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## The 1997 PMSE season - its relation to wind, temperature and water vapour

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**Abstract** Factors determining the onset and decay of the Polar Mesosphere Summer Echo (PMSE) season in 1997 are examined. PMSE from the ESRAD radar at 68° N, 20° E are compared with simultaneous observations of stratospheric winds, upper-mesosphere temperature, upper mesosphere water vapour and noctilucent clouds. There was a 3-week delay from the start of summer, defined by temperature or stratospheric winds, to the start of PMSE. At the end of the summer, the return to winter conditions was simultaneous in all three parameters. Noctilucent clouds at 55-60° N were confined to the period of lowest temperatures, when PMSE were also present throughout the day. Water vapour observations show an increase during the summer, possibly taking place in late May, at about the time PMSE first appeared. It seems likely that the start of the PMSE season is determined by water vapour availability, while the end of the season is determined by temperature.

### Introduction

PMSE, polar mesosphere summer echoes, are strong radar echoes commonly observed by VHF radars at high northern latitudes from heights between about 80-90 km. They are thought to be caused by the presence of small, charged aerosol particles, a few nm in diameter, in combination with neutral air or plasma turbulence (see Cho and Röttger, 1997 for a review). The region where they appear includes the same region of the atmosphere where noctilucent clouds (NLC) are seen, i.e. between about 82 - 85 km altitude, during the summer. NLC are considered to be composed of larger aerosols (a few tens of nm in diameter) and recent measurements of both phenomena in the same volume, made using co-located VHF radars and lidars, have shown that the NLC and PMSE are closely correlated, with the cloud layers often (but not always) lying in the lowermost 1-2 km of a PMSE layer (Nussbaumer et al., 1996, von Zahn, 1997).

Visual observations of noctilucent clouds over the past century have shown a tendency to more frequent cloud occurrence over the whole period and an oscillation with about 11 years period, apparently correlated with the solar cycle. These have been ascribed to increased greenhouse emissions and variations in solar radiation leading either to water vapour changes (Thomas et al., 1989, Thomas, 1995) or temperature changes (Gadsden, 1990) at NLC heights. In practice, it is difficult to obtain a consistent, detailed and long-term data set based only on visual observations, and it has been difficult to test these hypotheses. The closely related PMSE, on the other hand, are much more prevalent than NLC, can now be observed

continuously, independent of human observers and of the weather, and provide the potential for more exact studies of the state of the mesopause. Although it will be some years before sufficient PMSE observations are available to study long-term trends, it is already possible to address questions such as which factors influence their appearance and persistence.

It is clear that low temperatures are needed for the aerosols to form that constitute NLC and contribute to PMSE formation, while the turbulence and ionisation which are also needed for PMSE seem always to be available (Lübken et al., 1996, Kirkwood et al., 1995, Cho and Röttger, 1997). Regarding the temperature, it might be expected that ice aerosols would start to form as water vapour started to freeze out of the air at some threshold temperature, depending on the humidity. Similarly, they would be expected to evaporate when temperatures rose again above the threshold. Good consistency has been found in temperature measurements in this latter respect regarding NLC (temperature always below 154 K in NLC layers, Lübken et al., 1996), however attempts to find a threshold temperature for PMSE formation have so far been unsuccessful. The one available study (Balsley and Huaman, 1997), which compared the seasonal appearance of PMSE at the Poker Flat radar (Alaska), averaged over 3 separate years, with climatological temperature changes suggested that a seasonal change in water vapour content may be important since the PMSE season seemed to be delayed by 1-2 weeks with respect to the (climatological) period of lowest temperatures.

This paper presents the first results from a new VHF radar, ESRAD, situated near Kiruna in northern Sweden, which has been built with the primary purpose of making long-term studies of PMSE. First results comprise the seasonal variation of PMSE for the summer of 1997, which we examine in the context of its relation to the seasonal variation of the temperature at 80-90 km altitude, and the water vapour concentration at 65/80 km, from the same time interval. We further examine the relation to the process which is considered to be the primary one controlling the season of cold temperatures at the polar mesopause, namely the direction of the stratospheric circulation.

