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Composite analysis of the temporal development of waves in the polar MLT region during stratospheric warmings

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ABSTRACT

During winter the wind field in the mesosphere/lower thermosphere (MLT) at middle and polar latitudes is characterized by a strong variability due to enhanced planetary wave activity and related stratospheric sudden warming (SSW) events. Such events are considered as distinct vertical coupling processes influencing the atmosphere below and above the stratosphere. In the last 12 years, an enhanced number of SSW, compared to the period from 1989 to 1998, has been observed in the northern hemisphere. Every SSW is connected with different effects in the MLT (strength and temporal development of wind reversals, temperature changes, wave activity, longitudinal dependence). To characterize the average behavior of the mesospheric response to strong SSWs, we combine high-resolution wind measurements from MF- and meteor radar at Andenes (69°N, 16°E) with global temperature observations from MLS aboard the Aura satellite for SSW events with a return to the middle atmosphere normal winter condition afterwards. Our aim is to identify characteristic wave patterns which are common to the majority of these events and to define the average characteristics of the SSW-related wave activity in the MLT. These will be compared to the relatively quiet winter 2011 with only a short minor warming without a wind reversal and to the wave activity in 2009 and 2010. The results show clear signatures of enhanced mesospheric planetary wave activity before and during the SSW and an earlier onset of the short term wind reversal in the mesosphere compared to wind and temperature changes in the stratosphere. The strong eastward winds at altitudes below 80 km after SSW are connected with an enhanced gravity wave activity caused by changed filter conditions. This provides evidence for a strong modulation of semidiurnal tidal amplitudes before and during SSW by planetary waves. However, no clear relation has been found in the temporal development of tides relative to the onset of the selected SSW events.

1. Introduction

Stratospheric sudden warming (SSW) events are exceptional vertical coupling processes during winter which significantly affect all atmospheric layers. The main physical mechanism has first been explained by Matsuno (1971). According to that, SSWs are caused by upward propagation of planetary waves (PW) and their interaction with the zonal mean flow (for details see also Andrews et al., 1987, Chapter 6). SSW can be classified into minor, major and canadian warmings (Labitzke and Naujokat, 2000). Major SSWs, which will be considered in this paper, occur when the zonal mean zonal wind reverses from a westerly to an easterly direction, connected with a displacement or even splitting of the polar vortex at stratospheric heights (e.g., Krüger et al., 2004).

There is a large number of studies describing the individual responses of SSWs regarding the dynamical and thermal structure of the tropo- and stratosphere and of the mesosphere/lower thermosphere (MLT). For tropospheric and stratospheric altitudes, Charlton and Polvani (2007) constructed a mean climatology to summarize the main characteristics of SSWs between 1958 and 2002. They also showed a reduction in the SSW activity during the mid-1990s. While there is consensus that coupling processes in the lower atmosphere during SSW are mainly related to PW anomalies, the coupling processes to the upper layers including the role of PW, tides and gravity waves (GW) are less clear. In connection with SSWs, a weakening or reversal of the dominating eastward directed zonal wind to summerly westward directed wind in the MLT has been observed by a large number of authors (e.g., Gregory and Manson, 1975; Cevolani, 1989, 1991; Singer et al., 1994; Jacobi et al., 1997, 2003).

Based on observations at mid-latitudes (Juliusruh, 54°N, 13°E) during the winter months from 1989 to 2000, Hoffmann et al. (2002) summarized the responses of the mesospheric wind field

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to stratospheric circulation disturbances and to the stratospheric PW activity. Their results showed that $\sim 85\%$ of all mesospheric wind variations are related to changes of meridional temperature gradients between 90°N and 60°N towards positive values at the 10 or 30 hPa levels during winter. They also showed indications of enhanced long period oscillations in the mesosphere during all SSWs, in agreement with the case study of Cevolani (1989).

In general, it is well accepted, that also in the mesosphere most processes in connection with SSW are related to planetary wave anomalies. These waves interact with tides and GW. For example, during the SSW in January 2006, Hoffmann et al. (2007) found a modulation of the amplitudes of semidiurnal tides by PWs at Andenes (69°N, 16°N). The two most dominant PWs during major SSWs seem to be the 10-day (here: periods between 8 and 12 days) and 16-day wave (periods between 12 and 20 days) (see e.g., Palo et al., 2005; Pancheva et al., 2008; Krüger et al., 2004), even if there are other planetary wave periods too (see e.g., Pancheva et al., 2009; Azeem et al., 2005; Chshyolkova et al., 2007, 2006). Interestingly, these processes are more pronounced at polar latitudes above 60°N (e.g., Manney et al., 2005). However, the study of the mesospheric response to the SSW 2010 by Stober et al. (2012) indicate a stronger effect at Juliusruh (54°N) compared to the results at Andenes (69°N).

