The Unusual Midwinter Warming in the Southern Hemisphere Stratosphere 2002: A Comparison to Northern Hemisphere Phenomena

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ABSTRACT

A strong midwinter warming occurred in the Southern Hemisphere (SH) stratosphere in September 2002. Based on experiences from the Northern Hemisphere (NH), this event can be defined as a major warming with a breakdown of the polar vortex in midwinter, which has never been detected so far in the SH since observations began at the earliest in the 1940s. Minor midwinter warmings occasionally occurred in the SH, but a strong interannual variability, as is present in winter and spring in the NH, has been explicitly associated with the spring reversals.

A detailed analysis of this winter reveals the dominant role of eastward-traveling waves and their interaction with quasi-stationary planetary waves forced in the troposphere. Such wave forcing, finally leading to the sudden breakdown of the vortex, is a familiar feature of the northern winter stratosphere. Therefore, the unusual development of this Antarctic winter is described in the context of more than 50 Arctic winters, concentrating on winters with similar wave perturbations. The relevance of preconditioning of major warmings by traveling and quasi-stationary planetary waves is discussed for both hemispheres.

1. Introduction

Since their discovery by Scherhag (1952), sudden stratospheric warmings in midwinter have been thoroughly studied; however, most of our current knowledge stems from the NH, where these events contribute to the large interannual variability of the stratospheric circulation in winter. One reason for this, especially in the early years, is the existence of more complete synoptic datasets in the NH. Moreover, they provide particularly interesting examples of wave–mean flow interactions, unparalleled in the SH. In NH winters, forced quasi-stationary waves are dominant, with the planetary wavenumbers 1 and 2 accounting for most of the spatial variance in the stratosphere (van Loon et al. 1973). They play a minor role in SH winters, compared with NH winters, because of the weaker amplitudes (van Loon and Jenne 1972). However, eastward-traveling waves—mainly wavenumber 2—dominate the variability in the Antarctic winters, occasionally leading to midwinter warmings (e.g., Shiotani et al. 1993).

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Midwinter warmings must be distinguished from final warmings, which mark the transition from the cold vortex in winter to the warm anticyclone in summer over the polar regions, in the Arctic as well as in the Antarctic. In both hemispheres, their intensity and the time of their occurrence varies considerably, exhibiting sudden or gradual warming of the polar regions. Thus, final warmings cause the largest interannual variations in the SH stratospheric circulation (Phillpot 1969; Hartmann 1976; Farrara and Mechoso 1986; Mechoso et al. 1988; Rao et al. 2002). An early study of SH final warmings was presented by Godson (1963), who inspected stratospheric observations over Antarctica already reaching back to 1940.

Midwinter warmings have been classified on the basis of their NH synoptic appearance up to 10 hPa (Julian 1967; Labitzke 1968). They were grouped into major and minor warmings, depending on their influence on the wintertime circulation of the stratosphere:

- Major warmings are associated with a breakdown of the polar vortex as well as a warming of the polar region and the reversal of the meridional temperature gradient between 60° latitude and the Pole. The vortex breakdown is defined by the reversal of the mean zonal westerlies poleward of 60° latitude into easterlies, at least down to 10 hPa. This can happen when the vortex center is either displaced to midlatitudes or entirely split into two centers.
- Minor warmings can be as intense as their major

counterparts in terms of temperature increase, and they sometimes also reverse the temperature gradient, but they do not result in a reversal of the circulation at 10 hPa.

These categories are based on zonal means of temperatures and winds, which might obscure the dynamical structure of the systems involved. However, the terminology first adopted by the International Council of Scientific Unions for the alerts of stratospheric warmings during the International Quiet Sun Year (IQSY) 1963, was later taken over by the World Meteorological Organization (WMO) and is still most applicable when classifying the warming phenomena.

A typical NH major warming development was described by Labitzke (1977), mainly on the basis of the analysis of the zonal harmonic wavenumbers 1 and 2 for the 12 NH winters 1964/65–1975/76. In the prewarming phase, the wavenumber 1 amplifies and reaches a well-marked peak coincident with a pronounced minimum in wavenumber 2. This amplification of wavenumber 1 was described by Labitzke (1981) as a characteristic precondition for a major warming that is needed to change the zonal flow and to favor the propagation of wavenumber 2. In the breakdown phase, a rapid decay of wavenumber 1 occurs mostly with a simultaneous development of wavenumber 2 but sometimes without. Concurrently, the temperature gradient between polar and middle latitudes reverses and the midlatitudinal zonal winds rapidly decelerate.

We would call this a typical wavenumber-1 warming because this wave is responsible for the eddy heat transport poleward leading to the warming, regardless of whether wavenumber 2 develops or not, that is, irrespective of if the vortex splits or is strongly displaced. This notation is in contrast to that sometimes found in the literature. Wavenumber-2 warmings, in which the increasing heat flux is connected to wavenumber 2, are only very rarely observed, for example, in February 1963, January 1985, and February 1989 (see Naujokat and Labitzke 1993).

There have been very early reports of SH midwinter warmings, for example, in September 1956 (Godson 1963), July 1957 (Labitzke and van Loon 1965), July/August 1963 (Quiroz 1966; Julian 1967), August 1964, and September 1967 (Phillpot 1969), despite the sparse observations [radiosondes, a few rocketsondes, and first radiances from the Television Infrared Observation Satellite (TIROS) and Nimbus satellite series]. A midwinter SH warming in July 1974, of comparable magnitude to those of the NH, was well documented by satellite observations from the Selective Chopper Radiometer on board *Nimbus-5* (Barnett 1974; Al-Ajmi et al. 1985).

