JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 102, NO. D2, PAGES 2001-2020, JANUARY 27, 1997

An updated review of polar mesosphere summer echoes: Observation, theory, and their relationship to noctilucent clouds and subvisible aerosols

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Abstract. Peculiar atmospheric radar echoes from the high-latitude summer mesosphere have spurred much research in recent years. The radar data (taken on frequency bands ranging from 2 to 1290 MHz) have been supplemented by measurements from an increasing arsenal of in situ (rocket borne) and remote sensing (satellites and lidars) instruments. Theories to explain these polar mesosphere summer echoes (PMSEs) have also proliferated. Although each theory is distinct and fundamentally different, they all share the feature of being dependent on the existence of electrically charged aerosols. It is therefore natural to assume that PMSEs are intimately linked to the other fascinating phenomenon of the cold summer mesopause, noctilucent clouds (NLCs), which are simply ice aerosols that are large enough to be seen by the naked eye. In this paper we critically examine both the data collected and the theories proposed, with a special focus on the relationship between PMSEs and NLCs.

Introduction

The Earth's atmosphere is characterized by many fantastic phenomena that can be seen with the naked eye. We observe a variety of clouds in the troposphere, the stratosphere, and the mesosphere. Deep convective storms produce spectacular lightning displays. At night we see meteoroids burning during their impact into the lower thermosphere and upper mesosphere. In the polar ionosphere, beautiful aurora result from atoms excited by precipitating magnetospheric particles. All these phenomena (clouds, lightning, meteors, aurora) are also detected by radars, although there are sometimes marked differences in the mechanisms that create the optical and the radar phenomena, and there are many cases when the radar and optical observations do not coincide in space and time. A radar can, for instance, observe the development of tropospheric convection, which cannot be seen visually; only at a later stage when the hydration process has started to create large enough water droplets do we see the cloud. To understand the physical-chemical reasons behind these observations, various theories, models, remote sensing techniques, and in situ instruments have been developed and applied.

Paper number 96JD02030.
0148-0227/97/96JD-02030$09.00

In this paper we will focus on radar observations of polar mesosphere summer echoes (PMSEs) and their relationship to noctilucent clouds (NLCs). NLCs have been observed for more than 100 years [*Gadsden and Taylor*, 1994a]. They occur in the summer months at altitudes around 82-83 km. They can be seen from the ground under twilight conditions when the Sun is below the horizon but is illuminating them in the mesosphere. Mesospheric clouds have also been studied with satellites [*Donahue et al.*, 1972; *Thomas*, 1984; *Evans et al.*, 1995] and by astronauts [*Packer and Packer*, 1977]; because these observations from space were not restricted to the nighttime, the clouds were given a more general name, polar mesospheric clouds (PMCs). Because of the different viewing geometries, NLCs and PMCs appear not to have exactly matching characteristics, even though they may be two facets of the same phenomenon. The most recent comparison of satellite versus ground-based observations support this interpretation [*Wiens et al.*, 1995]. For more information we refer the reader to the NLC papers in this issue.

PMSEs have mostly been observed with MST (mesosphere-stratosphere-troposphere) radars, which were introduced in the 1970s for observations of the structure and dynamics of the lower and middle atmosphere [*Woodman and Guillén*, 1974]. These radars detect echoes scattered from refractive index fluctuations of the clear and cloudy air, such as due to density, temperature, humidity, and electron density variations. They usually operate in the low VHF band around 50 MHz with peak powers of some 10 to 1000 kW and antenna areas of more than a few 1000 m^2. Typically, their height resolution is 150 m and their altitude coverage ranges up to 20-25 km in the stratosphere and (intermittently) 60-90 km in the mesosphere.

One usually assumes that the MST radars detect echoes from refractive index variations induced by turbulence and/or air mass mixing. In the troposphere, echoes can also be detected from hydrometeors and lightning. In the mesosphere, turbulence and air mass mixing occur, too, as the dominant scattering mechanism, but there is a major exception. This happens during PMSE events, which we will describe in more detail in this paper. We will also point to significant similarities with NLCs.

In recent years the polar mesosphere has also received attention in the popular press [*Stone*, 1991; *Gore*, 1992] because of the proposition that NLCs are a harbinger of global change. *Thomas et al.* [1989] posited that NLCs really were absent before their discovery in 1885 and that they have been steadily increasing due to the anthropogenic increase in atmospheric methane (about half of the mesospheric water vapor is believed to come from the photodissociation and oxidation of upwardly transported methane). Alternatively, a cloud increase can also be caused by a drop in mesopause temperature [*Gadsden*, 1990], which could result from an anthropogenic increase in CO_2 [*Roble and Dickinson*, 1989]. There is some evidence for an increase in NLC occurrence in the last 20 to 30 years [*Gadsden*, 1990]. And, as explained in the "Theory" section, PMSEs are also likely to be very sensitive to changes in temperature and water content; thus they too could be used as an index of global change.

Observations

Morphology

When the Poker Flat 50-MHz radar started operation in Alaska in 1979, the investigators immediately noticed that echoes from the summer mesosphere were several orders of magnitude stronger than those observed during other seasons [*Ecklund and Balsley*, 1981]. The averaged signal profile peaked at a height of 86 km and echoes were observed between about 75 km and up to 100 km. These characteristics were confirmed in the following years at Andenes in northern Norway by observations with the mobile souding system (SOUSY) 53.5-MHz radar [*Czechowsky et al.*, 1989].

For a general historical summary of PMSE radar observations we refer the reader to *Cho and Kelley* [1993] and *Röttger* [1994b]. In this paper we will concentrate on the comparison of radar-observed PMSEs and the visually observed NLCs.

The seasonal variation of PMSEs in the northern hemisphere shows a steep increase in occurrence at the end of May and a fade-out in mid-August [*Balsley et al.*, 1983b]. They also have a marked semidiurnal variation in echo strength with a prominent minimum near 2000 LT in all observations and a maximum just after local noon in most cases [*Balsley et al.*, 1983b; *Czechowsky et al.*, 1989; *Kirkwood et al.*, 1995; *Williams et al.*, 1995; *Palmer et al.*, 1996].

The PMSEs occur in layers up to a few kilometers in thickness and can also be as thin as the best radar range resolution of 150 m [*Franke et al.*, 1992]. They often occur in double or multiple sheets separated by a few kilometers. Their scatter cross section can change by 2 orders of magnitude within a few minutes, which is probably an indication of their horizontal patchiness, as observed by *Collis et al.* [1994] and *Bremer et al.* [1996b]. The PMSE layers are frequently lifted up and down in height by up to a few kilometers (Figure 1). This vertical motion can be quite dramatic, either wavelike with vertical velocity amplitudes up to 8–10 m s^{-1} for 6–20 minutes or even jumps of the same order of velocity occurring in less than 1 min [*Röttger and La Hoz*, 1990]. On longer timescales, such as many hours, the PMSE layers mostly move downward by 1–2 km h^{-1}. This is also observed in the mean vertical velocity, although we are not claiming an equivalence between these two velocities. Note that an apparent vertical movement of a layer can be due to the horizontal advection of a tilted layer, which has been observed [*van Eyken et al.*, 1991].

Czechowsky et al. [1988] and *Reid et al.* [1988] reported a substantial aspect sensitivity of PMSEs at 53.5 MHz of about 1–2 dB per degree zenith angle, an observation that is incompatible with isotropic scatter. Statistically, the aspect sensitivity of 50-MHz PMSEs grows weaker with increasing height [*Huaman and Balsley*, 1996].

Frequency Dependence

PMSEs have been observed at frequencies other than around 50 MHz. For example, PMSEs observed with the European incoherent scatter (EISCAT) 224-MHz radar show similar features, as observed at 50 MHz [*Hoppe et al.*, 1988]. *Röttger et al.* [1988] presented Doppler spectra of PMSEs at 224 MHz that were frequently much too narrow for turbulent scatter. However, quite broad spectra were also observed at times, indicating strong neutral turbulence. This was confirmed by simultaneous radar and rocket measurements [*Kelley et al.*, 1990]. These signals either developed from narrow spectra during gravity wave breaking events or were broad and turbulent from the beginning of their observations. The latter type frequently occurred in the upper portion of the PMSE observation region. The role of neutral gas turbulence in PMSEs is discussed further in the "Theory" section.

Later, PMSEs were also briefly observed on 933 MHz with the EISCAT UHF radar [*Röttger et al.*, 1990b] and on 1290 MHz with the Sondrestrom radar [*Cho et al.*, 1992b]. The former observation could be clearly discriminated from the incoherent scatter echoes due

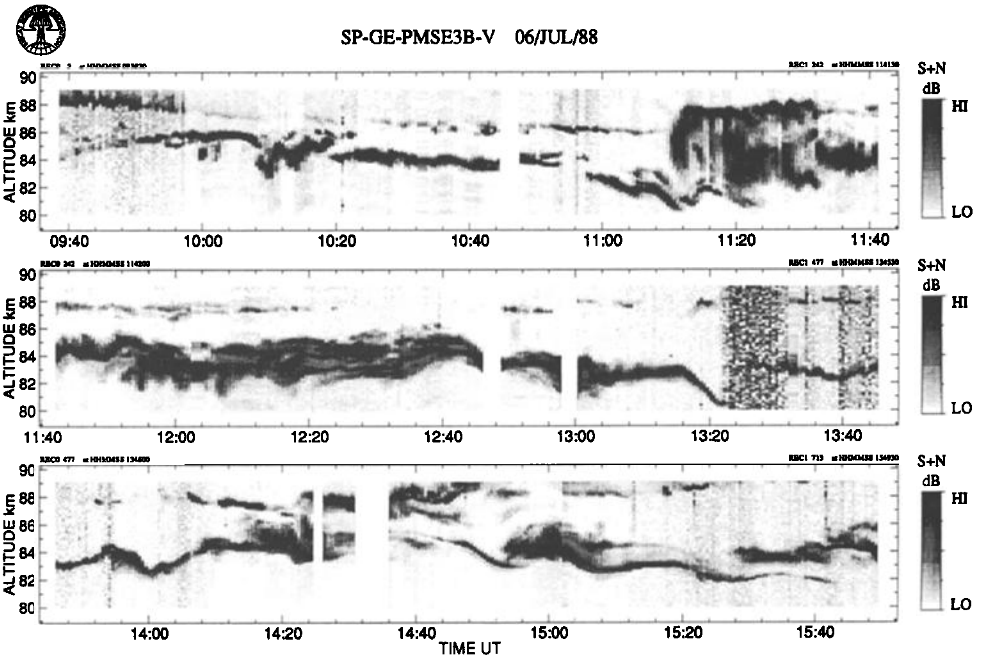


Figure 1. Six hours of height-time-intensity (HTI) plot of polar mesosphere summer echoes (PMSEs) observed with the European incoherent scatter (EISCAT) VHF radar, July 6, 1988. Each time slice is self-normalized to bring out the fine structural features [from *Havnes et al.*, 1992].

to their narrow spectra and high echo power. The 933-MHz incoherent scatter observations of the electron density around the later occurring PMSEs, observed by the collocated 46.9-MHz Cornell University portable radar interferometer (CUPRI), showed a biteout, as also observed by rocket probes [*Ulwick et al.*, 1988; *Inhester et al.*, 1990].

