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Observations of polar mesosphere summer echoes at EISCAT during summer 1991

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Abstract. Polar mesosphere summer echoes (PMSE) have been observed with the European incoherent scatter (EISCAT) VHF radar operating on 224 MHz during summer 1991. The mean height of PMSE was about 85 km during daytime and about 87 km during nighttime, with a markedly enhanced frequency of occurrence during daytime. The occurrence frequency of PMSE is higher during geomagnetically quiet periods than during disturbed periods. There are indications of a PMSE modulation by vertical velocities, which may be caused by atmospheric gravity waves. Comparisons of PMSE structures detected with the EISCAT VHF radar on 224 MHz and the Cornell University portable radio interferometer, which was operated at the same time on 46.9 MHz, demonstrate some common features when operated collocated but marked differences when operated at a distance of some 126 km.

1. Introduction

Polar mesosphere summer echoes (PMSE) have been observed with radar measurements near 50 MHz [*Ecklund and Balsley*, 1981; *Czechowsky et al.*, 1989], on 224 MHz [*Hoppe et al.*, 1988], and in the UHF band on 933 MHz [*Röttger et al.*, 1990], as well as 1.29 GHz [*Cho et al.*, 1992a]. Such strong radar echoes are mainly detected at polar latitudes although also at midlatitudes there are indications of similar structures [*Reid et al.*, 1989; *Thomas et al.*, 1992]. The PMSE phenomenon shows a clear seasonal variation. According to the early observations with the 50-MHz radar at Poker Flat, Alaska [*Ecklund and Balsley*, 1981; *Balsley and Garello*, 1985], as well as measurements with the Sounding System (SOUSY) VHF (53.5 MHz) radar at Andoya, Norway [*Czechowsky et al.*, 1989], PMSE are normally restricted to the summer period between the middle of May and the middle of August. In the southern hemisphere PMSE have not been detected yet [*Balsley et al.*, 1993].

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The causes of the PMSE are not yet obvious in detail. If one would assume standard turbulence scattering theory [*Hocking*, 1985], the irregularities necessary for scattering of radar waves on 224 MHz from the mesopause region should be in the viscous subrange of the neutral turbulence spectrum. Therefore strong radar backscatter should be impossible, and we must find another scattering mechanism. Heavy water cluster ions [*Kelley et al.*, 1987], large charged aerosols [*Cho et al.*, 1992b], or small ice particles [*Klostermeyer*, 1994], however, should shift the turbulence-driven spectrum of irregularities in the electron density to considerably shorter scales than those of the neutral turbulence itself. As these cluster ions, aerosols, or ice particles favorably occur near the cold polar summer mesopause region, they are assumed to play an important role in the PMSE phenomenon, at least in the VHF range (Bragg wavelength for backscatter 5.0–0.5 m). In the UHF range (0.5–0.05 m) enhanced Thomson scatter may be possible [*Havnes et al.*, 1990], whereas in the medium frequency and lower part of the high-frequency range (corresponding to about 50 m Bragg wavelength) partial reflections could also be taken into account. A detailed review of observations and theories of PMSE is given by *Cho and Kelley* [1993] as well as *Röttger* [1994].

In this paper PMSE results of summer 1991 are presented, using mainly observations with the EISCAT VHF radar and including some data obtained from the Cornell University portable radio interferometer (CUPRI) radar. The EISCAT VHF radar near Tromsø (69.6°N, 19.2°E), Norway, is monostatic

