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The sudden stratospheric warming of the Arctic winter 2009/2010: comparison to other recent warm winters

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Abstract

The Arctic winter 2009/10 was moderately cold in December. A minor warming occurred around mid-December due to a wave 2 amplification split the lower stratospheric vortex into two lobes. The vortices merged again and formed a relatively large vortex in a few days. The temperatures began to rise by mid-January and triggered a major sudden stratospheric warming (SSW) by the reversal of westerlies in late (24–26) January, driven by a planetary wave 1 with a peak amplitude of about 100 $m^2 s^{-2}$ at 60° N/10 hPa. The momentum flux associated with this warming showed the largest value in the recent winters, about 450 $m^2 s^{-2}$ at 60° N/10 hPa. The associated vortex split confined to altitudes below 10 hPa and hence, the major warming (MW) was a vortex displacement event. Large amounts of Eliassen-Palm (EP) and wave 2 EP fluxes (3.9×10^5 kg s^{-2}) are found shortly before the MW event at 100 hPa over 45–75° N, suggesting a tropospheric preconditioning of the MW event. We observe an increase in SSWs in the Arctic in recent years, as there were 6 MWs in 6 out of the 7 winters of 2003/04–2009/10, which confirms the conclusions of previous studies on the SSWs in winters prior to 2003/04. Each MW event was unique as far as its evolution and related polar processes were concerned. As compared to the MWs in the recent Arctic winters, the strongest MW was observed in 2008/09 and was initiated by a wave 2 event. A detailed diagnosis of ozone loss during the past fifteen years shows that the loss is inversely proportional to the intensity and timing of SSWs in each winter, where early MWs lead to minimal loss. The ozone loss shows a good correlation with the zonal mean amplitude of zonal winds in January over 60–90° N, suggesting a proxy for MWs in the Arctic winters.

1 Introduction

One of the intriguing phenomenon in climate science is the large interannual variability of Arctic stratospheric winters, characterized by high extreme warm and very cold winters. These year-to-year vacillations are dominated by sudden stratospheric warmings (SSWs) during which the polar temperature rises and the zonal flow reverses abruptly within a short span of time (Labitzke, 1981; Limpasuvan et al., 2004). In some extreme cases the temperature rise can be as high as 50–60 °C. The accompanied zonal wind reversal displaces or splits the polar vortex toward midlatitudes.

The meridional transport in the winter stratosphere is largely controlled by large amplitude planetary waves. The most important of them are quasi-stationary Rossby waves that propagate upward from the troposphere and are quite strong and variable in winter (Andrews et al., 1987). Other planetary waves are the traveling normal modes and they do not transport much momentum, but can interact with other waves or with zonal mean flow. The interaction of planetary waves and the zonal mean flow is known to be the major driver of winter stratospheric dynamics. The key process in a major warming (MW) is the growth and interaction of upward propagating transient planetary waves (Matsuno, 1971). The breaking and dissipation of westward propagating planetary waves relative to the zonal flow in the stratosphere decelerate or even reverse the prevailing eastward flow of the polar stratosphere and induce heat, which often result in a MW. Alternatively, there can be an upward circulation in the mesosphere that induces adiabatic cooling there.

There are a number of different definitions for a warming to be called major or minor. Most of them come under the label of World Meteorological Organisation (WMO), though there is no documented WMO definition. Therefore, we use McInturff (1978), by which a stratospheric warming can be said to be *major* if at 10 hPa or below the latitudinal mean temperature increases abruptly poleward from 60° latitude with an associated circulation reversal. A warming is called *minor* for a significant temperature increase at any stratospheric level in any area of the wintertime hemisphere (in our case at 60° N at 10 hPa), provided the criteria for a MW is not met.

Though studies use different definitions for MWs, there is a general agreement on the poleward temperature increase from 60°. Some studies are critical about the timing of wind reversal that it must last for 5 days (e.g. Limpasuvan et al., 2004), though no

strict time condition is followed by some others (e.g. McInturff, 1978; Labitzke, 1981). Regarding the wind reversal, the latter two use a circulation reversal poleward of 60° whereas Charlton et al. (2007) consider that the winds must reverse at 60°. Nevertheless, Limpasuvan et al. (2004) applied the same condition of temperature increase and wind reversal except a slight difference in latitude, 65° N instead of 60° N.

The dynamical activities in recent winters reveal that the frequency of MWs in the Arctic is increasing. Studies showed that there were 5 MWs in 6 winters in 1967/68–1972/73 (Labitzke and Naujokat, 2006). Similarly, there were 5 MWs in 6 winters from 1983/84 to 1988/89. On average, prior to 1990/91, MWs occurred only once every two Arctic winters. Conversely, no MWs occurred in 9 consecutive winters from 1989/90 to 1997/98, except a minor warming in early February 1990 (Manney et al., 2005). In contrast there were 7 MWs in 5 out of the 6 winters from 1998/99 to 2003/04 (Naujokat et al., 2002; Manney et al., 2008a). The winter 1999/00 was unusually cold but each other winter was prone to MWs. Furthermore, two MWs were observed in 1998/99 and 2001/02. This warming sequence continued and there were 5 MWs in 5 winters again in 2005/06–2009/10 (Hirooka et al., 2007; Harada et al., 2010; Labitzke and Kunze, 2009; Manney et al., 2009a,b). Many of the MWs in recent years have been atypically early (December/early January) than those found before 1990s, which were observed mostly in February (Naujokat et al., 2002; Labitzke and Naujokat, 2006; Manney et al., 2008a). However, the unusual frequency of MWs in recent years has not translated into early final warmings in most cases. Moreover, the final warming in 2003/04 was very late, similar to that of 1996/97 and 1989/90. These results are consistent with findings of Waugh et al. (1999), who found no relation between vortex characteristics and its long-term persistence.

It is a very difficult task to understand the variability of Arctic winters and to predict the influence of the stratosphere on the troposphere. The large interannual variability makes the detection of trends in the Arctic extremely difficult (Manney et al., 2008a). Studies on polar vortex evolution and stratospheric warmings can provide further insights on this issue. Since the winters before 2003/04 are relatively well studied, detailed comparisons are not available on the winters thereafter. Therefore, we examine the warming process in the Arctic winter 2009/10 and compare that with other recent warm winters of the Arctic in 2003/04–2008/09 in a dynamical perspective by analyzing the zonal wave amplitudes and momentum, heat and Eliassen-Palm (EP)) flux evolution during the winters. To this end, this is a companion article of Dörnbrack et al. (2011) (in this issue), who state in their conclusion that *... to elucidate the contributions of the different planetary wave numbers to the stratospheric warming event and its subsequent evolution more precisely could be one topic to be explored*. This is what exactly this study addresses: an analysis of the presence and evolution of planetary waves in this winter. Moreover, we compare those processes with the other similar warming events in the recent Arctic winters.

