TURBULENCE AND TEMPERATURES IN THE UPPER SUMMER MESOSPHERE RELATED TO POLAR MESOSPHERE SUMMER ECHOES

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ABSTRACT

In the last ten years a total of 8 insitu measurements of neutral number densities were performed in the polar summer mesosphere during nearly co-located observations of very strong radar echoes called 'polar mesosphere summer echoes' (PMSE). The insitu density measurements were used to derive turbulent parameters, such as the turbulent energy dissipation rate ϵ. From the same instrument high resolution temperature profiles in the altitude range of approximately 110 to 70 km are derived. There is no apparent correlation between PMSE and neutral air turbulence, however, occasionally both PMSE and turbulence coincide. The temperature gradient within the PMSE layer shows no tendency for an adiabatic lapse rate, which indicates that persistent turbulent mixing cannot have taken place. We note that PMSE was present for typically more than one hour before the sounding rocket was launched, thus long enough to affect the thermal structure if PMSE were related to turbulence. The fact that the thermal structure is not affected leads us to the conclusion that the occasional coincidence of PMSE and turbulence deduced from insitu measurements is accidental. This also implies that the main mechanism creating PMSE remains unidentified.

We performed a detailed analysis of the high resolution temperature measurements in the vicinity of PMSE. In the PMSE layer the temperatures are generally small enough for water ice particles to exist, i. e., the degree of saturation of water vapor over ice is significantly larger than unity (we assume a water vapor mixing ratio of 4 ppmv constant with altitude). It is interesting to note that in most of the flights the PMSE layer covers less than half of the altitude range where ice particles can exist. This stresses the importance of other physical mechanisms required to create PMSE except the presence of water ice particles.

Key words: Summer mesosphere; polar mesosphere summer echoes.

1. INTRODUCTION

In the summer season at polar latitudes very strong radar echoes are received from the altitude region around 85 km, i. e., from a few kilometers below the mesopause. These echoes are called 'polar mesosphere summer echoes' (PMSE) and are created by fluctuations in the electron number density at the Bragg scale corresponding to the radar wavelength, typically 3 m for a VHF radar operating at a frequency of 50 MHz [*Czechowsky et al.*, 1979; *Ecklund and Balsley*, 1981; *Cho and Röttger*, 1997]. It is generally accepted that the mechanism creating PMSE must be related to charged aerosols and the creation of small scale disturbances in the electron number densities [*Cho et al.*, 1996; *Havnes et al.*, 1996; *Blix*, 1999].

Since the first detection of PMSE in the late 1970s neutral air turbulence is believed to be the main physical mechanism for PMSE since turbulence creates small scale fluctuations in the neutral gas. However, unrealistically strong turbulence with turbulent energy dissipation rates on the order of $\epsilon \sim 100$ W/kg, corresponding to a heating rate of 86400 K/d(!) is required in order to support neutral air fluctuations at such small scales. Therefore, the turbulence theory was developed further by introducing a scale separation between plasma and neutral air fluctuations at very small spatial scales caused by the reduced diffusivity of the electrons which are electrically bound to the 'heavy' aerosols [*Kelley et al.*, 1987; *Cho et al.*, 1992]. The scale separation occurs if the Schmidt number $Sc=\nu/D$ is significantly larger than unity, where ν is the kinematic viscosity, and D is the diffusion coefficient for electrons which is actually given by the diffusion coefficient of

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the charged aerosols. Indeed, insitu measurements of neutral air, electrons, and charged aerosols occasionally showed Schmidt numbers much larger than one [*Lübken et al.*, 1994].

First doubt that neutral turbulence in combination with increased Schmidt numbers gives a complete explanation for PMSE came from simultaneous radar observations and insitu measurements of neutral air fluctuations which showed that in some cases neutral air turbulence was totally absent in the vicinity of PMSE [*Lübken et al.*, 1994, 1998]. If so, the prime process for the Schmidt number theory outlined above, namely neutral air turbulence, is not present and the theory fails to explain the observations. In this paper we will further discuss the role of neutral air turbulence in creating PMSE. We will also study the background thermal structure since persistent turbulence should leave its footprint in the thermal structure because turbulent mixing drives the temperature gradient towards the adiabatic lapse rate. Whereas insitu measurements on sounding rockets give a snapshot of the physical conditions in the upper mesosphere, the thermal structure may allow us to identify the long term effect (or its absence) of turbulence in the atmosphere.

