Pergamon

Adv. Space Res. Vol. 14, No. 9, pp. (9)139–(9)148, 1994

0273–1177/94 $6.00 + 0.00

STUDIES OF POLAR MESOSPHERE SUMMER ECHOES BY VHF RADAR AND ROCKET PROBES

U.-P. Hoppe,* T. A. Blix,* E. V. Thrane,* F.-J. Lübken,**
J. Y. N. Cho*** and W. E. Swartz***

* *Norwegian Defence Research Establishment, P. O. Box 25, N-2007 Kjeller, Norway*
** *Physikalisches Institut der Universität Bonn, D-5300 Bonn, Germany*
*** *School of Electrical Engineering, Cornell University, Ithaca, NY, U.S.A.*

ABSTRACT

At radar frequencies in the range 50 MHz to 250 MHz, at times even to over 1 GHz, strong enhancements of scattering cross section occur between $\simeq 80km$ and $\simeq 95km$ altitude in summer at high latitudes. These echoes, termed "Polar Mesosphere Summer Echoes" (PMSE), have attracted considerable experimental effort. Observations of this phenomenon are reviewed in the context of atmospheric dynamics and of scattering processes. Recent rocket and radar measurements indicate that a partial reflection from a multitude of ion layers and constructive interference causes at least some of the PMSE. It is discussed which further observations are necessary and some possible practical consequences of PMSE are pointed out.

1. INTRODUCTION

The summer season at polar latitudes is very special. This is true not only on the ground, but also in the mesosphere and in the thermosphere. We have known for many years that the mesopause at high latitudes is much colder in summer than in any other season or at any other place (Stroud et al.,1959 /1/), and even colder than most models predict (von Zahn and Meyer, 1989 /2/; Lübken and von Zahn, 1991 /3/). It is believed that the reason is adiabatic cooling due to a large-scale average upward motion of a few cm/s (Murgatroyd and Singleton, 1961 /4/; Garcia and Solomon, 1985 /5/) superimposed on the many gravity wave oscillations that have vertical amplitudes of a few m/s (Fritts et al.,1990 /6/). The average upward drift in summer is thought to be caused by the deposition of momentum by breaking gravity waves being different from other seasons due to the different filtering characteristics for gravity waves of the atmosphere below (Lindzen, 1981 /7/).

One consequence of the very low temperatures is the formation of noctilucent clouds, NLC (Witt, 1967 /8/), and polar mesospheric clouds, PMC (e.g. Thomas and Olivero, 1989 /9/), which some workers consider to be the same phenomenon observed under different conditions.

Another phenomenon observed close to the mesopause at high latitudes and only in summer is a very strong enhancement of radar scattering cross section at radar frequencies of 50 MHz to over 250 MHz. It has been shown that this enhancement cannot easily be explained by simple scattering from isotropic turbulence (Inhester et al.,1990 /10/), and it cannot be explained by incoherent scatter (e.g. Hoppe et al.,1990 /11/). These echoes have been dubbed Polar Mesosphere Summer Echoes, PMSE. The phenomenon has attracted a considerable amount of attention in the past few years, and many observations and theoretical studies have been undertaken to establish their origin.

An overview over these observations is given in section 2 to describe the characteristics of PMSE. Observations of other phenomena and by other methods are also included when they seem to apply to the explanation of PMSE. Section 3 is a discussion of the observed characteristics in view of some of the theories that try to explain PMSE. The significance of recent rocket and radar observations for the understanding of the scattering mechanism is also discussed.

2. THE EVIDENCE

At present we do not know what PMSE really are. We cannot be certain that their occurrence near the cold summer polar mesopause and near NLC or PMC as mentioned above is due to a common cause. Until we know better, we will attempt to explain the three phenomena together, but we must also be aware of the possibility that even PMSE themselves might, in fact, be several distinct processes with different characteristics that we merely have not been able to discern. Since we cannot give a real definition of PMSE in terms of physical processes, we must use a descriptive working-definition for the time being. We will use the following: PMSE are

- persistent, but dynamic, strong radar echoes at $\simeq$50 MHz to $\simeq$ 250 MHz
- that occur at latitudes of $\simeq 65^0$ N to $\simeq 70^0$ N
- in the height region $\simeq 80km$ to $\simeq 95km$
- in the period mid-May to mid-August.

They may well also occur poleward of 70^0 N, as well as south of 65^0 S from mid-November to mid-February; we simply have no measurements yet. There are few observations of PMSE at a latitude as low as 52^0 N (Reid et al.,1989 /12/; Thomas et al., 1992 /13/). There were also observations of PMSE at almost 1 GHz radar frequency by Turunen et al. (1988) /14/ and by Collis et al. (1988) /15/, as well as at 1.29 GHz (Cho et al., 1992 /16/), but at UHF frequencies our first defining characteristic (persistent, strong) must be replaced by "of a spectral width too narrow to be readily explained by incoherent scatter" (see section 2.1 below).

2.1 Radar Observations of PMSE

The earliest known observation of PMSE was made in the summer of 1979 by Ecklund and Balsley (1981) /17/ with the 50 MHz MST radar at Poker Flat, Alaska (65^0 N). Although they were not called PMSE (but "Summer Mesospheric Echoes") at the time, their Figure 1 proves how nicely they fit our descriptive definition. The average summer profile given by these authors has a maximum signal-to-noise ratio of 32 dB near 86 km. It falls off rapidly towards 78 km and more slowly towards 99 km. The authors note that particle precipitation has no apparent effect on the echoes.

Similar observations were made from June 1984 onwards by Czechowsky et al. (1989) /18/ with the 53.5 MHz SOUSY radar at 69^0 N in northern Norway.