The more recent pronounced SH midwinter warming in August/September 1988 was studied by Kanzawa and Kawaguchi (1990) and Hirota et al. (1990). By using a dataset up to the 1-hPa level provided by the Japan Meteorological Agency, Hirota et al. (1990) discussed the dynamical role of the eastward-traveling wavenumber 2 and its interaction with the quasi-stationary, forced wavenumber 1, which led to a quasi-periodic amplification of wavenumber 1.

All studies agree in the fact that the SH midwinter warmings observed so far have been minor events following the definition for the NH. They were mainly a feature of the upper stratosphere, reaching comparable intensities to NH warmings (even major ones), but they did not lead to a breakdown of the normal winter circumpolar vortex. No previous evidence of an SH vortex split was found either by Roscoe et al. (2005), on inspecting the radiosonde data series of Halley Bay since 1956, or by Simmons et al. (2005), who searched through the European Centre for Medium-Range Forecasts (ECMWF) Re-Analysis (ERA) archives.

The objectives of this paper are to analyze and check if the WMO criterion of a major warming was fulfilled for the SH 2002 winter and to compare this event with a similar NH phenomenon. For this purpose, the Arctic winter 1988/89 was chosen because of the similar preconditioning phase in terms of the wave evolution prior to the sudden warming. Particular emphasis will be placed on the wave activity, especially the role of traveling waves, and on the fluxes involved in the breakdown of the polar vortex. Finally, similarities and differences between the two warming events are highlighted.

2. Data used

Different datasets have to be used, because of limited spatial and temporal availability for the SH and NH winter stratosphere. The historical analyses of the Free University Berlin (FUB) are available for the NH stratosphere from July 1957 to June 2001 and can be regarded as the main time series for long-term monitoring of northern winters, reaching back as far as 1952 (Labitzke and Naujokat 2000). A description of the FUB data is given in Naujokat and Labitzke (1993) and on a data CD released by Labitzke et al. (2002). Global coverage since 1979 is provided by the operational analyses of the ECMWF and the Stratospheric Sounding Unit/TIROS Operational Vertical Sounder (SSU/TOVS) data. The data assimilation systems of the ECMWF have been extended into the upper stratosphere up to 1 hPa in 1999 and will be used here to describe the recent SH winter of 2002. A description of these data and respective references can be found in Manney et al. (2003) and Simmons et al. (2005). The SSU/TOVS data, provided by the U.K. Met Office (UKMO), were available from January 1979 until June 1998 and have been used for the NH winter of 1988/89 in addition to the FUB data. A precise description of the SSU/TOVS dataset is given by Bailey et al. (1993). A detailed comparison between these three datasets among others is presented in the recent data intercomparison by Randel et al. (2002). Radiosonde data have been used for the SH winter of 2002 as were made available from the Global Telecommunication System of the WMO.

3. Synoptic development

a. The SH winter of 2002

To investigate if the WMO criterion for a major warming is fulfilled, the zonal-mean state is analyzed, and polar stereographic maps are inspected for more spatial details. The vertical time sections of the zonal-mean zonal winds at 60°S ($\bar{u}$) and the zonal-mean temperature differences between 60°S and the South Pole (ΔT) from July to November are illustrated in Fig. 1. The early winter of 2002 began unusually disturbed, starting already in May with positive temperature deviations from the long-term mean (not shown here; see also Allen et al. 2003; Newman and Nash 2005). Beginning in July, a periodic weakening and strengthening of $\bar{u}$ is clearly visible, which is not present in a cold undisturbed Antarctic winter, for example, in 2001 (Baldwin et al. 2003). Simultaneous warming pulses are visible in the upper and middle stratosphere. From mid-August onward, four strong minor warmings with a frequency of 1–2 weeks lead to a substantial weakening of the polar night jet (PNJ) from values exceeding 120 m s^{-1} in the upper stratosphere in July to 50 m s^{-1} throughout the stratosphere in mid-September. Around 20 September (3–4 days earlier than the response in $\bar{u}$), a positive ΔT (a warming signal) is emanating from the upper stratosphere down to 200 hPa with a simultaneous cooling in the uppermost stratospheric levels and in the mesosphere (Hernandez 2003). On 26 September, the WMO criterion of a major warming is fulfilled with a reversal of the upper stratospheric winds at 60°S in 10 hPa from westerlies to easterlies, reaching down to 20 hPa a few days later. There is a hint of a tropospheric signal in $\bar{u}$ propagating upward into the stratosphere on 16 September, but no stratospheric signal is emanating down into the troposphere as is typical for many NH major warmings (e.g., Naujokat et al. 2002). Note that the southern annual mode (SAM) analyzed by Baldwin et al. (2003, their Fig. 7) also shows no clear downward propagation of stratospheric anomalies; the signal appears to occur first in the lowermost stratosphere. After a few days, the PNJ establishes once more for a duration of about 3 weeks, before the easterlies of the final warming appear at the end of October. Additional to the unusual winter development, the final warming started early, comparable in time to that after the 1988 midwinter warming, both being exceptionally early (see Rao et al. 2002; Orsolini et al. 2005).

