First observations of Southern Hemisphere polar mesosphere winter echoes including conjugate occurrences at ~69°S latitude

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[1] We present the first account of polar mesosphere winter echoes (PMWE) observed from the Southern Hemisphere (SH), using measurements from Davis, Antarctica (68.6°S; 78.0°E). PMWE were observed by mesosphere-stratosphere-troposphere (MST) radar during solar proton events (SPEs) and auroral substorms. We supplement the MST radar measurements with profiles of temperature and turbulent velocity from co-located Rayleigh lidar and medium frequency (MF) radar, respectively, as well as temperature data from the Microwave Limb Sounder (MLS) onboard the Aura satellite. We establish that SH PMWE exhibit similar characteristics to their well-studied northern hemisphere counterpart. Significantly our observations reveal that these radar echoes in the lower mesosphere (~50–80 km) can occur year-round, and on occasions simultaneously in both hemispheres. We report the seasonal occurrence distribution of SH PMWE is linked to the seasonal distribution of atmospheric turbulence in the lower mesosphere. We hypothesise that given sufficient turbulent velocities in the neutral atmosphere and co-located gradients in electron density, PMWE can occur throughout the year. However they are more likely in winter when turbulent velocities in the lower mesosphere maximise.

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1. Introduction

[2] Polar mesosphere winter echoes (PMWE) were identified three decades ago in the NH as enhanced patchy backscatter in VHF radar measurements. Based on observations between ~54°N to 78°N latitude, the general characteristics of PMWE can be summarised as follows: duration minutes to tens of hours; vertical thickness from 300 m to 23 km; height range 50–80 km; diurnal occurrence peaking around local solar noon (daylight) throughout the boreal winter [*Czechowsky et al.*, 1979; *Zeller et al.*, 2006]. PMWE have also been observed using incoherent scatter radar (ISR) [*Kirkwood et al.*, 2006a] and appear closely related to isolated lower mesospheric echoes (ILME) on MF radar [*Hall et al.*, 2006]. PMWE occurrence is correlated with enhancements in electron density primarily following SPEs and auroral substorms [*Kirkwood et al.*, 2006b]. The association with electron density enhancement differentiates PMWE from the more frequently observed polar mesosphere summer echoes (PMSE), which occur with low temperatures (T < 150 K) and the presence of ice-aerosols [*Rapp and Lübken*, 2004] in the summer mesopause region.

[3] A common physical requirement for PMWE (50–80 km) and PMSE (80–96 km) arguably relates to neutral air turbulence associated with atmospheric gravity wave (AGW) breaking in the mesosphere [*Rapp and Lübken*, 2004; *Lübken et al.*, 2006]. *Lübken et al.* [2007] provided convincing evidence to support the turbulence theory of PMWE, whereby the radar echoes occur in regions of neutral air turbulence that have a sufficiently high vertical electron density gradient. *Kirkwood et al.* [2006a] canvassed an alternate infrasound theory, whereby PMWE occur following scatter from highly damped ion-acoustic waves generated by partial reflection of infrasonic waves. *Kirkwood* [2007] argued that infrasound theory cannot be discounted, at least until reported observation of large horizontal velocity within PMWE (e.g., ~220 m s^{-1} for 12 November 2004; *Kirkwood* [2007, Figure 3]), and EISCAT radar evidence for similar large spectral widths both within and above PMWE events, are accounted by turbulence theory. Reanalysis of EISCAT PMWE measurements by *Lübken et al.* [2007] and results from a HF heating experiment by *Kero et al.* [2008] found different spectral widths within PMWE compared with the background. These findings supported turbulence theory.

[4] Here we present the first observations of SH PMWE and compare them with the NH record. We discuss our findings in relation to both turbulence theory and infrasound theory.

2. Experiment

[5] We use data collected from November 2004 to December 2005 using 55 MHz MST radar, ~2 MHz MF radar, and Rayleigh lidar at Davis, Antarctica (68.6°S, 78.0°E). The three instruments are separated by less than 1 km. Technical parameters and data processing techniques utilized for the MST and MF radar observations were reported by *Morris et al.* [2006] and for the lidar by *Klekociuk et al.* [2008].