In July 1985, Turunen et al. (1988) /14/ and Collis et al. (1988) /15/ observed what we today would call PMSE with the 933 MHz EISCAT UHF radar at 70^0 N at Tromsø, northern Norway. They report a 2 km layer of slightly enhanced radar scattering cross section near 86 km in an otherwise quiet region and time period. This event lasted for about 10 minutes. The coherence time of this echo (23 ms) was much longer than would be expected for incoherent scatter from that height. The authors tentatively interpreted their observation as a layer of heavy positive ions (as high as 200 amu), possibly $H^+(H_2O)_n$, with n as high as 10. Note that at 933 MHz, PMSE are not especially strong compared with incoherent scatter. Their main characteristic at this frequency is an exceptionally long coherence time, or an exceptionally narrow spectrum. Simultaneous observations of PMSE on 933 MHz and on 224 MHz are possible with EISCAT and such measurements have been made. They are presently being analysed. Simultaneous measurements of PMSE at 46.9 MHz and 933 MHz have been made by the CUPRI and EISCAT UHF radars (Röttger et al., 1990 /19/). In this instance, PMSE were observed in the same altitude range by both radars.

The first observations of PMSE at 224 MHz were made with the EISCAT VHF radar at 70^0 N at Tromsø in June and July 1987 (Hoppe et al.,1988 /20/). These PMSE are very localized in height, their power varies by an order of magnitude within a minute, and they are much stronger than D- and E-region incoherent scatter. PMSE at 224 MHz clearly have the same altitude distribution as at 50 MHz, and their maximum occurs 2-3 km below the temperature minimum as measured at the same time by von Zahn and Meyer (1989) /2/. As with the Poker Flat radar and the SOUSY radar, PMSE were observed the first time the radar was ever used in the summer months. Kelley et al. (1987) /21/ had already suggested that PMSE might be observed with the 224 MHz EISCAT radar, but the greatest surprise about these observations was that the PMSE were much stronger and much more persistent than was expected from the earlier 50 MHz measurements. Many hours of simultaneous radar observations from EISCAT (69.6^0 N, 19.2^0 E) and Andøya (69.3^0 N, 16.0^0 E) or ESRANGE (68^0 N, 21^0 E) show that PMSE often extend several 100 km horizontally.

PMSE have even been observed over Germany at 52^0 N with the 53.5 MHz SOUSY radar (Reid et al.,1989 /12/) and over the United Kingdom at 52.4^0 N and 46.5 MHz (Thomas et al., 1992 /13/).

Note that all first observations of PMSE that could be found in the literature were made in the months of June and July, except for the ones from Poker Flat, which covered the whole PMSE season from the start. Also, the more spectacular observations, such as those at the much higher radar frequencies of 933 MHz and 1.29 GHz or at the much lower latitude of 52° N, were made in June and July, suggesting that PMSE are stronger and more extended in the middle of their season.

2.2 Further Characteristics

In addition to the basic characteristics that we have used to define PMSE, more have accumulated with the number of observations and observers. It has been mentioned above that the spectra at 933 MHz are much narrower than expected for incoherent scatter. This effect is even more pronounced at 224 MHz. A comparison of Röttger et al.'s (1988) /22/ Figure 4 with Hall et al.'s (1987) /23/ Figure 1 (neither shown here) makes this clear. Both sets of spectra were obtained with the same radar, at the same location, and in the same height range. The narrowest summer spectra are about 1 Hz FWHM, the winter ones about 50 Hz. Hoppe et al. (1990) /11/ point out that incoherent scatter spectra from 86 km in summer over Tromsø and at 224 MHz cannot be narrower than 21 Hz, no matter how heavy the positive ions are.

Czechowsky et al. (1988) /24/ have measured the aspect sensitivity of PMSE at 53.5 MHz. They found that the half-width at half-power of the backscatter at this radar frequency is approximately 5° to 6°. Results on the aspect sensitivity at 224 MHz has not yet been published. Observations and analysis are in progress (van Eyken and Hall, 1992 /25/), and seem to indicate no aspect sensitivity of PMSE at 224 MHz.

Several cases have been reported when PMSE were modulated by atmospheric waves. Fritts et al. (1988) /26/ have used Poker Flat radar data and temperature profiles from rocket experiments to determine the most unstable phase of a gravity wave that was present during their observation. The radar scattering cross section maxima agree very well with this phase, suggesting that turbulence plays an important role in the formation of PMSE. Rishbeth et al. (1988) /27/ report a time series of 7 hours when PMSE were observed to recur with a period of about 45 minutes. They suggest that this modulation might be due to a gravity wave of that period, although they do not have available the temperature and velocity data to support it. Williams et al. (1990) /28/ report a similar modulation. They have wind data that is in agreement, but no temperature data. Not all gravity waves modulate the PMSE scattering cross section, however, but they do advect the PMSE in altitude (Hoppe et al., 1990 /11/).

Rishbeth et al. (1988) /27/ found a weak, but significant correlation between the occurrence of PMSE and variations of the horizontal component of the geomagnetic field.

In many in situ electron density measurements which were performed simultaneously with radar observations of PMSE, a depletion of the electron density was observed at the PMSE heights (e.g. Ulwick et al., 1988 /29/). A partial reflection mechanism was ruled out at the time, because the echoes were not strongest where the largest electron density gradients occurred. Recent high-resolution observations have revised this picture (see section 3.4 below). The electron density depletion was certainly not an artifact of the nose-tip probe employed by Ulwick et al. (1988) /29/, since such depletions had also been observed by Faraday rotation and Positive Ion Probe (Johannessen et al., 1972 /30/; Johannessen, 1974 /31/).

Another important parameter for the understanding of PMSE is the dependence of radar reflectivity η on radar frequency. We know of no simultaneous absolute observations of η at different radar frequencies that are published. Taking published absolute values for η at 53.5 MHz (Inhester et al., 1990 /10/), at 224 MHz (Hocking and Röttger, 1992 /32/), at 933 MHz (Röttger et al., 1990 /19/), and at 1290 MHz (Cho et al., 1992 /16/), one can arrive at the following order-of-magnitude functionality:

$$\eta \approx 10^{-11} m^{-1} \cdot k^{-4.6} \tag{1}$$

where k is in $radians \cdot m^{-1}$. The observations were made at different places and times, and the one at 224 MHz is about 8.5 times larger than given by the empirical relation (1). Such measurements must be made simultaneously at at least three radar frequencies to be conclusive.

