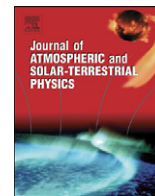




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Inter-hemispheric asymmetry in polar mesosphere summer echoes and temperature at 69° latitude

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ABSTRACT

An inter-hemispheric asymmetry is found in the characteristics of polar mesosphere summer echoes (PMSE) and upper mesosphere temperatures at conjugate latitudes ($\sim 69^\circ$) above Antarctica and the Arctic. The second complete mesosphere–stratosphere–troposphere (MST) radar summer observation season at Davis (68.6°S) revealed that PMSE occur less frequently, with lower strength and on average 1 km higher compared with their northern counterparts at Andenes (69.3°N). We consider the thermodynamic state of the mesosphere for conjoining hemispheric summers based on satellite and ground-based radar measurements, and show the mesopause region near ~ 80 – 87 km of the Southern Hemisphere (SH) to be up to 7.5 K warmer than its Northern Hemisphere (NH) counterpart. We show that this is consistent with our observation of asymmetries in the characteristics of PMSE and demonstrate how the mesosphere meridional wind field influences the existence and strength of the echoes in both hemispheres.

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1. Introduction

PMSE were first identified almost three decades ago by VHF radars in Germany (52°N) (Czechowsky et al., 1979) and Alaska (65°N) (Ecklund and Balsley, 1981) as enhanced backscatter in the height range 78–92 km during the boreal summer. Studies followed primarily in the Northern Hemisphere (NH) as far north as 78°N (Lübken et al., 2004b), although recently more focus has been given to Southern Hemisphere (SH) observations (Woodman et al., 1999; Morris et al., 2004). PMSE layers are believed to comprise charged aerosols that are created near the temperature minimum of the polar summer mesopause. Their theoretical interpretation has evolved (Cho and Röttger, 1997) to the current level of understanding whereby most characteristics of PMSE can readily be explained (Rapp and Lübken, 2004).

Initial limited SH observations of PMSE from Machu Picchu (62.1°S) were compared with PMSE observations from Poker Flat (65°N) albeit displaced by 10 years (Woodman et al., 1999). This work revealed a significant difference in PMSE strength between the sites in the order of 25 dB, with the echo power observed at the SH site being up to 300 times less. Subsequently, Sarango et al. (2003) reported PMSE some ~ 11 dB stronger at Artigas (62.18°S)

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(~ 30 km away) during 2000–2001 on a smaller un-calibrated MST radar, arguing these results support inter-annual variability in PMSE characteristics. Morris et al. (2004, 2006) pointed out that PMSE strengths of ~ 32 dB observed at Davis appeared consistent with published NH PMSE strengths for Andenes (69°N), albeit with the caveat that inter-hemispheric comparisons required observations from similar calibrated radars.

Hosokawa et al. (2005) extracted PMSE signatures from identical SuperDARN (Super Dual Auroral Radar Network) radars operating at 10 MHz, to reveal ~ 1.5 greater occurrence rate of PMSE at Iceland (63.77°N) compared with Syowa (69.01°S) for two consecutive NH (1999 and 2000) and SH (1999–2000 and 2000–2001) seasons, concluding that an inter-hemispheric asymmetry in PMSE occurrence exists, albeit much weaker than reported from (un-calibrated) VHF radar observations. However, Jarvis et al. (2005) compared PMSE detected on a Dynasonde (at 28 MHz) at Halley (76°S) for the 2005 season with PMSE strengths reported by Woodman et al. (1999, Fig. 4) for Machu Picchu (62.1°S) and Poker Flat (65°N) a decade earlier on MST radars. These authors estimated PMSE relative SNR (dB) for Halley and Poker Flat (separated by 11° poleward in latitude) to be similar, concluding that no inter-hemispheric difference exists in PMSE strength.

