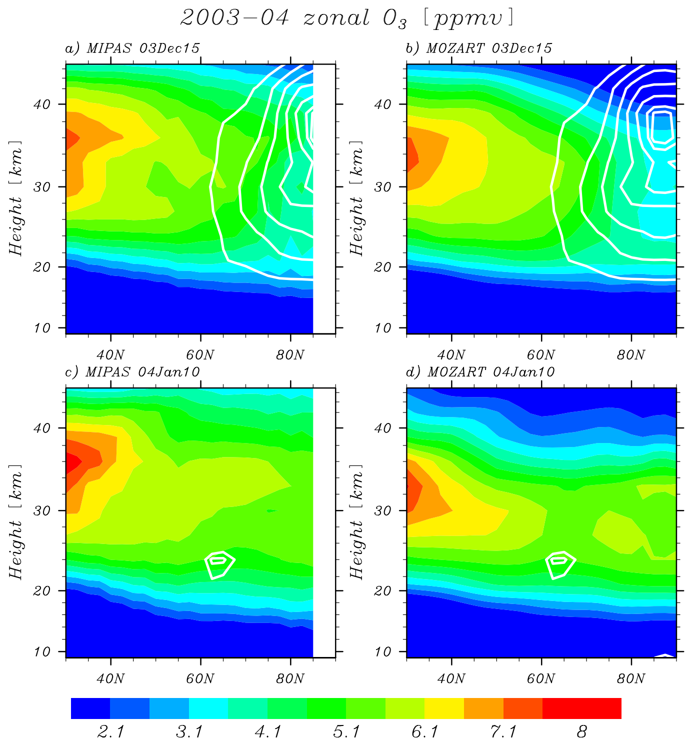

Fig. 5. Same as Fig. 3, but for the ozone mixing ratio (ppbv).

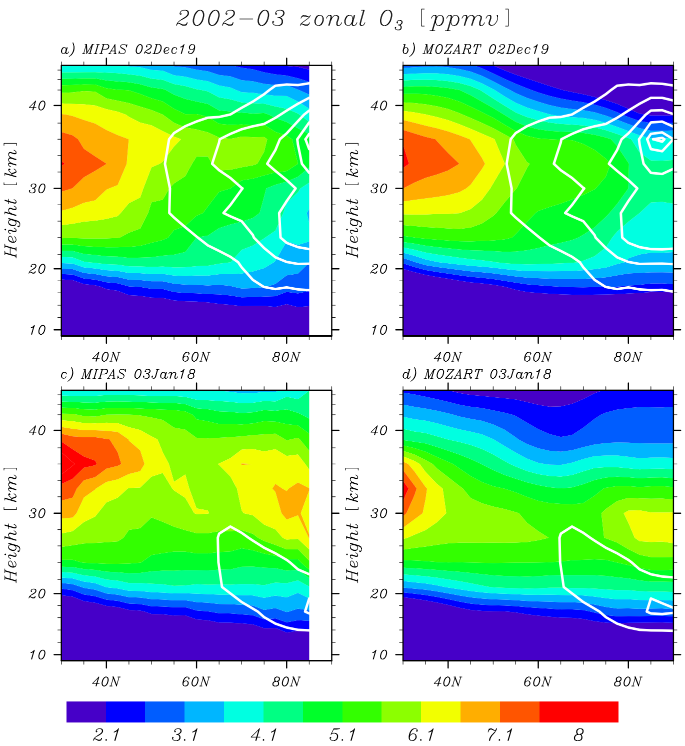

Fig. 6. Same as Fig. 4, but for the ozone mixing ratio (ppbv).

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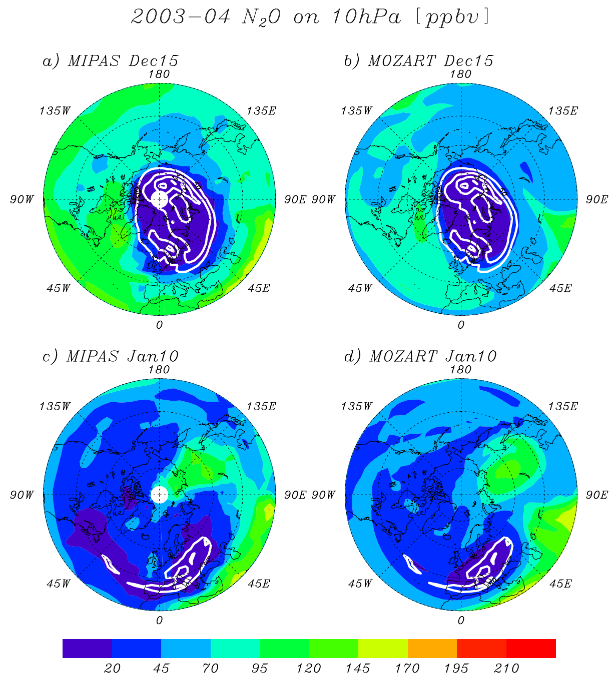

Fig. 7. Distribution of the N_2O mixing ratio (ppbv) on the 10 hPa isobaric surface poleward of 30° N before and after the 2003–2004 SSW: **(a)** MIPAS N_2O on 15 December 2003; **(b)** MOZART N_2O on 15 December 2003; **(c)** MIPAS N_2O on 10 January 2004; **(d)** MOZART N_2O on 10 January 2004. The MPV contours larger than 35 MPVU are also shown as the solid lines with the interval of 10 MPVU.

