Low latitude 2-day planetary wave impact on austral polar mesopause temperatures: revealed by a January diminution in PMSE above Davis, Antarctica

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Received 22 February 2009; revised 23 April 2009; accepted 4 May 2009; published 5 June 2009.

[1] A new characteristic of the austral summer polar mesopause as revealed by ground-based radar and satellite temperature measurements is reported, that is linked to inter-annual variability of the low-latitude easterly wind jet. Four consecutive seasons of polar mesosphere summer echoes (PMSE) and mesosphere temperature observations above Davis, Antarctica (68.6°S) show a mid-January diminution in PMSE occurrence rate that coincides with a minor mesopause warming of several degrees. Spectral analyses of PMSE, Aura Microwave Limb Sounder (MLS) temperatures and radar meridional winds show the presence of ~4–5-day planetary waves (PWs) throughout the austral summer in the polar upper mesosphere together with enhanced ~2-day PW activity from mid-January to mid-February. Analysis of MLS temperatures show that the ~2-day PWs have zonal wavenumbers (S) with both westward (S = −2, −3) and eastward (S = +2, +3) components. Although displaying some inter-annual variation in the peak onset time, the mid-January mesopause warming coincides with a weakening of the equatorward meridional wind above Davis and enhancement of low-latitude 2-day PW activity. **Citation:** Morris, R. J., A. R. Klekociuk, and D. A. Holdsworth (2009), Low latitude 2-day planetary wave impact on austral polar mesopause temperatures: revealed by a January diminution in PMSE above Davis, Antarctica, *Geophys. Res. Lett.*, *36*, L11807, doi:10.1029/2009GL037817.

1. Introduction

[2] Polar Mesosphere Summer Echoes (PMSE) at high latitudes is linked to charged ice-aerosol layer formation at extremely low temperatures (~150 K). Free electrons generated from Lyman-α radiation or electron precipitation attach to growing ice-aerosol clusters (≤50 nm radii) as they sediment under gravity. Neutral air turbulence creates a gradient in electron density which enables PMSE detection as backscattered Bragg scale (~λ/2) echoes on MST (mesosphere-stratosphere-troposphere) radar. PMSE are produced or advected above the radar by the prevailing wind field [see *Cho and Röttger*, 1997; *Rapp and Lübken*, 2004]. In recent years the knowledge base of Southern Hemisphere (SH) PMSE has gradually expanded [e.g., *Woodman et al.*, 1999; *Morris et al.*, 2006, 2009; *Latteck et al.*, 2008; M. F. Sarango et al., Further observations of PMSE in Antarctica, paper presented at 10th International Workshop on Technical and Scientific Aspects of MST Radar, Scientific Committee on Solar Terrestrial Physics, Piura, Peru, 2003] relative to the more extensive literature on Northern Hemisphere (NH) PMSE (see above reviews). More recently inter-hemisphere comparisons using calibrated MST radars revealed that southern PMSE occur less frequent with lower average volume reflectivity, and peak ~1 km higher than their northern counterparts, at least for comparable latitudes [*Latteck et al.*, 2008; *Morris et al.*, 2009]. In a pan-hemispheric study of PMSE above Davis (69°S) and Andenes (69°N), *Morris et al.* [2009] suggested that the main reason for the differences in echo occurrence rates and strengths is related to summer mesopause temperatures being ~3–7 K warmer in the SH compared with the NH.

[3] A significant difference has been noted in the spatio-temporal height-time intensity seasonal envelope of PMSE between Davis and Andenes [*Morris et al.*, 2009]. For Davis a distinct mid-January to the end of season diminution in PMSE and for several days complete disappearance of PMSE was observed for the 2004–05 and 2005–06 austral summers, which is not evident in the NH. This point was briefly considered by *Klekociuk et al.* [2008] whereby PMSE and polar mesosphere clouds (PMC) were observed to decline from mid-January toward the end of the 2005–06 austral summer. These authors found evidence of 2-day and ~4–5-day planetary waves (PWs) from periodogram analyses of PMSE and Aura Microwave Limb Sounder (MLS) temperatures, and zonal spectral analyses of MLS temperatures indicated the presence of eastward 2-day (zonal wave number S = +2) PWs for the interval of PMSE decline. The S = +2 2-day PW has been investigated by other authors including *Limpasuvan and Wu* [2003, 2009] and *Palo et al.* [2007].