Figure 2 shows the SH distribution of temperature (T) and geopotential height (Z) on selected days when the warming started to develop at 10 hPa. Several warming pulses occurred already in July/August. At the middle and end of August, two of the above-mentioned minor warmings are visible with a strong wavenumber 1 in Z and T, shifting the cold vortex off the Pole. High temperatures almost reached the South Pole. During that period, the anticyclone and the warm pool regularly moved eastward from the Greenwich meridian to-

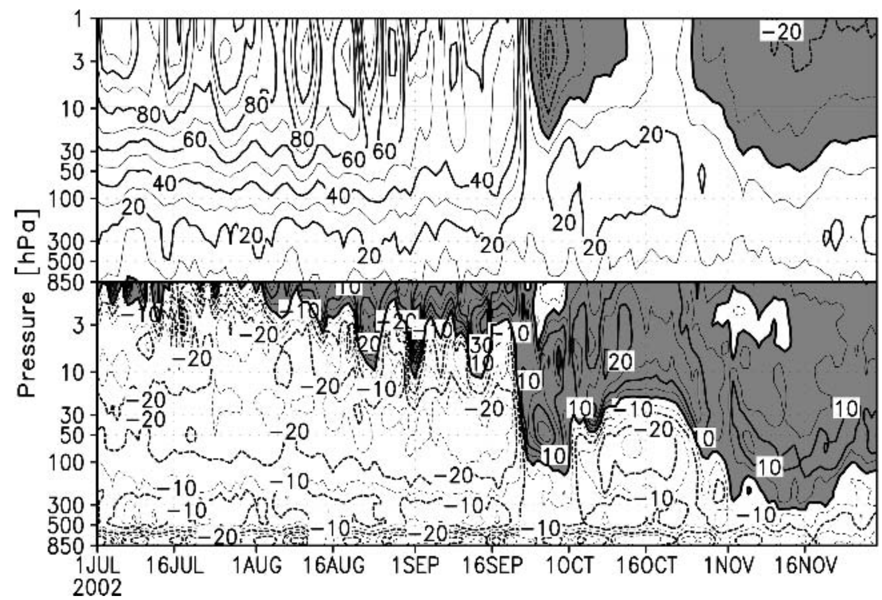
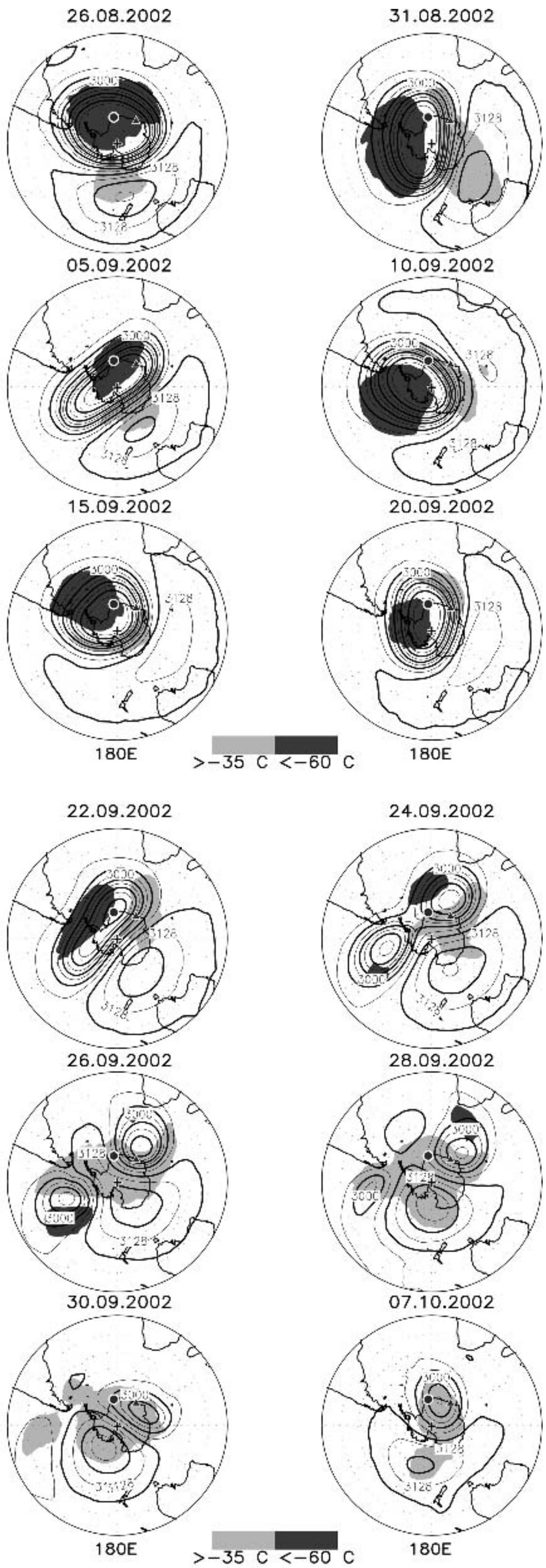


FIG. 1. Time–height sections of zonal-mean zonal wind (m s^{-1}) at 60°S and of the temperature gradient (K) between 60°S and the South Pole from 1 Jul to 30 Nov 2002; easterly winds and positive temperature gradients are shaded; the thin horizontal line in the wind plot indicates the 10-hPa level (ECMWF data).



ward New Zealand and then restarted again. At the beginning of September, another warming pulse followed, this time connected with a strong wavenumber 2 on 5 September and wavenumber-1 and -3 components on 10 September. Around mid-September, the anticyclone is located southwest of Australia, being quasi-stationary, strengthening and moving poleward after 20 September and pushing the vortex off the Pole. After that strong wavenumber-1 impulse, the polar vortex began to elongate and split into two centers on 24 September. On 26 September the evolution of the major warming is complete, culminating in the breakdown of the polar vortex with associated warm air and a high ridge over the South Pole within only 5 days. The vortex reestablished at the end of September, but T at 10 hPa stayed high over Antarctica, indicating the strength of radiation during that time of the season.