2.3 NLC and PMC

As mentioned in the introduction, there may be a connection between PMSE and PMC or NLC. Jensen et al. (1988) /33/ have studied the correlation between PMSE observed with the Poker Flat radar and PMC observed from the SME satellite. They find only a weak correlation and argue that this is due to the observed volumes not being exactly the same. Also, the frequency of occurrence of PMC given by Thomas and Olivero (1989)

/9/ matches the occurrence of PMSE. Taylor et al. (1989) /34/ have performed a case study of the occurrence of PMSE and NLC. In seven nights of observations, they find cases of all possible combinations: NLC but no PMSE, PMSE but no NLC, PMSE and NLC, and neither PMSE of NLC, suggesting no direct connection between the two phenomena. The most frequent altitude of NLC, as given by e.g. Fogle and Haurwitz (1966) /35/, is near 83 km which is 3 km below the maximum of PMSE and 5-6 km below the observed mesopause temperature minimum. These observations together seem to suggest that subvisual aerosol particles or ion clusters play a role in the formation of PMSE. When and if they grow large enough to be seen, they cause PMC or NLC, but by this time they have sedimented down to a lower altitude. Björn et al. (1985) /36/ have observed proton hydrates $H^+(H_2O)_n$ under NLC conditions with hydration rates n generally between $n = 4$ and $n = 10$, but reaching $n = 12$ and $n = 20$ at some heights. The largest of these have an ion mass of $\simeq 360$ *amu*. Schulte and Arnold (1992) /37/ have observed negative ions with masses up to and over 400 *amu* under the same conditions. They interpret these particles as the negatively charged fraction of meteor smoke particles. Thomas (1991) /38/ has given an excellent review of the connection between NLC/PMC and PMSE. Wälchli et al., (1993) /39/ report simultaneous observations of PMSE by radar and NLC in situ, where the PMSE was 300–1000 m above the NLC.

3. PROPOSED SCATTERING MECHANISMS

This review of observations does not attempt to be complete on the subject of proposed scattering mechanisms. However, some of the proposed mechanisms will be discussed in view of the observational evidence.

3.1 Turbulence

Turbulence has been suggested as the cause of PMSE (Balsley et al., 1983 /40/; Fritts et al., 1983 /41/), and this is supported by the gravity-wave modulation of PMSE summarized above. Maxima of the energy dissipation rate (or of the eddy diffusion coefficient) have been observed in polar summer at the heights of the PMSE, (Kelley and Ulwick, 1988 /42/). The radar scattering cross section of PMSE at 50 MHz agrees with the levels of turbulence measured simultaneously by rocket on some occasions (Kelley et al., 1990 /43/), but Schmidt numbers greater than 1 must be invoked (see explanation in the next section). On other occasions, the radar reflectivity which can be estimated from the level of observed turbulence is smaller than the observed radar reflectivity unless an anisotropy of the fluctuations is assumed. Inhester et al., (1990) /10/ found that a ratio of the horizontal to the vertical coherence length of about 10 agreed with their observations. At 224 MHz, the radar cross section is consistently too large (Röttger et al.,1988 /22/), and the spectral width does not seem to increase with the cross section as one would expect if turbulence were causing the echoes. Hoppe et al. (1990) /11/ have found that the spectral width is inversely correlated with the cross section, whereas Röttger and La Hoz (1990) /44/ show cases where the spectral width is independent of echo power. The apparent disagreement may make it necessary to subdivide PMSE further. Thomas et al. (1992) /13/ have found two types of echo: one where high reflectivities weakly correlate with large spectral widths, and one where there is a strong anticorrelation between reflected power and spectral width. Lübken et al. (1993) /45/ report on in situ rocket observations of neutral, electron, and ion fluctuations simultaneous with radar observations of PMSE. They find two types of PMSE, one with relatively wide spectral width which is connected to turbulence and one with very narrow spectral widths which is definitely independent of turbulence.

3.2 Heavy Cluster Ions

Kelley et al. (1987) /21/ have put forward an explanation for PMSE at 50 MHz that requires the narrow spectral widths occasionally observed at 933 MHz (see above). They argue that heavy (positive) cluster ions as observed by Björn et al. (1985) /36/ at the cold summer polar mesopause modify the diffusion coefficient of the electron gas, which of course is the tracer observed by the radar. When the turbulent cascade is damped for the neutrals by viscosity at scales near the Kolmogorov microscale, the heavy cluster ion density would continue to fluctuate at even smaller scales in a so-called viscous-convective subrange (spectral index -1) and, because of charge neutrality, force the electron density to fluctuate in the same way. Note that the Debye length is only a few *cm* at these heights. If the viscous-convective subrange extended out to scales smaller than 3 *m*, fluctuations could be strong enough to explain the 50 MHz echoes. If it extended to scales smaller than 0.67 *m*, even the 224-MHz echoes could be explained. Cho et al. (1992) /46/ have refined this concept to include charged aerosol particles. They identify a test with three radar frequencies to prove or disprove their suggestion. In their Figure 3, the volume reflectivity η for $S_c = 1000$ (defined below) is only a factor of

4—5 smaller than in the empirical relation (1). The spectral width of the 224 MHz echoes described above is, however, an open question.

The dimensionless Schmidt number S_c describes to what extent the power spectra of the electron density fluctuations and of the neutral density fluctuations are different. It is defined as $S_c = \nu/D$, the (local) kinematic viscosity ν divided by the (local) diffusion coefficient D of the electrons. If $S_c = 1$, the two spectra are in essence the same, and there is no viscous-convective subrange. In the situation described above, S_c becomes larger than one. Kelley et al. (1990) /43/ have estimated Schmidt numbers from observations in the presence of PMSE as high as 100.

3.3 Charged Dust

Havnes et al. (1990) /47/ have suggested that the modifications which the presence of positively charged dust particles impose upon the electron gas might account for the radar echoes. Hagfors (1992) /48/ has shown that this mechanism alone cannot create radar echoes as strong as they are observed. Havnes et al. (1992) /49/ have suggested that charged dust particles sedimenting near the mesopause may be inhomogeneously distributed (on a scale corresponding to radar wavelengths) by turbulent eddies. They find that the size distribution of the dust particles must have a sharp cutoff towards large particles for this mechanism to work. They suggest a frequency dependence of the radar reflectivity $\eta \propto k^{-6}$ for their scattering mechanism. This does not agree well with the empirical relation (1). As Cho et al. (1992) /46/, these authors stress the need for simultaneous, collocated radar observations at different radar frequencies to decide between the different proposed mechanisms. Relation (1) is from different times and places.