Jarvis et al. (2005) and more recently Kirkwood et al. (2007) suggested that their inter-hemispheric results agreed with those reported by Morris et al. (2004), although the Davis radar was not

yet calibrated. Also the SH studies of Morris et al. (2004), Jarvis et al. (2005) and Kirkwood et al. (2007) covered only the last 3 weeks of the austral summer, when PMSE occurrence rates and strength decline (from a peak volume reflectivity at Davis of $\eta \sim 4 \times 10^{-11} \text{ m}^{-1}$) (Morris et al., 2007) during the late season warming of the mesopause region (Lübken et al., 2004a). Latteck et al. (2005) stressed the importance of using calibrated radars (i.e. the delay-line methodology) for inter-site comparison of PMSE strength or more correctly volume reflectivity, η (a radar-independent parameter) over a complete season.

Subsequently, Latteck et al. (2007) reported the first inter-hemispheric comparison of PMSE recorded on similar calibrated MST radars located near the same latitude (Davis (68.6°S) and Andenes (69°N)), which revealed a lower peak volume reflectivity at Davis ($\eta \sim 3.7 \times 10^{-11} \text{ m}^{-1}$) compared with Andenes ($\eta \sim 6.8 \times 10^{-10} \text{ m}^{-1}$). Kirkwood et al. (2007, Fig. 4) using calibrated radars (i.e. sky noise methodology) then reported little difference in volume reflectivity between Wasa (73°S) and Kiruna (68°N), where $\eta \sim 6 \times 10^{-14} \text{ m}^{-1}$ for 2007, concluding that Arctic PMSE are similar to Antarctic PMSE toward the end of the PMSE season. The Kirkwood et al. (2007) results show that the 5° poleward location of the SH site supports the case for an inter-hemisphere difference in PMSE reflectivity based on a latitude profile of increasing volume reflectivity toward higher latitude. Indeed, a preliminary comparison of PMSE between Davis and Wasa (for 2007) revealed larger reflectivity and occurrence rates with increasing latitude (S. Kirkwood, personal communication, 2007).

A significant knowledge gap relates to whether there is an inter-hemispheric difference in the thermal state of the mesopause region. Early satellite temperature measurements suggested the SH polar mid-summer mesopause region to be warmer than the NH by 9 K (Huaman and Balsley, 1999). Bailey et al. (2005) were the first to report a similar inter-hemispheric difference in polar mesospheric clouds (PMC), and subsequent work by Bailey et al. (2007) revealed that SH PMC exhibit larger variability, more markedly at latitudes below 75°. Wrotny and Russell (2006) demonstrated that NH PMC were more frequent and brighter compared with SH PMC. Similarly, a comprehensive discussion of inter-hemispheric mesospheric temperature and PMC differences determined from HALOE data, together with a comparison with a model was presented by Hervig and Siskind (2006), revealing PMC to be more frequent and 30% brighter, consistent with the observed lower NH mesospheric temperatures. On the other hand, in situ observations from falling spheres launched from rockets at Rothera (68°S) for January show temperatures to be similar but 2–3 K warmer, compared with earlier Arctic measurements (although warmer again in February) (Lübken et al., 2004a).

In Section 2 we extend and consolidate the inter-hemisphere knowledge base of PMSE morphology and characteristics for Davis (2005–2006) and Andenes (2005) to a second season (using calibrated radars), beyond the previous conjoining seasons reported by Latteck et al. (2007). The first corresponding seasonal spatiotemporal envelopes of mesopause region MLS temperature measurements and MF radar-derived meridional winds are presented in Section 3. Finally, we discuss the reported inter-hemispheric differences in PMSE (similar to PMC) in relation to variations in mesopause region temperatures and prevailing meridional wind flow, concluding that our findings support recent experimental and model evidence of an inter-hemisphere differences in polar mesopause region temperatures (Section 4).

2. Inter-hemispheric PMSE observations

Here we present a comparison of PMSE layers in each hemisphere, displaced in time by 183 days, using measurements

by calibrated mesosphere–stratosphere–troposphere (MST) radars at Andenes, Norway (69.3°N) for May–August 2005 and at Davis, Antarctica (68.6°S) for November 2005–February 2006. The respective MST radar operation parameters were recently published (Morris et al., 2006; Latteck et al., 2007). Both MST radars were calibrated using a delay-line calibration technique to determine the respective PMSE volume reflectivity (backscatter cross-section per unit volume), as discussed in Latteck et al. (2007).

