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CUPRI OBSERVATIONS OF PMSE DURING SALVO C OF NLC-91: EVIDENCE OF A DEPRESSED MESOPAUSE TEMPERATURE

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Abstract. The Cornell University Portable Radar Interferometer (CUPRI) observed two extremely strong layers of Polar Mesosphere Summer Mesosphere (PMSE) thirty minutes prior to the launch of Salvo C of the NLC-91 campaign. The lower layer exhibited a S/N ratio of 42 dB (the second strongest event of NLC-91), vertical velocities of a few m/s, and a narrow spectral width, suggesting that it was the result of partial reflections. The upper layer, in contrast, exhibited sinusoidal structures in vertical velocity with peak amplitudes greater than ± 10 m/s and wide spectral widths. These structures were observed to grow and steepen with altitude until they broke and produced turbulent radar scattering. We conclude that the rapid rate of growth of the wave with altitude was the result of a depressed mesopause temperature and a nearly adiabatic temperature gradient at PMSE heights and that the simultaneous measurement of both a low mesopause temperature and strong PMSE supports recent theories that find the presence of charged aerosols to be the key to the unique radar cross sections associated with PMSE.

Introduction

The presence of enhanced coherent backscatter signals observed by UHF and VHF radars (polar mesosphere summer echoes or PMSE), the highest clouds in the Earth's atmosphere (noctilucent clouds or NLC), and the lowest naturally occuring temperatures recorded in the Earth's near environment have made the summer polar mesopause an active region of scientific study. The NLC-91 campaign was designed to take advantage of the differing capabilities of a wide variety of instruments by bringing them together at Esrange, Sweden to simultaneously probe this region and help resolve a number of questions concerning PMSE, NLC, and their interrelationship. (For an overall view of the campaign, see *Goldberg et al.* [1993], *this issue.*)

Of the three rocket salvos launched during NLC-91, the smallest was designated Salvo C and was devoted exclusively to the study of PMSE. Salvo C consisted of two rocket payloads: a MISTI payload which measured plasma densities and a Viper falling sphere payload which measured neutral atmospheric horizontal winds and density from which temperatures were derived. For Salvo C, as with the entire campaign, PMSE diagnostics were provided by the Cornell University portable radar interferometer (CUPRI), a 46.9-MHz Doppler radar system. For a complete description of the CUPRI configuration for NLC-91 and discussions of CUPRI observations during Salvos A and B, we refer the reader to two companion papers in this issue [*Swartz et al.*, 1993; *Cho et al.*, 1993]. For discussions of the temperature and wind data from Salvo C, we refer the reader to *Schmidlin* [1992].

Observations

Salvo C Launch

The primary launch criterion for Salvo C was the presence of very strong, multiple PMSE layers in the CUPRI radar beam. This condition was met at approximately 23:00 UT on August 5, 1991 when CUPRI recorded backscatter returns 42 dB above the noise level at an altitude of 85 km. A S/N ratio of 30 dB was also recorded in a second layer 2 km above the first. The 42 dB event was the strongest seen in the first thirteen days of the campaign, and ultimately the second strongest; a 60 dB event was observed the following day, August 6, at 12:00 UT. MISTI-C was launched at 23:21 UT, by which time the lower layer strength had fallen to roughly 10 dB. The falling sphere was launched at 23:32 UT.

Immediately after the first launch, the CUPRI radar beam was shifted to 8° north of zenith to measure the aspect sensitivity of the PMSE layers and to improve the spatial coincidence between the in situ measurements and the radar scattering volume. Subsequently, the radar beam alternated between zenith and 8° twice more, finally returning to zenith permanently at 23:52 UT. These changes are easily visible in Figure 1 as data gaps arising from the need to physically change cables in the antenna array. Finally, for a few minutes on either side of 23:30 UT, the CUPRI sample window was shifted away from the radar by ~ 2 km to determine the complete vertical extent of a third PMSE layer.

