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Isolated lower mesospheric echoes seen by medium frequency radar at 70° N, 19° E

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Abstract. We have noted sporadic instances of strong isolated reflections of medium frequency (MF) radar waves from the mesosphere from as low as 50 km altitude and have devised a set of criteria for isolating these apparently anomalous echoes from those normally occurring from progressive partial reflections in the D-region. The object of this study is to map the occurrences of such echoes facilitating comparisons with other observations. For example, the similarity and simultaneity of the echo structure for the 20 January 2005 with VHF radar results presented by Lübken et al. (2006) are particularly striking. In presenting a number of such echo events since 2001 selected from the MF radar dataset (which spans 1997 to present), we find that virtually all echo occurrences coincide with enhanced solar proton fluxes suggesting that substantial ionisation of the mesosphere is a necessary condition. Strong partial reflections of the radio wave in the lower mesosphere combined with seasonally varying total absorption higher up, thus giving false impressions of lower mesospheric layers preferentially in winter, constitute a scenario consistent with our observations.

1 Background

Various instances of radar echoes, particularly at VHF, that are both unusually strong and limited in altitude extent have been reported, and Ecklund and Balsley (1981) have often been credited with the first observations of Polar Mesospheric Summer Echoes (PMSE). Predating this, however, Czechowsky et al. (1979) surveyed mesospheric structures visible at VHF in summer, autumn and winter and, furthermore, from mid-latitude, although these authors did not attempt to differentiate between backscatter or reflection mechanisms. It should come as no surprise therefore that phenomena described as Polar Mesospheric Winter Echoes (PMWE) (e.g. Kirkwood et al., 2002; Belova et al., 2005; Lübken et al., 2006; Zeller et al., 2006) and perennial equatorial mesospheric echoes (e.g. R. Woodman and J. Chau, private communication) should exist. While the reader might be forgiven for asking why we refer to PMSE and PMWE etc., since anomalous echoes seem to appear all year round and at non-polar latitudes, perusal of Lübken et al. (2006) and references therein will quickly reveal that different mechanisms are visualized depending on height, latitude, season and method of observation.

The prime instrument used in this study is the Tromsø medium frequency (MF) radar situated at 70° N, 19° E operating at 2.78 MHz and described in detail by Hall (2001) and, importantly, recently calibrated for altitude by Hall and Husøy (2004). Also important to note for this study are the time and height resolutions of 5 min and 3 km respectively. During early years, prior to unattended operation and automatic wind determination, the system was often used as a diagnostic tool to assist in determining launch conditions for in situ experiments. At the time it was often noted that, over periods of order of hours, there were preferred heights for echo occurrence. This had been studied earlier in New Zealand and Canada in some detail (Gregory, 1961; Manson and Meek, 1989). In contrast to radar echoes at VHF which arise from structures complying with the Bragg condition, at MF progressive partial reflections occur arising from local gradients in electron density until an altitude is reached at which the plasma and radar frequencies are equal and total reflection takes place. While interesting, since the mechanism responsible for refractive index gradients causing partial reflections was not fully understood, the study of echo strength in itself at Tromsø was shelved when the system became primarily used for studying dynamics using the spaced receiver technique. While revisiting the preferred echo height phenomenon, it was noticed that on occasion low altitude echoes

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occurred in which the radio wave was strongly reflected from the lower mesosphere and that no radar returns were perceivable from the usual progressive partial reflections of the wave from irregularities in refractive index as it propagates through the D-region. The presence of such strong echoes below 70 km combined with absence of usable signal above is an unusual condition occurring on only a few days each year. This current study was instigated when we noted that the January 2005 PMWE event reported by Lübken et al. (2006) at VHF coincided exactly with such a low-altitude strong reflection at MF. Apart from determining reflected power, the Tromsø MF radar is able to measure both wind speed (from the motion of the reflected radio wave diffraction pattern on the ground) (Meek, 1980) and rough estimates of turbulent energy dissipation rates (from echo fading times) (Hall et al., 1998). The former are at too low an altitude resolution to be useful for estimation of wind shear and hence Richardson Number (Ri) and furthermore accurate temperatures and their gradients are not available for around 60 km above the radar site, these being necessary for determination of the Brunt-Väisälä frequency also needed for estimation of Ri. Unfortunately, neither can the co-located meteor wind radar (e.g. Hall et al., 2003) obtain intra-day wind and temperature information at such low altitude due to scarcity of meteor trail echoes. Finally, a co-located ionosonde (Hall and Hansen, 2003) is able to provide information on the state of the ionosphere, and, in particular the degree of particle precipitation for most anomalous echo events (although the system was off the air in January 2005).