[4] PMSE provide a portal into mesopause region processes since perturbations in temperature are manifested in the properties of these charged aerosol layers [e.g., *Rapp and Lübken*, 2004]. In this paper we present four consecutive seasons of SH PMSE observations that clearly show their diminution in occurrence rate and strength to be an annual event at latitude 69°S. Following on from the initial work of *Klekociuk et al.* [2008] we examine the spectral features of mesospause region PMSE, temperature and meridional winds above Davis, Antarctica (68.6°S; 78.0°E). Our spectral observations support the evolution of PWs dominated by westward 2-day PW (S = −3)

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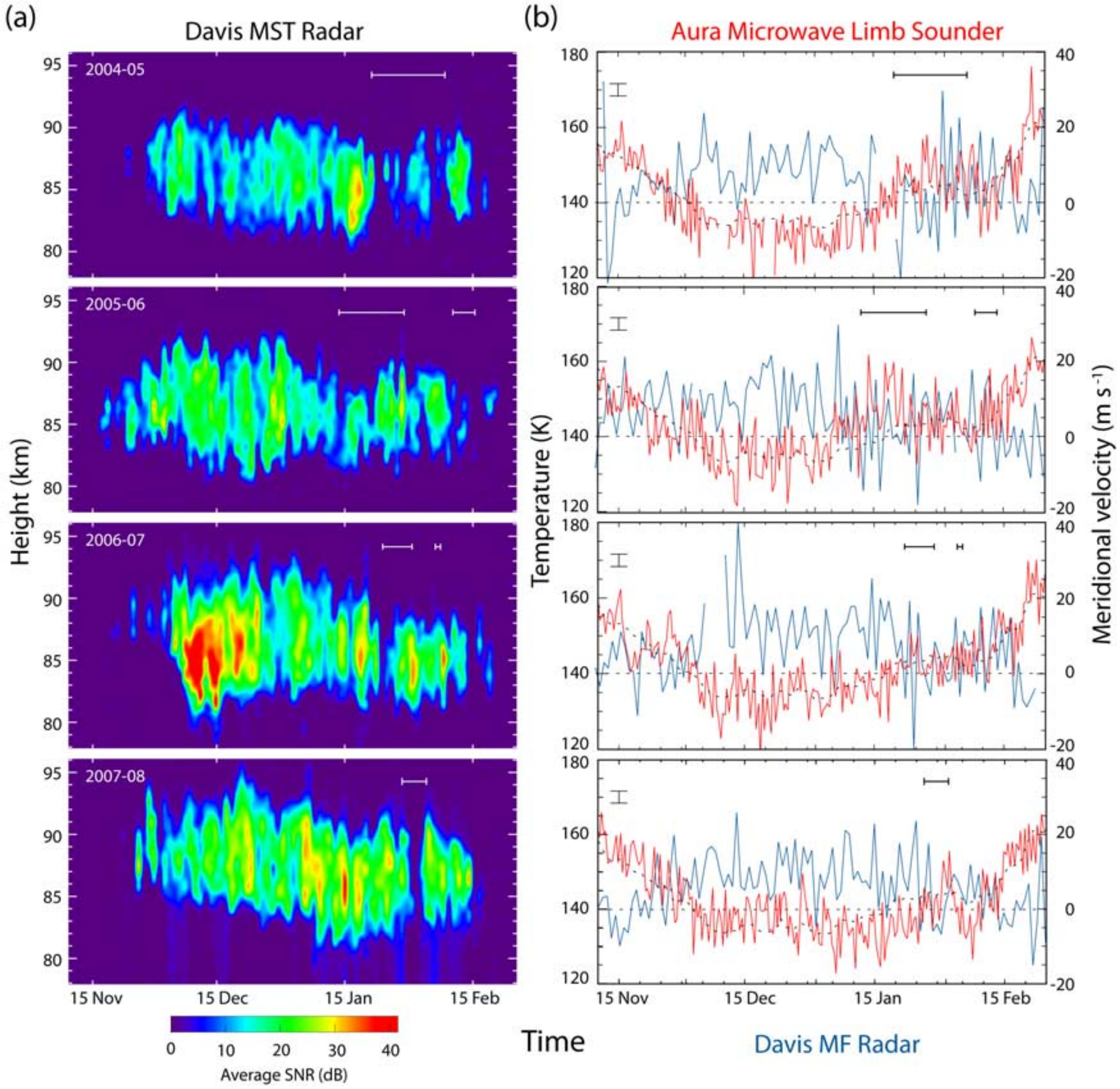

