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Characterisation of quasi-stationary planetary waves in the Northern MLT during summer

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ABSTRACT

Observations of planetary wave (PW) activity in the northern hemisphere, polar summer mesosphere and lower thermosphere (MLT) are presented. Meteor winds from a northern hemisphere chain of SuperDARN radars have been used to monitor the meridional wind along a latitude band (51–66°N) in the MLT. A stationary PW-like longitudinal structure with a strong zonal PW number 1 characteristic is persistently observed year-to-year during summer. Here we characterize the amplitude and the phase structure of this wave in the MLT. The Modern-Era Retrospective Analysis for Research and Application (MERRA) of the NASA Global Modelling and Assimilation Office has been used to evaluate possible sources of the observed longitudinal perturbation in the mesospheric meridional wind by investigating the amplitudes and phases of PWs in the underlying atmosphere. The investigation shows that neither gravity wave modulation by lower atmospheric PWs nor direct propagation of PWs from the lower atmosphere are a significant cause of the observed longitudinal perturbation. However, the data are not of sufficient scope to investigate longitudinal differences in gravity wave sources, or to separate the effects of instabilities and inter-hemispheric propagation as possible causes for the large PW present in the summer MLT.

1. Introduction

Planetary waves are global scale waves where the latitudinal gradient of the Coriolis force serves as the restoring force. They can be generated in the lower atmosphere and, due to their westward intrinsic phase speeds (Forbes, 1995), they transport energy and westward momentum as they propagate upward, growing in amplitude.

Charney and Drazin (1961) showed using a simplified analytical solvable system of the atmosphere that planetary waves can only propagate into regions where the zonal mean wind is more eastward than the zonal phase velocity of the wave. The strong westward stratospheric winds that form during summer at mid- to high-latitudes should inhibit the upward propagation of planetary waves from below. More detailed analyses showed that the relationship is more complex and that vertical planetary wave propagation can be related to the effective refractive index (e.g. Smith, 1983; McDonald et al., 2011). In the quasi-geostrophic approximation, this refractive index depends primarily on the zonal wind and its latitudinal and vertical gradients (Smith, 1983). Nevertheless, vertical planetary wave propagation through the stratosphere from below is still unlikely during summer, and several studies have shown that there is little planetary wave activity present in the middle atmosphere during summer (e.g. Alexander and Shepherd, 2010; McDonald et al., 2011).

In spite of this, signatures of planetary waves in the summer mesosphere and lower thermosphere (MLT) have been modelled and observed (e.g. Forbes et al., 1995; Espy et al., 1997; Wang et al., 2000; Smith, 2003). Since vertical propagation through the stratosphere is unlikely during summer, the existence of planetary waves in the summertime MLT is puzzling. It has been suggested that the planetary wave signatures in the MLT might arise from the breaking of gravity waves whose momentum flux has been modulated by the selective filtering of the planetary waves present in the lower atmosphere (Smith, 2003). That is, gravity waves with eastward momentum would reach their critical levels in the eastward phase of the planetary waves (as manifested in the zonal wind field), allowing gravity waves carrying westward momentum to reach the MLT, and vice versa. The gravity waves that reach and break in the MLT would deposit their momentum and force the mean wind, imprinting in the MLT a mirror image of the planetary wave in the lower atmosphere.

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Free travelling planetary waves are also possible in the summer mesosphere. These waves are considered to be global normal (resonant) modes that are not maintained by particular travelling forcing effects (Andrews, 1987). As shown by Salby (1981), the amplitudes of these wave disturbances can become large locally when the background wind speed approaches their phase speeds. The most prominent travelling wave in the summer mesosphere is the so-called 2-day wave (e.g. Limpasuvan and Wu, 2003). These features take on zonal wave numbers 2–4 and tend to amplify shortly after the solstice. As discussed below, fluctuations associated with the 2-day wave are removed in our analyses so their impacts are not relevant to our results.

Additionally, in situ generation of planetary waves by the baroclinic and barotropic instabilities created by the steep wind and temperature gradients in the middle atmosphere near solstice (e.g. Plumb, 1983; Baumgaertner et al., 2008) have also been proposed as a possible source of planetary waves in the MLT. Finally, it has been suggested that the source of the planetary waves in the summertime MLT might be the winter hemisphere, where the waves duct along the near-zero wind line that stretches from the winter stratosphere into the summer mesosphere (e.g. Forbes, 1995; Espy et al., 1997; Hibbins et al., 2009). While all these mechanisms are plausible and fit the existing measurements, there has been a lack of simultaneous observations of planetary wave amplitudes and phases, as well as the underlying wind field during summer that could be used to separate the relative importance of these proposed mechanisms.

