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PMSE dependence on long-period vertical motions

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Abstract. We analyze the temporal relationship between PMSE (polar mesosphere summer echoes) and long-period vertical motions using the Poker Flat, Alaska radar data. The results show that the vertical velocity leads PMSE by 90° to 180° with a possible upward trend in phase with increasing frequency. We show that this is consistent with the current PMSE theories which depend primarily upon the presence of charged ice aerosols for the enhancement of radar scatter.

Introduction

Strong VHF radar echoes from the upper mesosphere were a complete surprise when they were discovered by *Ecklund and Balsley* [1981] during the polar summer season. Neither incoherent scatter nor classic turbulent scatter could explain their occurrence, much less their enormous signal powers. Most of the recent theories proposed to explain these polar mesosphere summer echoes (PMSE) [*Röttger et al.*, 1988] have revolved around the existence of ice particles, the largest of which become visible as noctilucent clouds, in the cold summer mesopause where PMSE are observed. (Reviews of PMSE observations and theories have been published by *Cho and Kelley* [1993], *Hoppe et al.* [1994], and *Röttger* [1994].)

Even early on there was speculation that PMSE was somehow related to the peculiarly low temperatures of the summer mesopause [*Balsley et al.*, 1983]. Following an initial attempt to make a concrete connection between low temperature and PMSE [*Kelley et al.*, 1987], a number of candidate theories have emerged recently [*Cho et al.*, 1992; *Havnes et al.*, 1992; *Klostermeyer*, 1994; *Trakhtengerts*, 1994]. Without going into the details, let us simply summarize that all of them require the presence of charged ice aerosols, dynamically driven by the neutral gas and coupled to the ionized constituents through electric fields. Unfortunately, it has proved to be quite difficult to observe these subvisible ice particles; thus, there has been no definitive answer to whether any of these theories are correct. The formation of ice is directly dependent on the temperature (which must fall below the critical level for ice nucleation and growth), so comparison of PMSE with temperature provides a fair proxy for comparison with the aerosols themselves. So far, such comparisons have supported the theories [*Miller et al.*, 1993; *Inhester et al.*, 1994], but because the temperature measurements were made only intermittently with sounding rockets, we do not have as robust a statistical result as we might hope. Since a continuous record of temperature in the summer mesosphere is not available to us, we have instead decided to compare vertical velocities (on which the local temperature ought to be heavily dependent) with PMSE power. (We note in revision that *Rüster* [1995] has recently conducted a similar study using horizontal velocities.)

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Data

In order to calculate the degree of correlation and phase relation between the radar echo power and vertical velocity with respect to time, we decided to use the cross-spectral technique which has the added advantage that the results are sorted according to frequency. We analyzed the original Poker Flat, Alaska radar data set which is still the only long-term record of PMSE, covering 1979 to 1985. (For a description of the system and the data processing procedures used see *Carter and Balsley* [1982].) The pertinent information here is that the radar operated at 50 MHz with a range resolution of about 2.2 km with three 2.2° antenna beams—vertical and two oblique—giving both vertical and horizontal wind data. It was located at 65.13° N and 147.46° W with 50-kW peak power on the vertical beam. The data to which we had access were hourly averages, which were carefully screened by the analyst who reduced the data to reject bad points due to interference, equipment failure, and lack of signal-to-noise ratio (SNR). Therefore, we do not expect a bias in the cross-spectral coherence due to both the SNR and velocity values being simultaneously too low.

Gaps in the hourly data points were interpolated up to two consecutively missing hourly points using a cubic spline-fitting routine. Data between June 1 and July 31 were chosen to cover the peak PMSE season. Altitude gates between 82 and 90 km, the region of PMSE occurrence, were selected and 64-point FFTs of both the vertical velocity, w, and the logarithm of the SNR, s, were taken at each altitude if missing data points did not force zero padding of more than half the length of

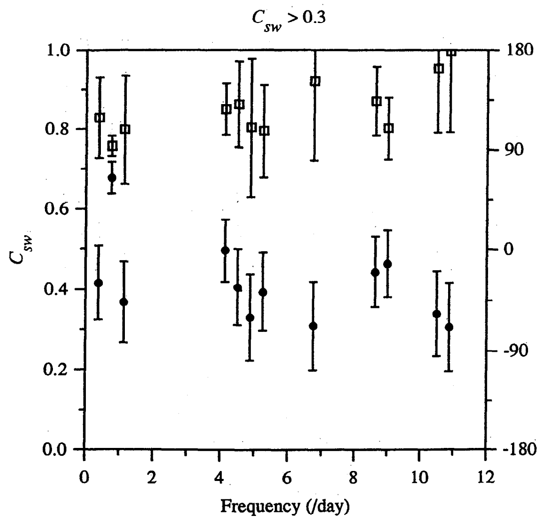

Figure 1. The cross-spectral coherence (solid circles) and phase (open boxes) for s and w observed with the Poker Flat radar. Only data points corresponding to coherence greater than 0.3 are plotted. The variances are plotted as error bars. The sense of the phase is defined such that a positive sign corresponds to w leading s. The input data was between 1982-6-1 and 1982-7-31 in time, and 82 km and 90 km in altitude.

the transform. Parzen windowing was applied in the time domain to decrease the variance in the spectral domain at the cost of effectively smoothing the spectral resolution. The frequency-domain segments were then averaged to form the auto-spectra and the cross-spectrum. This averaging process was performed first over altitude, then over time.

