Observational study of the 4-day wave in the mesosphere preceding the sudden stratospheric warming events during 1995 and 2002


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[1] We have examined the Michelson Interferometer (MI) OH airglow measurements at the South Pole Station and the National Center for Environment Prediction (NCEP) temperatures to investigate the dynamical effects of sudden stratospheric warming (SSW) events on the Antarctic mesosphere and stratosphere. Comparisons of stratospheric and mesospheric temperatures at the South Pole during the 1995 and 2002 observing seasons show evidence of mesospheric cooling preceding the SSW events. Spectral analyses of South Pole OH air glow brightness measurements from the 1995 and 2002 observing season and NCEP stratospheric temperatures show amplification of the 4-day wave planetary wave before the start of the mesospheric cooling trend, the latter preceding the onset of SSW event. A similar behavior of planetary wave is also seen in the stratosphere where the 4-day wave is seen to grow in amplitude just before the peak of the sudden increase in temperatures. Citation: Azeem, S. M. I., E. R. Talaat, G. G. Sivjee, H.-L. Liu, and R. G. Roble (2005), Observational study of the 4-day wave in the mesosphere preceding the sudden stratospheric warming events during 1995 and 2002, Geophys. Res. Lett., 32, L15804, doi:10.1029/2005GL023393.

1. Introduction

[2] The winter polar stratosphere is characterized by an extensive vortex region that dynamically interacts with the winter mean flow. Under certain atmospheric conditions, the mean winds in the high latitude winter stratosphere reverse from westerly to easterly, and the polar vortex breaks down causing sudden stratospheric warmings (SSW) [Scherhag, 1960; Labitzke, 1965]. Such an event can strongly affect the entire middle atmosphere, causing variations in the mesosphere and lower thermosphere (MLT) region circulation [Lysenko et al., 1975]. During a “major” SSW event, the stratosphere warms up by ~60 K [Schoeberl, 1978] and has a profound influence on the thermal and dynamical structure of the polar mesosphere. A major SSW event is classified as one in which, poleward of 60° latitude and around 32 km altitude or below, the zonal mean temperature increases and the net zonal mean wind flow becomes easterly [Labitzke and Naunykot, 2000]. In contrast, a minor SSW event occurs when the polar temperature at 32 km level or below increases in a period of a week or less but the zonal-mean zonal wind there does not change its direction [Andrews et al., 1987].

[3] Although the basic principles of SSW are well understood [Matsuno, 1971; Schoeberl, 1978; Hartman, 1983], the manifestation of stratospheric warming events in MLT is not fully known. There is a growing body of evidence [Myrabo et al., 1984; Whiteway and Carswell, 1994; Gregory and Manson, 1975; Liu and Roble, 2002; Hernandez, 2003; Cho et al., 2004] which suggests that the SSW event causes temperature to decrease in the MLT region. Walterscheid et al. [2000] studied the connection of SSW and mesospheric cooling over Eureka, Canada (80°N) and their measurements indicated that a mesospheric cooling trend preceded the stratospheric warming during the SSW event. It is expected that such a drastic change in the atmosphere will significantly alter the dynamical state of the mesosphere.

[4] Mean flow and upward propagating planetary wave interactions seem to play a key role in the initiation and progression of major SSW [Matsuno, 1971]. Using the coupled National Center for Atmospheric Research (NCAR) Thermosphere, Ionosphere, Mesosphere, and Electrodynamics General Circulation Model/Climate Community Model (TIME-GCM/CCM3) to self-consistently generate a SSW, Liu and Roble [2002] examined the growth of planetary waves during the warming and showed that planetary wave 1 is the dominant component during this period. Traveling planetary wave and wave-wave interaction seem to be key mechanisms of minor SSW generation [Lordi et al., 1980; Hsu, 1980; Schoeberl, 1978; Hartman, 1983]. Below, we examine OH airglow temperature data from the South Pole Station for evidence of planetary wave activity during SSW events.

2. Data

[5] The OH M (3,1) airglow temperature values used in this study were derived from brightness of rotational lines measured from Michelson Interferometer (MI) located at the South Pole Station (SPS), Antarctica. The instrument and its operation are described in detail by Walterscheid and Sivjee [2001]. In this section, we briefly describe the salient characteristics of the instrument. The MI has a very narrow field-of-view (~2°) and operates in a continuous (24 hour) mode for six months during Antarctic night extending from April to September. Data were collected from three grid azimuths (0°, 120°, and 240°) at 25° elevation with 5-minute integration at each dwell position. In this study, we use brightness and temperature data derived from OH airglow measurements near 87 km altitude taken during the Austral winter 1995 and 2002 seasons. Data from the three azimuths were combined together to generate a single time series for a
In section 4 we present spectrogram obtained using wavelet analyses of the MI OH mesospheric brightness and NCEP stratospheric temperatures. In contrast to the conventionally used Short Time Fourier Transform (STFT), the wavelet transform is a localized transform in both space (time) and frequency, and this property can be advantageously used to extract spectral information from a temporally evolving signal while retaining commensurate frequency resolution. The time-frequency resolution of a wavelet is not constant, but varies with frequency. For a more detailed explanation of wavelet transform in the context of frequency-time decomposition of a signal, the reader is referred to Daubechies [1992] and Flandrin [1988].

