Polar Mesosphere Winter Echoes
- by ESRAD, EISCAT and lidar

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Abstract

The ESRAD 52 MHz MST radar (67° 53 ‘ N, 21 ° 06 ‘ E) has observed thin layers of enhanced radar echoes in the winter mesosphere during several recent solar proton events. The detection of these polar mesosphere winter echoes (PMWE) is generally found to correlates well with low values of λ (the ratio of negative ion density to electron density). However PMWE are found to persist for values of λ up to ~100. Present knowledge of the nature of neutral turbulence in the winter mesosphere suggests that such turbulence cannot generate electron density fluctuations with scale-sizes as short as the 3 m needed to produce radar echoes at 52 MHz. This is particularly true as λ increases to ~100. Joint observations from ESRAD and the EISCAT 224 MHz radar suggest that PMWE is also detectable at 67 cm scale-sizes, further increasing the difficulty in explaining the echoes by neutral turbulence. Joint observations from ESRAD and lidar are also inconsistent with the expected behaviour of turbulence. Together with results concerning the thickness, echo aspect-sensitivity and echo spectral-width of the PMWE, these observation leads to the conclusion that the layers cannot be explained by turbulence alone. A role for charged aerosols in creating PMWE is proposed. The presence of aerosols is supported by the lidar observations.

Introduction

Thin layers of enhanced radar echoes in the winter mesosphere have been observed by the ESRAD 52 MHz MST radar (67° 53 ‘ N, 21 ° 06 ‘ E) during several recent solar proton events. These have been named Polar Mesosphere Winter Echoes, PMWE (Kirkwood et al., 2002). The second-top panels of Figures 1 and 2 show PMWE from November 2000 and April 2001 and the top panels show corresponding solar proton fluxes recorded by the geostationary GOES satellites. An energy deposition / ion-chemical model (Kirkwood and Osepian, 1995) was used to calculate electron and ion densities caused by the incoming protons. In Figures 1 and 2, the panel second from the bottom shows the modelled electron densities and the bottom panel the ratio of negative ion density to electron density (λ). All of the ESRAD PMWE observations during the winter 2000/2001 have been reported in detail in Kirwood et al., 2002. However, the two examples in Figures 1 and 2 are sufficient to illustrate the main results of that study. PMWE were detected for a wide range of solar proton fluxes, from the GOES proton detection limit of about 0.2 protons $cm^{-2}s^{-1}sr^{-1}$ to levels reaching almost 10^4 protons $cm^{-2}s^{-1}sr^{-1}$. PMWE could be detected at any time of day or night above 70 km altitude, whereas below this height they were seen only during daytime.. The narrowest PMWE were as narrow or narrower (full width at half maximum echo power) than the 300 m resolution of the radar measurements. When the radar echoes were strong enough for spectral information to be derived they were found to have narrow spectral widths corresponding to very small turbulent rms velocities (as small as 0.2 ms^{-1}). They showed substantial anisotropy (irregularity length/height ratio about 12). The PMWE occurrence over the whole winter was found to correlate well with low values of λ, which occur only during daytime at altitudes below about 70 km. A sharp cut-off in PMWE occurrence was found at $\lambda \sim 10^2$, independent of electron density . No direct dependence of PMWE occurrence on electron density could be found within the range represented by the model calculations for the detectable solar proton events, with PMWE being observed at all levels of electron density corresponding to values of $\lambda \sim 10^2$.

Enhanced radar echoes in winter at mesospheric heights have been reported previously by two other high-latitude radars operating at about the same frequency (the Poker Flat radar, reported in Ecklund and Balsley, 1981 , Balsley et al., 1983, and the mobile SOUSY radar at Andöya, reported by Czechowsky et al. ,1989). Although it was noted in both cases that daytime conditions and some extra ionisation source seemed to be needed before the layers could be seen, no systematic study of these dependencies was possible. The enhanced radar echoes were assumed to be due to layers of neutral turbulence which, in the presence of normal or precipitation-enhanced electron densities, are expected to produce fluctuations in radar refractive index.

