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Global normal mode planetary wave activity: a study using TIMED/SABER observations from the stratosphere to the mesosphere-lower thermosphere

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Abstract A comprehensive study of three normal mode travelling planetary waves, namely the quasi-16, -10 and -5 day waves, is carried out globally using 5 years (2003–2007) of TIMED/SABER temperature measurements from the stratosphere to the mesosphere-lower thermosphere (MLT) by employing the two dimensional Fourier decomposition technique. From preliminary analysis, it is found that significant amplitudes of normal modes are confined to wave numbers-2 (westward propagating modes) to 2 (eastward propagating modes). The westward propagating quasi 16-day waves with zonal wave number 1 (W1; W1 refers to westward propagating wave with zonal wave number 1) peaks over winter-hemispheric high latitudes with northern hemisphere (NH) having higher amplitudes as compared to their southern hemispheric (SH) counterpart. The W1 quasi 16-day waves exhibit a double peak structure in altitude over winter hemispheric high latitudes. The eastward propagating quasi 16-day waves with wave number 1 (E1; E1 refers to eastward propagating wave with zonal wave number 1) exhibits similar features as that of W1 waves in the NH. In contrast, the E1 quasi 16-day waves in the SH show larger amplitudes as compared to the W1 waves and they do not exhibit double peak structure in altitude. Similar to the quasi 16-day waves, the quasi 10- and 5-day wave amplitudes with respect to their wavenumbers are delineated. Unlike quasi-16 and -10 day waves, quasi-5 day waves peak during vernal equinox both in the SH and NH. The peak activity of the W1 quasi-5 day wave is centered around 40°N and 40°S exhibiting symmetry with respect to the equator. A detailed discussion on the height-latitude structure, interannual variability and inter-hemispheric propagation of quasi 16-, 10- and 5-day waves are discussed. The significance of the present study lies in establishing the 5-year climatology of normal mode planetary waves from the stratosphere to the MLT region including their spatial–temporal evolution, which are very important from the middle atmospheric dynamics standpoint.

Keywords Middle atmospheric dynamics · Planetary waves · Interhemispheric propogation · TIMED/SABER

1 Introduction

Planetary scale waves dominate the middle atmospheric dynamics by depositing energy and momentum which they carry from the lower atmosphere. These waves also play a key role in filtering of gravity waves. By now, it is well established that the wave driven dynamics is one of the most important processes in the middle atmosphere apart from the dynamics driven by solar radiation. The unforced solutions to the linearized equations of an isothermal and dissipationless atmosphere are referred to as "free oscillations" or "normal modes (Forbes et al. 1999). These normal modes can take the form of gravitational modes, Rossby modes, mixed Rossby-Gravity or Kelvin modes. Other free mode travelling planetary waves are the commonly observed modes with periods of around 2, 5, 10 and 16 days. The gravitational modes are usually referred to as Lamb waves (Bretherton 1969; Lindzen and Blake 1972). The Lamb waves are also referred as "gravitational normal modes". The period of these waves are much shorter as compared to other normal mode waves. The various terms like "Lamb waves", "Rossby waves", "Gravitational

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modes” are not all mutually exclusive. The differentiation between Rossby waves and various other modes are in their generation mechanism, but they all obey similar mathematics when it comes to the vertical structure, and all are subsets of Lamb modes in this regard. The present study focuses on normal mode planetary waves. The normal mode planetary waves can be broadly classified as quasi-stationary and traveling planetary waves. Both types of waves contribute significantly to the middle atmospheric variability, especially during the winter. Realizing the importance of these planetary scale disturbances, a host of studies have been carried out to characterize these waves (Charney and Drazin 1961; Muller 1972; Kingsley et al. 1978; Madden 1979; Salby 1984; Forbes et al. 1995; Mitchell et al. 1999; Manson et al. 2003; Lima et al. 2006; Day and Mitchell 2010a, b; Babu et al. 2011, 2012). Charney and Drazin (1961) focused on quasi-stationary planetary waves and their upward propagation into the stratosphere. These authors also discussed the role of mean zonal wind in altering the transmitivity of stationary waves. However, the theory proposed by these authors can be applied for travelling planetary waves also by taking intrinsic phase speed of the waves into account. Salby (1984) reviewed the planetary scale travelling waves with a focus on their theory and observations. There were studies, which reported the interaction of the stationary waves and the traveling waves (Hartmann et al. 1984; Ushimaru and Tanaka 1992). These studies focused on theoretical, observational and modeling aspects of both stationary and travelling planetary waves. The observational studies based on both ground and space based measurements included characterization, propagation, long- and short-term variability, wave-mean-flow and wave–wave interaction of planetary waves. By interacting with the background atmosphere while propagating, planetary waves modify the circulation and thermal structure in the middle and upper atmosphere and play a significant role in coupling various regions of the atmosphere. The present study focuses on the travelling planetary waves.

Theoretical studies show that many of these planetary waves correspond to normal-mode solutions for oscillations in an isothermal atmosphere (e.g. Salby 1984). For realistic conditions, the most significant periods of normal modes are the quasi 2-, 5-, 10- and 16-day waves (Miyoshi and Hirooka 1999; Mitchell et al. 1999; Pancheva et al. 2008). The planetary waves at these specific periods are regarded as preferred atmospheric response to broadband forcing (Volland 1988). There have been studies on planetary waves at these periods using network of MF/meteor radars and satellite observations in the middle and upper atmosphere (Luo et al. 2002; Manson et al. 2003; Garcia et al. 2005; Chshyolkova et al. 2005; Jiang et al. 2008). As satellite observations have rendered sufficiently reliable data in recent times, there have been a considerable number of studies of planetary waves of global/climatological nature. The northern hemisphere (NH) planetary waves in the stratosphere for the winter season of 2003–2004 were studied by Pancheva et al. (2009a). Using SABER and UKMO data, the latitudinal and seasonal structure of the normal modes were studied extensively, but limited to the winter and to the stratosphere. In a sequel to this work, Pancheva et al. (2009b) extended their study to the lower thermosphere region (30–120 km) and to the 50°N–50°S latitudes for the winter season. The altitude and latitude structures of the planetary waves clearly indicated that the stratosphere and mesosphere are coupled by direct vertical propagation of the planetary waves, while the lower thermosphere is more coupled through various gravity wave mechanisms. Mukhtarov et al. (2010) using the same dataset also investigated the global structure and temporal variability, particularly seasonal and interannual behavior of the stationary planetary waves with zonal wave number 1 and 2, and found the Southern Hemisphere (SH) magnitudes to be larger than those in the NH. But they did not report the propagating components i.e., travelling planetary waves.

Planetary waves with periodicities varying from 12 to 20 days are usually referred to collectively as quasi-16 day waves. These waves were first observed in the mesosphere lower thermosphere (MLT) region by Kingsley et al. (1978) over NH high latitudes. Following this study, there has been large number of studies concentrating on this periodicity, but mostly in the MLT heights or confined to a specific atmospheric altitude region. Most of these studies reported that these waves are very commonly observed in the winter hemispheric middle atmosphere over mid and high latitudes. However there are observations which show enhanced quasi 16-day wave activity in the summer hemispheric middle atmosphere (Williams and Avery 1992). Forbes et al. (1995) showed the quasi-16 day oscillation with zonal wave number 1 in the winter mesopause region. Numerical simulations confirmed that this is the result of direct upward penetration from the lower atmosphere. This study also suggested that the observation of quasi 16-day wave in the summer MLT region is due to the ducting of these waves from winter to summer hemisphere. However, these authors also suggested the possibility of gravity wave modulation by quasi 16-day wave in the stratosphere. The quasi 16-day modulated gravity waves can deposit their momentum in the MLT region, which can in turn generate quasi 16-day oscillation. Luo et al. (2000) studied the quasi 16-day planetary waves using a network of MF and meteor radars over the NH mid-and high latitudes and found that the interannual variability of these waves are governed by quasi biennial oscillations (QBO), which is an equatorial phenomenon. However the authors did not provide any explanation for the signature of QBO in quasi-16 day wave variability over mid-and high latitudes. Pancheva et al. (2008) examined the vertical coupling of the stratosphere-mesosphere system through planetary waves of different scales during the NH sudden stratospheric warming (SSW) event of 2003–2004 using observations from eight radar stations, UKMO winds and SABER temperatures. Prior to the SSW, the system was dominated by the quasi-16 day wave whereas after the onset of SSW, the system was dominated by longer period waves. Day and Mitchell (2010a) reported the 16-day planetary wave in the polar MLT using meteor radars at Esrange (68°N, 21°E) in the Arctic and Rothera (68°S, 68°W) in the Antarctic. These authors noted that the wave activity is stronger in winter months as compared to other seasons and there are no significant differences in wave activity over the two Polar Regions. Lima et al. (2006) observed the quasi-16 day wave over the SH low latitudes using meteor radar winds for several years. Though they found strong inter annual variability, they could not bring out a clear seasonal trend because in some years the austral autumn–winter showed more activity whereas the summer-spring activity peaked for some other years. Das et al. (2010) reported quasi 16-day wave activity over the NH low latitude simultaneously in wind and temperature using meteor radar observations. Over this latitude, quasi-16 day waves showed their maxima during winter with a secondary maximum during summer. Day et al. (2011) using satellite observations from Aura MLS reported propagating $s = 1$ quasi-16 day wave from the stratosphere to the MLT region with prominent amplitudes in the midlatitudes and poles. More recently, McDonald et al. (2011) analyzed the EOS-MLS temperatures and found that the quasi 16 day wave-field is made up of a number of components, with westward and eastward propagating $s = 1$ and $s = 2$ waves most dominant. All modes of the quasi 16-day wave exhibited strong seasonal patterns and significant interannual variability. Thus the quasi-16 day planetary waves have been studied using ground and space based observations. However, the space based observations of quasi 16 day are limited as compared to ground based observations.

The quasi 5-day wave is the first symmetric mode with respect to the equator with zonal wave number 1. Studies on the quasi 5-day waves are relatively less common as compared to that on quasi 16-day waves. Wu et al. (1994) investigated the quasi 5-day wave in the MLT region using HRDI (UARS) wind data and found it transient with a lifetime of 10–20 days. They found the wave phase and amplitude to be consistent with the (1, 1) Rossby wave normal mode. Miyoshi (1999) using numerical simulations showed that the amplitude of quasi 5-day wave in the summer hemisphere is larger than that in the winter hemisphere in the MLT region. On the other hand, in the stratosphere, the amplitude in the summer hemisphere is smaller than that in the winter hemisphere. This study also emphasized the importance of moist convection in triggering the quasi-5 day wave. Kirkwood et al. (2002) observed 5-day planetary wave variations in temperature, zonal wind, noctilucent clouds and polar mesosphere summer echoes (PMSE) near Kiruna, Sweden, at heights between 80 and 95 km. They found that temperature variations correlated with the 5-day wave reach 15 K peak-to-peak and correspond to modulation of PMSE occurrence by up to 50 %. Merkel et al. (2003) also observed the 5-day planetary wave in Polar Mesospheric Cloud (PMC) measurements from the Student Nitric Oxide Explorer Satellite. Using TIMED/SABER temperature measurements, Riggin et al. (2006) studied the 3 year climatology of quasi 5-day wave by employing 2D Fourier analysis. These authors emphasized the importance of source strength and background winds in explaining the interannual variation of quasi 5-day waves, which peaked during April/May months. Chshyolkova et al. (2005, 2006) studied the planetary wave coupling processes in the middle atmosphere using MF radar network under CUJO program. These authors suggested that there is a strong vertical coupling between stratospheric and mesospheric heights during winter months. It is also reported that the short-period (<10-days) planetary waves dominate in the summer hemisphere whereas as longer-period (>10-days) dominate the winter hemisphere. von Savigny et al. (2007) used satellite observations to detect signatures of 5-day wave in noctilucent clouds and mesopause temperatures using SCIAMACHY/Envisat limb scattering measurements and MLS/Aura respectively. Nielsen et al. (2010) investigated the quasi-5 day wave in both temperature and water vapor in the stratosphere and mesosphere as seen in the NOGAPS-ALPHA analysis fields for summer 2007. They emphasized the cause for the variability of PMCs in relation to the 5 day wave. The polar 5 day wave activity in the MLT region was analyzed by Day and Mitchell (2010b) using meteor radars. They found wave activity very strong in the winter, absent in the equinoxes and strong again in late summer. Thus there have been several studies on quasi 5-day waves and their manifestation in winds, temperature and composition throughout the middle atmosphere.

