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**Study on the impact
of sudden
stratosphere
warming**

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Study on the impact of sudden stratosphere warming in the upper mesosphere-lower thermosphere regions using satellite and HF radar measurements

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Abstract

The occurrence of sudden stratospheric warming (SSW) excites disturbances in the mesosphere-lower thermospheric (MLT) wind and temperature. Here, we have examined the high frequency (HF) radar wind data from the South African National Antarctic Expedition, SANAE (72° S, 3° W), a radar which is part of the Super Dual Auroral Radar Network (SuperDARN). Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) on board the Thermosphere-Ionosphere-Mesosphere-Energetics and Dynamics (TIMED) satellite temperature data and National Centre for Environmental Prediction (NCEP) temperature and wind data were used to investigate the dynamical effects of the unprecedented September 2002 SSW in the Antarctica stratosphere and MLT. The mean zonal wind (from SANAE HF radar) at the MLT shows reversal in approximately 7 days before the reversal at 10 hPa (from NCEP). This indicates that there was a downwards propagation of circulation disturbance. Westerly zonal winds dominate the winter MLT, but during the 2002 winter there were many periods of westward winds observed compared to other years. The dynamic spectrums of both meridional and zonal winds show presence of planetary waves (of ~14-day period) before the occurrence of the SSW. The SABER vertical temperature profiles indicated the cooling of the MLT region before the SSW event.

1 Introduction

The first ever detection of a major SSW in the Southern Hemisphere (SH) occurred during 2002 Antarctic winter (Baldwin et al., 2003). During this exceptional event the 60° S winds at 10 hPa reversed on the 26 September, before it returned to a weak flow on about 15 October. The primary cause of the sudden stratospheric warming is thought to be planetary waves originating from the troposphere and propagating upwards to the stratosphere and mesosphere lower-thermosphere (MLT) region (Matsuno, 1971; Holton, 1976; Andrews et al., 1987). These planetary waves interact with

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the mean-flow and due to that interaction an upward and pole-ward directed heat and momentum flux leads to decreasing eastward winds and increasing temperature in the polar region (Matsuno, 1971; Hoffmann et al., 2002).

Planetary scale waves are generated in the troposphere by topographic and thermal features, and propagate up into the middle atmosphere (Shepherd et al., 2000). The instabilities arising from horizontal and/or vertical gradients in the temperature and wind disturbances can also induce planetary waves. Because of the topography of the Northern Hemisphere NH, planetary wave energy is significantly large in the NH compared to the SH, and hence the usual detection of the SSW in the NH. Planetary and gravity waves are critical for mixing processes and for the Brewer-Dobson circulation in the middle atmosphere. The winter hemisphere is dominated by large amplitude stationary planetary waves which originates from the troposphere, and intermittently, these waves break, stirring air more or less isentropically across large distances of the stratosphere within a region that has become known as the “surf zone”, bounded by sharp gradient of potential vorticity (PV) and of tracers in the winter subtropics and the edge of the polar vortex (Plumb et al., 2002; Sivakumar et al., 2004). In fact, interactions between planetary waves and the zonal-mean flow in the middle atmosphere induce a westward forcing in the winter hemisphere, resulting in deceleration and/or reversal of the eastward winter polar night jet. The deceleration and reversal of the eastward night polar jet in the high-latitude stratosphere also changes the filtering of internal gravity waves and allows increasing amounts of eastward propagating gravity waves from the troposphere to penetrate into the MLT and break there, while blocking westward propagating gravity waves (Sathishkumar et al., 2009). Hence, the eastward forcing due to eastward propagating gravity wave breaking increases and may even replace the previously dominant westward forcing in the MLT. This process also changes the meridional circulation in the upper mesosphere from pole-ward/downward to equator-ward/upward (Liu and Roble, 2002).

Labitzke and Nanjokat (2000) classified a SSW as a minor warming if there is a significant increase of temperature (at least by 25 K per week) at any stratospheric level

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in any area of the winter hemisphere. This temperature increase can be intense and sometimes also reverse the temperature gradient, but they cannot cause any reversal at the 10 hPa pressure level. On the other hand, a SSW is classified as a major warming if at 10 hPa height, or below, the latitudinal mean temperature increases pole-ward from 60° latitude and an associated circulation reversal leads to a change from the usual dominant eastward directed flow to westward directed flow and hence to a splitting of the polar vortex. In late September 2002, the first major SSW ever observed in the SH occurred in the polar region: significant temperature increase followed by the zonal wind reversal as depicted in Fig. 1 by the use of daily NCEP (National Centre for Environmental Prediction) reanalysis data.