The spectral analysis presented here uses the Morlet wavelet [Vecsey and Matyska, 2001] to describe the temporal variations of the planetary waves in the stratosphere and mesosphere. We first use the NCEP data to identify periods of SSW events and then compute wavelet spectrogram of stratospheric temperature fields for all available zonal wavenumbers. The wavelet spectrogram is also calculated for the concurrent mesospheric brightness measurements from the SPS MI.

4. Results

Figure 1 shows wavelet amplitude spectra (top panel) for the South Pole OH brightness data and $s = 1$ stratospheric temperature ($\sim 32$ km) values at $-87.5^\circ$ latitude during a 70-day period from late April to July with the corresponding mesospheric and zonally averaged stratospheric temperatures shown in the bottom two panels. Wavelet spectrum of stratospheric temperature for $s = 1$ wavenumber was used in the current analyses since it was noticed that among all the wavenumbers considered, the $s = 1$ wave showed the strongest planetary 4-day wave feature. The NCEP results shown here are computed at the latitude grid point (or $-87.5^\circ$) closest to the South Pole. Wavelet spectra were used to identify prominent wave-periods present in the mesosphere and stratosphere regions during the SSW event. The dominant response occurs near the 4-day period in both the mesospheric and stratospheric data. Following the amplification of the 4-day wave amplitude, the mesospheric temperature sharply decreases by about 15 K within a period of $\sim 5$ days. The mesospheric cooling event lasts for about another 12 days after which the mesosphere warms back towards its pre-SSW state. The observed planetary wave period correlates well with the commencement of mesospheric cooling noted in Figure 1. Stratospheric temperature data obtained from NCEP shows a warming trend around day 185 (July 4, 1995) and about 15 days after cooling trend preceding stratospheric warming. The peak zonal mean temperature during this stratospheric warming event at the South Pole occurred on day 193 whereas the peak amplitude of the 4-day wave oscillation in the stratosphere is around day 165 (June 14, 1995).

[10] In 2002, a major stratospheric warming was recorded in the Antarctic region [Baldwin et al., 2003]. The main warming event occurred during late September and mid October when the winds at 10 hPa reversed their direction. Figure 2 shows zonal mean temperature results of TIME-GCM run, as described by Liu and Roble [2005], at the South Pole from mid April to September of 2002. In their simulation of the 2002 stratospheric warming event, Liu and Roble [2005] prescribed the lower boundary ($\sim 30$ km) of the TIMEGCM using the 2002 NCEP reanalysis data. The major stratospheric warming event is evident in September. In addition, during the stratospheric warming period, the model mean temperature shows cooling at mesospheric heights. Figure 3 shows the wavelet power spectrum of the TIMEGCM temperature perturbation at zonal wave-
number 1 near 87.5°S latitude. Peak amplitude at a period of 4-day is evident prior to day 200 (July 19, 2002) and occurs shortly before the minor cooling trends in the mesosphere during the interval 200–230 days. It is important to note that the model run shows simultaneous mesospheric cooling and stratospheric warming which does not follow the observed temperature response in the mesosphere and upper stratosphere (see Figure 4). The simultaneity in model mesospheric cooling and stratospheric warming can be explained in terms of gravity wave filtering. The weakening jet in the stratosphere changes gravity wave filtering, thus allowing more eastward gravity waves to propagate in to mesospheric heights leading to circulation change and adiabatic cooling [Liu and Roble, 2002]. However, the planetary waves in the mesosphere in the model are generally underestimated and there is large uncertainty related to the parameterized gravity wave forcing. Therefore, we advise caution when comparing the time evolution of mesospheric cooling and stratospheric warming in the TIMEGCM run, as our understanding from the model may not fully address the observed behavior.