We organize this article in the following way: the introduction of the study is followed by the data and the method used for the analyses in Sect. 2. Sect. 3 checks the temperature and zonal wind data to categorize the warming events. The dynamical activities are diagnosed in Sect. 3.2 with heat flux, momentum flux, EP flux, EP flux divergence and planetary wave amplitude calculations. The polar vortex condition before, during and after the SSW is illustrated with potential vorticity (PV) maps in the same section. The succeeding Sect. 4 examines the influence of wave forcing on the MWs. The connection between ozone loss and MWs are analysed in Sect. 5 and the important points from the study are concluded in Sect. 6.

2 Data analysis and methods

In order to discuss the dynamical evolution, we have derived EP, heat and momentum fluxes, and wave EP fluxes in each winter using the European Centre for Medium-Range Weather Forecasts (ECMWF) operational data. These data have 2.5° horizontal resolution on 14 pressure levels between 1000 hPa and 1 hPa. The impact of the SSW events on the threshold of Polar Stratospheric Clouds (PSCs) are analyzed with area of PSC (A_{psc}), which is calculated using 4.5 ppmv of H_2O and HNO_3 climatology for the

Arctic winter (Kleinboehl et al., 2002), as computed in Rex et al. (2004) and Kuttippurath et al. (2010).

To enable the reader to follow the article, we only briefly explain the physical and dynamical terms used here. For a detailed discussion, the readers are requested to refer to Andrews et al. (1987). In order to estimate the aforesaid fluxes, we have calculated the zonal means and their fluctuations (eddies) from the zonal means. Throughout this section we denote the zonal mean with an over-bar and eddies with a prime symbol. The intensity of the dynamical process can be diagnosed by the fluxes and we derive the heat and momentum fluxes as:

$$F_{\mathrm{heat}} = \overline{\Theta' v'} \tag{1}$$

$$F_{\mathrm{momentum}} = \overline{v' u'} \tag{2}$$

where v', Θ', and u' are the eddies of meridional wind, temperature, and zonal wind respectively. To describe the motions, which can be of synoptic to planetary scale, the amplitude of planetary waves are derived by Fourier analysis of geopotential fields. Since the observed waves in the stratosphere are usually of zonal wave numbers 1–3, we estimate the wave number 1 and 2 amplitudes for our study. The meridional (ϕ) and vertical (z) EP fluxes are derived as:

$$\mathrm{EP}_{\phi} = -\rho_0 a \cos\phi \left[\overline{u'v'} - \frac{\partial \overline{u}}{\partial z} \frac{\overline{v'\Theta'}}{\partial \overline{\Theta}/\partial z} \right] \tag{3}$$

$$\mathrm{EP}_{z} = \rho_0 a \cos\phi \left[\left(f - \frac{1}{a\cos\phi} \frac{\partial \overline{u}\cos\phi}{\partial \phi} \right) \frac{\overline{v'\Theta'}}{\partial \overline{\Theta}/\partial z} - \overline{u'w'} \right] \tag{4}$$

where ρ_0 is density, a is the radius of the Earth, f is Coriolis parameter and Θ is any function of entropy (potential temperature in this case), w is the vertical velocity, and

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ϕ is latitude. However, for planetary waves these equations are reduced because of geostrophic scaling and are:

$$\mathrm{EP}_\phi = -\rho_0 a \cos\phi \overline{u'v'} \tag{5}$$

$$\mathrm{EP}_z = \rho_0 f a \cos\phi \frac{\overline{v'\Theta'}}{\partial\Theta'/\partial z} \tag{6}$$

These EP flux equations show that the meridional component is proportional to the momentum flux and the vertical component is proportional to the heat flux.

3 Synoptic evolution of the winters

We first examine the evolution of the zonally averaged temperature and zonal wind at 60° N and 10 hPa for the Arctic winter 2009/10 in comparison with the most recent 6 winters to check the warming criterion. The 90° N temperatures are also analyzed to probe the intensity of the warming. We then assess the vertical development of MW events and evolution of polar vortex during the winters.

3.1 Temperature and zonal wind

3.1.1 The warming criterion at 10 hPa

Figure 1 shows the distribution of temperature at 60° N and 90° N and zonal wind at 60° N for 10 hPa in the Arctic winter 2009/10 and compares with those of other recent Arctic winters. The warming in 2009/10 was severe as it shows a rapid increase of temperature from 207 K in early January to 235 K in late-January at 60° N. However, the highest increment of temperature at 60° N was observed in 2008/09, during which low temperatures of about ~207 K were found in November–December and they suddenly rose to 239 K by late January. In winters 2003/04, 2005/06, and 2006/07 there were an increase of about 25 K (from 205 K to 230 K) from late November to late-December,

mid-January and late December, respectively, in each winter and hence, a prolonged warming is evident in 2005/06 at 60° N. There were two warming episodes in 2006/07; in late December and late February at the same altitude level. In 2007/08, the temperature in early December was ~202 K and that slowly increased to 232 K by late February at 60° N. The temperatures at 90° N show similar distribution in all winters, but with significantly higher values. The striking feature found at 90° N as compared to the temperature distribution at 60° N is the rise in temperature in late January 2007/08, which is equal to that of the warmest winter 2008/09.

Apart from a sudden rise in temperature, the reversal of zonal wind is the other MW criterion. In all winters the maximum temperature is followed by a reversal of the zonal wind with a couple of days lag at 60° N. In 2009/10, the MW criterion was accomplished around 24–26 January and the winds reversed at least thrice before the final warming. The wind reversal in 2009/10 was comparatively weak and short, and was analogous to that of 2003/04, 2006/07 and 2007/08. However, the westerlies show very small amplitudes of the order of 1–5 $\mathrm{ms^{-1}}$ in February and March 2010. In 2006/07 and 2007/08, the warmings were very late as the wind reversals were observed in 17–21 February. All these winters show short (10 days or less) and weak (5–15 $\mathrm{ms^{-1}}$) easterlies. On the other hand, in 2008/09 and 2005/06 the MW criterion was attained around 18–24 January and associated easterlies prevailed for about 30 days, with a maximum speed of about 30–35 $\mathrm{ms^{-1}}$ during the MW periods. In 2004/05 the temperature was relatively lower (e.g. 2003/04, 2005/06 and 2006/07) in November–January at both latitudes and there were no MWs, though the final warming was in mid-March, as indicated by a sharp increase in temperature accompanied by the zonal wind reversal at 60° N. In 2006/07 the MW criterion was reached in 19–21 February and the easterlies were observed for 4–5 days only. Note that some studies recommend presence of at least 5 days of easterlies for a warming to be called *major* (Limpasuvan et al., 2004). Therefore, we exclude 2004/05 and 2006/07 winters in the following comparisons. We have not specified the exact day of the MW since it depends on data (e.g. ECMWF analysis) and time (e.g. at 12 h) and thus, a range of days is given.