In the winter hemisphere, the stratospheric and MLT temperature and wind at high- and mid-latitudes can undergo significant changes before, during and after the occurrence of SSW (e.g., Walterscheid et al., 2000; Cho et al., 2004; Liu and Roble, 2005). These changes can range from the zonal mean wind reversal (Dowdy et al., 2004) to the cooling of the MLT temperature (Hernandez et al., 2003; Liu and Roble, 2005). Dowdy et al. (2004) used three medium frequency (MF) radars located at Davis (69° S, 78° W), Syowa (69° S, 40° W) and Rothera (68° S, 68° W) to study the dynamics of the MLT during the SH 2002 SSW. In their study, the most noticeable feature was the reversal of the mesospheric zonal winds a week earlier before the reversal in the stratosphere and a different winter mesospheric wind field, in 2002 compared to other years, primarily due to the increase of planetary wave activity during winter period. This behaviour shows similarities when compared to studies of the major SSWs in the NH.

Due to the unusual behaviour of the Antarctic stratosphere in 2002 it is expected that the MLT wind field measured by SANAE high frequency (HF) radar (72° S, 3° W) also exhibits this unusual behaviour. Espy et al. (2005) proved capabilities of Super Dual Auroral Radar Network (SuperDARN) HF radar to study SSW events by examining meridional winds from Syawo, SANAE and Halley stations and also the Rothera MF radar in order to assess whether long quasi-periodic oscillations in 2002 has a longitudinal phase progression characteristic of planetary waves.

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Thus, in the present work, we examine zonal and meridional wind data from SANA E HF radar to explore the response of the MLT to the SSW. Although there are number of MF radars in Antarctica, any available wind measurements, especially from a global network of identical instruments like SuperDARN is a desirable option for studying wind variations dynamics, atmospheric waves and associated characteristics in the MLT region. The details of the HF radar are explained in the next section. NCEP reanalysis temperature and zonal wind data are used to identify the SSW as well as to examine variations of temperature and zonal wind in the stratosphere during the SSW event. The Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) on board the Thermosphere-Ionosphere-Mesosphere-Energetics and Dynamics (TIMED) satellite is used to examine temperature structure in the middle atmosphere during the 2002 SSW event.

2 Instruments and method

2.1 SANA E HF radar and data acquisition

The SANA E HF radar is part of the SuperDARN Radar network and it is located in Antarctica (72° S, 3° W). SuperDARN (Greenwald et al., 1995) is a network of HF radars originally designed to study plasma flow in the high-latitude ionosphere. Hall et al. (1997) demonstrated that echoes at ranges close to the SuperDARN radars are actually due to scatter from meteor trails near 94 km altitude, except during periods of high K_p (an indication of geomagnetic disturbance). Hence, the near-range scatter can be utilised to study neutral winds at meteor heights. Greenwald et al. (1995) have reviewed the SuperDARN radars and their operation, thus, in the present work only a brief description of the SuperDARN radars is given.

The SuperDARN radars operate at frequencies between 8 and 20 MHz. Each radar site consist of 16-antenna array connected to a phasing matrix which permits the single beam to be swept through 16 successive positions in increments of 3.25° , giving an

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azimuth extent of $\sim 52^\circ$. The azimuthal resolution depends on the operating frequency and it ranges from 2.5° at 20 MHz to 6° at 8 MHz. The peak power is about 10 kW, and the range resolution is 30–45 km with a typical pulse width of 200–300 μs . Measurements are taken for every 7 s at each of the 16 beam positions. The backscatter information from these pulses is sampled and then processed giving multi-lag autocorrelation functions (ACFs). The ACFs are thereafter used to deduce backscatter power, mean Doppler velocity and the width for the Doppler power spectrum for each range with significant returns. The pulse sequence has about 40 ms duration, and pulses sequence is separated by 60 ms, giving 60 ACFs in each of the 7 transmitting seconds; and these are averaged together for each measurement.