Recently, PMSE-like echoes were observed in the HF (8–9 MHz) band over Vasil'sursk, Russia (56°N) [*Karashtin et al.*, 1996]. The occurrence rate was close to 100% in the 83 to 91-km altitude zone. The coarse height resolution of 3 km precluded a detailed study of echo characteristics, but the general features, such as slowly descending layers, were very similar to those of VHF PMSEs.

At the very low end of the frequency spectrum, radar echoes were also recently observed on MF (2.78 MHz) at high latitudes in summer, which appear to be related to the PMSEs observed simultaneously with the EISCAT 224-MHz radar [*Bremer et al.*, 1996a]. Not many simultaneous, collocated observations of PMSEs at multiple frequencies have been done so far, and only rough estimates of their scatter cross sections exist as a function of frequency. *Röttger* [1994b] presented a multifrequency (or multiwavelength) schematic for PMSEs that outlines the possible scattering mechanisms, ranging from partial diffuse reflection from steep electron density gradients causing echoes at few-hundred-meter scales to enhanced Thomson scatter resulting in echoes for radars with short wavelengths of less than 1 m. These different mechanisms must be kept in mind when comparing scatter cross sections at different frequencies. Estimates yield cross sections at 50 MHz that are up to 6 orders of magnitude larger than those at 933 MHz [*Röttger et al.*, 1990b]. Here we must insert a note of caution regarding these cross-section comparisons, since the scattering volume is usually not homogeneous (causing errors in cross-section estimates) and the observations were not done with collocated radars or equivalent radar configuration [*Hoppe et al.*, 1990].

Latitudinal Dependence

PMSEs are not just confined to high latitudes above ~ 60°, but they also occasionally occur at midlatitudes. *Czechowsky et al.* [1979] first observed summer echoes at 52°N with the 53.5-MHz SOUSY radar that were quite similar to PMSEs, later confirmed by *Reid et al.* [1989]. *Thomas et al.* [1992] and *Thomas and Astin* [1994] have recorded similiar echo characteristics with the 46.5-MHz radar in Aberystwyth, Wales, also at 52°N.

PMSEs should also occur in the Antarctic. However, it appears that there is a hemispheric difference in the occurrence of PMSEs, since they are almost absent (reported to be at least 30 dB weaker during the first 2 years of observations) at 62°S over King George Island, Antarctica, which may be an indication of a warmer summer mesopause in the southern hemisphere [*Balsley et al.*, 1993, 1995]. *Olivero and Thomas* [1986] noticed that southern hemisphere PMCs were dimmer than northern hemisphere PMCs, which could be explained by either less water vapor or warmer temperatures in the south. If the water vapor is assumed to be the same, then the southern summer mesopause must be 3 to 4 K warmer than the northern one [*Thomas*, 1995]. The satellite data of *Barnett and Corney* [1985] support this temperature difference. Thus the hemispheric asymmetry in mesospheric clouds and temperature observed by satellites is consistent with the PMSE observations and the idea that they are critically dependent on low temperatures and ice particles. Global regions of temperatures low enough to produce PMCs have been calculated by *Memmesheimer et al.* [1986], and similar calculations using the MSIS-E-90 model have been done with respect to PMSEs [*Hall*, 1995, 1996]. Their results confirm the north-south asymmetry and the northern midlatitude extension of PMSE occurrence.

Connections With Other Phenomena

The first mention of NLCs and their potential relationship to PMSEs was made by *Ecklund and Balsley* [1981], who suggested that water vapor, being a prerequisite for NLCs, might acquire electrons and thus create sharp gradients increasing the scatter cross section of VHF radar waves. This was not an unreasonable proposal, since sharp electron density gradients/bite-outs were already observed with rockets by *Pedersen et al.* [1970]. Several later rocket measurements, carrying different kinds of probes, have proved the existence of these bite-outs [*Kelley and Ulwick*, 1988; *Inhester et al.*, 1990]. They are also seen in electron density profiles measured with the incoherent scatter radar technique [*Röttger et al.*, 1990b]. These bite-outs (and also the less dramatic depletions of electron density in the PMSE region) are now believed to be created by subvisible ice particles scavenging the electrons [*Reid*, 1990, 1995; *Klostermeyer*, 1996]. Within these bite-outs and at their edges, small-scale electron density irregularities are observed, and their spatial fluctuation spectra can extend to scales smaller than the inertial subrange of neutral turbulence [*Kelley and Ulwick*, 1988]. The irregularities were shown to be the scatterers for PMSEs that were observed simultaneously with the Poker Flat VHF radar [*Ulwick et al.*, 1988].

Czechowsky et al. [1989] and *Kelley et al.* [1990] noticed a correlation of cosmic noise absorption (i.e., *D*-region electron density) with integrated PMSE power. One expects some dependence of the echo power on electron density (after all, the echoes would be negligible without any free electrons), but there is no clear case-to-case correlation with high-energy particle precipitation [*Luhmann et al.*, 1983; *Kirkwood et al.*, 1995]. In the sunlit summer mesopause of the polar region there is probably enough *D*-region electron density most of the time to provide a sufficient background level for whatever mechanism generating PMSEs. This may not be true in the very late part of the PMSE season (especially at night) and there have been some hints that particle precipitation might have some effect in that case [*Hoffmann et al.*, 1995]. *Rishbeth et al.* [1988] noticed the same periodicity in PMSE variation as those in the magnetic field (i.e., the auroral electrojet), whereas *Kirkwood et al.* [1995] found no correlation between PMSE and magnetic field fluctuations. On a related note, some correlation between auroral electrojet intensity and the upper mesospheric wind field in the summer was reported by *Balsley et al.* [1982]. However, a direct causality between these variations has not been verified [*Röttger et al.*, 1990b; *Kirkwood et al.*, 1995].

Several features of PMSEs are quite similar to those of NLCs, such as their geographic appearance at high latitudes, their seasonal variation, their altitude of occurrence near the mesopause (although the mean NLC altitude is about 2-3 km below the mean PMSE altitude [*Ecklund and Balsley*, 1981; *Gadsden and Taylor*, 1994b]), their thin and layered formation, and in particular their wavelike, steepened, and breaking structures.

Correlative studies between mesospheric clouds and PMSEs have been difficult because of either poor spatial resolution (PMCs) or the impossibility of continuous observation (NLCs). Comparisons of satellite-observed PMCs and the Poker Flat radar record of PMSEs yielded a weak correlation [*Jensen et al.*, 1988], while ground-observed NLC occurrence have not been correlated with PMSE occurrence [*Taylor et al.*, 1989; *Kirkwood et al.*, 1995]. On the other hand, simultaneous rocket and radar observations have shown a PMSE layer lying above an NLC layer [*Wälchli et al.*, 1993; *Blix and Thrane*, 1993; *Swartz et al.*, 1993]. Recently, *Lübken et al.* [1995] have been able to measure NLCs and PMSEs with high spatial resolution in the same volume. Their simultaneous VHF radar and lidar observations, together with rocket-deployed passive falling-sphere temperature profiles, over Andøya, Norway are shown in Figure 2. *Nussbaumer et al.* [1996] studied the temporal development of the same data set and showed the lower ledge of the PMSE layer indeed coinciding very well with the layer of enhanced lidar scatter cross section (Figure 3). Although visual observations were not available to confirm that the lidar was scattering from particles big enough to be seen from the ground as NLCs, this is a clear proof that there are constituents of the same structure in the mesopause that increase the cross section of lidar and radar scatter. It is interesting to note that there were PMSEs observed above the lower ledge of the layer where the lidar did not show any echo. We will take this up again in the section "Evidence for a Connection Between Subvisible Charged Ice Aerosols and PMSEs."

Dynamics and Thermal Structure

We find many exquisite displays of NLCs in the literature [e.g., *Witt*, 1962], *Gadsden and Schröder* [1989], *Thomas* [1991], and *Gadsden and Taylor* [1994a]. All of these images show articulated organization of waves with different wavelengths, diverse propagation directions, steepened patterns, and occasional breaking into turbulent structures. Some of these features have been reproduced by recent dynamical simulations [*Fritts*

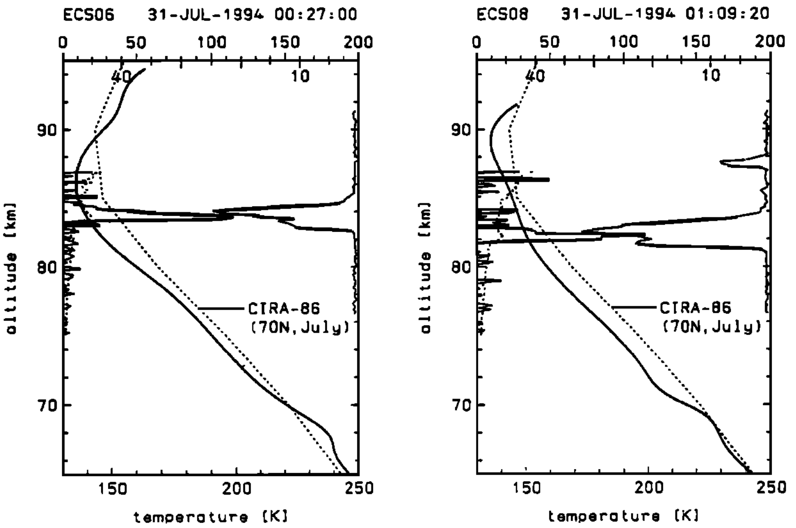


Figure 2. Temperature profiles (thick lines) measured by falling spheres launched from the Andøya Rocket Range in Norway at 0027 UT (left panel) and 0109 UT (right panel). The backscatter ratios from the Bonn University Rayleigh lidar (left ordinate, upper scale from 0 to 200) and the signal-to-noise ratio of the Arctic lidar observatory for middle atmospheric research sounding system (ALOMAR SOUSY) VHF radar in dB (right ordinate, upper scale from 50 to 0) are shown in each panel at the time of the falling sphere measurement [from *Lübken et al.*, 1995].