The characteristics of wintertime, mesospheric turbulence layers have been studied by Lübken et al (1993, 1997) , through a succession of sounding rocket experiments. The turbulent layers found by Lübken (1997) were generally a few km thick, much more than the <300 m observed for many PMWE. Typical turbulent velocities implied by the rocket experiments reported by Lübken (1997) were ca 1-2 ms^{-1}. This is close to the values found for the relatively thick PMWE seen in November 2000 (Figure 1) but much more than found for the very thin PMWE in April 2001 (Figure 2). As mentioned above, the anisotropy found in PMWE is rather high so that, if PMWE are due to turbulence, that turbulence must be highly anisotropic.

However, the major problem in explaining PMWE by the turbulent-layer hypothesis arises when we consider Lübken et al's (1993) results regarding their direct observations of the inner scale of turbulence in wintertime turbulent layers. This is illustrated by Figure 3. For scale sizes smaller than a few tens of meters, the turbulence is sharply attenuated. With only positive ions and ion masses close to those of the main neutral molecules, fluctuations in ion and electron density will have close to the same scale-size distribution as the neutral air density (Kelley et al., 1987). This will be the case for daytime conditions, with roughly equal numbers of positive ions and electrons in the mesosphere. This means that there should be very little amplitude in turbulrnt fluctuations at 3 m scale size (the size needed to produce radar echoes at the ESRAD radar or the other radars referred to above).

Further, when negative ions are present, the diffusivity of the electrons is effectively increased by a factor $(1+ \lambda)$ (Hill, 1978) and the shortest-scale fluctuations in neutral and ion densities should no longer be present in the electron density. We observe PMWE at values of λ up to about 100. According to Driscoll and Kennedy (1985) this should put the 'inner scale size' for electron-density fluctuations at about 10 times more than for neutral density. This is far above the 3 m to which the ESRAD radar is sensitive. This is illustrated also in Figure 3.

A similar mismatch between the inner scale of turbulent fluctuations and the scale-sizes needed to give radar echoes is found for polar mesosphere summer echoes. The only reasonable way to increase the electron Schmidt number and extend turbulence-produced electron-density fluctuations to short enough scale sizes is thought to be through the presence of heavy, charged aerosols (as reviewed by Cho and Röttger, 1997). Our observations of PMWE at times when no negative ions are present might then similarly be explained by the presence of charged aerosols, if those increase the Schmidt number to about 100. The disappearance of PMWE at $\lambda \sim 100$ could then be explained by the increased electron diffusivity causing a reduction of the Schmidt number to about 1, at which point the inner-scale size of the electron density fluctuations should increase to above the radar half-wavelength (3 m). Alternatively, if aerosols are present in a positive-ion / electron plasma they may scavenge electrons and form layers of negatively charged aerosols and 'bite-outs' in the electron density profile (as at the summer mesopause, Croskey et al., 2001, Havnes et al., 2001). Once large numbers of negative ions become available, they can be captured by aerosols in a similar way to electrons. Capture rates are expected to be proportional to the number flux of the charged particles N x C, where N is the number density of charged particles and C is their mean thermal velocity (Natanson, 1960). The ratio of capture rates for negative ions and electrons, R , is then:

$$R \propto \lambda C_-/C_e = \lambda (m_e/m_-)^{1/2}$$

where m_e and m_- are the masses of electron and negative ions, respectively.
Assuming that the main negative ions are O_2^-, CO_3^- and NO_3^- , this gives

$$R \propto \lambda\, (0.3\text{-}0.4) \times 10^{-2}$$

Thus $\lambda=3 \times 10^2$, about the value we find to correspond to the cut-off for PMWE occurrence, corresponds to the situation when electrons and negative ions have equal capture rates. For higher values of λ , aerosols should preferentially scavenge negative ions leading to a negative-ion 'bite-out' rather than an electron 'bite-out'. This would not cause enhanced radar echoes since the echoes require a gradient in electron density, not a gradient in ion density.

