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Abstract. Variations in PMSE (Polar Mesosphere Summer Echo) occurrence with 4-6 day periods were observed by the ESRAD radar during the summer of 1997. These are compared with temperature fluctuations in 5-day planetary waves extracted from the UKMO assimilated global data analyses. At the beginning and end of the PMSE season, the PMSE variations are closely anti correlated with temperature variations associated with 5-day planetary waves at the 1 mb level. The planetary wave amplitudes expected at the mesopause are 1-2 K. This is found, by comparison with the seasonal decay of PMSE as the temperature rises at the end of the summer, to be sufficient to explain the observed 5-10% amplitude fluctuations in PMSE daily occurrence.

Introduction

Polar Mesosphere Summer Echoes (PMSE), are strong radar echoes returned by thin layers lying between about 80-90 km altitude, close to the summer mesopause (~88 km altitude) at high latitudes. They are considered by some to result from the presence of small-scale turbulence affecting very small, charged aerosols (see review by Cho and Röttger, 1997 and references therein). They are related to noctilucent clouds, which are layers of rather larger aerosols which form in the same season in the same height region (e.g. Nussbaumer et al, 1996; K. Stebel and K.H. Fricke, unpublished data, 1997). The aerosols are thought to be formed by water ice and the appearance of PMSE seems to require both low temperature (below 180 K) and high water vapour content (several ppmv) near the mesopause (Balsley and Huaman, 1997; Kirkwood et al., 1998), both of which are generally available between late May and mid-August. During this season, when PMSE are present at some time almost every day, their persistence is modulated by strong 24 h and 12 h variations. Tidal wind oscillations with the same periods are detected in the same region but the wind-shears associated with the wind field, which are expected to control turbulence, are not sufficient to explain the variations in PMSE (Barabash et al, 1998). It is likely that temperature controlled modulation of the sub-visual aerosols is instead responsible (H. Nilsson, unpublished data, 1997). A 12-h modulation of noctilucent clouds has also been reported (von Zahn et al., 1998). Here a combination of tidal temperature changes and size-selective vertical transport of aerosols is proposed to explain the modulation.

Further modulations of PMSE and of noctilucent clouds, with about 5-days period, have been reported by Sugiyama (1994) and Sugiyama et al. (1996). The latter authors have proposed an explanation for this in terms of a 5-day humidity modulation due to slow sedimentation of aerosols. In this paper we use PMSE observations from 1997 to study the 5-day modulation and investigate whether it might instead be explained in terms of temperature modulation by 5-day planetary waves.

PMSE and mesopause wind observations by ESRAD

PMSE observations for the entire summer of 1997 were made by ESRAD, a 50 MHz MST radar situated near Kiruna in northern Sweden (the radar and the PMSE observations are described in more detail in Chilson et al., 1998 and Kirkwood et al., 1998, respectively). The spectrum of PMSE occurrence during the period 1 June - 31 July is shown in Figure 1. The occurrence has been taken as the binary series of whether or not the average hourly signal-to-noise ratio (SNR) for the altitude interval indicated exceeds -10 dB (see Kirkwood et al, 1998). The original measurements were made with two different height resolutions (150 m and 600 m), i.e. with different length radar pulses, time-slicing between the two. The results from both are shown separately in Figure 1, to give an indication of the reliability of the spectral peaks. There are clear peaks at 12 h, 24 h and 4-6 days. The form of the spectrum is not particularly sensitive to the choice of detection level within ±3 dB, however at higher thresholds the peaks at 5-6 days and shorter periods become indistinct and the spectrum becomes dominated by 10-day periods and longer. The spectrum in Figure 1 shows, therefore, sensitivity to small changes in the threshold for PMSE appearance. Spectral analysis simply using the average signal strength for each hour gives the same result as using a high threshold, i.e. is dominated by long period variations as the time series includes a small number of very high values. The peak at 4-6 days in our data is

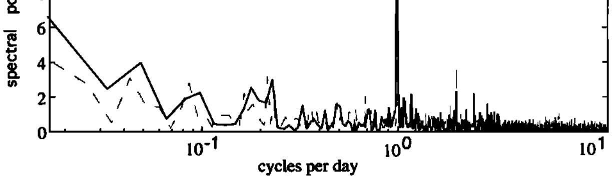

Figure 1. Spectrum of PMSE occurrence at ESRAD between 1 June and 31 July 1997. Occurrence is defined as SNR > -10 dB, and is based on one-hour average SNR for the height interval 84-86 km: solid line corresponds to measurements with 150 m original radar resolution, dashed line to 600 m.