The local temperature evolution is shown in Fig. 3 from 1 August to 31 October 2002 at 30 and 10 hPa, measured at three radiosonde stations, Amundsen Scott (90°S), Neumayer (71°S, 08°W), and Syowa (69°S, 40°E). Although observations are sometimes sparse, especially at 10 hPa, the main features are apparent (cf. with the synoptic charts of Fig. 2). The preceding minor warmings in August/September are most pronounced at Syowa. The major warming in the second half of September is evident as a strong temperature increase at all three stations, first at Syowa, then at the South Pole, and finally at Neumayer. The temperature increase of about 50 K in 10 days is comparable to the SH midwinter warming in 1988, when extremely high temperatures of about −25°C at 30 hPa were observed over Syowa (Hirota et al. 1990), but that warming did not reach the South Pole and did not split the vortex. The highest temperature of the 2002 warming (from the available radiosonde measurements) was also observed over Syowa: 0°C at 7.2 hPa on 27 September. ECMWF operational analyses show at 10 hPa a maximum value of +10°C on 26 September over the South Pacific Ocean region between Chile and Antarctica. Thus, the magnitude of the warming corresponds to the strongest midwinter warmings observed in the NH stratosphere (e.g., Naujokat et al. 2002), where the time evolution of maximum temperature usually occurs some days ahead of the polar vortex breakdown (Labitzke 1977).

b. The NH winter of 1988/89

The NH winter of 1988/89 was characterized by a cold early winter and midwinter, interrupted only by

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FIG. 2. The SH distribution of temperatures (°C) and geopotential heights (dam) at 10 hPa on selected days in Aug, Sep, and Oct 2002; geopotential height intervals are 32 dam, light (dark) shaded temperature areas are warmer (colder) than the indicated values (ECMWF data; south of 20°S, Greenwich meridian at the top). The symbols (△, •, and +) indicate the radiosonde stations shown in Fig. 3.

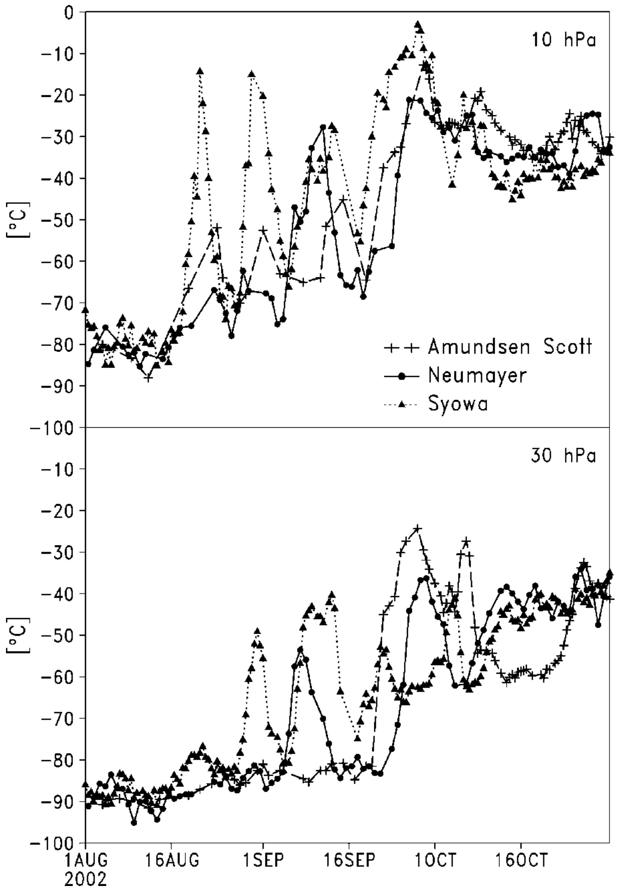

FIG. 3. Temperature time series of available radiosonde measurements at the 10- and 30-hPa pressure levels for Syowa (69°S, 40°E), Neumayer (71°S, 08°W) and Amundson-Scott (South Pole). The symbols mark the day of measurements.

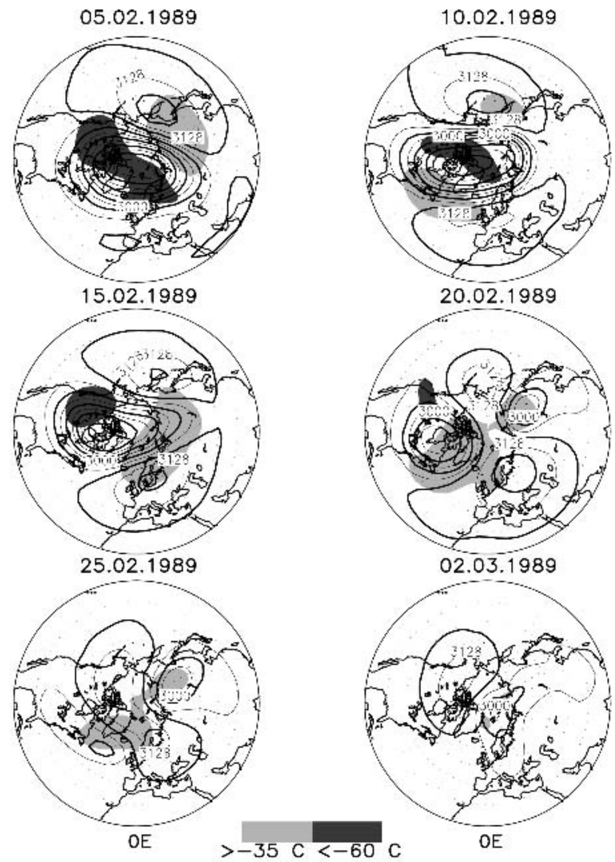

FIG. 4. The NH distribution of temperatures (°C) and geopotential heights (dam) at 10 hPa on selected days in Jan, Feb, and Mar 1989; details as in Fig. 2 (FUB data; north of 20°N, Greenwich meridian at the bottom).