Typical height–Universal Time volume reflectivity images of PMSE are given in Fig. 1 for Andenes (25 June 2005) and Davis (25 December 2005), where the volume reflectivity is stronger in the NH for these days. PMSE can form single or multiple layers or simply appear as patches of varying temporal scales from minutes to many hours, which monotonically fall with rates of 1–5 km h⁻¹, although on occasions move upwards—presumably under the influence of atmospheric dynamics—or simply disappear when temperatures exceed T_f . The layer thickness ranges from a few hundred meters up to about 10 km. PMSE occurrence rates are higher at Andenes compared with Davis.

In Fig. 2, we present the seasonal average PMSE occurrence rates for a minimum volume reflectivity of $\eta_{\min} = 5 \times 10^{-16} \text{ m}^{-1}$. We see that PMSE at Davis occur in a narrower layer; however, the PMSE layers at both sites overlap at the top, but diverge and occur at lower heights at Andenes; and the median height of PMSE layers differ by 1 km (higher at Davis). To place the PMSE layers into perspective we have plotted the respective Davis and Andenes summer atmosphere temperature profiles against height, as derived from Aura Microwave Limb Sounder (MLS) version 2.2 data averaged for the same time interval as the PMSE observations in both hemispheres (solid lines). The temperature difference between the two sites shown in this figure of 3–7.5 K (Davis warmer than Andenes) is also apparent when we compared the other summer seasons available in the MLS version 2.2 data set for the sites (not shown). Furthermore, we see that the average temperature profile in the mesosphere occurs at a slightly higher height in the SH, and similar to the respective PMSE occurrence plots, the SH temperature profile is narrower and diverges from the NH temperature profile at lower heights. We note that there are known measurement biases in the MLS temperature and geopotential height data products (Froidevaux et al., 2006; Schwartz et al., 2008) but no inter-hemispheric distinction in these biases has been reported.

Fig. 3a shows that the occurrence of PMSE rapidly rise at the start of summer (~ 17 November at Davis, and 28 May at Andenes with an outlier events on 20 and 13 May), and gradually falls

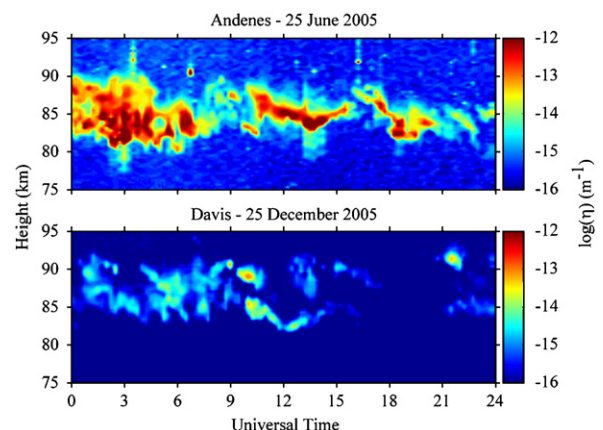


Fig. 1. Height–Universal Time volume reflectivity images of representative PMSE at Andenes on 25 June 2005 (top) and Davis on 25 December 2005 (bottom), where the colour bar shows reflectivity intensity levels (m^{-1}).

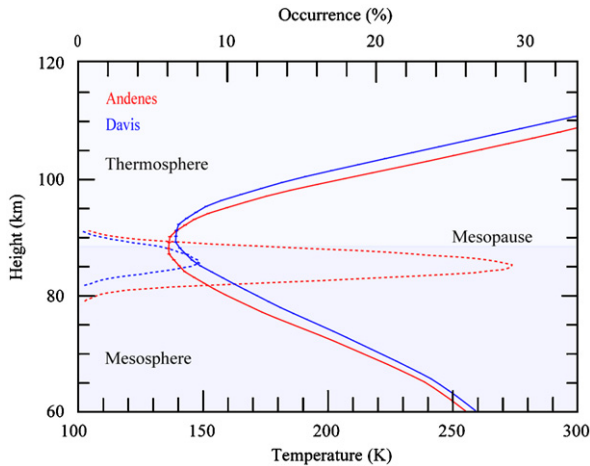


Fig. 2. Aura/MLS temperature profiles (solid lines) within a 500 km radius of each site with 1 km altitude scaling derived from the standard hypsometric relation and linear interpolation averaged with equal weighting. The error bars relate to the measurement uncertainty in the mean obtained using interpolated individual $1-\sigma$ measurement uncertainties given in the original data. Season average PMSE occurrence rates for a volume reflectivity, $\eta > 5 \times 10^{-16} \text{ m}^{-1}$ (dashed lines) plotted against height. For the intervals 21 November 2005–13 February 2006 Davis (blue) and 28 May–20 August 2005 Andenes (red).