3.4 Recent Rocket and VHF Radar Observations

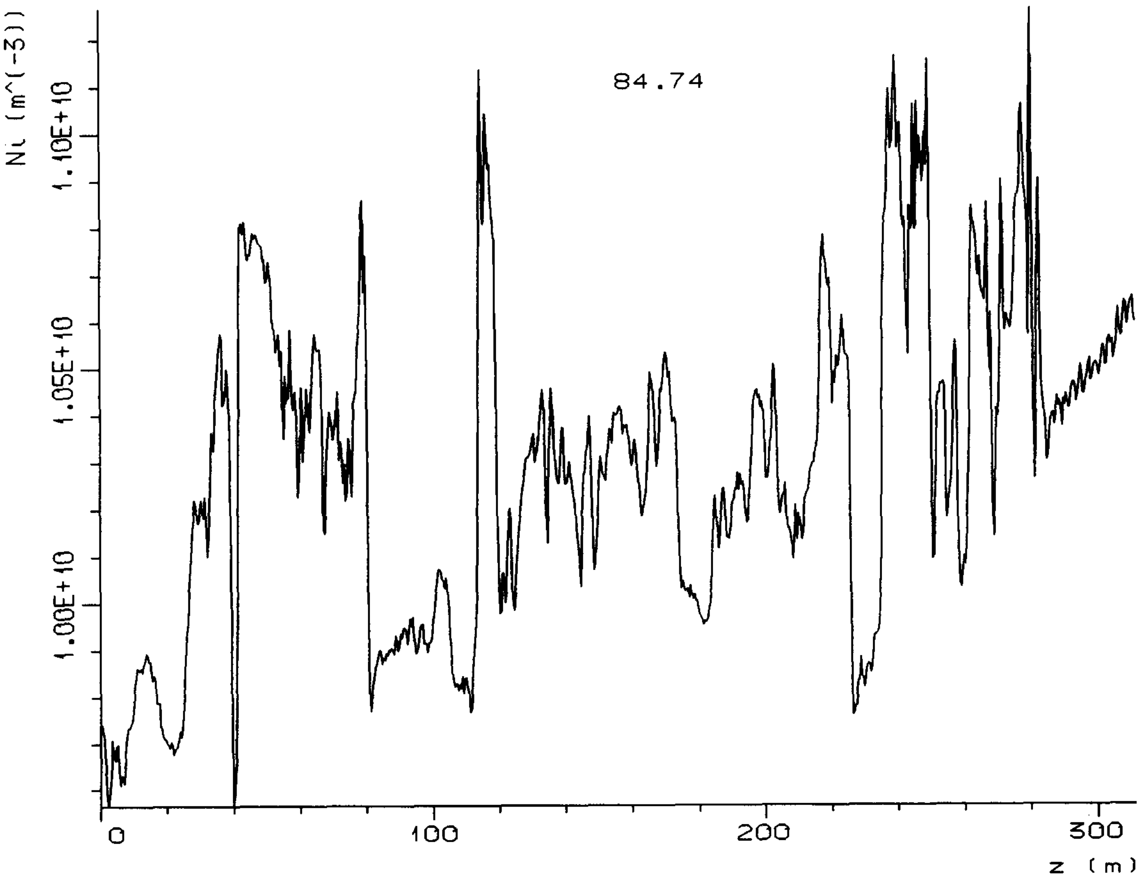

Fig. 1. Positive ion density as measured by rocket probe within a PMSE layer. 300 m of the vertical profile, centered on 84.74 km. The height resolution is approximately 0.3 m. Upleg data from rocket flight N-B-T05 from ESRANGE. The data plotted was taken at 1:41:23 UT on 1 August 1991.