two unpronounced minor warmings at the beginning of December and January (Naujokat and Labitzke 1993). As often happens, the major warming occurred in several phases. The first pulse started in the upper stratosphere in the middle of January, while in the lower stratosphere, extremely low temperatures were reached. In February, the warming became fully effective in the middle and lower stratosphere, and the winter circulation broke down. In the lower stratosphere, this warming led to an early final transition to the summer circulation, while a pronounced late-winter cooling was observed in the upper levels. The most important features of this winter are summarized in Fig. 4, showing the NH distribution of T and Z at 10 hPa. The meteorological situation on 20 February 1989 is very similar to 26 September 2002 in the SH (Fig. 2), which shows the typical breakdown of the polar vortex into two centers and the anticyclonic ridge located over the Pole. However, there is one striking difference: the 1989 NH major warming developed with a strong wavenumber 2 and broke up with a wavenumber 2, with a much longer evolution period (more than 2 weeks) compared to the SH 2002 major warming. The SH major warming developed with a typical wavenumber-1 pattern, and after the major disturbance evolved, the polar vortex split into two segments resulting in a strong wavenumber-2 component.

4. Wave activity and fluxes

The wave quantities presented here are calculated as used in the wave climatology of Pawson and Kubitz (1996). Zonal, Fourier-analyzed geopotential height fields Z_s of wavenumber s = 1–3 are calculated as well as the wave components of the heat fluxes $\overline{v'T'_s}$. For completeness, ΔT and $\bar{u}$ are shown for both winters in Figs. 5 and 6 in a time series together with the wave amplitudes and phases of $Z_{1,2}$ and $v'T'_{1-3}$ for different stratospheric levels. In 2002, the highest amplitude for Z_1 was 2200 m at the end of August (Fig. 5), stronger than ever observed in the SH since 1979 and even stronger than in the NH (not shown). Z_2 reached more than 1200 m at the beginning of September 2002. Both wave maxima were connected with the above-mentioned

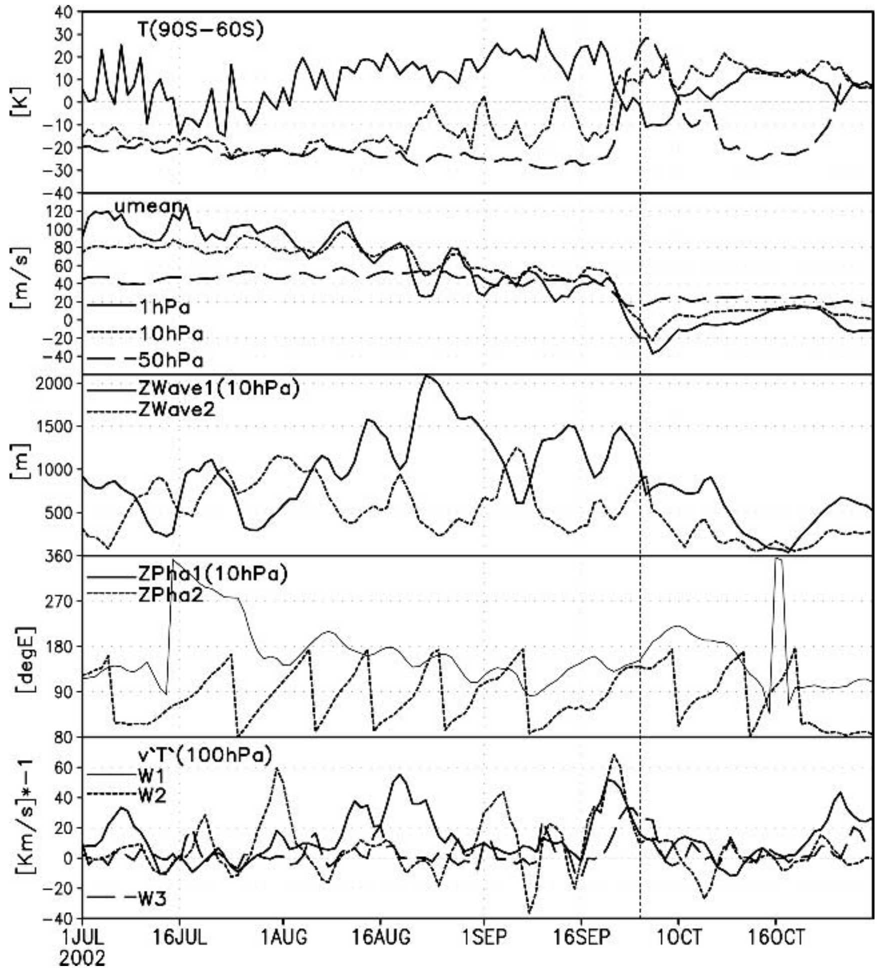

FIG. 5. Time series of ΔT (K), $\bar{u}$(m s^{-1}), the amplitude (m) and phases (°E) of $Z_{1,2}$, and the heat flux of $Z_{1\text{–}3}$ (K m s^{-1}) $\times -1$ through 60°S for the indicated pressure levels, from 1 Jul to 30 Nov 2002 (ECMWF data).

strong warming pulses, which decelerated the PNJ substantially. From June (not shown here), Z_2 traveled eastward regularly until mid-September with a period of about 10 days. This wave mode is a common feature in the SH stratospheric winter (e.g., Shiotani et al. 1993). A periodical amplification of Z_1 is noticeable when the ridges of phases Z_1 and Z_2 overlap, indicating a nonlinear wave–wave interaction, as was first pointed out by Hirota et al. (1990) for the SH midwinter warming in 1988. This interaction is also visible by a periodic change of the Z_1 phase toward eastward propagation. One week before the sudden breakdown of the polar vortex, quasi-stationary Z_1 and Z_2 became dominant, when the phases of the two waves began to synchronize just prior to the major disruption, indicating one homogeneous disturbance not determined by a particular "analyzed" wavenumber.