Figure 1. (a) Spatiotemporal envelopes of Davis MST radar hourly averaged PMSE height-time intensity plots with mid-January diminution highlighted (2004–08). (b) Corresponding Aura mesopause region temperature profiles at the altitude 87 km derived from the ascending daily orbit within 500 km distance of Davis (red) with climatological average (dashed black curve) of the four seasons. Corresponding average meridional wind amplitude at 88 km derived from the Davis MF radar (blue) with zero wind speed (dashed black line). The median Aura MLS standard error on each measurement is shown by the vertical bar in the upper left of each panel. Time intervals discussed in the text are shown by the horizontal bars.

activity, originating from the low-latitude easterly jet [e.g., *Salby and Callaghan*, 2008; *Limpasuvan and Wu*, 2003, 2009].

2. Experimentation

[5] Half-hourly averaged PMSE and meridional wind measurements were obtained from 55-MHz MST and 2-MHz medium frequency (MF) radars at Davis for November 2004–February 2008. The MST- and MF-radar operation parameters are detailed by *Morris et al.* [2006]. Mesopause region temperatures were derived using Aura MLS version 2.2 data [*Schwartz et al.*, 2008] averaged for the same time interval as the PMSE observations above Davis, using the methodology outlined by *Morris et al.* [2009].

3. Multiseason Observations of PMSE, Temperature, and Meridional Wind Field

[6] Four consecutive seasons of mesosphere PMSE, temperature and meridional wind observations are displayed in Figure 1 for the austral summers 2004–05, 2005–06, 2006–07 and 2007–08 (down the page) for the geometric height range (70–100 km). The spatiotemporal envelopes of PMSE are shown in Figure 1a. Mesopause region temperatures at 87 km (red curve in Figure 1b, where black dotted curve shows the four season mean temperature) and meridional wind at 88 km (blue curve in Figure 1b) reveal both