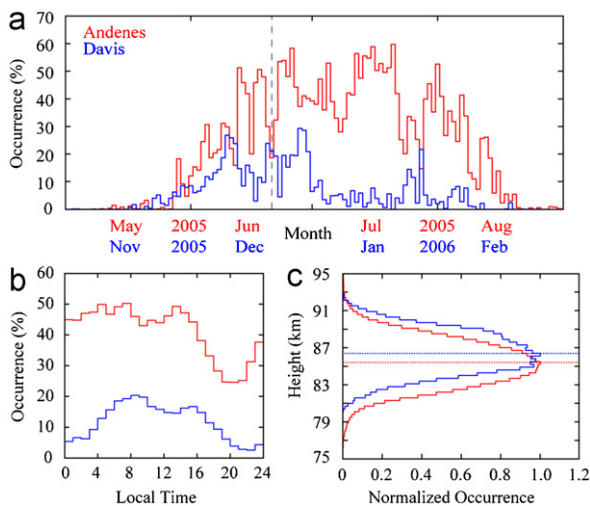


Fig. 3. (a) Seasonal percentage occurrence rates of PMSE versus month where the dashed vertical line indicates the respective hemisphere summer solstice. (b) Daily percentage occurrence rates of PMSE versus local time. (c) Season normalized height versus percentage occurrence distributions of PMSE, where the dashed horizontal lines show the respective median occurrence heights of 86.3 km at Davis (blue) and 85.3 km at Andenes (red). We count an event for PMSE occurrence in each $300 \text{ m} \times 1 \text{ h}$ spatiotemporal bin in the height range 78–92 km, i.e. 1128 bins per day.

toward the end of the season (~ 13 February at Davis with weak outlier events on 18 and 19 February, 20 August at Andenes with a weak outlier event on 2 September). The PMSE occurrence rate at Andenes remains at high levels for most of the season, whereas at Davis it declines from mid-January/February, apart from the peak in late January. PMSE peak after the summer solstice (21 June) at Andenes, although they peak each side of the summer solstice (21 December) at Davis. Another striking feature is the similarity of the occurrence rates between the sites before solstices. However, the PMSE season mid-range occurs about 2 weeks after the summer solstices in both hemispheres (near 5 January/July).

The diurnal variation of PMSE occurrence at Andenes/Davis for 2005/2005–2006 reveals a primary peak at 08/09 h local time (LT) and a secondary peak at 14/16 LT, and distinct minima at 21/23 LT (Fig. 3b). However, at Davis the primary/secondary peaks occurred at 14/06 LT for 2004–2005 (Latteck et al., 2007) and flipped to 06/15 LT for 2006–2007 (not shown). The Andenes diurnal occurrence distribution is relatively stable, whereas at Davis it is more variable with a bimodal distribution. The normalized height–occurrence distributions (Fig. 3c) clearly show that the Davis PMSE peak is 1 km higher than at Andenes (86.3 km at Davis and 85.3 km at Andenes). A comprehensive multi-season inter-hemispheric comparison of the Davis and Andenes PMSE morphology and inter-annual variability is presented elsewhere (see Latteck et al., 2008).