While proposing presence of aerosols at the summer mesopause is not controversial (they are readily observed in the form noctilucent clouds), proposing aerosols in the winter mesosphere certainly needs further evidence. Here we report two further observations which lend support to this proposal.

PMWE observation with the EISCAT 224 MHz radar

The EISCAT VHF radar located near Tromsö in northern Norway is sensitive to irregularities in refractive index at scale-size 67 cm. This is further beyond the turbulent 'cut-off' in Figure 3. If PMWE were observed with this radar it would provide a more stringent test that neutral turbulence is unlikely be responsible for the radar echoes.

On 4 November 1997, a solar proton event was in progress and the ESRAD radar detected a moderately strong, narrow PMWE. The EISCAT VHF radar was operating a routine observation programme measuring radar returns from heights 70 km and upwards with a height resolution of 1.05 km. The observations from the two radars are shown in Figure 4. Whereas ESRAD sees only a single, thin (coherent) echoing layer (PMWE), EISCAT sees also incoherent-scatter from the ionospheric plasma. This makes for substantial differences between the two panels in Figure 4. However, there is a thin layer seen at times at about 72 km altitude in the EISCAT data which corresponds closely with the PMWE seen at ESRAD. Figure 5 plots altitude profiles close to 10 UT when the feature is strongest at both radars. Considering that the radars are 200 km apart, the coincidence is remarkable. However, further observations will be needed before we can be sure that this is not pure chance.

Enhanced lidar backscatter observation with the Bonn University lidar at Esrange.

If the aerosols suggested to be responsible for PMWE are sufficiently large they will scatter light and may be detectable by lidar. From the heights of interest, lidar returns are generally weak and only the direct, Rayleigh-scattered light can be measured. The scatter depends on the molecular density of the air and on any aerosols that might be present in the scattering volume. The two contributions cannot, a priori, be separated. The normal assumption for the winter mesosphere is that there are no aerosols. The form of the lidar profile of backscatter vs. height is assumed to be determined by the height profile of molecular density which, in turn, is determined by the temperature profile. So, the lidar backscatter profile is used to determine the temperature profile and deviations from a smooth height variation in backscatter become waves in the temperature profile.

On 12 and 13 January 2002 we were fortunate to be able to obtain several hours of high-quality lidar measurements during a solar proton event. The ESRAD PMWE observations for this period are shown in the upper panel in Figure 6. Lidar data were obtained during the 10-hour period between the vertical black lines marked on the ESRAD data panel. As the radar echoes are seen mostly during daytime and the lidar provides it's best-quality data at night, there is only a small overlap between PMWE and the lidar interval. The normal analysis of the lidar profiles indicated an unusually large temperature minimum at about 72 km altitude. Between 65 and 72 km, the temperature decreases by about 40 K, rising again by about 25 K by 78 km altitude. The temperature gradient in the lower part at almost the adiabatic lapse rate (i.e. the region is close to thermally unstable). An alternative analysis of the lidar data is shown in the lower panel of Figure 6. Now the temperature profile is (in effect) assumed to be smooth, without the sharp minimum described above, and the measured backscatter is interpreted as an enhancement due to aerosols over and above what is to be expected from molecular scatter alone.

Clearly, the anomalous feature in the night-time lidar data, whether it be interpreted as a temperature minimum or a backscatter maximum, is coincident in height with the PMWE seen during the previous and subsequent daytime intervals. This coincidence requires an explanation. One possibility to be considered is that PMWE are due to turbulent layers caused by gravity-wave breaking. Such waves are more likely to break in the less-stable part of the temperature profile, i.e. in the lower half of the anomaly seen in the lidar profile, if the latter is due to a temperature minimum. However, clearly the PMWE is as common or more common in the upper (more stable) part of the supposed temperature structure. This is not consistent with expectations. The second possibility is that the lidar indeed has detected a weak aerosol layer. According to our discussion above, this is fully consistent with the requirements for PMWE.

