FIRST IN-SITU OBSERVATIONS OF NEUTRAL AND PLASMA DENSITY FLUCTUATIONS WITHIN A PMSE LAYER

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Abstract. The NLC-91 rocket and radar campaign provided the first opportunity for high resolution neutral and plasma turbulence measurements with simultaneous observations of PMSE (Polar Mesospheric Summer Echoes). During the flight of the TURBO payload on August 1, 1991, CUPRI and EISCAT observed double PMSE layers located at 86 and 88 km altitude, respectively. Strong neutral density fluctuations were observed in the upper layer but not in the lower layer. The fluctuation spectra of the ions and neutrals within the upper layer are consistent with standard turbulence theories. However, we show that there is no neutral turbulence present in the lower layer and that something else must have been operating here to create the plasma fluctuations and hence the radar echoes. Although the in situ measurements of the electron density fluctuations are much stronger in the lower layer, the higher absolute electron density of the upper layer more than compensated for the weaker fluctuations yielding comparable radar echo powers.

Introduction

Strong VHF radar echoes are frequently observed in the polar summer upper mesosphere, a phenomenon known as 'polarspheric summer echoes' (PMSE) [Ecklund and Balsley, 1981; Röttger et al., 1988; Hoppe et al., 1988]. It was realized earlier that it is difficult to explain the PMSE echoes by the traditional theory of backscatter from turbulent structures in the electron gas. The reason for this is that the spatial extent of the density inhomogeneity must be in the order of the radar half-wavelength (3 m and 0.67 m for 50 and 224 MHz radars, respectively). These very small scales are normally located in the viscous subrange of the spectrum, where molecular diffusion destroys fluctuations caused by turbulent cascading. Only unrealistically strong turbulence could support these small scales against molecular diffusion. Kelley et al. [1987] suggested that the electrons may not be good tracers of neutral air turbulence because they are coupled to the ions, which in turn can exhibit smaller structures than the neutrals, provided their diffusivity is significantly reduced due to unusually high masses caused by clustering. This process is supported by the very low temperatures in the summer mesopause region. In the theory of a passive scalar turbulent spectrum a low molecular diffusivity, $D_0$, of a passive tracer $\theta$ results in a high Schmidt number defined as $Sc = \nu/D_0$ ($\nu$ = kinematic viscosity).

Mechanisms to create very small structures in the electron gas other than turbulence have been discussed in the literature. For example, Röttger and LaHoz [1990] have proposed the creation of steep electron density gradients due to the enhanced recombination coefficient of electrons with clustered positive ions. If these gradients are steep enough (significant changes over a spatial distance of $\lambda_{H2}/2$) they result in Fresnel backscattering. Some weak background turbulence may cause mixing of these steep gradients, which in turn increases the scatter cross section. Experimental evidence for a non-turbulent backscatter mechanism was found from in situ and radar measurements [Ulwick et al., 1988; Röttger et al., 1988].

In order to better understand the role of turbulence in the creation of PMSE echoes, reliable in situ measurements of neutral air and plasma turbulence together with simultaneous observations of PMSE were needed. Such measurements were performed during the recent NLC-91 campaign. First results are presented in this paper and in the companion papers in this issue.

Instrumental

The 'Noctilucent Cloud' campaign (NLC-91) was conducted at Esrange (67.9°N, 21.1°E), North Sweden, in August 1991. The scientific objectives and the measurements performed in situ and by radars are described in other papers in this issue. Here we will mainly discuss data from the TURBO payload launched on August 1, 1991 at 01:40:00 UT ('Salvo B'). The payload name 'TURBO' indicates that it is primarily designed to measure turbulence. The payload is equipped with sensors to measure neutral (TOTAL, downleg), positive ion (PIP, up- and downleg) and electron densities (EPIP, downleg). More details can be found elsewhere [Hillert et al., 1992; Bliz et al., 1990]. Background temperatures were measured by falling spheres, one of which was launched 44 min after TURBO.

Concerning small scale fluctuations, the data reduction is similar for all three probes: relative density fluctuations...
(n(z) - n_{ref})/n_{ref}, also called 'residuals' \( r(t) \), are deduced from the measured density profile \( n(z) \) and from a reference profile \( n_{ref} \), obtained by smoothing the density profile. A spectral analysis of the time series \( r(t) \) is performed and quantitative turbulent parameters, such as turbulent energy dissipation rates \( \epsilon \), are derived [Lübben, 1992].

Two VHF radars were operational during the NLC-91 campaign: the Cornell University Portable Radar Interferometer ('CUPRI') at 46.9 MHz and the EISCAT VHF radar at 224 MHz. Technical details can be found elsewhere [Providakes et al., 1983; Hoppe et al., 1988]. CUPRI was located close to the rocket launch site. Still, there is a substantial horizontal distance to the atmospheric volume probed by TURBO at 85 km: CUPRI looked in the vertical direction, whereas TURBO flew through the 85 km layer at a horizontal range of 13.3 and 51.9 km on upleg and downleg, respectively, nearly northward from CUPRI. The EISCAT VHF system is located in Tromsø (69.7°N, 19.0°E), approximately 220 km from Esrange.