We also present a detailed discussion on temperatures and PMSE since it is sometimes taken for granted that a one-to-one relationship exists between the occurrence of PMSE and low enough temperatures. As will be shown in this paper this is not necessarily the case.

The sounding rocket and radar measurements presented in this paper were performed at the Andøya Rocket Range (69°) in northern Norway and at Esrange in northern Sweden (68°). Details about the launches with neutral air density measurements in the vicinity of PMSE and specifications of the various radars used in different field campaigns are presented elsewhere [*Lübken et al.*, 2001].

2. NEUTRAL AIR TURBULENCE AND PMSE

Turbulence in the atmosphere creates fluctuations in the neutral number density relative to a smooth background. Rocket borne insitu measurements of these small scale neutral density fluctuations are performed since the early 1990s by means of ionization gauges such as the Combined Neutral and Electron instrument CONE [*Giebeler et al.*, 1993]. A spectral analysis of relative density fluctuations is used to derive quantitative results, for example the turbulent energy dissipation rate ϵ [*Lübken*, 1992]. This energy dissipation rate corresponds to a heating rate of $dT/dt = 0.086 \cdot \epsilon$ [K/d], where ϵ is in mW/kg. A total of 8 flights with small scale neutral number densities were performed with nearly co-located measurements of PMSE (see *Lübken et al.* [2001] for a recent review). In Fig. 1 a PMSE is shown which was detected by the ALWIN radar during the MIDAS/DROPPS campaign on July 5/6, 1999 [*Latteck et al.*, 1999]. We also show an ϵ profile derived from CONE measurements taken on board the MIDAS payload launched at 00:06 UT in that night. It is obvious that there is no turbulence in the central part of the PMSE layer ; only some weak activity is present at the lower and upper edge of the PMSE layer with ϵ values of 6.3 and 17.4 mW/kg, respectively (corresponding heating rates are 0.5 and 1.5 K/d). It is interesting to note that rather strong turbulence is present above the PMSE layer with ϵ values up to 138 mW/kg (corresponding heating rate is 12 K/d).

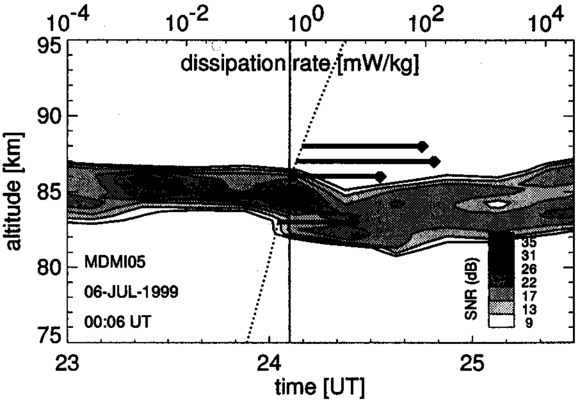

Figure 1. Signal-to-noise ratio of the backscatter power of the ALWIN VHF radar operating at 53.5 Mhz (grey scale contour) and the ϵ profile derived from small scale density fluctuations by CONE on board the sounding rocket MDMI05 (scale on the upper axis). The sounding rocket was launched at 00:06 UT on July 6, 1999. The dotted line indicates the theoretical lower limit given by $\epsilon_{min} \sim \nu \cdot \omega_B^2$ (ν=kinematic viscosity; ω_B=Brunt-Väisälä frequency).

3. NEUTRAL AIR TEMPERATURES AND PMSE

The insitu ionization gauge measurements mentioned above are also used to derive high resolution neutral density profiles which are converted to temperatures assuming hydrostatic equilibrium. Significant progress in the data analysis of these measurements has been made in recent years when wind tunnel calibrations and Monte Carlo simulations have been used to convert densities inside the CONE sensor to ambient densities correcting for the effect of the rocket motion on the measurement ('ram effect'). This method gives temperature profiles with high spatial resolution of approximately 100–200 m (given by the spin period of the payload) in the altitude range from 110 to 70 km with a typical accuracy of a few Kelvin [*Rapp et al.*, 2001a]. This is certainly an improvement (but also much more costly) compared to the falling sphere technique which is frequently used to determine temperature profiles in the mesosphere and upper stratosphere with an altitude resolution of several kilometers [*Lübken*, 1999].