Conclusions

Evidence is growing that there are significant amounts of aerosol, gathered into layers, present in the winter mesosphere, at least during solar proton events. This represents a considerable challenge to previously accepted ideas regarding the composition and chemistry of the atmosphere both regarding how such aerosols can form and what role they might play in, for example, heterogeneous reactions. This also presents a problem for interpretation of Rayleigh-lidar and similar data which depend on the assumption of an aerosol-free mesosphere.

Acknowledgements

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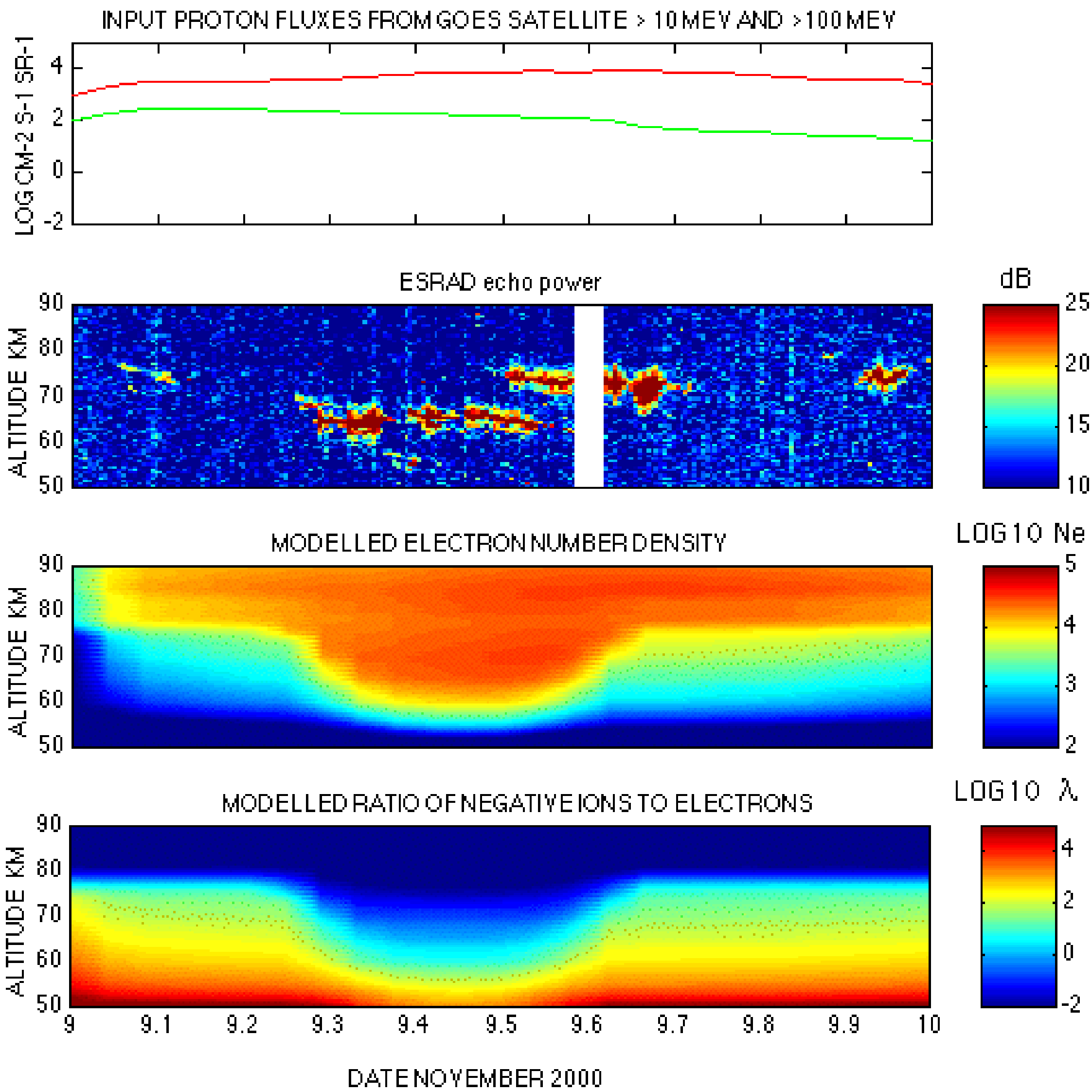

Figure 1. Observations and model results for 9 November 2000. Top panel : Solar proton fluxes from GOES 10 satellite) 2nd panel :. Echo power recorded by the ESRAD radar (colour scale dB) 3rd panel : modelled electron densities of electrons Colour scale shows $\log_{10}$ of the density in cm^{-3}. 4th panel : modelled ratio of negaitive ion densities to electron densities Colour scale shows $\log_{10}$ of the ratio.