We present the results in terms of the coherence, C_{sw}, and the phase, Φ_{sw}, which are the magnitude and phase of the complex cross-spectrum. The coherence varies between 0 and 1; it can be thought of as a measure of the cross-correlation between s and w in a particular frequency band. The phase is defined such that a positive sign corresponds to w leading s.

Figure 1 shows the resulting coherence and phase for the 1982 season. Due to the fairly numerous gaps in the hourly time series, the number of acceptable 64-point segments according to the requirements discussed above were not as many as one might have expected. We chose the 1982 data set because it contained the most number, 27, of such segments. The post-spectral averaging was taken over the 27 segments with respect to altitude, then time. Note that although there is a fairly large peak at a frequency of 0.75 day^{-1} (corresponding to a period of 32 hours), overall, the coherence values are low. Thus, in order to eliminate the less significant phase values, we have plotted only the Φ_{sw} values which met the criterion $C_{sw} > 0.3$. Note the distinct tendency for Φ_{sw} to cluster in the zone of 90° to 180°, with, perhaps, an inclination for Φ_{sw} to increase from 90° to 180° with higher frequency. These trends were also observed in the other years analyzed.

Interpretation

If adiabatic motion is assumed, then the temporal phase of the temperature variation should lead the phase of the vertical velocity oscillations by 90°, i.e., the temperature should be lowest when the air parcel is at the zenith of its trajectory. Furthermore, if one naively presumes that the lower the temperature, the more ice there are, and thus more PMSE, then the temperature should be 180° out of phase with PMSE, and, thus, $\Phi_{sw} = 90°$ is the result one would expect. This thinking, however, implicitly assumes that the number of ice particles capable of producing PMSE is perfectly out of phase with the temperature variation (as would be the case if rapidly forming water cluster ions were capable of producing PMSE [*Hall*, 1990]); we shall show that this is not quite true.

Figure 2 shows a sinusoidally oscillating w at the top. In the middle is the temperature, T, which is phase-shifted by 90° according to the basic adiabatic assumption. We then assume a critical water condensation temperature, below which ice can begin to form, indicated by the horizontal dashed line. The value of the critical level is arbitrary and is not important to the argument. (It is realistic to assume that T falls below the critical level only part of the time, since polar mesospheric clouds are not ubiquitous.) All the recent theories require ice aerosols that have grown to at least a radius of $\sim$ 10 nm in order to have enhanced radar scatter. Growth to that level requires a time scale on the order of a few hours [*Turco et al.*, 1982]; this is the

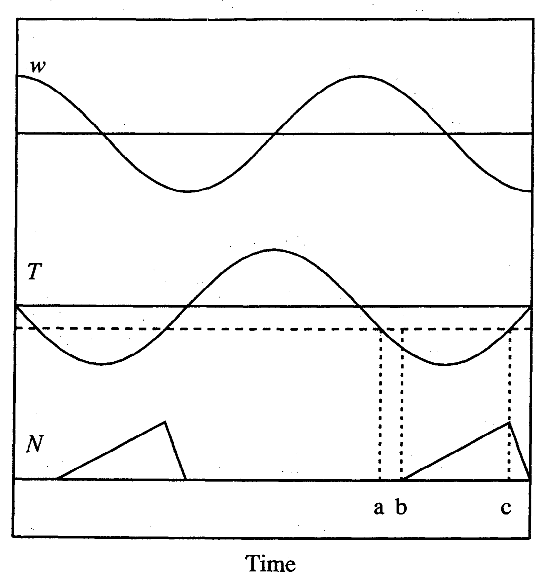

Figure 2. Illustration of the dependence of the ice particle number density capable of producing PMSE, N, on the temperature, T, and the vertical velocity, w. The dashed horizontal line is the hypothetical water condensation temperature. At (a) the temperature falls below the condensation level. At (b) ice particles capable of producing PMSE begin to appear. At (c) the temperature rises above the saturation level and ice begins to sublimate rapidly.

delay from (a) to (b) in Fig. 2 for N, the number density of ice aerosols which are capable of producing PMSE. On the other hand, the sublimation of ice is extremely rapid once T rises above the condensation level; thus, the quick drop in N after (c). (Note that the variation in N is simply a zeroth-order depiction and is not the result of a calculation from an ice particle growth model.) Because the time period for growth is constant relative to the frequency of temperature oscillation, one can see that the delay due to particle growth will be a much larger fraction of the whole cycle at higher frequencies. In other words, at low frequencies where the growth delay time is much shorter than the T variation, N will be more or less out of phase with T, but at high frequencies where the growth delay time becomes appreciable relative to the period of the T oscillation, N will have an increasingly additional (but not more than 90°) phase shift from T. Thus, Φ_{sw} should increase from 90° at low frequencies toward 180° at higher frequencies, which is what we observe.