[11] During 2002, the South Pole MI airglow measurement season ended in early September and thus MI data does not include the period of major SSW. However, the stratospheric data prior to September 2002 show periods of sudden stratospheric temperature enhancements, which could be attributed to minor stratospheric warming. OH mesospheric temperature and NCEP stratospheric temperature at ~32 km for April to September and their corresponding wavelet spectra are shown in Figure 4. Planetary wave activity is apparent in the mesospheric brightness and stratospheric temperature data. Oscillations with periods of about 4-days can bee seen in the OH brightness wavelet spectrum prior to the cooling of the mesosphere, which occurred around day 210 (July 29, 2002). This cooling event precedes the 15 K enhancement in the zonally averaged stratospheric temperatures near the South Pole. As a precursor to stratospheric warming event, a 4-day wave oscillation can be seen in the wavelet spectrum of the stratospheric temperature data.

[12] Manney and Randel [1993] examined the source mechanism for the 4-day wave in the winter upper stratosphere and mesosphere using a model that allowed them to separate the Potential Vorticity components due to horizontal and vertical shears of the basic flow. They suggested that the generation of the 4-day wave was in part due to baroclinic and barotropic instability at the stratopause. It is possible that the amplification of the 4-day waves we have seen at stratospheric and mesospheric levels near the SSW event is linked to the instability of the region preceding the break down of the polar vortex which initiates the sudden warming trend in the stratosphere. Using the TIMEGCM to simulate the 2002 Southern Hemisphere major sudden warming, Liu and Roble [2005] have shown that the planetary wave surf zone descends from the mesosphere heights down to the stratosphere during the SSW episode. This downward moving reversed potential vorticity gradient zone has instabilities associated with it [Hartman, 1983] which could be a possible source mechanism for the observed 4-day wave amplification [Manney and Randel, 1993], first at mesospheric heights and then later at stratospheric heights. As the surf zone descends below, it first leads to the cooling of the mesosphere and ultimately warms the stratosphere as the surf zone reaches...
stratospheric altitudes few days after the peak of mesospheric cooling.

5. Summary and Conclusions

[13] We have studied two MLT cooling events associated with Sudden Stratospheric Warming (SSW) at the South Pole Station (SPS), Antarctica. In this paper, we have analyzed the time evolution of the 4-day wave planetary wave during SSW events. OH airglow measurements (at ~87 km) taken from the MI at the SPS and NCEP stratospheric temperature data (at ~32 km) during 1995 and 2002 SSW events were spectrally analyzed to investigate the dynamical response of the mesosphere to these events at planetary wave periods. Consistent with the findings of Walterscheid et al. [2000] and Hernandez [2003], our observations show mesospheric cooling trend preceding the onset of SSW event. The peak zonal mean stratospheric temperatures during the SSW event seen in the NCEP data generally lags by about 10–12 days from the leading edge of the mesospheric cooling trend. In late May of 1995, a sudden cooling of the mesosphere by ~15 K is observed which coincides with the warming of the stratosphere by ~10 K at the 3.16 hPa level. Amplification of the zonal wavenumber 1, 4-day planetary wave is seen in both the mesosphere and stratosphere. These occurrences of the 4-day wave in mesospheric brightness and stratospheric temperature data precede the MLT cooling and stratospheric warming, respectively.

[14] The occurrence of the zonal wavenumber 1, 4-day planetary wave at the South Pole during the 2002 observing season in the mesosphere and stratosphere is consistent with similar observations during the 1995 season. Similarities include amplification of the 4-day wave in the mesosphere and stratosphere preceding the commencement of mesospheric cooling and sudden stratospheric warming, respectively. The cooling at mesospheric heights by 15 K occurred in mid July of 2002 followed by warming of the stratosphere in mid August of 2002. The well documented major stratospheric warming of 2002 in the Antarctic region occurred in late September [Liu and Roble, 2005]. Our South Pole MI data coverage ended prior to the onset of this major SSW event. However, analysis of NCEP stratospheric data from 2002 suggest occurrence of a minor stratospheric warming during the month of August, the effects of which are duly evident in our MI data at ~87 km.

[15] The occurrence of large wave amplitude with a period of about 4-days and a zonal wavenumber 1 dominates the mesospheric as well as the stratospheric wave spectrum. Changes in the stratospheric circulation leading up to the SSW event can produce changes in the instability of the region resulting in the amplification of the 4-day planetary wave. Our analyses of two years of mesospheric and stratospheric data produce a picture of the dynamical coupling between these regions in which the 4-day wave signature appears as a common feature in the spectrum of the mesospheric and stratospheric data. A further understanding of the linkage between the occurrence of the 4-day wave and atmospheric instability during the SSW period will be established in the ongoing study by investigating the Potential Vorticity (PV) gradients and Eliassen-Palm (EP) fluxes [Manney and Randel, 1993].

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References


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