Overall Morphology of PMSE

The PMSE strength plotted in the top panel of Figure 1 seems to show, at first glance, the presence of two similar PMSE layers which tracked each other in response to wave-like oscillations of the background atmosphere, slowly faded into a single layer, and finally split into two layers again after 01:00 UT. Upon closer examination, however, the homogeneity of the two layers in both altitude and time rapidly breaks down, especially in the highly active 30 minutes preceding the launch of MISTI-C. In fact, distinct spectral characteristics suggest that there were at least three different events occurring during this time period which are of interest.

The upper layer between 22:30 and 23:10 UT was characterized by very large sinusoidal structures (±10 m/s) in the vertical velocities that grew and steepened with alti-

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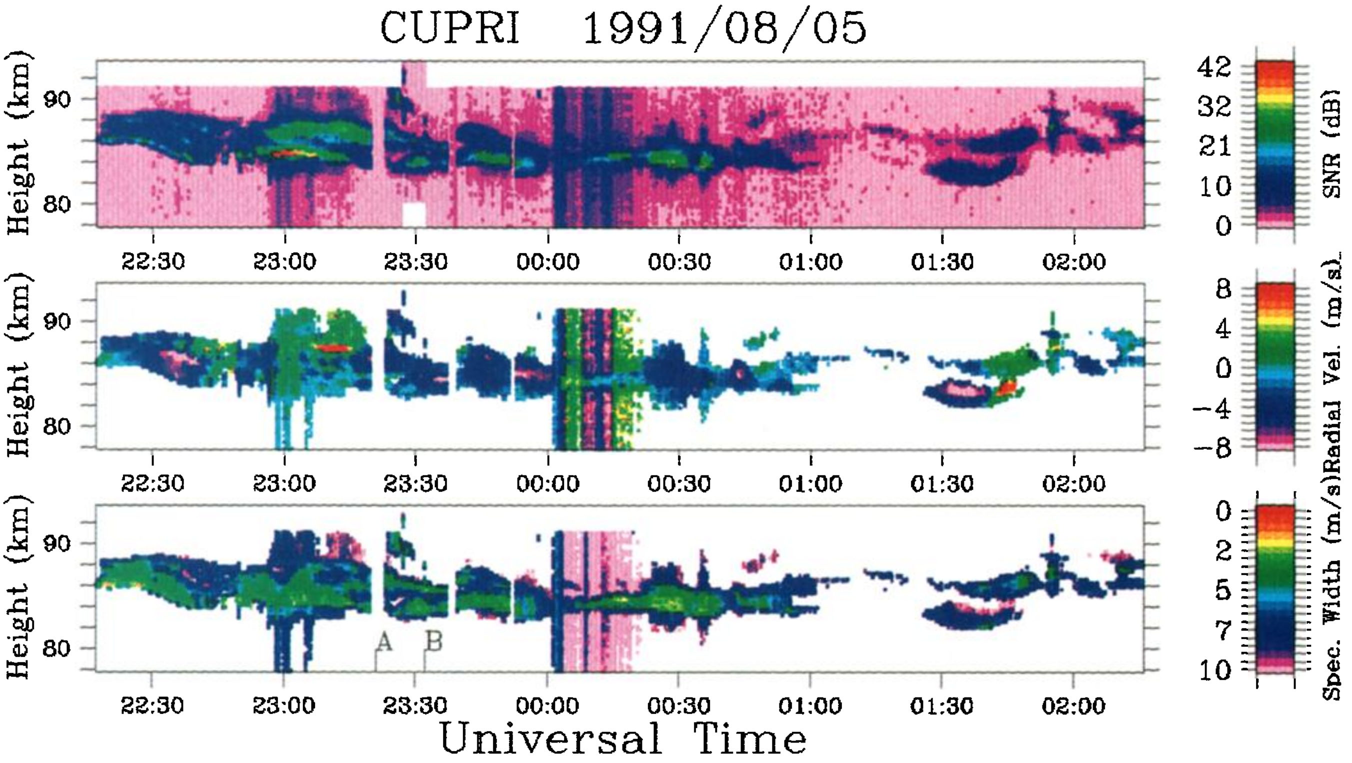