### PMSE observations with ESRAD at 68° N

Table 1 lists the radar parameters used for the measurements reported here. The presence of PMSE is determined on the basis of the radar SNR (signal-to-noise ratio, determined as described by Briggs, 1984). One-hour averages of this parameter have been computed for the whole period when high-resolution observations were made from the 80-90 km height interval, which was from 8 May to 2 October 1997. PMSE is judged to be present if the SNR exceeds -10 dB at any height in each 1-hour profile. This limit was found to represent the detection limit for the particular mode run, i.e. setting the limit 1 dB lower gave a large increase in false 'signals', with uniform

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**Table 1.** ESRAD Technical Characteristics and measurement mode for PMSE during the period 8 May - 2 October 1997.

ESRAD location : 67° 56' N, 21° 04' E, 295 m	
Transmitter :	
peak power	72 kW
frequency	52 MHz
pulse repetition rate	1450 Hz
pulse length	16 x 1 $\mu$ S compl. code
Antenna :	
2 x 12 array of 5-element yagis	
yagi spacing	0.7 $\lambda$
antenna area	1973 m <sup>2</sup> (44.4 x 44.4 m)
Receivers :	
filters	1 MHz
Digital Processing :	
heights	80-90 km
height resolution	150 m
pre-integration	64 samples
wind analysis	spaced antenna
Other information :	
time standard	GPS

height distribution. The system parameters were held constant during the whole period of measurements and there were no major disturbances (such as solar proton events) causing variation of the sky noise during the period of observation, so we can assume that the 'noise' represents a sufficiently stable reference level.

Figure 1a shows how the daily prevalence of PMSE varies over the season. The clearest feature is the very rapid increase in PMSE at the beginning of the season. From the first PMSE on 20 May (day 140), which lasted only 3 hours (9 - 12 UT) there are only 8 days until the PMSE prevalence reaches almost saturation (present at all times except 9-10 UT) on 28 May (day 148). In contrast, the decay of PMSE from maximum values, which were maintained up until 24 July (day 205, the last occasion when PMSE was present all day), to the last day PMSE was observed, 26 August (day 238), took a whole month.

### UKMO-UARS stratosphere / mesosphere winds and 'forcing' at 59° N and 69° N

Panels g and c in Figure 1 show the stratospheric zonal winds from 59° and 69° N (the exact grid points are at 58.75° N and 68.75° N), between heights of about 16 km (100 hPa) and 60 km (0.3 hPa). These winds are from the UKMO-UARS data assimilation, that is they are based on a combination of the world-wide radiosonde network and observations from satellites, which are computed on a daily basis (Swinbank and O'Neill, 1994). We show the zonal mean of the zonal wind at each latitude, which are the grid values closest to the measurement locations for PMSE (ESRAD) and OH temperature (Stockholm). The winds show the rather abrupt change of circulation from winter (eastward) to summer (westward), at day 127 (defined at the 30 hPa level at 59° N), and a slow return to winter circulation around day 232. The differences between 59° N and 69° N are very small.

In the panels above the winds, we show a 'forcing' estimate derived from the winds. The anomalous warm winter and cold summer temperatures at the mesopause are considered to result from forcing of the circulation by gravity waves. Gravity waves propagating up from the troposphere are expected to be filtered by the stratospheric winds, i.e. waves will not reach heights above those where their phase velocity matches the wind velocity. The change in stratospheric circulation between winter and summer means a change in forcing direction by the waves reaching the mesosphere. To make a rough estimate of this, we consider only zonal velocity components, assume a momentum spectrum for gravity waves which is