2 Method

Normally, as discussed above, most of the reflected power received by an MF radar results from progressive partial reflections from horizontally stratified structures in refractive index (a function of electron density at radio frequencies) extending over a Fresnel zone, as the radio wave propagates through the D-region; often, when the E-region is reached, the wave is substantially retarded by the increasing electron density and is ultimately reflected. This propagation of radio waves in an ionized medium is described by the Appleton-Hartree equation and more fully by the Sen-Wyller formulation (e.g. Hargreaves, 1992). If the electron density is sufficiently high, the radio wave may be completely absorbed, a condition which may be detected by checking whether the f_{min} parameter from an ionosonde exceeds the radar frequency – a “blackout” in communications parlance. In order to obtain partial reflections from the mesosphere, there must be sufficient ionization, and this is usually created by insolation. Thus in winter at high latitude, during quiet auroral conditions, we often see a diurnal variation in signal with few or no partial reflections below heights at which the sun has not risen above the shielding ozone limb, while in summer the sun illuminates the mesosphere all the time. A good overview of ionization processes in the D-region (and for that matter above) can also be found in Hargreaves (1992). Given adequate plasma density, created by either auroral precipitation or photo-ionization, partial reflections from as low as 50 km are not uncommon, especially for more modern radar systems than that at Tromsø. Here, however, we describe more seldom isolated reflections from these low altitudes above which the radio wave is completely absorbed by the overlying ionosphere giving the appearance of a layer, as we shall show forthwith. Such echoes from low altitudes (viz. 40–70 km) were thus discerned by applying the following criteria:

(i) very low signal-to-noise ratios (SNR) for radar returns from all altitudes between 70 and 82 km inclusive, indicative of insufficient radio wave power propagating above the lowest echoes; we parameterize this by a failure to determine echo fading times at these heights.

(ii) maximum power in the region up to and including 68 km exceeding the typical echo power for D-region partial reflections under normal circumstances – 40 dB in our case.

(iii) filtering of the data at each altitude to exclude individual 5-min profiles, thus the minimum duration of an echo in order to be selected was 10 min.

The typical background power for the system is around 20 dB, and for cosmetic purposes the signal was set to 21 dB wherever there was deemed to be no anomalous echo. The selection process thus effectively removes all data that normally would yield useful wind and turbulence values in the upper mesosphere and lower thermosphere, and leaves noise and dominant anomalous echoes. The effect of applying the selection criteria to the data of the 20 January 2005 is somewhat spectacular, not least when comparing with the PMWE reported by Lübken et al. (2006). See also Seppälä et al. (2006) for a further description of this period. In Fig. 1, upper panel, the original echoes are shown versus time and height; before 07:00 UT and after 15:00 UT the reflected power can be considered “normal”, with the exception that ionization levels were higher than average giving useful signal during night time; note that typical reflections around 70 km altitude have powers of $\sim$40 dB or more. Between 07:00 UT and 15:00 UT, however there is an absence of signal above 65 km. We then identify these times by very low SNR (identified by a failure to derive fading times/winds) in the region 70–82 km, retain only echo profiles with peaks of 40 dB or more and which persist for 10 min or more as described above, and assign all other (i.e. non-qualifying) times/heights a value of 21 dB (giving an arbitrary purple background in the colour plot). The result is seen in the lower panel of Fig. 1 – these are what we shall refer to as isolated lower mesospheric echoes (hereafter “ILME”, preferring not to be so presumptuous as to refer to it as PMWE).

Table 1. Notable ILME events since 2001.