The SuperDARN radars were primarily designed to study the convection patterns in the high-latitude ionosphere. However, there are several studies which have proved that SuperDARN radars can also be used to study the dynamics of the MLT region. For example, Hussey et al. (2000) performed a comparison of NH winds using SuperDARN meteor trail and Saskatoon (52.2° N , 106.6° W) MF radar wind measurements. In their results, they found good agreement between the two radar systems at altitude of $\sim 95\text{ km}$. Bristow et al. (1999) also compared SuperDARN wind results with those of High Resolution Doppler Imager (HRDI) aboard the Upper Atmosphere Research Satellite (UARS), and found that both instruments observed a 2-day wave with wave number 3. Malinga et al. (2007) used the SuperDARN radar network in the NH to study the characteristics of the quasi-two-day wave at meteor heights.

The meteor trail echoes occur predominantly in and below the lower E ($\sim 95\text{ km}$) (Hussey et al., 2000), thus acquisition of the winds in the meteor region is accomplished by using data from the first several range gates of the radar. The backscatter at this distance is primarily due to meteors, and thus a nominal height of 90–95 km is assumed. Hourly wind averages are computed for each beam direction giving a line of-sight wind velocity. Figure 2 depicts the hourly averaged zonal winds observed by SANA E HF radar during September 2002. The mean winds were deduced by averaging 4-day time sequence of hourly averaged zonal and meridional wind velocities

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(see Fig. 3). The 4-day data window is then shifted by 1-day at a time and the average of the data window are attributed to the second day of the interval.

2.2 TIMED/SABER temperature data and NCEP data

In the present study, the vertical temperature profiles are derived from the version 1.07 of SABER level 2A data (downloaded from the web site <http://saber.gats-inc.com/>). The TIMED satellite was launched on 7 December 2001 into a 625 km orbit of 74.1° inclination, and the SABER instrument began taking measurements in late January 2002. By step-scanning the atmosphere limb, SABER measures height profiles of temperature and selected chemical species in the 10–180 km altitude range, with a horizontal resolution along track of 400 km. Details about the SABER temperature data and SABER sampling are given by Pancheva et al. (2009).

Temperature and wind fields used to follow the evolution of the SSW event are obtained from the NCEP/NCAR reanalysis project available on the National Oceanic & Atmospheric Administration (NOAA) Climate Diagnostics Center web (<http://www.cpc.ncep.noaa.gov/>). This co-operational project between NCEP and NCAR provides daily meteorological values on 2.5° latitude by 2.5° longitude resolution. The NCEP/NCAR reanalysis data is formed by the combination of the assimilation of data from different meteorological instruments which are scattered globally. In the present study, we have used the NCEP zonal-mean zonal winds at 60° S and 10 hPa pressure levels (~ 32 km height) and zonal-mean temperature at 80° S and 10 hPa to examine wind and temperature daily variation during 2002 winter period (see Fig. 1).

3 Mean wind results and planetary waves signature during the SSW

Figure 3 shows the daily averaged zonal and meridional wind derived from the SANA HF radar observations from the start of July until the end of November 2002 (black dashed line), superimposed on the average wind values based on the same observa-

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tions from 2003 to 2006 (solid blue line). The years from 2003 to 2006 were identified as the period where there is no SSW observed. Thereby, the 2003–2006 averages represent the background wind patterns. During the period July–November one can see from Fig. 3a that eastward winds are primarily dominant in the polar winter in the MLT particularly during August and September. However, when comparing the 2002 zonal wind to the averaged zonal wind, one can clearly see that during 2002 there were many brief periods of westward wind (see Fig. 3a). The reversals of zonal wind start at around the beginning of July, which is approximately two months before the occurrence of the SSW in late September. The reversal of the zonal wind which is associated with the SSW event starts on 19 September (day 262, from Fig. 3a) and persisted for few days before it returned to eastwards direction, while in the stratosphere the zonal wind reversed on 25 September 2002 (Fig. 1) leading to the unprecedented major SSW in the Southern Hemisphere. This is consistent with results from Dowdy et al. (2004). They reported from MF radars at polar locations that during the 2002-major warming zonal wind reversed a week earlier in the mesosphere than in the stratosphere. The meridional mean winds during 2002 also show an enhancement during the period of the occurrence of the SSW event and this feature is not seen in the other years (see Fig. 3b).

