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Planetary wave oscillations observed in ozone and PMSE data from Antarctica

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ABSTRACT

The effect of temperature variations caused by planetary waves on the occurrence of Polar Mesospheric Summer Echoes (PMSE) has been a subject of recent research. These same temperature fluctuations have also been shown to modulate the ozone volume mixing ratio above 30 km. In this study, ground-based radiometer measurements of ozone mixing ratio profiles at Troll station (72°S, 2°E), Antarctica are compared with PMSE extracted from the near-range measurements of the Sanae (72°S, 2°W) Super Dual Auroral Radar (SuperDARN) over the radiometer field of view. We show here that the resulting quasi-periodic fluctuations in PMSE correlate with the variations seen in the ozone. The ozone mixing-ratio variations may then be used to trace the phase variation of planetary waves with height to demonstrate that they extend from the stratosphere up to the mesopause. The results indicate that the modulation of PMSE occurrence frequency during the summer of 2009/10 is the result of two planetary waves with similar zonal structure and period, but with different vertical phase structures.

1. Introduction

Traveling planetary waves (PW) are large-scale density and temperature oscillations in the stratosphere and mesosphere, which have horizontal scales of thousands of kilometers, vertical sizes of tens of kilometers, and periods from 2 to 30 days (e.g. Randel (1987); Salby, 1981; Smith, 1997). A number of ground and satellite-based studies have shown that temperature fluctuations associated with planetary waves can modulate Polar Mesospheric Clouds (PMC) and Polar Mesosphere Summer Echoes (PMSE) in the mesosphere (Kirkwood and Réchou, 1998; Kirkwood et al., 2002; Kirkwood and Stebel, 2003; Merkel et al., 2003, 2008; Von Savigny et al., 2007). Kirkwood and Réchou (1998) and Kirkwood et al. (2002) found that the temperature fluctuations associated with the 5-day PW in the stratosphere are negatively correlated with PMSE variations at a height of 80–90 km. In another study, Kirkwood and Stebel (2003) used ground-based observations of PMC over northwest Europe to investigate the effect of planetary waves on PMC. The results of their study showed a correlation between the 16-day and 5-day PW observed in stratospheric assimilation temperatures, extrapolated to the mesopause, and the probability of occurrence of PMC between 80 and 85 km. Merkel et al. (2003, 2008) identified a 5-day periodicity in the variation of PMC brightness, which they associated with the 5-day PW in the polar summer mesosphere. Merkel et al. (2008) further compared this 5-day periodicity in PMC brightness with mesospheric temperature variations measured by the SABER instrument on board the TIMED satellite, and found that the two were highly anti-correlated.

Belova et al. (2009) used satellite radiometric measurements to demonstrate that the ozone mixing ratio above 30 km in the upper stratosphere is controlled by temperature, with temperature and ozone variations 180° out of phase. Belova et al. (2008) also used satellite radiometric measurements to isolate the geographical structure of the 5-day wave in O_3 at several altitudes for comparison with mesospheric temperature variations. However, to our knowledge, none of these studies have used coincident and nearly simultaneous observations of PMSE and ozone to trace and quantify the vertical propagation of the PWs modulating the mesospheric aerosols throughout the middle and upper atmosphere so as to identify their phase structure and source regions.

In this study, ground-based radiometer measurements of the ozone mixing ratio profile at Troll station in Antarctica, together with PMSE extracted from near range measurements of the Sanae SuperDARN radar over the radiometer field of view are used as proxies for planetary wave temperature variations. The temperature oscillations modulating the PMSE at a single location may be the superposition of many PWs (Palo et al., 1999), so here we use

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ozone mixing ratio profiles to quantify the vertical phase structure of these waves in order to ascertain their source regions and their evolution in time and altitude throughout the Antarctic summer. Section 2, below, describes the data analysis techniques, and this is followed in Section 3 by a description of the planetary wave signatures in the O_3 mixing ratio and PMSE rate of occurrence.

2. Data analysis

2.1. Extraction of PMSE from SuperDARN radar data

Polar Mesosphere Summer Echoes (PMSE) are strong radar backscatter echoes that occur between 80 and 90 km during summer at high latitudes. They have primarily been observed and studied using radars operating at very high frequencies above 10 MHz (Cho and Kelley, 1993). The Super Dual Auroral Radar Network (SuperDARN) is a network of high frequency (HF) radars, whose combined field of view covers a large part of the northern and southern hemisphere polar ionospheres. The radars are typically used to study large-scale dynamical processes in the earth's ionosphere, magnetosphere and neutral atmosphere (Greenwald et al., 1995). There are a number of high-latitude SuperDARN radars currently working in both hemispheres, and PMSE have been detected in the near range measurements of these radars (Ogawa et al., 2002). However, the PMSE must be separated from other backscatter echoes coming from meteors and E region echoes (Hosokawa et al., 2004), as described below.