3. Inter-hemispheric mesopause region temperature and meridional wind field

To help understand why we observe an inter-hemispheric difference in the properties of PMSE we compare their seasonal occurrence variation (Fig. 4a) for both hemispheres, with similar height resolution records (70–100 km) of the difference of mesopause temperature and frost point temperature ($T-T_f$) (Fig. 4b) and meridional wind flow (Fig. 4c) following the methodology outlined in a recent SH study by Morris et al. (2007). Firstly, we glean that the seasonal envelopes of PMSE (Fig. 4a) reveal a greater and more persistent occurrence throughout the summer at Andenes, as opposed to the rather patchy occurrence evident at Davis with its mid-January/February diminution in occurrence—the latter appears to be a recurring feature (see Fig. 4a), which reveals an intrinsic property of the SH mesopause region (for all four summer seasons at Davis). Secondly, seasonal envelopes of $T-T_f$ (Fig. 4b) have similar spatiotemporal contours to the respective PMSE envelopes, as highlighted by the black line in Fig. 4a. The similarity in the broad-scale modulation of PMSE and mesopause region thermal characteristics supports current theory (Rapp and Lübken, 2004), as summarised earlier that temperatures below the water–ice frost point are required to create and sustain PMSE. Furthermore, we see a causal linkage between the magnitude and direction of meridional wind flow (Fig. 4c) on the thermal structure of the mesopause region (Fig. 4b), which in turn is reflected in the overarching PMSE envelope (Fig. 4a). Clearly, the envelope bounding the equatorward meridional wind flow or for near-stagnant wind flow corresponds with colder mesosphere conditions and thus PMSE existence. Moreover, during episodic poleward turnings of the meridional wind flow (e.g. near 17 January 2006) we observe a diminution in PMSE occurrence. Also, the ensuing persistent colder temperatures are associated with intervals of enhanced PMSE intensity similar to earlier reports (Morris et al., 2006). The close correspondence between the direction and strength of the meridional winds to the mesospheric temperature was pointed out earlier by Espy et al. (2003).

The volume reflectivity variation of PMSE over the respective summer hemisphere season (Fig. 5a) clearly shows volume reflectivity at Andenes ($\eta_{\text{max}} \sim 1 \times 10^{-12} \text{ m}^{-1}$) to be much greater than at Davis ($\eta_{\text{max}} \sim 8.5 \times 10^{-15} \text{ m}^{-1}$) (consistent with earlier indirect studies by Woodman et al. (1999), and direct comparisons by Hosokawa et al. (2005) and Latteck et al. (2007) using a full season of PMSE observations). Fig. 5a shows 5-day average volume reflectivity values of PMSE to remove the effects of 5-day planetary waves, as discussed by Kirkwood et al. (2002). Considering a height slice near 86–87 km we can see how the mesopause temperature profile (Fig. 5b) is influenced by the magnitude and direction of the meridional wind (Fig. 5c).

