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Latitudinal and longitudinal variability of mesospheric winds and temperatures during stratospheric warming events

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Abstract

Continuous MF and meteor radar observations allow detailed studies of winds in the mesosphere and lower thermosphere (MLT) as well as temperatures around the mesopause. This height region is characterized by a strong variability in winter due to enhanced planetary wave activity and related stratospheric warming events, which are distinct coupling processes between lower, middle and upper atmosphere. Here the variability of mesospheric winds and temperatures is discussed in relation with major and minor stratospheric warmings as observed during winter 2005/06 in comparison with results during winter 1998/99.

Our studies are based on MF radar wind measurements at Andenes (69°N, 16°E), Poker Flat (65°N, 147°W) and Juliusruh (55°N, 13°E) as well as on meteor radar observations of winds and temperatures at Resolute Bay (75°N, 95°W), Andenes (69°N, 16°E) and Kühlungsborn (54°N, 12°E). Additionally, energy dissipation rates have been estimated from spectral width measurements using a 3 MHz Doppler radar near Andenes. Particular attention is directed to the changes of winds, turbulence and the gravity wave activity in the mesosphere in relation to the planetary wave activity in the stratosphere.

Observations indicate an enhancement of planetary wave 1 activity in the mesosphere at high latitudes during major stratospheric warmings. Daily mean temperatures derived from meteor decay times indicate that strong warming events are connected with a cooling of the 90 km region by about 10–20 K. The onset of these cooling processes and the reversals of the mesospheric circulation to easterly winds occur some days before the changes of the zonal circulation in the stratosphere start indicating a downward propagation of the circulation disturbances from the MLT region to the stratosphere and troposphere during the stratospheric warming events. The short-term reversal of the mesospheric winds is followed by a period of strong westerly winds connected with enhanced turbulence rates and an increase of gravity wave activity in the altitude range 70–85 km.

Keywords: Stratosphere/mesosphere interactions; Middle atmosphere dynamics; Turbulence; Gravity waves; Energy dissipation

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1. Introduction

The mesosphere and lower thermosphere (MLT) is characterized by a strong variability during the winter months. Possible causes are planetary wave activity and related sudden stratospheric warmings (SSWs), discovered first by Scherhag (1952, 1960). After the generally accepted model by Matsuno (1971), the main physical mechanism responsible for SSWs is the interaction of planetary waves with the mean flow in the upper stratosphere, leading to an upward and poleward-directed heat and momentum flux connected with a weakening or reversal of the eastward-directed mean zonal flow in the stratosphere. Finally, such an event can lead to a breakdown or a splitting of the polar vortex at stratospheric heights. The occurrence of SSWs is also influenced by solar activity, especially during the east phase of the quasi-biennial oscillation (QBO) (Labitzke, 2000).

In connection with SSWs, a weakening or reversal of the dominating eastward-directed zonal winds to summerly westward-directed winds in the MLT region has been observed as reported e.g. by Gregory and Manson (1975), Cevolani (1989, 1991) Singer et al. (1992, 1994) and Jacobi et al. (1997, 2003). This effect is more pronounced at high northern latitudes (Hoffmann et al., 2002; Manson et al., 2006), but has also been observed in the Southern Hemisphere during the unusual midwinter warming of 2002 (Dowdy et al., 2004). Bhattacharya et al. (2004) investigated the variability of atmospheric winds and waves using a Michelson interferometer at Resolute Bay (75°N, 95°W) during stratospheric warming in February 2001. They found a decrease in the amplitude of the semi-diurnal tide after the reversal of the zonal winds in the MLT region and an increase in the activity of waves with periods of about 8 h before stratospheric temperatures reached their maximum. Furthermore, their results suggest that the amplitude of the diurnal tide is stronger during peak stratospheric temperatures.

Additionally, case studies have shown that events with a sudden temperature increase at stratospheric heights not only affect the zonal wind in the stratosphere, but also lead to a cooling at mesospheric heights as reported for the first time by Labitzke (1972). These results have been confirmed by Walterscheid et al. (2000) and recently by Cho et al. (2004) in relation with airglow observations. Liu and Roble (2002) examined SSWs using model studies and concluded that the deceleration and reversal of the stratospheric jet allows more eastward propagating gravity waves into the MLT region, forcing an equatorward-directed meridional circulation responsible for the upper mesosphere cooling. Also, temperature data from the sounding of the atmosphere with broad band emission radiometry (SABER)—instrument on the NASA TIMED satellite show a clear signature of mesospheric coolings during three winter periods with SSWs in February 2002, August, 2002, and February 2003, respectively (Siskind et al., 2005).

The present study deals with the dynamical and thermal status of the mesosphere using radar wind measurements supplemented by daily mean mesopause temperatures at Andenes in winter 2005/06 partly in comparison with results from winter 1998/99. Measurements at other locations between 75°N and 54°N are used to study the longitudinal and latitudinal dependence of the mesospheric circulation during SSWs. Section 2 provides an overview of the radar experiments and data analysis. SSWs and the characteristic vertical coupling processes between lower, middle and upper atmosphere are discussed in Section 3. Particular attention is directed to the changes of winds, turbulence and gravity wave activity in the mesosphere in relation to planetary wave activity in the stratosphere.