In this study, the algorithm developed by Hosokawa et al., (2005) was applied to the SuperDARN data at Sanae station (72°S, 2°W). The centroid latitude and longitude of the Sanae beam pattern lie within the field of view of the Troll radiometer, and PMSE were extracted from the first range gate (Gate 0), which includes the PMSE altitude range from 80 to 100 km. All echoes from the first range gate measurements were initially identified, including PMSE, E-region backscatter and meteor-trail echoes. Then, the criteria adopted by Hosokawa et al., (2005) were applied to differentiate PMSE from the other two scattering mechanisms. First, the back-scattered power was required to be greater than 6 dB. Secondly, only Doppler velocities between $\pm 50\ \mathrm{ms}^{-1}$ were accepted. Finally, the spectral width was required to be less than $50\ \mathrm{ms}^{-1}$. Hosokawa et al., (2005) have shown that echoes passing these three criteria have a high probability of being PMSE. The occurrence rate for the first range gate was computed for each 10 min local-time (LT) bin during a given day by dividing the number of echoes passing the selection criteria by the total number of observations present there. Fig. 1 shows the occurrence rate of echoes that passed the selection criteria as a function of local time and day of the year.

2.2. Ozone measurement and analysis

Ozone measurements were obtained from the British Antarctic Survey's Antarctic Radiometer for Ozone and Nitric oxide (ARON) mm-wave radiometer. The instrument was operated at the Norwegian Polar Institute Troll station (72°S, 2°E) from December 2008 to January 2010, observing carbon monoxide (CO), nitric oxide (NO) and ozone (O_3) in different spectral lines ranging from 230–250 GHz. A detailed description of the Troll microwave radiometer and measurements may be found in Espy et al. (2006). Optimal estimation methods, as described by Rodgers (1976), have been used to invert the spectra of the ozone line at 249.96 GHz to obtain ozone volume mixing ratio (vmr) profiles (Kleinknecht, 2010). The *a priori* pressure, temperature, water vapor and ozone values used for the inversion below 45 km are derived from monthly mean ERA-40 profiles. Between 45 and 85 km, monthly

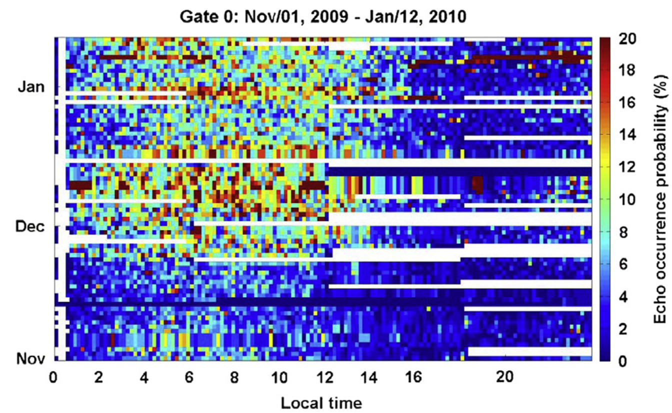

Fig. 1. Occurrence rates of PMSE (in percent of total measurements) from the SuperDARN radar at Sanae from November 1, 2009 to January 12, 2010 as a function of local time. White areas indicate periods of unavailable data.

mean temperature and pressure values were taken from the MSIS-00 model (Picone et al., 2002), and the ozone vmr was taken from the US Standard Atmosphere Supplements (1976) for winter and summer conditions. For the wave studies here, the *a priori* ozone values above 85 km were held at a constant value so as to ensure that the *a priori* values did not induce oscillations. The retrieved hourly ozone profiles as a function of altitude and time are shown in Fig. 2. As can be seen in Fig. 2a, the first ozone maximum is observed around 35 km, and ozone data up to 70 km are used in this study due to the decrease of measurement response in the region above 70 km. The vertical resolution, which is interpreted from the full width of half maximum (FWHM) of the averaging kernels, is ~10 km below 65 km, increasing to ~15 km by 70 km (Fig. 2c). The large altitude resolution above 70 km results in highly correlated data above this altitude.