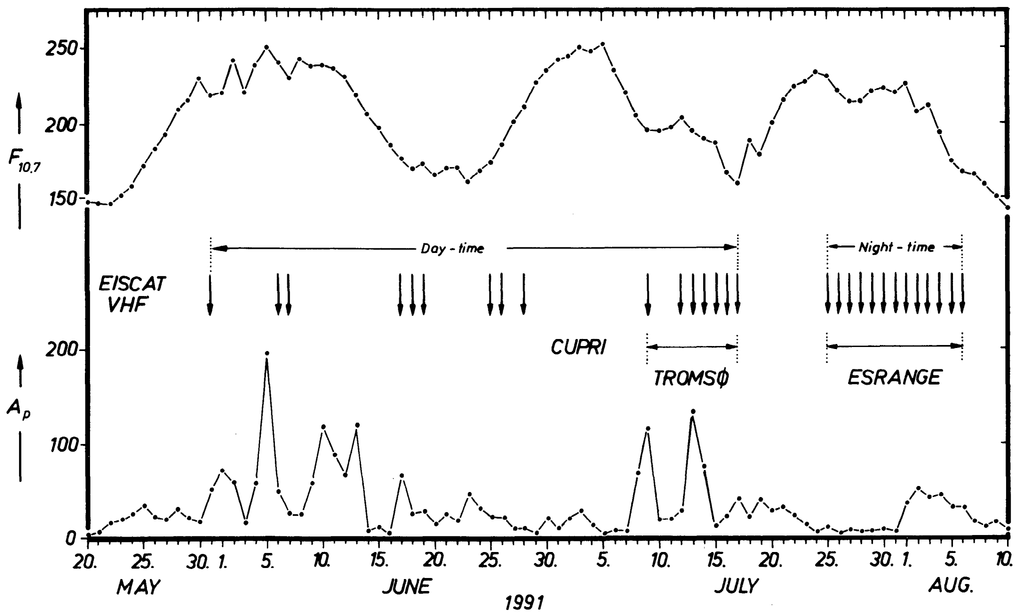

Figure 1. List of EISCAT VHF radar observations (224 MHz at Tromsø, Norway) and CUPRI radar measurements (46.9 MHz at Tromsø, Norway, and at Esrange, Sweden) during summer 1991 together with variations of solar 10.7-cm radio flux and of geomagnetic *Ap* index.

with a cylindrical paraboloid antenna (120 m × 40 m). It runs at 1.5 MW peak power on 224 MHz. During the PMSE campaign in summer 1991 the radar was operated with the pulse-to-pulse program SP-EI-CC6D7-V2, applying 64-bit complementary code and coherent integration over 29.85 ms. This is a radar code optimized for investigations of the mesosphere and mesopause region (72 to 96 km altitude) with a vertical height resolution of 300 m and a time resolution of 2 s (for other technical details of this radar code see *Wannberg* [1991]).

During these EISCAT operations the CUPRI radar was also run, part of the time at the EISCAT radar site at Tromsø and part of the time at Esrange, (68.5°N, 18.3°E) Sweden, about 126 km southeast of Tromsø. The CUPRI radar was operated at 20–30 kW peak power on 46.9 MHz with a coaxial collinear antenna. The height resolution of 300 m of CUPRI was similar to the resolution of the EISCAT VHF radar. A more complete technical description of the CUPRI equipment is given by *Swartz et al.* [1993].

2. Experimental Results

The EISCAT observations have been carried out in Tromsø, Norway, for 16 days (in time periods of 2–7 hours around local noon) between May 31 and July 17, 1991, as well as during 12 nights (in general, 2200–0400 UT) between July 25 and August 6, 1991. The time restrictions of these operations result from the fact that the EISCAT high-power radar is available only over limited time periods. We had chosen these to match in an optimum way to the requirements of the availability of the CUPRI radar in Tromsø and EISCAT-determined scheduling, as well as to the scheduling of operations for the NLC-91 campaign [*Swartz et al.*, 1993]. During this interval the solar 10.7-cm flux was relatively high ($F_{10.7}$ = 150, $\cdots$, 250 × 10^{-22} W m^{-2} Hz^{-1}), and individual days with high and low geomagnetic activity occurred, represented by the daily mean geomagnetic index A_p. In Figure 1 we show the summary of EISCAT and CUPRI operation days, the solar flux, and the daily geomagnetic index A_p. We have investigated the PMSE characteristics during these periods and also their potential relation to variations of the Earth's magnetic field.

Height Distribution

The mean occurrence frequency of PMSE as function of height was derived stepwise for chosen values of the signal-to-noise ratio (SNR) of the EISCAT VHF radar measurements. In these anal-