2. Radar experiments and data analysis

Continuous measurements of winds in the mesosphere and lower thermosphere as well as temperatures around the mesopause have been carried out with MF radars and meteor radars at Andenes (69°N, 16°E), Juliusruh (55°N, 13°E) and Kühlungsborn (54°N, 12°E); for details see also e.g. Hoffmann et al. (2002) and Singer et al. (1992, 2003a, 2005). The observations in the European region are supplemented by observations at Resolute Bay (75°N, 95°W) and Poker Flat (65°N, 147°W) in Canada and Alaska (Hocking et al., 2001a; Murayama et al., 2000). The basic parameters of the radars used in this study are summarized in Table 1.

The Andenes MF radar operates at 1.98 MHz with a peak power of 40 kW applying the spaced antenna technique. A wide-beam antenna transmits vertically radio wave pulses of 4 km length. Their atmospheric returns are received by three crossed horizontal dipoles arranged in an equilateral triangle (Singer et al., 1997). The radar continuously

Table 1
Radar specifications

Parameters	Poker Flat	Resolute Bay	Andenes	Andenes	Andenes	Kühlungsborn	Juliusruh
Location	65°N, 147°W	75°N, 95°W	69°N, 16°E	69°N, 16°E	69°N, 16°E	**54**°N, **12**°E	54°N, **13**°E
Frequency (MHz)	2.43	51.5	1.98	3.17	32.55	53.5	3.18
Peak power (kW)	50	12	40	116	12	40	128
Half power pulse width (μs)	27	13	27	10	13	13	27
Observation mode	FCA	Meteor	FCA	Doppler	Meteor	Meteor	FCA

provides horizontal winds and tides at altitudes between 60 and 92 km since 1998 using the full correlation analysis method.

The all-sky meteor radars at Andenes (32.55 MHz) and Kühlungsborn (53.5 MHz) apply an antenna system with crossed antenna elements to ensure a nearly azimuthal sensitivity to meteor echoes. A three-element Yagi antenna is used for transmission. On reception a five-antenna interferometer provides a range resolution of 2 km and an angular resolution of 2° in meteor location. From each meteor the radial velocity of the meteor trail due to its movement with the background wind is estimated. One-hour bins of data arranged in height intervals of 3 km are used to determine horizontal winds between 80 and 98 km. An all-sky least-squares algorithm is used in each bin to estimate the mean zonal and meridional wind from the measured radial velocities (for details see Hocking et al., 2001b).

Daily mean temperatures were estimated at the peak of the meteor layer at about 90 km (32.55 MHz) and about 87 km (53.5 MHz). Temperatures were derived from height variation of the meteor decay time (inversely proportional to the log of the ambipolar diffusion coefficient) in combination with an empirical model of the mean temperature gradient at the peak altitude of the meteor layer (for details see Singer et al., 2004; Hocking et al., 2004).

We combined here the winds obtained by the MF radar and meteor radar to get reliable winds over an extended altitude range from 70 to 94 km. The most reliable data with optimum acceptance rates are selected from both experiments at Andenes as well as at Juliusruh/Kühlungsborn: MF radar winds from 70 to 82 km and meteor winds from 82 to 94 km. Similar selection criteria were also used by Hocking and Thayaparan (1997) and Manson et al. (2004). The estimation of gravity wave activity is based on hourly mean winds. Prevailing winds,

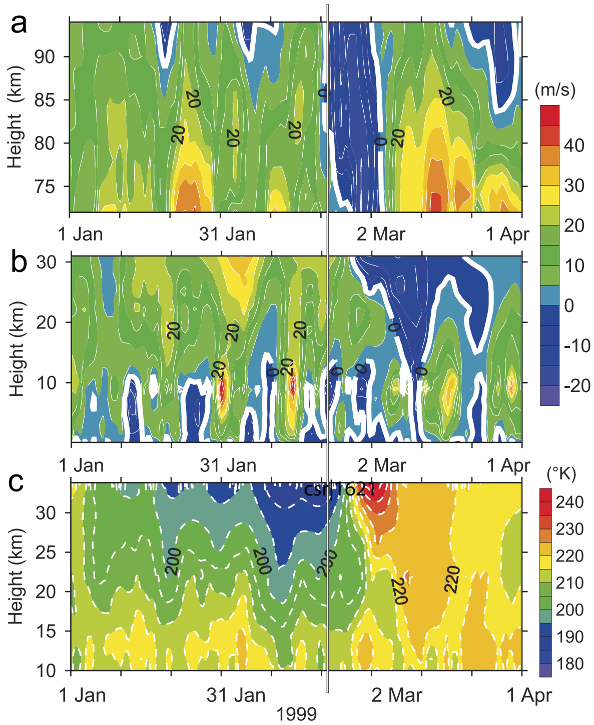

Fig. 1. Characteristic changes of zonal winds (chart a: mesosphere; chart b: stratosphere) and temperatures (chart c: stratosphere) above Andenes during a stratospheric warming event in winter 1998/99 (mesospheric data: Andenes MF radar; stratospheric data: ECMWF). The vertical line indicates the onset of the wind reversal in the mesosphere.

diurnal and semi-diurnal tides are obtained from least-squares fits of 4-day composite days shifted by one day. Spectra of long-term wind variations were derived from hourly mean values for overlapping 30-day intervals shifted by 10 days. The spectral analysis is based on a modified discrete Fourier transform with a non-linear scale to expand the low-frequency range (e.g. Meek et al., 1996).