Discussion

We need to address the objections that one might have against the above interpretation of the data. For example, according to the theories, the presence of charged ice particles is a necessary but not sufficient condition for PMSE; each one of the ideas requires, in addition, a generation mechanism for density inhomogeneities. Depending on the theory, this can be turbulence [*Cho et al.*, 1992; *Klostermeyer*, 1994], a horizontal vortex roll [*Havnes et al.*, 1992], or a dusty plasma wave caused by a steady updraft [*Trakhtengerts*, 1994]. Is it possible that what we observed in Fig. 1 was due to the modulation of PMSE by one of the dynamical mechanisms?

Turbulence is most likely to be produced during the most unstable phase of a wave, which is when the vertical velocity is maximum (for an upward-propagating wave); therefore, Φ_{sw} would be 0° in that case. Horizontal vortices should preferentially occur in the region of maximum vertical shear in the horizontal winds, i.e., in the nulls of the wave velocity amplitude; thus, in that case, Φ_{sw} should be $\pm$ 90°. A plasma wave requiring an updraft is directly linked to the vertical velocity, so Φ_{sw} would again be 0°. It appears that the phase trend seen in Fig. 1 cannot be accounted for by the dynamical mechanisms.

On the other hand, for a data set with a higher sampling frequency than the hourly one we used, one would expect to see more and more dependence of PMSE on the dynamical mechanisms rather than the presence of ice particles. Because of the delay time of a few hours required to produce the ice aerosols, oscillations in PMSE power which occur on shorter timescales cannot possibly be modulated by the creation and destruction of such particles. For example, *Williams et al.* [1989] have documented a case where the PMSE power was clearly modulated by a 27-minute wave, with the phase of maximum power corresponding to the phase of maximum upward velocity ($\Phi_{sw} = 0°$).

One might also object to the fairly low values of coherence on which we based our interpretation of the phase values. But considering the fairly involved chain of causality which must be followed, one could not expect such a strict correlation between PMSE and vertical velocity. It is the consistency of the phase values across frequency (and over different years) which suggests a certain significance. Also, because of the coarse altitude resolution of the data and the further averaging which we performed, one cannot expect to achieve low-variance statistics on PMSE which is often limited to very thin layers of a few hundred meters in thickness.

One could take issue with the quality of the radar data. Vertical velocity measurements with MST radars have always been problematic (see, e.g., *Nastrom and VanZandt* [1994]) and PMSE measurements have been an area of special concern [*Balsley and Riddle*, 1984; *Hall et al.*, 1992; *Hoppe and Fritts*, 1995]. But the problems concern the DC bias in the measurements; for our purposes, a DC bias is not a problem—it is the fluctuations that matter.

The gaps in the data necessitated some interpolation and zero-padding, although the data which we presented came from the year with the fewest number of gaps. The zero-padding should not produce any bias in the cross-spectral phases. It is less clear how the interpolation affects the cross-spectrum. To minimize the possible effects, we were careful to interpolate only up to two consecutively missing points. It is difficult to imagine that these short interpolations could result in a bias in the cross-spectral phase across all frequencies.

Finally, we would like to consider the observations of vertical velocity leading PMSE layer displacement by 90° for short-period oscillations [*La Hoz et al.*, 1989]. If the vertical layer displacement is larger than the radar vertical resolution, then the signal power will be coherently out of phase with the vertical velocity by plus or minus 90°, depending on whether the layer is coming into the range gate from below or above. This phenomenon is not an appropriate explanation for our results, because the 2.2-km resolution of the Poker Flat radar is larger than most oscillatory PMSE layer displacements, and also because of the ambiguity in sign of the phase shift. We point out, however, that our results are not in conflict with the short-period observations, since we are looking at a different regime in time and space.

Conclusion

We have examined the temporal phase relationship between PMSE signal power and vertical velocity in the long-term Poker Flat radar data using a cross-spectral technique. The results showed a tendency for the vertical velocity to lead PMSE by 90° to 180°, with a possible upward trend with increasing frequency. The results support the recent PMSE theories which depend on the presence of ice aerosols for the enhancement of radar scattering.