Here observations of summertime wave number 1 (S_1) and 2 (S_2) planetary wave activity in the MLT (~95 km) are derived from meteor winds recorded with a chain of SuperDARN radars using the technique described by Kleinknecht et al. (2014). The possible sources of these planetary wave-like longitudinal perturbations of the MLT meridional wind that show a stable phase behaviour from year to year are evaluated using the underlying winds from the Modern-Era Retrospective Analysis for Research and Application (MERRA) of the NASA Global Modelling and Assimilation Office (Rienecker et al., 2011). By combining these data sets we discuss which of the proposed mechanisms for the appearance of planetary waves in the summertime MLT are likely.

2. Data

In order to examine the wind and planetary wave field in the mesosphere and the lower thermosphere (MLT), meridional winds have been retrieved from the meteor winds at each of 8 SuperDARN radars (Greenwald et al., 1985, 1995) at high northern latitudes (51–66°N). Since the orientation of most of the SuperDARN radars is toward the north, the meridional component derived from the line of sight winds of all beams is used due to its smaller uncertainty. Planetary wave amplitudes with wave numbers 1 and 2 in the mesopause region (~95 km) have been retrieved from these meridional meteor winds by taking advantage of the longitudinal chain (150°W–25°E) formed by these 8 SuperDARN radars. The technique is fully described and the validation studies are presented in Kleinknecht et al. (2014). Briefly, after an initial quality check, a daily mean wind, the 24-h, 12-h and 8-h sinusoidal tidal periods and a 2-day wave period were fitted to a 4-day sliding window of the hourly meridional wind for each of the 8 SuperDARN stations. The window was shifted in 1 day intervals to retrieve the time series of daily mean meridional winds at each station. These daily mean meridional winds at each station are then fitted as a sinusoidal function of longitude with 360° (S_1) and 180° (S_2) spatial periods to retrieve the amplitude and the phase of the wave number 1 and 2 components for each day.

To quantify the lower atmosphere, the zonal and meridional winds from MERRA (Rienecker et al., 2011) have been used to monitor the wind structure in the troposphere and the stratosphere. The horizontal resolution of the MERRA data used in this study is 0.5° × 3.3° (latitude × longitude). The vertical grid consists of 72 pressure levels from the ground to 0.015 hPa (~80 km). MERRA is measurement driven up to approximately 50 km (~1 hPa), above which it is free running. For this analysis only the measurement driven region of MERRA has been used. Since MERRA outputs are produced four times a day (0, 6, 12, and 18 UT), the daily means of the meridional wind averaged over the latitude band between 51°N and 66°N were produced to minimise tidal effects and to obtain wind profiles at latitudes similar to the latitude coverage of the SuperDARN chain.

Fig. 1 shows an altitude–longitude profile of the meridional (left panel) and the zonal (right panel) wind produced by MERRA for the 18 July 2000 between the ground and 1 hPa averaged over the latitude band of 51–66°N.

Red and blue colours signify poleward (eastward) and equatorward (westward) meridional (zonal) winds, respectively. While the zonal-mean zonal wind is predominantly eastward in the troposphere and turns westward in the stratosphere due to surface and ozone heating, the zonal-mean meridional wind is close to zero throughout the troposphere and the stratosphere due to geostrophic balance. Fig. 1 also shows that there are strong

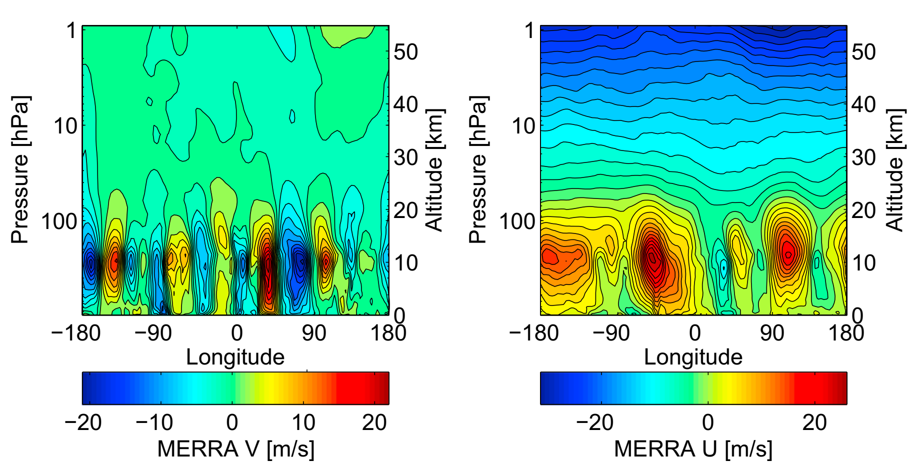

Fig. 1. MERRA meridional (left) and zonal (right) wind (m/s) for the 18 July 2000 between the ground and 1 hPa (~50 km) averaged over the latitude band between 51°N and 66°N. Red and blue colours signify poleward (eastward) and equatorward (westward) winds, respectively.