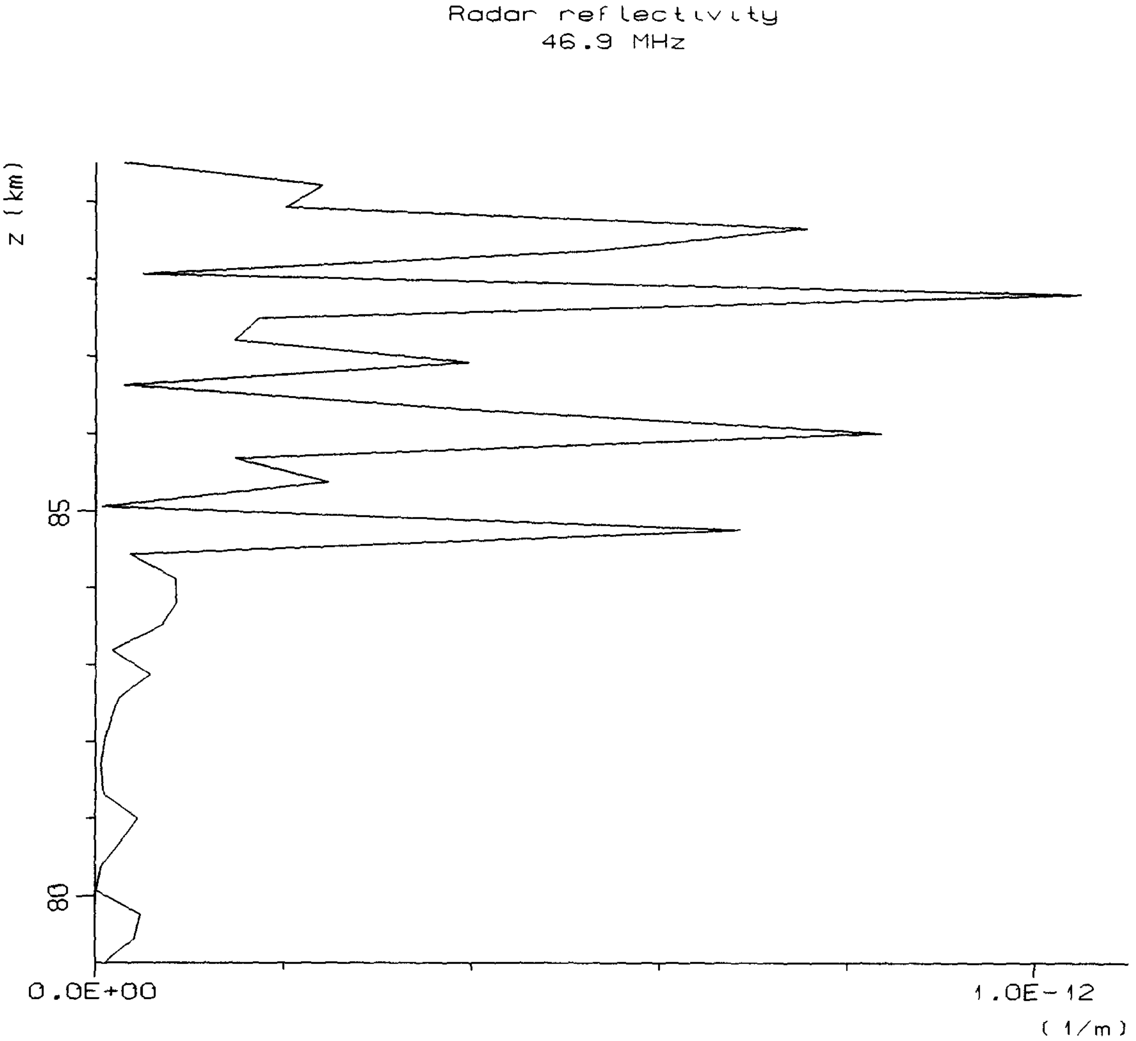

Fig. 2. Radar reflectivity as predicted from the complete ion density profile measured by rocket flight N-B-T05 on upleg.

In the summer of 1991, an international campaign, NLC-91 (Kopp et al., 1991 /50/), was aimed at understanding, among other things, the mechanism of PMSE. One of the rocket instruments flown was the TURBO payload (Blix and Thrane, 1991 /51/), which observed neutral density, positive ion density, and electron density simultaneously. All these observations were precise enough to allow fluctuations to be determined down to 0.1% . The height resolution of these observations is about 30 *cm*. Figure 1 shows the positive ion density measured over 300 *m* within a PMSE layer. Note that there are strong ion density fluctuations by as much as 10^9 m^{-3}, most of which occur over as little as 2—3 m in vertical extent. The spectra of the ion and electron fluctuations, and the absence of fluctuations in the neutrals, prove that there is no turbulence in this volume (Lübken et al., 1993 /45/). From the rocket observations, which give only two vertical profiles, we cannot decide whether or not the fluctuations are isotropic. If we assume that they are horizontally layered, as the similarity of the structures on upleg and downleg suggests, we can calculate the partial reflection from each transition. This has been demonstrated for lower radar frequencies by Haug et al. (1977) /52/. All the partial reflections can then be combined with appropriate phase to estimate a radar reflectivity from the in situ observation. The details of this method will be elaborated in another paper (Hoppe et al., 1993 /53/). The radar reflectivity at 46.9 MHz resulting from the complete rocket profile is shown in Figure 2. The actually measured radar reflectivity at this radar frequency is shown in Figure 3. The rocket and radar observations were taken 14 km and 140 s apart. We note very similar structures as far as the actual heights, gradients, and the ratio between maxima and background are concerned. We also note a discrepancy in the absolute magnitudes. The radar reflectivity calculated from the ion profile measured by rocket instrument is 100 times larger than the measured one. However, the PMSE were fading at the time of these observations: Two minutes later the radar showed only half the echo power. We do not know if a temporal variability of the PMSE also implies a spatial variability. Another possible explanation could be to speculate that the horizontal extent of