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3.1.2 Vertical development of the MWs

Figure 2 displays the vertical structure and temporal evolution of the zonal mean temperature (color contours) and zonal mean easterlies (white contours) in 2009/10 compared to other selected Arctic winters with MWs. The winter 2009/10 exhibits high temperatures in the upper stratosphere by early-January, which slowly extend down to 10 hPa by mid-January. The westerlies turned to easterlies by late January and moved down to 10 hPa for a short period of about 10 days. The westerlies reestablished by mid-February throughout the stratosphere, but the temperatures started to increase in the upper stratosphere again by early March.

As compared to winters, higher temperatures are found in mid-December in 2003/04, early January in 2005/06 and mid-January in 2008/09. The easterlies appeared by mid-December, early January, and mid-January, respectively, for each winter. The easterlies were comparatively stronger and extended down to 75 hPa in 2008/09, and to 30 hPa in 2005/06 and thus, the MW was stronger in these two winters. In 2009/10, although the temperatures above 10 hPa were higher than those of other winters, the wind reversal was weaker and restricted to the upper stratosphere. In contrast, a late MW with weak easterlies that seldom propagated down to 20 hPa was observed in 2007/08. The coldest December–January temperatures in the lower stratosphere were observed in 2009/10, 2008/09 and 2007/08 among the winters, in agreement with the analyses of Dörnbrack et al. (2011) and Khosrawi et al. (2011). In 2003/04, relatively lower temperatures in the upper stratosphere and the temperatures similar to those found before the SSWs in the middle stratosphere were observed in late January and early February. This makes the winter 2003/04 unique as there was no such cooling feature in any other Arctic winters, as also shown by Manney et al. (2005).

3.2 Fluxes and waves

Since wave interaction is a key phenomenon in MWs, it is necessary to look at the nature of waves present during the MW periods to further characterize the events.

Therefore, in Fig. 3 we analyze the temporal evolution of the waves, heat flux, momentum flux, and EP flux divergence during the winter 2009/10 and compare with those in the other warm winters in 2003/04–2008/09 at 10 hPa/60° N, where the MW criterion is defined.

Large heat flux of about 400 m K s^{-1} and the largest momentum flux among the recent winters (500 $m^2 s^{-2}$) are estimated during the MW period in 2009/10. Enhanced wave 1 amplitude of about 110 $m^2 s^{-2}$ and wave 1 EP flux of 1.5×10^5 kg s^{-2} are also found during the period. Elevated EP flux divergence (20×10^{-5} kg s^{-2}) suggests strong planetary wave sources consisting of mountainous upward EP flux in and around the MW period. Another interesting feature to note is the minor warming initiated by a strong wave 2 event with significant heat flux (200 m K s^{-1}), geopotential flux (50 $m^2 s^{-2}$) and momentum flux (250 $m^2 s^{-2}$) in early January. However, the zonal winds remained westerlies and hence, the event limited to a minor warming.

In agreement with the higher temperatures and longer duration of easterlies, large heat flux (up to 750 m K s^{-1}), momentum flux (up to 425 $m^2 s^{-2}$) and the highest EP flux divergence (up to -65×10^{-5} kg s^{-2}) are estimated during the MW in 2008/09. The amplitude of wave 2 and its EP flux during the MW are also highest among the winters, with a maximum of about 110 $m^2 s^{-2}$ and 3×10^5 kg s^{-2}, respectively. It is striking that the difference between the maximum heat flux at the time of MW in 2008/09 to that of 2009/10 is ~400 m K s^{-1}. Furthermore, the wave 2 amplitude is twice that of other winters, indicating the intensity of the MW in 2008/09. However, the EP flux divergence during the minor warming in mid-December 2009/10 shows matching values to those found during the strongest MW in January 2008/09, suggesting great wave activity in both winters. The heat flux derived in 2008/09 is in very good agreement with that estimated in other studies (Harada et al., 2010; Labitzke and Kunze, 2009). Another prominent feature to note is the minor warming due to a wave 1 amplification during late January in 2007/08. The largest heat flux (600 m K s^{-1}), wave 1 amplitude (145 $m^2 s^{-2}$) and its EP flux (3×10^5 kg s^{-2}) are recorded during this warming event. Nevertheless, there was no zonal wind reversal to convert the event into a MW. The other winters also

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show significant heat flux, momentum flux and wave 1 amplitude during their respective MW periods, but in relatively smaller magnitudes.

It is interesting to note the high momentum flux and both types of waves in the form of large pulses prior to the SSWs in all winters. These intermittent pulses normally build the momentum for the forth-coming MWs (e.g. Polvani and Waugh, 2004; Coy et al., 2009) (this will be discussed in detail in Sect. 4). The winters 2008/09 and 2009/10 exhibit massive momentum fluxes of about 200–400 $m^2 s^{-2}$ associated with a number of bursts in November through the end of January. The momentum flux magnitude in 2009/10 and 2008/09 is about 200 $m^2 s^{-2}$ and 100 $m^2 s^{-2}$ higher than that of other winters during the MW period, reiterating the strength of MW in these two winters.

3.3 PV diagnostics

We now discuss the development, movement, and dissipation of the polar vortex to characterize the MWs. To perform this, we analyze the PV fields at two representative altitudes in the middle (850 K or ∼10 hPa/30 km) and lower (475 K or ∼85 hPa/18 km) stratosphere. Figs. 4 and 5 depict the status of vortex on selected days at 850 K and 475 K, respectively. The dates are selected by checking all days in each winter to illustrate the main vortex evolution processes consisting of splitting, merging, restrengthening, and dissipating. Since these processes are occurred on different days in each winter, those key days are selected for the maps instead of common days for all winters with entirely different dynamical activity.

3.3.1 Vortex evolution at 850 K and 475 K

In 2009/10, the vortex was stable and strong from December through January in the middle stratosphere, at 850 K. The temperatures started to increase by mid-January and the wave disturbances pushed the vortex to the adjacent midlatitudes. The vortex was still relatively large, strong and nearly concentric until early February, but was not pole-centered. The MW shifted the vortex off to the Atlantic and split into two parts,

with a large strong near-concentric vortex in the Atlantic and a small patch of vortex air above Russia as observed on 5 February, at 850 K. The vortex started to dissipate afterwards and shrunk to a very small area by mid-March. In contrast at 475 K, the minor warming split and separated the vortex to two independent lobes in the midlatitudes around 12 December as illustrated in the figure. The vortices of considerable size with one over North America and another over Russia are observed for a few days after the split. However, the vortex bulbs merged again to form large vortex and it stayed near the pole until early February, as displayed in the PV maps. The vortex split again during the MW period, just after reaching the MW criterion, and the two separated vortices sustained intact until early March in the lower stratosphere, at 475 K. Our vortex analyses with high resolution PV maps are consistent with those discussed with geopotential height fields by Dörnbrack et al. (2011).