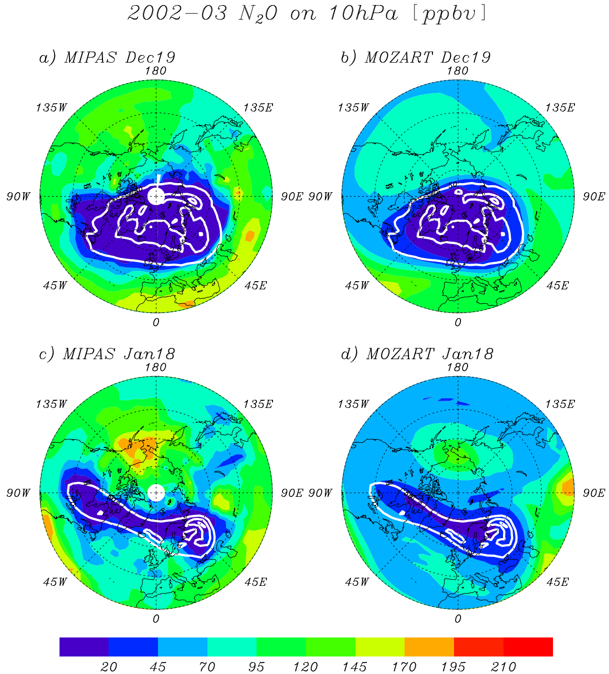

Fig. 8. Distribution of the N_2O mixing ratio (ppbv) on the 10 hPa isobaric surface poleward of 30° N before and after 2002–2003 SSW (unit: ppbv): **(a)** MIPAS N_2O on 19 December 2002; **(b)** MOZART N_2O on 19 December 2002; **(c)** MIPAS N_2O on 18 January 2003; **(d)** MOZART N_2O on 18 January 2003. The MPV contours larger than 35 MPVU are also shown as the solid lines with the interval of 10 MPVU.

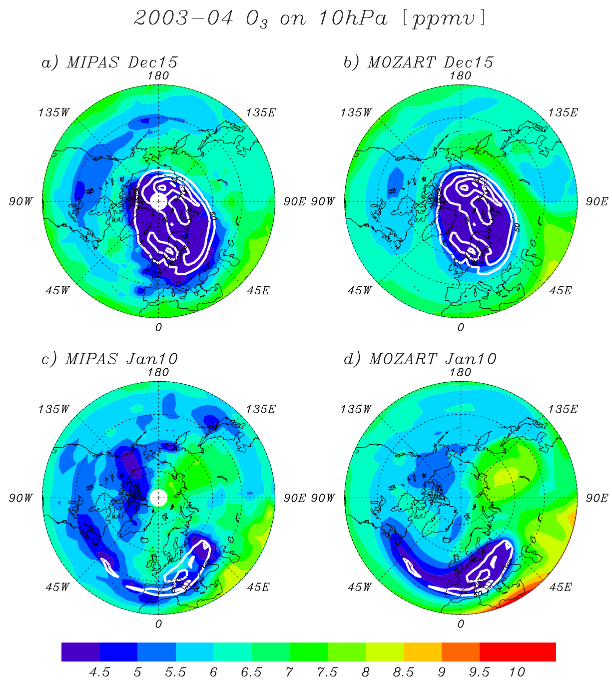

Fig. 9. Same as Fig. 7, but for the ozone mixing ratio (ppmv).

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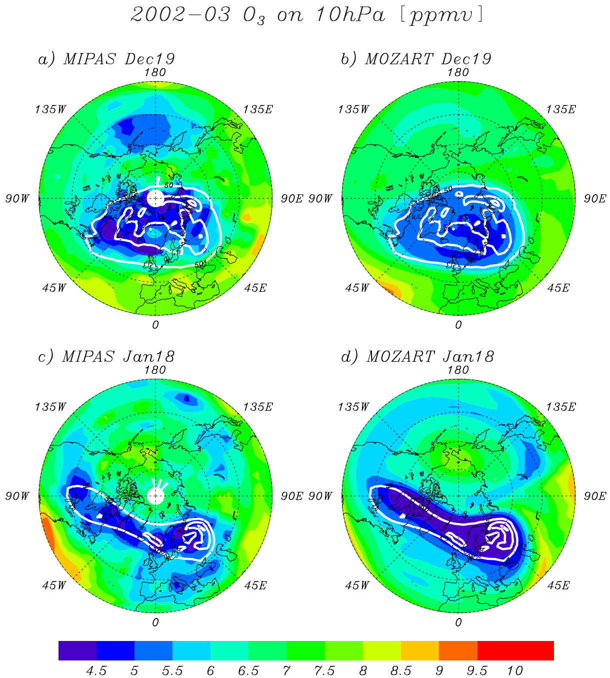

Fig. 10. Same as Fig. 8, but for the ozone mixing ratio (ppmv).