According to this wave development, the total heat flux at 100 hPa exceeded -140 K m s^{-1} not shown), a strong value even for NH major warming events (see Weber et al. 2003). Simultaneously, the momentum flux showed positive values (not shown), leading together with the heat flux to a poleward and upward directed Eliassen–Palm (EP) flux vector (Manney et al. 2005; Newman and Nash 2005). Strong wave–mean flow interactions led to a sudden and intense deceleration of the PNJ with a reversal of the westerly winds in the upper and middle stratosphere (see Fig. 1). Only during this period, all three wave components of $\overline{v'T'_s}$ showed a simultaneous peak, also indicating one homogeneous wave disturbance. Nevertheless, the SH 2002 major warming can be categorized as a "wave-1 warming," according to the synoptic charts and the wave evolution, which both implied a stronger Z_1 amplitude than Z_2.

The NH winter of 1988/89 was not only exceptional in terms of the record low temperatures never observed since 1965 (see Naujokat and Labitzke 1993); a strong eastward-traveling height wavenumber 2 also played a major role during the winter period prior to the major

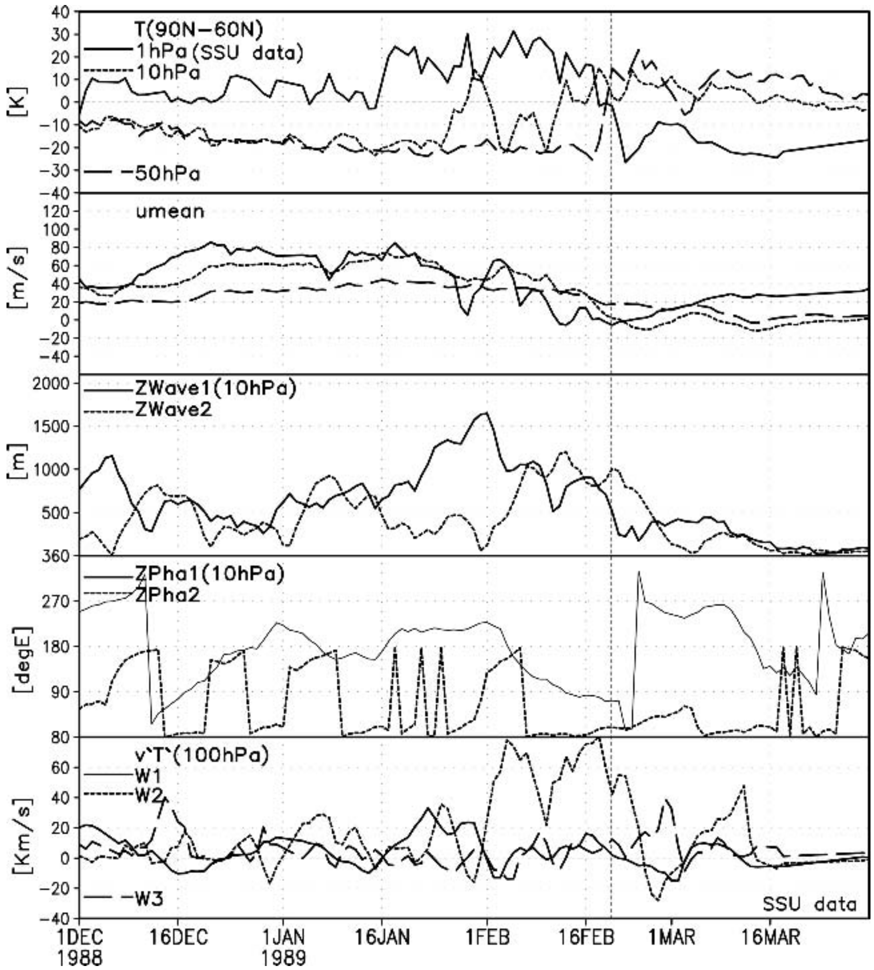

FIG. 6. As in Fig. 5, but for the NH from 1 Dec 1988 to 31 Mar 1989 (FUB and SSU/TOVS data).

warming development. In that respect, the 1988/89 Arctic winter is comparable to Antarctic winters, for example, in terms of the strength of the vortex and the wave occurrence, as are the SH winters of 1988 and 2002 (Krüger and Pawson 2003). The height wavenumber 2 began to travel eastward from November 1988 until the beginning of February 1989, less regularly in contrast to the SH case, with a period of about 16 days (see Figs. 6 and 7b). A quasi-periodic amplification of Z_1 alternating with the amplitude of Z_2 is visible, indicating a nonlinear wave–wave interference as was observed in the SH winter of 2002. An NH wave climatology, based on frequency analyses from 1972 to 1997 of such events, reveals only five distinct quasi 16-day eastward-traveling height wavenumber-2 winters, with only one such winter characterized also by a major warming event, namely the winter of 1988/89 (Krüger and Pawson 2003). As is clearly visible from the wave amplitudes and the corresponding heat flux components, a quasi-stationary Z_2, amplifying from the beginning to the end of February, led to the (slow) deceleration of the PNJ in contrast to the sudden deceleration in the SH winter of 2002 (Fig. 6). Again, from the wave analysis it seems clear that the NH winter of 1988/89 is a typical "wave-2" major warming, developing with a wavenumber 2 and breaking with a wavenumber 2. The maximum amplitude of Z_2 is of comparable size to the SH 2002 winter, in both cases exceeding 1000 m. The upward propagation of the planetary waves addressed by the heat flux component $v'T'_2$ is higher in the case of the NH winter of 1988/89, whereas the total heat flux of 100 K m s^{-1} (not shown) was lower than in the SH 2002 winter.