3. Analysis and results

To extract wave periods in the PMSE and ozone mixing ratio profile as function of altitude, spectral analysis was performed on each of the two datasets. In order to prepare the data for analysis, the ten-minute PMSE data were averaged into hourly bins over the period from November 1, 2009 to January 12, 2010. PMSE have been observed to maximize around 12:00 LT (Morris et al., 2009; Palmer et al., 1996) whilst meteor echoes maximize around 07:00 LT and decrease through to late afternoon (Beldon and Mitchell, 2010; Singer et al., 2004). In addition, E-region echoes occur mostly at night (Milan and Lester, 2001). Thus, the hourly average between 11:00 and 12:00 LT was chosen to maximize the discrimination of PMSE from meteors and E-region echoes. Only four days of data were missing and linear interpolation was used to fill these data gaps. In the case of ozone, the ozone mixing ratio was averaged for one hour about local midnight, where mesospheric ozone maximizes. This daily averaged profile at 4 km intervals between 30 and 70 km was used for comparison with the PMSE.

Longer time-scale variations of PMSE and ozone mixing ratio were removed since our interest was on waves with periods between 2 and 12 days. Temperature fluctuations, which cause changes in both ozone and PMSE, have been observed to have strong annual and semi-annual oscillations (Niciejewski and Killeen, 1995), and significant oscillations with periods from months to as long as a solar cycle (Espy and Stegman, 2002). A high-pass filter was applied to both datasets to remove long-period background fluctuations while retaining the variations with shorter periods (higher frequency). A Butterworth IIR high-pass filter was used to remove periods greater

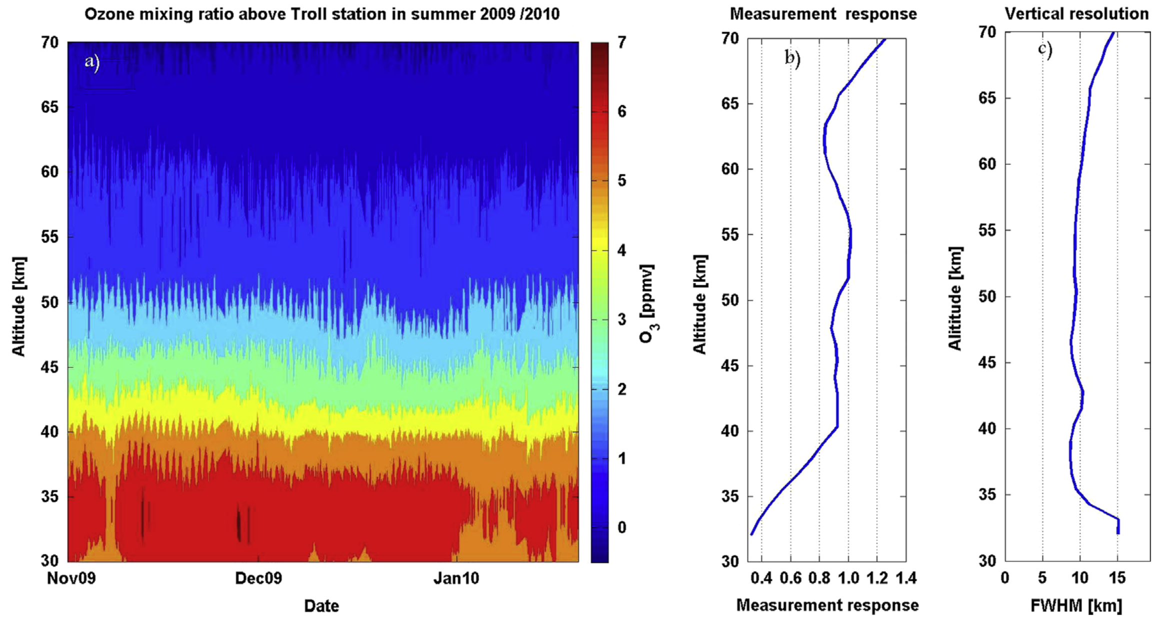

Fig. 2. (a) Retrieved ozone mixing ratio profile from November 1, 2009 to January 12, 2010 at the Troll station. (b) Measurement response of a sample inversion. The lower the response, the greater the contribution the *a priori* value has to the retrieved profile. (c) Vertical resolution of a sample inversion given as the FWHM of the averaging kernel in km.