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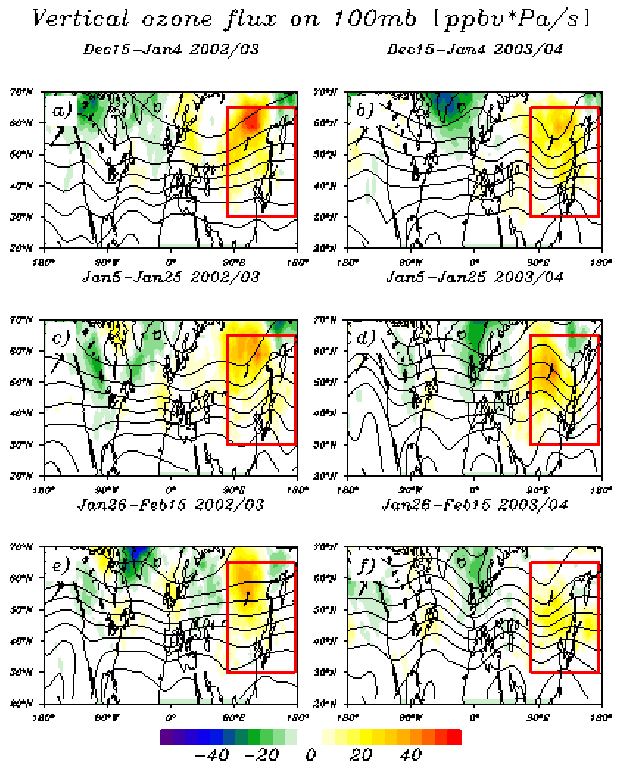

Fig. 11. Vertical ozone flux (ppbv*Pa/s) provided by MOZART on the 100 hPa isobaric surface. Panels **(a)**, **(c)**, **(e)** represent the averaged fluxes for period-1, period-2, period-3 of the 2002–2003 winter respectively; panels **(b)**, **(d)**, **(f)** correspond to the averaged fluxes for period-1, period-2, period-3 of the 2003–2004 winter respectively. The contours of the geo-potential height are also shown by the solid lines with intervals of 100 m. The area corresponding to East Asia (30°–65° N, 80°–180° E) is highlighted by the red box.

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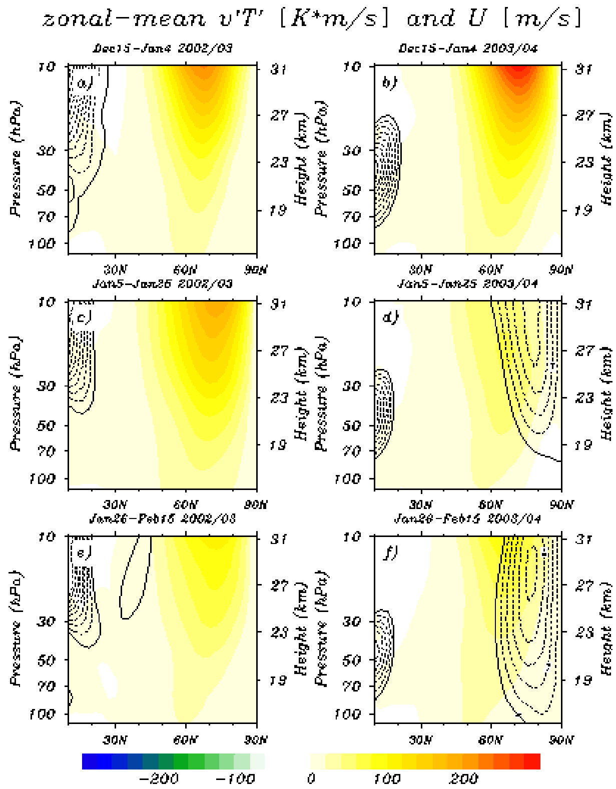

Fig. 12. Zonal-mean eddy heat flux cross-section (K*m/s): Panels **(a)**, **(c)**, **(e)** represent the average flux for period-1, period-2, period-3 of the 2002–2003 winter respectively; panels **(b)**, **(d)**, **(f)** correspond to the average flux for period-1, period-2, period-3 of the 2003–2004 winter respectively. The contours of easterly winds shown by dashed lines with intervals of 2 m/s.