Pergamon

Journal of Atmospheric and Terrestrial Physics, Vol. 57, No. 1, pp. 35–44, 1995

0021-9169/95 $9.50+0.00

0021–9169(93)E0032–5

A comparison of PMSE and other ground-based observations during the NLC-91 campaign

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(*Received in final form* 29 *November* 1993; *accepted* 29 *November* 1993)

Abstract—During the period July–August 1991, observations were made of Polar Mesospheric Summer Echoes (PMSE) at 46.9 MHz and 224 MHz by the CUPRI and EISCAT radars, respectively, at two sites in northern Scandinavia. Those observations are compared here with observations of noctilucent clouds, energetic particle precipitation and magnetic disturbances. The appearance and morphology of PMSE are found to be closely correlated at the two frequencies and the two sites, 200 km apart. No correlation is found between PMSE and noctilucent clouds or magnetic disturbance. No correlation is found between energetic particle precipitation and the appearance of PMSE at 46.9 MHz for the whole time period. At 224 MHz, there is no evidence for a correlation before the beginning of August and only one event suggesting a possible correlation after the beginning of August. A minimum in occurrence frequency for PMSE is found between 16 and 21 UT (17–22 LST) which may be related to an expected minimum in background wind strength in that time interval.

1. INTRODUCTION

Polar Mesospheric Summer Echoes (PMSE) are unusually strong radar echoes from thin layers in the 80–90 km altitude interval which are observed at high-latitudes during summer. They were first reported by ECKLUND and BALSEY (1981) in observations from the Poker Flat MST radar, operating at 50 MHz. Interest in the echoes grew considerably, however, when they were also observed at 224 MHz with the EISCAT VHF radar (HOPPE *et al.*, 1988), as KELLEY *et al.* (1987) suggested might be possible. Since then, PMSE echoes have been observed even at 1.29 GHz (CHO *et al.*, 1992a) although they are much weaker there than at 224 MHz. The cause of the echoes is, as yet, not completely understood. It is clear that there must be large fluctuations in the refractive index for radar waves confined within narrow layers, and *in-situ* rocket measurements of the electron-density fluctuations prior to the NLC-91 campaign had indicated that these could, in some cases, be explained in terms of isotropic (ULWICK *et al.*, 1988; KELLEY *et al.*, 1990) or anisotropic (INHESTER *et al.*, 1990) turbulence. In other cases, observed electron density 'bite-outs', suggested to be due to the presence of negatively charged ice-particles, have been proposed to be an explanation for PMSE (ULWICK *et al.*, 1988; REID, 1993). Direct measurements during the NLC-91 campaign of both neutral and plasma-density fluctuations (LÜBKEN *et al.*, 1993) show that at least two types of PMSE occur, one due to neutral turbulence with embedded plasma-density fluctuations, and the other due to purely plasma-density fluctuations. Suggestions have been made that layers of charged aerosols or dust may be responsible for the echoes, even when they are too few to cause 'bite-outs' (CHO *et al.*, 1992b; HAVNES *et al.*, 1990). If aerosols are involved and they are noctilucent cloud particles, or dust which acts as condensation nuclei for noctilucent cloud particles (NLC), which also occur in the same season, at similar altitudes and latitudes, we might expect a close correlation between the appearance of PMSE and NLC. Alternative suggestions are that layers of strong turbulence are produced by shear-instabilites in the prevailing winds, or by non-linear dissipation of gravity waves propagating up from the troposphere as their

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phase speed becomes equal to the background wind speed (BALSLEY et al., 1983; YI et al., 1992). Since the prevailing background winds at mesopause heights are predominantly tidal, we might then expect a tidal modulation in the occurrence of PMSE. The situation might be complicated by the need for the presence of sufficient background ionisation to make the fluctuations 'visible' to the radars. Since solar produced ionisation is very weak at night, we might expect to see a day–night variability in PMSE, modified when extra ionisation is added by energetic precipitating particles. A third possibility is that layer formation may be affected by magnetospheric electric fields, as has been documented to occur for neutral and ionised minor-species layers just above 90 km altitude (KIRKWOOD and VON ZAHN, 1991).

During the period 24 July–10 August 1992, almost continuous measurements of PMSE were made using the 46.9 MHz CUPRI radar located at Esrange near Kiruna in Sweden. During this interval, PMSE observations were also made for 6 h each night with the EISCAT 224 MHz radar, situated 200 km north of Kiruna. The operating mode of the CUPRI radar is described in SWARTZ et al. (1993). The EISCAT radar operated a complementary code scheme with 300 m height resolution, 2 s time resolution and an altitude coverage from 72 to 90 km. Observations of the presence or absence of NLC over the Kiruna area were made almost every evening, both from ground sites and from an aircraft flown over central Sweden. Continuous measurements of energetic particle precipitation were made using riometers, and measurements of magnetic activity (related to magnetospheric electric field intensifications) were made using magnetometers. Although the most intensive part of the measurement campaign did not start until 24 July, NLC observations were also made from southern Sweden from 27 June onwards, the CUPRI radar operated in Tromsö during the first part of July, and EISCAT common-program measurements also provided PMSE observations on 10–11 July. The locations of the observing sites are shown in Fig. 1, the measurements are summarised in Fig. 2 and the relationship between the occurrence of PMSE and each of the other phenomena is discussed below. Note that comparisons have been made on an hour-by-hour basis, i.e. if the phenomenon of interest was observed any time during one hour, it is counted as 'present'.