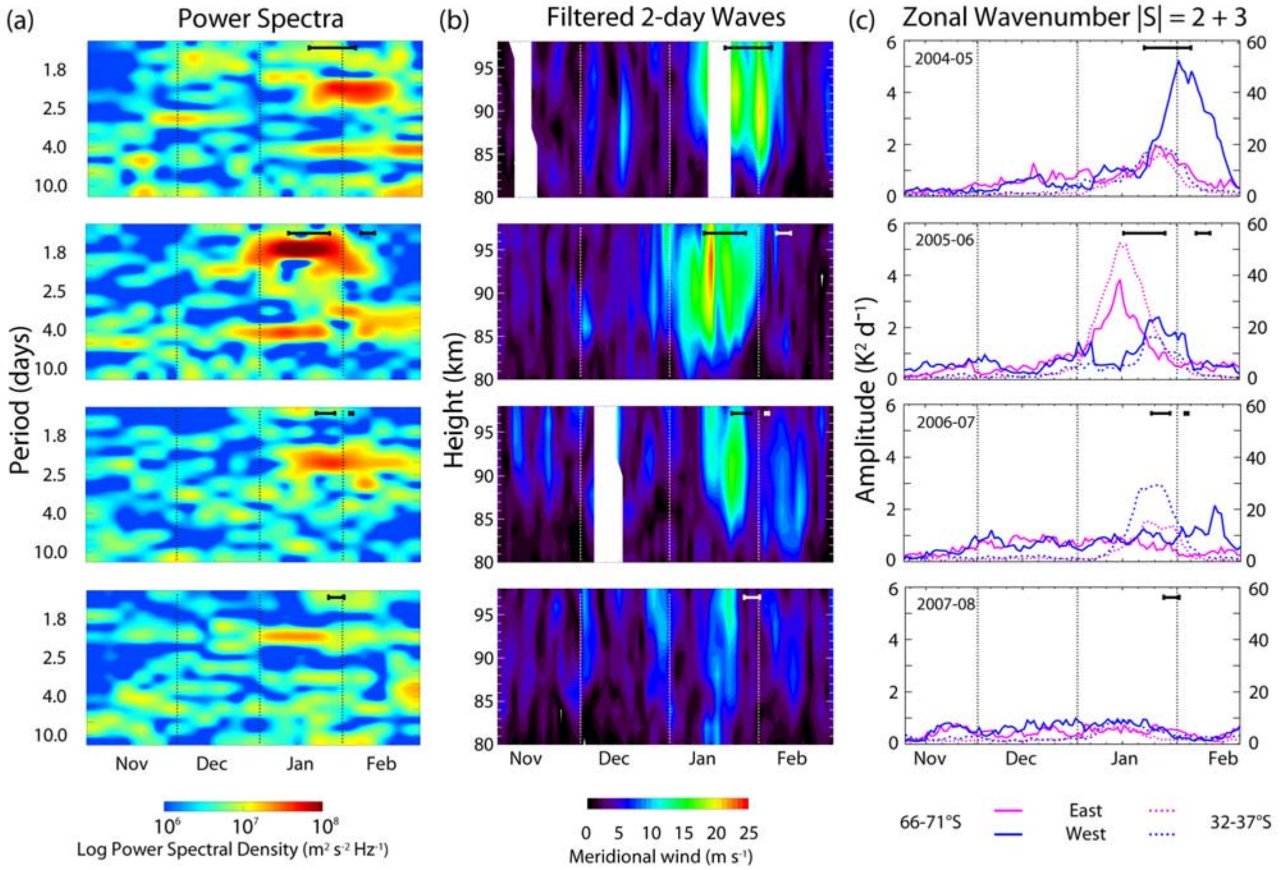

Figure 2. (a) Dynamic spectral plots of the meridional winds. (b) Filtered MF radar derived meridional wind reveals the presence of 2-day waves. (c) Composite amplitude time-series of Aura MLS temperature zonal wavenumbers with |S| = 2 + 3 (eastward pink; westward blue) for summed wave periods between 2 and 3 days for two latitude swaths 66–71°S (solid) and 32–37°S (dotted).

intra-seasonal and inter-seasonal variations. Aspects of the relationship between these basic parameters, i.e., PMSE occurrence and strength, mesopause temperature, and the meridional wind speed and direction were discussed by *Morris et al.* [2009] and *Latteck et al.* [2008] for the 2004–05 and 2005–06 austral summers. These studies implicitly showed the meridional wind influence on the start, duration, and end of the PMSE season (i.e., inter-annual variability) – in line with the expectation on the summer pole to winter pole meridional wind flow.

[7] The horizontal bars in Figure 1 highlight the mid-January diminution and sudden disappearance of PMSE which appears to be an annual recurring feature, at least for Davis (~69°S). In particular, we note that during the late 2004–05 and 2005–06 austral summers PMSE either episodically disappear or their strength is noticeably diminished for a sustained interval, whereas during the late 2006–07 and 2007–08 austral summers PMSE disappearance is more distinctive and short lived. Interestingly and objectively, the corresponding mesopause region temperatures shown in Figure 1b (red curve) indicates warmer temperatures (151–162 K) during the intervals where PMSE occurrence and strength are diminished or completely ablate – which also correspond to temperatures above the four season mean in Figure 1b (black curve). Moreover, during these intervals the pre-existing equatorward meridional wind flow suddenly turns poleward or the flow vacillated above Davis as shown in Figure 1b (blue curve), consistent with earlier reports by *Morris et al.* [2009]. Also evident throughout each season is that intervals of enhanced PMSE intensity are usually linked to colder temperatures [*Morris et al.*, 2006] or to additional electron precipitation during solar proton events (SPE), i.e., January 2005 [*von Savigny et al.*, 2007] and December 2006 (Figure 1a).