Date	Description
29 October–6 November 2003	Long occasionally strong sequence
17–28 January 2004	Long moderate sequence
3–5 February 2004	Moderate sequence strongest on 5 February
12–14 February 2004	Long intermittent sequence
10–11 March 2004	Moderate sequence strongest on 11 March
11–12 April 2004	Weak sequence but strong on 11 April
14–15 September 2004	Moderate sequence
8–12 November 2004	Strong sequence
16–21 January 2005	Strong sequence culminating on 20 January
8–18 September 2005	Strong sequence culminating on 14 September

3 A survey of events since 2001

In principle reflected power data are available from the Tromsø MF radar since late 1996. However, at that time the rather ageing tube transmitter was delivering power considerably less than its original specification and in 1998 the system was upgraded with a solid state transmitter. There is evidence for ILME in 1997, but we shall not document it here since the selection parameters need to be tailored to the transmitter power. Other data analysis problems have resulted in incomplete years of searching for ILME, so we restrict our summary of findings to the complete years 2001–2005 inclusive, in this study. In Table 1 we have listed the most striking events during this period; this list is, however not exhaustive: isolated events will have to be examined individually. In particular, we have attempted to document sequences of events in which echoes occur on consecutive days. We can also see that there is a dearth of events during summer, suggesting ILMEs to be winter phenomena. A more complete statistical study of echo occurrence will be required investigating echo height, time of day of occurrence, and states of the background dynamics and ionization. We have selected three entries from Table 1 as examples of ILME sequences, shown in Fig. 2. In all three cases no significant events were seen on previous and successive days. Note that the ILMEs occur during daylight hours (lack of direct sunlight is indicated by hatching in Fig. 2) and that the base of the echoes tends to fall as the sun rises and vice versa. This signature effectively precludes ILMEs being related to layers formed by auroral particle precipitation (but not by solar proton flux). For the 2003 and 2004 sequences we have checked ionograms (not shown) and confirm that enhanced ionization is a feature of daylight hours. There are exceptions to this, however. For the short-lived night-time events in November 2004, we have examined ionograms from the co–located Dynasonde (Sedgemore et al., 1996) (the Tromsø digisonde being inoperative between November 2004 and February 2005). Although we have not made an exhaustive comparison, it is evident that when the MF radar echoes appear, the ionogram "disappears" (i.e. there is total absorption) and vice versa. We do not know, at this time, what has caused these enhancements in electron density. Since this study has a statistical character, we shall not investigate these few events in detail, although it may well transpire that these are related to auroral precipitation. On the 20 January 2005 (top panel of Fig. 2) in particular, we see evidence for the so–called "twilight effect" (Hargreaves and Birch, 2005; Mitra, 1974). Protons impinge on the polar cap all the time, the reason for the diurnal variation in the signal being the nighttime formation of negative ions which deplete the electron population. In this particular case, the evening twilight lasts about 2.5 h – the time from sunset to a solar depression angle of 10 degrees during which negative ions form and assume the night-time state. The twilight effect is presumed to be responsible for the slight shift of echo occurrence with respect to local solar time as seen in a number of plots on closer inspection.

Using GOES spacecraft data (courtesy of the U.S. Dept. of Commerce, NOAA, Space Environment Center) for ILME events at Tromsø between 2001 and 2005 inclusive, and Saskatoon 2005, we have formulated the maps shown in Fig. 3. For each year we show maps of up to 31 days vs. 12 months. Total numbers of hours of ILME are indicated against a background of >1 MeV proton flux. Black pixels indicate days when problems with radar operation occurred. Our selection criterion failed to identify any ILME events during 2001 and 2002, presumably due to interference problems from co-located radars; an inspection of the data on days when the proton flux suggests ILME might be observed has revealed possible problems with the radar (low signal strengths and interference from co-located systems). Further investigation may prove that refined criteria can still recover ILME information during this period. With the exception of 3 February 2004, every day exhibiting ILMEs was associated with a >1 MeV proton flux exceeding $10^7\,\mathrm{cm}^{-2}\,\mathrm{day}^{-1}\,\mathrm{sr}^{-1}$. Since solar proton flux is not exclusively an auroral zone phenomenon, we tentatively compared the 2005 events shown in Fig. 3 with results from the similar