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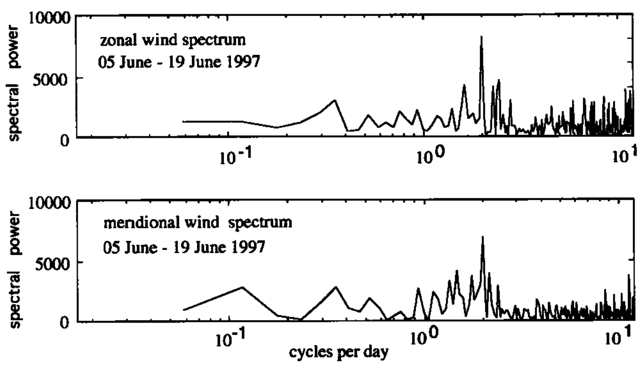

Figure 2. Spectrum of each of zonal and meridional wind components measured by ESRAD using spaced antenna technique applied to the PMSE between 05 June and 19 June 1997 for the height interval 84-86 km. 1-hour averaged winds are used with original radar height resolution 150 m, averaged over 13 gates.

perhaps even clearer than reported by Sugiyama et al. (1996) using data from the Poker Flat radar in Alaska. The 12 h and 24 h peaks, on the other hand, are not visible in Sugiyama et al's (1996) spectrrum of PMSE SNR. This is likely due to the different analysis technique he used, which was to take the spectrum directly of average SNR

Figure 2 shows the spectrum of each of the zonal and meridional wind components at PMSE altitudes from ESRAD (measured by the spaced antenna technique). In order to have sufficient coverage of each day in the wind measurements for a spectral analysis, the analysis is restricted to the period 05 - 19 June. These spectra show also the 12 h components, and some energy around 24 h but the noise level and the shortness of the time period makes it uncertain if there is any energy detectable at 5-6 days. These spectra are similar to, but have a much higher noise level than, the spectra of the corresponding wind components from Poker Flat (Sugiyama et al., 1996), which was a considerably higher-power radar.

Upper stratosphere planetary waves and zonal winds from UKMO analyses

In order to look for planetary waves we use the global, daily analyses from UKMO (UKMO-UARS assimilative correlative analyses) which are based on standard radiosondes and meteorological satellites and cover altitudes from the ground to about 55 km (0.3 mbar) (Swinbank and O'Neill, 1994). The primary data used in preparing these daily analyses for the higher altitudes are temperatures from the satellites. We therefore extract the planetary waves from the temperature fields. Westward-propagating planetary waves with zonal wave number 1 and period around 5 days are known to be common in the atmosphere (e.g. Andrews et al., 1987). We extract them by, for each altitude, first performing a spatial fourier analysis around each latitude circle (to extract wave number 1), followed by time-domain filtering (each altitude and latitude independently) with a 4-6 day bandpass filter. Figure 3a shows the resulting 5-day planetary wave amplitudes for the 1 mb level, for the whole globe, for each day in 1997. Although data is available at higher altitudes we find that the phase consistency between latitudes becomes poor there suggesting that we are at the limit of the resolving power of the data. Figure 3b shows the zonal-mean zonal winds on the same grid, for comparison.

The strongest planetary waves are clearly seen in the winter hemispheres. This is expected since they can propagate upwards from the troposphere most easily when the stratospheric wind is eastward, opposite to the direction of the waves' phase propagation. Rather surprisingly, there is even considerable