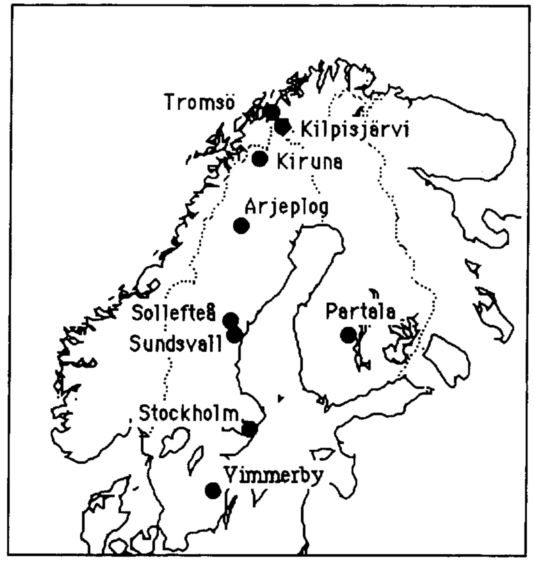

Fig. 1. Map of Scandinavia showing the locations of the observing sites referred to in the text.

2. COMPARISON OF PMSE SEEN BY CUPRI WITH PMSE SEEN BY EISCAT

Before we can make a meaningful comparison between measurements made at slightly different locations, we need to know how localised a phenomenon PMSE might be. Figure 3 compares the occurrence of PMSE echoes at the two locations Tromsö (EISCAT) and Esrange (CUPRI), 200 km apart, for the time interval 22-04 UT, when observations were made with EISCAT (a total of 72 h). The figures below the panel indicate the proportion of the observations in each category with the figures in brackets indicating the proportions expected if the echoes appear entirely independently at the two locations with the observed occurrence frequencies. For example, with the observed 61% occurrence rate of PMSE at CUPRI and 67% at EISCAT, we would expect PMSE to be observed at both sites simultaneously $61\% \times 67\% = 41\%$ of the time, just by pure chance. In fact, they occur simultaneously 53% of the time, and are absent simultaneously 25% of the time, as compared with an expected 'random chance' of 13%.

Closer examination of the form of the echoes confirms this further—of those occasions when both radars see PMSE, the echo is of the same form (single or multiple layer) at the two sites 72% of the time (only 50% would be expected by chance). In individual cases, a close correlation between the layer morphology at the two locations can also be seen. For example, between 22 and 04 UT on 26–27 July, the layer form changes from double to single and back again essentially simultaneously at the two locations and on 1 August between 01 and 04 UT, the height of the PMSE layer decreases from about 90 to 85 km at both locations. The correlated appearance at the two