The quasi 10-day wave is the second asymmetric mode with respect to the equator with zonal wavenumber 1. Studies exclusively on the 10-day normal mode are rather few. Nevertheless they have been studied along with other modes. Hirooka (2000) reported the global behaviour of the 5- and 10-day waves for the region up to the mesopause. This study showed that in the month of April, the quasi 10-day wave penetrates deeply into the mesosphere in the SH owing to weak westerly background winds during that period. Pancheva and Mitchell (2004), using meteor radar measurements in the MLT region over Esrange, reported the quasi- 10 and 23 day waves in zonal and meridional winds. However, studies on quasi-10 day are limited as compared to quasi-2, 5 and 16-day waves.

The majority of past planetary wave studies have been in the MLT region using meteor/MF radar observations and thus limited to certain geographical locations. There are few studies focusing on global climatology of planetary waves which cover the full region from the stratosphere to the MLT region using satellite observations. Also, most of the recent satellite based studies focused on individual planetary scale waves and there are very few simultaneous studies of all the normal mode travelling planetary waves. The inter-hemispheric ducting of planetary waves from winter hemisphere to summer hemisphere is not fully explored using recent satellite observations. In this regard, the present study focuses on simultaneous and comprehensive observations of normal mode travelling planetary scale waves using 5 years of SABER observations from the stratosphere to the MLT region. The simultaneous observations of the three normal modes, the climatology of quasi 10-day waves and interpretation of observed wave patterns using MERRA zonal winds are new aspects of the present study. Section 2 describes the data used and the methodology followed for the planetary scale wave analyses. Section 3 provides the results and discussions and Sect. 4 gives the concluding remarks.

2 Data and methodology

Global analyses of planetary waves require temperature/wind/chemical composition measurements from satellite based observations. The requirement would be to obtain at least one profile of the measured geophysical parameter within the chosen grid [one observation in 1(day) × 5 (latitude) × 20 (longitude) grid] so that meaningful extraction of the wave component with global coverage can be ensured. Considering these factors, for the present study, the data are obtained from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) payload which is one among the four instruments onboard the Thermosphere–Ionosphere–Mesosphere Energetics and Dynamics (TIMED) satellite. The TIMED is positioned in a highly inclined orbit (74°). The SABER instrument is a limb viewing multi-channel (1.27–17 μm) infrared radiometer designed to measure emissions in the atmosphere over a wide spectral range and altitude. CO_2 infrared limb radiance from 4.3 and 15 μm bands in approximately 20–120 km altitudes are measured by SABER and the kinetic temperature profiles are retrieved using a non-LTE inversion method (Mertens et al. 2001; Remsberg et al. 2003). The errors, in addition to those associated with instrumental noise, are also estimated by Mertens et al. (2001) and the errors are found to between 1.4 % at 80 km and 22.5 % at 110 km. In addition to this, the systematic and random errors from SABER that can affect wave studies are dealt with by John and Kumar (2012).

In the present study, we have used the kinetic temperature measurements, version 1.07 of SABER level 2A data. Daytime and nighttime measurements are fixed at almost corresponding local times, drifting backward by about 12 min on subsequent days. The daytime as well as nighttime measurements during both ascending and descending orbits are important for planetary wave studies. Over the course of one orbit, SABER observes between about 52°S and 83°N if in a northward-viewing yaw, switching after 60 days to a corresponding southward-viewing yaw. Thus at any instance, SABER misses one pole, but provides data with near-global coverage spanning 24 h in local time over a period of 60 days. Kishore Kumar et al. (2008), did a comparative study of the mean thermal structure of the low-latitude middle atmosphere by using Rocket, Lidar and SABER data and showed the capability of SABER in deriving reliable vertical temperature profiles. John and Kumar (2012) have also shown good comparison between SABER and Lidar derived gravity wave potential energies and have thus illustrated the capability of the payload in obtaining derived parameters also. It is generally assumed that temperature profiles of the atmosphere are comprised of a background temperature on which there is an imposed fluctuating component corresponding to large-scale planetary and small-scale gravity waves. In the present study, the SABER temperature measurements are binned in 1 (day), 5 (latitude) and 20(longitude) grids respectively. The daily binning of the data will not allow extraction of the quasi-2 day wave information from the present analysis but will be sufficient enough to delineate the quasi-5,-10 and -16 day planetary waves (Riggin et al. 2006). There were only a few data gaps, which were interpolated using cubic spline interpolation technique. After binning the data in the above mentioned grid, a two-dimensional Fourier Decomposition (2DFD) method proposed by Park et al. (2004) is used to extract the amplitude and phase of eastward/westward propagating planetary waves with periods 5-, 10- and 16-days. This method can be used to decompose the stationary or propagative components of a Longitude/Time signal with Fourier harmonics. The advantage of the 2DFD method for planetary wave analysis is that we can separate waves according to their propagation directions, i.e., westward, eastward and stationary waves. Hence we segregated planetary waves with respect to their zonal wave-number, propagation direction and periodicity at every 5° latitude in the entire stratosphere-mesosphere-lower thermosphere region. A two-dimensional time series with 32 continuous days at a stretch is considered for the analysis as 16 day is the maximum periodicity that we are interested in the present study. Thus we obtain amplitude and phase of planetary

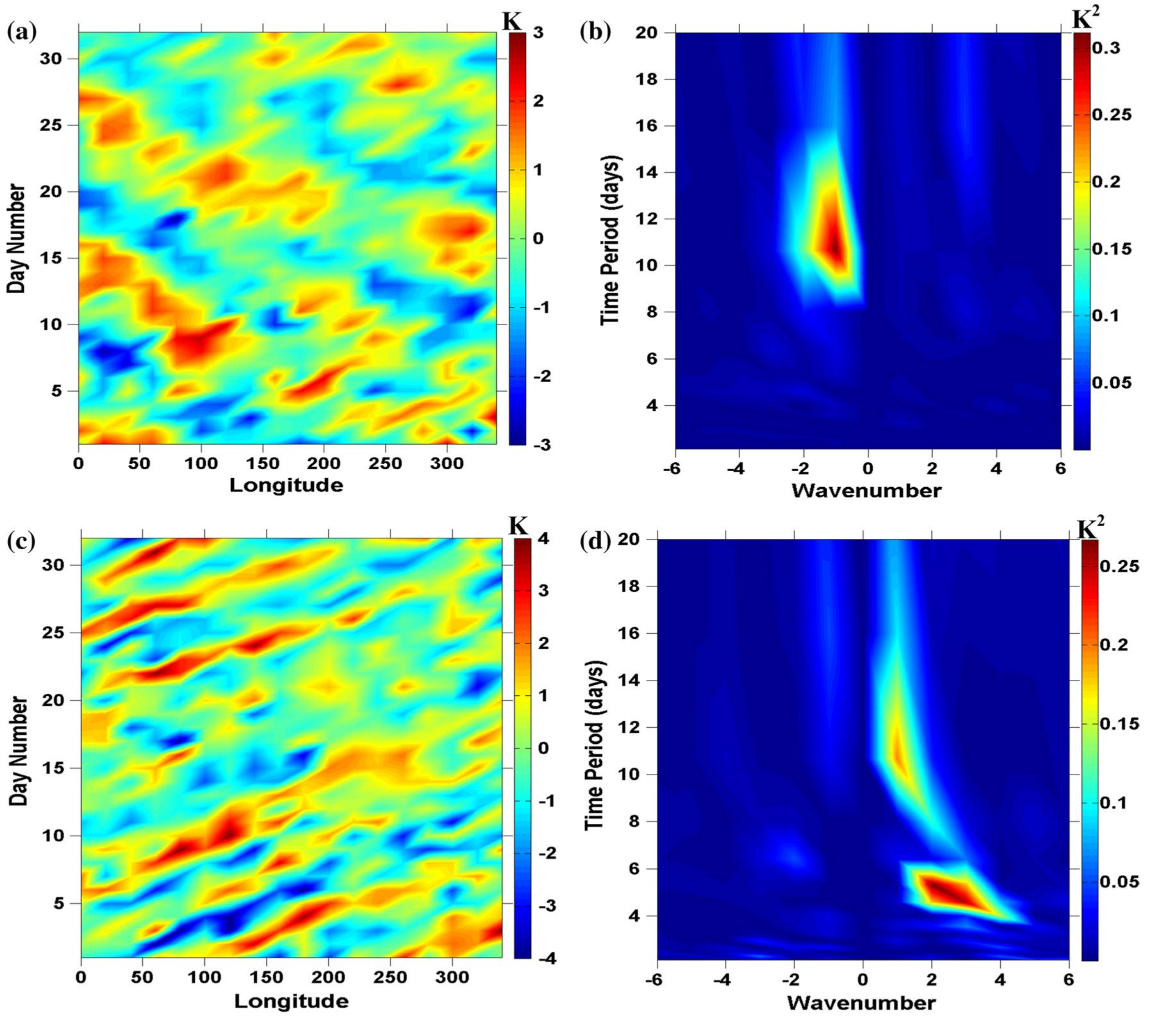

Fig. 1 **a** The time-longitude section of temperature perturbations at 30 km altitude over 50°S during January 2007 and **b** the corresponding 2DFD for propagating components. **c**, **d** are same as **a** and **b** but for equatorial latitudes

waves for every month, which are then used to interpret their latitudinal structure, seasonal variation and interannual variability. For example, we have taken 1–32 days (from 01 January to 01 February) of data for the month of January and 32–64 days (01 February–04 March) for February and so on. The wavenumber resolution is 1 and the frequency resolution is ~0.031 day^{-1}. We also use Modern-Era Retrospective Analysis for Research and Applications (MERRA) reanalysis data during the years 2003–2007 for background zonal winds. MERRA uses a three-dimensional variational data assimilation algorithm based on the Grid-point Statistical Interpolation scheme for deriving the winds.