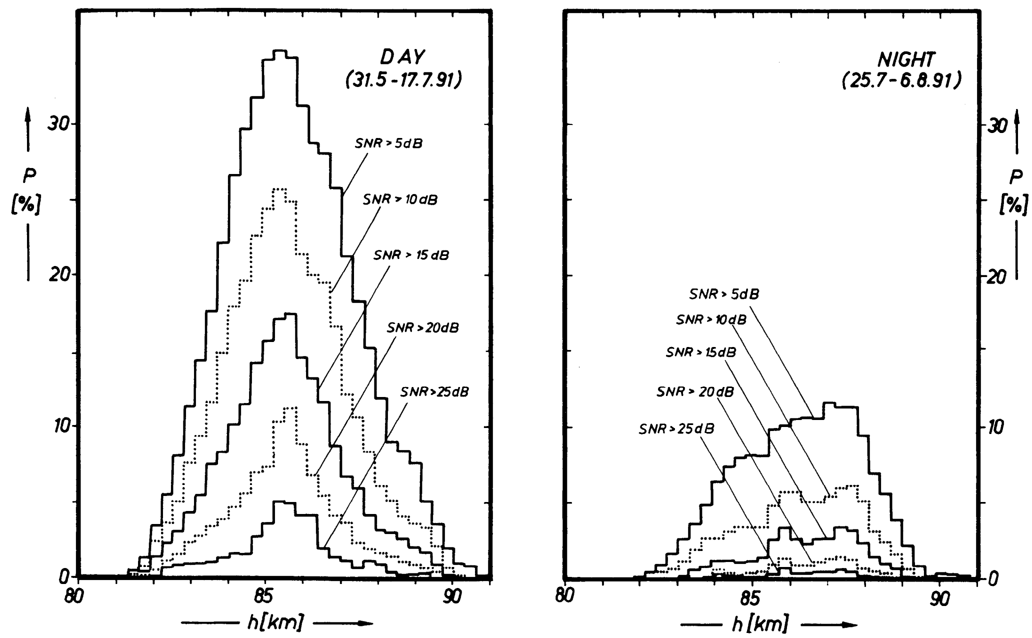

Figure 2. Occurrence frequency of PMSE in dependence on altitude deduced from EISCAT radar observations on 224 MHz during summer 1991 for different signal-to-noise ratios (SNR) during daytime and nighttime conditions.

yses we refer to signal-to-noise ratio, since we are interested only in relative changes of PMSE and their occurrence. *Röttger and La Hoz* [1990] have given the absolute estimates of scatter cross section or radar reflectivity of PMSE. We accept that SNR = 10 dB corresponds to a radar reflectivity of 2×10^{-17} m^{-1}.

The results of our analyses are shown separately in Figure 2 for daytime and for nighttime. Whereas the PMSE height distribution of occurrence during daytime is relatively symmetrical, with a maximum near 85 km, the distribution during nighttime is broader and unsymmetrical, with maximum values near 86.0–87.5 km. The gradient in the nighttime distribution is steeper on the topside than on the bottomside. In dependence on the SNR level, PMSE are more often observed during daytime than at night by a factor of 3 to 7. These results are generally consistent with those obtained for 224 MHz of *Hoppe et al.* [1988] and *Jones et al.* [1989] but provide more details.

Relation of PMSE to Geomagnetic Activity

A short-term correspondence of PMSE power and magnetic field variations was reported for an event analyzed by *Rishbeth et al.* [1988], but *Röttger et al.* [1990] did not find such a relation. Here we study the statistical relation for all PMSE events with geomagnetic variability. The dependence of PMSE occurrence during the observation periods in summer 1991 on geomagnetic activity is shown in Figure 3. Here we deduced the PMSE occurrence between heights of 80 to 90 km and time intervals between 2 and 4 hours. P = 100% means that PMSE above the SNR level (given in the Figure) had been observed in all range gates between 80 and 90 km during the selected time interval. Since we have separated the PMSE data into intervals of 2–4 hours, it is suitable to use the 3-hourly K index, which describes the local geomagnetic activity. We used the 3-hourly K indices of Tromsø for the corresponding periods of PMSE observations. We chose these local indices instead of the global daily geomagnetic activity values A_p because these values are more applicable to describe the geomagnetic disturbance level at the EISCAT radar near Tromsø during short-term intervals of 2–4 hours. The upper panel of Figure 3 shows the results of this analysis for the daytime observations; in the middle panel nighttime values have been chosen, and in the lower panel both data sets are combined.