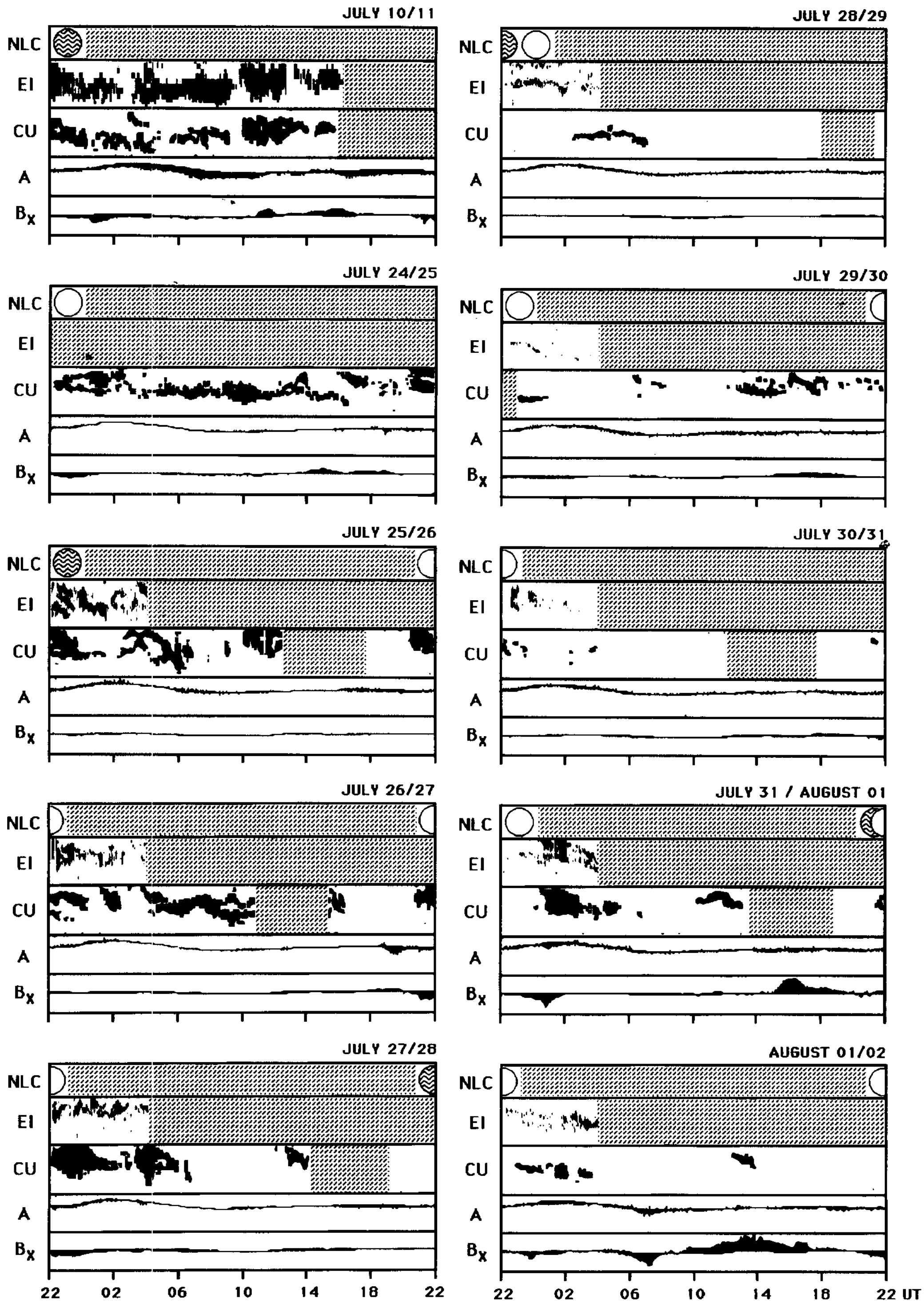
JULY 10/11
JULY 28/29
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Fig. 2.