Fig. 1. CUPRI observations during the Salvo C launch sequence. The top panel displays post-processing S/N ratios derived from the zeroth moment of the spectra. The center panel shows the line-of-sight Doppler velocity (positive upwards) derived from the first moment of the spectra. The bottom panel gives the Doppler spectral width derived from the second moment. The radar beam was vertical except for the times from 23:20 to 23:40 and from 23:50 to 00:00 when it was moved 8° north from zenith. Between 23:28 and 23:32, the sample window was temporarily raised 2 km. The height resolution of the data is 300 m, and the time resolution is 34 s.

tude, as shown in Figure 2, and spectra that widened in areas of stronger signal strength, as shown in the top and bottom panels of Figure 1. We will examine this layer in much more detail below. In contrast, the lower layer was characterized by peak velocities of, at most, 2-3 m/s and narrow spectral widths which became narrower in areas of stronger signal strength. If simultaneous PMSE layers can result from different scattering mechanisms, as *Cho et al.* [1993] and *Lübken et al.* [1993] have suggested occurred during Salvo B, then it seems probable that the upper layer was the result of turbulence due to wave breaking, while the lower layer was due to some form of partial reflection mechanism. Specifically to distinguish between turbulent and partial reflection scattering mechanisms, the CUPRI beam was deliberately moved off zenith twice during Salvo C to measure the aspect sensitivity of the PMSE layers, as was done by *Cho et al.* [1993] for Salvo B. Unfortunately, the spatial variations in signal strength were too large and masked any changes in aspect sensitivity which may have been present.

The third region of interest is the upper layer between 23:05 and 23:20 UT. Here, the layer was characterized by a single half-wave structure with peak velocities of nearly 15 m/s, as shown in Figure 2. Unlike the upper layer at previous times, the regions of peak echo strength occurred at the velocity maximum as opposed to the velocity reversal/displacement maximum that occurred in the wave breaking. Also, the spectrograms are remarkably coherent given the turbulence of the wave at 23:00 UT where the velocities were comparable. Finally, unlike other regions which exhibited very high Doppler velocities, the altitude of the layer does not seem to have been affected by the motion of the scattering mechanism and, if anything, actually appears to have descended during this period. Compare this to the behavior of the layers at 22:30 and 01:45 UT. At 22:30 UT, with predominantly large negative velocities, the layers descended roughly 2 km, and at 01:45 UT, with large positive velocities, the layers rose almost 4 km.

These large scale motions of the PMSE layers have significance in their own right. The accepted explanation of extremely cold mesopause temperatures during the polar summer is the existence of atmospheric circulation cells which result in upward air flow at the poles [*Holton*, 1983]. As the air parcels are advected upward, they cool at the adiabatic lapse rate of $g/c_p = 0.01$ K/m. Vertical velocities of 10 m/s applied over 10 minutes, such as those measured in the upper PMSE layer, could have resulted in as much as a 6 km movement of the neutral atmosphere (although, at least in this case, not the scattering mechanism), which would represent a temperature drop of 60 K. This drop is consistent with the temperature decrease necessary to produce the measurements of *Schmidlin* [1992] during Salvo C