3 Results and discussion

The SABER temperature measurements during the years 2003–2007 are used to study the global planetary wave activity with emphasis on travelling normal modes. The components of the quasi 16-, 10- and 5-day modes are extracted using the 2DFD method as mentioned in Sect. 2. Before obtaining the amplitude and phase of various planetary waves, the 2DFD algorithm is tested using a few well-defined wave structures seen in SABER temperature perturbations. Figure 1a shows the two-dimensional time series of mean removed temperature perturbations over 50°S at 30 km altitude and Fig. 1b shows the corresponding 2DFD for propagating components during the month of January 2007. The signature of westward propagating waves can be clearly noticed from the time-longitude structure of temperature perturbations. Further, the wave number-time period section of temperature perturbations shown in Fig. 1b reveal that a westward propagating planetary wave with wavenumber 1 and time period of 10–12 days dominate the observed perturbations. Figure 1c, d show the time-longitude section of temperature perturbations and corresponding 2DFD

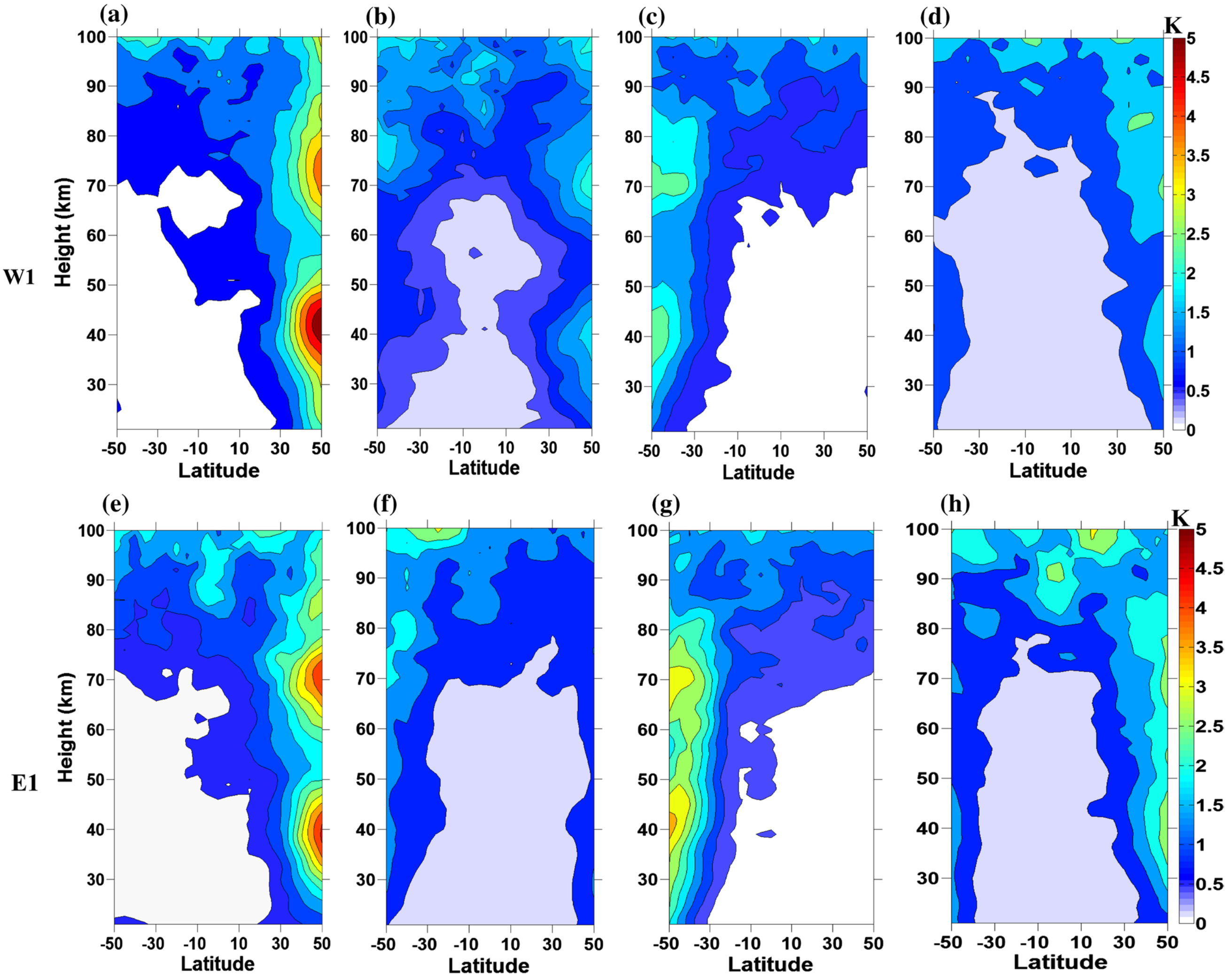

Fig. 2 Five year mean latitude-height section of amplitudes of the W1 quasi 16-day waves during **a** boreal winter, **b** vernal equinox, **c** boreal summer and **d** autumnal equinox. **e**–**h** Are same as **a**–**d** but for the E1 quasi 16-day waves

respectively over the equatorial latitudes at 30 km during January 2007. In this case also, well-defined wave perturbations can be observed from the time-longitude sections. Further, 2DFD shown in Fig. 1d reveals the presence of two eastward propagating waves with periods ~5 and ~10 days and wavenumbers 2 and 1 respectively. From Fig. 1, it is evident that the algorithm used for obtaining 2DFD reliably quantifies the observed temperature perturbations in both wave-number and time-period domain. In most of the cases, we have observed that the significant amplitudes are confined to wave numbers −2 to 2 and hence we will restrict our discussion to these wave numbers.

3.1 The quasi 16-day wave

Figure 2a–d shows the latitude–height section of amplitudes of the westward propagating quasi-16 day wave with zonal wave number 1 (W1) during boreal winter/austral summer (December–January–February), vernal equinox (March–April–May), boreal summer/austral winter (June–July–August) and autumnal equinox (September–October–November) respectively. Each latitude–height section is the mean of five years of quasi 16-day wave observations (2003–2007). From this figure, it can be noted that the W1 quasi 16-day waves peak over winter-hemispheric high latitudes of ~50°N and 50°S as shown in Fig. 2a, c respectively. In the present study, planetary wave observations are restricted to ± 50° latitude where continuous observations of SABER throughout the year are available. However, it has to be remembered that the quasi 16-day wave activity will have a broad peak around 40°–60° in both the hemispheres as reported by Luo et al. (2002) using HRDI observations. Nevertheless, the wave activity over 50° latitude in both hemispheres is representative of the variations

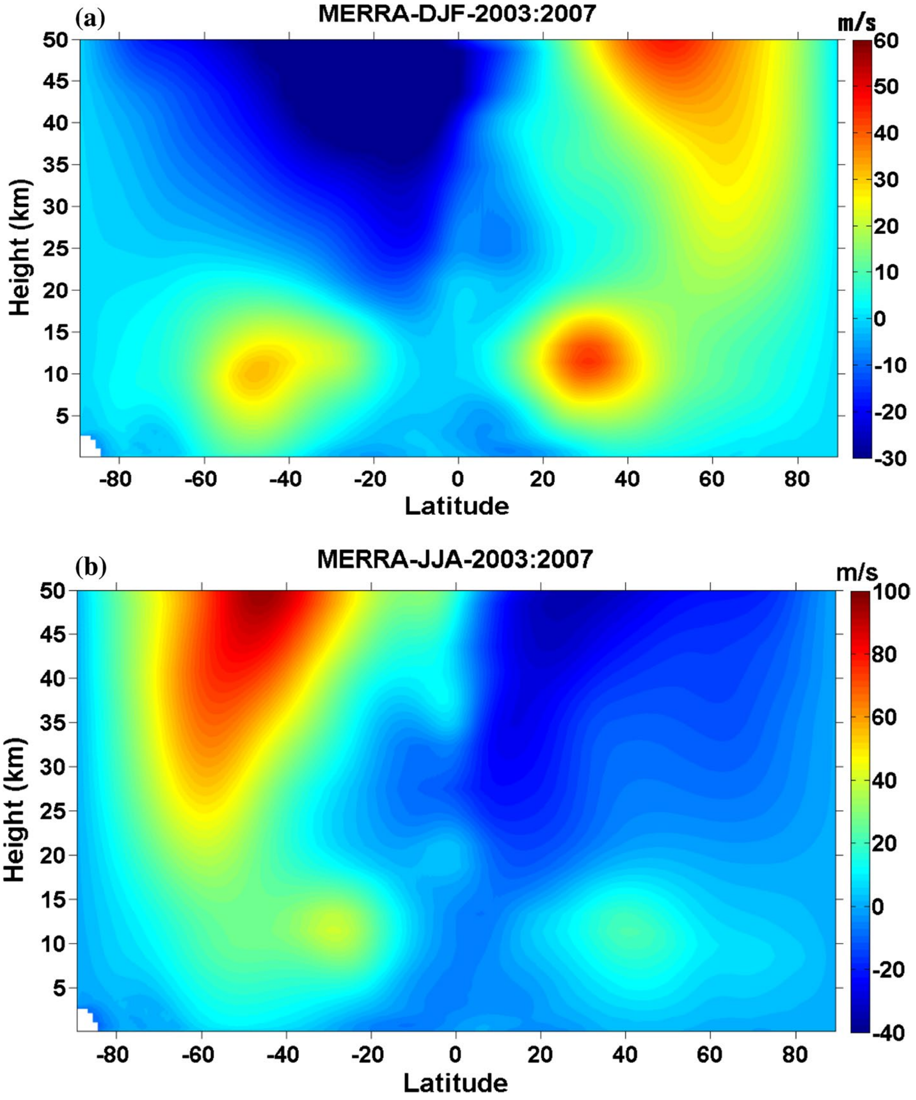

Fig. 3 Five year mean latitude-height section of zonal mean zonal winds during **a** boreal and **b** austral winters from MERRA reanalysis data

in the planetary wave activity over the mid-high latitudes. From Fig. 2a, c, it can be noted that wave activity is relatively higher over the NH high latitudes as compared to their SH counterparts during respective winters. During vernal and autumnal equinoxes also, W1 quasi 16-day waves show higher activity over the NH as compared to the SH as shown in Fig. 2b, d. During all the four seasons, there are two peaks in the wave activity, one in the upper stratosphere at ~40 km and another in the mesosphere at ~70–75 km, separated by a low wave activity region near the stratopause around 50–60 km. This double peak altitudinal structure is very consistent in both NH and SH high latitudes during all seasons. One of the known reasons for this structure is the strong vertical shear of horizontal winds near the stratopause region over high latitudes. The sharp changes in winds and temperature with height modify the vertical propagation of waves. To examine the background wind conditions during the observational period (2003–2007), we use zonal wind information in the 0–50 km altitude region from MERRA reanalysis data. Figure 3a, b shows the 5 year mean latitude-altitude section of zonal mean zonal winds during NH and SH winters respectively. From this figure, it can be noted that during respective winters in NH and SH, the winds are eastward throughout the stratosphere. It is now well established that the eastward background winds are conducive for westward propagating waves and hence during winters the W1 quasi-16 day wave show their maximum amplitudes throughout the stratosphere. On the other hand, in the summer hemisphere, zonal mean zonal winds are westward in the stratosphere, which are not conducive for W1 quasi 16-day wave vertical propagation. Figure 3 shows zonal winds up to 50 km altitude region and the sharp change in the winds appears just above this region i.e., in the 50–60 km height region, where minimum W1 quasi 16-day wave activity is found. However, earlier studies by