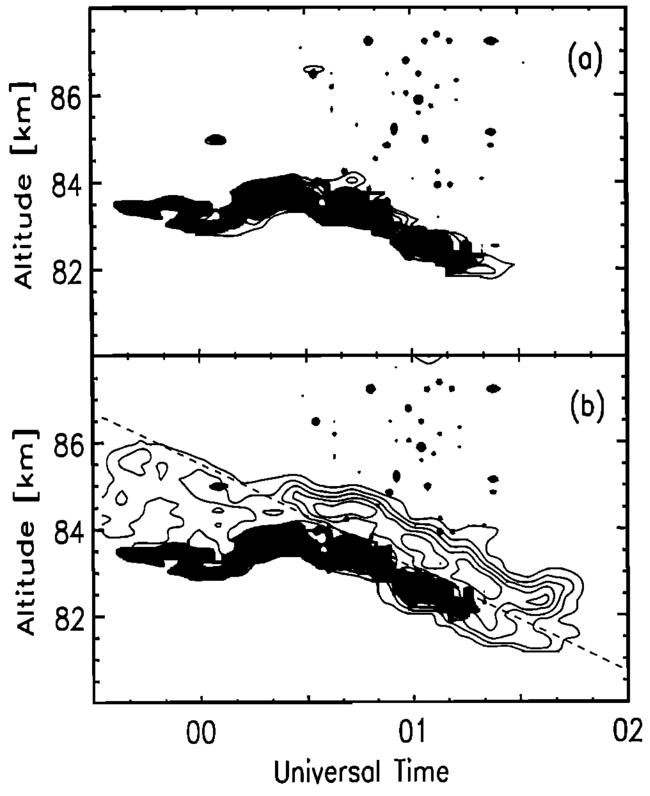


Figure 3. (a) Backscatter ratio plot from the ALOMAR lidar (contour lines) and the Bonn University (BU) lidar (shaded). (b) The BU lidar backscatter (shaded) versus the ALOMAR-SOUSY radar signal-to-noise ratio (contour lines). All instruments were located in Andøya, Norway, and the plots are from the night of July 30/31, 1994 (the same time frame as the previous figure) [from *Nussbaumer et al.*, 1996].

et al., 1993], showing once again the importance of these observations in advancing our knowledge of mesopausal dynamics.

PMSE observations also show a variety of dynamic features. These are observed in the height variation of the echoes and their Doppler velocity as functions of time (e.g., Figure 1 and Figure 4). Whereas visual NLC observations provide a horizontally extended image of the light-scattering ice particles, the radars observe a small section of the horizontal plane but with high vertical and temporal resolution; the radar scatterers are related to but not necessarily the same as the visual ones, as explained in the section "Evidence for a Connection Between Subvisible Charged Ice Aerosols and PMSEs." It is obvious, however, that both the NLCs and the PMSEs are displaying the dynamical structure of the mesopause. Knowing about the dynamical structure lets us deduce the temperature structure and investigate its mutual relationship to the generation of the light and radar scatterers.

Long-period (5-10 hours) waves and tidal components were first noted to be related to the occurrence and echo power of PMSEs by *Carter and Balsley* [1982] and *Balsley et al.* [1983b]. Recent studies have verified and quantified these relationships, but their interpretation varies [*Rüster*, 1995; *Cho and Morley*, 1995; *Williams et al.*, 1995]. The first two invoke wave-induced temperature changes as the link between the dynamics and PMSEs, while the third (and the early papers) attribute the link to wave-induced shear instabilities. In support of the latter explanation, *Fritts et al.* [1988] observed in a case study that the highest PMSE power occurred in the most unstable phase of a 7-hour wave.

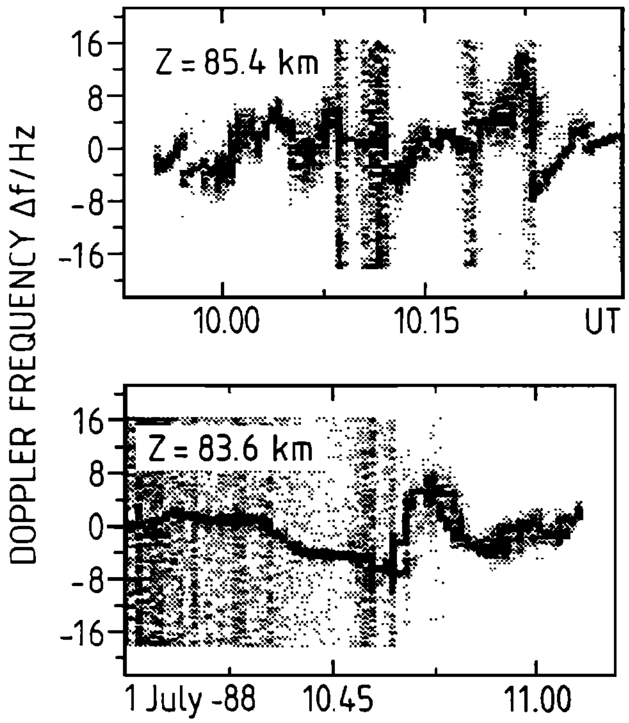


Figure 4. Self-normalized dynamic spectra of vertical velocity of polar mesosphere summer echoes (PMSEs) observed in single range gates with the EISCAT VHF radar. The Doppler frequency of 16 Hz corresponds to a vertical velocity of 10.7 m s^{-1} [from *Röttger*, 1994a].

And *Klostermeyer* [1992] has argued that layered turbulent structures are produced by parametric instability of long-period waves. On the other hand, *Czechowsky et al.* [1989] noted that the PMSE power did not generally correlate with wind shear. The case for PMSE dependence on dynamical temperature modulation is presented in the "Theory" section.

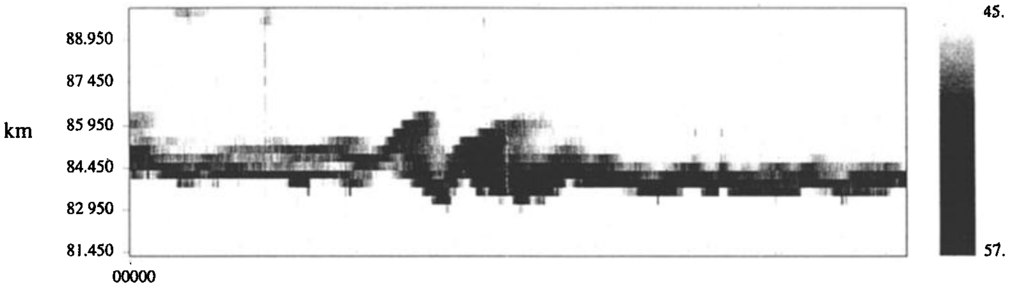
Another fascinating example of the dynamical processes in the mesosphere that can be observed due to the presence of PMSEs are short-period gravity waves. The radars observing PMSEs have very good altitude resolution (better than 100 m with frequency-domain interferometry [*Franke et al.*, 1992]), good horizontal resolution (by using spatial-domain interferometry [*Alcala et al.*, 1995]), and good Doppler frequency and time resolution [*Röttger et al.*, 1990a]. Multibeam radars can also glean information regarding the horizontal variation of scattering layers [*Rüster et al.*, 1996]. These capabilities allow, for instance, observations of rapid changes in velocity, as we noticed in Figure 4. *Röttger et al.* [1990a] claimed that these fairly regularly occurring jumps in frequency (see also *Cho and Kelley* [1993] and *Miller et al.* [1993]) are a signature of nonlinearly steepened gravity waves that move PMSE layers up and down. Thus the motion of PMSE layers can be regarded as accurate images of the dynamics of their environment. We still need to investigate how much these short-period dynamic processes affect the PMSE scatter cross section, however.

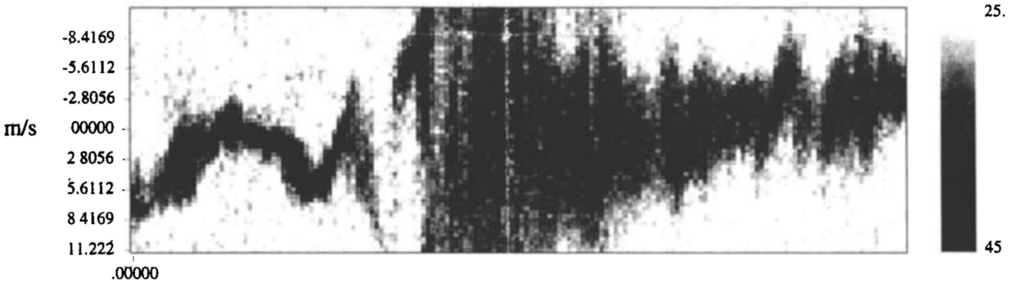
As a specific example of how PMSEs help us to image the dynamics, *Alcala et al.* [1995] described a thin sheet of PMSE that was lifted vertically by 300 m within a couple of minutes. Using spatial interferometry, they were able to show that during this event the horizontal wind also changed its direction dramatically. These observations are consistent with the so-called wind corners detected by rocket chaff experiments [*Widdel and von Zahn*, 1990]. These observations hint at the existence of solitary waves in the mesopause region.