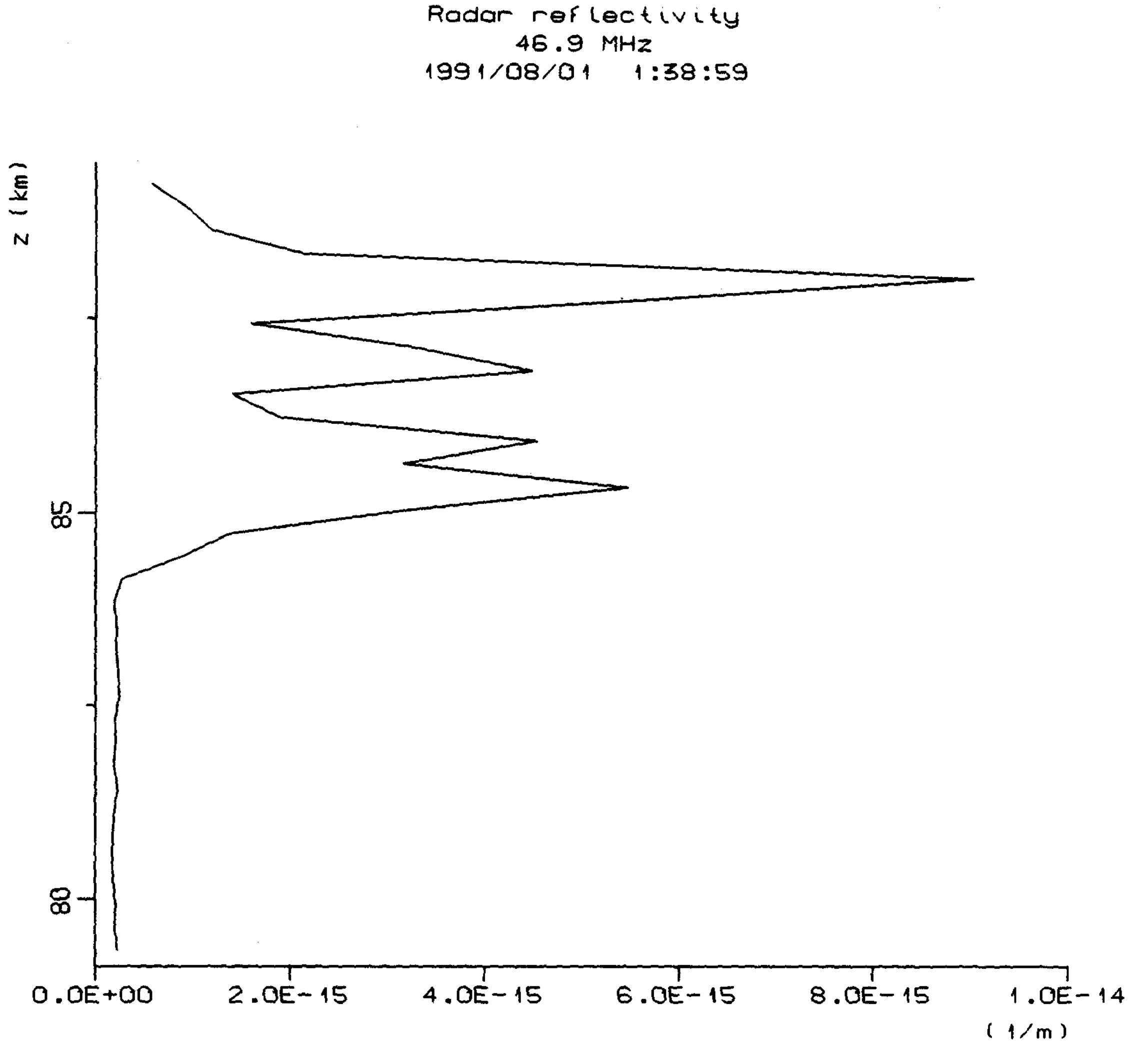

Fig. 3. Radar reflectivity as observed 14 km south of the rocket trajectory. Data from the CUPRI radar (Cornell University).

the structures is smaller than a Fresnel zone of the radar ($\simeq 1.5\ km$ diameter), contrary to our assumption in the simulation. Inhester et al. (1990) /10/ have measured radar reflectivities 4 times larger than our calculated result at another time. This shows that our result is not totally unrealistic. A comparison such as between Figures 2 and 3 can also be performed for 224 MHz and shows a structure in the predicted radar reflectivity similar to what is observed with EISCAT 224 MHz at the same time, but 190 km further north (Hoppe et al., 1993 /53/).

4. CONCLUSION

Some of the PMSE can be caused by an ensemble of partial reflections from structures as shown in Figure 1. There are, however, several open questions: We do not know by what mechanism structures such as those in Figure 1 are generated and sustained against molecular diffusion. Röttger and La Hoz (1990) /44/ have suggested spatial and temporal variability of the recombination rate of electrons due to a number of processes. Hoppe (1993) /54/ has proposed the combination of a large-scale upwelling and molecular diffusion against this average updraft. Turbulence and differential molecular diffusion as proposed by Havnes et al. (1992) /49/ is another candidate. Radar observations at two to three frequencies, together with rocket measurements of the type shown in Figure 1 are needed to decide between the several proposed mechanisms. — Most of the PMSE observations are from the auroral zone. Is there a connection here? The EISCAT Svalbard radar planned for 78° N for the near future may help to answer this question. — Then there is the climatological question of whether we have not observed PMSE earlier because we did not have the means (VHF radars were not used at the right time and place), or because the process as such is new.

The water vapor content in the mesosphere in general is not satisfactorily known, observations vary by as much as two orders of magnitude. The saturation vapor pressure of H_2O as a function of temperature is an important parameter for the formation of PMC and NLC, probably also PMSE. The values used today are from laboratory measurements or extrapolated from them. It is not clear whether they apply unmodified to mesopause pressure and to the D-region environment. This leads of course to the important field of atmospheric ion chemistry as a whole.

Present-day D-region incoherent scatter theory assumes positive ions of a single mass and electrons as minor species in the neutral atmosphere. Negative ions of a single mass have been included. What will the incoherent scatter spectra look like when heavy particles, negative, neutral, and positive ones, are added? Hansen et al. (1991) /55/ have studied a number of published D-region spectral observations. They found that the observed spectral widths are generally narrower than predicted, not only in polar summer, but also at lower latitudes and in other seasons.

It may be worthwhile to reanalyze earlier radar data, e.g. EISCAT Common Program data. Earlier instances of PMSE may have been discarded as interference or clutter. Polar cap communication links may also reveal PMSE signatures.

The characteristics of PMSE allow very precise measurements of a number of atmospheric parameters. We must be careful to remember that whatever we observe in PMSE may or may not be present at other places in the atmosphere, too. Not every phenomenon that we happen to observe in PMSE is necessarily connected with their generation process.

Independent of understanding the details of formation of PMSE, we can employ them in a number of ways. They have very large scattering cross sections in a range of radio frequencies, they are very localized in altitude, and they have very narrow spectra. They can thus be used for very precise wind measurements. Radar experiments can be devised with a high degree of sensitivity, range resolution, or spectral resolution, and these parameters can be traded off against one another. It should also be possible to use PMSE for communication within and across the polar cap.

ACKNOWLEDGMENTS

The first author is grateful to Drs. Asgeir Brekke, Richard A. Goldberg, and Marvin A. Geller for encouraging him to compile this review, and to Dr. Jürgen Röttger for useful comments. The Cornell group was supported under NASA Grant NAG5-666 and NSF Grant ATM-9021915. The EISCAT Scientific Association is supported by Naturvetenskapliga Forskningsrådet of Sweden, the Max-Planck Gesellschaft of Germany, Suomen Akatemia of Finland, Norges Almenvitenskapelige Forskningsråd of Norway, the Science and Engineering Research council of the United Kingdom, and Centre National de la Recherche Scientifique of France.

REFERENCES

1. W.G. Stroud, W. Nordberg, W.R. Bandeen, F.L. Bartmann, and P. Titus, Rocket-grenade observation of atmospheric heating in the Arctic, *J.Geophys.Res. 64*, 1342 (1959).

2. U. von Zahn and W. Meyer, Mesopause Temperatures in Polar Summer, *J.Geophys.Res. 94*, D12, 14647 (1989).

3. F.-J. Lübken and U. von Zahn, Thermal Structure of the Mesopause Region at Polar Latitudes, *J.Geophys. Res. 96*, D11, 20,841 (1991).

4. J. Murgatroyd and F. Singleton, Possible meridional circulations in the stratosphere and mesosphere, *Quart.J.R.Met.Soc. 87*, 125 (1961).