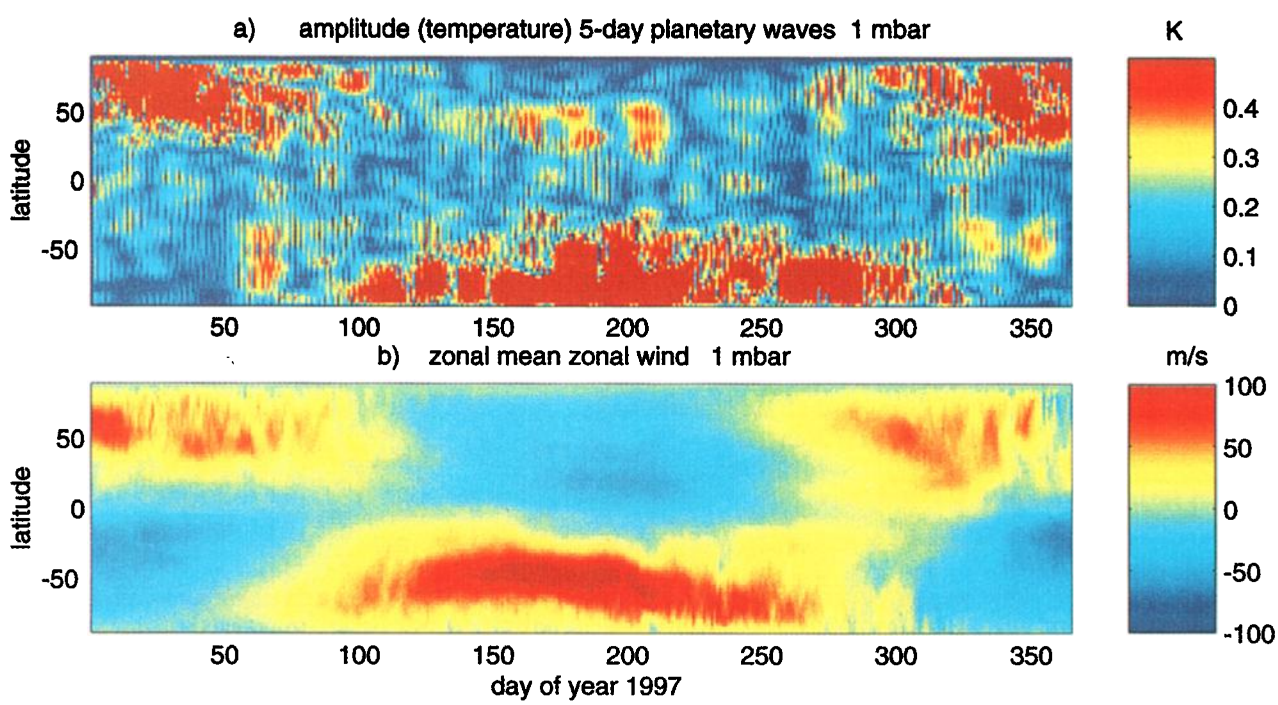

Figure 3. a) Amplitude in K (colour scale) of 4-6-day, wave-number-one, planetary waves as a function of day of the year (x-axis) and latitude (y-axis) for 1997. Data are derived from UKMO-UARS assimilated correlative analysis as described in the text. b) Zonal mean zonal winds (colour scale, positive eastward, units ms^{-1}) on the same grid and from the same data source as a).

planetary wave energy in the summer hemispheres, despite the unfavourable stratospheric wind direction. Planetary waves reaching the summer mesosphere have, however, been reported elsewhere (e.g. Espy et al., 1997; Jacobi et al., 1998), so we do not doubt their authenticity. They are clearest at mid-latitudes but careful scrutiny of Figure 3a shows that they extend even to fairly high latitudes at the start and end of the summer (i.e. for the northern summer between days 120-150 and 220-250).

Correlation between PMSE and Planetary Waves

Figure 4a shows the time series of PMSE occurrence from ESRAD, Figure 4b the same time series after the application of a 4-6 day bandpass filter. At the beginning and in the second half of the season (before day 160 and after day 200), the PMSE is strongly modulated at 4-6 day periods. In the first half of the season, after the first few days, it seems to be less affected.

Figure 4c shows the temperature variation associated with the '5-day planetary waves' at 1 mb altitude, and the location of ESRAD (68 N, 20 E) together with the filtered PMSE variation (with sign reversed) for comparison. The (anti-) correlation in