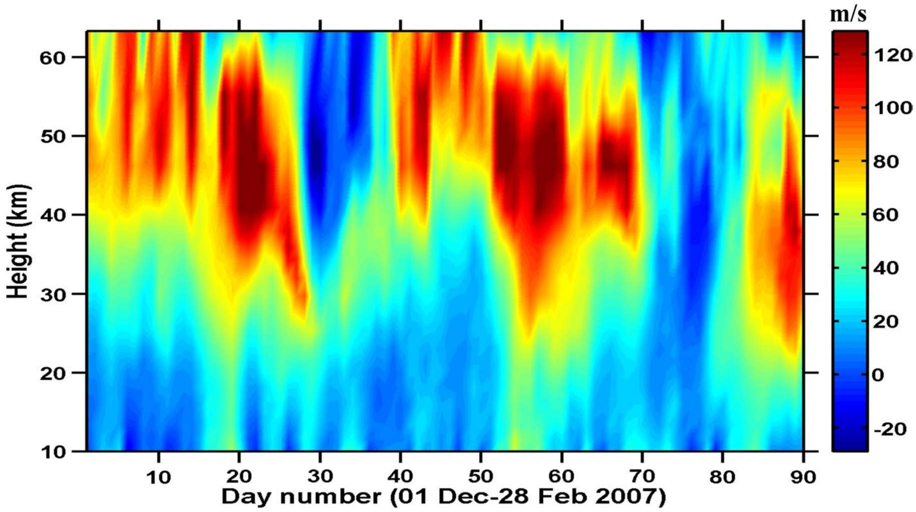

Fig. 4 Day-to-day zonal winds from 0 to 50 km altitude over 50°N, 150°E from MERRA reanalysis data during 2007 boreal winter

McDonald et al. (2011) and Day et al. (2011) showed that this type of sharp wind gradients do appear in this altitude region using reference wind climatology. McDonald et al. (2011) also pointed out that the sharp wind gradients in the vertical direction can facilitate the meridional propagation of planetary waves. This assertion can be verified using the latitude-altitude structure of wave amplitudes shown in Fig. 2, which readily shows wave amplitudes spreading in the meridional direction from the winter hemisphere to the summer hemisphere at around ~60 km region. However, height at which the meridional propagation starts varies from one season to the other. Also, the observed amplitudes of meridionally propagating waves are somewhat weaker as compared to vertically propagating waves. In the summer hemisphere, the W1 quasi 16-day waves show their peak magnitudes in ~90–100 km altitude region. Presently, there are two theories existing to explain the westward propagating waves in the summer hemispheric MLT region; one is the inter-hemispheric propagation of waves from winter to summer hemisphere as seen in the present study and the other is the in situ excitation of the quasi 16-day wave by dissipating gravity waves modulated by the quasi 16-day planetary waves in the lower atmosphere (Smith 1996). Simultaneous observations of planetary and gravity waves from the troposphere to the MLT region on global scales are required to verify these two theories. However, the present study provides evidence for interhemispheric propagation of the quasi 16-day waves. From Fig. 2, it can be noted that there is no propagation of the quasi-16 day wave from the lower altitudes to the MLT region over the equator and low latitudes. Thus the presence of quasi-16 day waves in the MLT region over the equator and low latitudes of both hemispheres can be attributed to the cross-equatorial propagation of this wave from winter to summer hemisphere. Earlier studies using meteor radar over low-latitudes have reported the presence of the quasi 16-day wave during winter and summer in the MLT region (Das et al. 2010).

Figure 2e–h shows the seasonal evolution of eastward propagating quasi 16-day waves with wavenumber 1 (E1). As in the case of W1 quasi 16-day waves, E1 waves also show their peak over winter hemispheric high latitudes. The W1 waves are relatively stronger than E1 waves during winter in the NH and both waves show similar double peak structure (refer to Fig. 2a, e). Interestingly, in the SH winter, the E1 waves are relatively stronger than the W1 waves. Moreover, the E1 waves in the SH do not exhibit the double peak structure as shown by W1 waves (refer to Fig. 2c, g). Thus there are notable differences in the propagation characteristics of W1 and E1 quasi 16-day waves in both hemispheres. There are very few studies focusing on the eastward propagating waves in the winter hemisphere (McDonald et al. 2011). It is now well established that during winter, the stratosphere is dominated by strong eastward winds and there is little probability that eastward propagating waves can pass through this wind regime. However, the present observations show the presence of E1 quasi 16-day waves in the stratosphere and also in the mesosphere during the winters of both hemispheres. These observations suggest that there may be westward or weak eastward winds during some parts of the winter, which facilitate the upward propagation of eastward waves. To examine the background wind conditions, we used day-to-day zonal wind information from the 0 to 50 km altitude region over 50°N, 150°E from MERRA reanalysis data during NH winter of 2007 and the results of the analysis are shown in Fig. 4. From this figure, it can be noted that during most of the winter, winds are eastward in the upper stratosphere, which are conducive for westward propagating waves. However, one can notice short bursts of westward winds in the upper stratosphere, which can facilitate the upward propagation of eastward propagating waves, thus penetrating into the

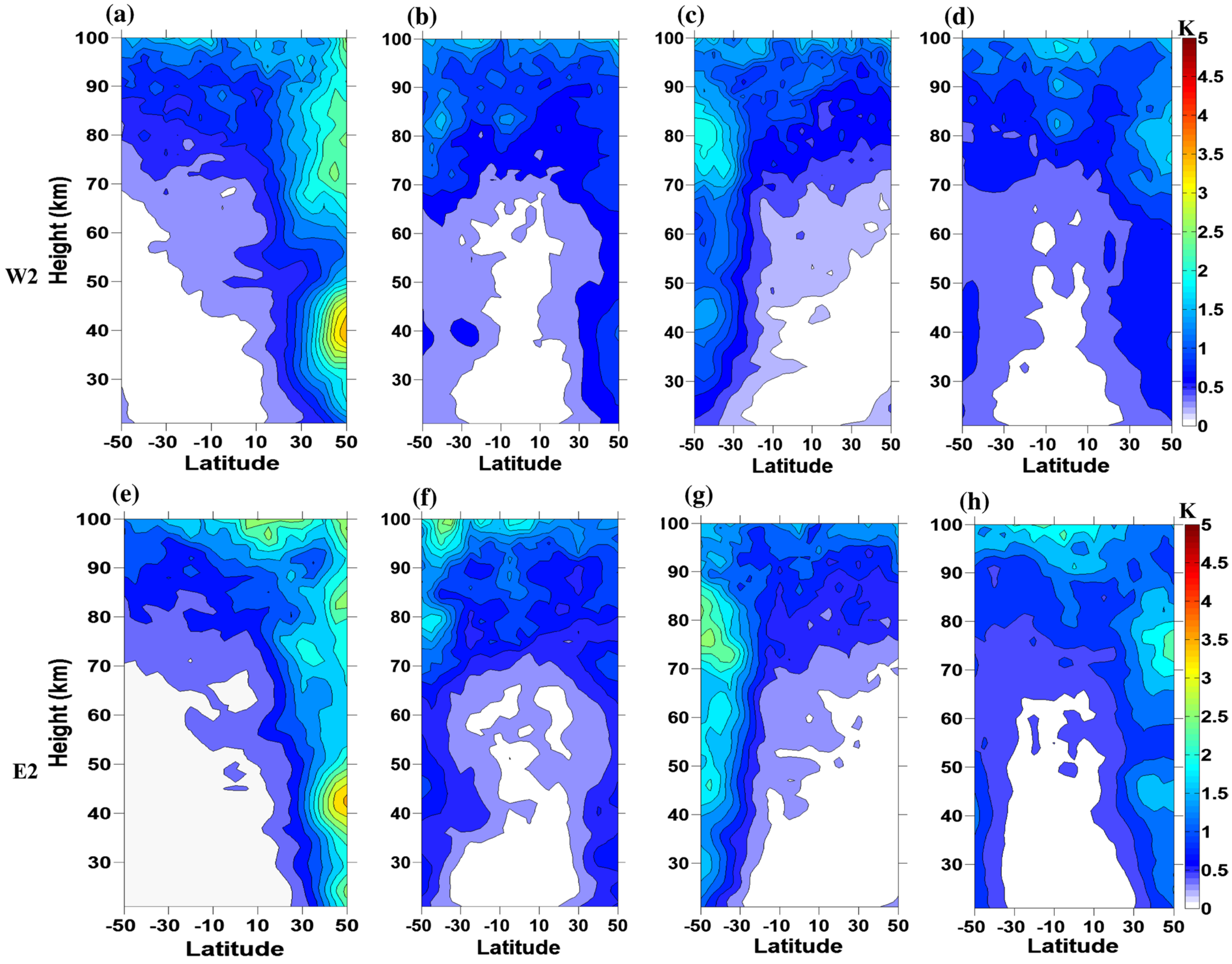

Fig. 5 Same as Fig. 2 but for W2 and E2 quasi 16-day waves

mesosphere. The relationship between W1 and E1 quasi 16-day wave amplitudes and background wind is verified. The mean wave amplitudes in 50–80 km altitude region and zonal wind observations at ~50 km are compared (figures not shown). The zonal winds exhibit an annual cycle with eastward winds during boreal winter and westward winds during boreal summer in the northern hemisphere. There is almost one-to one corresponds between eastward winds and W1 amplitudes as expected. Except for 2 months (month number 36 and 48), E1 wave peaks during relatively moderate eastward winds. There is one more possibility that the winds are not uniform along the longitude. To verify this assertion, we have constructed longitude-month section of zonal winds at ~50 km (figure not shown). The longitude-month section of zonal winds shows that the strong eastward winds are limited over ~−100° to 100° longitude and the winds are relatively weaker over other longitudes. The horizontal phase speed of E1 quasi-16 day wave is 12 m/s. So there is a possibility that E1 waves penetrate to higher altitude over the longitudes where eastward winds are weaker. Moreover, the day-to-day variability of zonal winds shown in Fig. 4 (which can be westward winds on some days) also facilitates the propagation of E1 waves. The occurrence of westward wind bursts during the winter and the propagation of E1 quasi 16-day waves into the mesosphere are relatively new results highlighted by the present study. Figure 2 thus depicts the seasonal evolution of W1 and E1 quais-16 day waves in the 20–100 km altitude region over latitudes ranging from 50°S to 50°N.