5. R.R. Garcia and S. Solomon, The effect of breaking gravity waves on the dynamics and chemical composition of the mesosphere and lower thermosphere, *J.Geophys.Res. 90*, 3850 (1985).

6. D.C. Fritts, U.-P. Hoppe, and B. Inhester, A Study of the Vertical Motion Field near the High-Latitude Summer Mesopause during MAC/SINE, *J.Atmos.Terr.Phys. 52*, 927 (1990).

7. R.S. Lindzen, Turbulence and stress due to gravity wave and tidal breakdown, *J.Geophys.Res., 86*, 9707 (1981).

8. G. Witt, Optical characteristics of mesospheric aerosol distributions in relation to noctilucent clouds, *Tellus XIX*, 4 (1967).

9. G.E. Thomas and J.J. Olivero, Climatology of Polar Mesospheric Clouds 2. Further Analysis of Solar Mesosphere Explorer Data, *J.Geophys.Res. 94*, D12, 14673 (1989).

10. B. Inhester, J.C. Ulwick, J. Cho, M.C. Kelley, and G. Schmidt, Consistency of rocket and radar electron density observations: Implications about the anisotropy of mesospheric turbulence, *J.Atmos.Terr.Phys. 52*, 855 (1990).

11. U.-P. Hoppe, D.C. Fritts, I.M. Reid, P. Czechowsky, C.M. Hall, and T.L. Hansen, Multiple-Frequency Studies of the High-Latitude Summer Mesosphere: Implications for Scattering Processes, *J.Atmos.Terr.Phys.52*, 907 (1990).

12. I.M. Reid, P. Czechowsky, R. Rüster, and G. Schmidt, First VHF Radar Measurements of Mesopause Summer Echoes at Mid-Latitudes, *Geophys.Res.Lett. 16* 135 (1989).

13. L. Thomas, I. Astin, and I.T. Prichard, The characteristics of VHF echoes from the summer mesopause region at mid-latitudes, *J.Atmos.Terr.Phys 54*, 969 (1992).

14. E. Turunen, P.N. Collis, and T. Turunen, Incoherent scatter spectral measurements of the summertime high-latitude D-region with the EISCAT UHF radar, *J.Atmos.Terr.Phys. 50*, 289 (1988).

15. P.N. Collis, T. Turunen, and E. Turunen, Evidence of Heavy Positive Ions at the Summer Arctic Mesopause from the EISCAT UHF Incoherent Scatter Radar, *Geophys.Res.Lett. 15*, 148 (1988).

16. J.Y.N. Cho, M.C. Kelley, and C.J. Heinselman, Enhancement of Thomson scatter by charged aerosols in the polar mesosphere: Measurements with a 1.29-GHz Radar, *Geophys.Res.Lett. 19*, 1097 (1992).

17. W.L. Ecklund and B.B. Balsley, Long-Term Observations of the Arctic Mesosphere with the MST Radar at Poker Flat, Alaska, *J.Geophys.Res. 86*, A9, 7775 (1981).

18. P. Czechowsky, I.M. Reid, R. Rüster, and G. Schmidt, VHF Radar Echoes Observed in the Summer and Winter Polar Mesosphere over Andøya, Norway, *J.Geophys.Res. 94*, D4, 5199 (1989).

19. J. Röttger, M.T. Rietveld, C. La Hoz, T. Hall, M.C. Kelley, and W.E. Swartz, Polar mesosphere summer echoes observed with the EISCAT 933-MHz radar and the CUPRI 46.9-MHz radar, their similarity to 224-MHz radar echoes, and their relation to turbulence and electron density profiles, *Radio Sci. 25*, 671, (1990).

20. U.-P. Hoppe, C. Hall, and J. Röttger, First Observations of Summer Polar Mesospheric Backscatter with a 224 MHz Radar, *Geophys.Res.Lett. 15*, 28 (1988).

21. M.C. Kelley, D.T. Farley, and J. Röttger, The Effect of Cluster Ions on Anomalous VHF Backscatter from the Summer Polar Mesosphere, *Geophys.Res.Lett 14*, 1031 (1987).

22. J. Röttger, C. La Hoz, M.C. Kelley, U.-P. Hoppe, and C. Hall, The Structure and Dynamics of Polar Mesosphere Summer Echoes Observed with the EISCAT 224 MHz Radar, *Geophys.Res.Lett. 15*, 1353 (1988).

23. C.M. Hall, U.-P. Hoppe, P.J.S. Williams, and G.O.L. Jones, Mesospheric Measurements Using the EISCAT VHF System: First Results and their Interpretation, *Geophys.Res.Lett. 14*, 1187 (1987).

24. P. Czechowsky, I.M. Reid, and R. Rüster, VHF Radar Measurements of the Aspect Sensitivity of the Summer Polar Mesopause Echoes over Andenes (69^{0}N, 16^{0}E), Norway, *Geophys.Res.Lett. 15*, 1259 (1988)

25. A.P. van Eyken and C.M. Hall, private communication (1992).

26. D.C. Fritts, S.A. Smith, B.B. Balsley, and C.R. Philbrick, Evidence of gravity wave saturation and local turbulence production in the summer mesosphere and lower thermosphere during the STATE experiment, *J.Geophys.Res., 93*, D6, 7015 (1988).

27. H. Rishbeth, A.P. van Eyken, B.S. Lanchester, T. Turunen, J. Röttger, C. Hall, and U.-P. Hoppe, EISCAT VHF Radar Observations of Periodic Mesopause Echoes, *Planet.Space Sci. 36*, 423 (1988).

28. P.J.S. Williams, A.P. van Eyken, C. Hall, and J. Röttger, Modulations in the Polar Summer Mesosphere Echoes and associated atmospheric gravity waves observed by EISCAT, *Geophys.Res.Lett., 16*, 1437 (1989).

29. J.C. Ulwick, K.D. Baker, M.C. Kelley, B.B. Balsley, and W.L. Ecklund, Comparison of Simultaneous MST Radar and Electron Density Probe Measurements During STATE, *J.Geophys.Res., 93*, D6, 6989 (1988).

30. A. Johannessen, D. Krankowsky, F. Arnold, W. Riedler, M. Friedrich, K. Folkestad, G. Skovli, E.V. Thrane, and J. Trøim, Detection of Water Cluster Ions at the high Latitude Summer Mesopause, *Nature, 235*, 215 (1972).