Here we used different SNR thresholds for day-

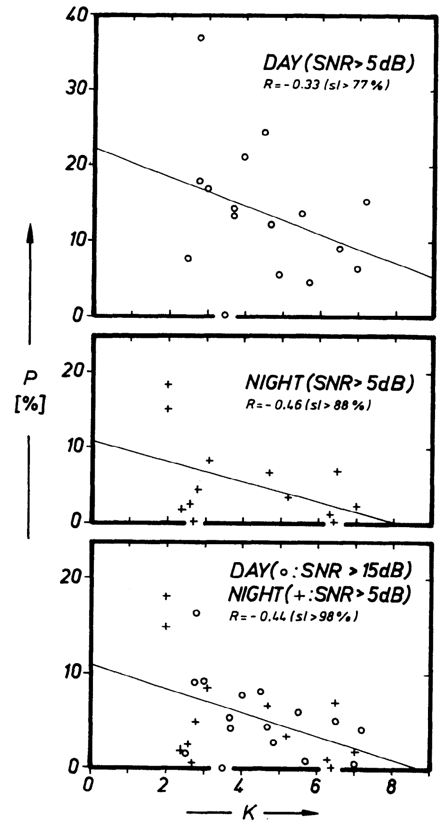

Figure 3. Correlation of PMSE occurrence in the height interval 80–90 km derived from EISCAT VHF radar observations and geomagnetic activity (deduced for each measuring interval during daytime or nighttime from geomagnetic K values of Tromsø).

time and for nighttime PMSE observations by normalizing the daytime and the nighttime distributions of Figure 2. The threshold of 5 dB for nighttime corresponds to the threshold of 16.5 dB for daytime. We observed PSME in most measuring intervals. During just 1 day (July 17, 1991) we did not detect PMSE. During some nighttime observations echoes were so weak that most of them did not exceed the threshold of 5 dB. This resulted in the low occurrence around 0.5%. All results shown in Figure 3 indicate a negative correlation between PMSE occurrence and geomagnetic activity. A sufficient significance level $sl > 95\%$ is only obtained for daytime data (upper panel of Figure 3) and for the combined data (lower panel of Figure 3). When using the data of the combined set we subdivided the PMSE height range into two regions, below and above the height of maximum PMSE occurrence at 86 km. The correlation of PMSE occurrence with geomagnetic activity for both regions is again negative. In the lower range (81–86 km) it is markedly more pronounced (with correlation coefficient $R = -0.40$) than in the upper range (86–91 km), where the correlation coefficient is -0.19. Summarizing, we note that PMSE occurrence in summer 1991 was statistically higher during magnetically quiet periods than during disturbed periods, especially at heights below the PMSE occurrence maximum.

Relation of PMSE to Vertical Velocity

Several authors have suggested that there is a relation between PMSE and velocity variations due to gravity waves [e.g., *Fritts et al.*, 1988; *La Hoz et al.*, 1989; *Williams et al.*, 1989; *Hall*, 1990]. We have investigated a possible connection between gravity waves and PMSE in a case study taken from our summer 1991 data. In Figure 4 the power of PMSE during the night of July 27, 1991, between 0130 and 0220 UT is presented in a quasi three-dimensional form. The maximum backscattered power is about 10 dB above the noise level; thus this PMSE event is only moderate. We assume that the remarkable variations of the power near 0150 UT could be related to an upward motion which we note in the measured velocity.

In Figure 5 the vertical velocity is shown for the same period as used in Figure 4. The velocity field is, however, only derived for those times and height ranges where the backscattered power is more than 1 dB above the noise level. Near 0150 UT a marked short periodic variation (period about 7 to 8 min) can be detected at PMSE heights which could be connected with variations of the PMSE power. If we would assume that these velocity variations are caused by a gravity wave, it is ambiguous to derive the individual wave parameters due to the limited region of PMSE occurrence. We notice also a spectrum widening by a factor of 2.5–3 following the large upward velocity which could be an indication of wave breaking into turbulence. In the following we will restrict ourselves to investigate only the possible connection between the vertical velocity with the power of the PMSE.

In Figure 6 the time series of vertical velocity (dash-dotted curves) and the SNR (crosses) of PMSE are shown for heights between 83.15 and 87.35 km. Regions with upward directed velocity are hatched. The single solid line marks the mean variation of the velocity maxima in dependence on