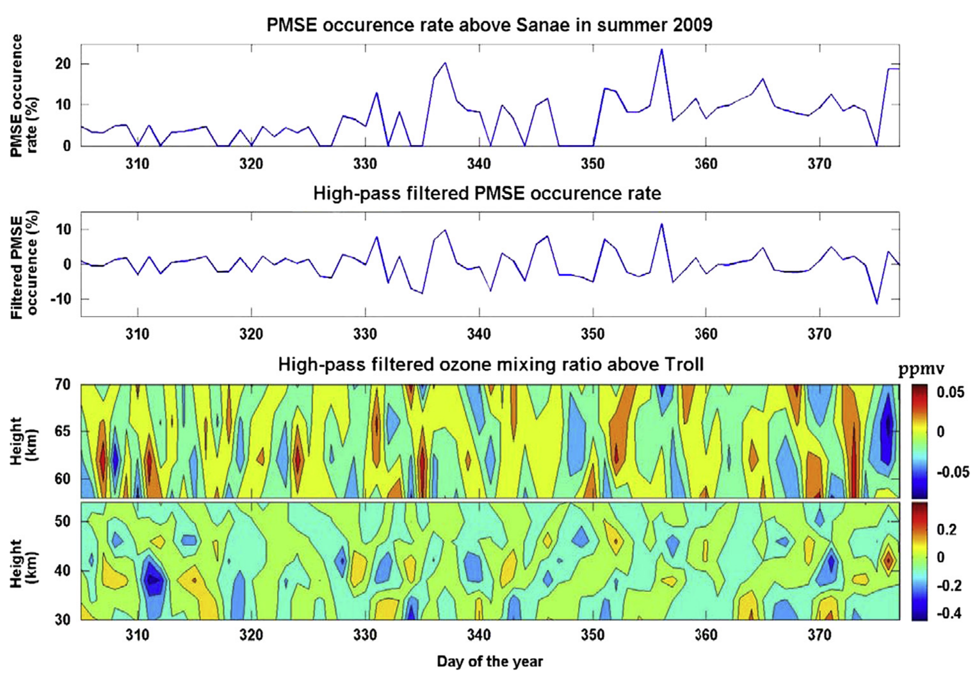

Fig. 3. Upper-panel: Unfiltered PMSE occurrence rate data averaged around 12:00 LT from November 1, 2009 to January 12, 2010. Middle-panel: High-pass filtered PMSE occurrence rate. Lower two panels: Ozone mixing ratio profile data from November 1, 2009 to January 12, 2010 for the altitude range of 30 to 70 km.

than 12 days since it has a flat frequency response in the selected pass band. Fig. 3 shows the time series of the unfiltered and high-pass filtered PMSE occurrence around 87 km as well as the high-pass filtered ozone vmr profiles from 30 km to 70 km. Due to the change of ozone mixing ratio as a function of height, the lower panel in Fig. 3 is further subdivided into two parts, with the upper section, covering from 56 to 70 km, expanded by a factor of 10. Fig. 3 shows a large amount of variability in wave activity in the period ranging from 2 to 10 days at all heights.

A fast Fourier transform (FFT) was performed on the filtered datasets to confirm the removal of the long-period backgrounds and to identify periodic fluctuations observed in the ozone and PMSE fields at higher frequencies. The high-pass filtered data were apodized using a Hamming window (Nuttall, 1981) before the FFT was performed in order to minimize spectral leakage and side-lobe effects in the FFT. Fig. 4 shows the amplitude of the PMSE and ozone vmr at each height. Three high-amplitude regions are found in the PMSE data with periods around 2–3 days, 4–5 days and 6–8 days. Due to the daily sampling, periods between 2–3 days are too close to the Nyquist limit to yield quantitative results, and will therefore not be discussed here. However, high-amplitudes in regions between 4–5 days and 6–8 days are also observed in the

