The early major warming in December 2001 – exceptional?

B. Naujokat, K. Krüger, K. Matthes, J. Hoffmann, M. Kunze, and K. Labitzke
Meteorological Institute, Free University Berlin, Germany

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[1] The early major warming in December 2001 is described and compared to the two other December major warmings in 1998 and 1987, showing a strong tropospheric-stratospheric coupling in all three cases. We argue that the occurrence of free westward propagating Rossby waves interacting with a forced quasi-stationary wave number 1 led to these three early events. The possible excitation of these waves is discussed with respect to the tropospheric circulation, which showed strong blockings over the northern Atlantic prior to the early major warmings. *INDEX TERMS:* 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions; 3384 Meteorology and Atmospheric Dynamics: Waves and tides. **Citation:** Naujokat, B., K. Krüger, K. Matthes, J. Hoffmann, M. Kunze, and K. Labitzke, The early major warming in December 2001 – exceptional?, *Geophys. Res. Lett.*, *29*(21), 2023, doi:10.1029/2002GL015316, 2002.

1. Introduction

[2] Major midwinter warmings, defined by a reversal of the meridional temperature gradient between midlatitudes and the North Pole and an associated breakdown of the polar vortex, are a phenomenon of the Arctic stratosphere and mostly occur in January or February. A summary of the occurrence of stratospheric warmings since 1952 can be found in a SPARC Newsletter [*Labitzke and Naujokat*, 2000]. Despite the large interannual variability during the Arctic winters, major warmings became more rare in January/February of the last 15 years, but were observed instead in December, i.e. in 1987 [*Baldwin and Dunkerton*, 1989], in 1998 [*Manney et al.*, 1999], and in 2001. They should not be mistaken for Canadian warmings which often happen in early winter but are mostly confined to the lower stratosphere and do not lead to a breakdown of the vortex [*Labitzke*, 1982].

[3] Forced stationary waves of wave numbers 1–3, excited in the troposphere by mountains and by heat sources, can propagate upward into the stratosphere during weak westerlies [*Charney and Drazin*, 1961] and play a crucial role in the development of stratospheric warmings [*Matsuno*, 1971]. Free westward propagating Rossby waves, also known as normal mode Rossby waves, can interfere with forced stationary waves and are often observed prior to major warmings. A theoretical background of these wave phenomena and a wave classification of the normal modes can be found in *Hirooka and Hirota* [1989] and references herein. A detailed analysis of such wave interactions during January 1979 has been carried out by e.g. *Madden and Labitzke* [1981].

[4] In this paper, we describe the December 2001 major warming in comparison with the two other December major warmings in 1998 and 1987, which all show a strong tropospheric-stratospheric coupling.

2. Data Used

[5] Different data sets have to be used, depending on their availability, to describe the vertical development of the warmings consistently from the troposphere to the upper stratosphere. The historical analyses of the Free University Berlin (FUB) are available from Jul 1964–Jun 2001 but only for three stratospheric levels. The data assimilation systems of the European Centre for Medium-Range Weather Forecasts (ECMWF) are operational since 1979 but a version extending into the upper stratosphere is available since 1999; this data set is used for the recent winter 2001–02. The data of the United Kingdom Meteorological Office (UKMO), from the data assimilation system developed for the Upper Atmosphere Research Satellite project, are available since Oct 1991 and have been used here to describe the winter 1998–99. A detailed description of these three analysis systems and respective references can be found in *Manney et al.* [2002]. The Stratospheric Sounding Unit (SSU) analyses from UKMO are referred to TOVS/SSU after the main stratospheric instrument of the TIROS Operational Vertical Sounder (TOVS) systems measuring radiances. A detailed description of these data is given by *Bailey et al.* [1993]. They were available from Jan 1979–Jun 1998 and have been used for the winter 1987–88.

3. Synoptic Comparison

[6] The march of daily 10 hPa temperatures at the North Pole (Figure 1) clearly shows the magnitude and timing of the three earliest major warmings in the FUB data set. For all three winters similar features appeared:

- An early major warming took place in December.
- A second major warming occurred in the same winter in February/March, which was defined as a major final warming in 1987–88, but as a second major midwinter warming in 1998–99 and 2001–02. Two major warmings in the same winter were never observed before.

