THE NATURE OF VHF RADAR ECHOES FROM THE MESOSPHERE

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ABSTRACT

Thin layers of enhanced radar echo power from the winter mesosphere, named Polar Meosphere Winter Echoes, PMWE, have been studied using the ESRAD 52 MHz and the EISCAT 224 MHz radars in northern Scandinavia. The PMWE show very high horizontal scatterer travel speeds and high aspect sensitivity (ESRAD), and spectral widths indistinguishable from those produced by the background D-region plasma (EISCAT). We show that PMWE characteristics are incompatible with their being generated through neutral air turbulence and propose that scatter from highly-damped ion-acoustic waves generated by partial reflection of infrasonic waves provides a more reasonable explanation for PMWE.

1. INTRODUCTION

Thin layers of enhanced radar echo from the winter high latitude mesosphere have been observed by many VHF radars both in Alaska and in Northern Scandinavia, since the first radars were deployed in the 1970s [1]. They have generally been assumed to be due to turbulence, but observations in recent years with the relatively low-power ESRAD 52 MHz radar (located at Esrange in northern Sweden) have shown that turbulence cannot explain many of the characteristics of the echoes and their origin is unclear. They are simply too strong to be explained by reasonable levels of turbulence [2], [3], [4], and they appear in conditions which would not allow active turbulence (monitored by meteorological rockets during the MacWAVE campaign in January 2003) [5]. The echoes have been named Polar Mesosphere Winter Echoes, PMWE. PMWE have been observed by ESRAD during every wintertime solar proton event since operations began in 1996. Improvements in radar hardware (larger antenna, faster digital processing) allowed interferometric study of particularly strong PMWE during a solar proton event in November 2004 [6]. The EISCAT 224 MHz radar observed the same PMWE layer and here we use the combined observations from the two radars to support the proposal that evanescent, highly-damped ion acoustic waves resulting from partial reflection of infrasound can explain PMWE. This is closely related to the mechanism proposed earlier [7] to explain VHF echoes from the lower stratosphere and MF echoes from the mesosphere.

2. ESRAD 52 MHz PMWE

Fig. 1 illustrates the most important results of the analysis of the strongest PMWE observed by ESRAD during November 2004. The technique used to determine horizontal scatterer velocity is 'full correlation analysis [8]. The ESRAD antenna consists of an 18 x 16 array of 5-element yagis, spaced at about 4 meter intervals (0.7 x the radar wavelength). This array is divided into 6 sub-arrays, each with 6 x 8 yagis, with each sub-array connected to a separate receiver. The two-way half-power beam width for each segment is about 7° x 9°. During November 2004, 5 receivers were available and full correlation analysis was made by least square fitting to the cross- correlation functions formed between every available sub-array pair. The scattering structures responsible for the radar echoes are found to have very high horizontal travel speeds, up to 500 m/s or more, particularly at the lower edge of the PMWE layer where the signal strength is highest. This is far in excess of neutral wind speed and rather suggests a connection to wave propagation.

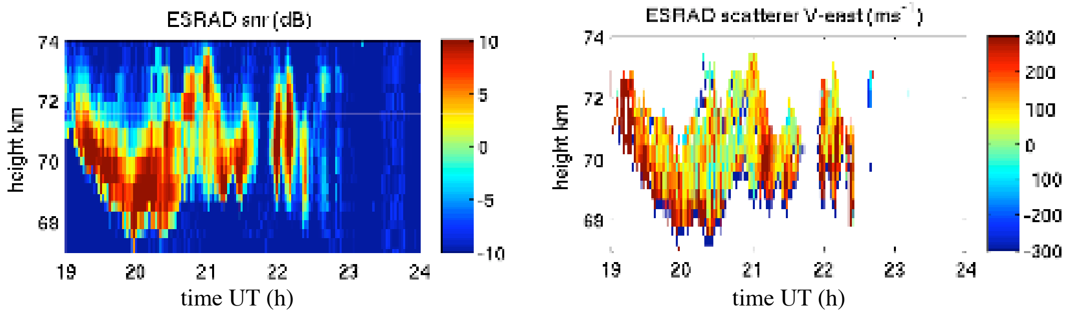

Fig. 1. Signal-to-noise ratio in dB (left) and zonal scatterer drift speed in m/s for PMWE observed by ESRAD on 10 November 2004. Note the very high drift speeds, > 300 m/s in the lower part of the PMWE

Cross-spectral analysis in the frequency domain [9] can be used to determine the angular distribution of radar scattering regions within the antenna field of view. The result is a map of the direction of arrival of echoes corresponding to different parts of the frequency spectrum (different 'Doppler' frequencies) of the scattered signal. Representative results are shown in Fig. 2., which shows a pattern which is found to be characteristic of PMWE. Echoes come from a narrow 'streak' across the sky, which is about 1-2 ° in length and 0.5° or less in width. The Doppler frequency increases systematically from one end of the streak to the other. This is consistent with the concept of radar scatter from the phase-fronts of some kind of waves, moving across the field of view. It is not consistent with what is expected if turbulent eddies are responsible for the scatter. It is generally expected that turbulent vertical motion should cause the Doppler spreading of the spectrum in the latter case, and scattering regions corresponding to different turbulent velocities should be randomly distributed over the field of view.