That PMSEs have such characteristics of passive tracers are supported by other interferometric observations. *Pan and Röttger* [1996] investigated a PMSE event (Figure 5), during which an existing PMSE layer was modulated by a large-amplitude gravity wave. The spectrogram and the spatial coherence showed that during this wave event turbulence was almost negligible, but the PMSE power was strong. The wave grew in amplitude and finally ended up in a steep and fast frequency jump when the layer was lifted vertically by several hundred meters. Immediately thereafter, a Kelvin-Helmholtz instability structure was observed and the Doppler spectrogram was dominated by extreme turbulence. We conclude that during this event a preexisting PMSE layer was perturbed and broken up by violent turbulence, and the turbulence did not initially create the PMSE layer. These observations are consistent with in situ measurements by *Lübken et al.* [1993], who noted a PMSE layer in a nonturbulent environment but with sufficiently large electron density fluctuations to create the PMSE (Figure 6). They also reported a higher layer in which turbulent mixing caused the electron density fluctuations corresponding to the simultaneously occurring PMSE [*Cho et al.*, 1993]; *Ulwick et al.* [1993] also showed evidence for two different structuring and scattering mechanisms during the same rocket salvo.

Information on the momentum flux and nonlinear wave-wave interactions can also be gleaned from PMSE data. *Reid et al.* [1988] measured the gravity wave momentum flux and suggested that the most intense wave breaking occurred above 86 km, which they regarded as consistent with the onset of supersaturation as proposed by *VanZandt and Fritts* [1989]. *Rüster and Reid* [1990] used PMSE observations to estimate the mean flow acceleration due to wave momentum transfer as well as the mean winds and tides. *Rüster* [1994] showed that there were nonlinear interactions between waves in the mesopause region, and he presented results of interactions of the diurnal and semidiurnal tides and planetary waves with periods of 2 and 3 days. These kinds of measurements that involve variation with height would not be possible by NLC observations alone.

There is no question that both NLCs and PMSEs are related to the low temperature of the high-latitude summer mesopause. The temperature can be as low as 110 K [*Schmidlin*, 1992]. This is sufficiently lower than about 140 K at which condensation occurs for a water vapor content of 1 ppmv [*Gadsden*, 1981]. It


(a) HEIGHT-TIME INTENSITY


(b) SPECTROGRAM / 84.15 km

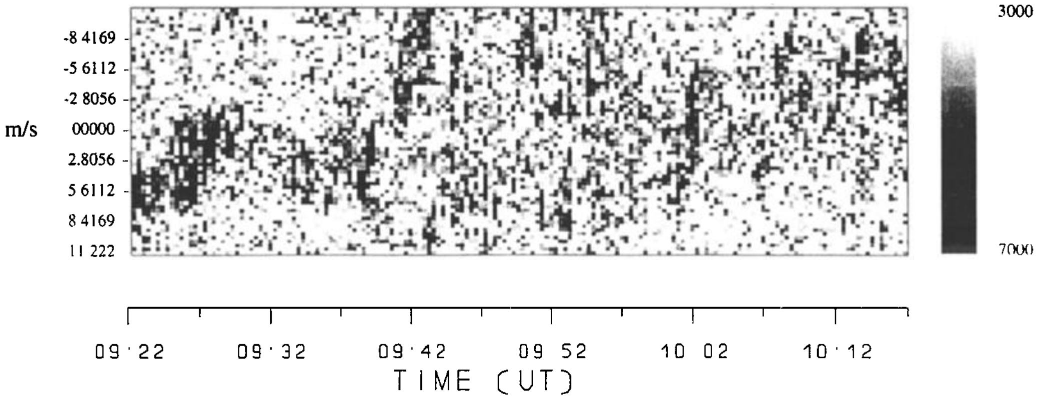

(c) COHERENCE SPECTRA / 84.15 km

Figure 5. (a) HTI, (b) Doppler spectrogram, and (c) coherence spectra from *Pan and Röttger* [1996], taken with the EISCAT VHF radar.

has been noted that the mean mesopause is at about 88 km [*von Zahn and Meyer*, 1989; *Lübken and von Zahn*, 1991; *Lübken et al.*, 1996], the mean height of PMSE peak power is at about 86 km [*Ecklund and Balsley*, 1981; *Czechowsky et al.*, 1989; *Bremer et al.*, 1995; *Palmer et al.*, 1996], and the mean height of NLCs is around 82-83 km [*Gadsden and Taylor*, 1994b; *Evans et al.*, 1995]. Why is there this difference in the altitudes of phenomena that we think are related? We have to recall that these are averages of height distributions that have a width of several kilometers and the instantaneous values differ. On the other hand, there is a real physical mechanism behind such a difference, which is explained in the section "Evidence for a Connection Between Subvisible Charged Ice Aerosols and PMSEs." Here we would just like to point out the relationship of the thermal structure to the dynamics. The mesopause is not a smoothly behaving minimum in temperature, and the temperature profile is undulated by tides and waves; the variance is significantly greater above 84 km than below [*Lübken et al.*, 1996]. This means that several temperature minima can occur in the range of interest between about 80 km and 90 km, which are only observable with a high-resolution instrument such as the accelerometer [*Philbrick et al.*, 1984]; the commonly deployed passive falling sphere method unfortunately has a resolution of a few kilometers in this height regime. These multiple temperature minima may be caused by steepened long-period waves [*Röttger*, 1993, 1994b] and could be the source of ice particle layers [*Reid*, 1995] that, in turn, create the multilayered structure of PMSEs.

We have no doubt that turbulence affects many of the PMSE observations. However, the predominantly narrow Doppler spectra (Figure 4), the recent radar interferometer observations (Figure 5), and the lack of neutral gas turbulence observed by rocket (Figure 6) lead us to conclude that turbulence is not a necessary precondition for PMSEs. Even the strongest turbulence in the mesopause would not cause any PMSEs for VHF radars without the reduction of electron diffusivity. The necessary (but not sufficient) factor for PMSE production is the presence of large charged species (such as

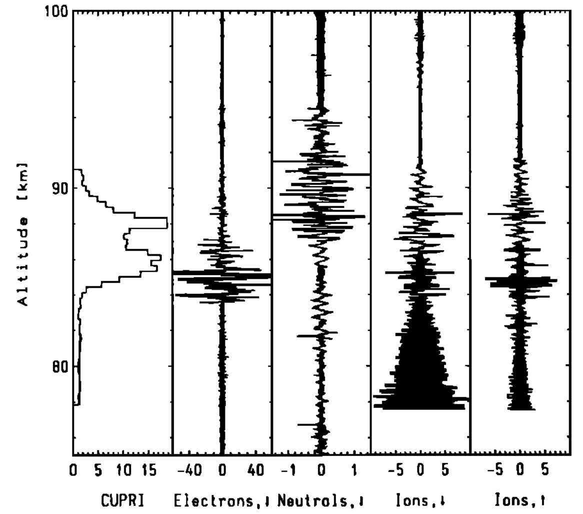


Figure 6. Signal-to-noise ratio from the 46.9-MHz Cornell University portable radar interferometer (CUPRI) and relative density fluctuations (in percent) simultaneously measured in situ by a rocket launched from Esrange, Sweden, at 0140 UT, August 1, 1991 (upward arrow is upleg, downward arrow is downleg) [from *Lübken et al.*, 1993].

ice aerosols and extremely large cluster ions) that lower the electron diffusivity. Low temperatures are required for the growth of such particles and thus also PMSEs. However, reduced diffusion alone is not the whole story; there must be a fluctuation production mechanism, of which turbulence is one, but definitely not the only one. The next section covers this topic in more detail.

Theories for VHF PMSEs

Before the discovery of PMSEs, VHF radar scatter in the mesosphere was thought to result from only three mechanisms: short-lived echoes from meteors, weak incoherent scatter from the *D*-region plasma, and electron density fluctuations directly produced by neutral gas turbulence. The peculiar nature of PMSEs soon convinced researchers that another mesospheric radar scattering phenomenon had to be added to this list. Note that we only discuss the theories of VHF PMSEs in this paper. Dressed aerosol scatter, which is the only viable but still problematic explanation advanced for UHF PMSEs, is presented, discussed, and critiqued elsewhere [*Havnes et al.*, 1990; *Cho et al.*, 1992a; *Hagfors*, 1992; *La Hoz*, 1992; *Klostermeyer*, 1994a; *Trakhtengerts and Demekhov*, 1995; *Cho et al.*, 1996]. The observations of PMSEs at MF and HF (see "Frequency Dependence" in the previous section) are still too recent for us to comment on in a substantial way in this review.

Note that in this paper we prefer to use the general term "scatter" to describe the mechanism causing the PMSEs, since we do not know much about the arrangements and individual cross sections of single-scatter elements in the radar volume. This term includes the traditional pure scatter from a volume homogeneously filled with single scatterers, collective scatter from individual larger ensembles or multiple sheets of scatterers in the volume [*Hocking*, 1985], and even partial diffuse reflection [*Röttger and La Hoz*, 1990]. We include the last mechanism, since we do not believe that gradients are steep and extend horizontally wide enough (of the order of a Fresnel zone (500 m at 50 MHz)) to cause specular reflection (W. K. Hocking and R. Röttger, Studies of polar mesosphere summer echoes over the EISCAT VHF radar using calibrated signal strengths and statistical parameters, submitted to *Journal of Geophysical Research*, 1996) at the VHF radar wavelengths of several meters.

Electron Density Fluctuation Production Versus Diffusion

The most obvious characteristic of VHF PMSEs that must be explained by any theory is the tremendously large echo power. To this end, it is useful to think of the problem in the following way. The radar waves are scattered by inhomogeneities in the electron density. Any fluctuation in the electron density is constantly being smoothed out by diffusion. Thus for radar scatter to take place, the balance between density inhomogeneity generation and diffusion must be in favor of generation. A larger-than-normal radar scatter cross section must then be due to an increase in generation, a decrease in diffusion, or both.