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References

Balsley, B. B., W. L. Ecklund, and D. C. Fritts, VHF echoes from the high-latitude mesosphere and lower thermosphere: Observations and interpretations, *J. Atmos. Sci., 40*, 2451–2466, 1983.

Balsley, B. B., and A. C. Riddle, Monthly mean values of the mesospheric wind field over Poker Flat, Alaska, *J. Atmos. Sci., 41*, 2368–2375, 1984.

Carter, D. A., and B. B. Balsley, The summer wind field between 80 and 93 km observed by the MST radar at Poker Flat, Alaska (65°N), *J. Atmos. Sci., 39*, 2905–2915, 1982.

Cho, J. Y. N., T. M. Hall, and M. C. Kelley, On the role of charged aerosols in polar mesosphere summer echoes, *J. Geophys. Res., 97*, 875–886, 1992.

Cho, J. Y. N., and M. C. Kelley, Polar mesosphere summer radar echoes: Observations and current theories, *Rev. Geophys., 31*, 243–265, 1993.

Ecklund, W. L., and B. B. Balsley, Long-term observations of the Arctic mesosphere with the MST radar at Poker Flat, Alaska, *J. Geophys. Res., 86*, 7775–7780, 1981.

Hall, C., Modification of the energy-wavenumber spectrum for heavy proton hydrates as tracers for isotropic turbulence at the summer mesopause, *J. Geophys. Res., 95*, 5549–5556, 1990.

Hall, T. M., J. Y. N. Cho, M. C. Kelley, and W. K. Hocking, A re-evaluation of the Stokes drift in the polar summer mesosphere, *J. Geophys. Res., 97*, 887–897, 1992.

Havnes, O., F. Melandsø, C. La Hoz, T. K. Aslaksen, and T. Hartquist, Charged dust in the Earth's mesopause; effects on radar backscatter, *Phys. Scr., 45*, 535–544, 1992.

Hoppe, U.-P., and D. C. Fritts, On the downward bias in vertical velocity measurements by VHF radars, *Geophys. Res. Lett.*, 1995, (in press).

Hoppe, U.-P., E. V. Thrane, T. A. Blix, F.-J. Lübken, J. Y. N. Cho, and W. E. Swartz, Studies of polar mesosphere summer echoes by VHF radar and rocket probes, *Adv. Space Res., 14*, 139–148, 1994.

Inhester, B., J. Klostermeyer, F.-J. Lübken, and U. von Zahn, Evidence for ice clouds causing polar mesospheric summer echoes, *J. Geophys. Res., 99*, 20,937–20,954, 1994.

Kelley, M. C., D. T. Farley, and J. Röttger, The effect of cluster ions on anomalous VHF backscatter from the summer polar mesosphere, *Geophys. Res. Lett., 14*, 1031–1034, 1987.

Klostermeyer, J., A two-ion ice particle model of the polar summer mesopause, *J. Geophys. Res., 99*, 5487–5497, 1994.

La Hoz, C., J. Röttger, and S. J. Franke, Dynamic spectra of PMSE measured by EISCAT at 224 MHz, *Handbook for MAP, 28*, 248–256, 1989.

Miller, C. A., J. Y. N. Cho, and W. E. Swartz, CUPRI observations of PMSE during Salvo C of NLC-91: Evidence of a depressed mesopause temperature, *Geophys. Res. Lett., 20*, 2295–2298, 1993.

Nastrom, G. D., and T. VanZandt, Mean vertical motions seen by radar wind profilers, *J. Appl. Meteor., 33*, 984–995, 1994.

Röttger, J., Polar mesosphere summer echoes: Dynamics and aeronomy of the mesosphere, *Adv. Space Res., 14*, 123–138, 1994.

Röttger, J., C. La Hoz, M. C. Kelley, U.-P. Hoppe, and C. Hall, The structure and dynamics of polar mesosphere summer echoes observed with the EISCAT 224-MHz radar, *Geophys. Res. Lett., 15*, 1353–1356, 1988.

Rüster, R., Velocity and associated echo power variations in the summer polar mesosphere, *Geophys. Res. Lett., 22*, 65–67, 1995.

Trakhtengerts, V. Y., Generation mechanism of polar mesosphere summer echoes, *J. Geophys. Res., 99*, 21,083–21,088, 1994.

Turco, R. P., O. B. Toon, R. C. Whitten, R. G. Keesee, and D. Hollenbach, Noctilucent clouds: Simulation studies of their genesis, properties and global influences, *Planet. Space Sci., 30*, 1147–1181, 1982.

Williams, P. J. S., A. P. van Eyken, C. Hall, and J. Röttger, Modulations in the polar mesosphere summer echoes and associated gravity waves, *Geophys. Res. Lett., 16*, 1437–1440, 1989.

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