longitudinal perturbations in both the tropospheric zonal and the meridional wind. These perturbations are indicative of planetary waves and reach a maximum amplitude around the tropopause (~230 hPa, ~10 km) before rapidly falling in amplitude in the stratosphere. To quantify the planetary wave amplitudes in the lower atmosphere a longitudinal fit of the first four zonal wave numbers (S_0, S_1, S_2, and S_3) of the meridional and the zonal wind was calculated for each day and pressure level by fitting a mean (S_0), and sine functions with 360° (S_1), 180° (S_2) and 120° (S_3) spatial periods as follows:

$$S_0 + \sum_{i=1}^{3} S_i^{Amplitude} \cdot \sin\left(2\pi \cdot \left[\frac{i \cdot longitude}{360} + S_i^{Phase}\right]\right) \quad (1)$$

3. Results

Fig. 2(a) shows the climatology of the daily mean meridional wind at each of the 8 SuperDARN radar stations. The meridional wind is generally directed into the pole in winter (positive values) and out of the pole in summer. This is due to the residual mesospheric meridional circulation caused by the breaking of gravity waves that have been selectively filtered in the stratosphere (e.g Lindzen, 1981; Garcia and Solomon, 1985).

The climatology of the different stations also shows that the magnitude of the wintertime poleward meridional wind is generally smaller than the summertime equatorward winds. Model studies and observations (e.g. Lindzen, 1981) have shown that the gravity wave breaking altitude, and hence the strongest meridional forcing, varies between about 50 km in winter and 70 km in summer due to the different vertical temperature profiles in the middle atmosphere during winter and summer. Hence the meridional wind in the MLT observed in the SuperDARN measurements (~95 km) is generally stronger in summer than in winter.

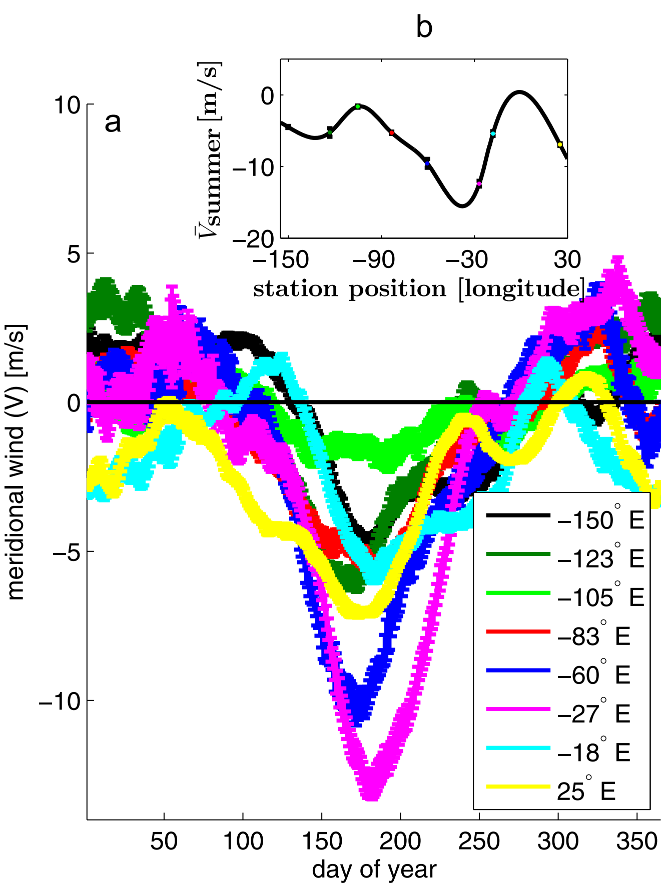

Fig. 2. (a) Climatology of daily mean meridional meteor winds for each of the 8 SuperDARN radar stations. The legend depicts the centroid longitude of the meteor wind measurements for each station. (b) A 20-day average about summer solstice of the daily mean climatological winds shown in (a) for each of the 8 stations, plotted as a function of the station longitude.