4. Spectral Analyses of PMSE, Temperature, and Meridional Wind Field

[8] Spectral analyses using high spatial and temporal resolution (2 km and 2 minute) MF radar wind field data above Davis revealed distinct period bands near ~2-day and ~3–5-day that appear episodically throughout each austral summer. Figure 2a presents band pass filtered (from 36 h to 15 days) Fourier-decomposed spectra with a moving data window length of 15 days of hourly averaged meridional wind, incremented every 5 days (for a representative PMSE layer height of 88 km) through each of the austral summers studied (2004–05 to 2007–08). Clearly the most remarkable spectral signature coincident with the interval of PMSE diminution (horizontal bars in Figure 1a) corresponds to a

~2-day PW. A height-time display of these 2-day PWs was obtained by application of a 48 hour filter to the meridional wind field in the height range 80 to 98 km, using a 6 day window with a two day increment for combined O- and X-mode radar measurements. Outcomes of this method are illustrated in Figure 2b which provided further information on the occurrence times and magnitude of the ~2-day wave (normalised to 25 m s^{-1}). A distinctive inter-annual variation of the ~2-day wave is evident for the respective austral summers (1 November to 28 February).

[9] Interestingly, for the austral summers 2004–05 and 2005–06 the more extended PMSE diminution appears related to a possible warm phase superposition of the 2-day and ~4–5-day PWs. Whereas the short duration reduction of PMSE during January 2006–07 and 2007–08 is clearly connected with the warm phase of the 2-day PW feature (negligible ~4–5-day PWs). Moreover there is a trend of decreasing duration and magnitude of the late season 2-day PWs from 2004–05 to 2007–08 corresponding with a marginal cooling of the mesopause region over this interval (Figure 1b red curve), and the peak in the meridional wind flow is either poleward or vacillates (Figure 1b blue curve) near the peak interval of PMSE diminution (Figure 1a) – we explain the significance of these observations in Section 5.

[10] Firstly, normalised Lomb-Scargle periodograms were prepared for hourly-averaged PMSE SNR data and daily MLS temperatures derived from the ascending node data for the four austral seasons (2004–2008) studied (methodology discussed by *Klekociuk et al.* [2008]). Our analyses reveal statistically significant spectral power, indicative of the presence of ~2-day, ~4–5-day (for 2004–05 and 2005–06) and ~10–15-day waves being observed above Davis during the austral summers. Secondly, longitude-time Fourier analyses of MLS temperature data for a latitude swath (65–77°S) decomposed the respective wave zonal components, for the 0.0046 hPa pressure surface (~84.7 km, and nearest the centre of the PMSE layer). The analysis shows wave features consistent with those in Figures 2a and 2b but importantly revealing their zonal wavenumber (S), where '+' is eastward and '−' is westward. We find PWs with period (wavenumber): ~2.2-day eastward wave (S = +2); ~2-day westward wave (S = −2); ~2-day eastward wave (S = +3); ~2-day westward wave (S = −3); ~4–5-day westward wave (S = −1) (for 2004–05 and 2005–06); and a ~10–15-day wave (S = 0).

[11] Amplitude-time series of the MLS temperature zonal wavenumbers were prepared (Figure 2c) to facilitate comparison with PMSE spatiotemporal plots (Figure 1a) and 2-day PWs derived from the meridional wind field (spectra in Figure 2a and filtered 2-day PWs in Figure 2b). Figure 2c shows composite eastward (pink) and westward (blue) zonal wavenumbers for |S| = 2 + 3 for 2-day PW amplitudes plotted as a function of time. A high latitude swath of 66–71°S near the latitude of Davis (solid) and a low latitude swath of 32–37°S near the equator (dotted) are illustrated. Remarkably, for intervals of PMSE diminution the ~2-day PW consistently dominated the spectral content during the latter part of the season, although with some minor temporal variability (however the low equatorward peak in PW amplitude could be positioned >37°S with minor temporal displacement [see *Limpasuvan and Wu*, 2003]). Westward PWs usually have the largest amplitudes, although large amplitude eastward PWs prevailed during the 2005–06 austral summer, but as pointed out by *Limpasuvan and Wu* [2009] for this particular season the spectral signature of PWs was complex and broadband. Nonetheless the low and high latitude linkage for |S| = 2 + 3 for 2-day PW amplitudes stands out as an annual feature for the study interval. Interestingly, the 2004–05 and 2005–06 austral summers exhibited extended PMSE diminution and both contained strong 2-day PWs – although ~4–5-day westward PWs (S = −1) also appeared concurrently. However, moderate and then weak 2-day PWs were present during the 2006–07 and 2007–08 summers respectively, corresponding to progressively less PMSE diminution apart from the short duration gap of total disappearance. It is strikingly evident, that high latitude ~2-day PWs observed in MLS temperature, PMSE occurrence and meridional wind records, are linked to the equatorward source region of the substantially stronger ~2-day PWs observed in the low latitude MLS temperature record.