[7] Figure 2 shows the zonal mean zonal winds at 60°N ($\bar{u}$) and the zonal mean temperature differences between 60°N and the North Pole (ΔT) for all three winters (the reversals of these down to at least 10 hPa are the criteria for a major warming). The winter 2001–02 started with relatively weak westerly winds in the stratosphere. Around 21 Dec, large positive ΔT appeared between 1 and 20 hPa followed by easterly winds a few days later in the upper stratosphere, which propagated downward to 10 hPa until

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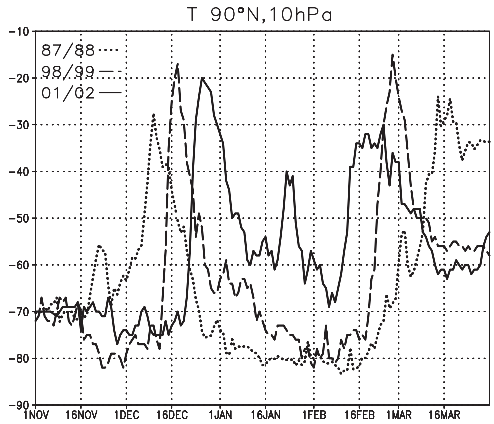

Figure 1. March of daily 10 hPa temperatures [°C] at the North Pole from 1 Nov to 31 Mar, derived from FUB analyses, except for the winter 2001–02 which is based on ECMWF analyses.

the end of December. The timing of ΔT and $\bar{u}$ reversals and their downward propagation are typical for a major warming. After this early event the circulation shortly recovered and westerlies re-established until the second half of January. Then a minor warming weakened the westerly flow before a second major warming took place in mid-February. For both major warmings in 2001–02 the criteria were fullfilled, however only for a short time.

[8] The early major warmings in the two other winters showed a more pronounced influence on the circulation in the middle and lower stratosphere, e.g. the easterlies in December 1987 and 1998 reached down to 30 and 50 hPa. In 1987–88, the first winter since 1955–56 with a December major warming, a very strong and cold midwinter period followed until mid-February and a second major warming occurred in March, leading directly to the final transition to summer conditions. The winter 1998–99 showed a similar cold, undisturbed midwinter period, however, the westerlies were not as strong as in 1987–88. The second major warming started at the end of February 1999 and led to a breakdown also in March. In contrast to the winter 1987–88, the polar vortex recovered and a late final warming took place in 1998–99 as in 2001–02. This strong event might have affected even the troposphere as can be seen in the easterlies as well as in the positive ΔT reaching down almost to the surface. Note that the development of the Northern Annular Mode as defined by *Baldwin and Dunkerton* [2001] in their Figure 1 resembles Figure 2 for the winter 1998–99: weak vortex regimes coincide with easterly winds and positive ΔT and vice versa for strong vortex regimes.

[9] Figure 3 shows the northern hemispheric distribution of temperatures and geopotential heights from the upper troposphere to the upper stratosphere on the days when the warming started to descend during the three similar events. The maps of 21 Dec 2001 show the typical vertical structure. A strong blocking is present over the northern Atlantic in the troposphere and is still visible in the lower stratosphere. At 10 and 1 hPa, an anticyclone is located over the northern Pacific and Siberia, respectively. A large warm area covers the western edge of this anticyclone, exhibiting maximum temperatures of about 0°C at 10 hPa and about +50°C at 1 hPa, which are not unusual during stratospheric warmings. The vortex centre is displaced from the pole and the geopotential height fields show a strong planetary wave number 1 with increasing amplitude and westward tilting phase as height increases. In the upper troposphere and lower stratosphere, wave numbers 2 and 3 are present too.

[10] The maps for the other cases, on 8 Dec 1998 and on 2 Dec 1987, show very similar patterns in the location and strength of the vortices and the distribution of temperatures. The similarity of the tropospheric situation is especially remarkable, with a strong blocking of the westerly flow over the northern Atlantic.