Cho et al. [1992a], following the ideas of *Kelley et al.* [1987], showed that a significant reduction in plasma diffusivity would occur in the presence of a large number of charged ice particles or very large (hydration number above 20) water-cluster ions. They also showed that if neutral gas turbulence was the generator of plasma fluctuations, then reasonable intensities of turbulence combined with reduced plasma diffusion could account for the observed PMSE cross sections. *Klostermeyer* [1994b] applied this idea to a height-dependent model for the ion and ice particle compositions and was able to reproduce the often observed feature of two maxima separated by a few kilometers in the power profile of PMSEs (Figure 7).

However, the observations tell us that neutral gas turbulence cannot be the only generator of plasma density fluctuations. In fact, it cannot even be the dominant generation mechanism, since for the majority of the time VHF PMSEs have spectral widths that are too narrow and aspect sensitivities that are too strong for turbulence scatter, as shown in the "Observations" section. (But there can be instances of very intense turbulence that dominate the fluctuation production [*Kelley and Ulwick*, 1988; *Kelley et al.*, 1990].) Therefore the search for an alternative generation mechanism has continued and has so far produced four candidates: dust-hole scatter [*Havnes et al.*, 1992], opalescence [*Trakhtengerts*, 1994a, b], charged-dust-diffusive (CDD) waves (W. K. Hocking, personal communication, 1996), and

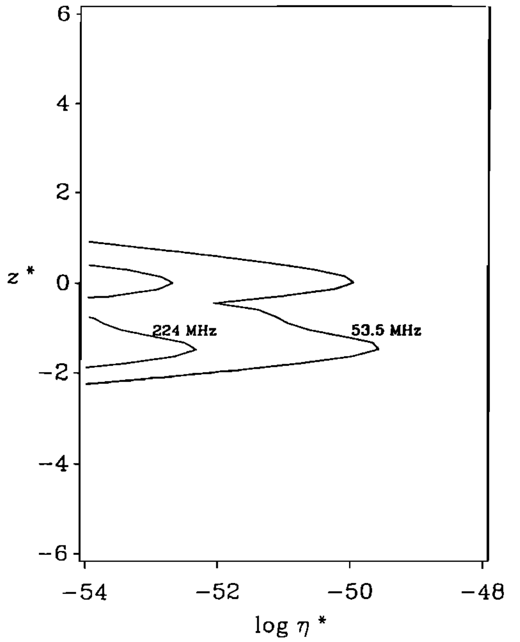


Figure 7. Height profiles of the radar reflectivity at frequencies 53.5 MHz and 224 MHz computed from the nominal model parameters; $z^* = 0$ is 88 km [from *Klostermeyer*, 1994].

vertical convergence (G. C. Reid, On the role of vertical convergence in the formation of electron biteouts and polar mesospheric summer echoes (PMSE), submitted to *Geophysical Research Letters*, 1996).

Dust-hole scatter. This mechanism requires the presence of horizontal vortex rolls embedded within a field of falling charged dust or ice aerosols. For a given range of fall speeds and vortex rotational rates, there will be a "forbidden" region within the vortex into which the aerosols cannot penetrate (Figure 8). Under such conditions there will be a sharp gradient in the aerosol concentration at the vortex wall. If the aerosols are charged, then there will be a corresponding gradient in the electron and ion densities. These density gradients, if sharp enough, will scatter radar waves at the top and bottom sides of the vortex wall.

There are four key conditions that must be met for this mechanism to work: the charged aerosols must dominate the overall plasma charge balance, the change in plasma density at the vortex wall must occur well within the radar Bragg scale (a half wavelength for monostatic radars), the plasma diffusion timescale must be much greater than the vortex turnover time, and the vortices must, of course, first exist in the neutral gas. (There is no experimental or theoretical proof yet for such vortices.) To meet the first three requirements, the upshot is that the aerosols must have a narrow size distribution with a fairly large mean size, and the vortices must be at scales that are small but are still possible in the neutral gas, say, of the order of a few tens of meters. More specifically, for VHF PMSEs the aerosols should have a mean radius ~ 0.1 μm, a number density of ~ 10 cm^{-3}, and a charge number of ~ 100.

Opalescence. This mechanism is a plasma instability somewhat reminiscent of the Farley-Buneman (two stream) instability [*Farley*, 1963; *Buneman*, 1963] that occurs in the electrojet region of the ionosphere. The counterstreaming components in the case of opalescence are ions and electrons versus charged aerosols, where gravity pulls down the heavy aerosols, while the lighter ions and electrons are advected upward by a neutral gas updraft. Because the aerosols are charged, electric fields provide the restoring force. A related idea was proposed by *Röttger and La Hoz* [1990] where the fall-speed differential leads to charge separation (a la thunderstorms) that produces a horizontal layering of the plasma that scatters radar waves.

The two key conditions for opalescence are that the aerosol-ion velocity difference must overcome the plasma diffusion and there must be enough charge-per-mass (apparently of the order of 5 C kg^{-1}) on the aerosols to create significant electric fields. Consequently, one needs a strong, sustained updraft and heavy aerosols with high charge numbers. For VHF PMSEs the updraft must be ~ 2 m s^{-1}, the aerosol ra-

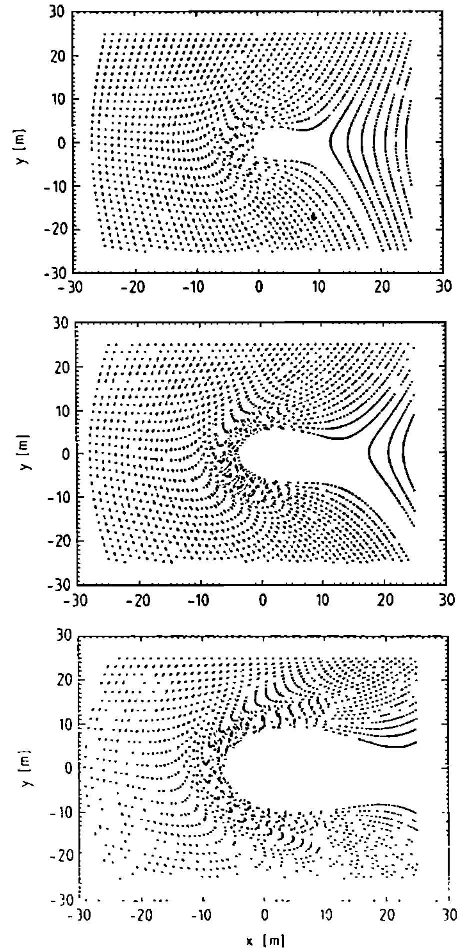


Figure 8. Calculations of dust orbits around neutral gas vortices for aerosol radii 0.15, 0.25, and 0.4 μm showing the differences in the size of the forbidden zone [from *Havnes et al.*, 1992].

dius must be $\sim 0.1\ \mu$m, and the aerosol charge number needs to be ~ 100.

Charged-dust-diffusive waves. A viscosity wave can be generated when an atmospheric gravity wave reflects from a discontinuity in the medium; it is a highly damped perturbation that results from a balance between the acceleration and the viscous dissipation terms in the momentum equation. It can also be thought of as a necessary product when the boundary conditions imposed at the discontinuity cannot be met with only the incident, reflected, and transmitted waves. (A loose analogy would be the creation of an evanescent wave on the other side of a total-reflection surface.) *Hocking et al.* [1991] proposed the viscosity wave as an explanation for the aspect-sensitive, Fresnel-type scatter evident in VHF stratosphere-troposphere radar data [*Hocking and Röttger*, 1983]. They postulated that gravity waves partially reflecting from regions of rapidly changing temperature gradient and gravity waves entering critical levels would create viscosity waves with the appropriate parameters for producing VHF radar scatter.

Charged-dust-diffusive (CDD) waves are driven by viscosity waves in the neutral gas but do not dissipate so quickly because of the aerosol-induced reduction in plasma diffusivity. As a candidate for generating mesospheric electron density perturbations that can scatter VHF radar waves, the key parameter is the vertical wavelength of the driving viscosity wave, which scales as $\nu^{1/2}\omega^{-1/2}$, where ν is the kinematic viscosity and ω is the forcing wave frequency. Because ν increases with height, in the mesosphere it is impossible for reflecting gravity waves to create viscosity waves with vertical wavelengths short enough to scatter VHF radar waves. This is why Hocking and Rottger invoked infrasound waves instead of gravity waves as the source. The idea is that infrasound inpinging on a region of rapidly changing temperature gradient in the vicinity of the mesopause produces viscosity waves in the neutral gas and, correspondingly, CDD waves in the plasma density with short enough vertical scale lengths to scatter VHF radar waves.

Vertical convergence. To visualize vertical convergence, one should look at a cumulus cloud tower as it grows upward to the stable "lid" of a tropospheric inversion or even the tropopause (i.e., a deep convection event). As the vertical convection encounters the bottom of the inversion, the flow is forced to spread horizontally and an anvil cloud begins to form; the flow convergence has transformed a vertically spread cloud into a thin, horizontal one. In the mesosphere, zones of convergence associated with the steepening of long-period gravity waves and their nonlinear interactions can distort regions of diffuse ice particles into thin, horizontal layers in much the same way. Then the ice aerosols can scavenge electrons to form abrupt depletions in the electron density that could scatter radar waves.

An idea somewhat related to vertical convergence is a layering process driven by the balance of a steady upwelling (a condition that exists for the summer mesosphere) with the diffusive gradient of a tracer in the opposite direction. *Hoppe* [1993] studied this phenomenon for water cluster ions and concluded that for reasonable upwelling velocities layers thin enough to produce PMSEs could not be created.

Charged Aerosols

Note the crucial role that charged aerosols (here we use the term to encompass the entire size range from cluster ions to noctilucent cloud particles) plays in every theory, either directly as a part of the fluctuation generating mechanism or, in every case, because they are necessary to maintain the electron density structure at the radar Bragg scales by reducing diffusivity. Therefore before being able to evaluate the likelihood of a given theory, we need to discuss the nature of these aerosols.