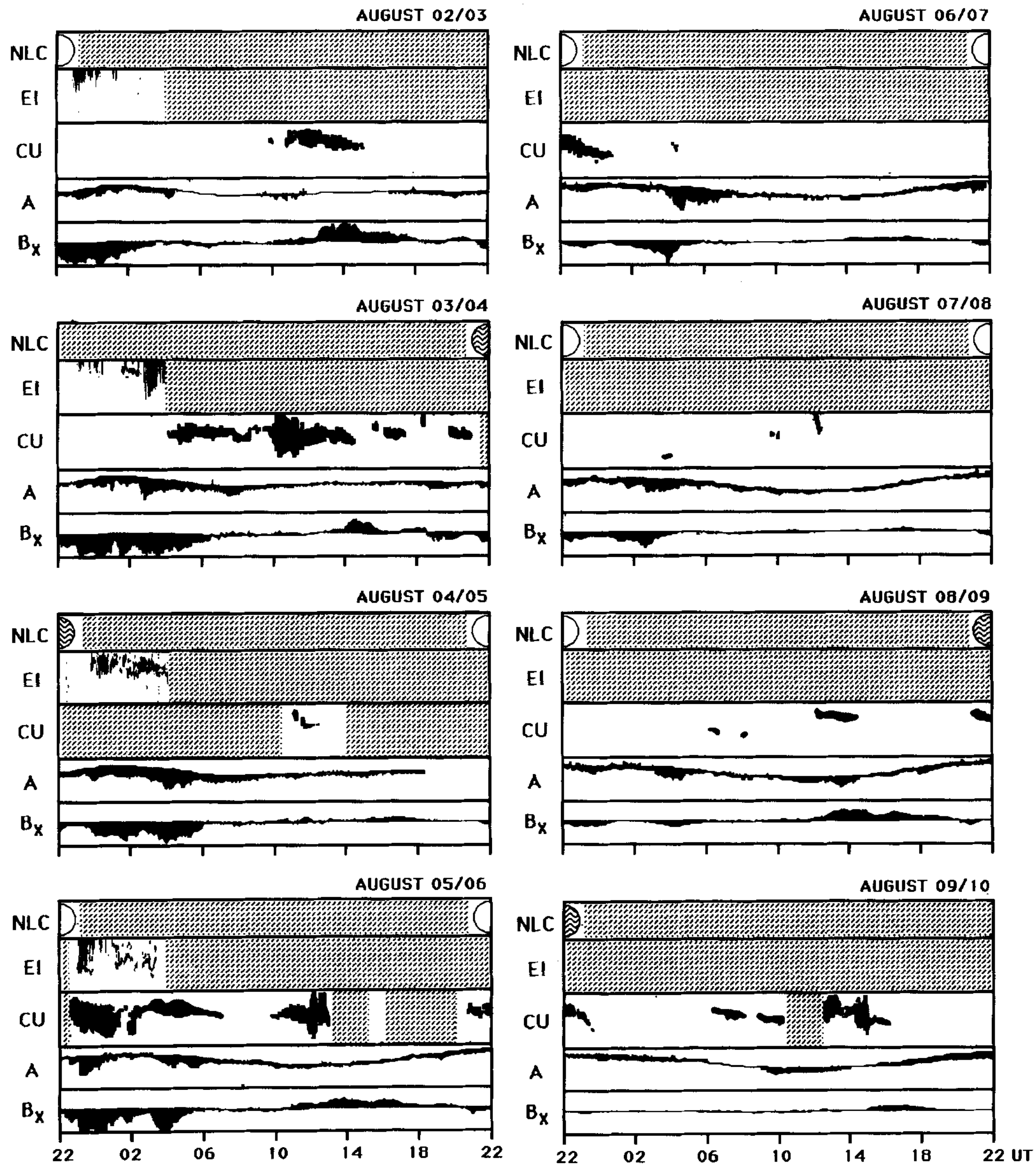

Fig. 2. Ground-based observations of magnetic disturbances (Bx), absorption of cosmic radio noise at 38 MHz observed by riometer at Kiruna (up to 4 August) or at 30 MHz at Kilpisjärvi (from 5 August) (A), PMSE at 46.9 MHz over Esrange (CU), PMSE at 224 MHz over Tromsö (EI) and ground based/aircraft observations of noctilucent clouds (NLC). For NLC, an observed absence of clouds is indicated by an open circle, and the presence of clouds by a circle filled with a wave pattern. The observations indicated in the figure are from Stockholm for 10–11 July, otherwise from Sollefteå, Sundsvall or from the aircraft flying from Sundsvall. For EI and CU, each panel shows the appearance of PMSE over the height interval 80–90 km. The absorption is indicated by the shading in black of the difference between the observed noise power level and the quiet level. The zero level is at the bottom of the panel. The magnetic field disturbances are indicated in the same way as for the riometers. The magnetic north–south component is shown, and the full height of the panel corresponds to a variation of 1500 nT. The grey areas indicate time intervals when no observations were made.

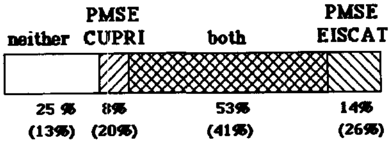

Fig. 3. Occurrence of PMSE over Tromsö (EISCAT), over Esrange (CUPRI) and over both sites simultaneously. Comparisons were made for each 1 h interval when EISCAT was operating between 22 and 04 UT (a total of 72 h). The figures below each section indicate the percentage of observations in each category. The figures in brackets show the percentages expected if PMSE occurred completely independently at the two sites with the observed individual occurrence rates for the time interval used. The uncertainty in the occurrence rates due to the limited sample size is about 6%.

sites indicates that the processes producing the echoes must generally have a horizontal extent in the N–S direction in excess of 200 km. Note, however, that PMSE is seen at only one or other of the two sites 22% of the time, suggesting that the extent is not too much greater than 200 km. Comparisons between earlier measurements over Tromsö and over Andöya have similarly indicated several 100 km extent in the east–west direction (HOPPE, 1993).

Note that the CUPRI and EISCAT observations on 10–11 July are both made from Tromsö, so that the excellent agreement between the morphologies seen by the two radars on this occasion indicates only that scale-sizes appropriate for both radar wavelengths are present in the refractive index variations causing the echoes.