Each winter shows unique features of vortex evolution such as splitting, merging or restrengthening of the vortices during the warming periods. As discussed previously, the warming was severe in 2005/06 and 2008/09 as compared to that of 2009/10. Therefore, highly disturbed vortices were observed throughout these winters. Moreover, the vortices split during the respective MW periods and thus, no strong vortex was evident after the MW around mid-February in 2005/06 and 2008/09. In contrast, the MW was early and subsequently, the vortex split around 5 January in 2003/04 at both altitudes. Yet as a unique feature, the temperatures became very low again and therefore, a strong concentric vortex reestablished by 22 February at 850 K, after nearly two months of intense and continuous disturbance in this winter. An identical situation is also found at 475 K, where even stronger but smaller vortex was observed throughout March in 2003/04. In 2007/08, the penetration of easterlies down to the lower stratosphere was ineffective (Fig. 2) and hence, the lower stratospheric vortex remained strong and unscathed until late March.

4 Tropospheric wave forcing

Stratospheric warmings are usually initiated from the troposphere from where the planetary scale disturbance propagates into the stratosphere and breaks there (Manney et al., 2009b; Charney et al., 1961). The MW periods normally preceded by high wave activity at the tropopause, in which more than one planetary wave (generally wave 1 and 2) will be present. Therefore, we check the tropospheric influence of SSWs for the studied winters in this section. The EP flux derived at 100 hPa is often regarded as a measure of wave activity entering the stratosphere (e.g. Coy et al., 1997; Pawson et al., 1999; Newman et al., 2001; Naujokat et al., 2002). Therefore, this quantity can well describe the preconditioning of the MWs. We now examine the zonal mean EP flux distribution at 100 hPa over 45–75° N displayed in Fig. 6, together with momentum flux and wave amplitude at the same pressure level and latitude band to further assist the interpretation.

Elevated EP fluxes and wave 1 amplitudes are found just before the warming in 2009/10 and they show values of about $3.5 \times 10^5\,\mathrm{kg\,s^{-2}}$ for EP flux and wave 1 EP flux, implying a profound wave forcing. The EP flux values are even comparable to those found during the severe MW in 2008/09, where it is about $4.2 \times 10^5\,\mathrm{kg\,s^{-2}}$. Wave 2 with a peak amplitude of about $30\,\mathrm{m^2\,s^{-2}}$ in January was the key in driving the intense MW in 2008/09. In 2005/06, a constant EP flux of around $1.5 \times 10^5\,\mathrm{kg\,s^{-2}}$ for about 45 continuous days is observed in January–February, with wave 1 EP flux of around $1 \times 10^5\,\mathrm{kg\,s^{-2}}$. The other winters also show their peak EP flux (2–$2.5 \times 10^5\,\mathrm{kg\,s^{-2}}$) and wave 1 amplitude ($12\,\mathrm{m^2\,s^{-2}}$) just before the MW, but in smaller magnitudes than those found in 2009/10. More importantly, the winters display short wave bursts prior to the MWs, indicating the preconditioning (e.g. Polvani and Waugh, 2004; Coy et al., 2009). These features are perhaps best described here by the EP fluxes associated with the waves, which show an advance shift of 5–7 days with the peak wave amplitude period. Also, the largest wave 1 EP flux of about $4 \times 10^5\,\mathrm{kg\,s^{-2}}$ for 2009/10 and wave 2 EP flux of about $5 \times 10^5\,\mathrm{kg\,s^{-2}}$ for 2008/09 are estimated shortly before the MW. In summary,

the winters show significant wave activity and considerable EP and momentum fluxes at the tropopause shortly before and during the MW, suggesting a good connection between wave forcing and MWs (e.g. Harada et al., 2010; Hirooka et al., 2007; Newman et al., 2001; Waugh et al., 1999). Further details about the wave activity in the troposphere during the major warming in 2009/10 can be found in Ayarzagena et al. (2011).

5 SSWs and ozone loss

Studies have already shown that the SSWs abruptly disturb polar vortices and their chemical composition (e.g. Manney et al., 2008b; Flury et al., 2009; Keil et al., 2007; Randall et al., 2006). The occurrence of SSWs especially in early winter is associated with warmer conditions that reduces the PSC formation potential. Therefore, we now look at the A_{psc} and ozone loss in the studied winters.

Figure 7 shows a time series illustrating the correlation between cumulative ozone loss estimated from ground-based UV-visible measurements (Goutail et al., 2005; WMO, 2007; Kuttippurath et al., 2010) and December–March mean of A_{psc} at 475 K, and January average of the zonal mean temperature, zonal wind and geopotential heights at 50 hPa averaged over 60–90° N in the Arctic in 1993/94–2009/10. The ozone loss is the maximum loss determined at the end of each winter, late March or early April for the cold winters and late February for 2010, as discussed in Goutail et al. (2005) and Kuttippurath et al. (2010).

As mentioned in Sect. 1, there were no MWs in 1989/90–1997/98 and therefore, temperatures were lower, A_{psc} were larger, westerlies were stronger, and geopotential heights were comparatively lower, which produced large ozone loss of about 25 % in 1994/95–1996/97. Note that, though there were no MWs in 1993/94, the temperatures were higher and A_{psc} was smaller and thus, ozone loss was relatively smaller. The situation was entirely different in the next five years, which experienced 7 MWs (Manney et al., 2005) and therefore, the winters except 1999/00 show warmer temperatures, smaller PSC areas, weaker westerlies and relatively higher geopotential heights. The warming in 1998/99 and 2000/01 was very severe (Naujokat et al., 2002), in which the lowest A_{psc} (nearly zero) in fifteen years is estimated at 475 K. Consequently, the ozone loss in these winters is the smallest among the winters, about 7–10 %. In 1999/00, the largest ozone loss since 1994 was estimated, where the lowest geopotential heights in the 15-yr period are registered. It must be noted that a similar situation is also found in 2004/05, a cold winter surrounded by 2 warm winters. As in 1999/00, very low temperatures, large A_{psc} and significant ozone loss are estimated in 2004/05. The winters from 2003/04 to 2009/10 had 7 MWs, where 2003/04 and 2005/06 show relatively higher temperatures, small A_{psc} and thus, minimal ozone loss. Since the MW was early and relatively strong in 2003/04, higher temperatures and even easterlies are appeared in the fifteen years of analyses. The comparison also shows that the winter 2009/10 was moderately cold (about 205 K) with average loss of ozone (~17 %).