In Fig. 7, Hovmöller diagrams for $Z_{1,2}$ are shown for the SH and NH major warming events; they are able to just resolve the existence of the dominant wave modes. To demonstrate the tropospheric forcing from below and the coupling with the stratospheric wave modes, 500- and 10-hPa pressure levels are shown. A clear eastward-traveling pattern of height wavenumber 2 is evident until mid-September 2002 (Fig. 7a). The periodical amplification of Z_2, which occurred around 10 July,

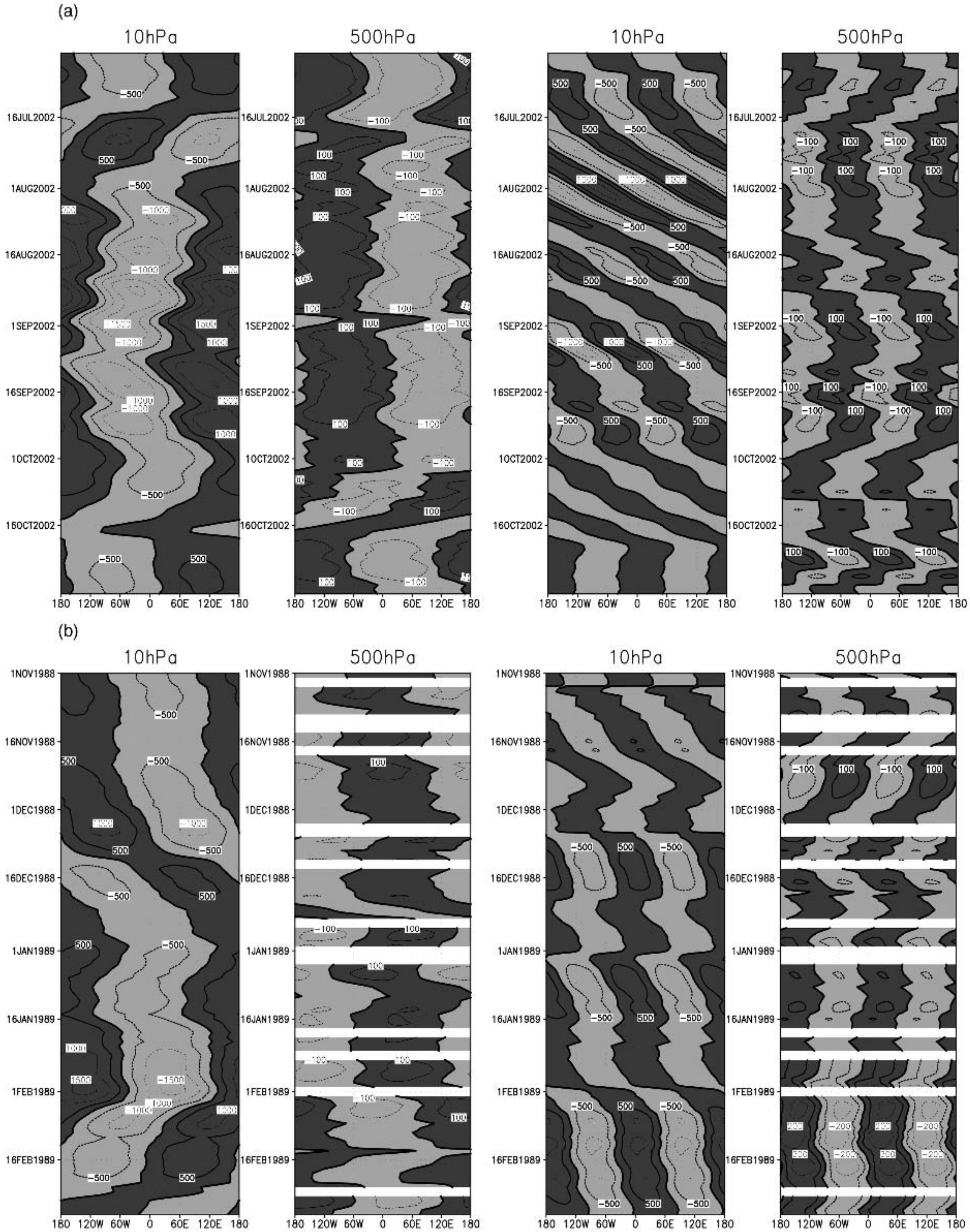

FIG. 7. Hovmöller diagrams of the planetary height wavenumbers (left) 1 and (right) 2 at 60°S/N for 10 and 500 hPa from (a) Jul to Oct 2002 (ECMWF data) and (b) Nov 1988 to Feb 1989 (FUB and SSU/TOVS data); contour intervals are 500 m for 10-hPa and 100 m for 500-hPa pressure levels, light (dark) shaded areas indicate negative (positive) values.