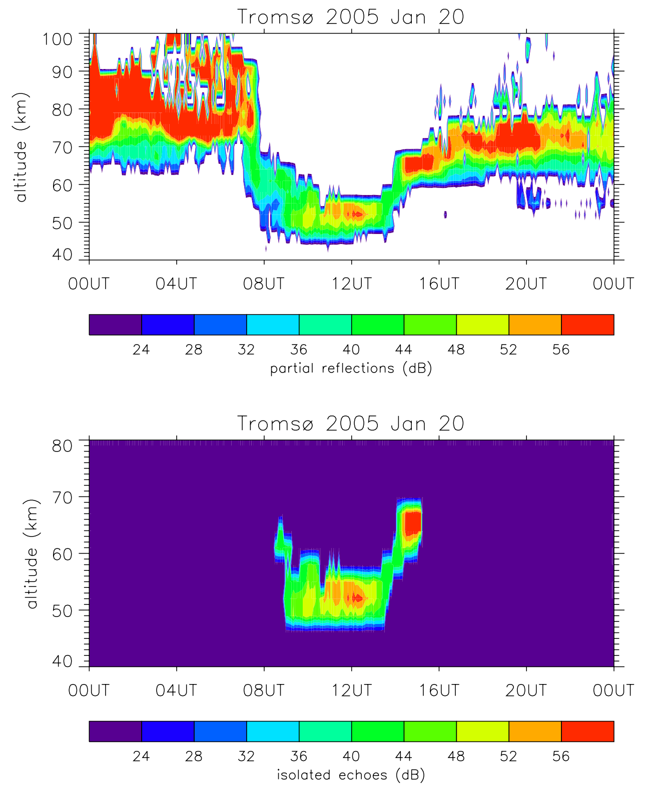

Fig. 1. Tromsø MF radar results for 20 January 2005. Upper panel: echo power (dB) versus time and height; lower panel: isolated mesospheric echoes according to the criteria described in the text.

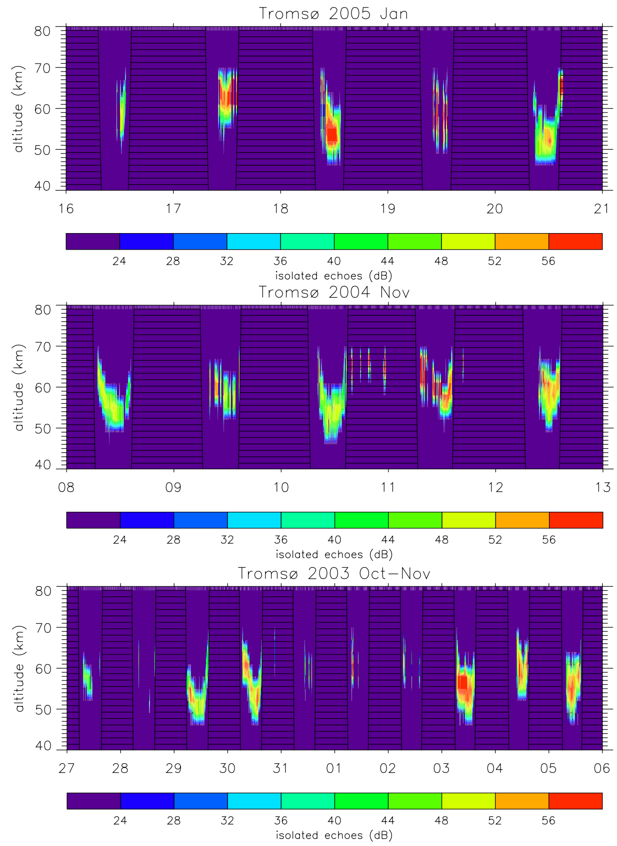

Fig. 2. Three examples of multi-day sequences of isolated lower mesospheric echo occurrence. The horizontally hatched areas indicate when the sun was below the (solid earth) horizon.

MF radars at Saskatoon (52° N) and Platteville (43° N) (e.g. Manson and Meek, 1989). ILMEs were also seen at Saskatoon on 18–21 January, but not September (Fig. 4), and no ILMEs were detected at Platteville whatsoever. Again, it should be stressed that the extension of our investigation to other sites is tentative, although the results hitherto are consistent with ionisation due to proton precipitation being restricted to mid- to high latitude.

A complete survey of PMWE events over the same time interval has not yet been compiled, however Kirkwood et al. (2002), Belova et al. (2005), Zeller et al. (2006) and Lübken et al. (2006) report events on (and around) 30 October 2003, 10 November 2004 and 18–21 January 2005. On each of these occasions we have also observed ILME (see Fig. 3). Similarly Lübken et al. (2006) report an absence of PMWE on 25 and 27 January 2005, again in agreement with our observations.