Turbulence parameters were derived from spectral width measurements performed by the Saura MF radar, which is only a few kilometers apart from the Andenes MF radar and meteor radar. The observed spectral width is determined by turbulent and non-turbulent processes. The dominant non-turbulent process is spectral broadening caused by the background wind in case of a radar beam width greater by about 4°. The Saura MF radar is operated at 3.17 MHz with a peak power of 116 kW (Singer et al., 2004). The transmitting/receiving antenna with a beam width of 6.4° (full width at half power) consists of 29 crossed half-wave dipoles arranged as a Mills Cross. The narrow beam is essential for reliable turbulence estimates since spectral broadening of the measured spectral width can be precisely estimated using winds simultaneously measured by the same radar to obtain the turbulent spectral width (Hocking, 1983; Latteck et al., 2005). Hourly means of turbulent energy dissipation rate are derived from the turbulent spectral width and the Brunt–Väisälä frequency taken from a climatology of in situ falling sphere measurements at Andenes (Lübken, 1999).

Information on stratospheric circulation disturbances in winter was taken from the stratospheric analyses regularly performed by the Stratospheric

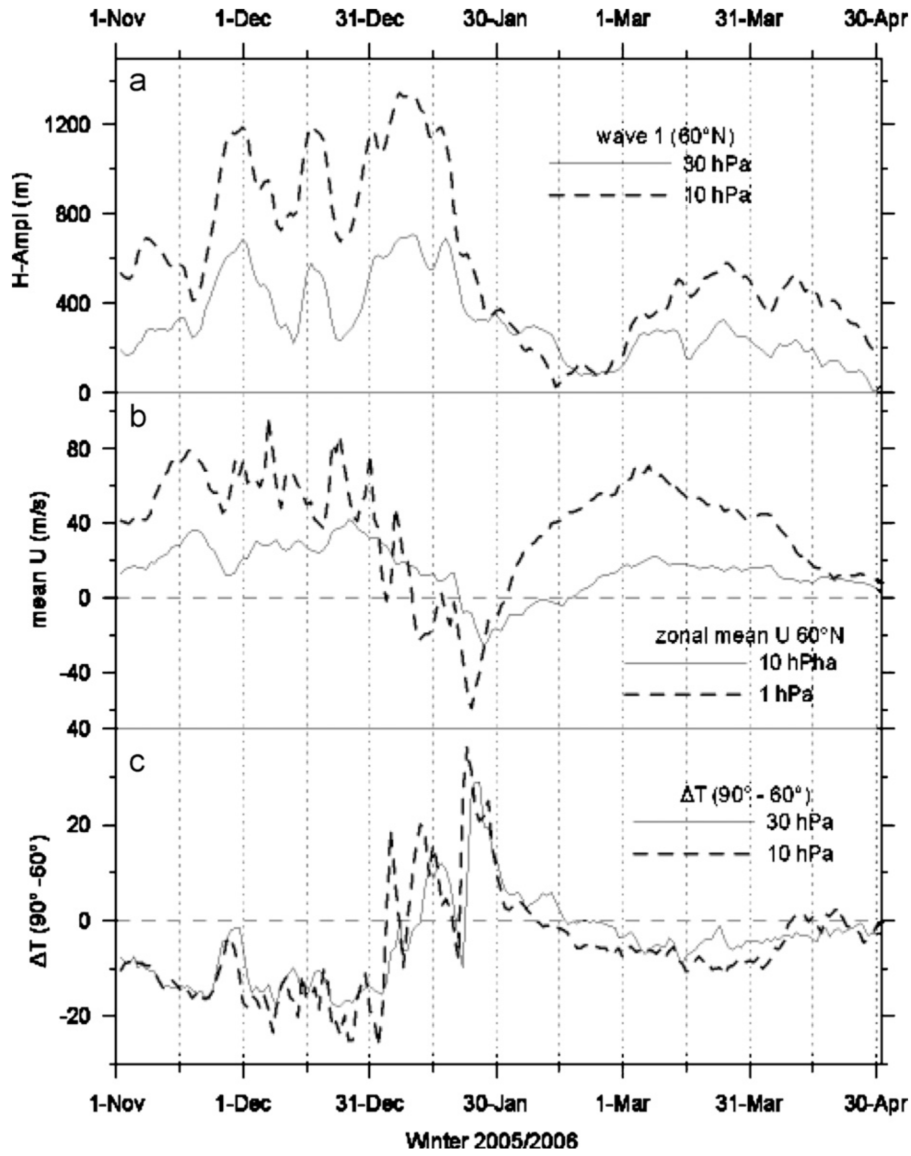

Fig. 2. The stratospheric winter 2005/06 at 60°N after ECMWF data at 60°N: (a) amplitudes of height wave 1; (b) mean zonal wind; and (c) temperature difference (90°N–60°N) at 30 and 10 hPa.