3. Observations

[6] An ongoing mesospheric winter experiment (60–80 km) was configured on the Davis MST radar from June 2005. Interlaced was an annual summer PMSE experiment (60–99 km) from 1 November to 28 February. Observations revealed PMWE simultaneous with the solar proton events (SPEs) of July, August and September 2005. We then

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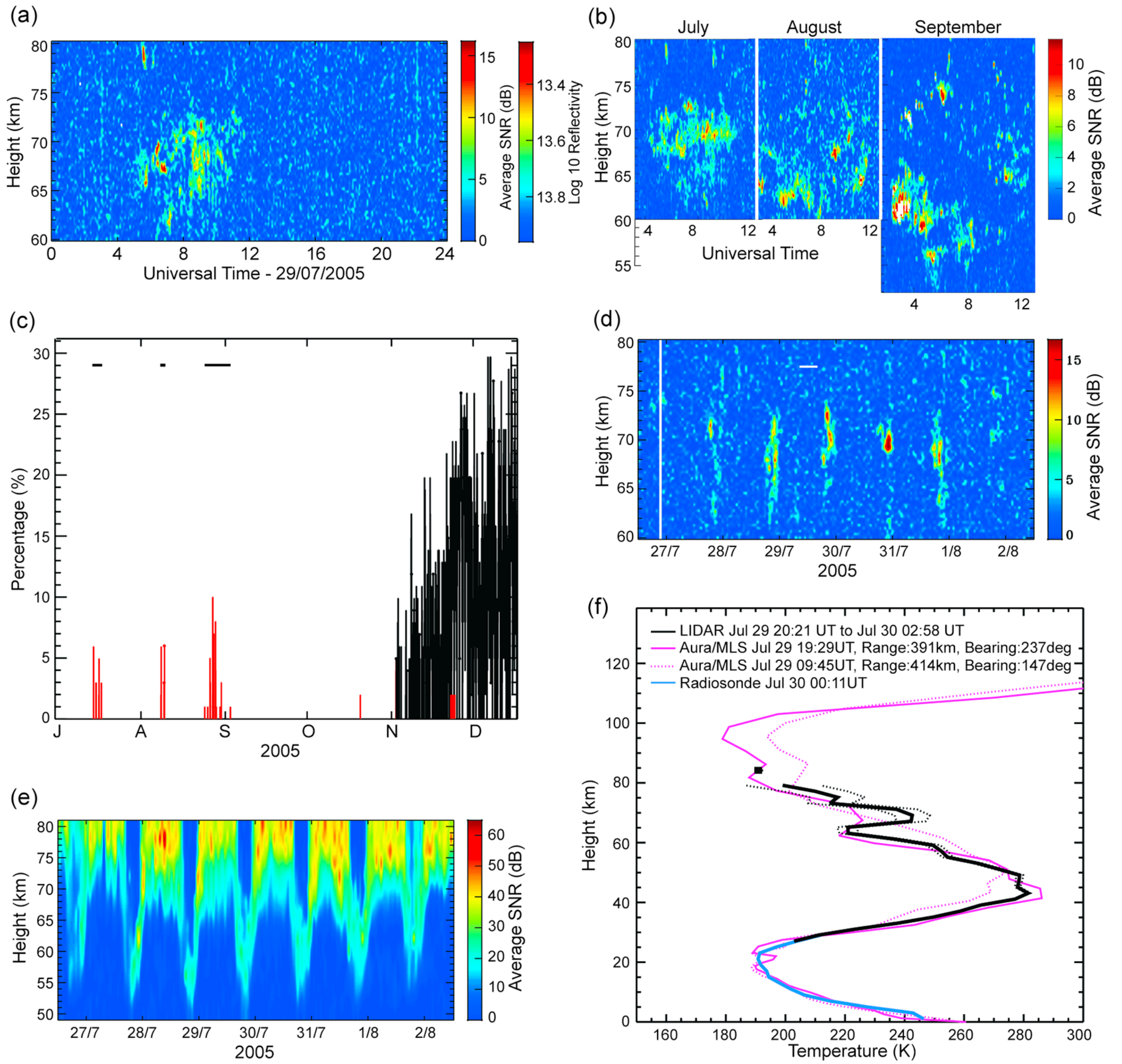