Even though the SuperDARN radars are closely spaced in latitude, Fig. 2(a) shows that the summer wind varies markedly as a function of the different longitudinal locations of the radars. Stations that are located close to each other in longitude however show similar wind magnitudes during summer as demonstrated in Fig. 2(b). The equatorward meridional wind during summer is observed to be strongest at longitudes around Greenland (30–60°W) with values of up to −13 m/s. In contrast, at other longitudes the climatological meridional wind falls to less than half this amount. Evidence for a longitudinal variation in the summertime MLT meridional wind that is stable from year to year has also been observed by e.g. Dowdy et al. (2007).

This longitudinal variation of the meridional wind, visible in Fig. 2(b), can also be seen on a daily basis and can be represented by the planetary wave number 1 and 2 components that have been retrieved for all days in summertime (May–August) for the years 2000–2008 as described in the previous section. The daily wave components fitted are presented as a function of time and longitude in the Hovmöller diagrams in Fig. 3. The longitudinal difference observed in the climatology of the different stations is clearly visible here as a quasi-stationary wave in both wave components with a longitudinal phase during mid-summer that is consistent year to year for all 9 years. The mean (summer solstice ±20 days) longitudinal position of the minimum (most southward) meridional wind in the observed S_1 wave component varies only between −64°E (year 2001) and −46°E (year 2007) and the mean amplitude of the S_1 wave component varies between 5 m/s (year 2007) and 13 m/s (year 2000).

The existence of such phase-stable wave components during summer adds a perturbation to the general equatorward meridional circulation. This results in a stronger meridional wind blowing out of the pole above the Atlantic sector while the equatorward winds are weaker over Russia. This longitudinal variation in meridional wind would then result in stronger outflow and more adiabatic lifting over the Atlantic sector, resulting in colder mesopause summer temperatures there compared to warmer temperatures above Russia. The longitudinal temperature perturbations associated with the meridional wind anomalies observed here have been reported by Chandran et al. (2010) using SABER temperatures as well as a temperature proxy, the occurrence frequency of Polar Mesospheric Clouds (PMC).

4. Discussion

As noted earlier, possible sources of the mesospheric planetary wave-like perturbation of the meridional wind observed here are (1) vertical propagation of the planetary waves from below, in situ generation through either (2) modulation of gravity wave filtering by planetary waves in the lower atmosphere, (3) longitudinal difference in gravity wave sources or (4) baroclinic and barotropic instabilities, and finally (5) inter-hemispheric coupling of planetary waves from the winter stratosphere. These different mechanisms will be evaluated for consistency with the observed wind and wave fields observed in both the MLT and the lower atmosphere.

4.1. Vertical propagation

Vertical propagation of planetary waves from the troposphere through the summertime stratosphere is unlikely due to the