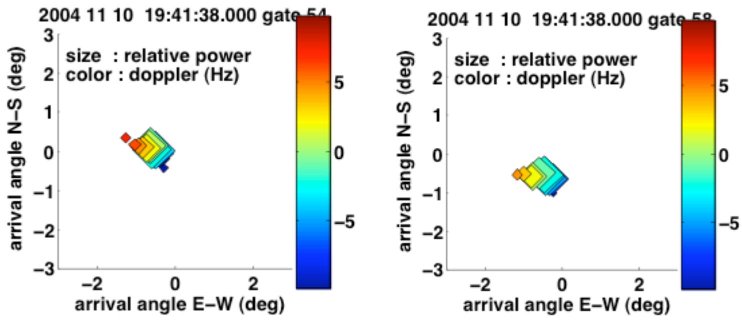

Fig. 2. Angle of arrival as a function of Doppler frequency (colour scale) seen by ESRAD at 1936-1942 UT on 10 November 2004 at the base (left) and maximum (right) of the PMWE layer. Points are included for all Doppler shifts where the cross spectral amplitude is at least half of the maximum.

3. EISCAT 224 MHz PMWE

The EISCAT VHF radar observed PMWE both simultaneously with the ESRAD results in Fig. 1 and earlier in the day. Representative profiles of the scattered power and spectral widths through these layers are shown in Fig. 3. The radar was operating a program optimized for D-region observations, which is described in more detail in [6]. The antenna, which has a very narrow beam-width, about 0.6 x 1.2 degrees, was directed vertically. Spectra of the radar signal returns below, inside, and above the PMWE layer are shown in Fig. 3. A remarkable feature of these spectra is that there is no obvious difference in spectral width inside the PMWE layer and above and below it. The PMWE spectral half-width is about 7 Hz in the pre-noon layer and 20 Hz in the evening - the radar scatter from the background ionospheric plasma (the "ion-line" [10]), varies with time of day in just the same way. The changes in background spectral width can be expected due to an increase of negative ions in the evening. The similarity between PMWE and ion-line spectral widths points towards a common explanation.

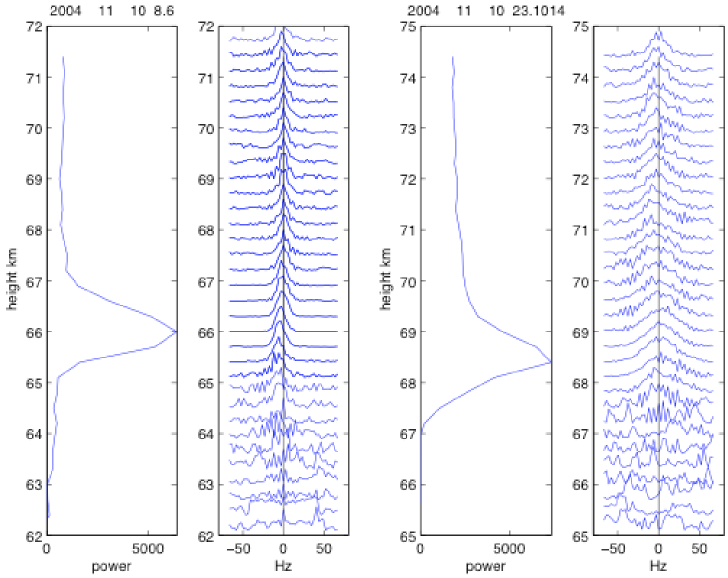

Figure 3. Scattered signal power and spectra measured by the EISCAT VHF radar, below, within and above the PMWE layer on 10 November 2004 during a pre-noon PMWE (left) and an evening PMWE (right)

4. DISCUSSION AND CONCLUSIONS

A potential explanation for the characteristics of PMWE seems to be provided by the 'viscosity' or 'diffusion' waves which have been proposed earlier to explain VHF radar echoes in the lower stratosphere, MF radar echoes in the mesosphere, or VHF radar echoes at the summer mesopause [7]. These are evanescent waves supposed to form at a (partially) reflecting boundary where gravity waves or acoustic waves are reflected by changes in temperature or wind speed. The waves which could cause radar scatter in the mesosphere are diffusion waves (i.e. governed by ion diffusion in the plasma). However these have the same wavelength and period characteristics as viscosity waves (which are in the neutral gas) when the ion diffusion and kinematic viscosity are equal, i.e. when the plasma is dominated by positive molecular ions and the ion-neutral collision frequency is high. When negative ions are present, the diffusivity is increased to higher values than the kinematic viscosity [10].