NLCs have been observed and studied for over a hundred years in the northern hemisphere [*Gadsden and Taylor*, 1994a]. Because of the difficulty in taking in situ samples, it has never been proven conclusively that they are composed of ice particles, but the community consensus is strong that such is the case. Ice particles nucleate around water-cluster ions and/or meteoric dust in the mesopause then grow, if the conditions are favorable, to larger sizes as they sediment to lower altitudes. Growth is limited by the availability of water vapor and the increase of temperature with decreasing height. Since the mean meridional flow around the summer mesopause is equatorward, there is also the horizontal advection of the particles into the warmer, lower latitudes that limit the extent of clouds. Sometimes the particles become large enough to be seen from the ground with the naked eye, and this is what we call NLCs.

Logically then, there must be ice particles that have radii ranging from the barely nucleated stage (< 1 nm) to that of NLCs ($\sim 0.1\ \mu$m), because the largest particles must have grown from smaller ones. Because of the technical difficulties involved, one has not been able to detect such particles until very recently. We discuss those observations in the next section.

The particle size is crucial. *Cho et al.* [1992a] showed that the diffusion coefficients of ions and small charged particles are proportional to the inverse square root of their reduced mass. This can never become greater than the mass of the lighter species, whereas the diffusivities of charged aerosols larger than a critical radius (~ 0.5 nm) are proportional to the inverse square of their size. So small cluster ions and meteoric smoke particles cannot decrease the plasma diffusivity, but the growing ice aerosols have the potential to do so.

The other critical parameter is the aerosol charge. A pure ice particle, with a high photoelectric work function, would not be affected significantly by the solar energy impinging on it in the continuous daylight of the polar summer. Therefore the charge on an ice aerosol depends on the balance of ion and electron current to its surface. *Jensen and Thomas* [1991] calculated a charge number of -1 for radius less than 10 nm, and a linearly increasing charge with size so that a particle with radius 0.1 μm would carry a charge of -4. On the other hand, if the ice is not pure but contaminated by metallic species (e.g., from meteoric dust), then the photoelectric component could become significant and the aerosol may become positively charged. Without further evidence, the negatively charged scenario is the more conservative assumption.

We have seen that domination of the overall plasma charge balance by the aerosols is an important key for reducing the diffusivity and thus for all the proposed theories. Because the aerosols are constrained to only a few units of charge even for the largest ones according to the pure-ice assumption, charge balance dominance favors a large number of small aerosols rather than the converse; the electron-scavenging theory of bite-out formation also favors a large number of small particles [*Reid*, 1990]. In concrete terms, 10-nm aerosols with a charge number of -1 and number density of 1200 cm^{-3} in an ambient electron density of 2000 cm^{-3} would be sufficient to reduce the plasma diffusivity by 2 orders of magnitude [*Cho et al.*, 1992a]. The difficulty with the dust-hole scatter and opalescence theories is that other physical constraints require larger aerosols, which leads to the necessity of having large charge numbers per aerosol ($\sim$ 100).

It is clear that only the direct measurement of aerosol population, size distribution, and charge state, with fine spatial resolution, along with the neutral gas dynamics, will sort out the various theories. For now, let us examine the evidence that we have obtained so far.

Evidence for a Connection Between Subvisible Charged Ice Aerosols and PMSEs

First let us consider the observed correlation between PMSEs and NLCs. A significant correlation was not found between PMSEs and ground-based observation of NLC occurrence, while only a low correlation was reported between PMSEs and satellite measurements of PMCs (see "Connections with Other Phenomena" in the previous section). We need to find a reason for this, since the aerosol-dependent theories of PMSEs would initially lead one to expect a high correlation between PMSEs and NLCs.

The high correlation should only materialize if the aerosols responsible for producing PMSEs were large enough to be visible as NLCs. This would be the case for both dust-hole scatter and opalescence according to the estimates of aerosol size necessary to generate PMSEs given by their proponents. Thus the lack of statistical correlation between PMSEs and NLCs would argue against these theories.

Here we come to a crucial point: On the other hand, if the aerosols capable of producing PMSEs were preferentially smaller, subvisible ones [*Reid*, 1990], then one would not expect PMSEs and NLCs to occur in the same volume of space. The cloud growth model dictates that the ice particles grow from a large number of small, nucleating particles to a small number of large, coalescing particles [*Turco et al.*, 1982]. That is, when a mature, visible cloud exists, the chance of a large number of small, subvisible particles residing in the same volume is decreased because they have been used up to build the big ones, assuming water vapor conservation. Also, because of sedimentation the lighter, PMSE-producing aerosols will tend to reside above the NLC. However, another factor for the average PMSE occurring higher than NLCs is the increase in ambient electron density with height. The radar echoes get stronger with more free electrons available.

In situ measurement of subvisible ice particles is a problem that has only recently been tackled with any success. Ion mass spectrometers and Gerdien condensers have an inherent upper measurement limit in size [*Mitchell et al.*, 1990; *Friedrich et al.*, 1994; *Li et al.*, 1994], while optical sensors have a lower size limit [*Wälchli et al.*, 1993]. So far, particle impact detectors have also been restricted to the large-size regime, although better design, technology, and characterization hold promise for extending their range to smaller sizes [*Wälchli et al.*, 1993]. Roughly speaking, mass spectrometers have been capable of detecting up to $\sim$ 0.5-nm radius particles and aerosol impact detectors down to $\sim$ 50 nm, so that aerosols with a size range of about 2 orders of magnitude have been "dark matter" (i.e., undetectable by existing instruments) to us, and coincidentally, this is the size range that theory predicts is most crucial for PMSEs. Measurements at smaller scales in the summer mesopause region yield both positively [*Björn et al.*, 1985] and negatively [*Schulte and Arnold*, 1992] charged microclusters, and water cluster ions have been observed in conjunction with NLCs [*Goldberg and Witt*, 1977]. In recent experiments a depletion of positive ions was measured inside NLCs, which was attributed to ion attachment to a large number ($\sim$ 100,000 cm^{-3}) of small (1–2 nm) ice particles [*Balsiger et al.*, 1993, 1995, 1996]. On the other hand, small depletions of electron density [*Mitchell et al.*, 1995] as well as drops in conductivity [*Croskey et al.*, 1990] have been observed in NLC layers.

The first results from an innovative, double-gridded electrostatic probe called the Dusty show promise for detecting charged aerosols in the previously unobservable size regime [*Havnes et al.*, 1996a, b]. A Dusty launched during PMSE conditions (no NLCs) yielded two electron density bite-out regions that matched well with negatively charged aerosol layers, supporting the idea that electrons are scavenged by ice particles (Figure 9). The investigators estimated aerosol parameters of radius 20 nm and number density 1100 cm^{-3} at altitude 87.6 km assuming a charge number of -1. Another Dusty was flown through a region of simultaneously occurring PMSEs and NLCs; in this instance a region of electron density enhancement was observed that ap-

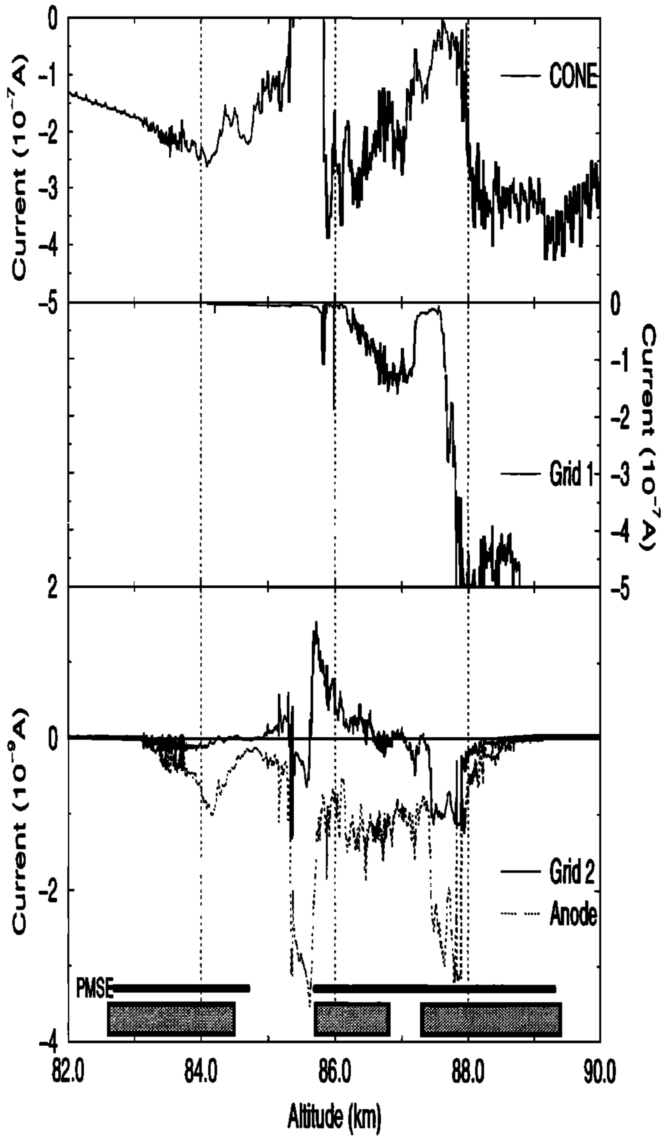


Figure 9. The measured currents as a function of height from grid 1 (biased at 6.2 V), grid 2 (biased at −6.2 V), anode (the dust collector at the bottom of the Dusty probe, biased at −2 V), and the electron portion of the CONE (combined neutral and electron probe mounted at the rear of the payload) probe. The height ranges of the PMSE backscatter signals given by the ALOMAR-SOUSY 53.5-MHz radar are indicated where the thin line refers to the signal at the time of rocket launch, and the thick bar is a "best fit" 9 min later (assuming advection of the rocket-probed volume). The rocket was launched from Andøya, Norway, at 2239 UT on July 28, 1994 [from *Havnes et al.*, 1996b].

parently corresponded to a layer of positively charged aerosols and NLCs. The authors inferred 60-nm particle radius with charge number $\sim$ 80 and number density $\sim$ 100 cm^{-3}. Note that these estimates should be taken with a grain of salt, since a number of assumptions had to be made to obtain them. However, this is the first evidence that photoelectric charging may be an important mechanism for NLC particles, and it is sure to motivate an intense debate on the nature of these aerosols.