4 Mechanism

Earlier we described the progressive partial reflection of the MF radio wave as it propagates into the lower ionosphere until total reflection occurs when the radio and plasma frequencies are equal. For ILME to be total reflections, which would explain the lack of signal from above the ILME peak, an electron density of $9.6\times10^{10}\,\mathrm{m^{-3}}$ would be required. During the 2005 event, an order of magnitude less than this was observed at 60 km, and elsewhere in the published literature (e.g. Hargreaves, 1992; Mitra, 1974, and references therein) there is a similar lack of evidence for electron densities sufficiently large to create total reflections in the lower mesosphere.

Accepting, that the echoes at MF must be partial reflections, we turn to the absorption of the radio wave in the height region above the ILME. To a first approximation we shall consider the case of non-deviative absorption since the path though the ionized media in the case of ILME is short compared to, for example to and from the E-region. Moreover, propagation of the radio wave is quasi-longitudinal with respect to the magnetic field at the latitude of Tromsø. Hargreaves (1992) gives the absorption A (dB) along the propagation path x as:

$$A = 4.5 \times 10^{-5} \int \frac{N_e \nu}{(\omega \pm \omega_L)^2 + \nu^2} dx \qquad (1)$$

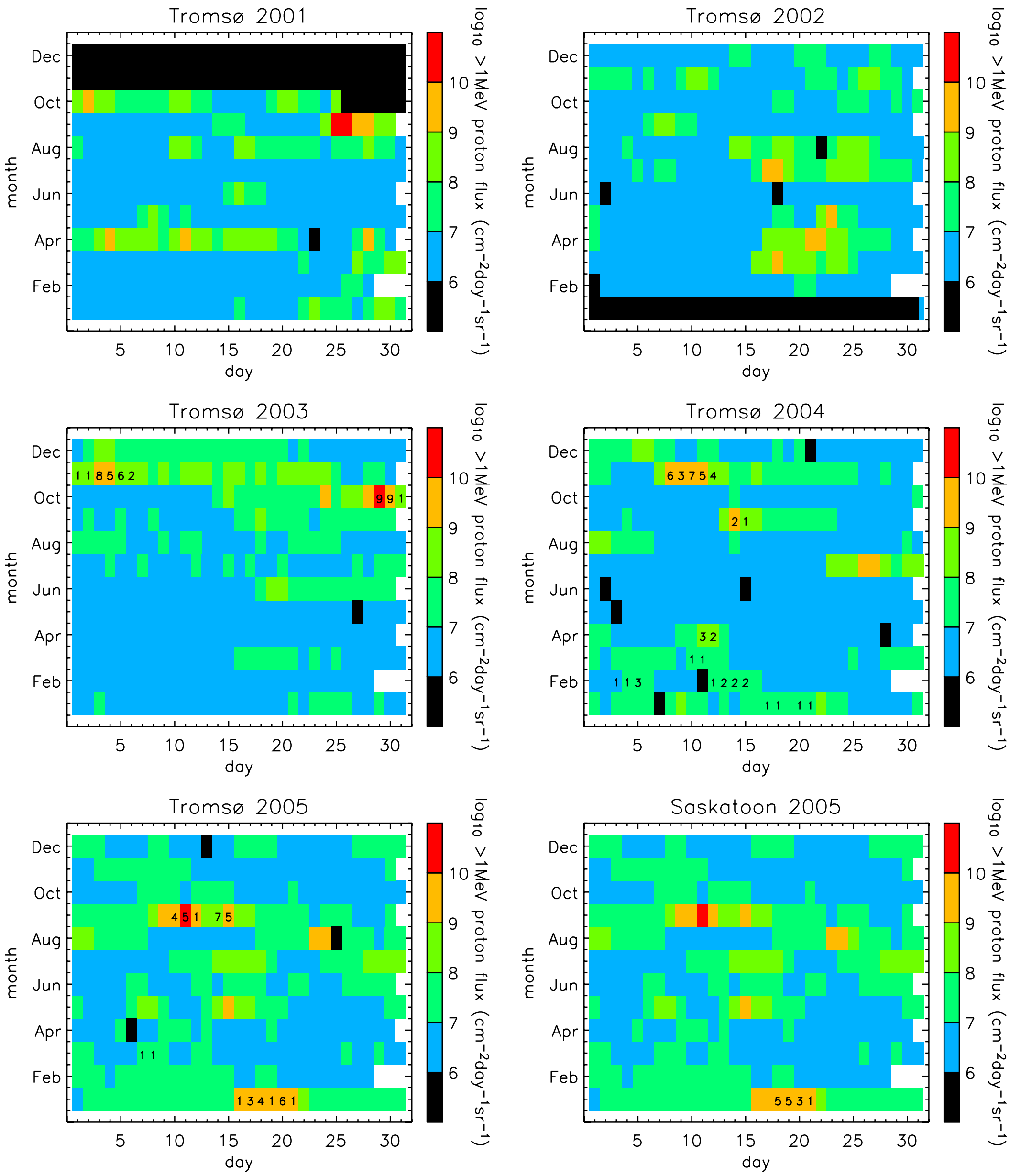