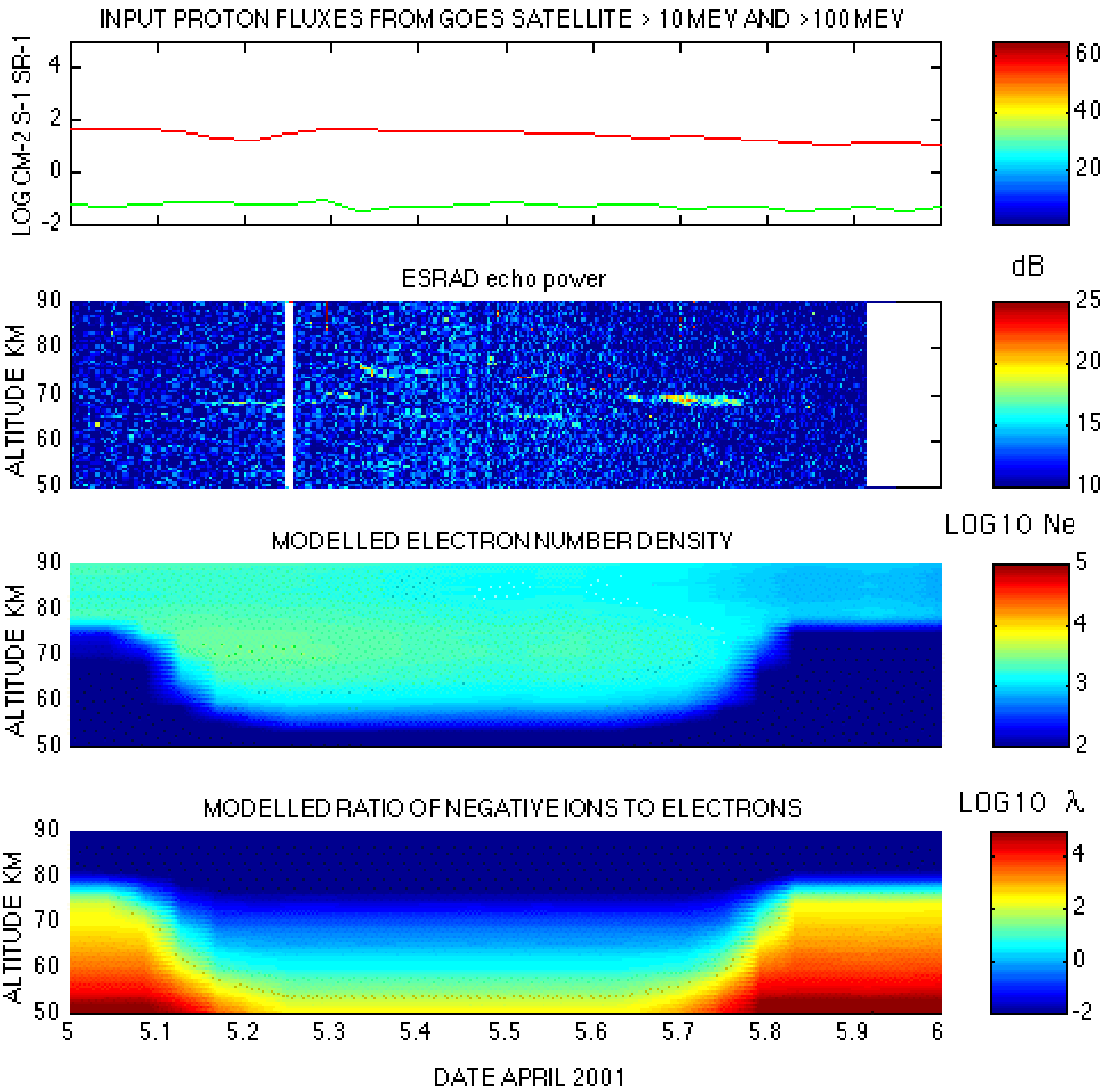

Figure 2. Observations and model results for 5 April 2001. Top panel : Solar proton fluxes from GOES 10 satellite) 2 nd panel :. Echo power recorded by the ESRAD radar (colour scale dB) 3rd panel : modelled electron densities of electrons Colour scale shows $\log_{10}$ of the density in cm^{-3}. 4th panel : modelled ratio of negaitive ion densities to electron densities Colour scale shows $\log_{10}$ of the ratio.