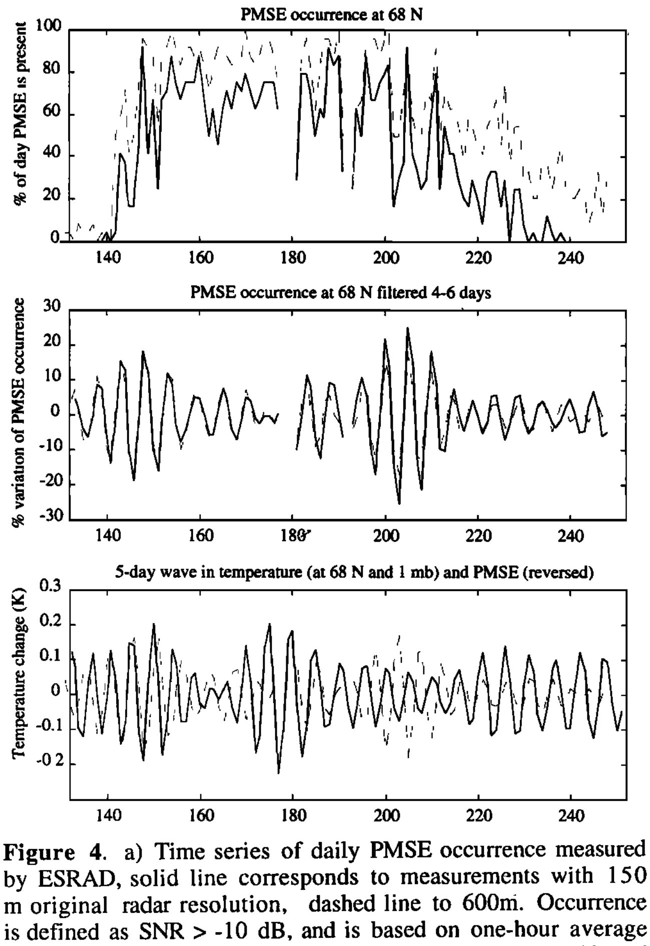

Figure 4. a) Time series of daily PMSE occurrence measured by ESRAD, solid line corresponds to measurements with 150 m original radar resolution, dashed line to 600m. Occurrence is defined as SNR > -10 dB, and is based on one-hour average SNR over the height interval 84-86 km; b) as a) but filtered with 4-6 day bandpass filter, c) temperature variation associated with 5-day planetary waves at 1 mb level for the location of the radar (solid line) and -1 x the filtered PMSE variation (dashed line, the inverse of the dashed curve in b).

phase is remarkably good at the beginning and end of the season (up to day 150 and after day 220) with high temperatures corresponding to less PMSE. Between days 150-180 however, the correlation is poor with little PMSE variation despite considerable 'wave' amplitude. This is what we might expect if temperature changes associated with the planetary waves raise and lower the average daily temperature bringing it further from or closer to the threshold for aerosol formation. The 24h and 12 h tides will then bring the temperature below the threshold for shorter or longer periods, respectively, each day. In the middle of the season the temperature is lower and likely below the threshold whatever the tidal or planetary wave activity.

The amplitude of the temperature fluctuations associated with the planetary waves at the radar latitude during the PMSE season is only 0.1-0.2 K at the 1 mb (~45 km) level. For a planetary wave propagating freely upward in an isothermal atmosphere, we would expect the temperature fluctuations to keep essentially constant phase and increase amplitude in proportion to $e^{2z/7H}$ (e.g. Andrews et al 1987), where z is the height change and H the atmospheric scale height (around 6 km in the mesosphere). So we could expect amplitudes 1-2 K at the mesopause, and the same phase as at 1 mb. This is less than, but of the same order of magnitude as the temperature fluctuations associated with tides which have been observed to reach around 10 K in the relevant height interval (e.g. Kirkwood, 1986; Hansen and Hoppe, 1996; Chilson et al., 1997; H. Nilsson, unpublished data, 1997).

From the seasonal decay of PMSE in 1997 (see Kirkwood et al, 1998) we know that an increase of average mesopause temperature by about 10 K corresponds to about a 50% drop in the daily occurrence of PMSE. Proportionally, 1-2K amplitude planetary waves would then be expected to give 5-10% amplitude fluctuation in PMSE. This is close to what we observe.

The high variability of the PMSE between days 200 and 210 however, is clearly not correlated to 'wave' activity and must have some other explanation. It should be noted here that the 'wave' amplitudes seen in our analysis at 68° N between days 150-220 are not consistent in phase with those at the same time at mid-latitudes (they also belong to separated 'islands' of enhanced 'wave' amplitude in Figure 3a). It may be that these are not true planetary waves in which case we cannot be at all sure whether they are representative of waves at PMSE heights.

In the UKMO analyses, winds are derived from the temperature fields so there are 5-day planetary wave signatures in the horizontal wind fields corresponding to those in the temperatures. During the PMSE season at the 1 mb level they are ~0.4-0.8 m/s. Freely propagating up to the mesopause these would reach 4-8 m/s. This is much smaller than the tidal wind amplitudes, which are 30-40 m/s. The very uneven data availability from ESRAD (mesopause winds can be measured only when PMSE is present) make even the tidal winds difficult to distinguish in the spectra in Figure 2. So we would not expect to be able to detect the planetary waves in these spectra.

Conclusions

We find distinct variations in PMSE occurrence with periods between 4-6 days. At the beginning and end of the PMSE season, these are closely anti correlated with temperature variations associated with 5-day planetary waves at the 1 mb pressure level. Propagating freely up to the mesopause, these planetary wave amplitudes should reach 1-2 K. This is found, by comparison with the seasonal decay of PMSE as the temperature rises at the end of the summer, to be sufficient to explain the observed 5-10% amplitude fluctuation in PMSE daily occurrence.

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