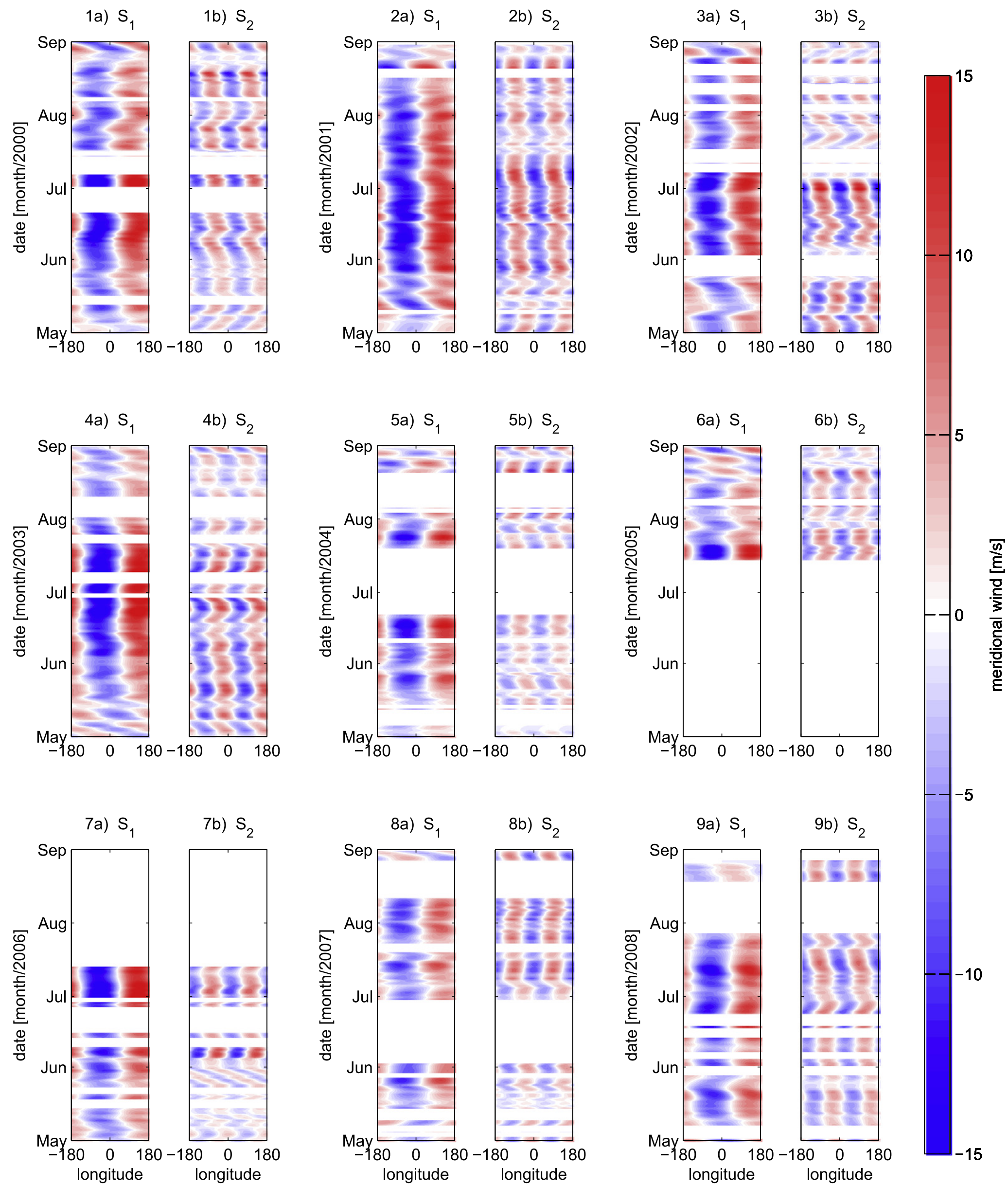

Fig. 3. Longitudinal wave components S_1 (a) and S_2 (b) of the mean meridional wind for summertime (May–August), years 2000–2008 (1–9). Red and blue colours signify poleward and equatorward wind, respectively. Adapted from Kleinknecht et al. (2014).

strong westward jet that theoretically inhibits vertical planetary wave propagation (Charney and Drazin, 1961). MERRA meridional winds have been used to monitor planetary-wave activity in the lower and the middle atmosphere to investigate if direct planetary wave propagation into the MLT from lower altitudes is possible. Fig. 4 shows the climatology of wave number 1 and 2 amplitudes. The upper panel shows the amplitudes in the MLT that have been extracted from the SuperDARN chain, while the lower panel shows planetary wave amplitudes in the troposphere and the stratosphere (up to 1 hPa, ~50 km) extracted from the data driven region of MERRA. The left panels show the climatology of the S_1 planetary wave component and the right panels the climatology of the S_2 planetary wave component.

In the troposphere and the stratosphere planetary wave amplitudes maximise in summer near the tropopause around 200–300 hPa (10–12 km) together with the zonal-mean zonal wind (Fig. 1). Above, the vertical gradient of the zonal wind becomes negative as the mean wind adjusts to the westward stratospheric wind regime, inhibiting vertical planetary wave propagation. This leads to a summertime minimum of planetary wave activity in the stratosphere. In contrast, observations in the MLT (~95 km) by the SuperDARN network show an increase of planetary wave amplitudes in summer. This indicates that direct propagation through the stratosphere is an ineffective source of the year-to-year persistent planetary waves observed in the MLT.