It is well-known that there is a good correlation between the column ozone loss and volume of PSC in the Arctic polar stratosphere (Rex et al., 2004; WMO, 2007). In this study we find a strong correlation between relative ozone loss (%) and December–March average of A_{psc} (r = 0.74), zonal mean January mean temperature (r = 0.75) and zonal mean zonal wind (r = 0.66) at 60–90° N. It is to be recalled that though the correlation between A_{psc}, ozone loss and temperature are expected and have already shown (Rex et al., 2004), the time period of ozone loss and temperature are different here. The correlation between ozone loss and zonal mean wind is also interesting, which can be taken as a proxy for SSWs. Note that there is a well established relation between spring time heat flux and ozone in the northern hemispheric high latitudes (Weber et al., 2011; WMO, 2007; Tegtmeier et al., 2008), which could also be considered as a proxy for warmings in the winter stratosphere. Since the timing of MWs is different in each winter, the data averaged in a particular month may not always reflect the intensity of SSW events. This is why the zonal mean wind does not always tightly correlate with ozone loss in the expected lines as they depend on the timing and duration of the warmings. For instance, the MW was intense in 2008/09 but the zonal wind

shows a speed of 120 ms^{-1} against −5 ms^{-1} in 2003/04. Therefore, care must be taken to delineate various parameters and their correlation in a particular time period. As expected, the analysis affirms that the MWs lead to lower ozone loss and its variability is unpredictably large in the Arctic winter stratosphere.

6 Discussion and conclusion

We have characterized the dynamical processes in the Arctic winter 2009/10 and compared with the other Arctic warm winters in 2003/04–2008/09. In 2009/10, the warming began with a strong wave 2 disturbance around mid-December that split the vortex in the lower stratosphere. The vortex merged afterwards, but later wave 1 episodes built momentum for the MW in late January and early February. Unlike in other MW winters, the split vortices of rather large size sustained until early March and the vortex lobes stayed mostly in the sunlit parts of the midlatitudes, and therefore, significant ozone loss (1.3 ppmv around 475–550 K or 89–100 DU over 350–850 K) was also estimated (until February 20) in this winter (Kuttippurath et al., 2010).

All winters, except 2008/09 show wave 1 amplification, that led to the MWs. In contrast wave 2 amplification was pivotal in driving the MW in 2008/09, which rarely happens. Previous wave 2 MW event occurred in 1984/85 and 1988/89 (Harada et al., 2010). In 2008/09, the EP flux for wave 2 was reportedly the largest since 1978/79. MWs tend to occur during solar maximum in the westerly phase of quasi-biennial oscillation (Harada et al., 2010). Some studies show negative values of Arctic Oscillation and North Atlantic Oscillation during the second half of January 2008/09. Interestingly, wave 2 warming occurs only in La Nina conditions, except for the winter 1978/79 (Charlton et al., 2007). In 2008/09, the wave forcing at the tropopause was unusually large before and during the MW, which initiated the atypical SSW, confirming the results of Harada et al. (2010). Among the studied winters, the MW in 208/09 can be categorized as a vortex split MW event and others were vortex displacement events, consistent with the findings of the previous works (Manney et al., 2009a,b; Dörnbrack et al., 2011).

Among the winters, 2003/04 had the earliest MW as it occurred in early January and the winters 2006/07 and 2007/08 had the late MWs, which happened in late February as for a typical pre-1989/90 MW. Manney et al. (2005) noted that the MW in 2003/04 was much longer than the previously observed longest MW in 1984/85 and 1986/87 with a duration of a month. In 2003/04, the rapid recovery of the upper stratospheric vortex, and long delay in disruption of the vortex in the upper and lower stratosphere were unique.

Exact reasons for the occurrence of stratospheric warmings are still unknown. A study by Taguchi (2008) using a 49-yr reanalysis data did not show any significant correlation between MWs and tropospheric blocking events. In contrast, a recent study by Martius et al. (2009) shows a clear relation between them. The analyzes of Taguchi (2008) were mostly at 500 hPa, while the study of Martius et al. (2009) shows that signals are more apparent at 200 hPa or above. So in this study we analyzed the wave forcing at 100 hPa and demonstrated a clear connection between wave forcing and the studied MWs. It is manifested more clearly with wave 1 and wave 2 EP fluxes, which show an advance shift in time (5–7 days) with the MW periods (e.g. Polvani and Waugh, 2004; Charlton et al., 2007; Coy et al., 2009), suggesting a preconditioning that was strongest in 2005/06 and 2008/09.

The polar ozone loss during the last fifteen years shows a high correlation with December–March average of A_{psc} at 475 K, and January zonal mean temperature and zonal winds at 50 hPa averaged over 60–90° N, suggesting a good proxy for MWs. It has to be borne in mind that, there are some studies showing a good correlation between winter/spring time ozone (average in March/April) with the heat flux calculated during the same months at 100 hPa (Rex et al., 2004; Weber et al., 2011). The interesting aspect of our results is that we use entirely different data sets (ground-based chemical ozone loss in relative units), time periods (maximum ozone loss vs. December–March A_{psc} and January zonal mean temperature, zonal wind and geopotential heights averaged over 60–90° N) and altitudes/pressure levels (50 hPa) for the comparisons, and hence, these analyses are different and new. Therefore, this study further attests the

robustness of the correlation between ozone loss and A_{psc} or temperature in the northern hemispheric winter polar stratosphere.

Our analysis shows an increase in SSWs in the Arctic winter stratosphere in the recent years, as there were 6 MWs in 6 out of 7 winters since 2003/04. This study thus confirms the results of previous analyses on the Arctic winters prior to 2003/04 (Manney et al., 2008a; Labitzke and Kunze, 2009). Each winter was different with respect to the chemical and dynamical processes associated with them.

Characterization of a warming process is important for the diagnosis of possible changes in dynamical activity and their representation in chemistry climate models needs to be improved. Models with temperature sensitive radiation schemes show a jump in tracer values after the MWs (e.g. Kuttippurath et al., 2010). So the diagnosis of warming events with respect to time is necessary to enhance the performance of the models. Further, trend studies on periods with MWs occurring in the beginning or at the end of the period make trend detection difficult and often confusing (Manney et al., 2008a). Therefore, studies on the frequency and variability of warm winters, as presented here, have a great importance in diagnosing trends in winter stratospheric conditions.