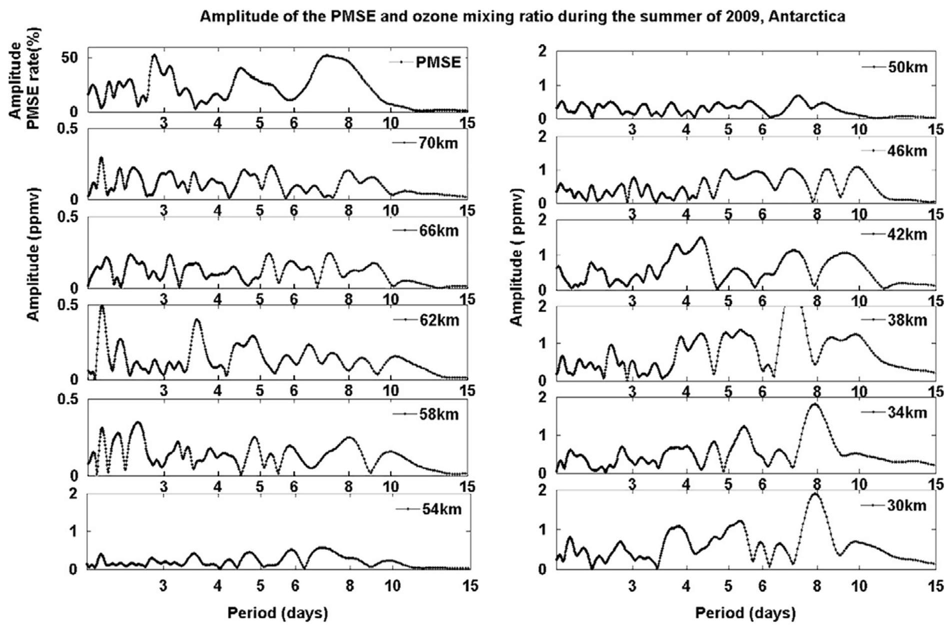

Fig. 4. Amplitude of the PMSE occurrence around the mesopause (upper left-panel) and ozone mixing ratio from heights 30 to 70 km with an interval of ~4 km. Note that the amplitude scale changes below and above 55 km.

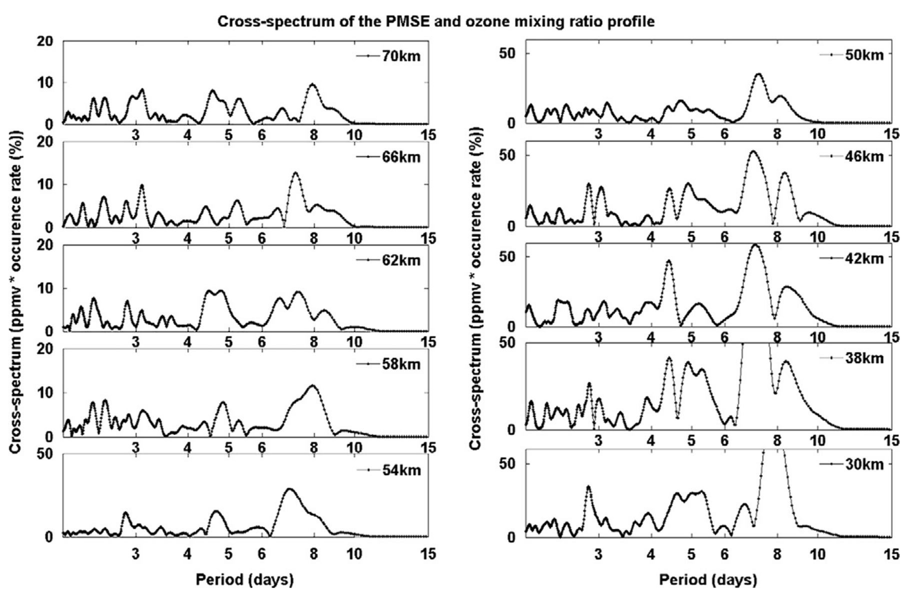

Fig. 5. Cross-spectrum of the PMSE occurrence and ozone vmr for different levels in the stratosphere and mesosphere during the summer of 2009 in Antarctica. Note that the amplitude scale changes below and above 55 km.

ozone data, most apparent at the lower altitudes. The oscillation with a 4–5 day period is most likely associated with the nominal 5-day wave, which has often been observed in PMSE and PMC (e.g. Kirkwood et al., 2002; Merkel et al., 2003). The longest oscillation, which has the largest amplitude in the PMSE, has a period of 6–8 days and is taken to be the ~6.5 day zonal wave number 1 planetary wave (Talaat et al., 2001, 2002; Jiang et al., 2008). Though present at all altitudes, the amplitude of both waves increases below 55 km. Unfortunately this technique cannot determine whether this amplitude change tracks the downward increase in ozone vmr, or if it decreases at high altitudes as the waves approach the zonal wind maximum near 68 km (Forbes et al., 1995; Hibbins et al., 2005; Day and Mitchell, 2010; McDonald et al., 2011). Below 40 km, the fall in wave amplitude is likely due to the large *a priori* contribution to the retrieved O_3, as the nearly constant *a priori* value tends to minimize the wave-induced departures from the *a priori* and reduce the extracted wave amplitudes.

To determine whether or not the 4–5 day or 6–8 day peaks in the Ozone and PMSE are related and phase coherent, a Fourier-based cross-spectral analysis was performed between the two datasets. Fig. 5 shows the cross-spectra between the PMSE and the ozone vmr at each level as a function of period in days. The cross-spectra show that despite the low amplitudes in the FFT, the amplitude associated with both waves in the O_3 vmr is coherent and phase coherent with the oscillation in the PMSE occurrence frequency. The amplitudes of the cross-spectra in Fig. 5 are reflections of the amplitudes in Fig. 4, which are influenced by a combination of factors. These include changes in the O_3 vmr or interaction with background wind, as well as *a priori* effects.