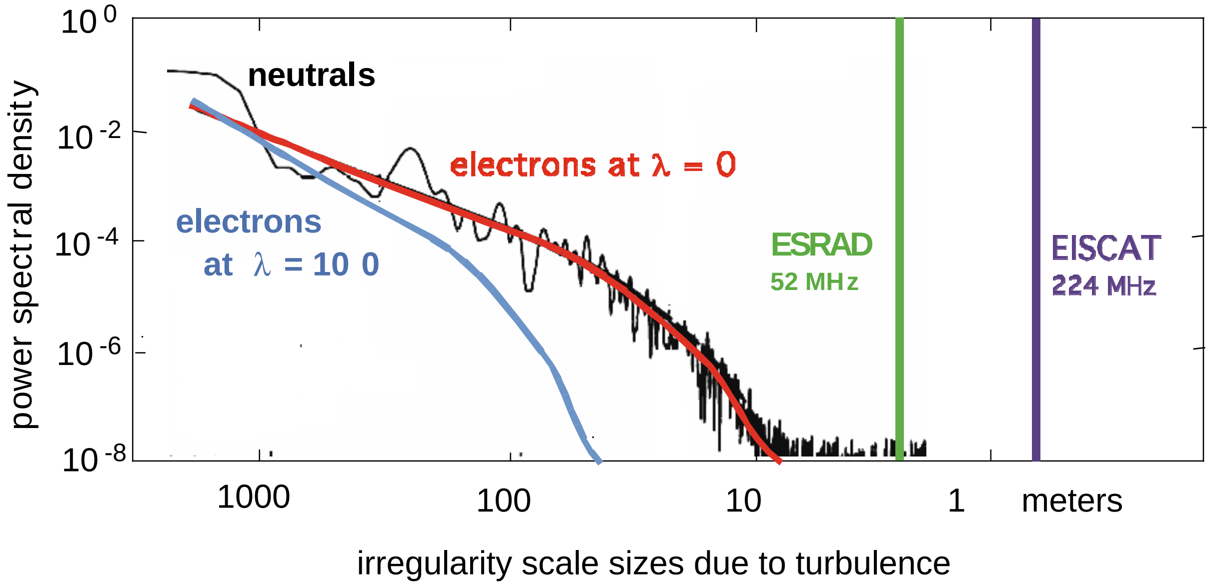

Figure 3. Scale-size spectrum of irregularities in wintertime, mesospheric turbulent layers. Black : typical spectrum of neutral density fluctuations measured by Lübken et al., 1993. Corresponding spectra of electron density fluctuations for $\lambda = 0$ (red) and $\lambda = 100$ (light blue). Green : scale size which can be detected by ESRAD 52 MHz radar. Dark Blue : scale size which can be detected by EISCAT 224 MHz radar.