4.2. Modulation of gravity wave filtering by planetary waves in the lower atmosphere

Zonal winds from MERRA have been used to investigate if the filtering of gravity waves can be modulated by stationary planetary waves in the lower atmosphere during summer and result in a mapping of these planetary waves into the MLT when the gravity waves break and deposit their momentum at mesospheric altitudes. Such a mechanism has been shown to be a possible source of stationary planetary waves in the wintertime mesosphere

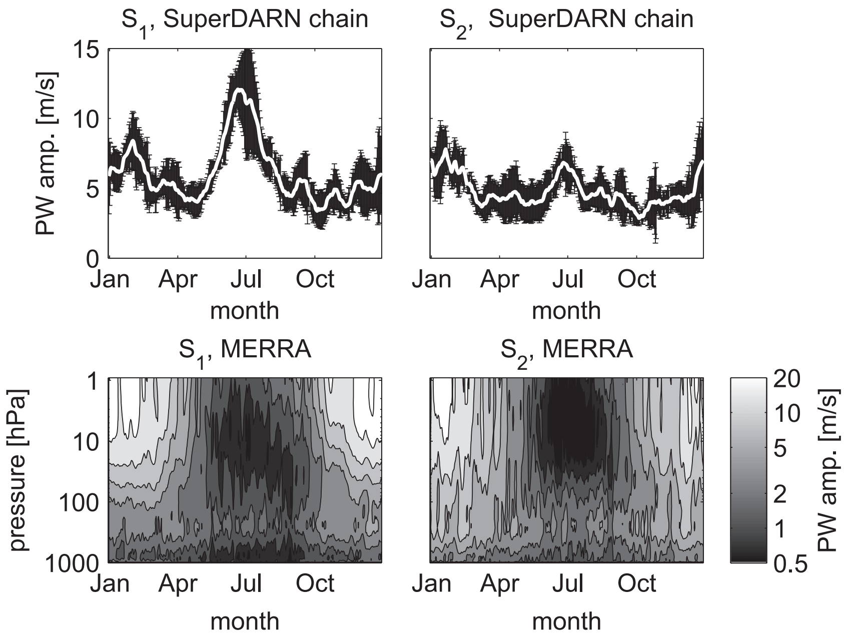

Fig. 4. Climatology of planetary wave amplitudes of the wave number 1 (left panels) and wave number 2 (right panels) components from the SuperDARN observations (upper panels) and MERRA (lower panels).

(Smith, 2003). During summer the planetary wave amplitudes are weakest in the stratosphere due to the westward winds there (Charney and Drazin, 1961). Thus, the strongest PW amplitudes that would modulate the filtering of gravity waves occur near the tropopause (~230 hPa ~10–12 km) where the winds are eastward. At this altitude the zonal-mean eastward wind as well as the planetary wave magnitudes maximizes in summer, as can be seen in Figs. 1 and 4, respectively, and any modulation of the gravity wave filtering by planetary waves would be expected to be strongest there. Fig. 5 (upper panel) shows the climatologically stable S_1 planetary wave component around the tropopause (~230 hPa, 10–12 km) retrieved from MERRA (a) and at the MLT (~95 km) retrieved from the SuperDARN network (b). At the tropopause the observed wave component shows a maximum amplitude of 6 m/s with the eastward phase of the wave above the Atlantic sector (~0–60°W). The mean summertime background wind at this altitude is eastward with a magnitude around 10 m/s.

Above the tropopause, the zonal wind turns westward in summer throughout the middle atmosphere, and wind speeds exceeding −30 m/s (Fig. 1) effectively filter the bulk of westward propagating gravity waves (Lindzen, 1981). It has been shown that the deposition of eastward momentum from the remaining eastward gravity waves in the mesosphere increases drag on the zonal wind and increases the resulting residual circulation equatorwards, with the strength of the effect dependent on the amount of eastward momentum deposition (e.g. Lindzen, 1981; Fritts and Alexander, 2003). The wind fluctuations associated with planetary waves near the tropopause could modulate the upward gravity-wave momentum flux, thereby modulating the momentum transferred to the mesosphere by gravity waves.

Stronger eastward winds near the tropopause (red regions in Fig. 5a) will filter more eastward gravity waves and hence lead to less eastward momentum deposition in the MLT. This, in turn, will decrease the associated residual MLT equatorward wind, producing a poleward (red) perturbation of the meridional wind. Conversely, decreased eastward winds at the troposphere (blue regions in Fig. 5a) will result in less filtering and hence stronger momentum deposition in the MLT. This will result in a stronger equatorward residual circulation in the MLT, resulting in an equatorward (blue) perturbation of the meridional wind.