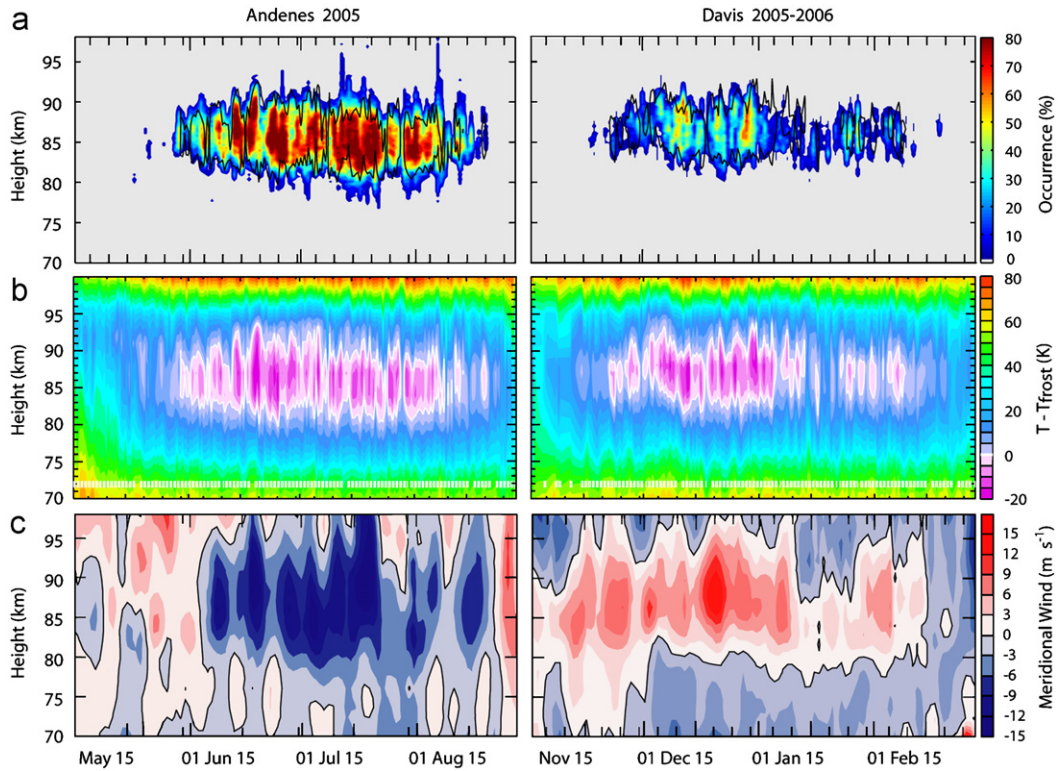


Fig. 4. (a) PMSE height–time occurrence plots for minimum volume reflectivity, $\eta_{\min} = 5 \times 10^{-16} \text{ m}^{-1}$, for the 2005 boreal (left) and 2005–2006 austral (right) summers, at a spatiotemporal resolution of $300 \text{ m} \times 1 \text{ h}$ bins. (b) Difference between observed temperature and the frost point temperature ($T - T_f$) derived from Aura/MLS measurements, gridded uniformly in geometric height and time with 1 km and 1 day spacing, respectively (black contour line in (a)). The times of individual measurements are shown by the white ticks near the time axis. (c) Corresponding meridional wind speeds derived from 2 MHz medium frequency (MF) radars in spaced antenna mode at Andenes (left) and Davis (right). The colour bar shows wind speed in 3 m s^{-1} increments, and poleward flow corresponds to blue or negative values in the NH and red or positive values in the SH.

Persistent PMSE first appear for $T < 146 \text{ K}$ on 17 November at Davis (on 28 May at Andenes), and finally disappear for $T > 146 \text{ K}$ on 13 February at Davis (20 August at Andenes), excluding outlier events. In both hemispheres the start and end of the PMSE season are influenced by the meridional wind sense. The earlier PMSE season start at Davis is linked to persistent pre-season equatorward winds, and the late start to the Andenes season is linked to a late switch of the meridional wind from poleward to equatorward. Similarly, a switching of the winds from equatorward to poleward corresponds with the end of the PMSE season in each hemisphere. Mesopause temperatures of 129 K (Andenes/2005) and 134 K (Davis/2005–2006) occurred at the summer solstice. At the 87 km height slice shown in Fig. 5 the greatest summer difference in PMSE volume reflectivity corresponded with the largest mesopause region temperature difference of $\sim 20 \text{ K}$ between Andenes ($\sim 133 \text{ K}$ /mid-July) and Davis ($\sim 153 \text{ K}$ /mid-January). An analysis of multi-season inter-hemispheric PMSE, ($T - T_f$), and wind field data are now needed to account for possible inter-annual variability.

4. Discussion and conclusions

The reported properties of PMSE observed at Davis (68.6°S) for the austral summer 2005–2006 and Andenes (69.0°N) for the boreal summer 2005 provide only the second inter-hemisphere season comparison of PMSE using these similarly calibrated MST radars. Our results support the earlier findings of Latteck et al. (2007) also using the Davis and Andenes calibrated MST radars, with key hemispheric aspects, whereby SH PMSE (in comparison to NH PMSE) exhibit: a lower occurrence rate (for $\eta_{\min} = 5 \times 10^{-16}$

m^{-1}); a lower volume reflectivity (or strength); more diurnal variability; an $\sim 1 \text{ km}$ higher season average peak height; and similar Davis/Andenes season start (17 November/13 May—both 6 days earlier) and end (19 February/2 September—1/3 days later). A detailed multi-season inter-hemispheric comparison of these basic PMSE properties and inter-annual variability between Davis and Andenes is presented elsewhere (Latteck et al., 2008).