3. COMPARISON OF PMSE SEEN BY CUPRI WITH NLC OBSERVATIONS

Table 1 summarises the NLC observations, and Fig. 4 compares the appearance of PMSE echoes with the NLC observations. The PMSE observations from Esrange have been used, as they are in the area which is visible from the NLC observing sites at Sundsvall and Sollefteå, and from the aircraft flying out of Sundsvall. We see that NLC and PMSE occurred together on only 20% of the 15 occasions when there are simultaneous observations. This is not significantly different from the 18% expected from random chance. Further, there does not seem to be any relationship between the form or persistence of the PMSE echoes and the appearance of NLC. Referring to Fig. 2, it can be seen that NLC is observed together with multiple, persistent PMSE on 25–26 July and with a single-layered, sporadic PMSE on 9–10 August. An absence of NLC is observed on other occasions with apparently very similar PMSE morphologies, i.e. 24–25 July when the PMSE is strong, multiple and persistent but the observations from the aircraft from Sundsvall indicated a complete absence of NLC, and 6–7 August, when a single, narrow, relatively short lived PMSE layer was observed and again, the aircraft observations showed an absence of NLC. There is no evidence, therefore, for any direct relationship between the appearance of NLC and PMSE. This confirms the earlier result, reported by TAYLOR *et al.* (1989), that the two phenomena are not directly correlated and rules out the possibility that PMSE is caused by scattering from the ice particles which are thought to be responsible for visible NLC. However, the possibility remains that PMSE may depend on the presence of aerosols too small to result in visible NLC.

A statistical correlation between PMSE and polar mesospheric clouds (the satellite-observed equivalent of noctilucent clouds) has been reported by JENSEN *et al.* (1988) which might appear to conflict with our present result. However, a close examination of their data reveals a distribution very similar to our own. Taking only their observations for the PMSE/PMC season, i.e. days 170–220, they observe PMSE 61% of the time, PMC 55% of the time and both together 38% of the time. (The satellite measurements are likely to be more sensitive than ground-based NLC observations, explaining the higher occurrence of PMC than NLC s in our study.) Combining the occurrence frequencies for PMSE and PMC gives an expected random chance for observing the two together of 34%, very close to that observed. It seems that the Jensen *et al.* statistical correlation mainly reflects the fact that both phenomena occur in the same season rather than being evidence that they are directly related to one another.

4. COMPARISON OF PMSE OCCURRENCE WITH ENERGETIC PARTICLE PRECIPITATION DETECTED BY RIOMETER

Figure 5 quantifies the relationship between the occurrence of PMSE at 46.9 MHz and 224 MHz and energetic particle precipitation detected by the riometers in Kiruna, close to Esrange (up to 5 August) and Kilpisjärvi, about half-way between Kiruna and Tromsö (from 5 August onwards). The comparison has been restricted to the 4-h time interval centred on local solar midnight, the time when energetic particle precipitation is most likely to be needed to produce sufficient ionisation to make the echoes 'visible' to the radar (a total of 62 h with CUPRI, 39 h with EISCAT). There is no evidence for any significant statistical correlation, neither at 46.9 MHz with CUPRI, nor at 224 MHz with EISCAT. This is some-

Table 1. Summary of NLC observations, summer 1991
abs = observed to be absent, *pres* = observed to be present,
doc = present and documented (photographed)

27/28 June	NLC *doc* Stockholm
28/29 June	NLC *doc* Stockholm
03/04 July	NLC *abs* Stockholm
04/05 July	NLC *pres* Stockholm
10/11 July	NLC *doc* Stockholm, Vimmerby—best display of the summer
18/19 July	NLC *abs* Stockholm
24/25 July	NLC *abs* 2215 UT Sundsvall, faint NLC *doc* Partala
25/26 July	NLC *pres* aircraft 2144–2317 UT, NLC *doc* Sundsvall 2225–2250 UT
26/27 July	NLC *abs* aircraft 2100–2200 UT, NLC *abs* Sollefteå
27/28 July	NLC *abs* aircraft 2100–2240 UT, NLC *abs* Sollefteå, NLC *abs* Örnsköldsvik
28/29 July	faint NLC *pres* aircraft 2150–2200 UT, faint NLC *doc* Partala, NLC *abs* Sundsvall, NLC *abs* Sollefteå 0015 UT
29/30 July	NLC *abs* Sollefteå
30/31 July	NLC *abs* aircraft 2130–2200 UT, NLC *abs* Sollefteå, NLC *doc* Partala
31/01 July	NLC *abs* Sundsvall, NLC *abs* Sollefteå, NLC *abs* Örnsköldsvik
01/02 Aug	NLC *abs* aircraft 2115–2200 UT, faint NLC *pres* Sundsvall 2100 UT NLC *abs* Sollefteå, NLC *abs* Lycksele, doubtful NLC Örnsköldsvik
02/03 Aug	NLC *abs* aircraft 2100–2230 UT, NLC *abs* Sollefteå
03/04 Aug	NLC *abs* Sollefteå (hole in cloud only)
04/05 Aug	faint NLC *pres* aircraft (time not logged), NLC *abs* Sundsvall, doubtful patch NLC Sollefteå 2240–2300 UT
05/06 Aug	NLC *abs* aircraft 2140–2310 UT, NLC *abs* Sollefteå, NLC *abs* Örnsköldsvik, NLC *abs* Lycksele
06/07 Aug	NLC *abs* aircraft 2115–2315 UT, NLC *abs* Lycksele
07/08 Aug	NLC *abs* Sundsvall, NLC *abs* Lycksele
08/09 Aug	NLC *abs* aircraft 2100–2330 UT, NLC *abs* Arjeplog (holes in cloud)
09/10 Aug	NLC *pres* aircraft 2130–2230 UT, *doc* Lycksele 2230–2248 UT *doc* Arjeplog 2328–2344 UT

what in contrast to previous results (TAYLOR *et al.*, 1989) indicating a correlation between the strength of PMSE and energetic particle precipitation for two events, on 9 and 12 August 1988. However, the present measurements are made earlier in the summer, and at solar maximum, when solar-produced ionisation at PMSE heights is substantially greater.