Figure 5a–d shows the latitude–height section of the amplitudes of the westward propagating quasi-16 day wave with zonal wave number 2 (W2) during four seasons as mentioned earlier. Most of the W2 quasi-16 day wave features, including the seasonal evolution, resemble their W1 counterparts shown in Fig. 2a–d except that W2 waves are relatively weaker as compared to W1 waves. The NH W2 waves are stronger than the SH W2 waves. During both the equinoxes, the W2 amplitudes are negligible throughout the

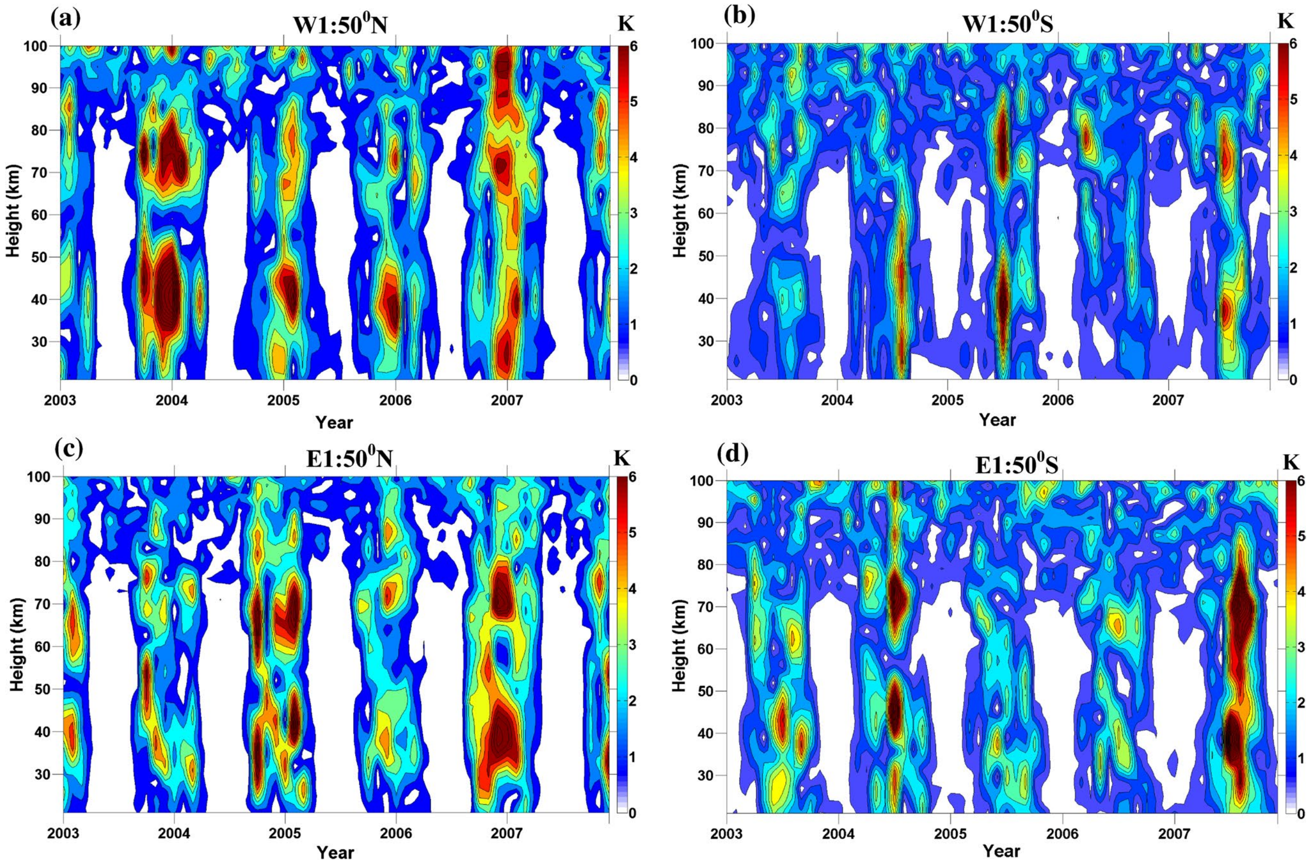

Fig. 6 The interannual variability (in term of height-time sections) of the W1 quasi 16-day waves during 2003–2007 over **a** 50°N and **b** 50°S. **c** and **d** are same as **a** and **b** but for E1 quasi 16-day waves

middle atmosphere as shown in Fig. 5b, d. The eastward propagating quasi 16-day waves with wavenumber 2 (E2) shown in Fig. 5e–h also exhibit similar seasonal evolution of their E1 counterparts depicted in Fig. 2e–h. It is interesting to note that E2 waves are stronger than W2 waves in the SH. Thus from Figs. 2 and 5, it can be concluded that the eastward propagating waves are stronger than the westward propagating waves in the SH and the opposite is true in the NH during respective winters. From Figs. 2 and 5, it is also can be noted that in the NH, both eastward and westward propagating waves with wavenumber 1 and 2 penetrate up to 100 km altitude whereas in the SH these waves abruptly terminate at ~85 km. The background winds in the MLT region in the respective hemispheres have to be examined in order to explain these observations. These observations are very important as there are very few studies focused on the simultaneous observations of planetary waves in both hemispheres from the stratosphere to the MLT region.

After establishing the mean latitude-altitude structure of W1, W2, E1 and E2 quasi 16-day waves, efforts are made to study their interannual variability. Figure 6a, b show the interannual variability of the W1 quasi 16-day waves over 50°N and 50°S respectively during the years 2003–2007. From these figures, it is once again confirmed that the quasi 16-day wave peaks during winter in both the hemispheres and propagates from the stratosphere to the MLT region. The striking difference in W1 quasi 16-day wave activity over the two latitudes is the number of wave pulses. Over 50°N latitude, the wave activity shows a broad band structure indicating more than one wave burst as shown in Fig. 6a, whereas over 50°S the wave activity exhibits narrow band structure. By examining the wave activity during individual years, it is observed that over 50°N, there are two peaks in wave activity, namely, one during October and another during December-January–February. In most of the years, the October peak is relatively weaker compared to the winter peak except for the year 2003, where the two peaks are comparable. In almost all the years, the wave activity persists during at least 2 months i.e. either in December-January or January–February, which is responsible for the observed broad band structure of wave activity over 50°N. Over 50°S, it is found that in most of the years the peak wave activity is confined to 1 month i.e., either July or August and giving rise to, the narrow band of wave activity as shown in Fig. 6b. A similar pattern of broad and narrow band wave activity is observed in E1 quasi 16-day waves over 50°N and 50°S as shown in Fig. 6c, d respectively. Thus from Fig. 6, it can be noted that in the NH there are more number of bursts of wave activity as compared to the SH.

The W1 quasi 16-day wave amplitudes show significant interannual variability in both hemispheres, as shown in Fig. 6a, b. There are changes in the altitudinal pattern as well from 1 year to the other. The W1 waves in the NH show large amplitudes of ~6 K during almost all years except during the year 2003, as shown in Fig. 6a. In the year 2003, the maximum wave amplitude is ~3 K, i.e., 100 % interannual variability as compared to other years. It is to be noted that the interannual variability in the stratosphere and mesosphere is not the same. For example, the wave activity in the mesosphere is weak during the years 2005 and 2006 compared to the years 2004 and 2007, but their amplitudes are comparable in the stratosphere during all these years. From this observation, it is obvious that the interannual variability in the stratosphere and mesosphere are controlled by two independent processes. From the present understanding, it seems that the interannual variability in the source strength of the W1 quasi 16-day wave is responsible for the observed variations in the wave activity in the stratosphere whereas the background winds, especially those near the stratopause, seem to be responsible for the observed variations in the mesosphere. The altitude structure of the wave amplitudes exhibits double peaked structure during all the years but with considerable variations. During the year 2007, the double peaks structure is less pronounced compared to all other years and the wave penetrates deep into the MLT region during this particular year. This observation also can be attributed to the background wind variations around the stratopause and in the MLT region. The simultaneous observations of winds in these height regions may provide new insights into the observed wave activity.

The W1 quasi 16-day waves in the SH also exhibit pronounced interannual variability as shown in Fig. 6b. The wave activity is relatively weaker during 2003 and 2006. Even though the mean wave activity in the SH is relatively weaker as compared to the NH (refer to Fig. 2a, c), the wave amplitudes in both hemispheres are comparable during individual years, especially during 2005. Interannual variability of up to 200 % can be noticed in both the stratosphere and mesosphere. Thus the W1 quasi 16-day waves show significant interannual variability in the SH compared to the NH. The interannual variability of the E1 quasi 16-day waves in the NH, depicted in Fig. 6c, shows strong wave activity during all the years except during 2006. In the SH, the E1 waves show their peak during the year 2007 as shown in Fig. 6d. Again, the interannual variability of the E1 waves is more pronounced in the SH in contrast to the NH, similar to the W1 waves. The E1 waves in the NH are reaching the MLT region in most of the years as compared to all other modes. It is also worthy to note that there is no one-to-one correspondence in the interannual variability of E1 and W1 wave activity, which is evident from Fig. 6a, c. It seems two different mechanisms are governing the interannual variability of E1 and W1 quasi 16-day waves in the NH. For example, during the years 2004 and 2005, W1 waves show a single burst of activity in the month of February, 2005, whereas E1 waves show two bursts, one in the month of October, 2004 and another in February, 2005. Similar results are found in the SH also as shown in Fig. 6b, d. In Fig. 6, it seems that W1 and E1 peaks appear at the same time in the contours maps. A line plot has been made to verify this aspect (figure not shown). There were three peaks of W1 and E1 which maximized during the same month (Months 25, 27 and 37). Further verifications showed that they occur in different longitude/time. Thus Fig. 6 provides a comprehensive view of the interannual variability of W1 and E1 waves in both the NH and SH. The interannual variability in source strength and background winds are the two important factors controlling the interannual variability of the observed planetary waves and quantitative studies of these aspects using realistic wind measurements are needed for further understanding.

Though Fig. 2 provides the signature of interhemispheric propagations of quasi 16-day waves, the interannual variability is not depicted. There are have been a few studies (both observations and modeling) in the past, which reported the possibility of inter-hemispheric propagation (Miyahara et al. 1991, Forbes et al. 1995; Day et al. 2011). To have further insights into the interhemispheric propagation of the quasi 16-day wave, the latitude-time sections of W1 and E1 wave activity at selected altitudes are shown in Fig. 7a, b respectively. From this figure, it can be noticed that at 40 km there is no sign of interhemispheric propagation as both W1 and E1 wave activity is restricted to a maximum of 30° latitudes in both hemispheres during respective winters. At 60 km, where relatively weaker wave activity is observed, there is advancement of waves towards low-latitudes, but not in all the years. However, at 80 km there is a clear evidence of interhemispheric propagation of both W1 and E1 waves. Further, at 100 km altitude the waves are smeared out and spread across the latitudes. Thus the present observations provide evidence for interhemispheric propagation of quasi 16-day waves at mesospheric heights.