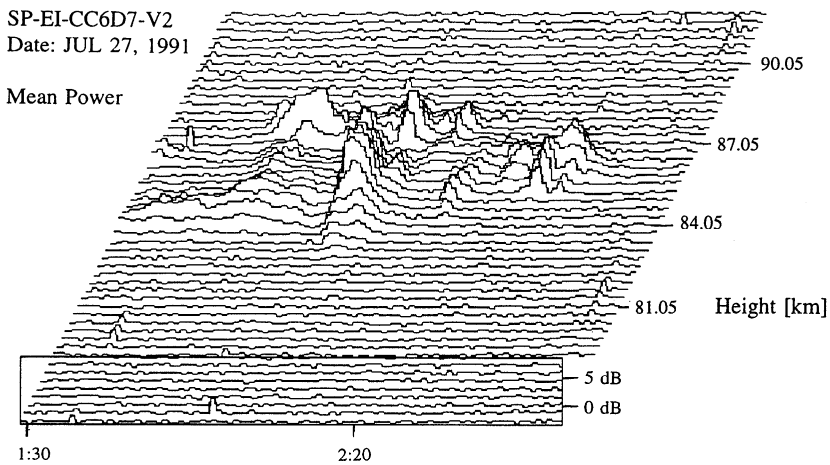

Figure 4. Height-time variation of PMSE power (signal-to-noise ratio in decibels) on July 27, 1991, observed with the EISCAT VHF radar in Tromsø.

height. If we assume that the wind variations are caused by a vertically propagating gravity wave, this solid line describes the expected negative phase shift with height, implying a vertical wave length about 17 km. The mean variation of the SNR maxima with height is marked by the single dashed line. These two thick lines are nearly parallel and prove a delay of power with respect to velocity by about 1.5 min. This can support a possible connection between PMSE power and vertical velocity.

This connection between the power of PMSE and vertical velocity can be even more clearly seen in Figure 7. Here the results of a cross correlation analysis between these two quantities are shown for different height ranges. The dotted curves represent the 99% significance level of the cross correlation analysis. The significant parts of the cross-correlation curves above this level are marked by hatched regions. According to Figure 7 the power of PMSE is highly significantly correlated to the vertical velocity. The maximum correlation between SNR and velocity v (marked by the arrows in Figure 7) is found at a time difference of about 1.5 min with a tendency to smaller values at greater altitudes and larger values at lower heights.

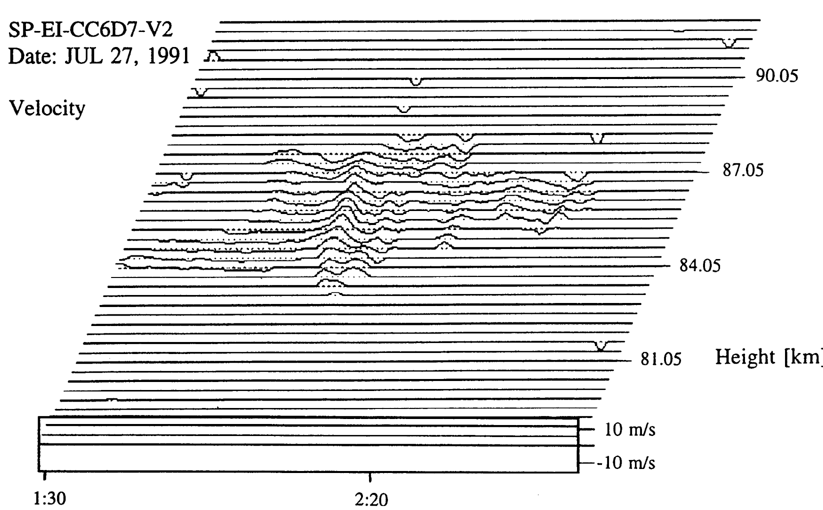

Figure 5. Vertical velocity observed with EISCAT VHF radar at Tromsø on July 27, 1991, for height regions where the signal-to-noise ratio is greater than 1 dB.

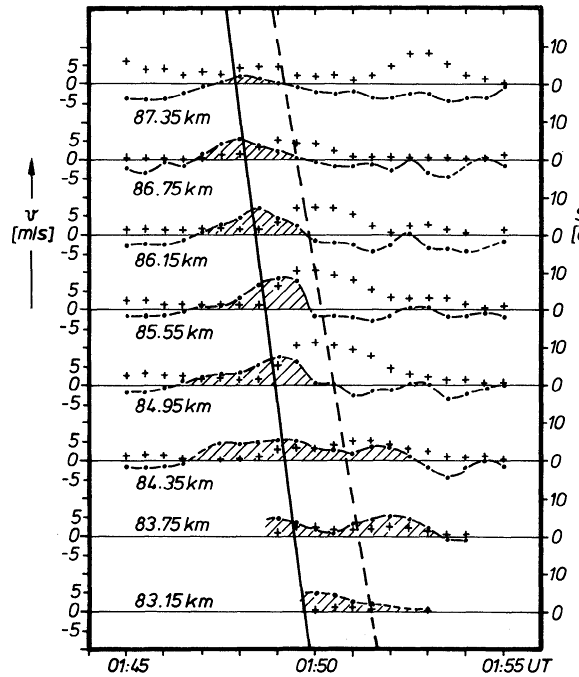

Figure 6. Temporal variation of SNR of PMSE (crosses) and vertical velocity (dash-dotted curves) measured with the EISCAT VHF radar on July 27, 1991, in different height ranges, showing the time lag of echo power with respect to the vertical velocity.