Figure 4 shows the time evolution of the zonal wind at 10 hPa (~32 km) derived from the NCEP at 60° S latitude during the period from 250 to 300 Julian days in 2002. The zonal wind observations from SANA E HF radar (for ~94 km MLT height) are superimposed with a solid black line. The SANA E HF radar data is smoothed by a 4-day running mean. The figure shows that the zonal wind started to reverse (became westward) in the MLT region on the 261th 2002-Julian day (18 September), i.e., about a week earlier than the reversal of the zonal wind in the polar stratosphere at ~10 hPa pressure level. The reversal in the MLT reaches a maximum magnitude of about –10 m/s on the 263th day (20 September 2002). The MLT zonal winds reversal lasted for a few days and thereafter returned to the eastward direction for more than 10 days, before another reversal which starts on day 282 (9 October) and persists until the beginning

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of summer. The reversal in the stratosphere begins on the 268th day and reaches its maximum amplitude of -20 m/s on day 270 before it turns back to the eastward direction on day 273.

As explained and evidenced by many other research studies (Matsuno, 1971; Andrews et al., 1987; Dowdy et al., 2004), dynamical mechanisms behind SSW generation involves planetary and gravity wave propagation from the troposphere into the middle atmosphere where they interact with mean flow. In order to examine wave characteristics in the MLT region from the SANA E HF radar data it is necessary to determine the dominant spectral components within the frequency band of interest. Thus, to do this, we performed dynamic Fourier spectra using a 28-day data window that is shifted forward by 1-day at a time. The deduced power for a given data window was attributed to a central day given by day 14 of that particular 28-day interval. Figure 5 shows results of power spectra analysis applied to the zonal and meridional wind components of SANA E HF radar wind observed from May to late October (150 to 300 Julian days). The sampled height is ~ 94 km. From Fig. 5a it can be clearly seen that the zonal wind power spectra is characterised by dominant peaks near to periods of 5-day, 10-day and 14- to 16-day waves in the mid-winter. The 5-day and 14- to 16-day waves are also seen around 250th of 2002 Julian day (7 September), and this period is about 2 weeks prior to the occurrence of the SSW. When comparing the year 2002 spectra to the other years (figure not shown) we see that other years do not have strong presence of the above mentioned planetary waves. The spectrum for the meridional wind component which is shown in Fig. 5b also shows the presence of a 14- to 16-day wave around 7 September (250th of Julian days). There is also an evidence of a 5-day wave on the spectrum.

4 Link with temperature variations

Previous studies have associated the occurrence of SSW events with the cooling of the MLT temperature (e.g. Walterscheid et al., 2000; Hernandez et al., 2003; Liu and Roble

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et al., 2005). Hernandez et al. (2003) reported a cooling of the mesopause region over the South Pole during the 2002 SH stratospheric sudden warming. Liu and Roble et al. (2005) used a Global Circulation Model (GCM) extending from 30 to 500 km to examine the interaction between planetary wave forcing and the evolving zonal mean state during the same event. They found significant mesospheric effects which include a cooling and reversal of the zonal wind prior to the SSW event. Figure 6 shows vertical temperature profiles obtained from SABER satellite data plotted for successive days from 1 to 19 September 2002 (244–262 Julian days). The main idea was to use those SABER vertical temperature profiles which are closer to the SANAE base during September 2002. However, SABER obtains profiles from 52° S to 83° N during its north-looking mode for 60 days before switching to an analogous south-looking mode and then repeats that sequence for the subsequent months (Remsberg et al., 2003). In this way, the polar cap data is available only in 60-day segments, with no information for the 60 days preceding or following. Thus, only the first 19 days of September 2002 are closer to the SANAE base (72° S, 3° W). The 19 profiles used in this work are the closest as the satellite overpasses over the SANAE site.

The vertical temperature profiles in Fig. 6 show the structure of the vertical temperature prior to the occurrence of the major SSW which only reaches its maximum on the 26 September 2002. In fact, that warming drove an unusual dynamical situation resulting in the split of the polar vortex (Baldwin et al., 2003) and transport of air-masses from pole to mid- and low-latitudes (Bencherif et al., 2007). The most noticeable feature in these temperature profiles is a substantial increase of temperature throughout the stratosphere which is visible on the 13 to the 19 September. This was an uncommon detection of rapid temperature increase in the Southern Hemisphere winter and is associated with the SSW event. Moreover, it can be mentioned that before this major warming event, which reached its peak on 26 September, a few minor warmings can be seen during the 2002 winter period primarily in mid-July, mid- and late-August onwards, until the beginning of September (see Fig. 1). At mesospheric heights, the vertical temperature profiles illustrate the persistence and the variability of

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the mesospheric temperature inversion layer during the continuous series of SABER measurements. These inversion layers are primarily observed between 70 and 110 km and in all profiles with a stronger signature on the 17, 18 and 19 September. Thus, there are signatures of mixing and viscous dissipation associated with turbulence generated by the breaking upward propagating gravity waves in the MLT region.