Figure 1. (a) Illustrative height-time signal-to-noise ratio (SNR) plot of PMWE observed at Davis on 29 July 2005. (b) Height variation of composite days hourly averaged SNR plots illustrating PMWE cluster intervals for three SPE intervals (July–September 2005). (c) Time histogram of the percentage occurrence of SNR > 9 dB from July to December 2005 showing days with PMWE (red: 60–78 km) and PMSE (black: 80–99 km). The horizontal bars highlight SPE intervals. (d) Sequence of height-time SNR plots illustrating PMWE observed on MST radar for the SPE from 27 July to 2 August 2005 [white bar corresponds to interval B (see text) shown in Figure 1f]. (e) Coincident hourly averaged height-time SNR plots illustrating ILME (small yellow regions in the downward enhancements below 65 km) observed on MF radar for the above SPE interval. (f) The corresponding Davis lidar temperature profile (black line) for interval B illustrating a temperature inversion centered on 69 km, within the PMWE height range [1-sigma confidence limit envelope (black dotted), MLS temperature (magenta solid and dotted), and Davis radiosonde temperature (blue); the times of the corresponding measurements are shown; the seeding temperature of the lidar retrieval is shown by the solid square, and the upper 5 km of the lidar profile has been removed to allow for convergence].

scrutinized the preceding seven months for evidence of PMWE during the summer PMSE campaign, and for range aliased PMWE within the troposphere experiment from March to June 2005. Revealing additional PMWE during the SPE of November 2004, and January, May and June 2005. Overall, PMWE occurred on 36 days during eight SPE events (see www.swpc.noaa.gov/ftpdir/indices/SPE.txt) and two auroral substorms during our study interval.

[7] Figure 1a presents a signal-to-noise ratio (SNR) height-time plot for 29 July 2005, wherein the patchy nature of the Bragg-scattered PMWE radar echoes is evident in the height range 60–78 km. In Figure 1b, average composite SNR height-time plots are shown for the hours of PMWE

occurrence during three SPE sequences: 4–11 UT for 28 July–1 August; 3–11 UT for 22–24 August, and 2–12 UT for 8–12 September. Figure 1b illustrates that during SPE events, the PMWE height range broadens and the intensity increases progressively toward lower heights (the experiment height range was lowered from 60 km to 52 km in September – third panel). In Figure 1c, we show the seasonal occurrence of PMSE (black, 80–99 km) and PMWE (red, 60–78 km) detected for hourly average Doppler Beam Steering (DBS) data within the height range 60–99 km for SNR > 9 dB (decibels). SPE events are indicated by horizontal bars in Figure 1c. The PMWE events of November–December 2005 occurred during auroral electron density enhancements. This importantly illustrates that PMWE can occur outside of the austral winter. Summer PMWE events occurred in the height range 50–78 km where temperatures were above the frost point as measured from Aura.

[8] We consider the sequence of PMWE observed during the SPE from 27 July to 2 August 2005 to examine the state of the mesosphere and changes in ionospheric electron density in the D-region. Figure 1d shows MST radar time-series images of PMWE SNR in the height range 60–80 km throughout this SPE. Faint PMWE are evident for SPE–d1 (day 1, 27 July) and SPE–d7 (2 August) at higher altitudes ~70–76 km, whilst more intense PMWE (average SNR > 4 dB) were clearly evident for SPE–d2 to SPE–d6 in the altitude range 62–72 km. There is a gradual decrease in the mean altitude of the peak PMWE SNR strength over time (i.e., between SPE–d2 and SPE–d6) suggestive of an overall downward phase progression of an AGW. However, successive daily occurrences of the PMWE suggest that similar mesosphere environment conditions prevailed throughout the SPE. Following *Hall et al.* [2006] we show the coincident hourly averaged SNR backscattered echoes observed on the co-located Davis MF radar in Figure 1e. Interestingly, ILME [*Hall et al.*, 2006] occur simultaneously, albeit at lower heights, with PMWE during the winter months, as illustrated in Figures 1d and 1e.