Fig. 3. Yearly tables of month versus day for Tromsø the period 2001-5 inclusive. For days when ILME were detected (by our criteria) the total numbers of hours are indicated. The background colours indicate >1 MeV proton fluxes. Black indicates whenever the Tromsø MF radar experienced operation problems of some kind. The lowest right-hand panel shows the corresponding statistics for Saskatoon 2005.

where N_e is the electron density, ν is the electron-neutral collision frequency, ω is the radar frequency (all SI units), $\omega_L=\Omega_e\cos\theta$ (where Ω_e is the local electron gyro frequency and θ is the angle between the magnetic field and direction of propagation of the radio wave). At 70° N θ is taken to be 12°, the radar beam being vertical, and ω_L is of the order of 10 MHz, which is somewhat larger than the MF radar frequency and not insignificant with respect to the electron-neutral collision frequency.

A cursory examination of Fig. 3 reveals that ILME is essentially a winter phenomenon as mentioned earlier. On the other hand, however, solar proton events are not restricted to any particular season. The clue to this dilemma lies in the seasonal variation of the electron-neutral collision frequency, ν, given by:

$$\nu = 5.4 \times 10^{16} N_n \sqrt{T_e} \quad (2)$$

where N_n is the neutral air number density and T_e is the electron temperature (which can be assumed to be identical to

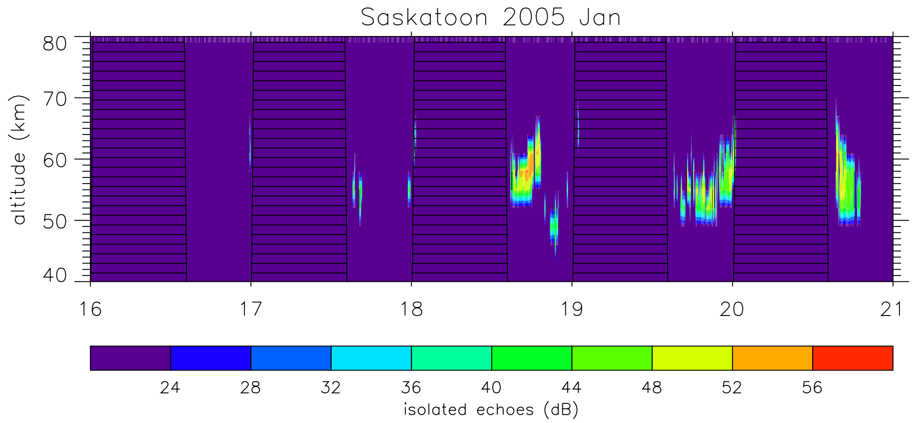

Fig. 4. Sequence (16–21 January 2005) of ILME seen by the Saskatoon MF radar (52° N), corresponding to the upper panel of Fig. 2. Note that the date axis is in UT and corresponds to that in Fig. 2, such that daylight hours occur some 7 h later relative to Tromsø.