Research Group of the FU Berlin since 1965. We are following here the classification of stratospheric warming effects after Labitzke and Naujokat (2000).

3. Results and discussion

SSWs are considered here as an exceptionally characteristic vertical coupling process between the lower, middle and upper atmosphere. One essential feature is the downward propagation of the circulation disturbances as demonstrated in Fig. 1 by a typical example of the reversal of zonal winds in the mesosphere at Andenes (69°N, 16°E) in comparison with the corresponding ECMWF data in the troposphere/lower stratosphere during winter 1998/99 (more details of this winter can be found in Hoffmann et al. (2002) and Fig. 3 therein). The vertical bar indicates the onset of wind reversal in the mesosphere, which occurs about 6 days before changes of the zonal circulation in the stratosphere start. The onset of the warming itself in the stratosphere at about 30 km coincides with the onset of the wind reversal at 30 km. Results from 1-D and 3-D model experiments by Plumb and Semeniuk (2003) yield similar behavior with a downward migration of zonal wind anomalies, induced by a purely local interaction between upward propagating waves and zonal mean flow.

The state of the stratosphere in winter 2005/06 at 60°N is described with ECMWF data in Fig. 2 by the amplitudes of planetary wave 1 at 30 and 10 hPa (a), by the reversal of stratospheric circulation (b), and by the meridional temperature difference between 90°N and 60°N at the 30 and 10 hPa levels (c). Planetary wave 1 is intensified from the beginning of December until mid-January. Due to wave/mean flow interaction, the enhanced planetary wave activity leads to an upward and poleward-directed heat flux connected with a reversal of the stratospheric circulation, which can be estimated from the divergence of the Eliassen–Palm flux

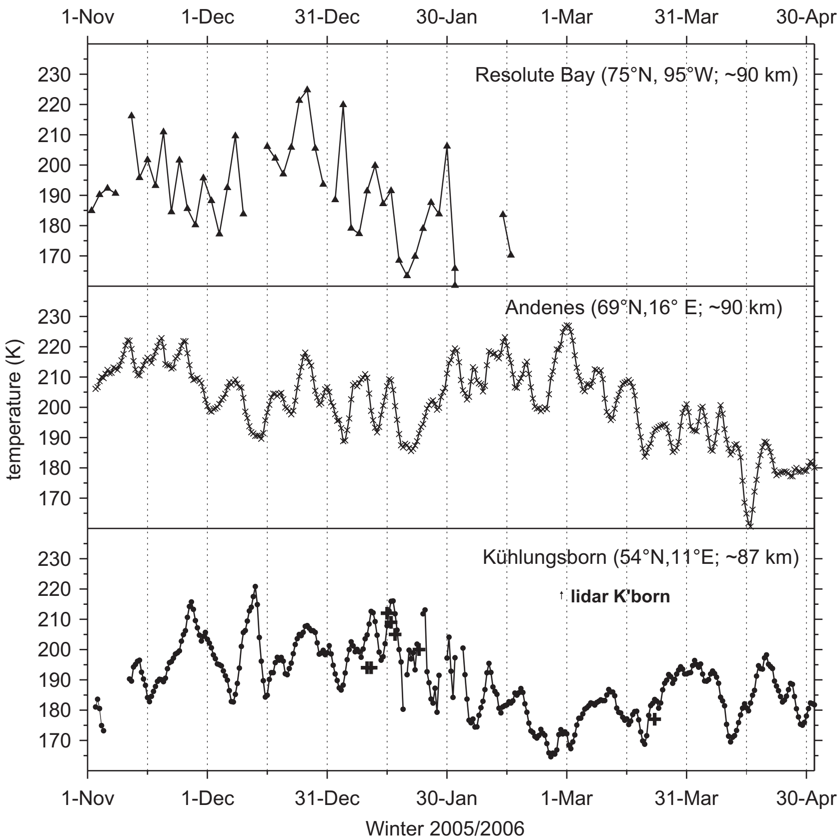

Fig. 3. Mesospheric temperatures derived from meteor radar decay times at Resolute Bay (75°N; ~ 90 km), Andenes (69°N; ~90 km) and Kühlungsborn (54°N; ~ 87 km); additional lidar temperature data at Kühlungsborn are marked with +. Stratospheric warming events, indicated by arrows, are accompanied by mesospheric coolings.

vector (e.g. Andrews et al., 1987), and to strong reversals of the meridional temperature gradients with a maximum on 23 January 2006 characterizing this event as a major stratospheric warming. This warming was preceded by two other warming pulses on 2 and 13 January 2006. All of the stratospheric warmings were accompanied by mesospheric coolings over Andenes (69°N, 16°E) as shown by temperatures derived from meteor radar observations at about 90 km (Fig. 3). The major warming on 23 January leads at all sites to a cooling with the lowest mesospheric temperatures at Resolute Bay (75°N, 95°W). The temperatures obtained at Kühlungsborn (lower panel of Fig. 3) are supplemented by mean night-time temperatures at 90 km derived from potassium lidar observations at the same site (Gerding and Rauthe, private communication), demonstrating an agreement between both techniques.