If the modulation of the filtering described above were to have a significant effect on the longitudinal modulation of meridional wind in the MLT one would expect to see poleward (red) wind perturbations above stronger eastward (red) wind at the tropopause. Similarly there should be an equatorward (blue) wind perturbations above less strong eastward (blue) winds at the tropopause. However exactly the opposite is the case as can be seen from Fig. 5(b). Modulation of the gravity wave filtering by zonal wave number 1 stationary planetary waves near the tropopause seems therefore not to be the primary mechanism behind the stationary summertime planetary wave-like longitudinal perturbation of the meridional wind observed in the MLT. In addition, the phase of the S_1 component at the tropopause can vary widely throughout summer and shows strong inter-annual variations. However, the S_1 wave in the MLT shows a stable phase throughout the summer, and is consistent year to year. As an example, the zonal wind at the tropopause (MERRA) and the meridional wind in the MLT (SuperDARN) during summer 2001 are shown in Fig. 5 (c) and (d), respectively.

4.3. Longitudinal difference in gravity wave sources

In the previous section it has been shown that the westward portion of the gravity wave spectrum will be nearly completely filtered by the strong westward winds in the stratosphere. Thus, the eastward gravity wave spectrum in the troposphere should dictate the momentum delivered to the MLT (Fritts and Alexander, 2003). As this spectrum of tropospheric gravity waves will grow and break in the mesosphere and force the mesospheric wind, any longitudinal variation in the tropospheric eastward gravity wave source spectrum could map into the mesosphere to provide the longitudinal modulation of the meridional wind observed in the MLT. For the longitudinal variations of the eastward gravity wave spectra to be a possible source of the meridional wind modulation observed by the SuperDARN chain in the MLT (~95 km) a strong source of free eastward propagating gravity waves above the Atlantic sector (30–60°W) has to exist. Studies by e.g. Limpasuvan et al. (2007) show that there is strong gravity wave generation