Comparison of PMSE on 224 MHz and 46.9 MHz

During a part of the EISCAT PMSE campaign in 1991 observations with the CUPRI radar at 46.9 MHz were also available at Tromsø, Norway, as well as Esrange, Sweden (see Figure 1). The EISCAT and CUPRI radars were operated collocated in Tromsø, whereas those of CUPRI at Esrange were separated by 126 km.

In Figure 8 two examples are shown for simultaneous measurements with both radars, one observation (Figure 8a) at the same location (Tromsø) and one observations at EISCAT, Tromsø, and CUPRI, Esrange (Figure 8b). It seems that strong and stable PMSE structures are normally detected by both radars at the same location (e.g., July 12, 1993, 1300–1430 UT), although also events occur when this is not as pronounced as shown in this Figure.

Frequently, marked differences are observed at both places, Tromsø and Esrange, especially when the PMSE signals are weaker and more fluctuating. The reasons of these differences may partly be caused by the distance between both observing sites. A similar observation was noted by *Kelley et al.* [1990] during experiments at EISCAT and Andoya and assumed to be due to advection of PMSE structures. We also would not exclude that different irregularity structures were formed at these two places. A more general statistical investigation between EISCAT and CUPRI observations was not tried because the number of available common observations is too small to get reliable statistical results.

3. Discussion and Conclusions

During our observations in summer 1991 the height of maximum PMSE occurrence near 85 km during daytime and between 86.0 and 87.5 km during nighttime agrees well with the results of other authors [*Ecklund and Balsley,* 1981;

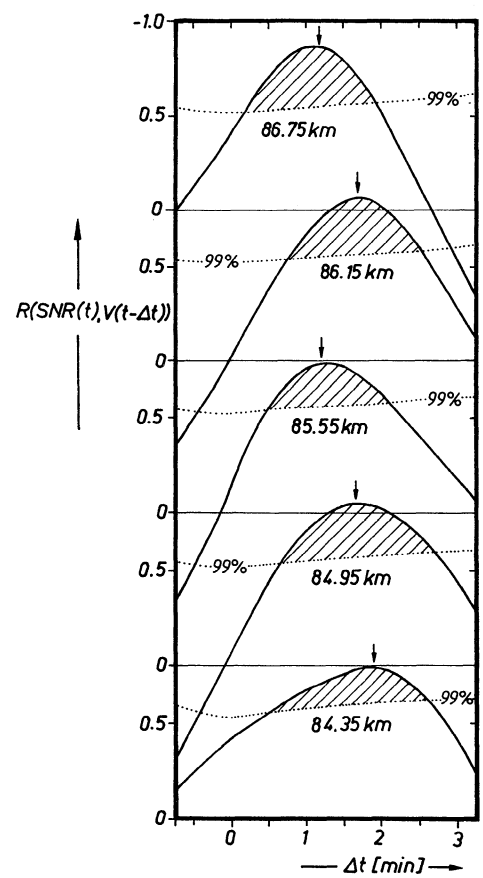

Figure 7. Cross-correlation analysis of SNR of PMSE and vertical velocity observed with the EISCAT VHF radar on July 27, 1991. The dotted curves mark the significance level of 99%.