5 Discussion and conclusions

In the present study, the HF radar data set from SANAE base in Antarctica was used to examine the dynamical structure of the MLT region during the unprecedented major SSW occurred in late September 2002. Only MF radars are usually used for this purpose both in the Southern and Northern Hemispheres. This work highlights and strengthens the idea that HF radars enable us to investigate dynamical processes on the MLT region. In our results, we have shown that the mean zonal wind (from SANAE HF radar) throughout 2002 winter at ~ 94 km showed enhancement due to a series of large planetary wave amplifications in the stratosphere during this period. The large amplitude planetary wave produces strong westward forcing in the high-latitude winter stratosphere. In general, westerly zonal winds dominate the winter MLT, but the 2002-winter showed obvious differences when compared to other years, with many brief periods of easterly winds observed. The power spectra in Fig. 5a depicts the presence of planetary waves (5-day, 10-day and 14- to 16-day waves) during the 2002 austral winter. In addition, Fig. 5b also showed presence of a 14- to 16-day wave in the meridional wind during winter. The observation of the 14-day oscillation is consistent with observations reported by Dowdy et al. (2004).

The circulation in the stratosphere was characterized by a series of planetary wave events in 2002 winter that weakened the polar vortex and triggered the SSW in the late September. In Fig. 4, we compare the zonal winds at ~ 94 km from SANAE HF radar with the zonal mean zonal winds from NCEP stratospheric data (at 10 hPa), and the results show that the reversal event in the lower thermosphere took place in few

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days (about a week) prior to the reversal in the stratosphere. This behaviour indicates that there may be a downward propagation of circulation disturbance in the middle atmosphere. Similar results were also reported by Dowdy et al. (2004), where they used the average of MF radars located at Davis (69° S, 78° E), Syowa (69° S, 40° E) and Rothera (68° S, 68° W) for MLT and UK Meteorological Office (UKMO) stratospheric assimilation. SANA E HF radar results show similarities to the previous observations of the major SSWs both in the Southern and the Northern Hemisphere. The NCEP reanalysis results shown in Fig. 1 was instrumental in identifying the SSW event as well as minor warming's before the major SSW and the final warming by late September.

Moreover, the response of the MLT region to the stratospheric warming depends on many different factors that still require more investigation. Mesospheric cooling is usually reported and associated with the major warming's in the Northern Hemisphere. In the present work, we have used the SABER temperature data to examine the response of the thermal structure to the SSW in the stratosphere and MLT region. The stratosphere showed an unusual increase in temperature, while MLT showed a cooling and temperature inversions few days before the SSW occurrence. This behaviour of the MLT region is associated with energy deposition due to gravity wave breaking in the mesosphere. Gravity wave momentum deposition drives the pole-to-pole meridional wind circulation that in turn causes the departure of mesospheric temperature from radiative equilibrium, keeping the winter MLT warmer and summer MLT colder (Holton, 1983). The above reported behaviour of the middle atmosphere strengthens the idea of coupling between the stratosphere and the MLT region.

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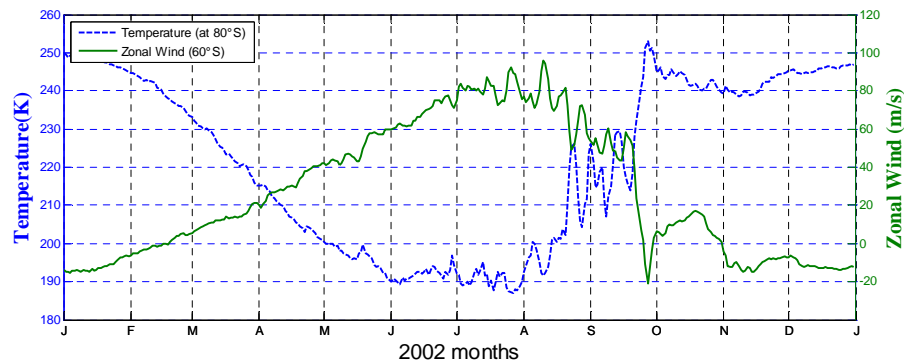


Fig. 1. 2002 records of daily zonal wind at 60° S (solid green line) and temperature at 80° S (blue dashed line) from NCEP reanalysis.