The sudden increase of the temperature at stratospheric heights does not only affect the zonal wind at all altitudes, but also leads to a cooling at mesospheric heights as first reported by Labitzke (1972). These results have been confirmed by Liu and Roble (2002) using simulations with the coupled TIME-GCM/CCM3. They found a cooling in the mesosphere by ~ 50 K which seems to be related to changes of GW activity as proposed by Holton (1983) and later discussed, e.g., by Siskind et al. (2005) using SABER temperatures for the investigation of mesospheric coolings during SSW.

The simulations by Liu and Roble (2002) also show a warming in the lower thermosphere by 20–30 K between 120 and 130 km, which has been recently confirmed by observations with the Incoherent Scatter Radar (ISR) at Millstone Hill (Goncharenko and Zhang, 2008) and by the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) experiment on board the Envisat satellite (Funke et al., 2010). However, the mechanisms leading to these changes are not clear. It is assumed, that both upward propagating tides and also GW and PW are responsible for these coupling processes during SSWs. The influence of tides on vertical coupling processes up to the ionosphere has been shown by Pedatella and Forbes (2010). Furthermore, model results by Liu et al. (2010) indicate that the planetary wave activity related to SSW is concentrated at high latitudes, but also that the nonlinear interaction between tides and PWs enhances migrating and nonmigrating tides globally.

Thus, the general contribution of waves with different scales to MLT dynamics during SSW is a matter of numerous recent studies. The dominating role of PW as mesospheric precursor of the record breaking SSW 2009 has been shown by Coy et al. (in press) using a data assimilation system spanning the 0–90 km altitude range. The characteristics of GW during SSW have been studied, e.g., by Ratnam et al. (2004), Wang and Alexander (2009), and at mesospheric heights by Siskind et al. (2010), Yamashita et al. (2010a,b), and Hoffmann et al. (2007). However, as pointed out by Siskind et al. (2010), the impact of GW together with PW and tides driving the mesospheric response to SSW remains still uncertain and seems to depend on the polar vortex (e.g., Ratnam et al., 2004; Wang and Alexander, 2009; Yamashita et al., 2010a).

Case studies clearly show that every SSW is connected with different effects in the MLT, e.g., regarding the strength and temporal development of wind reversals and temperature changes, the wave structure, but also the longitudinal dependence of all observed effects. However, while each major SSW reveals its own particular properties, some of the features are repeatable from event to event and form a characteristic pattern. It is this pattern which is common to all or at least most SSWs that we present in this article. In order to meet this objective, we will summarize the mean observations during the major SSWs between 1998 and 2010 to unravel the repeatable pattern of the most prominent waves dominating during these vertical coupling processes.

In this article, we analyze mesospheric wind observations during strong SSW events obtained with a MF- and meteor radar at Andenes (69°N, 16°E) in order to get mean characteristics of wind and wave activity. A comparison of the strong event results with the weak event in 2011 and with the wave activity of 2009 and 2010 is also a part of this analysis. Among 12 years of available data, we focus on those events which led to a wind reversal of the zonal mean zonal wind at 10 hPa and after which the regular winterly circulation was reinstalled. This results in a total of five events during the winters 1998/1999, 2004, 2006, 2009, and 2010. Note that we do not include data from the winter 2007/2008 where a series of four recurring SSW events including a major one occurred from late January to late February 2008 (e.g., Wang and Alexander, 2009). Furthermore, we use temperature data from the Microwave Limb Sounder (MLS), available since August 2004, for the estimation of planetary waves and their wavenumbers. Section 2 provides an overview of instruments and data analysis. We use a superimposed epoch analysis in Section 3 by centering the SSW events on a defined day to describe the main common characteristics of temperatures, mean winds and waves during SSW. The results are discussed in Section 4 and summarized in Section 5.

2. Experimental data and methods

2.1. Radar measurements

We used two radar systems for this study, namely the MF- and meteor radar at Andenes (69°N, 16°E). The MF-radar operates at 1.98 MHz with a peak power of 40 kW applying the spaced antenna technique. A wide-beam antenna vertically transmits 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 has been continuously providing horizontal winds and tides at altitudes between 60 and 92 km since October 1998 using the full correlation analysis method. Note, that during the winter months 2008/2009 and 2009/2010 external disturbances led to some data gaps at altitudes below 80 km.

The all-sky meteor radar (32.55 MHz) applies an antenna system with crossed antenna elements to ensure a nearly isotropic 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-fit is used in each bin to estimate the mean zonal and meridional wind from the measured radial velocities (for details see Hocking et al., 2001).

Prevailing winds and semidiurnal tides are obtained from least-squares fits of hourly mean winds for 4-day intervals shifted by one day while for the estimation of PW and GW in the mesosphere a wavelet analysis (Torrence and Compo, 1998) has been applied. The amplitude of the wavelet transform $W_n(s)$ is