The seasonal variation of mesospheric mean zonal winds at Andenes and Juliusruh/Kühlungsborn from 1 November 2005 to 30 April 2006 is shown in Fig. 4 by combined meteor radar and MF radar winds. At both locations (upper panel: Andenes; lower panel: Juliusruh/Kühlungsborn) short-term reversals from eastward to westward-directed winds are detected up to a height of 94 km around the SSWs. The zonal wind reversal related with the major warming on 23 January 2006 is followed by a period of intensified eastward-directed winds; this effect as well as the strengths of the short-term wind reversals are stronger at high

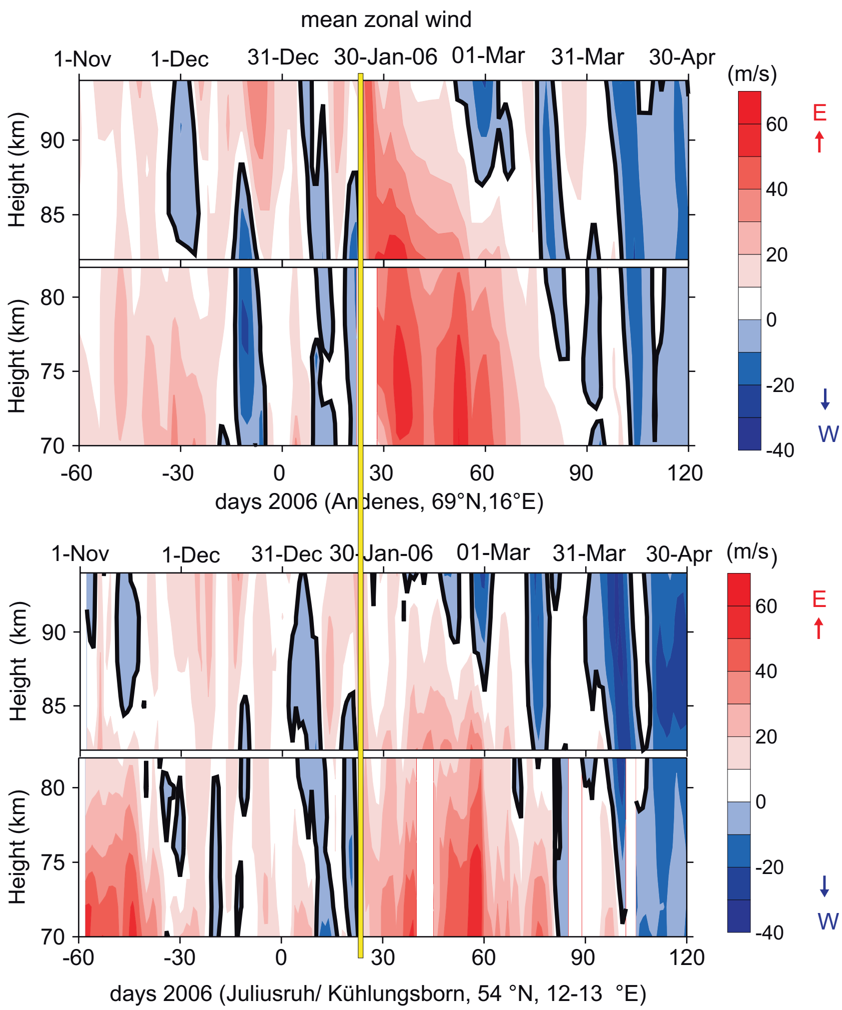

Fig. 4. Seasonal variation of mean zonal winds at Andenes (upper panel) and Juliusruh/Kühlungsborn (lower panel) from 1 November 2005 until 30 April 2006 (70–82 km: MF radar; 82–94 km: meteor radar). The yellow line indicates the date of the major warming on 23 January 2006.