24 July, 1 August, 18 August, and 4 September at 10 hPa, seemed to be coupled to the quasi-stationary wave of the same wavenumber in the troposphere (500 hPa) 1–2 days earlier. This indicates the possibility of a tropospheric influence on the amplification of this mainly stratospheric wave mode (see, e.g., Hirota et al. 1990; Krüger and Pawson 2003). Interesting to note is that the amplitudes of Z_2 and Z_1 strengthen alternately, beginning with a strong Z_2 on 10 July, then a strong Z_1 on 19 July and so on. This regular behavior suddenly stopped when the quasi-stationary planetary waves Z_1 and Z_2 became dominant in the troposphere and stratosphere during mid-September. A very similar Z_2 wave development was observed in the SH winter of 1997 (not shown here), but in this case, the tropospheric waves did not strengthen and did not lead to a major disturbance in the stratosphere.

The NH winter of 1988/89 also showed an eastward-traveling height wavenumber-2 pattern, but not as regularly as in SH winters (Fig. 7b). It is a characteristic difference between the hemispheres that the planetary waves in the stratosphere, especially Z_2, exhibit more phase changes during the Arctic winters. This is most likely because of the larger variety of dominant wave modes in the NH: quasi-stationary, westward-, and eastward-traveling wave modes. There is a period in December 1988 in which both wavenumbers (Z_1 and Z_2) propagated eastward with a phase overlap occurring around 14–18 December, leading to enhanced wave amplitudes and northward-directed heat fluxes comparable to the SH event in 2002. In February, the quasi-stationary planetary Z_2 is the dominant and clearly visible wave mode throughout the troposphere–stratosphere, compared to a less clear signal of the quasi-stationary Z_2 around mid-September 2002 (see Fig. 7a). During this period, Z_1 is moving retrogradely as is typical for many other major warming events in the NH and can sometimes lead to wave–wave interferences, as was discussed by, for example, Naujokat et al. (2002). Such retrograde movements or normal mode Rossby waves occur only occasionally during Antarctic winters as was observed in mid-July and at the beginning of October 2002. A connection of these wave modes with the unusual SH major warming cannot be detected with this Hovmöller diagram.

5. Summary and discussion

The WMO criterion of a major warming is fulfilled for the SH winter of 2002 for the first time since a regular monitoring of the Antarctic stratosphere began in 1957 with the International Geophysical Year (IGY). This unusual event is discussed in the context of more than 50 yr of monitoring the Arctic stratosphere, showing a comparable development in duration and strength to the NH events. We believe that preconditioning, in the sense of substantial weakening of the PNJ, plays a role in the development of the major warming through an unusual strengthening of the tropospheric wave activity into the entrance region to the stratosphere. Wave–mean flow interactions forced by eastward-traveling waves, mainly wavenumber 2, led to an unusual early and strong weakening of the PNJ in several phases during July/August 2002 prior to the major warming, compared to an SH climatology (see also Allen et al. 2003; Baldwin et al. 2003).

A similar dynamical development can also be found in Arctic winters, regarding the preconditioning period of the major warming evolution. Therefore, we compared the SH winter of 2002 with the NH winter of 1988/89. Wave–wave interactions between the eastward-traveling height wavenumber 2 with a period between 1 and 3 weeks and the quasi-stationary (occasional eastward traveling) wavenumber 1 played an important role in weakening the PNJ prior to the major warming in the compared winters. Both major warmings were initialized by quasi-stationary planetary waves, defined in this paper as a wave-1 major warming in the SH winter of 2002 and as a wave-2 major warming in the case of the NH winter of 1988/89. The two major warmings culminated in a split of the polar vortex into two segments, that is, in terms of wave quantities, a strong wavenumber 2.

In the SH winter of 2002, the tropospheric forcing of quasi-stationary waves played an important role in breaking up the Antarctic stratospheric polar vortex into two pieces. Early work by Labitzke and van Loon (1965), for example, has already investigated the role of tropospheric blocking events over the Australian sector in the SH winter of 1957, forcing comparably strong quasi-stationary waves. The influence of the upper troposphere on forcing the split of the stratospheric polar vortex in 2002 was investigated by Baldwin et al. (2003), which discussed the role of the strong temperature anomaly at the 100-hPa pressure level between Antarctica and Australia. Manney et al. (2005) found that they could simulate the breakdown of the vortex solely with a wavenumber-2 and -3 forcing at the 100-hPa pressure level without a necessary preconditioning of the polar vortex. This result may be surprising compared to the main results of this paper. However, the lower boundary at 100 hPa, used by Manney et al. (2005), already includes some preconditioning effects in neglecting the important lower entrance region to the stratosphere. The exact mechanism that finally led to such an unusually strong upward-directed wave flux remains uncertain and should be further addressed by modeling and observational studies.

This work has demonstrated the relevance of eastward-traveling waves in preconditioning the SH 2002 major warming event. The question arises of whether earlier, stronger, and more frequent eastward-traveling height wavenumber-2 events can occur in a changing climate. A stronger vertical temperature gradient and related strong PNJ could lead to an enhanced forcing of such eastward-traveling height wavenumber-2 events in both hemispheres (see, e.g., Hartmann 1983; Krüger and Pawson 2003). Since satellite observations began in 1979, the strongest eastward-traveling height wavenumber-2 events occurred in the SH winters of 1997 and 2002, supporting the above-mentioned theory. Roscoe (2005) also found a higher wavenumber-2 activity since 1979, upon analyzing the long-term radiosonde record from Halley Bay reaching back to 1956.

In light of this investigation, there arise several questions concerning the unusual occurrence of a major midwinter warming related to the climate change issue. Will more SH major warmings occur in the future? And if so, will Antarctic ozone depletion be weakened or even stopped, therefore implying an earlier-than-expected ozone recovery in the future? How reliable are current climate change scenarios from general circulation models with respect to their general shortcomings (e.g., the cold Pole bias problem) to model major warmings in the SH? Further future modeling studies are needed to try to address such open questions.

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