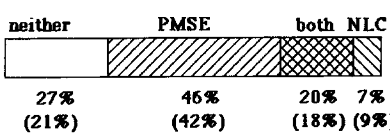

Fig. 4. Occurrence of PMSE over Esrange (CU) with an observed absence or presence of simultaneous NLC, from 24 July to 10 August. Each night, when NLC were observed to be either present or absent, is counted as a single observation. When both the presence and absence of NLC are reported on the same evening, it is counted as NLC present (a total of 15 observations). Figures below the sections indicate the percentage of observations in each category. The figures in brackets show the percentages expected if PMSE occurred completely independently of NLC with the observed individual occurrence rates. Uncertainties in the occurrence rates due to the limited number of observations are about 15%.

A close examination of the present measurements shows, indeed, three occasions when the onset of

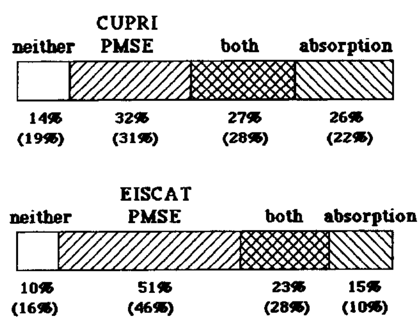

Fig. 5. Occurrence of PMSE with an observed absence or presence of simultaneous 38/30 MHz absorption (i.e. energetic particle precipitation). Comparisons were made for each 1 h interval between 21 and 01 UT (62 h with CUPRI, 39 h with EISCAT). Figures below the sections indicate the percentage of observations in each category. The figures in brackets show the percentages expected if PMSE and absorption occurred completely independently with the observed individual occurrence rates. The uncertainties in the occurrence rates due to the finite number of observations are about 6% for the comparison with CUPRI, 8% with EISCAT.

PMSE echoes as seen by EISCAT (but not by CUPRI), close to midnight, does seem to coincide with the appearance of energetic particle precipitation (close to 2300 UT on 3, 4 and 5 August). However, earlier (24 July–1 August) in the campaign, PMSE was seen by EISCAT close to midnight without any detectable energetic particle precipitation, and these observations dominate the statistics. This suggests that, if there is a threshold ionisation required to allow the radar to detect the PMSE at 224 MHz, it must be very low. It is clear that, before the beginning of August in 1991, sufficient ionisation was provided by solar illumination even at midnight (solar zenith angles 92–93°) for the threshold to be exceeded. It is possible that later in the summer, when solar zenith angles reach greater values than 93°, the threshold is exceeded only when some particle precipitation is present.

As regards the PMSE echoes at 46.9 MHz, there are no occasions when PMSE is seen to appear coincident with a sudden onset or increase in the energetic particle precipitation. In the case of the two events mentioned above, in the first case (3 August), no PMSE at all was seen at 46.9 MHz, in the second (4 August), there were no observations at 46.9 MHz and in the third, PMSE at 46.9 MHz was seen before the energetic precipitation started. Thus, as far as PMSE at 46.9 MHz is concerned, there is no evidence that energetic particle precipitation is necessary to produce PMSE.

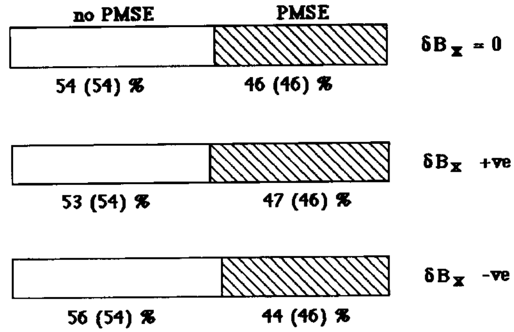

Fig. 6. Occurrence of PMSE in different magnetic disturbance conditions. Comparisons were made for each 1 h interval over the whole day with the results divided according to whether the magnetic field was undisturbed ($\partial Bx < 150$ nT), disturbed and positive (corresponding to northward electric field) or disturbed and negative (southward electric field). Figures below the sections indicate the percentage of observations in each category. The figures in brackets show the percentages expected if the occurrence of PMSE is independent of magnetic disturbance conditions. Uncertainties in the occurrence rates due to the finite number of observations are about 2%.