4. Tropospheric Preconditioning

[11] The development of the tropospheric circulation during December 2001 suggests a relation between intense

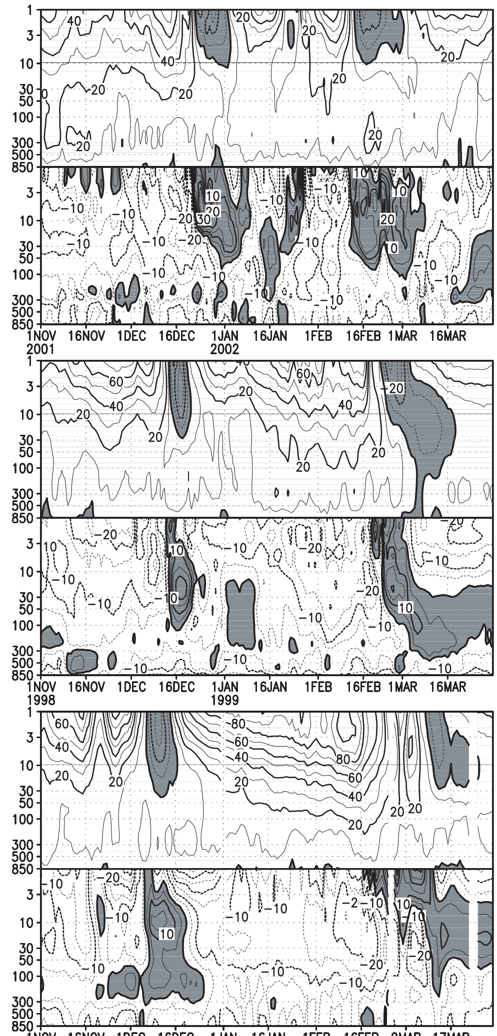

Figure 2. Time-height sections of zonal mean zonal wind [m/s] at 60°N and of the temperature gradient [K] between 60°N and the North Pole from 1 Nov to 31 Mar 2001–02 (ECMWF), 1998–99 (UKMO), and 1987–88 (TOVS/SSU); easterly winds and positive temperature gradients are shaded, the weak horizontal line in the wind plot indicates the 10 hPa level.

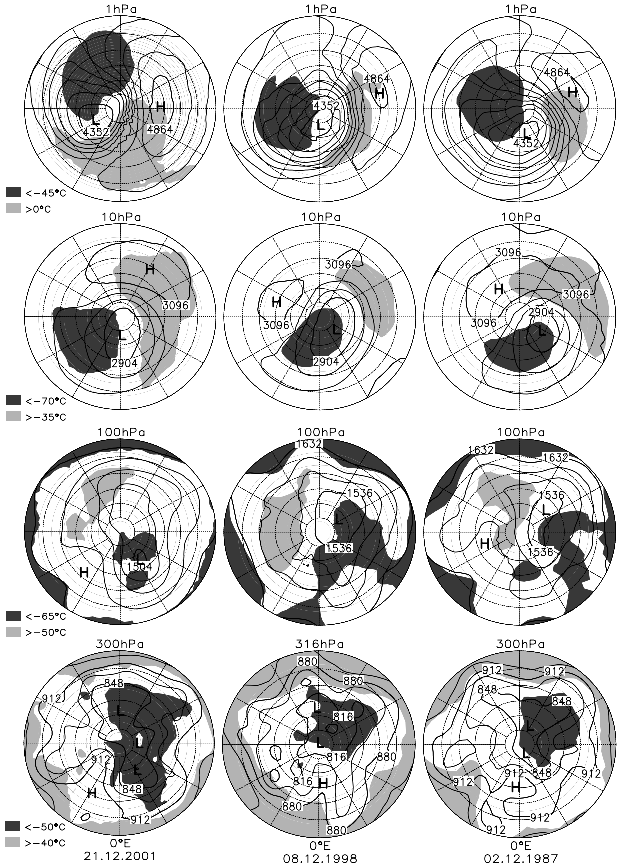

Figure 3. Northern hemispheric (north of 30°N) distribution of temperatures [°C] and geopotential heights [dam] at 1, 10, 100 and 300 (316) hPa on selected days in Dec 2001, 1998, and 1987; geopotential height intervals are 32 dam, light/dark shaded temperature areas are warmer/colder than the indicated values.