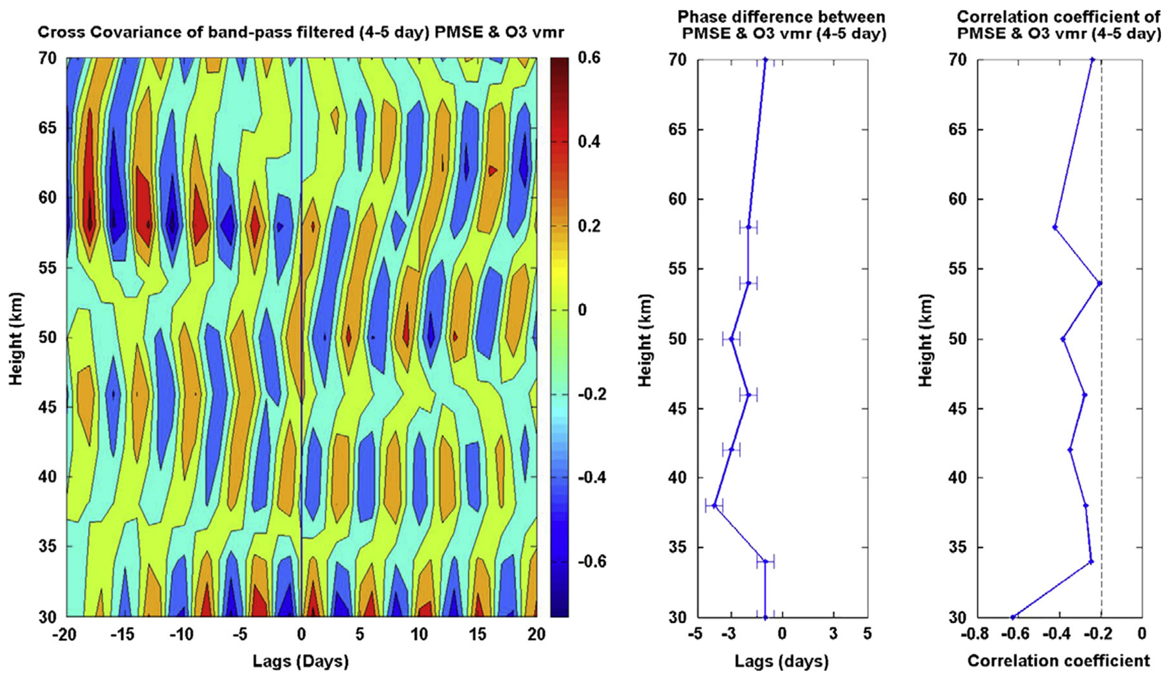

Fig. 6. The left panel shows the time-lagged cross-correlation between PMSE occurrence rate and ozone vmr at different altitudes for the 5-day wave. Red and blue colors represent positive and negative correlations, respectively. The vertical modulations reflect changes in the signal to noise. Middle-panel: The vertical profile of phase change between PMSE and O_3 vmr using only correlations points significant at the 95% confidence level. Right-panel: The vertical profile of the cross correlation coefficient between PMSE and O_3 vmr. The dashed line represents the 95% confidence threshold. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