Relative density fluctuations and PMSE

In Figure 1 the radar echo strength measured by CUPRI is shown together with the relative percentage fluctuations of all 4 in situ measurements. More details about the CUPRI observations are presented in the companion paper of Cho et al. [1993]. We have averaged the CUPRI signal in the period 20 minutes around the TURBO launch in order to account for the horizontal distance mentioned above: assuming 40 m/s horizontal wind speed and arbitrary direction, the distance of 51.9 km corresponds to a minimum time lag of ~ ± 20 min. A strong PMSE is observed by CUPRI in the altitude range 84 - 91 km. There is a tendency for a double layered structure which we use to distinguish between an 'upper' and a 'lower' PMSE layer throughout this paper.

The electron densities show strong fluctuations at the altitude of the lower PMSE layer and, to a lesser extent, also at the upper layer. The variability is small in the rest of the profile. The neutrals also show strong fluctuations but located at higher altitudes (~87-92 km). Comparatively small variations are observed in the rest of the profile. Please note that the neutral residuals are extremely small at the altitude of the lower PMSE layer. The ions show fluctuations from 84 - 91 km both on upleg and on downleg (the increase in the lowest part is due to instrumental noise). We note that the two ion profiles show some similarities: the fluctuations are virtually absent above 91 km and both profiles show a tendency to a maximum around 85 km. This suggests that the layer is horizontally stratified with a tilt smaller than 1-2 km / 40 km.

In Figure 2 expanded views of the residuals in the lower and upper PMSE are shown (we have not plotted the ion density fluctuations on upleg, since the horizontal distance to the other profiles is too large). When comparing absolute magnitudes the scaleheight effect has to be taken into account: following Thrane and Grandal [1981] neutral and ion density fluctuations are related by the 'F-factor' \( (\Delta n/n = F \cdot \Delta N/N) \) which is determined by neutral and plasma density scaleheights.

In Figure 2a strong fluctuations in the electron and ion densities are shown. An even closer look shows that significant fluctuations are present down to very small scales below 3 meters (see Figure 3). These type of 'spiky' fluctuations can explain the CUPRI radar echoes, provided the irregularities extend over at least a Fresnel zone (~ 1 km) [Hoppe et al., 1993]. We are also studying rocket
fluctuations in the two layers, we have studied the spectra found that the measured power spectral densities (PSD) in level: the noise current of the electrometer zero-line is very flat. We have compared this spectrum with theoretical model’ since no indication of an inertial subrange is observed. As can be seen from Figure 3, the power spectral densities at scales of 3 m are significantly above the noise level: the noise current of the electrometer zero-line is 10 pA (RMS) which corresponds to a PSD of 5 × 10^{-6} at 84 km, as is observed at very high frequencies in Figure 3.

Coming to the upper layer next: all indications suggest that there is turbulence present here. Apart from the anti-correlation between neutral and ion fluctuations mentioned above, the neutral density fluctuation spectrum nicely agrees with a theoretical model using $\epsilon \approx 83$ mW/kg (see Figure 2 in Lübken, 1992). When comparing this spectrum with that measured by the ion probe in the same height range (taking into account the F-factor) we find good agreement at large and medium scales. However, at larger wavenumbers the ion spectrum shows larger PSD compared to the neutral spectrum. This is expected if the diffusivity of the ions is significantly reduced and the Schmidt number is larger than 1. We have estimated $Sc$ by fitting the D&K model to the measured ion spectrum and found $Sc \approx 3$. We note, however, that the measured spectrum is not very well represented by a D&K model (the latter falls off too rapidly).

We now compare the observed electron fluctuations with the CUPRI radar echo power. The electron fluctuations are much smaller in magnitude in the upper layer compared to the lower layer, but the CUPRI echo power is approximately the same. This can be understood if we estimate...
Discussion and Conclusions

Further evidence for a fundamentally different backscatter process comes from the aspect sensitivity of the CUPRI echo [Cho et al., 1993]. In addition, the spectral width of the EISCAT VHF radar echo is also different at both layers: the spectrum received from 86 km has a width of 1 Hz (FWHM), the one from 89 km is 11 Hz wide and a factor of 2 - 3 less intense. Assuming that this width is entirely given by turbulence the turbulent velocity becomes \( w = 1.8 \text{ m/s} \). This agrees very well with the \( w = 2.2 \text{ m/s} \) that is derived from \( \epsilon = 83 \text{ mW/kg} \) given above.

In conclusion, we find that our in situ observations of neutral and plasma fluctuations during a PMSE event reveal the coexistence of different backscattering mechanisms in different parts of the PMSE layer: we have shown that the echoes from the lower part of the PMSE layer are not caused by neutral air turbulence. Some other non-turbulent process must have created the fine structures in the electron and ion gas (and must support it against destruction by diffusion). Simultaneously, in the upper part of the PMSE layer we find conclusive indications for neutral turbulence. Regardless of their creation mechanism, we estimate that the relative backscattered power show that the electron fluctuations at 3 m-scale lead to approximately the same echo strength in both parts of the PMSE layer, as is observed.

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References