[9] During this representative SPE, the Davis lidar was in operation for two intervals interleaved between successive daytime bursts of PMWE (A: from 21:18 UT 27 July to 02:11 UT 28 July, and B: from 20:21 UT 29 July to 02:58 UT 30 July) with interval A near the beginning and interval B near the peak of the PMWE activity sequence. Figure 1f presents temperature profiles for interval B, showing lidar-derived temperature (black) with 1-sigma confidence limit (dotted), the coincident Davis radiosonde temperature (blue), and temperature profiles from the Microwave Limb Sounder (MLS) onboard the Aura satellite [*Schwartz et al.*, 2008] for the two closest passes to Davis on 29 July (magenta solid and dotted). A distinct temperature inversion (amplitude 25 K compared with the confidence range of 10 K) is apparent in the lidar profile centred on 69 km, which is seen to a lesser extent by MLS (amplitude 12 K); the inversion has a half width of ~4 km which is similar to the MLS vertical resolution at this height. Inversions of this type have been reported by several authors [e.g., *Duck et al.*, 2001; *Sica et al.*, 2002], who ascribe these features to the action of breaking AGW, and possible interactions with tides. Lidar measurements during interval A show a much less pronounced inversion (amplitude 8 K) centred on 63 km. Note that the lidar measurements do not indicate any enhanced aerosol scatter in the lower mesosphere; the temperature retrieval is made assuming no aerosol scatter, but any such scatter would cause a negative bias compared with the true air temperature. From Figure 1d we see that PMWE observed prior and post interval B also occur in the altitude range 61–74 km. Similarly, other lidar temperature profiles adjacent to PMWE activity also reveal a vertical wave-like perturbations or temperature inversions during winter, suggestive of a dynamical influence at the altitude range of PMWE.

4. Inter-Hemispheric Simultaneous Occurrence of PMWE

[10] Unlike PMSE layers which only occur during the respective summer seasons of each hemisphere, we find that PMWE sometimes occur simultaneously in both hemispheres. Since PMWE observed in the NH winter throughout the SPE of 8–16 November 2004 were reported in the literature [*Kirkwood et al.*, 2006b; *Hall et al.*, 2006; *Kirkwood*, 2007; *Lübken et al.*, 2007], we examined the Davis MST radar record and found that PMWE also occurred, albeit constrained to discrete short duration episodic bursts on 10 and 11 November 2004 in the SH summer. For this interval *Kirkwood et al.* [2006b] reported PMWE intensity to peak at ESRAD (MST radar at Kiruna, 67.9°N; 21.2°E) on the evening of 10 November, although PMWE occurrence was patchy throughout the day in the altitude range 64–78 km (see their Figure 1). Whereas, a discrete 10 minute burst near 78 km at 17 UT was evident simultaneously at Davis. Indeed the peak PMWE intensity at Davis was observed on 11 November ~09:45–10:30 UT as a descending layer 79–78 km, and as two 10 minutes bursts near 66 and 60 km respectively – with layer thickness of 1.2 km (Figure 2a). For this interval a full correlation analyses (FCA) of the Davis MST radar spaced antenna mode data revealed a maximum horizontal velocity of ~30 m s^{-1} (Figure 2b) and turbulent RMS velocity of ~0.35 m s^{-1} [*Holdsworth et al.*, 2001] for this PMWE. *Kirkwood* [2007] reported similar PMWE characteristics for the events observed at Kiruna on 12 November (to those on 10 November) when no coincident PMWE were observed at Davis.