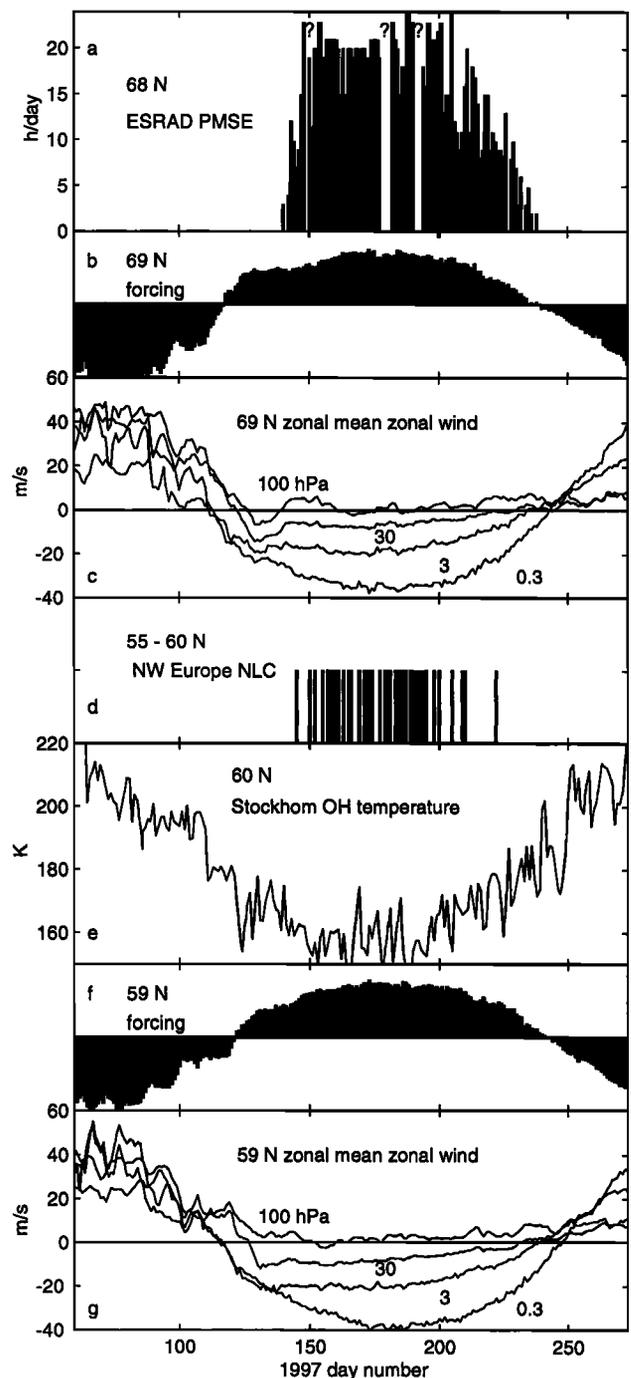


Figure 1. Seasonal variation during 1997 of: *a*: PMSE measured by ESRAD (? indicates data gap); *b* forcing in the mesosphere calculated from the stratospheric winds in *c* (see text for details); *c* - stratospheric zonal winds at 69°N for the 100, 30, 3 and 0.3 hPa pressure levels (approx. 16, 24, 40 and 60 km altitude) from the UKMO-UARS assimilation *d* - nights when noctilucent clouds were observed from Britain and northern Europe; *e* - OH temperatures at 86±4 km measured at Stockholm; *f* and *g* as panels *b* and *c*, but for 59°N.

constant for all phase velocities between -70 and +70 m/s (following Alexander and Rosenlof, 1996), and calculate the 'forcing' by integrating what is left after subtracting all phase velocities corresponding to stratospheric wind speeds.

The 'forcing' shows, more clearly than the winds, the abrupt change from winter to summer at day 122 at 59°N and day 118 at 69°N. The forcing at both sites increases towards mid-summer (day 180). After day 200 it decreases steadily, reversing sign at 69° N at day 239, four days later at 59°N.

We observe that the same asymmetry as is seen in the forcing, with an abrupt start and a slow decay, is also seen in the PMSE (Figure 1a). However it is noticeable that the PMSE starts long after (18-22 days) the transition to summer forcing. At the end of the season, on the other hand, the PMSE persists up to the time the forcing changes back to the winter direction.

### OH temperatures at 60° N

Nightly average temperatures at about 86 km  $\pm$  4 km, measured near Stockholm (60° N, 18.2° E) using the emission from OH are shown in the Figure 1e (for a description of the instrument and measurement technique see Espy et al., 1997). It is not feasible to make this type of measurement further north since the summer night sky is too bright. The temperatures at Stockholm are not expected to reach such low values as those observed instantaneously at 68°N by, for example, falling sphere techniques (see e.g. Lübken, 1996) both because of the slightly lower latitude and because of the large height interval over which the signal is averaged. For example, MSIS-90E (Hedin, 1991) predicts mesopause temperatures 6 K lower at 68°N than 60°N, and temperatures 5-6 K above the minimum within the volume sampled by the OH technique. However, the timing of the seasonal changes in the 68° N mesopause temperature and the 60° N OH temperature should be the same, given that the timing of the seasonal changes in the zonal wind and the expected forcing is essentially the same (see above).