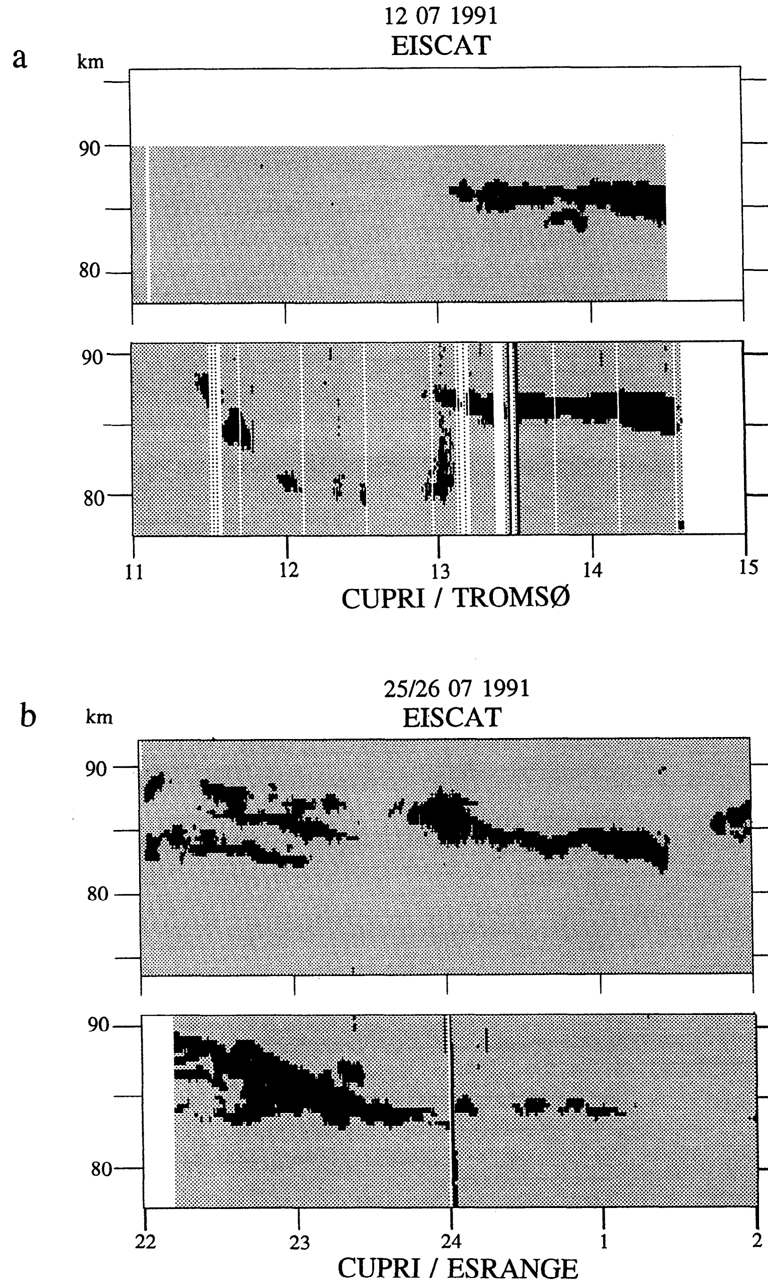

Figure 8. Comparison of PMSE observations with the VHF EISCAT radar (224 MHz) and with the CUPRI radar (46.9 MHz). PMSE with SNR > 5 dB are represented by solid areas; shading indicates observations with SNR < 5 dB; white areas indicate no measurements. (a) EISCAT and CUPRI at Tromsø on July 12, 1991. (b) EISCAT at Tromsø and CUPRI at Esrange on July 25 and 26, 1991.

Czechowsky et al., 1989; *Hoppe et al.*, 1988; *Jones et al.*, 1989]. We also found a more frequent occurrence of PMSE during daytime than during nighttime (see Figure 2). This is in general agreement with the initial EISCAT VHF radar observations in 1987 and 1988 [*Hoppe et al.*, 1988; *Jones et al.*, 1989]. As the nighttime PMSE observations were carried out after the daytime measurements (see Figure 1), it cannot completely be excluded that a part of our observed low nighttime PMSE occurrence may be caused by a possible seasonal variation with decreasing PMSE occurrence probability during August [*Ecklund and Balsley*, 1981].