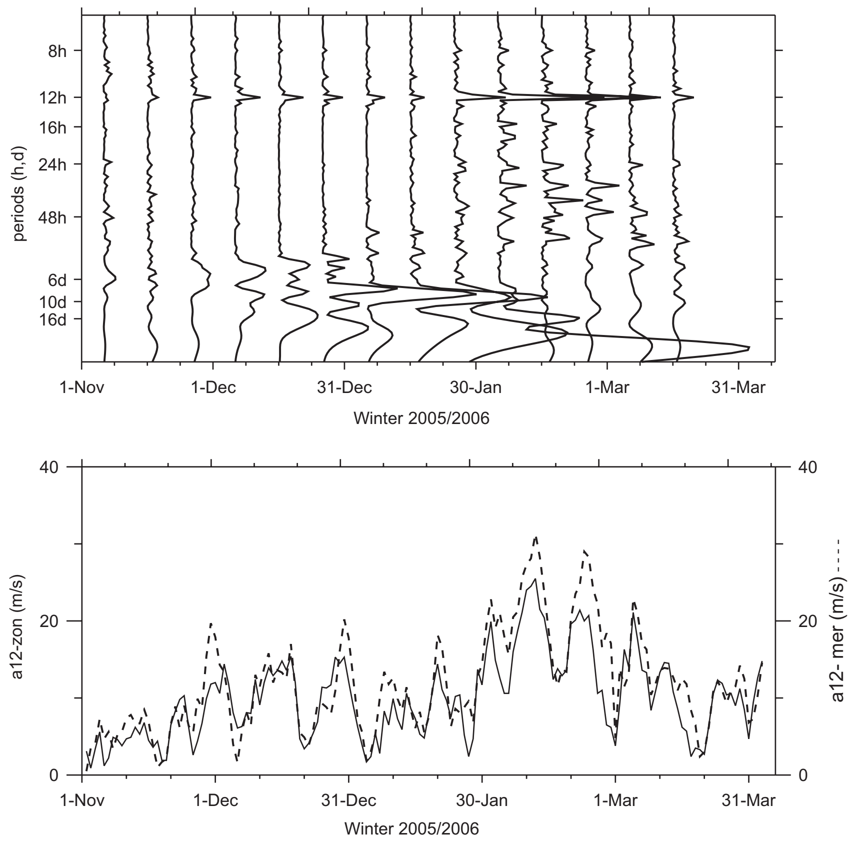

Fig. 5. Long periodic oscillations of meridional winds (upper panel) and semi-diurnal tidal components (lower panel; full line: zonal component; dashed line: meridional component) derived after meteor radar observations at an altitude of 82 km at Andenes in winter 2005/06.

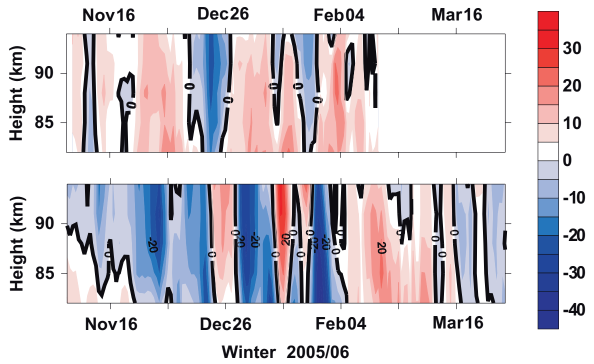

Fig. 6. Seasonal variation of meridional winds derived from meteor radar measurements at Andenes (69°N, 16°E; lower panel) and Resolute Bay (75°N, 95°W; upper panel) from 1 November 2005 until 31 March 2006.

latitudes at Andenes in comparison with the results at mid-latitudes. However, the observed latitudinal dependence of the wind reversal of eastward-directed winds with reduced magnitudes towards the equator was more pronounced during an SSW in 1998/99 (Hoffmann et al., 2002, Figs. 5 and 6).

As mentioned in the introduction after the generally accepted theory by Matsuno (1971), SSWs are caused by the interaction of planetary waves with the mean flow in the upper stratosphere leading to an upward and poleward-directed heat flux. To investigate the planetary wave activity in the mesosphere, spectral analyses of zonal and meridional winds have been performed to find long-period wind oscillations at mesospheric heights. The upper panel of Fig. 5 shows the results of the spectral analysis of meridional winds after meteor radar observations at an altitude of 82 km above Andenes during winter 2005/06. The spectra were derived from hourly mean values for overlapping 30-day intervals shifted by 10 days. The semi-diurnal tide is present during the whole winter with increased amplitudes in February 2006. During this time, long-period oscillations with a peak at about 10 days indicate enhanced planetary wave activity at mesospheric heights. It is remarkable that the amplitudes of the dominating semi-diurnal tidal components at 82 km (lower panel of Fig. 5) are also subject to a strong 10-day variation, indicating a modulation of the semi-diurnal tide by planetary waves. Studies of such modulation have been done by Pancheva et al. (2002, 2006). In contrast to the study of Bhattacharya et al. (2004) we found an increase in the amplitude of the semi-diurnal tide after the stratospheric warming events and no enhanced waves with periods of about 8 h before peak stratospheric temperatures are reached.

Fig. 6 shows a comparison of the seasonal variation of meridional winds derived from meteor radar measurements at Resolute Bay (75°N, 95°W; upper panel) and Andenes (69°N, 16°E; lower panel) for the period from 1 November 2005 until 31 March 2006. Around the time of the stratospheric warming the winds are nearly opposite at both stations, suggesting the presence of a zonal wave 1 structure in the mesosphere. A similar result was found in winter 1998/99 using MF radar observations at Andenes and Poker Flat (65°N, 147°W) during winter 1998/99. Fig. 7 describes the variability of the zonal and meridional winds at 82 km; the times of major stratospheric warmings are indicated by vertical dashed lines. The zonal wind undergoes only weak longitudinal variations during major warmings but the meridional winds are nearly opposite at both locations. The longitudinal distance of about 163° of both sites indicates the presence of a zonal wave number 1 structure.