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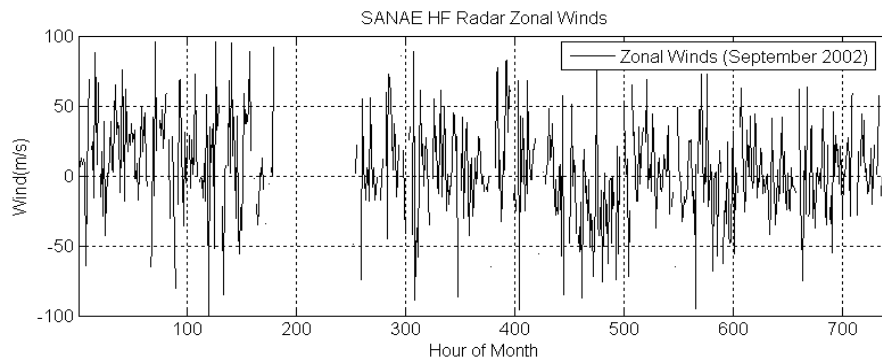


Fig. 2. Hourly averaged zonal wind as observed by the SANA E HF radar during September 2002.

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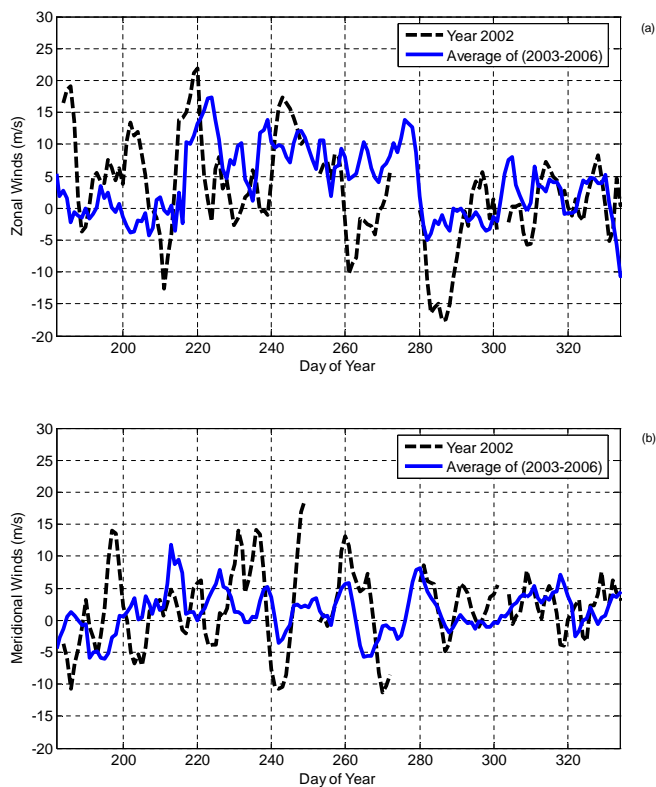


Fig. 3. Time evolution of daily averaged (a) zonal wind and (b) meridional wind obtained from SANAE HF radar observations from 1 July to late November 2002. The blue solid lines represent the averaged wind values derived from 2003–2006 SANAE HF radar observations.

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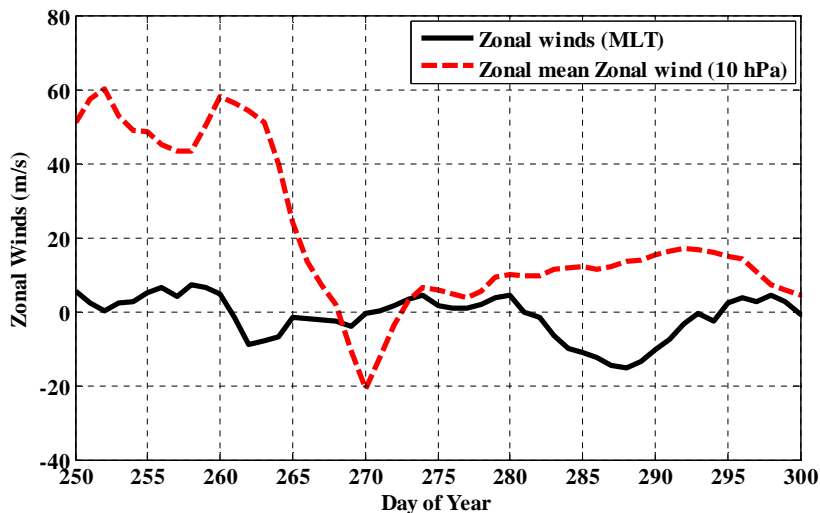