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References

Andrews, D. G., Holton, J. R., and Leovy, C. B.: Middle atmosphere dynamics, Academic Press Inc., 491 pp., 1987. 7245, 7248

Ayarzagena, B., Langematz, U., and Serrano, E.: Tropospheric forcing of the stratosphere: A comparative study of the two different major stratospheric warmings in 2009 and 2010, J. Geophys. Res., 116, D18114, doi:10.1029/2010JD015023, 2011. 7256

Charlton, A. J. and Polvani, L. M.: A new look at stratospheric sudden warmings. part i: Climatology and modeling benchmarks, J. Climate, 20, 449–469, 2007. 7246, 7258, 7259

Charney, J. G. and Drazin, P. G.: Propagation of planetary-scale disturbances from the lower into the upper atmosphere, J. Geophys. Res., 66, 83–109, 1961. 7255

Coy, L., Nash, E. R., and Newman, P. A.: Meteorology of the polar vortex: Spring 1997, Geophys. Res. Lett., 24, 2693–2696, doi:10.1029/97GL52832, 1997. 7255

Coy, L., Eckermann, S., and Hoppel, K.: Planetary wave breaking and tropospheric forcing as seen in the stratospheric sudden warming of 2006, J. Atmos. Sci., 66, 495–507, 2009. 7253, 7255, 7259

Dörnbrack, A., Pitts, M. C., Poole, L. R., Orsolini, Y. J., Nishii, K., and Nakamura, H.: The 2009–2010 arctic stratospheric winter – general evolution, mountain waves and predictability of an operational weather forecast model, Atmos. Chem. Phys. Discuss., 11, 32535–32582, doi:10.5194/acpd-11-32535-2011, 2011. 7247, 7251, 7254, 7258

Flury, T., Hocke, K., Haefele, A., Kampfer, N., and Lehmann, R.: Ozone depletion, water vapor increase, and psc generation at midlatitudes by the 2008 major stratospheric warming, J. Geophys. Res., 114, D18302, doi:10.1029/2009JD011940, 2009. 7256

Goutail, F., Pommereau, J.-P., Lefèvre, F., van Roozendael, M., Andersen, S. B., Kåstad Høiskar, B.-A., Dorokhov, V., Kyrö, E., Chipperfield, M. P., and Feng, W.: Early unusual ozone loss during the Arctic winter 2002/2003 compared to other winters, Atmos. Chem. Phys., 5, 665–677, doi:10.5194/acp-5-665-2005, 2005. 7256, 7271

Harada, Y., Goto, A., Hasegawa, H., Fujikawa, N., and Naoe, H.: A major stratospheric sudden warming event in January 2009, J. Atmos. Sci., 67, 2052–2069, doi:10.1175/2009JAS3320.1, 2010. 7246, 7252, 7256, 7258

Hirooka, T., Ichimaru, T. and Mukougawa, H.: Predictability of stratospheric sudden warmings as inferred from ensemble forecast data: Intercomparison of 2001/02 and 2003/04 winters, J. Meteorol. Soc. Japan, 85, 919–925, doi:10.2151/jmsj.85.919, 2007. 7246, 7256

Keil, M., Jackson, D. R., and Hort, M. C.: The January 2006 low ozone event over the UK, Atmos. Chem. Phys., 7, 961–972, doi:10.5194/acp-7-961-2007, 2007. 7256

Khosrawi, F., Urban, J., Pitts, M. C., Voelger, P., Achtert, P., Kaphlanov, M., Santee, M. L., Manney, G. L., Murtagh, D., and Fricke, K.-H.: Denitrification and polar stratospheric cloud formation during the Arctic winter 2009/2010, Atmos. Chem. Phys., 11, 8471–8487, doi:10.5194/acp-11-8471-2011, 2011. 7251

Kleinböhl, A., Bremer, H., von König, M., Küllmann, H., Künzi, K., Goede, A. P. H., Browell, E. V., Grant, W. B., Toon, G. C., Blumenstock, T., Galle, B., Sinnhuber, B. M., and Davies, S.: Vortex-wide denitrification of the Arctic polar stratosphere in winter 1999/2000 determined by remote observations, J. Geophys. Res., 107, 8305, doi:10.1029/2001JD001042, 2002. 7248

Kuttippurath, J., Godin-Beekmann, S., Lefèvre, F., and Goutail, F.: Spatial, temporal, and vertical variability of polar stratospheric ozone loss in the Arctic winters 2004/2005–2009/2010, Atmos. Chem. Phys., 10, 9915–9930, doi:10.5194/acp-10-9915-2010, 2010. 7248, 7256, 7258, 7260, 7271

Labitzke, K.: Stratospheric-mesospheric midwinter disturbances: A summary of observed characteristics, J. Geophys. Res., 86, 9665–9678, doi:10.1029/JC086iC10p09665, 1981. 7245, 7246

Labitzke, K. and Kunze, M.: On the remarkable Arctic winter in 2008/2009, J. Geophys. Res., 114, D00I02, doi:10.1029/2009JD012273, 2009. 7246, 7252, 7260

Labitzke, K. and Naujokat, B.: The lower Arctic stratosphere in winter since 1952, SPARC Newsletter, 15, 11–14, 2006. 7246

Limpasuvan, V., Thompson, D. W. J., and Hartmann, D. L.: The life cycle of the northern hemisphere sudden stratospheric warmings, J. Climate, 17, 2584–2596, 2004. 7245, 7246, 7250

Manney, G. L., Krüger, K., Sabutis, J. L., Sena, S. A., and Pawson, S.: The remarkable 2003–2004 winter and other recent warm winters in the Arctic stratosphere since the late 1990s, J. Geophys. Res., 34, 387–396, 2005. 7246, 7251, 7256, 7259

Manney, G. L., Daffer, W. H., Strawbridge, K. B., Walker, K. A., Boone, C. D., Bernath, P. F., Kerzenmacher, T., Schwartz, M. J., Strong, K., Sica, R. J., Krüger, K., Pumphrey, H. C., Lambert, A., Santee, M. L., Livesey, N. J., Remsberg, E. E., Mlynczak, M. G., and Russell III, J. R.: The high Arctic in extreme winters: vortex, temperature, and MLS and ACE-FTS trace gas evolution, Atmos. Chem. Phys., 8, 505–522, doi:10.5194/acp-8-505-2008, 2008a. 7246, 7260

Manney, G. L., Kruger, K., Pawson, S., Schwartz, M. J., Daffer, W. H., Livesey, N. J., Mlynczak, M. G., Remsberg, E. E., Russell III, J. M., and Waters, J. W.: The evolution of the stratopause during the 2006 major warming: Satellite data and assimilated meteorological analyses, J. Geophys. Res., 113, D11115, doi:10.1029/2007JD009097, 2008b. 7256

Manney, G. L., Harwood, R. S., MacKenzie, I. A., Minschwaner, K., Allen, D. R., Santee, M. L., Walker, K. A., Hegglin, M. I., Lambert, A., Pumphrey, H. C., Bernath, P. F., Boone, C. D., Schwartz, M. J., Livesey, N. J., Daffer, W. H., and Fuller, R. A.: Satellite observations and modeling of transport in the upper troposphere through the lower mesosphere during the 2006 major stratospheric sudden warming, Atmos. Chem. Phys., 9, 4775–4795, doi:10.5194/acp-9-4775-2009, 2009a. 7246, 7258

Manney, G. L., Schwartz, M. J., Krüger, K., Santee, M. L., Pawson, S., Lee, J. N., Daffer, W. H., Fuller, R. A., and Livesey, N. J.: Aura Microwave Limb Sounder observations of dynamics and transport during the record-breaking 2009 Arctic stratospheric major warming, Geophys. Res. Lett., 36, L12815, doi:10.1029/2009GL038586, 2009b. 7246, 7255, 7258