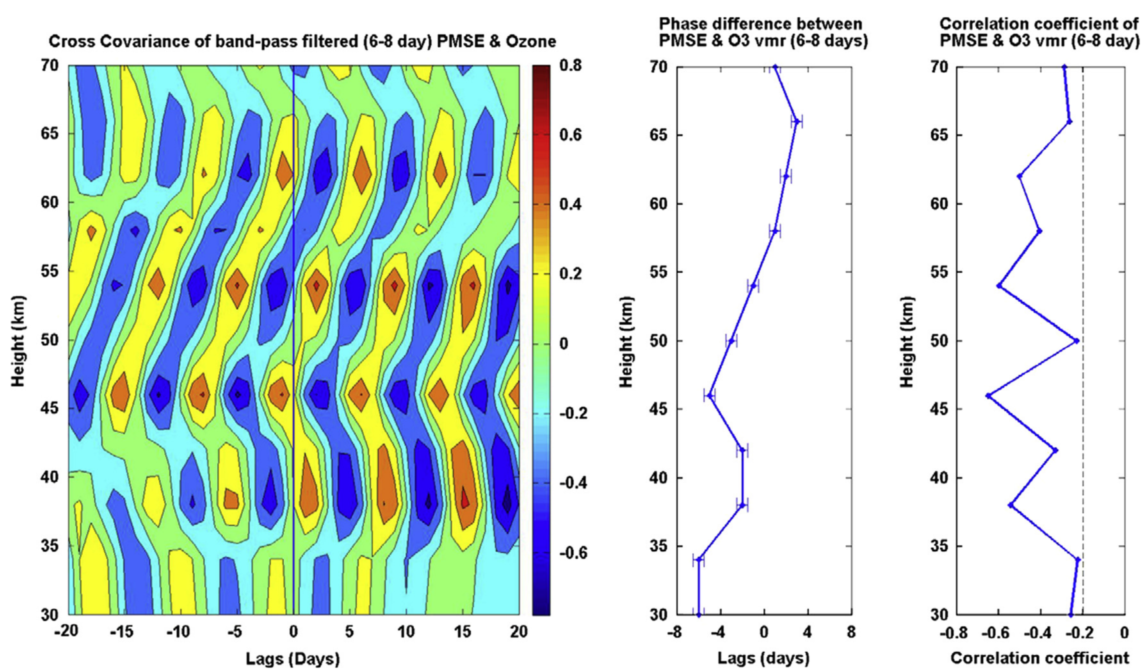

Fig. 7. The left panel shows the time-lagged cross-correlation between PMSE occurrence rate and ozone vmr at different altitudes for the 6.5-day wave. Red and blue colors represent positive and negative correlations, respectively. The vertical modulations reflect changes in the signal to noise. Middle-panel: The vertical profile of phase change between PMSE and O_3 vmr using only correlations points significant at the 95% confidence level. Right-panel: The vertical profile of the cross correlation coefficient between PMSE and O_3 vmr. The dashed line represents the 95% confidence threshold.

Having documented the presence of temporally and phase-coherent 5-day and 6.5-day waves in both the PMSE and ozone vmr through the amplitude- and cross-spectral analysis, the data were band-pass filtered to isolate the two periods. In this way the vertical phase structure of each individual component could be examined. Again, identical Butterworth IIR filters were used on the two data sets, with half-power points of 4 and 5 days for the 4–5 day wave, and 6 and 8 days for the 6–8 day oscillation, consistent with their periods in the cross-spectra. A time-lagged cross-correlation was performed between the PMSE and ozone vmr for each of these filtered data sets. The cross-correlation coefficients between the PMSE and the ozone vmr at each altitude for the 4–5 day and 6–8 day oscillations are shown in the left-panel of Fig. 6 and Fig. 7. Both oscillations show a significant coherence between the PMSE and ozone oscillations with correlation-coefficient magnitudes exceeding 0.7, indicating that the underlying temperature fluctuations are highly correlated and coherent in phase over altitude. In addition, the strong periodic modulation with lag indicates that both oscillations persist and are coherent over the entire data period.

4. Discussion and conclusions

The PMSE occurrence frequency has been extracted from the SuperDARN radar at Sanae station in Antarctica during the 2009–10 summer season using the algorithm developed by Hosokawa et al. (2005). The midday values were combined with spatially coincident midnight measurements of ozone mixing ratio obtained from the BAS microwave radiometer located at Troll station (72°S, 2°E) to measure the period and vertical structure of planetary waves in the stratosphere and mesosphere. This is possible due to the short chemical lifetime of ozone relative to transport times above ~30 km. This means that the planetary wave induced temperature fluctuations that modulate the PMSE occurrence will also modulate the ozone mixing ratio, with minima in temperatures associated with maxima in ozone (Finger et al., 1995; Huang et al., 2008; Belova et al., 2009). As a result these planetary wave variations in the PMSE have been traced downward to the upper stratosphere using variations in the ozone vmr.

The amplitude spectra show that there are a number of oscillations in the ~2–12-day period range, with the 4–5 day and 6–8 day oscillations being the most dominant and frequent in both the PMSE occurrence frequency as well as in the ozone vmr profiles from 30 to 70 km. These waves have been taken to be the 5-day and 6.5-day zonal wave-number one planetary waves. The 5-day wave is known to be a strong feature in the stratosphere and mesosphere during the polar summer (Salby, 1981; Williams and Avery, 1992; Meyer and Forbes, 1997; Kirkwood et al., 2002; Riggin et al., 2006; Belova et al., 2008; Day and Mitchell, 2010). However, the 6.5-day wave, while often observed in the lower stratosphere during the polar summer (Talaat et al., 2001), has only been observed sporadically in the westward zonal winds characteristic of that season (Jiang et al., 2008). In the present study, the amplitudes of the waves in the ozone are observed to decrease above 55 km. This may be due to the interactions of the waves with the increasing westward zonal winds at theses altitudes (Wu et al., 1994; Forbes et al., 1995; Day and Mitchell, 2010; McDonald et al. 2011). However, we cannot rule out that this decrease of amplitude is merely due to the decreasing O_3 vmr values above 55 km. Indeed, the strong wave amplitudes observed in the PMSE near 85 km would favor the latter explanation. Similarly, the decrease in wave amplitude below 40 km is likely due to the large *a priori* contribution to the retrieved O_3 at these altitudes minimizing the wave-induced departures and reducing the extracted wave amplitudes