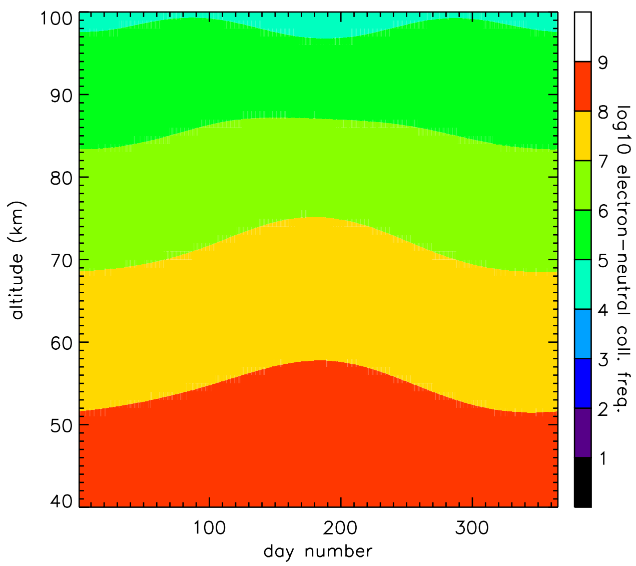

Fig. 5. Electron-neutral collision frequencies as a function of season and altitude, obtained by combining the NRLMSIS-00 model atmosphere (Picone et al., 2002) with expressions found in Brekke (1997).

the neutral temperature in the mesosphere) (Brekke, 1997). Figure 5 demonstrates the variation of ν with season and altitude using number densities and temperatures from the NRLMSIS-00 model (Picone et al., 2002): in the mesosphere there is a clear seasonal variation with maximum in summer, whereas at E-region heights the variation is actually bimodal and relatively flat. If we now take the semi-empirical electron density profiles from Lübken et al. (2006) as typical situations, combine them with the values of ν from Fig. 5 in Eq. (1) and integrate the non-deviative absorption from 50 km to different altitudes (simulating the progressive absorption of the MF radio wave as it propagates through the lowest regions of the ionized medium – in one direction only for simplicity), we arrive at Fig. 6. Disturbed and quiet electron density profiles are shown in the left-hand panel and absorption of a 2.78 MHz radio wave in the right-hand panel. Here we can see that, taking one example, for a radio wave propagating to 64 km during a winter solar proton event, up to 100 dB would be absorbed, against only 50 dB in summer. Thus an electron density structure at 63 km altitude capable giving a radar echo of 60 dB (for example) in the absence of absorption, would, in fact be rendered invisible in winter, yet could remain visible in summer. We have simulated typical MF radar power profiles, increasing monotonically with height in the absence of absorption, by simply dividing the Fig. 6 electron densities by 10^{10} for convenience, such that the echo from 80 km is of the order of 100 dB (an arbitrary value), taking 50 km as the base of the echo for the disturbed case and 70 km as the echo base for the quiet case, and then adding random dBs between 0 and 10 for realism. When we subtract the accumulated absorption for quiet, disturbed summer and disturbed winter cases we see, in Fig. 7 how absorption creates the false appearance of layers in the lower mesosphere. That the electron neutral collision frequency is greater in summer than winter results in less absorption during summer for a given electron density profile. In winter the apparent layer is more restricted in height extent, in our rough simulation with a cutoff at 66 km. In summer the profile extends to around 70 km and could easily be rejected by our criterion for isolated echoes.

Although we have considered results from both Saskatoon and Platteville, we will not show electron neutral collision frequencies for these latitudes. While the seasonal variation is somewhat different, the absorption is also affected by the orientation of the magnetic field to the vertical radar beam and, most importantly, proton precipitation is greatest in the auroral zones.