Martius, O., Polvani, L. M., and Davies, H. C.: Blocking precursors to stratospheric sudden warming events, Geophys. Res. Lett., 36, L14806, doi:10.1029/2009GL038776, 2009. 7259

Matsuno, T.: Circulation and waves in the middle atmosphere in winter, Space Sci. Rev., 34, 387–396, 1971. 7245

McInturff, R. M.: Stratospheric warmings: Synoptic, dynamic and general-circulation aspects, NASA Ref., 50, 1978. 7245, 7246

Naujokat, B., Krüger, K., Matthes, K., Hoffmann, J., Kunze, M., and Labitzke, K.: The early major warming in December 2001 exceptional?, Geophys. Res. Lett., 294, 2023, doi:10.1029/2002GL015316, 2002. 7246, 7255, 7257

Newman, P., Nash, E., and Rosenfield, J.: What controls the temperature of the Arctic stratosphere during the spring?, Geophys. Res. Lett., 106, 19999–20010, 2001. 7255, 7256

Pawson, S. and Naujokat, D. W.: The cold winters of the middle 1990s in the northern lower stratosphere, J. Geophys. Res., 104, 14209–14222, doi:10.1029/1999JD900211, 1999. 7255

Polvani, L. M. and Waugh, D. W.: Upward wave activity flux as precursor to extreme stratospheric events and subsequent anomalous surface weather regimes, J. Climate, 17, 3548–3554, 2004. 7253, 7255, 7259

Randall, C. E., Harvey, V. L., Singleton, C. S., Bernath, P. F., and Boone, C. D.: Enhanced NO_x in 2006 linked to strong upper stratospheric Arctic vortex, Geophys. Res. Lett., 33, L18811, doi:10.1029/2006GL027160, 2006. 7256

Rex, M., Salawitch, R. J., von der Gathen, P., Harris, N. R. P., Chipperfield, M. P., and Naujokat, B.: Arctic ozone loss and climate change, Geophys. Res. Lett., 31, L04116, doi:10.1029/2003GL018844, 2004. 7248, 7257, 7259

Taguchi, M.: Is there a statistical connection between stratospheric sudden warming and tropospheric blocking events?, J. Atmos. Sci., 65, 1442–1454, 2008. 7259

Tegtmeier, S., Rex, M., Wohltmann, I., and Krüger, K.: Relative importance of dynamical and chemical contributions to Arctic wintertime ozone, Geophys. Res. Lett., 35, L17801, doi:10.1029/2008GL034250, 2008. 7257

Waugh, D. W., Randel, W. J., Pawson, S., Newman, P. A., and Nash, E. R.: Persistence of lower stratospheric polar vortices, J. Geophys. Res., 104, 27191–27201, 1999. 7246, 7256

Weber, M., Dikty, S., Burrows, J. P., Garny, H., Dameris, M., Kubin, A., Abalichin, J., and Langematz, U.: The Brewer-Dobson circulation and total ozone from seasonal to decadal time scales, Atmos. Chem. Phys., 11, 11221–11235, doi:10.5194/acp-11-11221-2011, 2011. 7257, 7259

WMO (World Meteorological Organisation): Scientific assessment of ozone depletion: 2006, Global Ozone Research and Monitoring Project-Report No. 50, 572 pp., Geneva, Switzerland, 2007. 7256, 7257, 7271

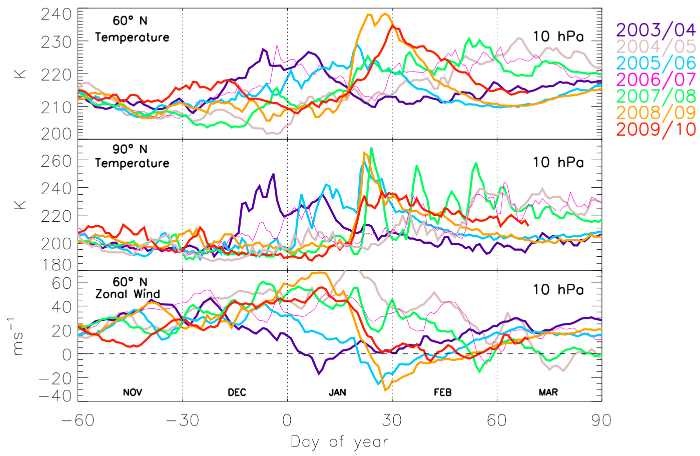

Fig. 1. Evolution of the zonally averaged temperature and zonal wind in the Arctic winters 2003/04–2009/10. The dashed horizontal line represents 0 ms^{-1} and the dotted vertical lines separate each month.

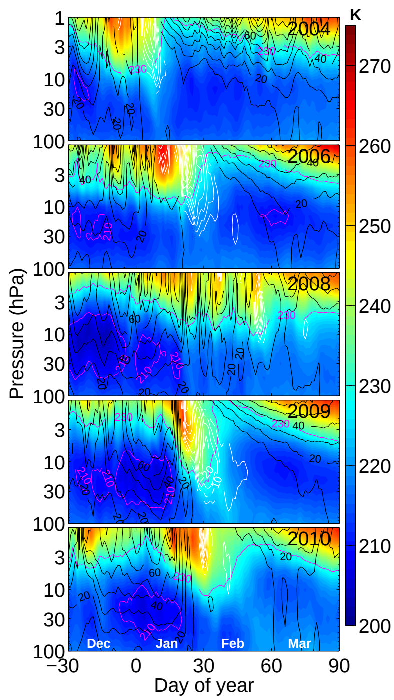

Fig. 2. Temporal evolution of the vertical distribution of zonal mean temperature (color contours) for selected Arctic winters. The overlaid white contours (in 10 ms^{-1}) illustrate the position and propagation of the zonal mean easterlies. The temperature contours for 210 K and 240 K are shown in *magenta*.

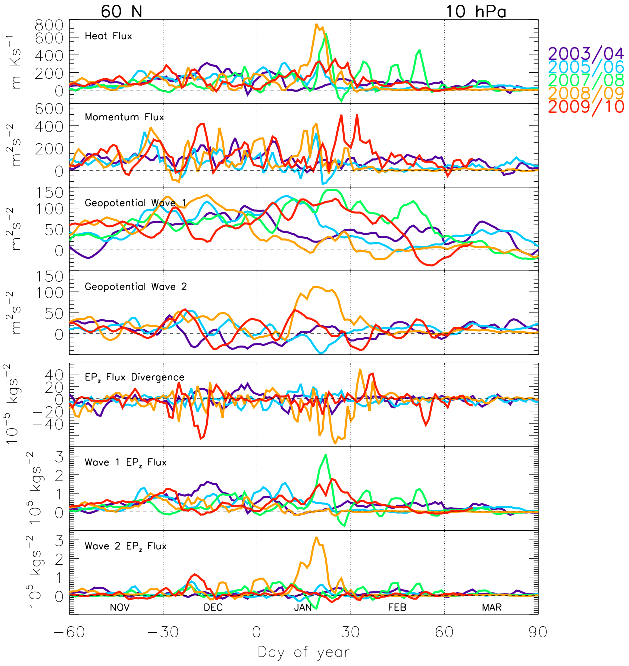

Fig. 3. Temporal evolution of various derived quantities for selected Arctic winters at 10 hPa and 60° N, where the MW criterion is considered. All derived quantities are zonally averaged. The quantity zero is marked with dashed horizontal lines. Since the warming was not severe in 2007/08, some entities are not shown for this winter for clarity reasons. The dotted vertical lines represent the month boundaries.