5. COMPARISON OF PMSE MEASURED BY CUPRI WITH MAGNETIC ACTIVITY

Figure 6 shows the occurrence of PMSE as seen by the CUPRI radar under different magnetic field disturbance conditions. $\partial Bx > 0$ corresponds to northward electric fields, $\partial Bx > 0$ to southward. Southward electric fields have been found to produce thin layers of metallic ions in the upper mesosphere as they cause a rapid downward transport of such ions from the thermosphere to mesospheric heights. They might, conceivably, affect other parameters also at these heights. However, there is clearly no evidence for any correlation between magnetic disturbance and PMSE occurrence. PMSE is equally likely to occur for $\partial Bx > 0$, $\partial Bx < 0$ and $\partial Bx = 0$. This is further confirmed by the comparison of the time variations of the two parameters over the full day (see below).

6. DAILY VARIATION OF PMSE, ENERGETIC PARTICLE PRECIPITATION AND MAGNETIC ACTIVITY

Figure 7 shows the distribution of the occurrence of the three phenomena over the day. Note that local solar midnight is at about 22.40 UT and local magnetic midnight at 21.30 UT. The only significant feature in the PMSE distribution is a minimum in occurrence between 16 and 21 UT. There is a minimum in energetic particle precipitation at a slightly earlier time, 13–18 UT, which is an expected consequence of the energisation and drift of electrons in the magnetosphere. At first glance, it might be thought that the minima in PMSE and precipitation could be related. However, the direct comparison above (Fig. 4) suggests they are not and a close examination of Fig. 7 shows that the maximum occurrence of energetic particle precipitation (20–21 UT) occurs within the interval of reduced PMSE occurrence; likewise, the maximum PMSE occurrence (12–13 UT) is at a time of very low probability of precipitation. The daily variation in the occurrence of magnetic disturbance is also shown, and it can be seen that this bears no similarity to that of PMSE. It seems likely, therefore, that the minimum in PMSE occurrence in the afternoon is due to a daily variation in one or more of the processes controlling the formation of the layer, such as a tidal wind.

The prevailing and tidal winds in the mesosphere above Tromsö have been studied in some detail by MANSON *et al.* (1992). At the heights where PMSE occurs, 85–90 km, MANSON *et al.* find that the winds in summer (June) are rather stable from day to day and from one measurement campaign (in 1984) to the next (in 1987). Combining the mean, 24-h and 12-h wind components found by MANSON *et al.* gives the

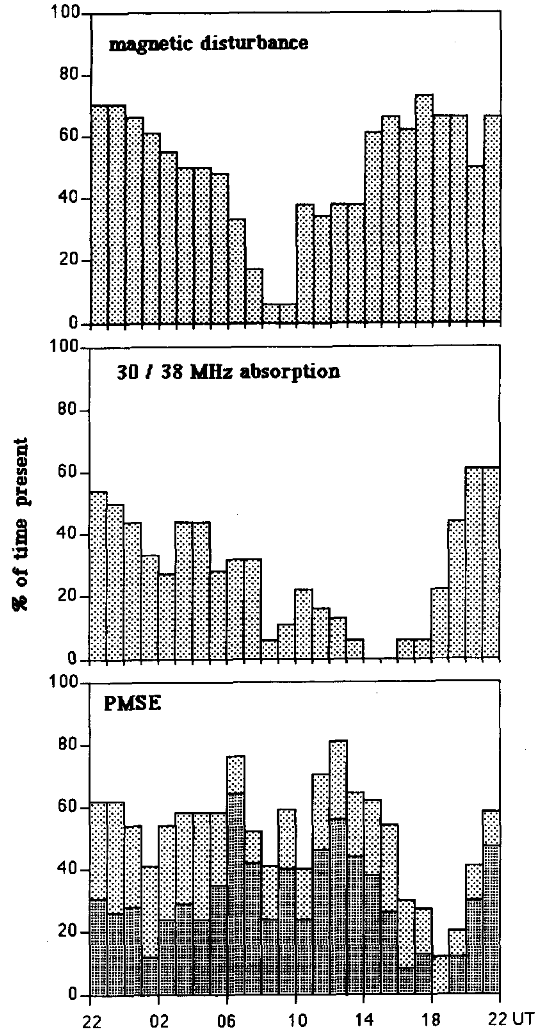

Fig. 7. Occurrence rates of magnetic disturbance (∂Bx > 150 nT), absorption (>0.5 dB) at 38/30 MHz and PMSE as a function of time of day. In the case of PMSE, the occurrence of single layers (heavy shading) and double or multiple layers (light shading) is indicated separately.