There is indirect evidence for a connection between subvisible aerosols and PMSEs. Statistically, the peak of PMSEs occurs at 86 km, which is between the average mesopause at 88 km where the ice particles start to nucleate and the mean height of NLCs at 82-83 km (see "Dynamics and Thermal Structure" in the previous section). Simultaneous rocket and radar observations have shown the NLC layer lying below (or in the bottom portion of) the PMSE layer [*Wälchli et al.*, 1993; *Swartz et al.*, 1993; *Blix and Thrane*, 1993; *Havnes et al.*, 1996b]. And simultaneous lidar and radar measurements showed a PMSE region where the observed NLC fitted like hand-in-glove along the lower boundary of the PMSE (Figure 3). Unfortunately, the authors could not determine the size of the lidar-scattering particles, but they were certainly large enough to be optically detectable. Also, the occurrence of electron density bite-outs and depletions in the area of PMSEs can be construed as a sign of charged ice particles, since the scavenging of electrons by subvisible ice aerosols is their most likely explanation (see "Connections With Other Phenomena" in the previous section).

Because the formation of ice aerosols is critically dependent on the temperature falling below a threshold [e.g., *Gadsden*, 1981], if one ignores the variation in the water vapor supply, then PMSEs ought to correlate well with some threshold temperature if it requires ice particles. Climatologically, this was noticed to be true from the beginning [*Balsley et al.*, 1983a], although the causal link via ice particles had not been made. A higher-resolution comparison was made with a series of rocket-launched sensors [*Inhester et al.*, 1994], which showed that more than 80% of the PMSEs occurred at heights where the temperature fell below 140 K, a reasonable threshold temperature for ice formation in the mesopause. Water vapor variation apparently does play a role, however. *Balsley and Huaman* [this issue] showed that the seasonal curve of low summer temperatures is displaced from the PMSE occurrence curve by somewhat more than a week; they attributed this difference to the water vapor content peaking later than the temperature minimum.

However, because we do not have the capability of continuously measuring temperature profiles, others have used dynamics as a long-term proxy for temperature variations. The basic idea, assuming that temperature variations are strictly due to adiabatic expansion and compression, is that an oscillation in the vertical displacement will lag vertical velocity by 90°, which will be in phase with negative excursions in the temperature, so low temperature will lag upward velocity by 90°. Then, because ice growth takes a certain amount of time (about a few hours for 10-nm particles [*Turco et al.*, 1982]), the maximum density of subvisible particles will lag low temperature by 0° for longer cycle times to 90° for shorter cycle times. Note that the hydration of cluster ions proceeds more quickly, so their growth will follow the low temperature phase with little lag [*Hall*, 1990]. The conclusion is that PMSE power should lag upward velocity by 90° to 180°. So far, statistical studies have produced results that fall in this range [*Cho and Morley*, 1995; *Hoppe and Fritts*, 1995b], whereas single case studies of a particular gravity wave have both supported [*Rüster*, 1995] and disagreed with [*Fritts et al.*, 1988; *Williams et al.*, 1989] this scheme. The latter papers showed a correlation of echo power with the most unstable phase of the wave or the maximum upward velocity phase, respectively, suggesting the importance of turbulence as a dynamic input to echo production in certain instances. Such clear correlations between vertical velocity and signal power naturally leads to the suspicion that mean vertical motions calculated from PMSE data would have a significant bias; this problem is discussed separately in the section "Problem of Mean Vertical Velocity."

In a related development, *Sugiyama et al.* [1996] noticed a 5.5-day periodicity in the Poker Flat PMSE signal strength that did not correlate with the dynamics. Using an NLC model that assumed ion nucleation rather than meteoric dust nucleation [*Sugiyama*, 1994, 1995], they were able to reproduce the same periodicity in ice cloud formation using reasonable parameters. Thus mesopausal ice cloud formation (and thus, perhaps, PMSEs) may have a "natural" oscillation frequency due mainly to the available water recycling between gas and solid phases in a period of about 5.5 days.

Evidence for the reduction in plasma diffusivity has come from both radar and rocket observations. *Collis et al.* [1988], *Hall and Brekke* [1988], and *Klostermeyer* [1994a] used incoherent scatter radar spectral widths (which narrow with decreasing plasma diffusivity) to infer the presence of large charged species in the summer mesopause region. We must add a note of caution here: *Hall and Brekke* [1988] used a VHF radar for which, during PMSE conditions, coherent scatter dominates. Therefore by definition, one cannot derive pure incoherent scatter spectral widths while PMSEs exists. One should use UHF radars for this purpose, although they may also be affected by nonincoherent scatter mechanisms [e.g., *Röttger et al.*, 1990b]. *Lübken et al.* [1994] used rocket-borne probes to simultaneously measure neutral gas and electron density fluctuations within a PMSE layer. They were also able to confirm, by using a turbulence model, that the electron diffusivity in the PMSE layer was reduced.

Electric field measurements can also give us more information about charged aerosols. A comparison of data from a rocket-borne photometer and a double probe showed an abrupt electric field perturbation and irregularities inside an NLC [*Goldberg*, 1989]. *Zadorozhny et al.* [1993] used a rocket-borne field mill and recorded anomalously large values of the vertical electric field encompassing a region of PMSEs and NLCs. While the interpretation of field mill data as true electric fields in the presence of aerosols is controversial, the disturbance detected was an indication of strong electrical activity within a PMSE layer that was likely produced by charged aerosols.

Evidence for Neutral Dynamics Producing Plasma Fluctuations

All the plasma fluctuation production mechanisms that we discussed require some form of neutral dynamics as an input: turbulence, vortex rolls from shear instabilities, updrafts, infrasound waves, long-period gravity waves, or vertical convergence. Let us examine each one with respect to the observations.

The presence of energetic turbulence is deduced from radar data when the scattering is isotropic and the Doppler spectrum is wide (minus any beam-broadening effects [*Hocking*, 1985]). Statistically, noticeable turbulence in PMSEs occurs during a minority of the time and in the higher-altitude area of the PMSE zone [*Röttger et al.*, 1988; *Thomas and Astin*, 1994; *Czechowsky et al.*, 1996; *Huaman and Balsley*, 1996]. A possible exception is the report by *Yi et al.* [1992] of critical levels and maximum wave energy density located at the lower edge of the PMSE region, which they interpret as a sign of turbulence production. This, however, is an indirect indication and not a direct observation of turbulence. The preference of turbulence to occur in the higher PMSE sector was also observed during the Noctilucent Cloud 1991 (NLC-91) campaign (for campaign overview, see *Goldberg et al.* [1993] and *Goldberg et al.* [1994]). Simultaneous measurements of neutral and plasma density fluctuations during a double-layer PMSE event showed the upper layer to have neutral and plasma turbulence as measured by rockets, wide Doppler spectra, and isotropic scattering as observed by VHF radars, whereas the lower layer displayed no neutral turbulence, spiky (nonturbulent) plasma fluctuations, narrow Doppler spectra, and aspect sensitivity [*Cho et al.*, 1993; *Lübken et al.*, 1993; *Ulwick et al.*, 1993]. This result was important because until then one had only measured the plasma fluctuations, which had shown both turbulent and nonturbulent characteristics [*Kelley and Ulwick*, 1988], without simultaneously observing what the neutral gas was doing. In the PMSE zone, one cannot assume the same dynamical behavior for the neutrals and the plasma [e.g., *Hall*, 1993].

Dust-hole scatter requires horizontal vortices that result from shear microinstabilities. We would thus expect a correlation between PMSEs and zones of maximum wind shear. Such a correlation sometimes exists, although at larger scales than the required vortices, especially for weaker, broad-spectral PMSEs [*Czechowsky et al.*, 1989], which could be a sign of turbulence rather than coherent vortices. We recommend further investigation using high-resolution radar interferometry to probe for vortex structures.

Opalescence depends on a neutral gas updraft, so correlation with upward velocity should be manifested. As discussed earlier, this correlation is not generally observed, but it can happen in specific instances [*Fritts et al.*, 1988; *Williams et al.*, 1989].

The presence of infrasound and its scatter by sharp changes in the vertical temperature gradient are the keys to charged-dust-diffusive (CDD) waves. To check this theory we need to be able to observe infrasound waves and measure very high resolution temperature profiles in the presence of PMSEs, which will require the launching of accelerometers or other high-resolution instruments rather than passive falling spheres.

To investigate regions of vertical convergence, one needs a mapping of the temperature and three-dimensional wind field. True images of the wind field are difficult to produce with existing radar systems due to their single-line Eulerian nature of measurement, but radar interferometry may be used within the radar volume for high-resolution mapping.

Finally, let us note that all the nonturbulent fluctuation generators rely on Fresnel-type scattering to produce PMSEs (i.e., some deterministic horizontal and vertical structure). Assuming this is the case, it is possible to compute radar cross sections from a high-resolution profile of rocket-observed electron density if one assumes some value for the coherency of the density structure transverse to the radar beam. Such calculations have been carried out [*Hoppe et al.*, 1994] with some degree of success in comparing them to the actual radar data. But to make a truly convincing calculation, one needs a physical measurement of the horizontal coherence of individual vertical structures.