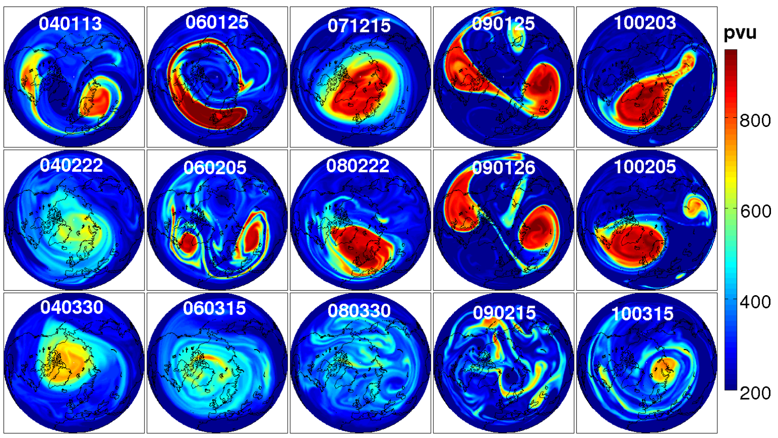

Fig. 4. Maps of potential vorticity at 850 K for various Arctic winters on selected days. The days are selected such that they represent the vortex movements before, during and after the warming events in each winter. It should also be recalled that the MW criterion at 10 hPa/60° N for each winter was fulfilled around 2–5 January in 2003/04, 18–21 January in 2005/06, 17–22 February in 2007/08, 19–24 January in 2008/09 and 24–26 February in 2009/10.

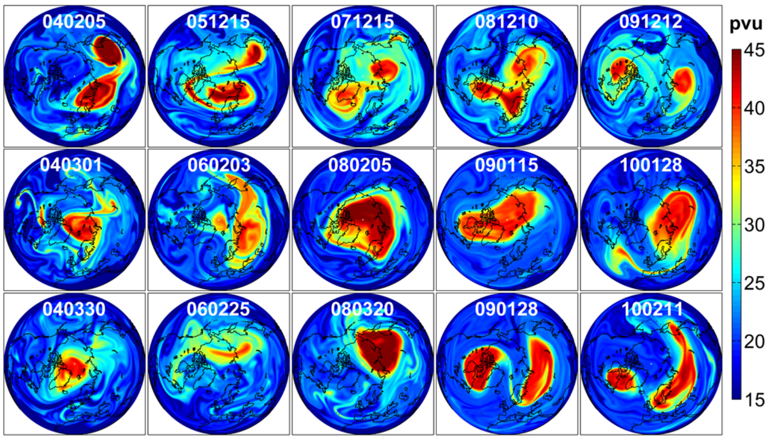

Fig. 5. Same as Fig. 4, but for 475 K.

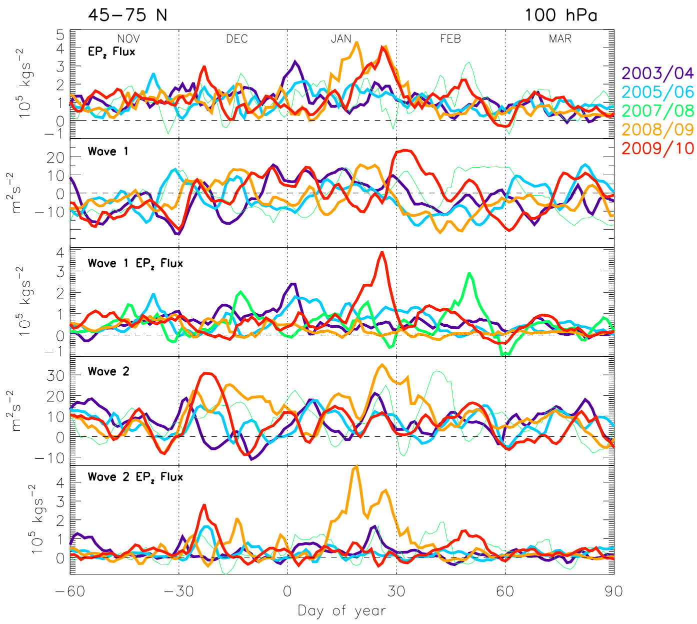

Fig. 6. Temporal evolution of various zonally averaged derived quantities at 45–75° N for 100 hPa to discuss the tropospheric forcing in selected Arctic winters. Since the warming was not severe in 2007/08, some entities are displayed in light shade (green) for this winter for clarity reasons. The quantity zero is marked with dashed horizontal lines and the dotted vertical lines separate each month.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

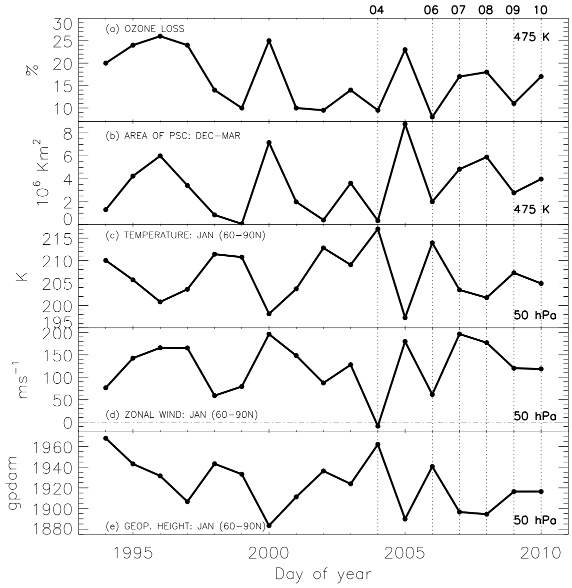

Fig. 7. The cumulative ozone column loss at the end of each winter (late March or early April and 20 February for 2009/10) in relative units, the average area of PSCs in December–March at 475 K, the zonal mean temperature, zonal wind, and geopotential heights averaged over 60–90° N in January at 50 hPa for the Arctic winter 1993/94–2009/10. The UV-visible ozone column loss values are taken from Goutail et al. (2005) and WMO (2007) and are updated with the results for the most recent winters from Kuttippurath et al. (2010). The studied warm winters are demarcated with dotted vertical lines and the zero-wind line is marked with a dash-dotted line.