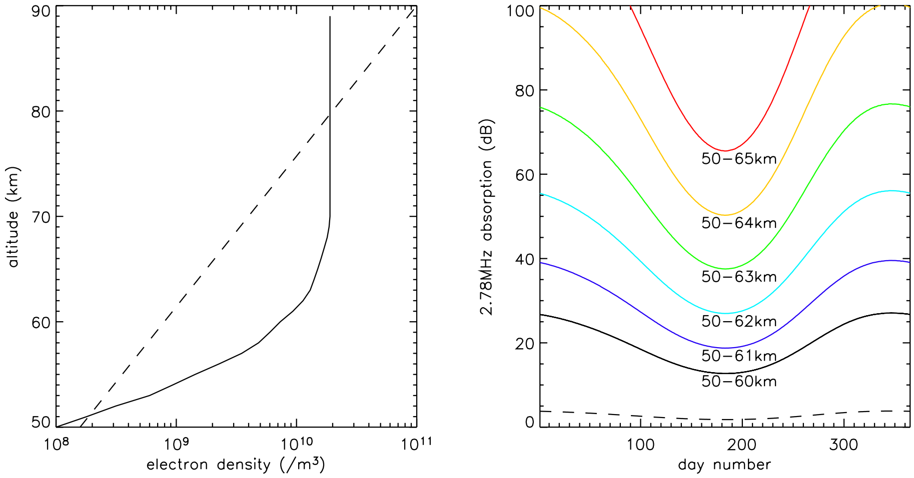

Fig. 6. Left: electron density profiles taken from Lübken et al. (2006) and presented as typical quiet (dashed line) and solar proton event disturbed (solid line). Right: resulting integrated non-deviative absorption as a function of season. Computations for progressively higher upper limits for the integral (Eq. 1) are shown, and with the 50–60 km interval for the quiet situation shown as a dashed line.

5 Conclusions

We have surveyed instances of unusually strong reflection of MF radio waves in the mesosphere from as low as 50 km altitude, which we refer to as isolated lower mesospheric echoes (ILMEs). What constitute "isolated" and "lower" are, to some extent defined by our selection criteria; however, we find that, on occasion, an MF radio wave is strongly partially reflected from the lower mesosphere and subsequently completely absorbed in the upper mesosphere giving the impression of a lower mesospheric layer. The routine analysis of MF radar data in order to obtain upper mesosphere winds can be expected to fail during ILMEs, due to lack of signal and we have used this very characteristic in identifying periods of interest. Checking three ILME sequences lasting several days (Fig. 2), we note a diurnal effect indicative of photoionization and/or proton precipitation, this being supported by examination of sequences of ionograms over the same period. Comparing with proton flux data from GOES spacecraft, we ascertain that ILMEs of at least 1–2 h day^{-1} duration are almost invariably associated with winter enhanced proton precipitation. These conditions are consistent with the background ionisation conditions for PMWE, deduced by Belova et al. (2005) and Lübken et al. (2006), although any relation to background turbulence (Lübken, 1996) has yet to be investigated. The review by Zeller et al. (2006) is arguably the best illustration of the degree of agreement between PMWE and ILME occurrence. While further study is required to establish patterns in occurrence with respect to altitude, latitude, season, and background dynamics and ionisation, accumulated observations to date show that ILMEs are winter phenomena. This is explained by the seasonal variation in electron neutral collision frequency and therefore non-deviative absorption in the mesosphere. During solar proton events more absorption in the mid- and upper-mesosphere in winter creates a false impression of a lower mesospheric layer, whereas in summer the echoes are distributed over a larger altitude range.

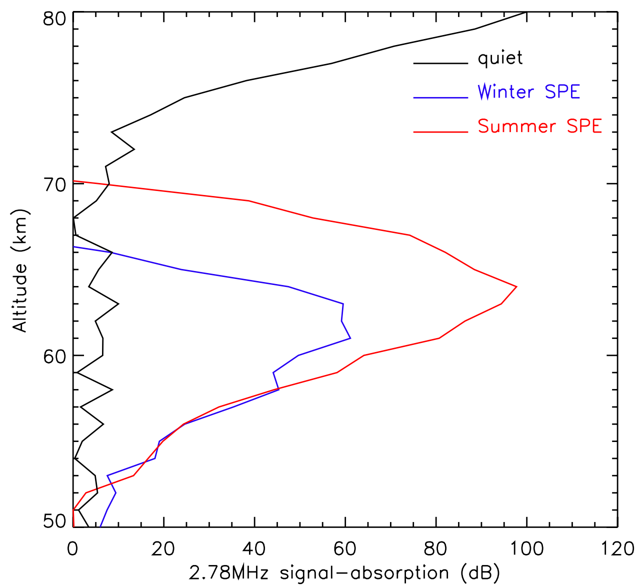

Fig. 7. Schematic illustrating conceivable profiles of MF radar returns. The black solid line shows a power profile from a quiet ionosphere with no non-deviative absorption present. The red and blue lines indicate echo power from the same electron density profile during a solar proton event (SPE), but with summer and winter non-deviative absorption taken into account.

We find that ILMEs seen by MF radars are closely related to the PMWE seen by VHF radars, at least in space and time, with solar proton events as a common factor. However, the mechanism for the echoes at MF is one of strong partial reflections combined with an overlying total absorption of the radio wave giving a false impression of a low-lying mesospheric layer, and therefore differs from the volume scatter seen at VHF due to the order of magnitude difference in wavelength.

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