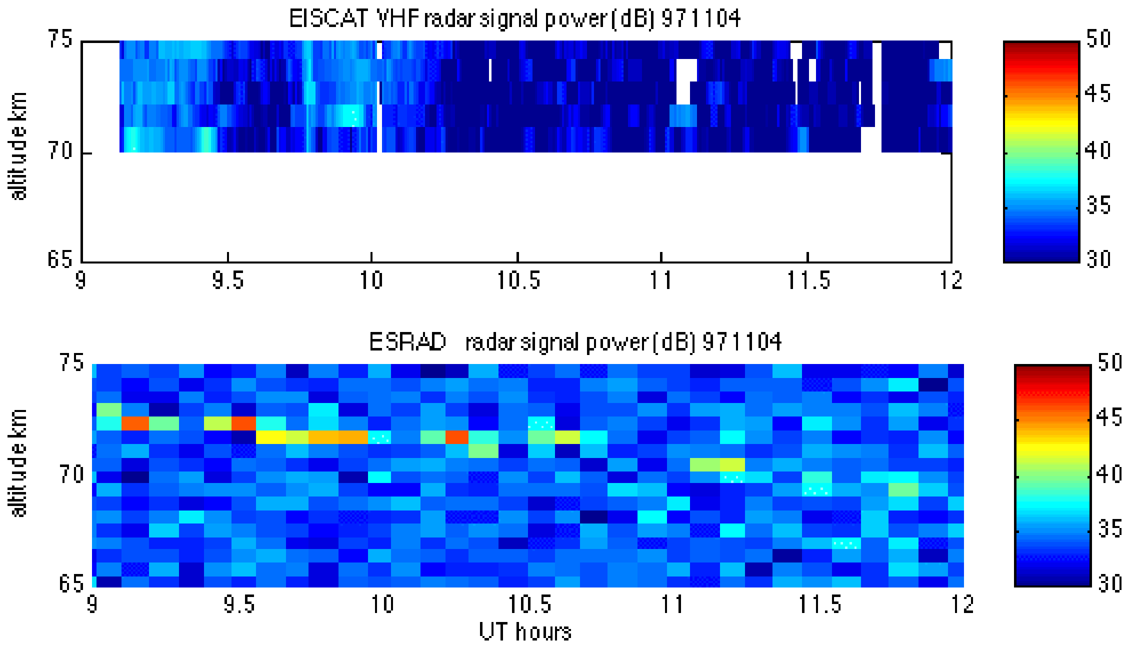

Figure 4. Received echo power at two different radars during a solar proton event on 4 November 1997.(data between 09 UT and 12 UT). Upper panel is from the EISCAT 224 MHz radar, lower panel the ESRAD 52 MHz radar.

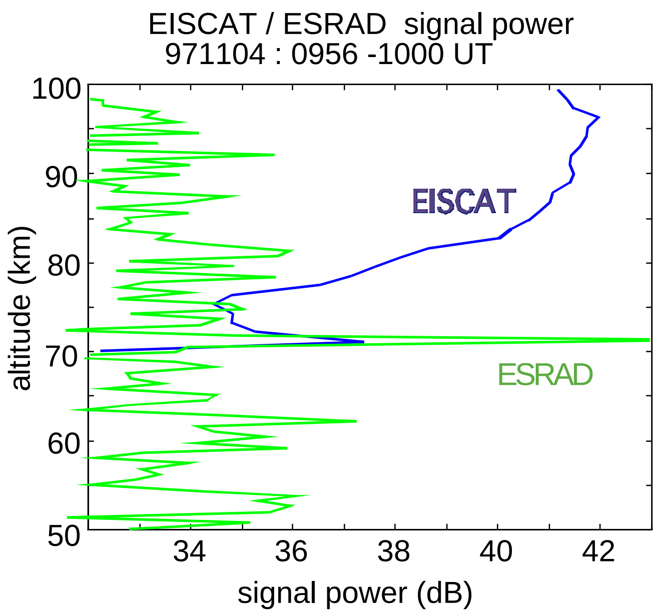

Figure 5. Received echo power at two different radars during a solar proton event on 4 November 1997.(average between 0954 UT and 10 UT). Blue line is from the EISCAT 224 MHz radar, green line the ESRAD 52 MHz radar.