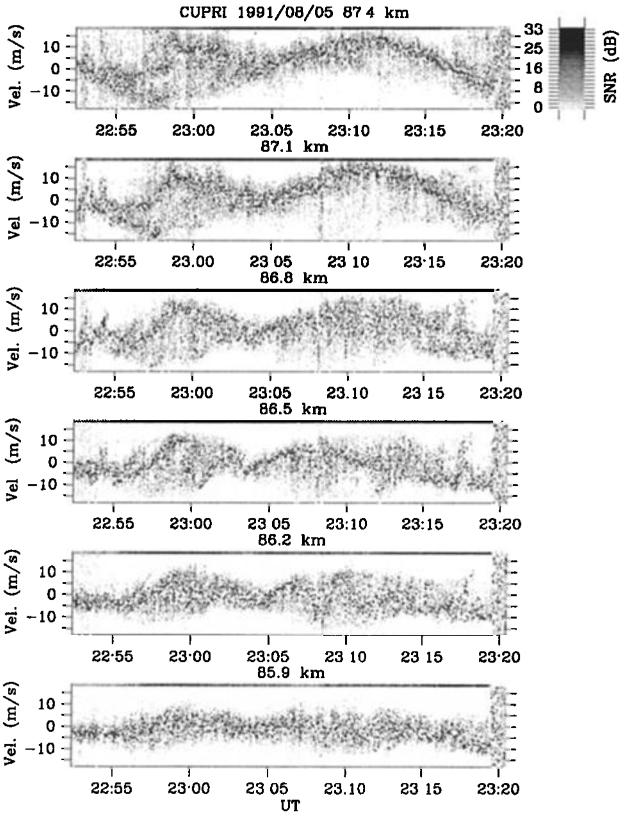

Fig. 2. CUPRI Doppler spectrograms for a selected range of altitudes. Each vertical strip is self-normalized, with the peak S/N ratio given in the grey-scale bar at the top of each panel. The time resolution is 5.6s. Since the integration time is different from that used in Figure 1, the S/N ratio is not directly comparable to the S/N ratio given in Figure 1.

from the Air Force Reference Atmosphere. More reasonably, the vertical velocities measured were likely to be localized, reducing the inferred temperature drop. As is seen after 01:30 UT, however, rises of 3 km did occur and are quite consistent with the difference in mesopause temperature reported by *Schmidlin* [1992] between August 5 and the other days of NLC-91. As we note below in our discussions of gravity wave e-folding rates, *Schmidlin* [1992] also reported the presence of a temperature lapse rate between 86 and 92 km that very closely approaches the adiabatic lapse rate of 0.01 K/m. This indicates that the atmosphere in this region was being cooled adiabatically and further suggests that the upward velocities measured by CUPRI were the likely cause of the depressed mesopause temperature.

Measurements of Doppler velocity made by CUPRI at 8° off zenith to the north can also be compared with measurements of horizontal velocities reported from in situ measurements during Salvo C by dividing the line of sight velocities by the sine of the zenith angle. While the horizontal component of the CUPRI beam is admittedly small, the line-of-sight velocity measurements at non-zero zenith angles are, nonetheless, usually dominated by the horizontal component of the wind which has a much greater magnitude than the vertical component of the wind. *Schmidlin* [1992] reported southward velocities of 30 to 80 m/s between 85 and 90 km altitude, which corresponded to the region of PMSE echoes. The middle panel of Figure 1 shows negative Doppler velocities of 4 to 9 m/s between 85 and 86 km, which correspond to southward horizontal velocities of 29 to 65 m/s. These velocities are quite comparable to the in situ measurements. It is possible that very large vertical velocities, such as those observed before the rocket launches, could have influenced these measurements. Measurements made just before, between, and just after beam swinging occurred, however, suggest that the vertical velocities were more typical velocities of a few m/s, and thus unimportant.

Gravity Wave Oscillations

During the period between 22:30 and 23:10 UT, the effects of a gravity wave propagating through the mesosphere are visible in the motions of the upper PMSE layer in Figure 1. These effects are most easily visible in the bottom panel where the spectral width measurements showed a clearly demarcated and sinusoidal boundary between a lower region with widths less than 4 m/s and a higher region with widths greater than 7 m/s. The motions of this boundary correspond with the oscillatory behavior in the Doppler velocities displayed in the center panel. The panel shows alternating upward and downward velocities with a period of 16 minutes and reversals at approximately 22:41, 22:50, and 22:57 UT. Finally, the effects also appear in the S/N ratios plotted in the top panel. The top layer descended initially from 22:30 UT, and then rose and fell again until 22:57 UT when a S/N ratio of 30 dB was measured at what appears to be a minimum of the upper layer displacement. Subsequently, the upper layer rose again and a second region of 30+ dB echoes was measured at 23:05 UT near the layer maxiumum.

Examining the spectrograms in Figure 2, a sinusoidal oscillation in the measured Doppler velocities that grew in amplitude with height can be seen between 22:55 and 23:05 UT and between 85.9 km and 87.4 km. The S/N ratios plotted at the top of each spectrogram indicate that the 30 dB PMSE event at 22:57 UT did, in fact, correspond to a period of velocity reversal. We believe that these growing sinusoidal velocity structures were the signature of an upward propagating gravity wave. As it grew with altitude, the wave underwent non-linear steepening to a sawtooth shape at 86.2 km, broke, and produced turbulence which significantly enhanced the radar backscatter and widened the Doppler spectra. We note, however, that the change in spectral width shown in Figure 2 could also have been the result of beam broadening due to cross-beam winds. A shear in the horizontal velocity would have produced a similarly demarcated boundary in the spectral width as was observed.