The OH temperature starts to fall rapidly at day 110 (following a drop in the stratospheric winds between days 90-100) but levels off at about 180 K for a further 10 days when the winter-type stratospheric winds recover. The temperature falls sharply again after day 120 when the upper-level stratospheric winds finally change to westward. Temperatures continue to fall (with some irregularity) as the stratospheric winds become stronger and westward at all heights. After day 200 the stratospheric circulation weakens and the OH temperatures rise steadily.

The main temperature changes over the season seem to correlate well with the changes in stratospheric winds and forcing, as might be expected. Since there is little difference in the stratospheric circulation between 59°N and 69° N, this allows us to assume that the timing of the seasonal changes in temperature should be the same at 69°N. We can now see that the period when PMSE is present almost all day (days 148-205) coincides roughly with the period when OH temperatures are lowest, below about 160 K (the day-to-day variations in temperature do not allow an exact comparison). Before this core period, when the PMSE is just starting to appear, from day 140-147, OH temperatures are below about 170 K, whereas after the peak season, from days 206 - 238, PMSE are still seen while OH temperatures rise to at least 180 K.

### Noctilucent clouds at 55° - 60° N

Noctilucent cloud observations from NW Europe are collected by a network of amateur observers (see e.g. Gavine, 1996). Preliminary sightings for 1997 are used here. (T. Mc Ewen, J. Rendtel, personal communication: <http://www.personal.u-net.com/~kersland/nlc/nlchome.htm>) and are shown in the middle panel of figure 1. Each night when noctilucent clouds were observed is indicated. Only observations made in continental Europe and the UK are included here (i.e. not from Norway, Finland or Sweden) and doubtful reports from only one observer are excluded, for consistency with previous NLC studies (e.g. Gadsden 1990). On 8 nights between days 140-150, and 10 nights between days 210-230, good viewing conditions were reported but no NLC. This gives good confidence that the apparent start and end of the seasons

are real and not an artifact of poor observing conditions. NLC were in practice seen more often in August (i.e. after day 213) at higher latitudes - e.g. visually from N. Sweden, Finland and Karelia on days 218, 220, 222, 225, 228, and 232 and by lidar in Kiruna on days 222 and 226 (V. Mäkälä, V. Roldugin, K-H. Fricke, personal communication). At the start of the season, it is too light at high latitudes to see NLC from the ground. However, it should be noted that the first lidar NLC detected by the ALOMAR observatory at 69° N during 1997, was not until 12 June, i.e. day 163 (von Zahn, 1997). Clearly, the noctilucent clouds at 55-60°N appeared during the times when the temperature was lowest, the eastward forcing strongest and PMSE was present at least half of the day. At 55-60°N there is no asymmetry discernible in the NLC season with respect to the summer season, as defined either by the OH temperature or by the forcing. However, the same asymmetry as in PMSE may be present at higher latitudes.

### HALOE water vapour at 60° - 75° N

Estimates of water vapour in the mesosphere are available from the HALOE instrument on the UARS satellite (Harries et al., 1996). Figure 2 shows observations for the summer of 1997. Measurements are available at the latitudes of interest for only a few days at a time at rather widely spaced intervals. The observations we are most interested in here are at 80 km, which is at the upper limit of the observation volume and subject to large uncertainties, particularly during summer when the presence of aerosols (NLC) in the line of sight of the instrument might give false (too high) estimates of water content. Thus the observations from 80 km can only be relied on before the NLC season starts, and so are shown only for March/April. Instead, we show observations from 65 km height, which are expected to be free of contamination from aerosols, for the whole summer. These show that there is an increase in water vapour between days 50-100 and 150-200. (Similar seasonal changes in water vapour in 1996 have been reported using ground-based microwave radiometry, von Zahn, 1997). The data are consistent with the increase taking place at around day 140, at about the same time as the PMSE showed a dramatic increase. It is also clear that the water vapour remains high up to days 205-215, that is during at least the first part of the declining PMSE season.