[11] We further illustrate the nature of PMWE occurrence at Davis in the SH summer following relatively intense long duration PMWE in the NH winter – with a second well documented PMWE event – observed during the SPE event of 16–21 January 2005 [*Lübken et al.*, 2006] (their Figure 1 for 20 January). Following the largest of these SPE events (on 20 January) we observed a 15 minute burst of PMWE (~75 km) at Davis on 21 January from 10:30 UT below an intense PMSE layer (83–88 km), and interestingly a 25 minute duration thin layer of PMWE after the SPE interval at 5:20 UT on 28 January 2005, descending parallel to a thin PMSE layer (Figure 2c). For the summer and winter hemisphere, SPE or precipitation induced ionisation in the D-region ionosphere is only part of the PMWE generation process – nonetheless the existence of isolated summer PMWE should provide important insight to their generation mechanism.

[12] Finally, an interesting SH end of winter (Davis) and NH end of summer (Kiruna) simultaneous PMWE sequence was observed on 23 August 2005, whereby their patchy long duration (~10 hours) characteristics were a feature at both

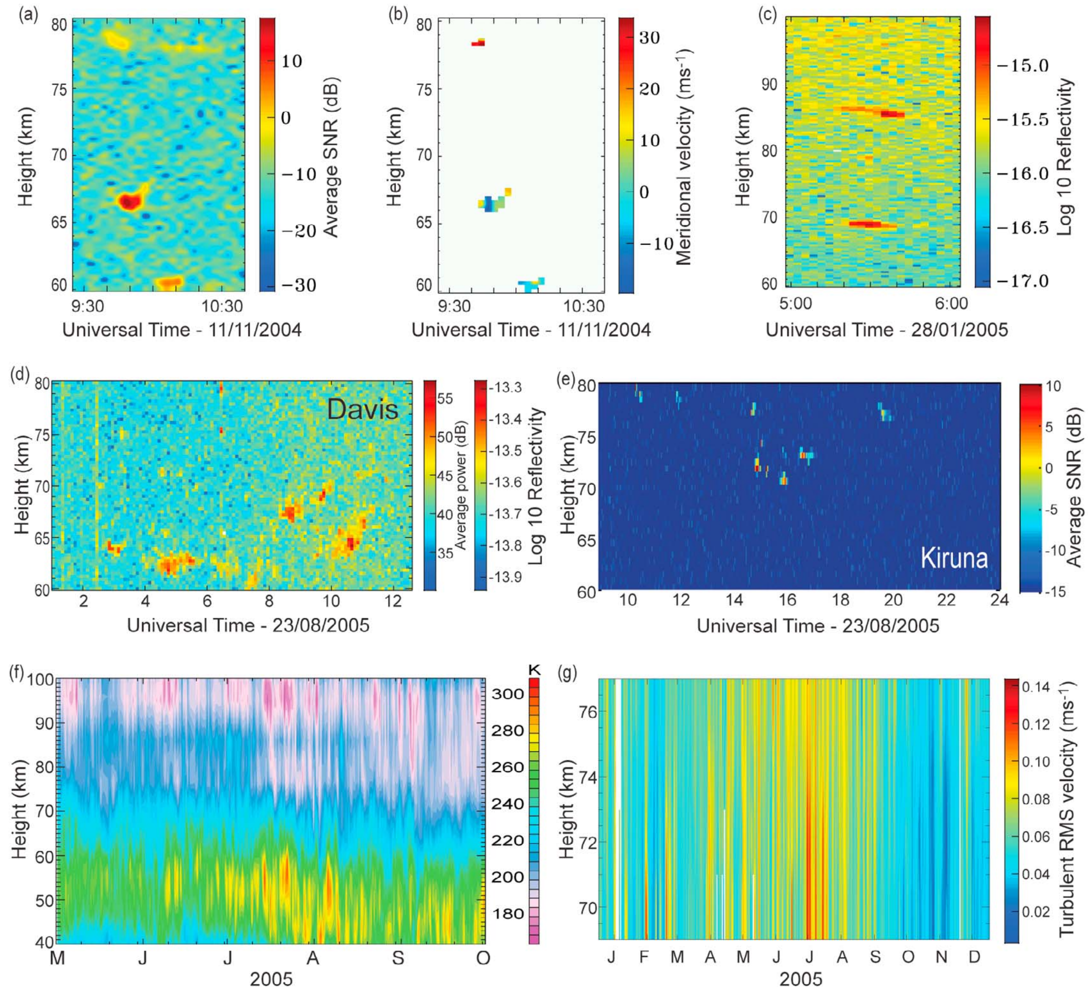

Figure 2. (a) Height-time SNR (dB) plot illustrating PMWE bursts observed at Davis on 11 November 2004 in the height range 60–80 km. (b) Height-time plot of meridional velocity derived from FCA analyses of the PMWE shown in Figure 2a. (c) Height-time volume reflectivity (m^{-1}) plot for simultaneous PMSE and PMWE observed at Davis on 28 January 2005 during the austral summer. (d) Height-time plot illustrating PMWE observed in the SH summer at Davis on 23 August 2005 (average power, dB/volume reflectivity, m^{-1}) simultaneous with (e) height-time SNR plot illustrating PMWE observed in the NH at Kiruna (SNR, dB) albeit displaced in time (S. Kirkwood, personal communication, 2009). (f) Aura MLS version 2.2 temperature measurements within 500 km of Davis interpolated to geometric height using the standard hypsometric relation. The measurements have been corrected for bias (using comparisons with SABER presented by *Schwartz et al.* [2008]). (g) Annual variation of daily averaged MF radar turbulent rms velocity in the height range 69–77 km above Davis.