31. A. Johannessen, Investigation of the positive ion composition in the upper mesosphere and lower thermosphere during daytime, *NDRE Report 64, Norwegian Defense Research Establishment, Kjeller, Norway* (1974).

32. W.K. Hocking and J. Röttger, Amplitude statistics, absolute scatter cross sections and persistency of scatterers of polar mesosphere summer echoes deduced with the EISCAT 224 MHz Radar, in: *Proceedings of the fifth workshop on technical and scientific aspects of MST radar*, Aberystwyth, UK, SCOSTEP Secretariat,

Urbana, Illinois, ed. B. Edwards, 1992, p. 135.

33. E.J. Jensen, G.E. Thomas, and B.B. Balsley, On the statistical correlation between Polar Mesospheric Cloud occurrence and enhanced mesospheric radar echoes, *Geophys.Res.Lett.* *15*, 315 (1988).

34. M.J. Taylor, A.P. van Eyken, H. Rishbeth, G. Witt, N. Witt, and M.A. Clilverd, Simultaneous observations of noctilucent clouds and polar mesospheric radar echoes: Evidence of non-correlation, *Planet.Space Sci.* *37*, 1013 (1989).

35. B. Fogle and B. Haurwitz, Noctilucent clouds, *Space Sci. Rev.*, *6*, 278 (1966).

36. L.G. Björn, E. Kopp, U. Herrmann, P. Eberhardt, P.H.G. Dickinson, D.J. Mackinnon, F. Arnold, G. Witt, A. Lundin, and D.B. Jenkins, Heavy ionospheric ions in the formation process of noctilucent clouds, *J.Geophys.Res.* *90*, D5, 7985 (1985).

37. P. Schulte and F. Arnold, Detection of upper atmospheric negatively charged microclusters by a rocket-borne mass spectrometer, *Geophys.Res.Lett.* *19*, 2297, (1992).

38. G.E. Thomas, Mesospheric clouds and the physics of the mesopause region, *Rev.Geophys.* *29*, 553 (1991).

39. U. Wälchli, J. Stegmann, G. Witt, J.Y.N. Cho, C.A. Miller, M.C. Kelley, and W.E. Swartz, First height comparison of noctilucent clouds and simultaneous PMSE, private communication, (1993).

40. B.B. Balsley, W.L. Ecklund, and D.C. Fritts, VHF Echoes from the High-Latitude Mesosphere and Lower Thermosphere: Observations and Interpretations, *J.Atmos.Space Sci.* *40*, 2451 (1983).

41. D.C. Fritts, B.B. Balsley, and W.L. Ecklund, VHF echoes from the Arctic mesosphere and lower thermosphere, Part II: Interpretations, in: *Proceedings of the U.S.-Japan Seminar on the Dynamics of the Middle Atmosphere*, Terra Scientific Publishing Company, Tokyo (1983).

42. M.C. Kelley and J.C. Ulwick, Large- and Small-Scale Organization of Electrons in the High-Latitude Mesosphere: Implications of the STATE Data, *J.Geophys.Res.* *93*, D6, 7001 (1988).

43. M.C. Kelley, J.C. Ulwick, J. Röttger, B. Inhester, T. Hall, T. Blix, Intense Turbulence in the Polar Mesosphere: Rocket and Radar Measurements, *J.Atmos.Terr.Phys.* *52*, 875 (1990).

44. J. Röttger and C. La Hoz, Characteristics of polar mesosphere summer echoes (PMSE) observed with the EISCAT 224-MHz radar and possible explanations of their origin, *J.Atmos.Terr. Phys.52*, 893 (1990).

45. F.-J. Lübken, G. Lehmacher, T.A. Blix, U.-P. Hoppe, E.V. Thrane, J.Y.N. Cho, and W.E. Swartz, First In-situ observations of neutral and plasma density fluctuations in the presence of PMSE, *Geophys.Res.Lett.* in press (1993).

46. J.Y.N. Cho, T.M. Hall, and M.C. Kelley, On the role of charged aerosols in Polar Mesosphere Summer Echoes, *J.Geophys.Res.* *97*, D1, 875 (1992).

47. O. Havnes, U. de Angelis, R. Bingham, C.K. Goertz, G.E. Morfill, and V.N. Tsytovich, On the role of dust at the summer mesopause, *J.Atmos.Terr.Phys.* *52*, 637 (1990).

48. T. Hagfors, Note on the scattering of electromagnetic waves from charged dust particles in a plasma, *J.Atmos.Terr.Phys.* *54*, 333 (1992).

49. O. Havnes, F. Melansø, C. La Hoz, and T.K. Aslaksen, Charged dust at the Earth's mesopause: Effects on radar backscatter, *Phys.Scripta* *45*, 535 (1992).

50. E. Kopp, G. Witt, and R.A. Goldberg, NLC-91, in: *Proceedings of the 10th ESA Symposium on European Rocket and Balloon Programs and Related Research, Cannes-Mandelieu, France (ESA SP-317)*, ed. B. Kaldeich, 1991, p. 85.

51. T.A. Blix and E.V. Thrane, Middle atmosphere turbulence at high and middle latitudes, in: *Proceedings of the 10th ESA Symposium on European Rocket and Balloon Programs and Related Research, Cannes-Mandelieu, France (ESA SP-317)*, ed. B.Kaldeich, 1991, p. 437.

52. A. Haug, E.V.Thrane, K. Bjørnå, A. Brekke, and O. Holt, Observations of unusually strong partial reflections in the auroral D-region during an absorption event, *J.Atmos.Terr.Phys.* *39*, 1333 (1977).

53. U.-P. Hoppe et al., private communication (1993).

54. U.-P. Hoppe, Molecular diffusion against large-scale upwelling — a layering process? in: *Coupling Processes in the Lower & Middle Atmosphere*, ed. E.V. Thrane, Kluwer Academic Publishers, NATO ASI Series (1993).

55. G. Hansen, U.-P. Hoppe, E. Turunen, and P. Pollari, Comparison of Observed and Calculated Incoherent Scatter Spectra from the D-region, *Radio Sci.* *26*, 1153 (1991).