Calculation of gravity wave e-folding distance

Conservation of energy requires that gravity waves which propagate upward grow exponentially with altitude to balance the decreasing density of the atmosphere. Since energy is proportional to velocity squared, the wave velocities grow as $e^{z/2H}$, where $H \equiv R\bar{T}/g$ is the density scale height for an isothermal atmosphere with temperature $\bar{T}$. With a temperature of approximately 130 K at 86 km [*Schmidlin*, 1992], we would expect an e-folding distance of roughly 7.6 km. From Figure 2, however, the peak-to-peak velocities near 23:00 UT appear to have e-folded in a distance closer to 2.1 km. Rederiving the gravity wave dispersion relation and retaining a linear background temperature gradient yields a new exponential growth term $e^{z/2H^*}$ where H^* is given by

$$\frac{1}{H^*} = \frac{1}{H}\left(1 + \frac{\kappa\lambda R}{N^2 H}\right), \tag{1}$$

λ is the temperature lapse rate $-\partial_z \bar{T}$, $\kappa = 2/7$ is the ratio of R to the heat capacity at constant pressure, R is the ideal gas constant, and N is the Brunt–Väisälä frequency given by

$$N^2 = \frac{R}{H}\left(\partial_z \bar{T} + \frac{\kappa \bar{T}}{H}\right). \tag{2}$$

Here, $\bar{T} \equiv T_0 - \lambda(z - z_0)$ is the temperature at height z_0. For the night of August 5, *Schmidlin* [1992] shows $T_0 = 130$ K at $z_0 = 86$ km and $\lambda \sim 0.0085$ K/m. For $\lambda = 0.0085$ and $z = 86$ km, we calculate $2H^* = 2H/2.9 = 2.6$ km, which is considerably closer to that measured. For comparison, $\lambda = 0.008$ yields a value of $2H/2.3 = 3.3$ km, and $\lambda = 0.009$ yields a value of $2H/4.3 = 1.8$ km for the e-folding distance $2H^*$. Comparing these to the measured e-folding distance of 2.1 km provides a strong correlation for the existence of the extremely cold temperatures and large temperature gradients measured by *Schmidlin* [1992].

Discussion

We have reported a number of interesting observations made by the CUPRI radar during Salvo C of the NLC-91 campaign. The spectral characteristics of the lower of two PMSE layers lead us to believe that it was the result of a partial reflection-type scattering mechanism. In contrast, the presence of growing, large-amplitude, sinusoidal structures in the early velocity spectrograms of the upper layer suggests that this layer was the result of turbulent wave breaking. Calculations of the e-folding distance of gravity waves have shown that the rapid rate of growth of these structures with altitude required the presence of very low temperatures and steep temperature gradients in the region of interest, thus corroborating the in situ measurements of *Schmidlin* [1992]. Further, the large upward velocities measured by CUPRI were consistent with the adiabatic cooling necessary to produce *Schmidlin* [1992]'s observations of both a sub-100 K mesopause temperature and the nearly adiabatic lapse rate of the mesosphere at PMSE heights. Together, the measurements of *Schmidlin* [1992] and the CUPRI observations of strong PMSE provide considerable support for recent theories which argue that the presence of charged aerosols is the key to producing the unique radar cross sections associated with PMSE [*Cho et al.*, 1992; *Havnes et al.*, 1992]. Low temperature is the most important element in the formation of ice particles at the summer mesopause, and thus our observation during Salvo C of some of the strongest PMSE of the NLC-91 campaign during a period of extremely low temperatures is exactly as these theories have predicted. Finally, we have left unexplained later observations of the upper layer which exhibited the presence of Doppler velocities equally as large as those of earlier observations, but with no indications of either wave steepening and breaking or corresponding layer movement.

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