3.2 The quasi 10-day wave

The quasi-10 day wave is one of the least studied normal modes of planetary waves with periodicity ranging from ~8 to 12 days. There are only a few studies on quasi-10 day

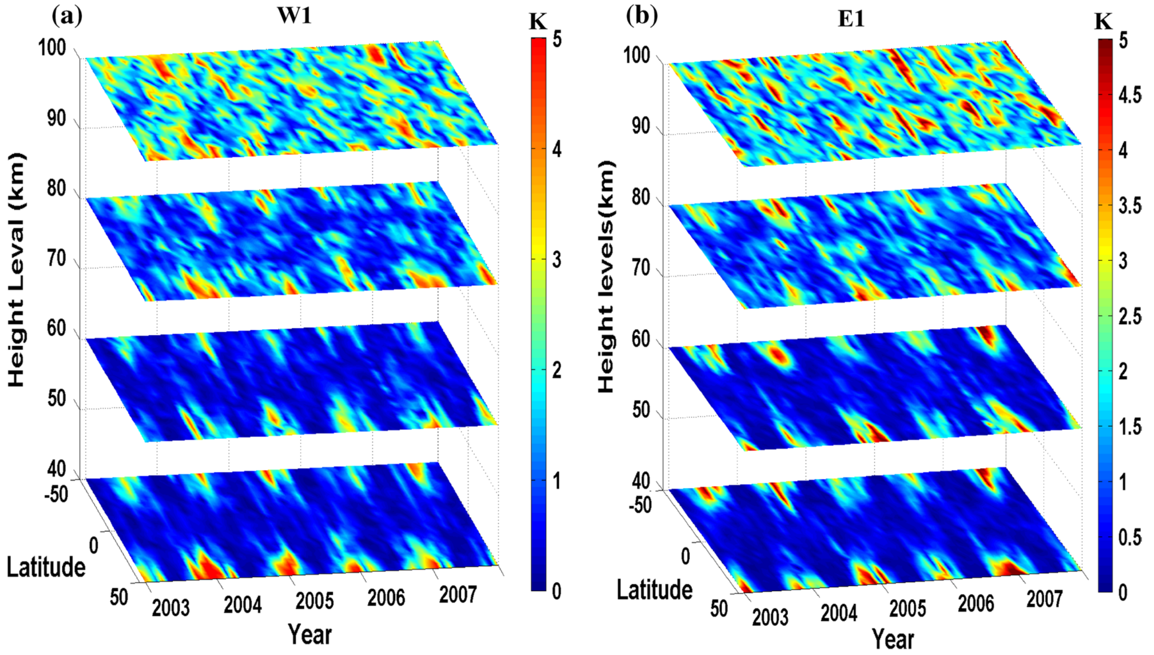

Fig. 7 The latitude-time sections of **a** W1 and **b** E1 quasi 16-day wave activity at selected altitudes

waves (e.g., Pancheva and Mitchell (2004)), but exclusive studies on a global structure regarding characteristics of these waves are limited. So an attempt is made to bring out the global climatology of these waves using 5 years of SABER measurements. As in the case of quasi 16-day waves, zonal wave numbers $s = 1$ and $s = 2$ are prominent in quasi 10-day waves and hence the results are restricted to these modes. Figure 8a–d depicts the height-latitude sections of 5 year mean W1 quasi 10-day wave amplitudes during boreal winter, vernal equinox, boreal summer and autumnal equinox respectively. As in the case of quasi 16-day waves, quasi 10-day wave amplitudes also maximize over high latitudes in both the hemispheres. The W1 quasi 10-day wave shows two peaks, one in the stratosphere (~at 40 km) and another in the mesosphere (~at 80 km), similar to quasi 16-day waves as shown in Fig. 8a. However, the altitude at which the peaks occur differs for 16-and 10-day waves in the mesosphere. The W1 quasi 16-day waves in the mesosphere show their peaks at 70 km whereas the quasi 10-day waves show their peaks at 80 km. As the quasi 10-day waves have higher phase speeds compared to quasi 16-day waves for a given wave number, the latter may have critical levels at lower altitudes compared to the former. The quasi 10-day wave activity shows their peaks during boreal winter over the NH high latitudes. However, in the mesosphere the wave amplitudes are comparable during boreal winter and autumnal equinox over the NH high latitudes, as shown in Fig. 8a, d. Over the SH high latitudes, the wave amplitudes during vernal equinox are more than those during austral winter, as shown in Fig. 8b, c in contrast to the seasonal variation of the quasi 16-day waves. As mentioned earlier, the seasonal variations in source strength and background winds play a major role in the observed seasonal variations in planetary waves. Figure 8e–h shows the seasonal variation of the E1 quasi 10-day waves. The E1 quasi 10-day waves also show their peaks during boreal and austral winters as in the case of the E1 quasi 16-day waves. From Fig. 8g, it is evident that the strongest component of quasi 10-day wave is the E1 over the SH high latitudes during the austral winter season, with amplitudes reaching up to ~4 K. The mesospheric peak in the W1 quasi 10-day wave is observed at ~80 km whereas it is observed at ~65 km in the case of E1 quasi 10-day waves. The E1 wave amplitudes in the mesosphere during both vernal and autumnal equinox are very weak compared to W1 waves. Thus there are notable differences in the seasonal variation of the W1 and E1 quasi 10-day waves in contrast to the quasi 16-day waves which show more or less similar seasonal variations in both W1 and E1 components.

The seasonal variations of latitude-height sections of W2 quasi 10-day waves are shown in Fig. 9a–d. The wave activity is relatively weak compared to their W1 counterparts and there are no notable seasonal variations. However, the seasonal variation of the E2 quasi 10-day waves depicted in Fig. 9e–h exhibits pronounced seasonal variations with maximum wave activity during austral and boreal winters in SH and NH respectively. The E2 quasi 10-day waves over SH high latitude during austral winter are the strongest among all the wave number 2 components. Thus from Fig. 9, it can be noted that among all the

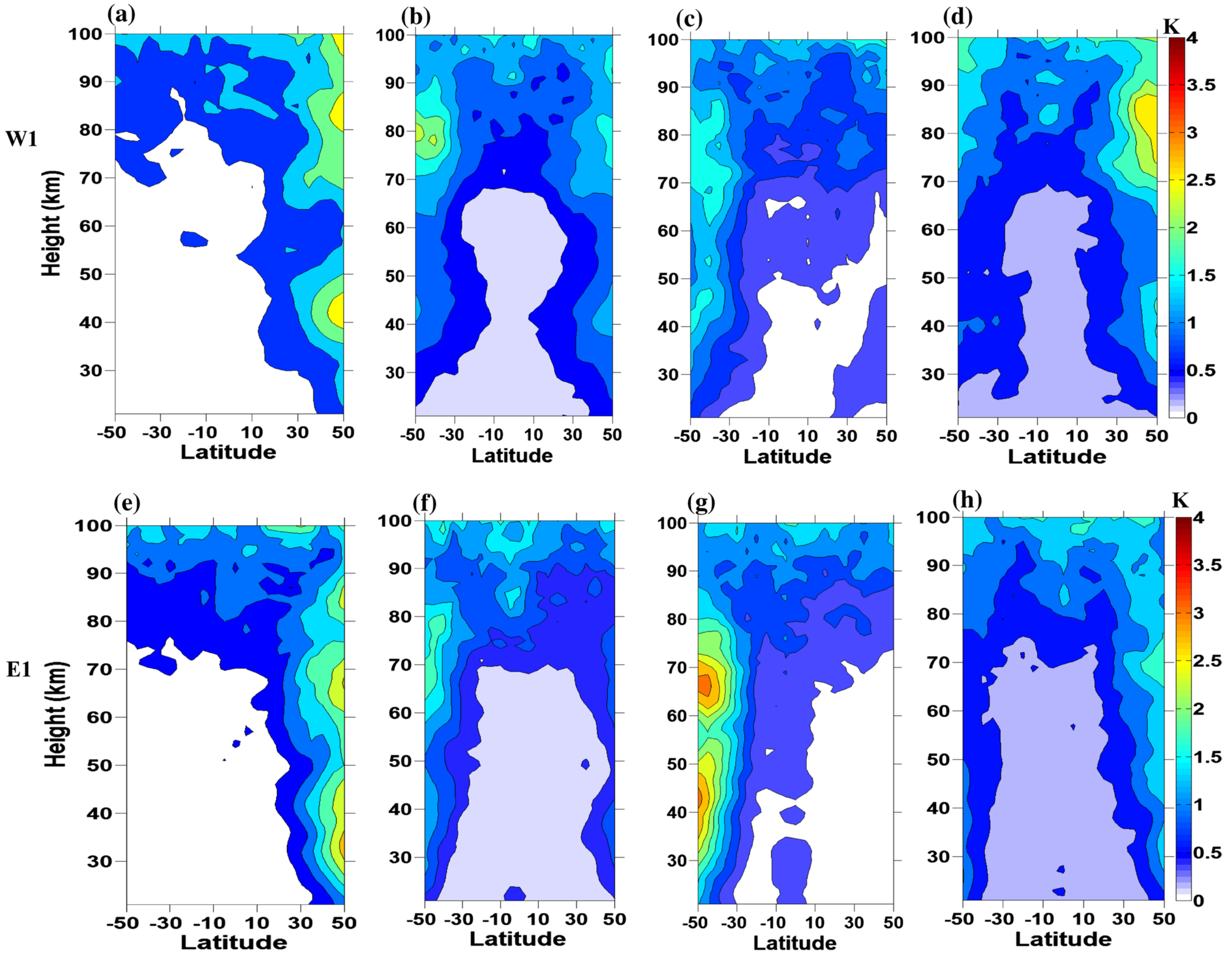

Fig. 8 Same as Fig. 2 but for W1 and E1 quasi 10-day waves

components of quasi 10-day waves, E1 and E2 over the SH high latitudes during austral winter are the strongest. Earlier Palo et al. (2005) reported the observations of eastward propagating quasi-10 day waves with wave numbers 1 and 2. These authors comprehensively showed the role of quasi-10 day wave in triggering the SH stratospheric warming during September 2002. The present results also show the dominance of the E1 and E2 quasi 10-day waves over the SH high latitudes.

Figure 10a–b shows the interannual variability of W1 quasi 10-day wave activity over high latitudes of the NH and SH respectively. Even though the mean climatology depicted in Fig. 8 shows the maximum amplitudes as ~4 K, considering individual years, the amplitudes are seen to reach as high as ~6 K in both SH and NH. There is a marked difference in the W1 quasi 10-day wave interannual variability in the SH and NH. In the NH, the W1 quasi-10 day waves show their presence in both the stratosphere and mesosphere whereas in the SH wave activity is limited to the mesosphere during most of the years. In the NH, the peak wave activity is observed during 2004 and 2006, whereas it is observed during 2004 and 2007 in the SH. The interannual variability of E1 quasi 10-day waves both in the NH and SH is shown in Fig. 10c, d respectively. Over the NH high latitudes, these waves are equally strong during the year 2006–2007, with a secondary peak during the year 2003–2004. Over the SH high latitudes, these waves are strongest during almost all the years except 2007. These waves over the SH abruptly terminate at ~70 to 75 km which is in contrast to their NH counterparts. As mentioned earlier, the wind regime in the 75–100 km altitude regions and the stability of the background atmosphere may be responsible for the attenuation of these waves. The E1 quasi 10-day waves over SH high latitudes show strong wave activity both in the stratosphere and mesosphere whereas W1 waves show their peak activity in the mesosphere only. Thus there exist contrasting features for the E1 and W1 quasi-10 day waves over the SH