Problem of Mean Vertical Velocity

If the thermal structure of the summer polar mesosphere were strictly determined by radiative equilibrium, it ought to be warmer than the winter polar mesosphere. In fact, it is much colder [e.g., *Lübken and von Zahn*, 1991]. The accepted theory accounts for the discrepancy by a mean upward flow of the order of 1 cm s^{-1} to the summer mesopause that lowers the temperature via adiabatic expansion [*Lindzen*, 1981]. There's one problem, however. The long-term measurements of vertical velocity in the summer polar mesosphere made by both VHF and MF radars yield a mean downward motion. In the case of the VHF radar measurement over Poker Flat [*Balsley and Riddle*, 1984] the sink rate was ~ 20–30 cm s^{-1} that was only manifested in the PMSE zone, i.e., during June-July and in the upper mesosphere. The MF radar observed large downward motions throughout all mesospheric heights during the summer [*Meek and Manson*, 1989], so clearly the downward bias is not peculiar to PMSEs. We say "bias" since such large downward motions are physically incompatible with the observed thermal structure and horizontal motion away from the polar mesopause. It may be that the bias is especially pronounced during PMSEs due to the fall speed of the charged ice particles as suggested by *Hall et al.* [1992], who were able to rule out the earlier explanation that relied on the Stokes drift [*Coy et al.*, 1986]. Alternatively, *Stitt and Kudeki* [1991] suggested that the distortions in the large-amplitude gravity waves of the upper mesosphere could cause preferential sampling of certain phases of the velocity field.

In fact, radar measurements in the troposphere also yield significant mean downward speeds that contradict theoretical considerations. *Nastrom and VanZandt* [1994] proposed that vertically propagating gravity waves introduce a correlation between the radar reflectivity and the vertical velocity that results in preferential sampling. That is, for an upward propagating wave the phase of maximum static stability (which these authors claim corresponds to maximum radar reflectivity whether the scattering mode is turbulent or specular) occurs during maximum downward velocity. *Hoppe and Fritts* [1995a] analyzed a particular 4-hour segment of VHF PMSE data and showed that there was a correlation between reflectivity and downward velocity that was capable of introducing a significant downward bias. However, as discussed in "Evidence for a Connection Between Subvisible Charged Ice Aerosols and PMSEs," other studies yield different phase relationships between reflectivity and vertical velocity. Furthermore, we note that a bias in the velocity estimate can result if the noise is not adequately subtracted from the signal. Therefore one must be very careful to eliminate this effect before calculating velocity values.

Summary Discussion and Future Research Directions

One of the first things noticed about PMSEs was their climatological correlation with low temperature. Statistical studies using in situ measurements have given further evidence that PMSEs occur below a threshold temperature (about 140 K). The theory of reduced electron diffusion via charged aerosols has provided the causal link between low temperature and enhanced radar scatter; the presence of very large water-cluster ions (hydration number above ~ 20) and electrically charged aerosols retards the diffusive destruction of inhomogeneities at scales smaller than the neutral turbulence fluctuations in the electron density that scatter radar waves.

There are two other mesopausal phenomena that are linked to these charged aerosols. First is the electron density bite-out/depletion that has been observed in conjunction with PMSEs. Here, theory has also provided the causal connection: assuming a composition of pure ice, the most likely mechanism for creating a bite-out is electron scavenging by a large number of small (~ 10 nm) aerosols. Because the reduced diffusion theory also favors the same type of particles (arising from the requirement of overall plasma charge balance dominance by the aerosols), it makes sense that PMSEs occur in the same region as the electron depletions.

The second aerosol phenomenon is, of course, the NLC. Because the creation of particles forming these clouds are also dependent on low temperature and because the PMSE theories rely on the presence of aerosols, it is natural to surmise that NLCs and PMSEs should be correlated. The observations so far have been mixed; until recently, there were no truly collocated and simultaneous observations of NLCs and PMSEs. New results using lidar and radar to probe the same volume (Figure 3 is an example) showed that the two phenomena can either be tightly or loosely coupled and that for the former case, the NLC existed along the bottom of the PMSE. If one looks carefully at the reduced diffusion theory, then one realizes that it prefers a large number of small, subvisible particles over a small number of big, visible aerosols, assuming that the aerosols are pure ice that cannot get charged above a few electrons per aerosol. In this case, the relationship between NLCs and PMSEs would be analogous to an iceberg, where the visible tip is the small number of big particles that manifest themselves as NLCs and where the submerged mass is the large number of smaller, subvisible particles that create the right condition for PMSEs. On the other hand, if large, NLC-type particles can get highly multiply charged, then they too can act to reduce plasma diffusion even though their number density may be low. Both the average and "snapshot" heights observed of the mesopause, PMSEs, and NLCs are staggered in altitude, where NLCs are lowest, PMSEs above them, and both are below the average temperature minimum.

Reduced electron diffusion is a necessary but not sufficient condition for PMSEs. Whereas the reduced diffusion allows the persistence of density fluctuations at small scales to which the radars are sensitive that otherwise would be wiped out, the fluctuations have to be generated by some mechanism in the first place. In recent years the emphasis has been shifting away from strong neutral gas turbulence as the fluctuation generator due to the predominance of extremely narrow Doppler spectra and aspect sensitivity observed by VHF radars. No doubt, strong turbulence does occur at times (especially, it seems, in the upper region of the PMSE zone) with the resultant viscous-convective subrange as documented by rocket and radar experiments. However, some other mechanism must be working for the majority of PMSE events, and this is where several theories (dust-hole scatter, opalescence, CDD waves, and vertical convergence) have been proposed but not yet proven experimentally.

We have not discussed in any detail the PMSEs observed at radar frequencies other than in the VHF band. However, the dressed aerosol scatter mechanism proposed for UHF PMSEs and the MF echoes that are likely resulting from steep gradients associated with the electron density bite-outs are both clearly linked to the same sort of conditions that create VHF PMSEs. On the other hand, since the actual scattering structures are different, the PMSEs at the different radar Bragg scales may not correlate well with each other. Future experiments will have to sort out their relationship to one other.

Assuming that the initiation of PMSEs is not overtly dependent on short-period waves and turbulence, they can be used effectively as passive tracers for the structure and dynamics of the mesopause region, much as NLCs have been used in this regard for many years. They provide us with information (high temporal and altitude resolution, near-continuous time coverage) that NLCs have not been able to provide. However, because PMSEs are strongly dependent on the temperature, which in turn is modulated by dynamics and sometimes even directly dependent on turbulence, they are not pure tracers but neither are NLCs. Perhaps it is one aspect of such a dependence on the state of the medium that PMSE-derived mean vertical velocity appears to be unusually biased in the downward direction, although we have some reservations regarding these results. Average vertical velocity is difficult to measure, in general, and by radar under any circumstance, but PMSEs pose a special problem since its scattering mechanism is still under investigation. The various ideas put forth to explain the downward bias are still on trial and it will take very careful measurements with well-calibrated, highly sensitive, fine-resolution radars, and very careful analysis procedures to sort out the problem.

We have some ideas for future research: Radars in both the Arctic and Antarctic should be operated as continuously as possible to keep track of long-term trends that may show signs of global change as well as to further study the latitudinal dependence and asymmetry between the north and the south. To obtain new information from case studies, the radar techniques used must be pushed to new standards of spatial resolution (down to tens of meters with spatial and frequency interferometry, for instance). More exactly collocated multifrequency radar observations should be made to illuminate the relationship between the scatterers at different length scales. Horizontal imaging (optical CCD arrays for passive NLC observations, steerable lidars, and digital beam-forming radars) must be incorporated to sort out the difference between Lagrangian and Eulerian measurements. Simply accumulating statistics will not help to test the various scattering theories. It will also be of great interest to investigate those highly nonlinear effects of wave-wave interactions as well as the possibility of solitary waves as apparently observed by the radars.

Other remote sensing instruments such as lidars and satellites have been developed to the point of becoming useful allies in measuring cloud particles with better and better spatial and temporal resolution. They should be used whenever possible to complement the radar observations. New techniques such as artificial periodic inhomogeneity (API) [*Terina*, 1996] and meteor-trail-decay [*Tsutsumi et al.*, 1994] methods are being developed to investigate the diffusivity in the mesosphere. Although the former measures eddy diffusivity and the latter may not be able to measure the reduction in plasma diffusion associated with PMSEs (the ice aerosols and cluster ions may be destroyed by the heat dissipation of the meteor), they should be examined for possible application to PMSE studies.

In situ measurements are absolutely necessary, combined with ground-based radar and lidar observations. In this regard there are three things we would like stress. First, none of the rocket/radar experiments so far have been truly collocated. Given the often patchy nature of PMSEs over scales of several tens of meters to some kilometers, we must make the in situ measurement inside the radar volume, which has to be as small as possible; otherwise, we cannot draw firm conclusions from the experiment. Second, new types of probes must be developed to measure the size distribution and charge state of subvisible aerosols. These are the particles that the reduced diffusion theory says are most crucial for PMSEs, and we have not had the capability of measuring their various properties. Third, temperature measurements should always be made with as fine a resolution as possible. The passive falling sphere technique smooths out multiple local minima that are very important to the layering of PMSEs and NLCs and is not highly accurate in the mesopause region and above. We recommend the accelerometer method [*Philbrick et al.*, 1984], which has proven capable of detecting finer scale temperature features and is reliable to greater heights.

Laboratory studies of mesopausal ions and aerosols have been sorely lacking. We suggest that those laboratory researchers investigating polar stratospheric clouds ponder extending their capabilities to lower pressure and temperature regimes to simulate the summer mesopause environment. We realize it would be extremely difficult to reproduce the right plasma and chemical conditions, but limited experiments such as growing ice on different kinds of nucleation cores and determining their charging characteristics may be possible.

Finally, the various fluctuation generation theories can be further tested even in the absence of new experimental data. For example, the different mechanisms can be simulated on computer, then a "probe" can be "flown" through them for comparison with rocket-derived plasma fluctuation spectra and calculation of radar cross section as a function of frequency, including temporal and spatial variations. But ultimately, of course, what we need are real measurements to test the theories and any simulations, something that we are hoping to obtain in the future.

Acknowledgments. The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation. The EISCAT Scientific Association is supported by CNRS (France), MPG (Germany), NIPR (Japan), NFR (Sweden), PPARC (U.K.), RCN (Norway), and SA (Finland). Thanks to all the authors who made their yet-unpublished material available to us.

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(Received February 23, 1996; revised June 18, 1996; accepted June 18, 1996.)