During winter 2005/06 the new narrow beam Saura MF radar (Latteck et al., 2005; Singer et al., 2003b) has been used to estimate turbulent energy dissipation rates from December 2005 until June 2006 as shown in Fig. 8c. This period includes both the time of the stratospheric warming and of the spring transition of the mesospheric circulation (marked by arrows at the top of Fig. 8). The observed zonal winds above Andenes between 10, December 2005 and 27, June 2006 are shown in Figs. 8a, b. Energy dissipation rates between about 3 mW/kg and up to 50 mW/kg are found at altitudes below 80 km in winter 2005/06. The dissipation rates decrease to values lower than 7 mW/kg in early summer starting in the middle of April. This reduction of turbulence is accompanied by the reversal of the mesospheric wind system from eastward-directed winds in winter to westward-directed winds in summer. The wind reversal

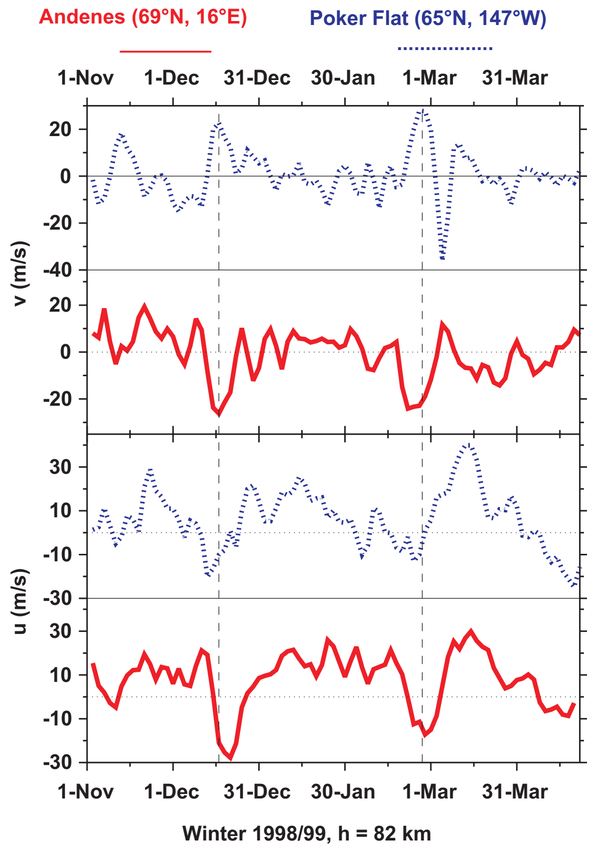

Fig. 7. Variability of zonal and meridional winds at 82 km above Andenes (solid lines) and Poker Flat (short dashed lines) in winter 1998/99. The vertical long-dashed lines indicate the times of major stratospheric warmings.

changes the propagation conditions of gravity waves which dissipate at higher altitudes in summer, resulting in a decrease of turbulence at lower heights. This result is consistent with in situ measurements of mesospheric turbulence during the MIDAS/SPRING rocket campaign at Andenes in May 2000 (Müllemann et al., 2002).

Enhanced turbulent energy dissipation rates are observed from February until the middle of March in the altitude range 60–85 km. This period of enhanced turbulence goes along with the presence of intensified westerly winds following the SSW-related wind reversal. At the same time enhanced activity of gravity waves with periods between 3 and 6 h as well as between 6 and 9 h is observed at altitudes between 70 and 85 km as shown in Figs. 8d–g. The gravity wave activity is derived from hourly MF and meteor radar winds using a summarized scaled-average wavelet power (Torrence and Compo, 1998). The results show a stronger activity of waves