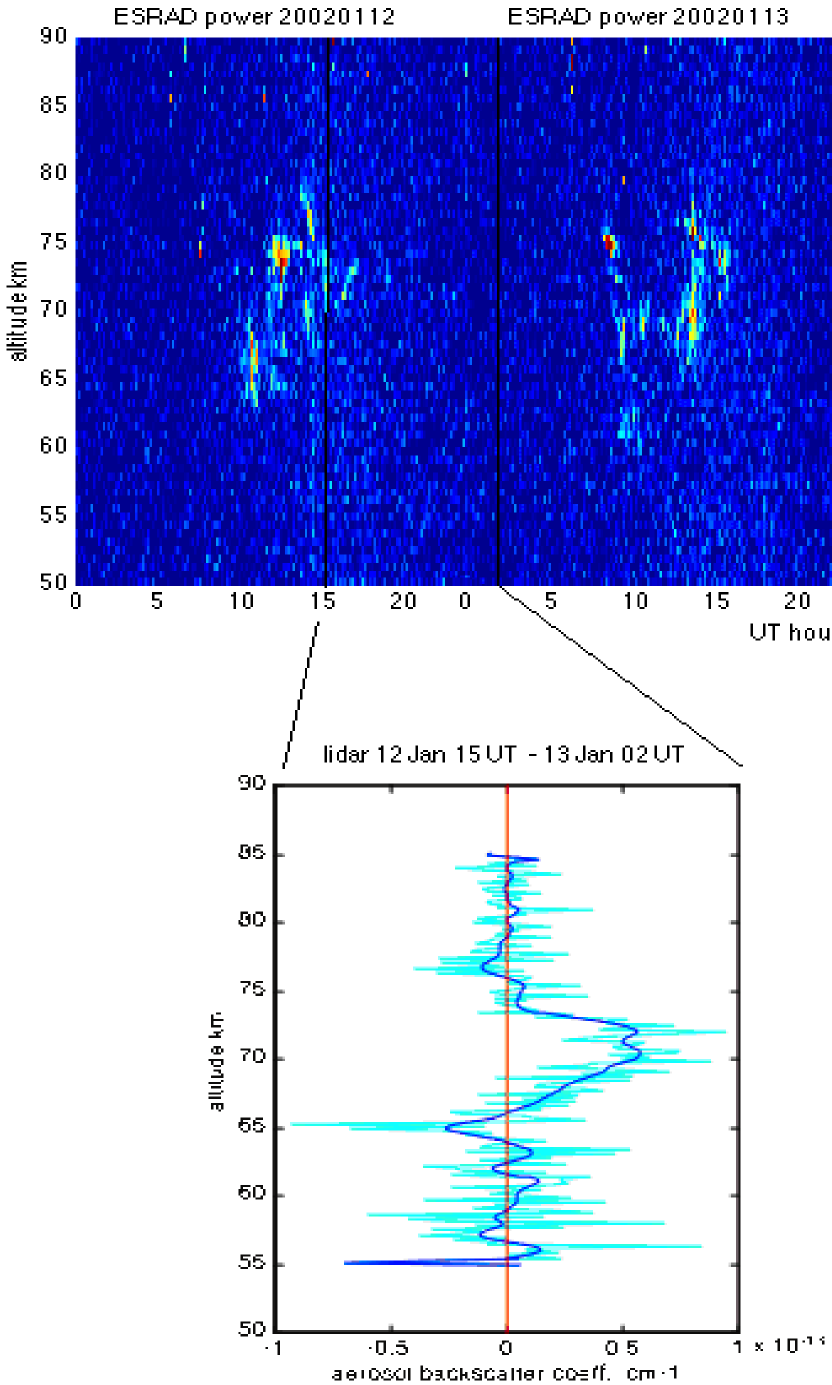

Figure 6. Upper panel : PMWE observed by the ESRAD 52 MHz radar during a solar proton event in January 2002. Data shown is for two consecutive UT days, 12 and 13 January. Black vertical lines indicate the start and end of the lidar observations integrated to produce the result in the lower panel. Lower panel : lidar backscatter ratio under the assumption of a minimum-free temperature profile (see text for details).