sites (see Figures 2d and 2e; S. Kirkwood, personal communication, 2009). Noteworthy is the temporal separation (SH 02–12 UT; NH 10–24 UT) and the corresponding altitude difference during the respective peak in intensity (SH 60–70 km; NH 70–75 km), although for the less intense intervals at both sites PMWE extended up to 80 km. Note for this SPE (22–25 August 2005) PMWE were observed at Davis each day, but only on 23 August at Kiruna (near the end of the boreal summer and without PMSE). Although the simultaneous PMWE plots for 23 August have different un-calibrated scales, the winter hemisphere intensity appears to be marginally higher. However, based on SNR levels, winter PMWE are generally of higher intensity in the NH than for the SH, possibly reflecting a hemispheric difference in the mesosphere state. We note that for this PMWE (Figure 2d) the maximum volume reflectivity was $\sim 10^{-13}$ m^{-1} at Davis which lies in the range 10^{-12} to 10^{-15} m^{-1} reported by *Kirkwood* [2007] measured using 50 MHz radar at NH sites.

5. Discussion and Conclusions

[13] Our findings provide experimental evidence that PMWE are common at Davis (68.6°S) during SPE and their intensity (SNR) is less compared with their NH counterpart during winter. Interestingly, PMWE above Davis were observed coincident with ILME [*Hall et al.*, 2006]. Indeed the terminology 'polar mesosphere winter echoes' (PMWE) is a misnomer since they can occur at low latitudes [*Czechowsky et al.*, 1979], in seasons other than winter (this paper), and they are distinct from PMSE. *Hall et al.* [2006] concluded that the apparent lower mesosphere height of ILME was a consequence of overlying absorption in the upper mesosphere during SPE events. Moreover, these

authors attributed the winter occurrence in ILME as being related to the seasonal variation in electron-neutral collision frequency and thus non-deviative absorption in the mesosphere (noting their selection criteria might inhibit ILME detection during summer).

[14] The mechanism for PMWE generation needs to account for our finding that on occasions PMWE are observed to occur simultaneously in both hemispheres. We next consider what this implies in the context of both turbulence theory [*Lübken et al.*, 2006] and infrasound theory [*Kirkwood et al.*, 2006a; *Kirkwood*, 2007].