Fig.4 illustrates the principles of the concept, and provides calculations of the periods of acoustic-gravity waves needed to produce viscosity or diffusion waves with wavelengths matching the Bragg scale of ESRAD (ca 3m) and EISCAT VHF (ca 70 cm). The periods needed are in the range 0.1 – 10 s, i.e. in the region of infrasound. It is well known [11] that infrasound can reach the mesosphere (and even the lower thermosphere) with very little attenuation. It is also known that infrasound is often reflected back to Earth by gradients in propagation characteristics in this region. Both temperature gradients and wind shears can effectively reflect, or partially reflect, infrasound. Since the atmosphere is to a large extent horizontally stratified, the reflecting levels will generally lie close to horizontal and the diffusion wave-fronts will be close to horizontal.

In the case of the ESRAD radar, infrasound with periods of 1-10 seconds and wavelengths of ~300 m – 3 km are needed to generate diffusion waves matching the 3 m Bragg scale. In this case, it is conceivable that one or a few diffusion-wave wave-fronts may be present in the field of view at any one time. They will lead to highly aspect sensitive echoes and will propagate across the field of view at the trace speed of the infrasound waves, which will be in excess of the speed of sound, consistent with the observations

In the case of the EISCAT radar, infrasound of much shorter periods and wavelengths is needed to match the Bragg scale of 70 cm. In this case, there will generally be several diffusion waves in the field of view at any one time and they may be moving in many different directions. However, it should be noted that diffusion waves are the same waves which are responsible for the normal 'ion-line' radar scatter from the background plasma, also known as heavily damped ion-acoustic waves. In the background plasma, diffusion waves are generated by thermal fluctuations in the plasma. Although the excitation mechanisms are different in the background plasma and in the PMWE, the damping mechanisms can be the same, leading to the strong similarities in spectral width of the radar echoes.

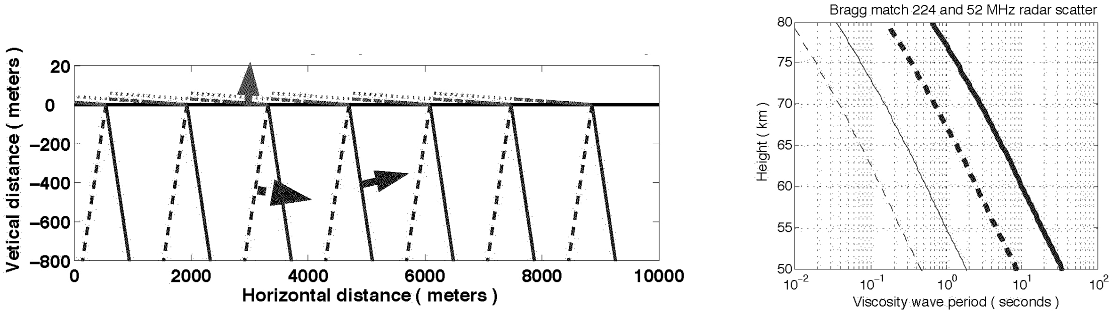

Fig. 4. Left-hand-side : sketch showing the principles of evanescent viscosity or diffusion wave at a boundary where (partial) reflection of an infrasound wave occurs. The infrasound approaches from below and the evanescent wave forms immediately above the reflecting surface. The scales are appropriate for an evanescent wave matching the Bragg wavelength for the ESRAD radar. Note that the vertical distance scale is expanded above the reflecting level. Right-hand-side : Period of evanescent wave (= period of incident infrasonic wave) matching the wavelength for radar Bragg scattering as a function of height (based on kinematic viscosity calculated from the MSIS90E model). Solid lines are for viscosity waves or ion-diffusion waves in the case of only positive molecular ions. Dashed lines are for ion-diffusion waves with 3 times more negative ions than electrons. Thick lines are for Bragg matching to a 52 MHz radar, thin lines for a 224 MHz radar.

6. REFERENCES

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