Of importance to the current discussion are the respective PMSE strength or volume reflectivity η and occurrence rates presented above, and as discussed in Section 1 (i.e., Woodman et al., 1999; Morris et al., 2004, 2006, 2007*, Jarvis et al., 2005; Hosokawa et al., 2005; Latteck et al., 2007*; Kirkwood et al., 2007*; S. Kirkwood, personal communication, 2007* [*—denotes calibrated MST radars]). At least for the SH the results from Machu Picchu (63.1°S), Davis (68.6°S), Wasa (73.0°S) and Halley (76.0°S) are fairly consistent if the PMSE strength and occurrence rate increase toward the pole. Moreover, for each high-latitude band it seems that there is a hemispheric asymmetry in the characteristics of PMSE as summarised above for the Davis/Andenes $\sim 69^\circ$ latitude band. These results are consistent with reported PMSE (or proxy) observations from hemispheric pairs of sites—Machu Picchu (62.1°S)/Poker Flat (65.0°N), Syowa (69.0°S)/Iceland (63.8°N), Davis (68.6°S)/Andenes (69.0°N), Wasa (73.0°S)/Kiruna (68.0°N) and Halley (76.0°S)/Poker Flat (65.0°N)—once allowances are made for the respective differences in latitude between the respective hemisphere sites (see Woodman et al., 1999; Hosokawa et al., 2005; Latteck et al., 2007; Kirkwood et al., 2007; Jarvis et al., 2005).

Davis (2005–2006) and Andenes (2005) summer mesosphere temperature profiles revealed temperature difference between the two inter-hemispheric sites in the range 3–7.5 K (Davis/SH

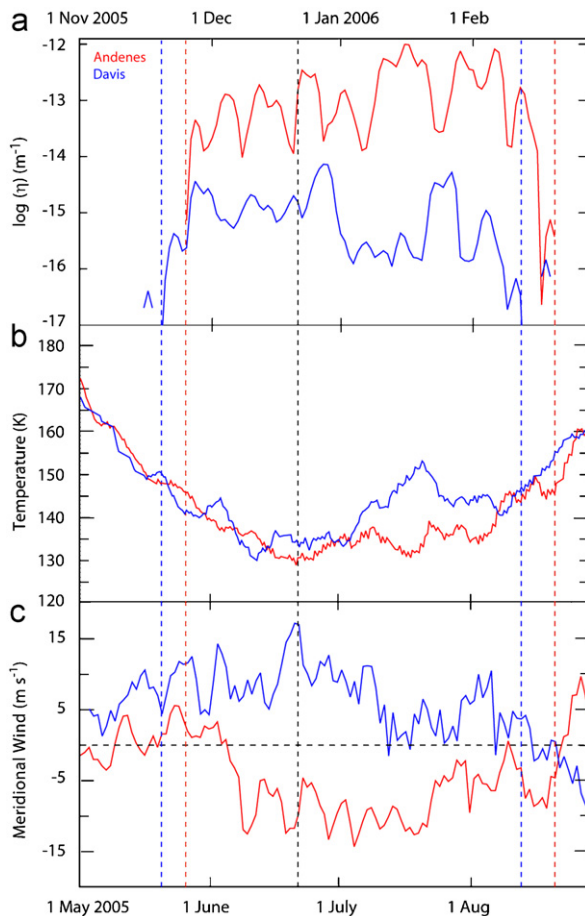


Fig. 5. The time axes relevant to Davis (blue) and Andenes (red) are shown by the horizontal scales at the top and bottom of the figure, respectively. The colour-coded vertical lines show the start and end of the PMSE season, whilst the black dashed line indicates the summer solstices. (a) Seasonal 5-day running mean of PMSE maximum volume reflectivity over all heights. (b) Aura/MLS ($T-T_f$) temperatures. The measurements within 500 km of each site were interpolated to a geometric height of 87 km using the standard hypsometric relation. A 4-day box-car smoothing has been applied. The typical $1-\sigma$ measurement uncertainty of mean individual measurements is ~ 2 K at 87 km. (c) Seasonal meridional winds observed at 86 km height using a 4-day composite day tidal analysis shifted by 1 day.

warmer than Andenes/NH), as derived from Aura Microwave Limb Sounder (MLS) version 2.2 data averaged for conjoining seasons of PMSE observations in both hemispheres. Moreover, seasonal envelopes of $T-T_f$ have remarkably similar spatiotemporal contours to the respective PMSE seasonal envelopes. The similarity in the broad-scale modulation of PMSE and mesopause region thermal characteristics supports current theory (Rapp and Lübken, 2004) that temperatures below the water–ice frost point are required to create and sustain PMSE.