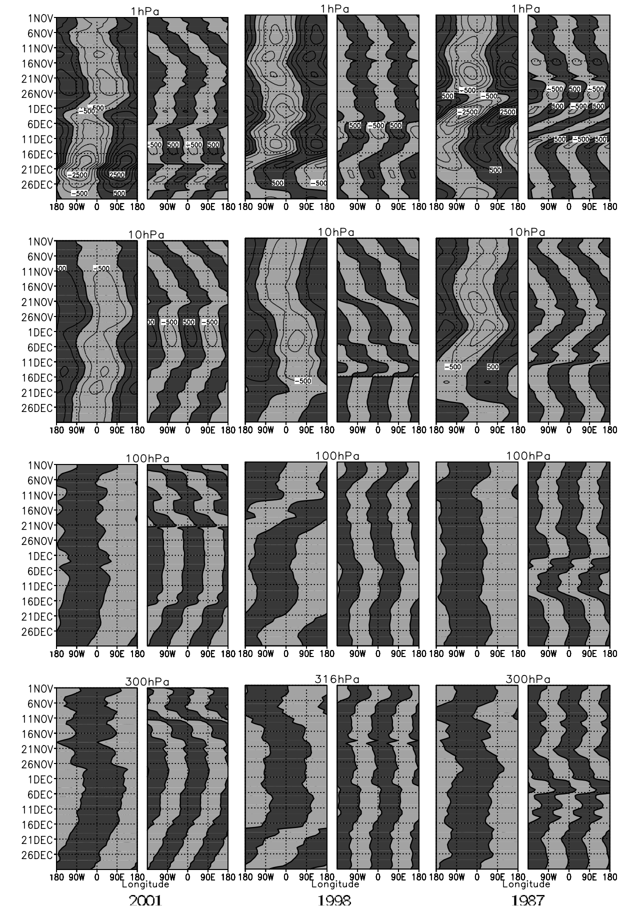

Figure 4. Hovmöller diagrams of the planetary height waves 1 and 2 at 60°N and at 1, 10, 100, and 300 (316) hPa in Nov/Dec 2001, 1998, and 1987; contour intervals are 500 m, light/dark shaded areas indicate negative/positive values.

Atlantic blocking phenomena and major stratospheric warmings as noted already by other authors, e.g. *Quiroz* [1986]. The first tropospheric disturbance was already observed in late November 2001, when a strong wave number 3 propagated from the troposphere into the lower stratosphere, weakening the polar vortex there (not shown). In early December, a large tropospheric blocking zone formed over Europe which continuously expanded westward. This unusual situation could be caused by small-scale, retrogressive travelling waves, leading to a highly disturbed tropospheric circulation. Finally, a strong blocking existed over the northern Atlantic from 11–24 Dec 2001 as was observed also from 27 Nov–11 Dec 1998 and from 1–14 Dec 1987. They all lasted about 14 days. The coincidence that this period was so close to the period of the travelling waves aloft (shown later) points to the possibility that the blocking high is building and decaying on a timescale similar to that of the travelling wave period and it therefore may be acting as an efficient forcing for these waves.

5. Wave Forcing

[12] Most of the time during winter, forced stationary waves dominate the stratospheric circulation. Sometimes free external Rossby waves are observed, which show coherent westward travelling components between the stratosphere and troposphere with some amplitude increase and almost no phase shift with height [*Hirooka and Hirota*, 1989]. They can not transport heat or momentum and hence do not directly influence the mean flow. Their influence arises from possible interactions with the quasi-stationary waves, leading through an amplification of that waves to fluctuations of the eddy heat transport into the stratosphere. Despite the obvious differences in the following wave

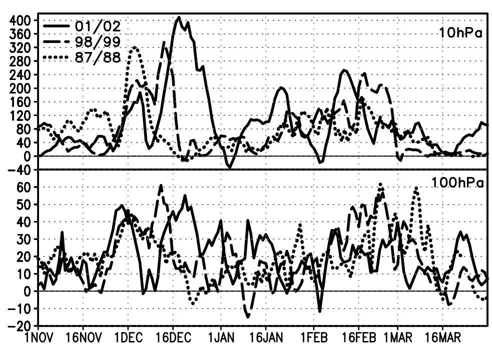

Figure 5. Heat flux [K m/s] at 100 and 10 hPa through 60°N from 1 Nov to 31 Mar.

analyses, all three cases show this interaction between a quasi-stationary wave number 1 and westward travelling waves number 1 or 2 (or both) in connection with a tropospheric blocking.