Fig. 4. Zonal wind evolution in the MLT region (~ 94 km) obtained by SANA E HF radar (solid black line) during the period from 250 to 300 2002-Julian days. The red dashed line illustrates the zonal-mean zonal wind variation at 10 hPa (32 km) derived from NCEP reanalyses at 60° south, for the same period of time.

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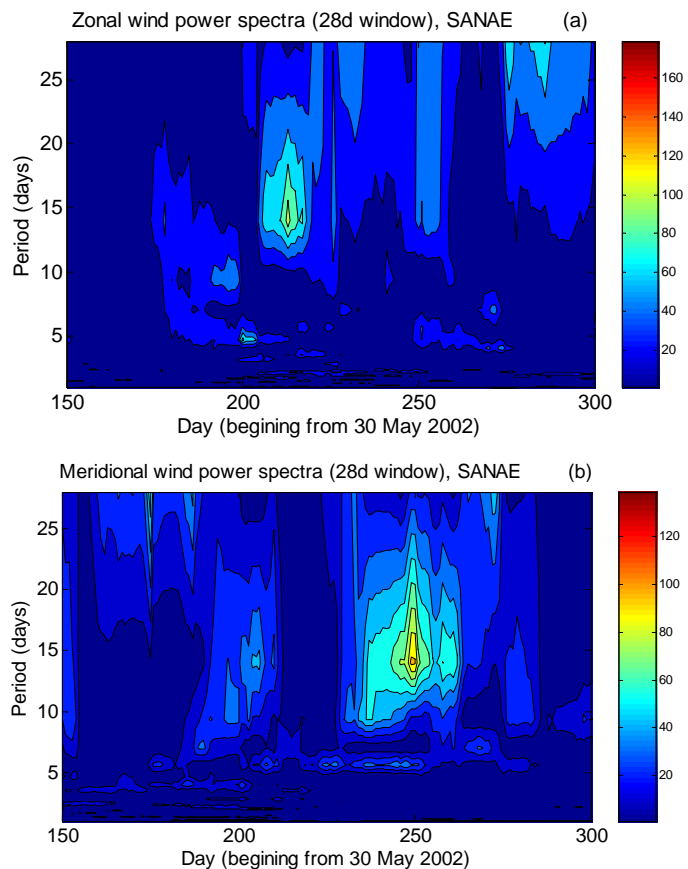


Fig. 5. Power spectra of daily zonal **(a)** and meridional wind **(b)** derived for the MLT region (~94 km) from SANAE HF radar for the period from 30 May to 27 October 2002 (150–300 Julian days).

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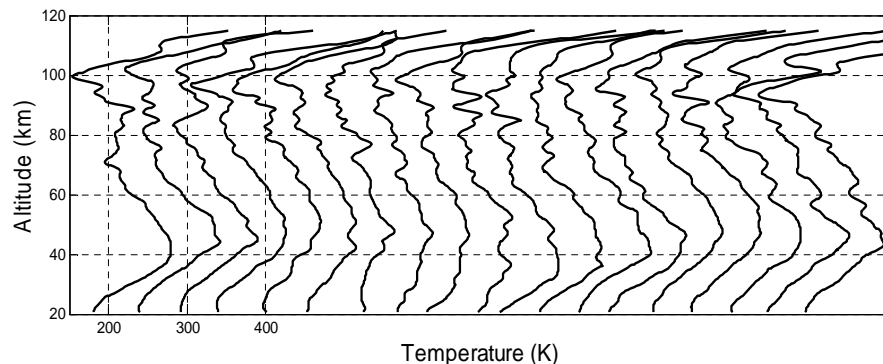


Fig. 6. Vertical temperature profiles from the SABER data for successive days from 1 to 19 September 2002 (244–262 Julian days), which are shifted by 100 K from each other. These profiles were obtained as the satellite closest overpass above SANA E site.

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