[15] Figure 2f presents MLS temperatures within 500 km of Davis as a height-time plot spanning four 2005 SPE events (May–September) during the PMWE experiment interval. Clearly mesosphere temperatures within the height range of PMWE (50–80 km) are well above the water-ice frost point temperature, i.e., $180 < T < 290$ K, thus precluding a role for ice-aerosols in their generation process. Following *Holdsworth et al.* [2001] we plot the mesospheric turbulent root-mean-square (rms) velocity estimation for 2005 in the height range 69–77 km (Figure 2g), using a FCA of Davis spaced antenna MF radar data. Figure 2g shows that mesosphere turbulent rms velocity has a broad winter maximum peaking around the winter solstices but with episodic enhancements throughout the summer. The mesosphere turbulent rms velocity distribution follows the plot of PMWE versus month (Figures 1b and 1c). This clearly illustrates a linkage between the seasonal occurrence of PMWE, electron density, and seasonal turbulent rms velocity in this region of the mesosphere. Thus the simultaneous occurrence of PMWE in the non-winter hemisphere is plausibly accounted for by the annual variation in mesosphere turbulence in the altitude range where PMWE are observed, given a confluence with an enhancement in electron density from SPE or auroral precipitation – which is entirely consistent with neutral air turbulence theory.

[16] Contrarily, the Davis PMWE observations present some difficulties for the infrasound theory – specifically our reported low horizontal velocity within PMWE of ~30 m s^{-1} for the 11 November 2004 event and the fact that Doppler spectral widths are high within PMWE compared to the background for this event (not shown). Note that similar characteristics appear common for the Davis PMWE events examined. Furthermore, the infrasound theory proposed by *Kirkwood et al.* [2006a] requires infrasound generation from ocean waves [*Garces et al.*, 2004], and the *Drob et al.* [2003] ray-tracing model requires a north-south source range of <300 km for infrasound ducting at the 50–80 km mesosphere height where PMWE form. However, for the latitude of Davis (68.6°S) the annual winter sea-ice extent (which peaks in September) exceeds this range, and thus ducting of infrasound in to the mesosphere is unlikely at this time. For the Davis summer or when the sea-ice northerly extent is <300 km, and for all seasons at the latitude of Kiruna (67.9°N) or Andenes (69.0°N), since the sea-ice extent never reaches these latitudes (http://nsidc.org/seaice/images/climatology.jpg), infrasound ducting into the mesosphere would still be plausible. The rarity of PMWE during the Davis summer despite large SPE appears inconsistent with infrasound theory, but the theory cannot be ruled out completely.

[17] Finally, we showed that PMWE observed on 55 MHz MST radar occur simultaneously at the same time-of-day, but not necessarily at the same height as ILME observed on 1.94 MHz MF radar at Davis. These radar techniques constrain echo range detection heights depending on the level of non-deviative absorption. Nonetheless, it is plausible that PMWE and ILME are produced by the same physical mechanism (atmospheric turbulence combined with sufficient ionisation) if the scale-size of the irregularities causing them increases with decreasing height. This is in part supported by Figure 2g which shows that the turbulence rms velocity is generally greater at lower heights. Consequently stronger turbulence at lower heights may produce larger scale-size irregularities where ILME are generally observed on MF radar. This hypothesis is supported by the inherent seasonal occurrence distribution of PMWE (and ILME) reported in this paper, as attributed to the seasonal distribution in turbulent velocity (and non-deviative absorption discussed in *Hall et al.*, 2006).

[18] Our inter-hemispheric simultaneous observations of PMWE are significant since they demonstrate that the mechanism of generation, i.e., neutral air turbulence in the presence of enhanced electrons, is the critical criteria for their existence. Moreover, PMWE is a misnomer since they occur at low latitudes and in summer. Although the PMWE terminology is entrenched in the literature, it is prudent to state PMWE are a winter based subset (albeit the most prolific) of a broader class of lower mesosphere echoes.

[19] We conclude that PMWE occur in the SH (68.6°S), with similar characteristics to those reported in the NH, albeit from this first investigation with lower intensity (during winter). Significantly, we reveal PMWE occurrence outside of winter and on occasions simultaneously in both hemispheres, with higher intensity in the winter hemisphere for coincident events. We show that the annual variability in mesospheric turbulent velocity – maximising during winter with a solstice peak, but with episodic bursts in summer – is consistent with turbulence theory to account for PMWE generation in the presence of enhanced electron density from SPE and/or auroral precipitation. Finally we suggest that PMWE are generated by the same combination of phenomena as ILME.

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