[13] The wave quantities presented here, are calculated as used in the wave climatology of *Pawson and Kubitz* [1996]. Zonal Fourier analysed geopotential height fields Z_s of wave number s = 1,2 are calculated as well as the total heat flux $\overline{v'T'}$. In Figure 4 Hovmöller diagrams for $Z_{1,2}$ are shown for all three discussed cases; they can just resolve the existence of dominant wave phenomena. To demonstrate the tropospheric forcing from below and its effect on the stratospheric circulation, $\overline{v'T'}$ at 60°N at 100 hPa and 10 hPa is illustrated in Figure 5.

[14] In winter 2001–02, a first peak of $\overline{v'T'}$ at 10 hPa arose from a strong eastward travelling Z_2, being at least partly responsible for an already weakened zonal mean flow in the stratosphere. Around Dec 11, when the strong blocking over the northern Atlantic was established, Z_2 clearly started to propagate westward at 300 and 10 hPa with a period of 16 days. After 21 Dec the Hovmöller diagram shows a coherent westward travelling Z_2 throughout the upper troposphere and stratosphere with an amplitude increase and no phase shift with height in correspondence with free external Rossby waves. It is interesting to note that the amplitude of Z_1 reaches maximum after Z_2 starts travelling westward, i.e., 16–22 Dec, suggesting a nonlinear wave-wave interaction as modeled by e.g., *Rose* [1983]. The interaction of these waves led to the second pronounced maximum of $\overline{v'T'}$ at 100 and 10 hPa on these days, which in turn indicate the preconditioning for the early major warming.

[15] The winter 1998–99 shows a weaker accordance to the other early warmings, however, a dominant westward propagating Z_1 with a shorter life time is visible from 1–11 Dec at 1 hPa (after 6 Dec at 316 hPa as well). This wave phenomenon possibly interacted with the quasi-stationary Z_1 leading to an amplification of that wave and of $\overline{v'T'}$ on these days.

[16] The earliest of all three major warmings, at the beginning of December 1987, started with a stationary Z_1 throughout the upper troposphere and stratosphere in November. At the end of November, when a strong tropospheric blocking over the northern Atlantic formed, Z_1 and Z_2 began to propagate westward, dominating the middle and upper stratosphere with a period of 20 days (around 5 days at 1 hPa). Again, almost no vertical phase shift was evident with an increase of the amplitude as height increases, indicating a free external Rossby wave. This time the interaction of two or even more waves led to a strong amplification of Z_1 (at 10 and 1 hPa) and $\overline{v'T'}$ (nearly simultaneously at 100 and 10 hPa). Around 10 days later the major warming criteria were fullfilled.

6. Summary

[17] We have presented clear evidence that in all three early major warming events strong tropospheric blockings were observed over the northern Atlantic 1–2 weeks prior to the warming, which seemed to initialize large-scale westward propagating waves with a coherent travelling component throughout the upper troposphere and stratosphere, resembling free external Rossby waves. Their influence on the zonal mean flow arose from possible interactions with tropospheric forced stationary waves which led through an amplification of that wave to fluctuations of the eddy heat transport into the stratosphere. We assume that the stationary waves broke and dissipated in the upper stratosphere where they decelerated the zonal mean flow and initiated the major warmings, which then started to descend downward and influenced the tropospheric circulation again.

[18] Such tropospheric-stratospheric interactions connected to major warming events in the stratosphere have been known already for a long time. In this, the December 2001 warming was not exceptional, however, the unusually early occurrence of such events in the last 15 years is possibly favoured by circulation changes in the troposphere/stratosphere which are a subject of current research. The most surprising coincidence of a second major warming in the same winter of the three comparable cases requires further studies.

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B. Naujokat, K. Krüger, K. Matthes, J. Hoffmann, M. Kunze, and K. Labitzke, Meteorological Institute, Free University Berlin, Carl-Heinrich-Becker-Weg 6-10, 12165 Berlin, Germany. (naujokat@strat01.met.fu-berlin.de)