### Summary and Conclusions

The measurements collected here, regarding the seasonal variation of PMSE, upper mesosphere temperature and stratospheric circulation show strong asymmetry in the summer season with a relatively abrupt change from winter to summer, and a rather slow, steady transition back from summer to winter. The temperature changes at 60° N correlate well in time with the changes in the stratospheric circulation at that latitude and at latitudes 10° further north. It is therefore reasonable to assume that the seasonal changes of temperature at 70°N occur at the same times as those at 60°N. The decay of the PMSE season at 68° N is closely correlated in time with the decay of the summer stratospheric circulation and the temperature at 60°N. The onset of the PMSE season is delayed by 2-3 weeks from the start of the summer, as defined by the temperature fall or by the reversal of the stratospheric circulation. The water vapour at 60° - 70°N appears to increase at about the time of the PMSE onset, whereas it remains relatively constant during at least the first half of the PMSE decay period.

Earlier work on the seasonal variation of PMSE (Balsley and Human, 1997) in relation to temperatures was based on PMSE observations from three separate years (1981, 1982 and 1984) and 'climatological' temperature variations from a variety of sources, all based in practice on a very small number of observations. Although this study pointed to a possible 1-2

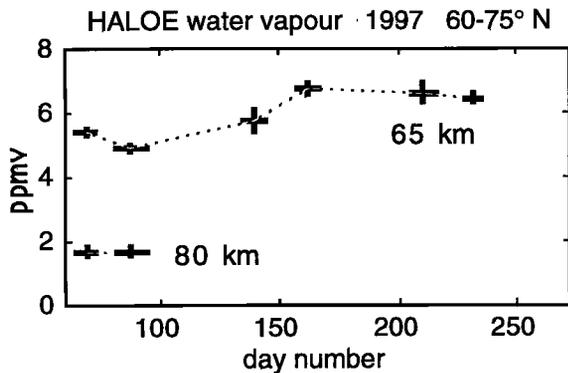


Figure 2. Water vapour at 65 km and 80 km heights, 60-75°N measured by the HALOE instrument on board the UARS satellite during the summer of 1997. The bars indicate the range of water vapour concentrations observed (zonal averages) and the time interval during which observations were made in the relevant latitude zone. Estimates from 80 km after day 100 are not shown as they are considered unreliable due to possible contamination by aerosol (NLC) in the absorption path.

week delay in PMSE onset with respect to the period of coldest temperatures, and it was suggested that low water vapour at the start of the season could be a possible explanation (although no water vapour measurements were available), the results could only be rather tentative because of the limitations of the observations.

The collected measurements from the 1997 summer season confirm that there is marked asymmetry between the seasonal variation of temperature and of PMSE. One reasonable interpretation of this is that lower temperatures, lower than those present, would be needed in early May to allow ice aerosols to form when less water vapour is available. Later in the season, when the water vapour concentration is slightly higher, ice aerosols would start to form at higher temperatures. However, for this to be significant, the seasonal increase of water vapour at the mesopause would have to be much more than that at 65 km. A 20% increase in water vapour would lead to less than 1 K increase in the saturation temperature. A factor of 5-10 increase in water vapour would be needed to increase saturation temperature by 5-8 K, which is about the amount needed.

Of course, other explanations are possible. The strong diurnal and semidiurnal modulation of PMSE (Kirkwood et al., 1995, Hoffmann et al., 1997), seen also in the present data set, indicates a significant influence of the tides. If the tidal amplitudes were much larger at the beginning of the season, and the time needed for aerosol formation of the order of several hours, then the aerosol might not have time to form before the temperature were forced by the tide above some threshold value. However, it should be noted that earlier results on tides from Poker Flat suggest rather that they are stronger in August than in May (Avery et al., 1989). Other factors which are not measured in this study, such as the amount of turbulence present at mesopause heights, might also have an influence on PMSE. On the other hand, the delay of NLC appearance until PMSE is well established supports rather the idea that it is indeed the aerosols which are lacking at the beginning of the season.

It is clear that we cannot use the prevalence of PMSE as a direct indicator of mesopause temperature. On the other hand, if the importance of water vapour for the onset of the PMSE season can be confirmed by future measurements, and the role of other factors ruled out, we may be able to study long-term changes of water vapour and temperature by studying separately the start and the end of the PMSE season, respectively.

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