5. Discussion and Conclusions

[12] In this paper we report the first observation of an annual mid-January diminution of PMSE strength and occurrence at the SH polar site Davis (69°S) based on four austral summers (Figure 1a). Spectral analyses of high resolution MF radar meridional winds (Figures 2a and 2b) showed the coincident occurrence of ~2-day PW for four austral summers (2004–05 to 2007–08) with the respective PMSE diminution intervals, and two summers (2004–05 and 2005–06) clearly exhibited strong ~4–5-day PWs.

[13] Periodogram analyses of the corresponding PMSE and MLS temperature records revealed a zoo of complex spectral features, whereby distinctive ~2-day, ~4–5-day and ~10–15-day PWs were evident for each austral summer, albeit exhibiting some annual variability. Zonal wavenumbers (S) were extracted for zonal averaged MLS temperature records between 65° and 75° southern latitudes (i.e., equatorward/poleward of Davis ~69°S). We found ~2-day PWs with S = ±2 and S = ±3, which is consistent in part with recent findings of *Limpasuvan and Wu* [2009, Figure 1] using Aura MLS temperature measurements for the 2004–05 and 2005–06 austral summers that extended to ~70°S for westward zonal wavenumbers (S = −2 and −3). Similarly our ~4–5-day PWs with S = −1 and 2-day PWs with S = −2 (−3) are consistent with previous austral summer findings of *Merkel et al.* [2008] for high southern latitudes >68°S from SNOE PMC (SABER temperature) observations for 2002–03 around solstice, albeit not near mid-January.

[14] The literature abounds with observational and theoretical studies of the 2-day wave [e.g., *Salby and Callaghan*, 2008; and references therein]. Briefly summarising *Rojas and Norton* [2007], the 2-day (or 43 to 55 h) wave appears predominantly for a few weeks each January–February with peak meridional (and zonal) wind amplitudes following the austral summer solstice (although it occurs with reduced amplitude in the boreal summer July–August, and also during the respective hemisphere winters). The robust period of the 2-day wave led to it being identified with the gravest planetary normal baroclinic mode of wave number 3 (S = −3), the 'Rossby-gravity mode' [*Salby*

and Roper, 1980], given its westward propagation with a period of 2.1 days. Whereas, the 2-day wave's semi-annual amplification (associated with the semi-annual reversal gradient in polar vorticity) near the summer solstice suggested additional forcing linked with the instability of the summer easterly jet [*Plumb*, 1983]. Moreover, the non-linear interaction of the 2-day wave with tides results in a range of additional wave numbers, i.e., 2-day eastward wave (S = +2) results from the superposition of 2-day westward wave (S = −3) and the diurnal tide [*Palo et al.*, 2007]. Our reported dominant spectral observations are consistent with the above equatorial source mechanisms, albeit our zonal averaged MLS temperatures reveal 2-day PWs with zonal wave numbers S = ±2 and ±3.

[15] Undoubtedly, the warm phase of the 2-day wave or planetary scale waves (PWs) as outlined above is the prime thermal process impacting mesopause temperatures during the mid-January diminution of PMSE at 69°S for the four season study interval. It is highly likely that the local coincident ∼4–5-day and 2-day PWs during the first two summers (2004–05 and 2005–06) resulted in a linear superposition of the warm phase of these PWs, contributing to a more prolonged and enhanced ice-aerosol ablation. Also note the reversal in meridional wind flow (equatorward to poleward) during the peak of PMSE diminution [*Morris et al.*, 2009, Figure 1b], is consistent with an increased meridional wind flow near the peak of the 2-day PWs (S = −2 and −3) as recently reported by *Limpasuvan and Wu* [2009, Figure 2]. Indeed, since the 2-day PWs are manifestations of the low latitude easterly jet instability – it is plausible that wave activity (Eliassen-Palm flux) could be pointed upward and their divergence results in a poleward heat flux that also warms the mesopause – that extends to the latitude of Davis (supported by the observed poleward meridional wind flow or movement of warm air mass). Also if there is a divergence in Eliassen-Palm flux, then a secondary circulation can result due to wave forcing that adiabatically compresses and warms the mesopause region [see *Salby and Callaghan*, 2008, Figure 9]. These dynamic processes elevate mesosphere temperatures for the duration of the 2-day PW – a condition not conducive for the growth cycle or sustenance of advected ice-aerosols above Davis when $T > T_{\mathrm{frost\ point}}$. Aura MLS measurements show warmer mesopause temperatures during these intervals (Figure 1b red curve).