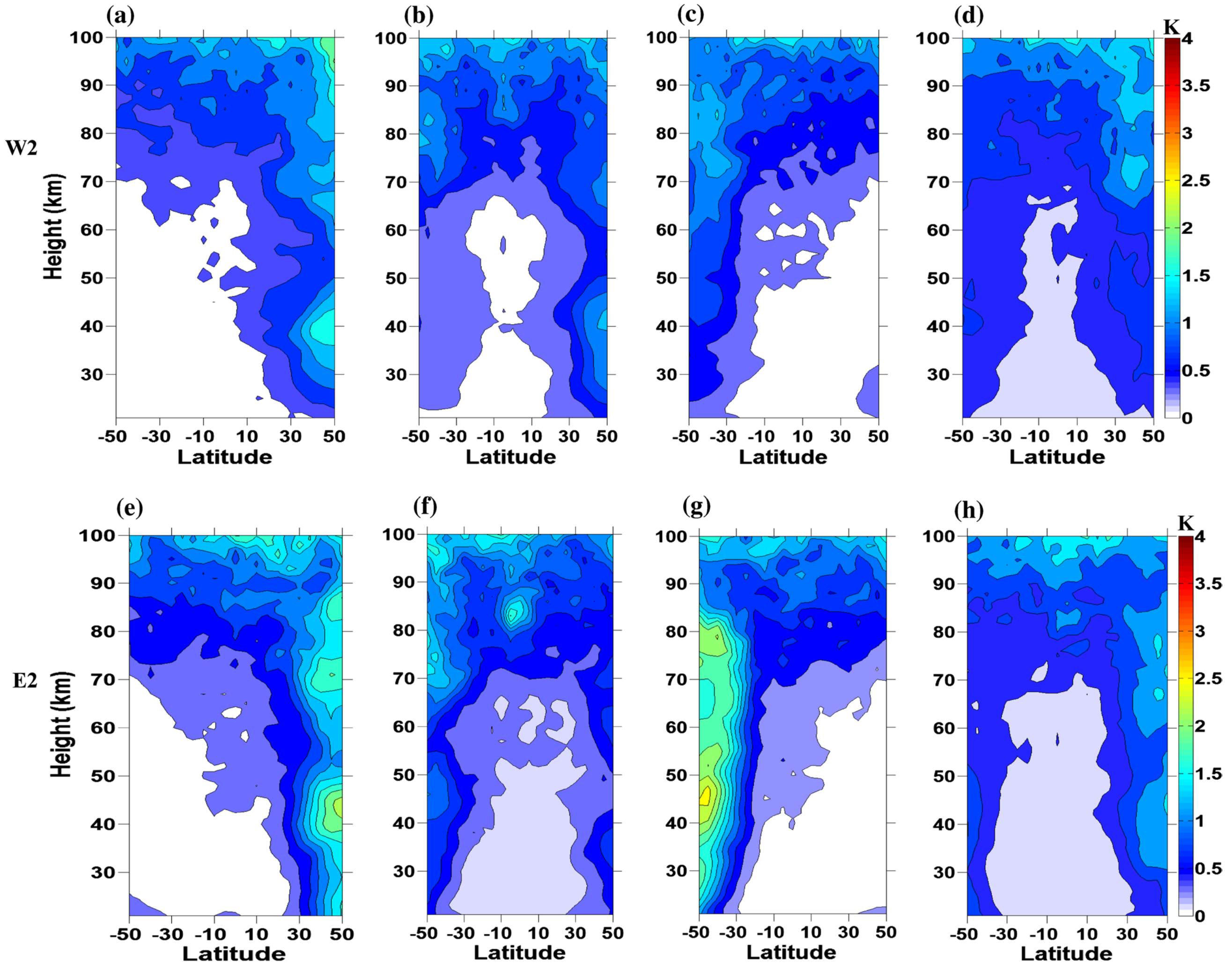

Fig. 9 Same as Fig. 2 but for W2 and E2 quasi 10-day waves

high latitudes. Again the interannual variability of both W1 and E1 quasi 10-day waves are different from each other, indicating that each is governed by different mechanisms. Thus Fig. 10a–d show pronounced interannual variability of the W1 and E1 quasi 10-day waves over both the NH and SH high latitudes. As mentioned earlier, the reports on quasi-10 day waves are relatively sparse and present observations provide a comprehensive view of these waves.

3.3 The quasi 5-day waves

Similarly to the quasi-16 and -10 day wave analysis, the global pattern and interannual variability of the quasi-5 day waves from the stratosphere to MLT heights have been established using the present observations. An earlier study by Wu et al. (1994) has shown that the quasi-5 day wave amplitudes are consistent with the Rossby wave normal mode. Figure 11a–d shows height-latitude cross-sections of the W1 quasi 5-day wave amplitudes estimated using the SABER measurements for four seasons viz., boreal winter, vernal equinox, boreal summer and autumnal equinox respectively. Unlike quasi- 16 and -10 day waves, which show their peak activity during winter, quasi-5 day waves peak during vernal equinox both in the SH and NH. However the observed mean amplitudes are relatively smaller than those of the other normal modes. The peak activity of the W1 quasi-5 day wave is centered around 40°N and 40°S exhibiting symmetry with respect to the equator (refer to Fig. 11b) whereas the quasi-16 and -10 day waves show their peak activity around 50° latitudes in both the hemispheres. Further, the wave amplitudes are relatively larger in the NH compared to their SH counterpart.

Earlier studies by Riggin et al. (2006) showed that the quasi 5-day wave is a gravest symmetric Hough mode. These authors also reported that the peak wave activity is observed during the month of April/May consistent with

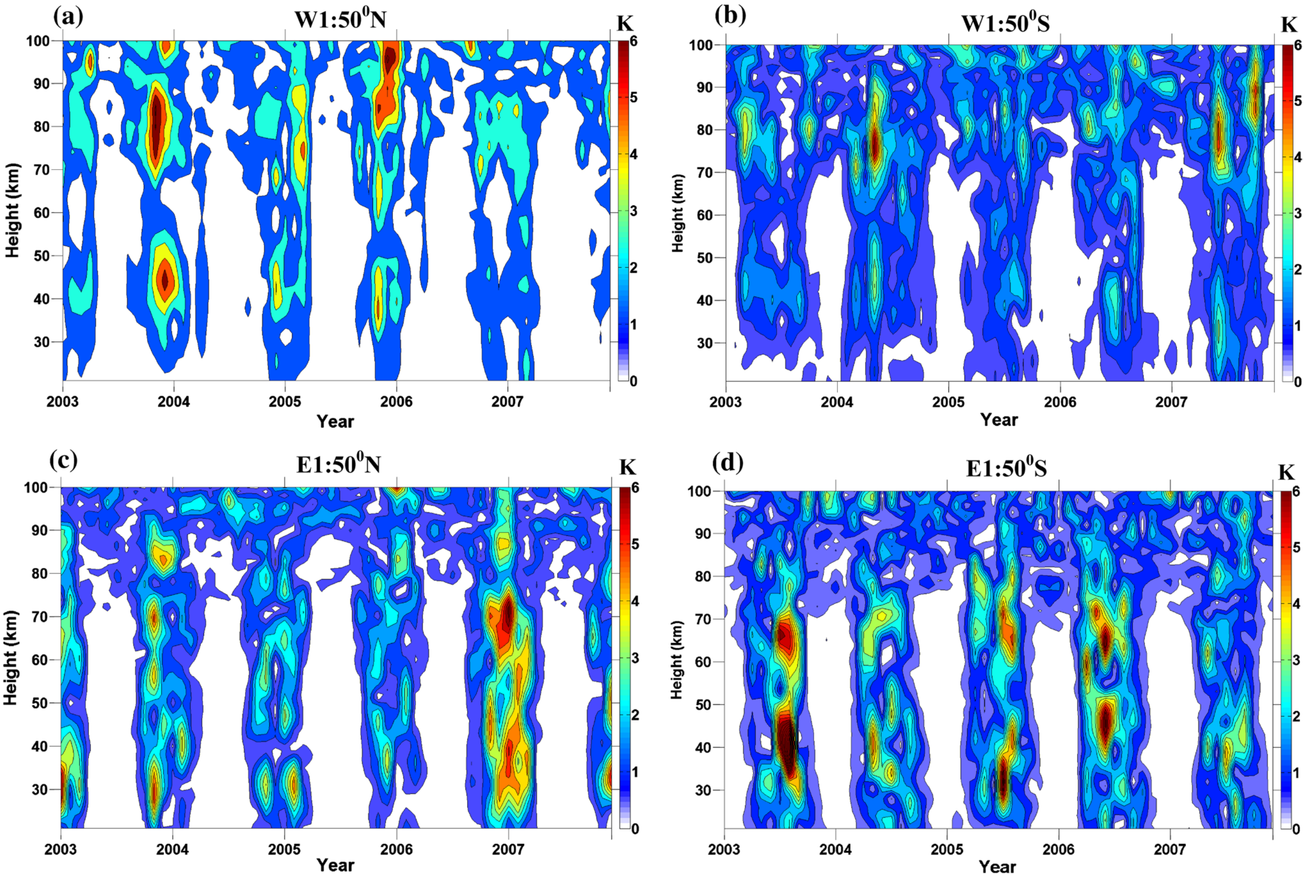

Fig. 10 Same as Fig. 6 but for W1 and E1 quasi 10-day waves

the present observations. The consistency observed in the present and earlier studies further strengthens the credibility of the analysis discussed here. In Fig. 11c, a secondary peak in the wave activity can be noted over the NH mid and high latitudes. However, the wave activity is not symmetric about the equator and hence cannot be attributed to the quasi 5-day wave normal modes. Thus the W1 quasi 5-day waves show significant differences in both seasonal variability and altitudinal structure when compared to other normal modes. Figure 11e–h shows the height-latitude cross-section of the E1 quasi 5-day wave for the afore-mentioned seasons. However, there is no significant amplitude compared to their W1 counterparts. The same can be said for the E1, E2 and W2 normal modes for all seasons. Hence further discussions on the quasi 5-day waves are limited to the W1 mode.

Figure 12a, b show the interannual variability of the W1 quasi 5-day wave during the study period over the NH and SH high latitudes. From Fig. 12a it can be noted that the wave activity is confined to the 75–100 km altitude with insignificant amplitudes below this region. The mean height-latitude sections depicted in Fig. 11 showed maximum amplitude of the order of ~3 K whereas during individual years, amplitudes more than 4 K are also observed. In most of the years, there are two peaks in the wave activity. In the year 2003, the peak wave activity is observed during the month of May, with a secondary peak in the month of August. In the year 2004, the peak amplitudes of are observed in the month of April and not in May. The secondary peak is observed during the month of August consistently in all the years with varying amplitude. During the year 2005, it is interesting to note that the April peak is weaker than the August peak and during the year 2006, the former is completely absent. In the year 2007, both the April peak and the August peak are comparable in magnitude. Thus the W1 quasi 5-day waves over the NH high latitudes show two peaks in a year, one in April/May and the other in August. The April/May peak shows pronounced interannual variability when compared to the August peak. The source mechanism of this wave along with their interannual variability may be required to explain the observed variability, which will be taken up in subsequent studies.