These new findings provide further experimental evidence of a hemispheric asymmetry in mesosphere temperature and the layered ice aerosol phenomena PMSE, which support recent experimental observations (Bailey et al., 2005, 2007; Wrotny and Russell, 2006) and model simulation predictions (Siskind et al., 2003; Hervig and Siskind, 2006) that the SH summer mesopause region is warmer than at the equivalent northern latitude. The reason for the hemispheric differences in mesosphere temperatures as measured from satellites, i.e., Aura (SH warmer by 3–7.5 K) and HALOE (SH warmer by 4–7 K) (Wrotny and Russell, 2006), is the topic of ongoing research. However, two important SH thermal mechanisms are: (i) radia-

tion effects due to the Earth's orbital eccentricity, i.e., closer to the Sun in the austral summer, contributes to an ~ 1 –2 K warming (Siskind et al., 2003), and (ii) atmospheric dynamical effects, i.e., stronger residual zonal wind circulation in the lower stratosphere results in a reduced gravity wave drag in the lower mesosphere and a weaker cooling in the austral summer by ~ 2 –6 K (Siskind et al., 2003). Further quantitative model estimates by Siskind et al. (2003) revealed a larger supersaturation (S = water vapour pressure/saturation vapour pressure) region in the NH (than in the SH), where contours ($S = 1$ –10; for H_2O concentrations of 1–6 ppmv) reach lower heights in the NH (higher in the SH), i.e., similar to the respective PMSE layers.

Furthermore, we have shown a causal linkage between the magnitude and direction of meridional wind flow on the thermal structure of the mesopause region consistent with the findings of Espy et al. (2003) and Morris et al. (2007), which in turn is reflected in the modulation of the overarching PMSE seasonal occurrence volume reflectivity envelope. Additionally we found that the meridional wind has an implicit 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. Also our reported mid-January/February warming at Davis (consistent with Lübken et al. (2004a)) is associated with a significant episodic reduction in the average meridional wind. Moreover, periodogram analyses of Davis PMSE intensity and Aura temperatures by Klekociuk et al. (2008) revealed enhanced wave activity with periods near 2 and 5 days suggesting that planetary waves are also associated with a warming of the late summer SH mesopause region. Both the meridional wind and planetary waves appear to contribute to our reported mid-January/February diminution in PMSE occurrence at Davis.

Interestingly, our PMSE results are consistent with recent findings from an inter-hemispheric comparison of PMC, whereby SH PMC were reported to be less frequent, dimmer, and appear ~ 1 km higher in height compared with NH PMC (e.g. Wrotny and Russell, 2006). In essence the inter-hemispheric asymmetry in properties of both PMSE and PMC can be explained by a similar asymmetry in mesopause temperature (colder in NH). We suggest that the marginal nature of Davis SH PMSE occurrence and volume reflectivity, being nearer to the point of existence relative to their northern counterpart, may provide a more sensitive indicator of the mesopause region condition; in particular, as a proxy for long-term change in mesosphere temperature and water vapour saturation. We suggest that inter-hemispheric comparisons of PMSE properties be conducted using calibrated radars for complete summer seasons. An important challenge for the radar community is to un-ravel the latitudinal profile of PMSE properties, which requires better volume reflectivity statistics than summarised in Section 1. Notwithstanding, a long-term record of PMSE in both hemispheres and the mesosphere condition (i.e. temperature and wind field) is now needed to ascertain the impact of any inter-annual variability on the findings reported in this paper.

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Distributed Active Archive Center (DAAC). J. Whelan and D. Ratcliffe provided assistance with the preparation of the figures.

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