[16] We contend that an inter-annual variation in the strength of the 2-day PW results in varying degrees of elevated mesopause region temperature (∼1–9 K at 87 km after allowing ∼3 K contribution from 5-day PW activity for 2004–05 to 2005–06, see Figure 1b), accounts for the reported partial or total ablation of charged ice-aerosols (or PMSE) during the late austral summer. Furthermore, we suggest that inter-annual variations (in particular enhancements) of the 2-day PW warm phase offers an explanation for several unresolved ice-aerosol layer observations in the literature: the decrease of PMC during January 2005 reported by *von Savigny et al.* [2007, Figure 2] (Figure 1); the reported mid-January–February warming at Rothera ∼68°S by *Lübken et al.* [2004]; and of historical importance, the nil and sporadic observation of PMSE during January–February at Machu Picchu ∼62°S by *Balsley et al.* [1993] and *Woodman et al.* [1999]. These studies were conducted during summers with strong to moderate 2-day PW activity, as detected on the Davis MF radar (from 1994), and earlier as reported by *Limpasuvan and Wu* [2003].

[17] A recent inter-hemispheric investigation of PMSE between Davis and the NH site Andenes (69°N) exhibited this diminution only over Davis, consistent with the reported warmer SH mesopause temperatures of 3–7 K [*Morris et al.*, 2009]. Since the 2-day PW is much stronger in the austral summer as opposed to the boreal summer, the warming due to the 2-day wave enhancement will not be as great over the NH polar region. As such, the diminution of the PMSE in the NH should be less. Moreover, any prevailing ∼2-day PW heating has a greater impact in the south, where PMSE are on the margin of existence (i.e., closer to the mesopause region frost point temperature) relative to equivalent NH latitudes. Indeed, it is plausible that inter-annual variability of SH 2-day PWs may account, in part along with background temperature differences, for the initial Antarctic nil PMSE detection (January–February 1993) [*Balsley et al.*, 1993] and sporadic detection of PMSE at Machu Picchu ∼62°S (January–February 1994) [*Woodman et al.*, 1999], if these seasons experienced strong 2-day PWs during these intervals (speculative). However, we note that *Limpasuvan and Wu* [2003, Figure 4] presented evidence for strong SH 2-day PW activity near 62°S for 15 January to 9 February 1993 that supports our hypothesis. Moreover, the subsequent higher occurrence rates of PMSE with inter-annual variation in strength at the closely located sites of Machu Picchu (1997–98) and Artigas ∼62°S (2000–01) reported by Sarango et al. (presented paper, 2003), followed seasons with progressively weaker 2-day PWs (based on Davis MF radar observations), particularly during the January–February interval.

[18] We conclude that low altitude low-latitude 2-day PWs influence high polar latitude ∼69°S mesopause region temperatures, as evidenced by PMSE disappearance, consistent with the Aura MLS temperature record. Our polar observations support the evolution of PWs spawned from 2-day PW (S = ±2 and ±3) activity, originating from the low-latitude easterly jet – albeit not previously linked to the reported mid-January diminution of PMSE at southern latitudes.

[19] **Acknowledgments.** We thank L. Symons, D. Murphy, and the Davis engineers for technical support of the MST and MF radars (projects 2325 and 674, respectively, of the Australian Antarctic Program). Aura/MLS data used in this study were acquired as part of the NASA's Earth-Sun System Division. D. Murphy processed the data for Figure 2b. D. Ratcliffe provided assistance with the preparation of the figures. We thank the reviewers for their helpful comments.

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