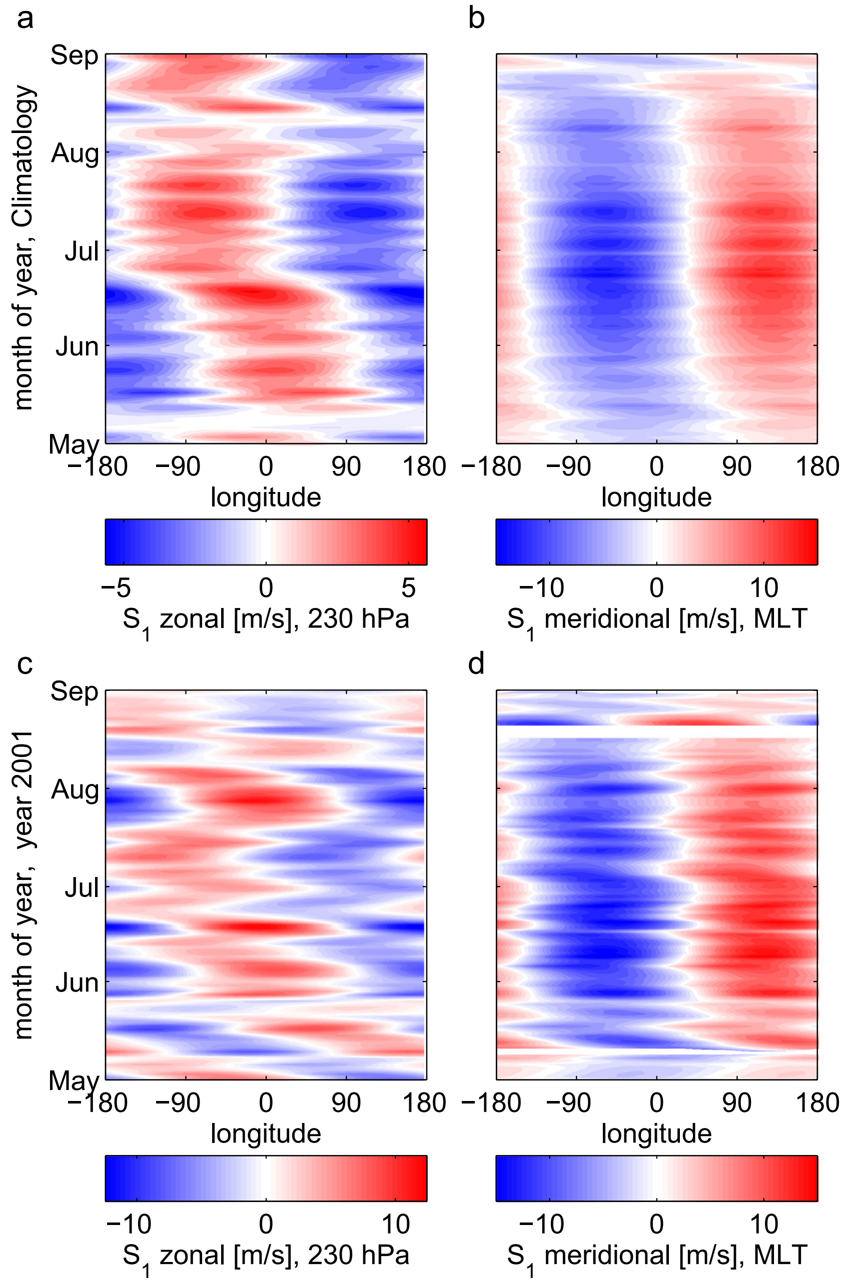

Fig. 5. Upper panel: climatology (year 2000–2008) of the longitudinal S_1 planetary wave component during summertime (May–August) retrieved from (a) the zonal wind from MERRA at the tropopause (230 hPa, ~10–12 km) averaged over 51–66°N and (b) the meridional wind from the SuperDARN network at MLT altitudes (~95 km). Lower panel: longitudinal S_1 planetary wave component during summer 2001 at (c) the tropopause (zonal wind, MERRA) and (d) at the MLT (meridional wind, SuperDARN). Red and blue colours signify eastward (poleward) and westward (equatorward) wind, respectively.

above Greenland. However a detailed analysis of the gravity wave source spectrum and its longitudinal distribution at these latitudes would be necessary to test this mechanism and is beyond the scope of this study.

4.4. Generation through baroclinic and barotropic instabilities

No observational or theoretical evidence of baroclinic and barotropic jet instabilities forcing climatologically stationary and phase-stable waves has been reported. However baroclinic and barotropic instabilities have been shown to be the cause of fast travelling planetary waves in the mesosphere during summer (Plumb, 1983; Limpasuvan and Wu, 2003; Baumgaertner et al., 2008) and it is therefore mentioned as a possible source. The necessary condition for instability states that the meridional gradient of the zonal mean (quasi-geostrophic) potential vorticity becomes negative. This condition reflects the zonal-mean zonal wind changing rapidly in the meridional direction (leading to barotropic instability) and/or vertical direction (related to thermal meridional gradient and leading thus to baroclinic instability). Initial results using the Whole Atmospheric Community Climate model with Specified Dynamics (WACCM-SD, Tweedy et al., 2013) indicate that there are potential source regions for the generation of instabilities near 70–90°N above 80 km (not shown). However, a thorough instability analysis is needed to examine unstable wave growth rates (in the face of damping) and the corresponding background conditions. Such analysis will be the subject of future work.

4.5. Inter-hemispheric coupling

Evidence for inter-hemispheric coupling of planetary waves has been shown in several studies (e.g. Forbes, 1995; Espy et al., 1997; Hibbins et al., 2009; Day and Mitchell, 2010). These studies focus mostly on travelling wave components. However one should keep in mind that the longitudinal wave components observed in this paper are the sum of all stationary and travelling planetary waves with the same longitudinal structure. While strong stationary wave components might exist in the winter mesosphere and migrate to the summer along the near-zero wind line, we currently lack the data needed to test this hypothesis. This would require a characterization of southern hemispheric stationary wave amplitudes and a theoretical model of horizontal wave transport that is beyond the scope of this paper. In addition several observational studies suggest large inter-annual variability in the inter-hemispheric propagation of PWs (e.g. Espy et al., 1997; Hibbins et al., 2009), which is inconsistent with the relatively stable stationary wave reported here. Thus, this must be considered as a viable, albeit untested mechanism which will be subject of future modelling work.

5. Summary and conclusion

Planetary wave observations in the mesosphere–lower thermosphere using meridional meteor winds from a chain of SuperDARN radars show strong quasi-stationary planetary wave activity of the zonal wave numbers 1 and 2 during mid-summer. The observed planetary wave activity shows a year-to-year consistent quasi-stationary phase. Supporting longitudinal wind and temperature variations in the mesosphere have been observed in other studies and show the impact of these structures on the longitudinal variability of PMC. Winds from the Modern-Era Retrospective Analysis for Research and Application (MERRA) of the NASA Global Modelling and Assimilation Office are used to investigate the source of the stationary planetary wave-like perturbations of the meridional wind observed in the MLT. The analysis downplays the role of planetary wave modulated filtering of gravity waves as well as vertical propagation through the stratosphere as a source. However, longitudinal differences in gravity wave sources, barotropic and baroclinic instabilities as well as inter-hemispheric coupling remain as possible explanations for the longitudinal structure in the meridional wind in the MLT and will be investigated further.

Acknowledgments

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