The indication that PMSE occur more frequently during magnetically quiet periods was not yet reported. Whereas we did a statistical comparison over 16 days and 12 nights, *Rishbeth et al.* [1988] did one case study. They found a correlation of periodical variations (period near 45 min) in both PMSE and geomagnetic data, whereas *Röttger et al.* [1990] for a singular case study did not find such a relation in the PMSE power variation. We thus suggest to discriminate between short-term power variations of PMSE and their overall, general occurrence. A small positive correlation between cosmic noise absorption (being an indicator for enhanced *D* region ionization) and PMSE observed with radars operating near 50 MHz was reported by *Ecklund and Balsley* [1981] and *Czechowsky et al.* [1989]. In general, an enhancement of electron density due to particle precipitation should improve the ionospheric radar scatter cross section, if one assumes either turbulence scatter [*Hocking*, 1985] or other phenomena [e.g., *Kelley et al.*, 1987; *Cho and Kelley*, 1993; *Röttger*, 1994]. Precipitating high-energy particles could, however, also destroy heavy water cluster ions [*Chandramma and Prasad*, 1986]. According to contemporary theories, these cluster ions play an important role in the explanation of PMSE in the VHF range. As discussed in detail by *Cho and Kelley* [1993] large ions extend the turbulence-driven spectrum of electron density irregularities to shorter wavelengths by reduced electron diffusivity D and enhanced Schmidt number $Sc = \nu/D$ (ν = kinematic viscosity). Large ions could be water cluster ions [*Kelley et al.*, 1987], large charged aerosols [*Cho et al.*, 1992b], or small charged ice particles [*Klostermeyer*, 1994]. For the latter two candidates water cluster ions are thought to be nucleation cores [*Cho and Kelley*, 1993]. Therefore, a destruction of water cluster ions should reduce the Schmidt number effect and influence the PMSE occurrence. According to *Cho et al.* [1992b] this effect should be more important at higher frequencies (e.g., 224 MHz) than in the lower part of the VHF range (46.9 MHz). Therefore, the influence of particle precipitation to PMSE can be different at different radar frequencies. According to our results it seems that the observed negative correlation between PMSE at 224 MHz and geomagnetic activity can be caused by particle precipitation. Since geomagnetic variations are not in a one-to-one relation with particle precipitation, we need to expand our investigations by including direct measurements of precipitating particles, for example, with simultaneous observations of D region ionization with the EISCAT UHF incoherent scatter radar or with slightly more indirect riometer observations. This will be subject of later studies.

The influence of atmospheric waves on PMSE has been suggested by *Fritts et al.* [1988], *Czechowsky et al.* [1989] (semidiurnal tidal wave), as well as *Williams et al.* [1989] and *Hall* [1990] (gravity waves). Our results, presented in Figures 6 and 7, could qualitatively be explained by the Schmidt number effect [*Kelley et al.*, 1987], assuming an adiabatic cooling during uplift and warming during downlift by the vertical velocity [*Hall*, 1990]. As the temperature variations induced by gravity waves are lagging the velocity changes by a quarter wave period, the minimum temperature is expected when the vertical velocity becomes zero following its upward direction. We consider water cluster ions to play a role in the Schmidt number effect, either directly or as nucleation cores of aerosols or ice particles. The characteristic recombination time of positively charged clusters with electrons is in the order of 10 s, assuming an effective recombination coefficient of about 10^{-5} s^{-1} cm^{-3} and electron densities of 10^4 cm^{-3} near 86 km [*Arnold*, 1980]. Furthermore, the characteristic time of water cluster ion production (hydration time) is in the same order as shown by *Arnold* [1980] and *Arnold and Joos* [1979]. Consequently, temperature changes should nearly instantaneously influence cluster ion density and the Schmidt number. During times of minimum temperature the density of cluster ions should increase, thus enhance the Schmidt number and cause maximum radar reflectivity. Just this is observed in Figure 6 where the maximum PMSE is observed near the times when the vertical velocity becomes zero.

In the EISCAT radar data there seems to be also some indications of a 2-day variability of PMSE occurrence. Due to the operational restrictions the available observation intervals are too short to deliver statistically significant results. Therefore in the future the long-term observations of PMSE are needed to search for 2-day or other long-period waves. Part of these data may also be found in longer operations of EISCAT Common Programme operations.

In general, we see equivalent structures when observing with collocated radars although some differences are noted. PMSE observations at different frequencies (46.9 and 224 MHz) could be caused by different irregularity structures. As known from in situ rocket measurements [*Kelley and Ulwick*, 1988; *Lübken et al.*, 1993; *Cho et al.*, 1993; *Ulwick et al.*, 1993] two different kinds of layers have been observed which cause PMSE with different characteristics. Anisotropy is reported in the lower part of the VHF range at 53.5 MHz [*Czechowsky et al.*, 1988]. These phenomena could also be different at the frequencies of 46.9 and 224 MHz. The differences observed with the locally separated radars are assumed to be due to structural changes during horizontal advection or due to local changes of small-scale features (e.g., gravity waves), which should be different at separated locations. Moreover, the different influence of particle precipitation on PMSE as discussed above can be an additional reason for differences of PMSE features at different frequencies and locations.

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