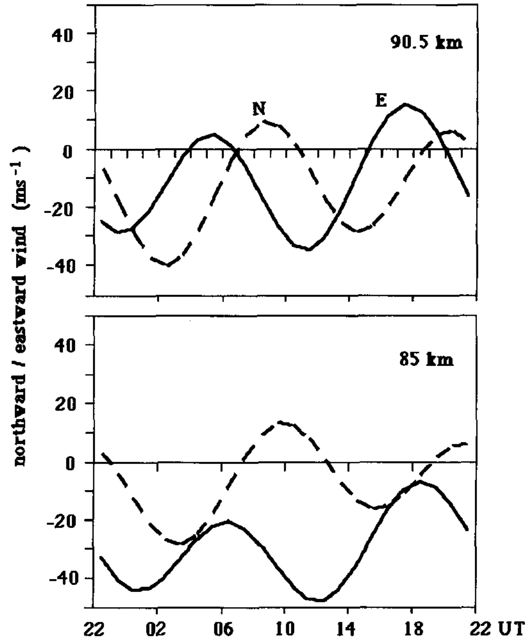

Fig. 8. Tidally varying background winds in the summer mesosphere. The winds are reconstructed from the mean, diurnal and semidiurnal components reported by MANSON et al. (1992) from radar measurements over Tromsö in June 1984 and June 1987.

daily variation in winds shown in Fig. 8. It can be seen that, at 85 km, the wind is mainly westward with a strong minimum between 17 and 22 UT, when both the diurnal and semidiurnal tidal components in the zonal wind combine to cancel the prevailing westward wind. This occurs together with low values for the meridional wind which is predominantly tidal. At 90.5 km, the mean westward wind has become much smaller and there are two time periods when the winds are small, 5–7 UT and 17–22 UT. If, as argued by BALSLEY et al. (1983) or YI et al. (1992), the turbulence causing PMSE is generated by shear-instability in the tidal wind field or by breakdown of gravity waves as they reach their critical level (i.e. the height where their horizontal phase velocity is equal to the background wind velocity), then we can explain the minimum in PMSE between 16 and 21 UT by the absence of high wind velocities or wind shears in the relevant height interval. In the case of the gravity-wave breakdown mechanism, we might expect that gravity waves with lower phase velocities have been filtered out by critical-level encounters at lower altitudes.

Here, it should be mentioned that the present results are in broad agreement with a previous study of the daily variation of PMSE from Andöya with the 53 MHz SOUSY radar (CZECHOWSKY et al., 1989). A minimum in occurrence frequency between 16 and 20 UT, was also found in that study, although the minimum was much less pronounced (80% occurrence as compared to a maximum of 100%). Periodicities in the echo power were also found, with a 12 h variation dominating, and simultaneous wind measurements showed that maxima in echo strength coincided with maxima in the westward winds associated with the semidiurnal tide.

7. CONCLUSIONS

From the intercomparison of the ground-based measurements made during the NLC-91 campaign, we can draw the following conclusions. PMSE echo layers have horizontal scale sizes somewhat in excess of 200 km in the north–south direction. This allows us to compare their occurrence with other parameters measured at slightly different locations. The occurrence of PMSE echoes is not correlated with the appearance of noctilucent clouds so that, if PMSE is a result of the presence of aerosols, these cannot be the same aerosols which are responsible for visible noctilucent clouds. The possibility remains, however, that subvisual aerosols may be involved in the maintenance of the plasma turbulence at small scale sizes which seems to be responsible for at least some PMSE (LÜBKEN *et al.*, 1993). During late July and early August 1991 (solar maximum), sufficient ionisation appears to have been produced by solar illumination for PMSE structures to be visible to both 46.9 MHz and 224 MHz radars, even at midnight (solar zenith angle 92–93°). There is no statistical correlation between PMSE occurrence and energetic particle precipitation (as detected by riometer), nor with magnetic activity. In individual events, after the beginning of August, there are indications of a correlation between the onset of energetic particle precipitation and the appearence of PMSE echoes at 224 MHz (but not at 46.9 MHz). There is a minimum in PMSE occurrence between 16 and 21 UT (17–22 LST) which may be related to shears in the tidally varying background winds or to their interaction with gravity waves. The tidal variations in the winds in the 85–90 km height interval are expected to result in much lower wind speeds at that time of day than at other times which would result in a reduction in the shear and in the number of gravity-wave critical-level encounters, both of which have been proposed to be responsible for generating the turbulent layers.

Acknowledgements—The EISCAT Scientific Association is supported by the Centre National de la Recherche Scientifique of France, Suomen Akatemia of Finland, Max Planck Gesellschaft of West Germany, Norges Almenvitenskaplige Forskningsråd of Norway, Naturvetenskapliga Forskningsrådet of Sweden and the Science and Engineering Research Council of the United Kingdom. The Cornell team was supported by NASA grant NAG5-666 and NSF grants ATM-9021915 and ATM-9217007. Riometer observations from Kilpisjärvi were provided by H. Ranta of the Sodankyla Geophysical Observatory.

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