Despite the instrumental effects, the cross-spectral analysis demonstrates that the amplitude corresponding to the 5-day and 6.5-day PW oscillations in the O_3 is phase coherent with the corresponding oscillation in the PMSE occurrence frequency. This indicates a common cause, and the temperature fluctuations associated with the planetary waves, known to affect both the O_3 and the PMSE, are likely responsible (e.g. Belova et al., 2009; Kirkwood and Stebel, 2003). The presence of peaks in the cross spectra demonstrates that despite the low amplitudes, this coherence is maintained at all altitudes from 30–70 km. The variation in amplitude of the cross spectrum reflects the variation in the amplitude spectra, with low amplitudes between 55 and 70 km.

The oscillations in the O_3 vmr have the same frequency and are phase coherent with those in the PMSE. Therefore, a band-pass filter was used to isolate the individual 5-day and 6.5-day components, and a lagged cross-correlation was performed for each. For the 5-day wave, the peak magnitudes of the correlation coefficient are between 0.63 and 0.21, with the majority significantly different from zero at the 95% confidence level. This indicates a significant correlation between the temperature fluctuations in the middle atmosphere and the PMSE variations near the mesopause. The continuity of the correlation with lag demonstrates the persistence of the wave over the data period, while the stability of the correlation pattern with altitude illustrates the vertical phase structure of the wave. Tracing either a single minimum or maximum in the correlation downward yields the altitude variation of the wave's phase. For the 5-day wave, the lag of the minimum correlation nearest to 0 lag is shown in the middle panel of Fig. 6. As shown in the right panel of the same figure, only points significant at the 95% level have been used. The lag is seen to vary between -1 and -4 days, or less than one cycle of phase shift between 38 and 70 km. This very nearly vertical phase structure is consistent with the 5-day wave being a normal mode oscillation (Forbes, 1995; Miyoshi, 1999).

The magnitude of the correlation coefficient of the 6.5-day wave is similar to the 5-day wave, approaching 0.8 at the some altitudes. However, here the phase lag, shown in the middle panel of Fig. 7, is seen to change by 9 days, or almost 1.4 cycles, from 34 to 66 km. Once again, only points significant at the 95% level have been used in the phase analysis. This large phase shift with altitude would indicate that the wave is propagating upward through the upper stratosphere and mesosphere into the PMSE region with a vertical wavelength on the order of 23 km. Previous observations of the 6.5 day wave (Talaat et al., 2001, 2002 and Jiang et al., 2008) also found the wave propagating upward in the mesosphere and lower thermosphere (MLT) region. There is an abrupt change in phase of the wave between 65 and 70 km, near the peak in the summertime zonal wind jets around these latitudes (Hibbins et al., 2005). This may indicate that this slower wave may be more strongly Doppler shifted by the winds (e.g. Wu et al., 1994 and references therein). However, we cannot rule out instrumental effects as the cause of this phase change as it does occur at the altitude above which the degraded altitude resolution of the measurements creates a constant phase.

In conclusion, this study demonstrates that the PMSE oscillations appear to be driven by two planetary waves with similar periods, 5- and 6.5-days, that are known to have similar zonal wavenumber-1 structure. Despite the climatologically westward zonal winds in the middle atmosphere, these waves have been traced downward into the stratosphere using the ozone vmr variations, and they are observed to have distinctly different vertical structures. The 5-day wave has nearly vertical phase fronts consistent with a normal mode structure, and is seen to extend from the PMSE region near 85 km down to the upper stratosphere. However, the phase structure of the 6.5-day wave indicates that it is propagating upward from the stratosphere into the PMSE region. The amplitude changes of ozone vmr with altitude cannot unambiguously be used to infer the interaction between the waves and the mean flow. However, the rapid phase changes observed in the 6.5 day wave near the zonal wind maximum may be indicative of such interactions.

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