Figure 12b shows the interannual variability of W1 quasi 5-day waves over the SH high latitudes. A striking contrast between Fig. 12a, b is the absence of W1 quasi

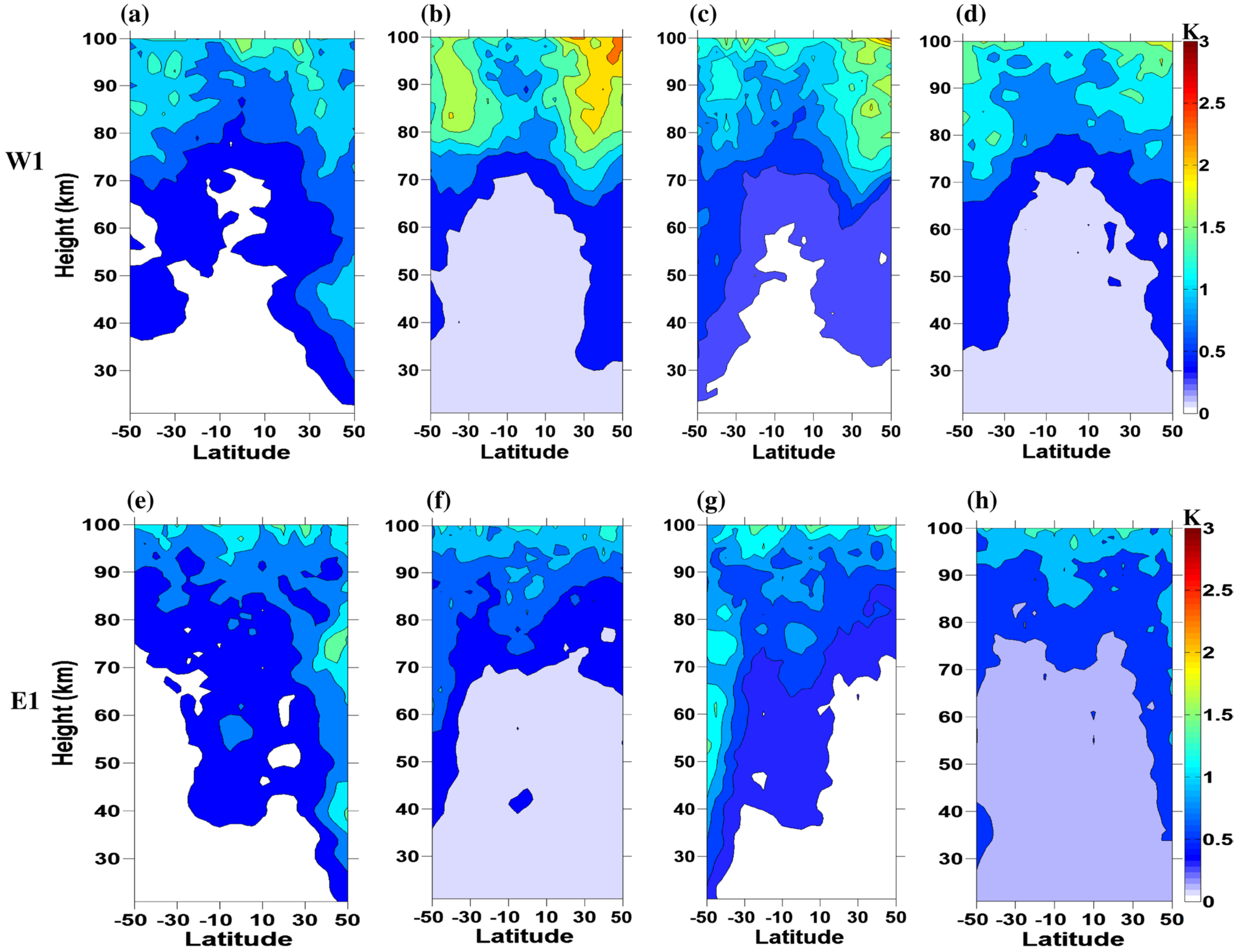

Fig. 11 Same as Fig. 2 but for W1 and E1 quasi-5 day waves

5-day wave activity during the month of August over SH high latitudes. However, from Fig. 11c, it is evident that during boreal summer, the W1 quasi 5-day wave activity peaks over 30–40°S rather than over 50° latitudes in the SH. The height-month section of the wave activity over 40°S does show the presence of relatively weak quasi 5-day waves during the month of August (figure not shown). As depicted in Fig. 12b, the W1 quasi 5-day wave shows pronounced interannual variability in the wave activity, with peak amplitudes during the years 2003 and 2004 similar to their NH counterpart. The wave activity in the SH is also confined to 75–100 km altitude region. Thus over both NH and SH high latitudes, the W1 quasi 5-day waves show pronounced interannual variability. The amplitudes of the E1 quasi 5-day wave during the individual years are of the order of ~3 K over the SH high latitudes. In contrast to the W1 modes, these waves are observed in the 20 -70 km height regions during most of the years (figure not shown). However the amplitudes of these waves are negligible over the NH. Thus the present study has established the climatology and interannual variability of quasi -16, 10- and 5- day normal modes using 5 years of SABER observations from the stratosphere to the MLT region. Dynamics of stationary planetary waves and their vertical propagation using SABER and re-analysis datasets will be addressed in subsequent studies.

4 Concluding remarks

A comprehensive study of the three normal modes of planetary waves, namely the quasi-16, quasi-10 and quasi-5 day waves, are carried out in the present study. Employing the 2DFD technique, planetary wave components are delineated globally using 5 years of TIMED/SABER temperature measurements right from the Stratosphere to the MLT. Preliminary analyses showed that there are both westward and eastward propagating normal modes with significant

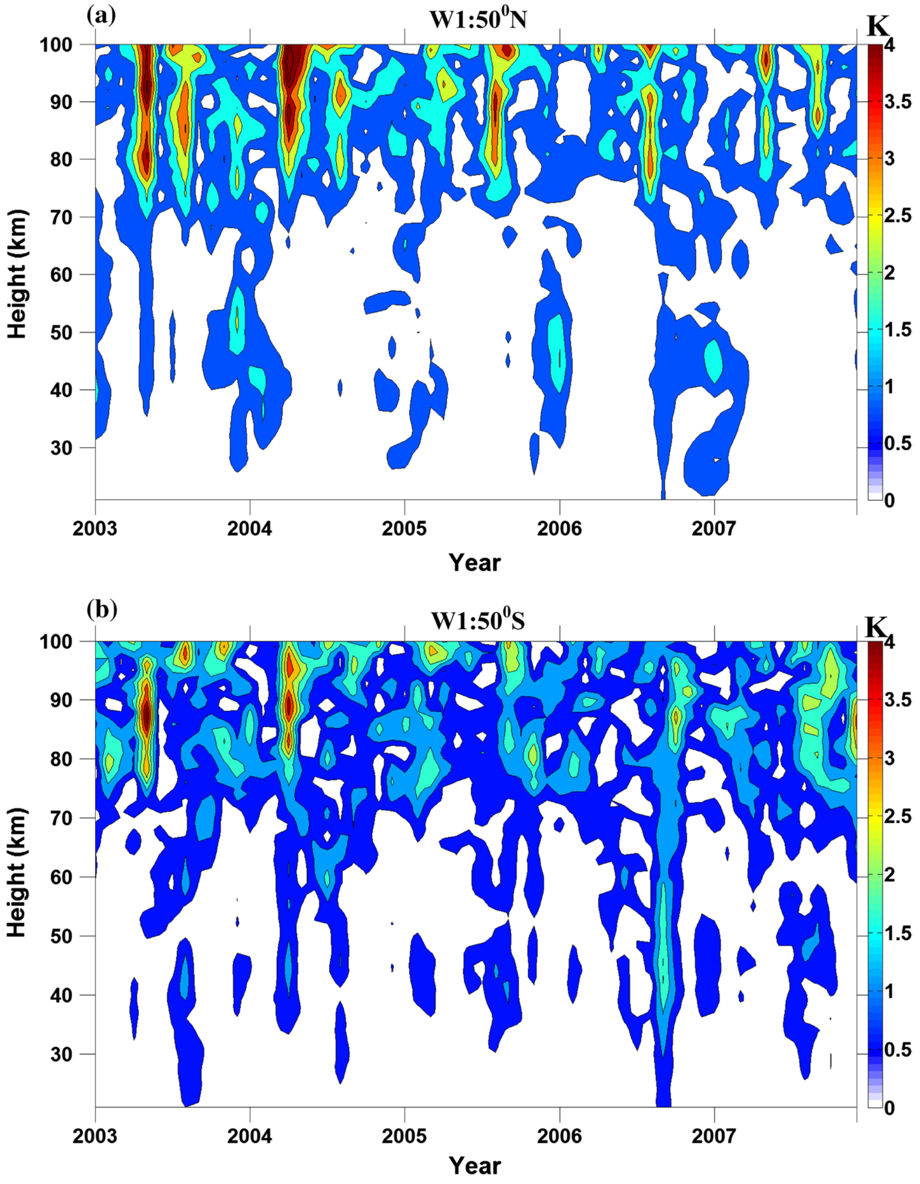

Fig. 12 The interannual variability (in term of height-time sections) of the W1 quasi 5-day waves over **a** 50°N and **b** 50°S during 2003–2007

amplitudes confined to wave numbers −2 to 2. Hence the study was restricted to these components for all the three modes. The present study then focused on the global structure and interannual variability of these modes. It was found that the W1 quasi 16-day wave peaks over winter-hemispheric high latitudes with the NH having higher amplitudes throughout the year as compared to their SH counterparts. The W1 quasi 16-day wave also exhibited a double peak structure in altitude with one peak in the stratosphere and another in the mesosphere with low wave activity around the stratopause for all seasons in both hemispheres. This is explained in terms of the background wind conditions at the stratopause level. The E1 quasi 16-day waves showed similar seasonal evolution and altitudinal structure as those of the W1 waves in the NH. But in the SH, the amplitudes of the E1 quasi 16-day waves are relatively higher than that of the W1 quasi 16-day waves and they do not exhibit double peak structure in altitude. Eastward waves observed in the mesospheric heights are explained by depicting short bursts of westward winds in the upper stratosphere, which can facilitate their upward propagation, thus allowing penetration into the mesosphere. The W2 and E2 structures of the quasi 16-day waves are also investigated and found to have lower amplitudes than their wave number 1 counterparts. It is concluded that the eastward propagating waves are stronger than the westward propagating waves in the SH and the opposite is true in the NH during respective winters. Detailed analysis was carried out to emphasize the interannual variability of the W1, E1, W2 and E2 components of the quasi-16 day wave. Signatures of inter-hemispheric propagation are also depicted in the analysis at mesospheric altitudes.

The latitude-altitude structure of the quasi 10-day wave amplitudes showed that these waves also maximize over high latitudes in both the hemispheres during winter. The W1 component has a double peak in the NH though at a different altitude when compared to the quasi 16-day wave. E1 is more prominent in the SH. There are notable differences in the seasonal variation of the W1 and E1 quasi 10-day waves. The W2 and E2 quasi 10-day waves have relatively lower amplitudes than the wave number 1 components. The E1 and E2 quasi 10-day waves are the strongest in the SH and during austral winter. The E2 component is the strongest among all the wave number 2 components. There is a marked difference in the W1 quasi 10-day wave interannual variability in the SH and the NH. The interannual variability of both W1 and E1 quasi 10-day waves are also different from each other indicating that both are governed by different mechanisms.

The present results showed that the quasi-5 day waves peak during vernal equinox in both SH and NH, unlike quasi- 16 and -10 day waves, which show their peak activity during winter. The peak activity of the W1 quasi-5 day wave is centered around 40°N and 40°S, exhibiting symmetry with respect to the equator, whereas the quasi-16 and -10 day waves show their peak activity around 50° latitudes in both the hemispheres. Thus the W1 quasi 5-day waves showed significant differences in both seasonal variability and altitudinal structure when compared to other normal modes. The wave activity is confined to the 75–100 km altitude with insignificant amplitudes below this region. The W1 quasi 5-day waves over the NH high latitudes showed two peaks in a year, one in April/May and the other in August. The amplitudes of E1 quasi 5-day wave during the individual years are of the order of ~3 K and are significant only in the SH high latitudes. It is also found that these waves are more or less confined to the 20–70 km altitude region and do not penetrate beyond. Thus a comprehensive global picture of the normal modes of planetary waves emerged as a result of this study, detailing the westward and eastward propagating modes and their interannual variability. In order to carry out precise quantitative studies and to look further into the mechanisms that control the generation and propagation of these waves, one needs reliable wind measurements to monitor the background atmospheric conditions, coherent information about sources and generation mechanisms in the lower atmosphere, as well as in situ sources in the middle atmosphere.

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