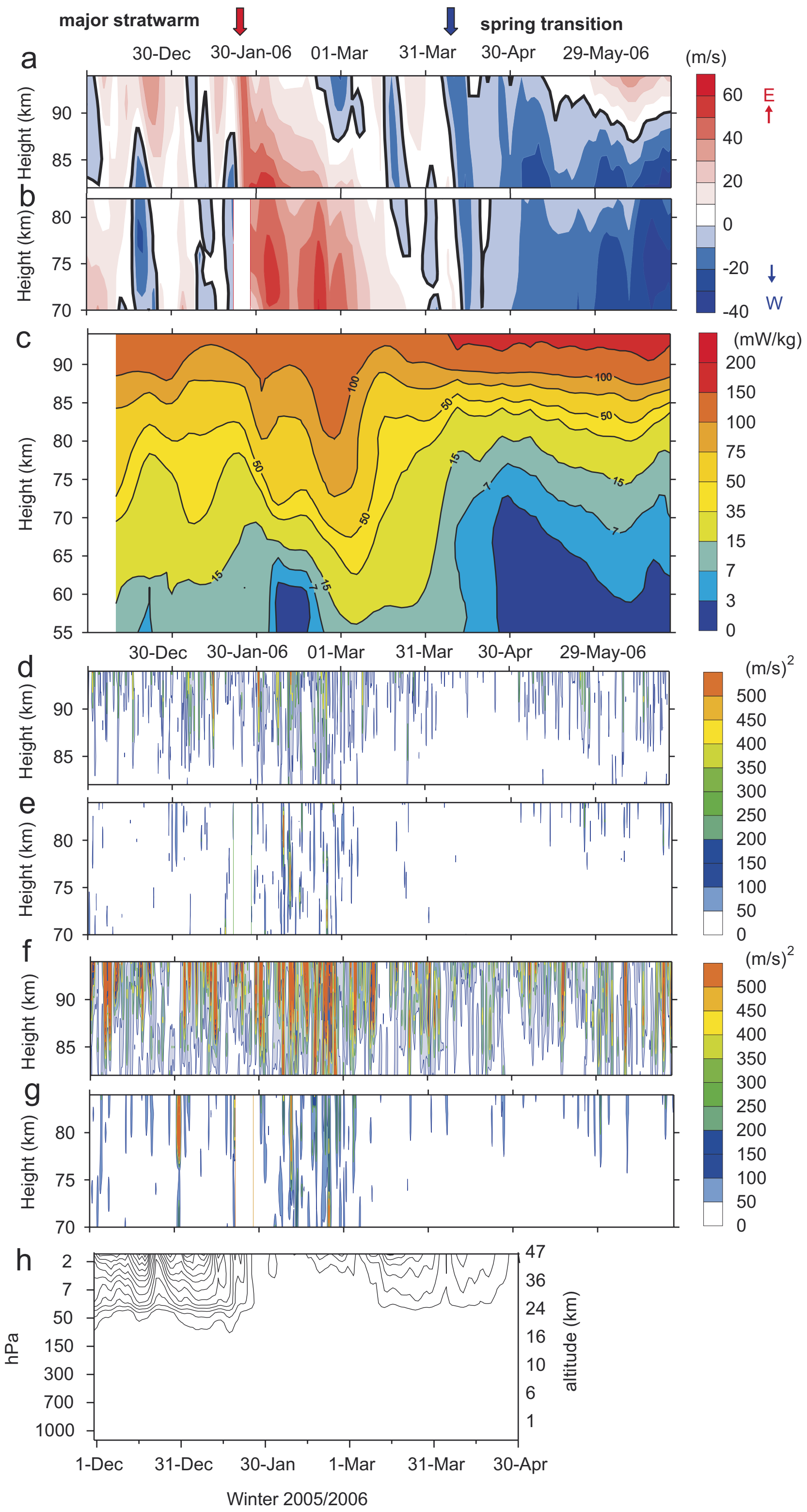

Fig. 8. Seasonal variation of zonal winds (a, b), turbulent energy dissipation rate (c), activity of gravity waves with periods between 3 and 6 h (d, e), as well as between 6 and 9 h (f, g) and amplitude of height wave 1 in the stratosphere (h) presented by contour lines starting with an amplitude of 500 m in steps of 200 m. The data are provided by meteor radar (a, d, f), Saura MF radar (c), Andenes MF radar (b, e, g) and ECMWF (h).

with periods between 6 and 9 h, whereas waves with periods between 3 and 6 h contribute with a rate of about 20% to the total gravity wave activity between 3 and 9 h.

The period of enhanced gravity wave activity appears if the amplitudes of stratospheric planetary wave 1 are reduced as depicted in Fig. 8h by the amplitude variation of height wave 1 (amplitudes less than 500 gpm are suppressed). The reduced planetary wave activity allows the propagation of gravity waves through troposphere/stratosphere up to mesospheric heights, where the waves dissipate resulting in enhanced turbulent energy dissipation rates.

The planetary wave activity is enhanced in the stratosphere until the end of January when the stratospheric warming appears and also in the mesosphere long-period wind oscillations with periods of about 10 days are found at the same time (Fig. 5). The open question "Can planetary waves propagate from the stratosphere up to the mesosphere and essentially change mesospheric winds and temperatures?" is the subject of a further study using simulations with the Kühlungsborn mechanistic general circulation model (KMCM); for details see Becker and Schmitz (2001, 2003) and Becker (2004).

4. Conclusion

Continuous MF and meteor radar observations have been used for detailed studies of winds and temperatures in the upper mesosphere and lower thermosphere to understand the strong variability in winter due to enhanced planetary wave activity and related stratospheric warming events. These events are considered as an exceptionally characteristic vertical coupling process between the lower, middle and upper atmosphere. The observations clearly show a downward propagation of circulation disturbances with an earlier onset of zonal wind reversal in the mesosphere compared with that in the upper stratosphere. The strength of wind reversal or weakening of the eastward-directed winds decreases with latitude. There are only weak longitudinal variations of zonal winds and temperatures at mesopause heights during major warmings but stronger longitudinal variations of meridional winds. The observations indicate the occurrence of a planetary wave 1 structure in the mesosphere.

During winter 2005/06 daily mean temperatures have been derived from meteor decay times. Strong warming events are connected with a cooling of the 90-km region by about 10–20 K. The short-term reversal of the mesospheric winds is followed by a period of intensified westerly winds connected with enhanced turbulent energy dissipation rates below 85 km and an increase of the gravity wave activity in the altitude range of 70–85 km. The enhanced gravity wave activity goes along with a period of reduced activity of planetary wave 1 in the stratosphere.

The reduced gravity wave activity and energy dissipation rate in the MLT region as well as the observed cooling of this region during the SSW are consistent with the interpretation of mesospheric cooling by Holton (1983). This mechanism suggests that strong planetary waves propagate up to mesospheric heights and filter out most of the gravity waves. When the polar vortex is reestablished after the SSW as indicated here by the period of intensified westerly winds, the planetary waves are rather weak and gravity waves can propagate up the mesopause where they dissipate in accordance with the observed strong energy dissipation rates and enhanced gravity wave amplitudes.

Future tasks are directed to modeling studies to understand the experimental results and to a detailed analysis of gravity waves, tides and long-period waves in combination with observed turbulent heating rates to get a better knowledge of "wave–wave" and "wave–mean flow" interactions.

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