In Fig. 2 a temperature profile deduced from CONE measurements taken on July 31, 1994, at 00:50 UT is shown together with a PMSE detected by the ALOMAR/SOUSY radar (a precursor of the ALWIN radar). Within the PMSE layer the temperatures are very low, i. e., smaller than ~140 K. In that Figure we have also indicated the altitude region where the degree of saturation of water vapor over ice (S) is larger than unity assuming a reasonable water vapor concentration [H_2O] of 4 ppmv independent of altitude. This value of [H_2O] is within the range deduced from models and from indirect measurements [*Körner and Sonnemann*, 2001; *von Cossart et al.*, 1999]. A value of S>1 is a necessary condition for water ice particles to exist or to grow. Within the PMSE layer the degree of saturation is much larger than unity which supports the general understanding that the strong radar echoes are somehow related to (charged) ice particles. It is interesting to note that the PMSE coincides with a local temperature minimum which is a common feature in all available measurements and which is nicely reproduced by model calculations taking into account all important physical mechanisms influencing the creation of water ice particles in the upper mesosphere [*Rapp et al.*, 2001b].

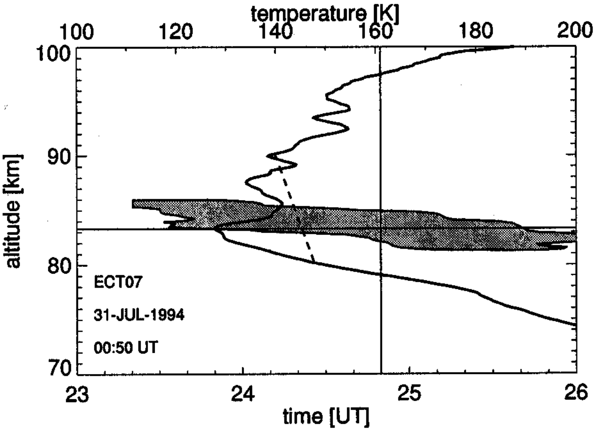

Figure 2. Temperature profile measured by the CONE sensor on the sounding rocket ECT07 launched during the ECHO campaign in Andenes (69° N) on July 31, 1994, at 00:50 UT. The time development of the PMSE detected by the ALOMAR-SOUSY radar is shown as grey coded contour. The altitude region where the degree of saturation for water vapor over ice is larger than unity (assuming a water vapor mixing ratio of 4 ppm independent of altitude) is indicated (dashed line).

From Fig. 2 we also see that there is an extended altitude interval where S>1 outside the PMSE layer, namely between 85 and 91 km. This demonstrates that temperatures can be very low but still PMSE is not observed. We have performed a statistical analysis of the altitude regions with supersaturation, both within and outside the PMSE layer. The main results are summarized in Table 1. We have taken a limit of S>0.5 (rather than S>1) in order to take into account various uncertainties when determining the degree of saturation, e. g., the unknown concentration of water vapor. We note that particles can still exist for a substantial time period (hours) when the degree of saturation is somewhat smaller than unity. When determining the PMSE altitude range we have taken into account the PMSE layer in a substantial time period around the rocket flight (typically ±1/2 hour) to allow for uncertainties introduced by the horizontal distance of several tens of kilometers between the radar and the insitu measurements (see *Lübken et al.* [2001] for more details). We have tentatively performed the same statistical analysis using the altitude range of the PMSE layer exactly during the rocket launch, and the results are basically the same.

As can be seen from Table 1 the degree of saturation is sufficiently large for water ice particles to exist or to grow, i. e. S>0.5, in the entire PMSE layer (see also Fig. 5 in *Lübken et al.* [2001]), except for flights NAT13 and NBT05 during the NLC-91 campaign. Here we find S significantly smaller than unity in a noticeable part of the PMSE layer which means that the layer indeed is disappearing (as is the case during flight NBT05) or that the thermal structure within in the PMSE is significantly different from the place of the rocket measurement. We note that in these two flights the TOTAL ionization gauge was used which differs substantially in the geometrical layout of the sensor compared to CONE which is used in the other flights listed in Table 1 (see *Hillert et al.* [1994] and *Rapp et al.* [2001a] for more details). We can speculate that the ram correction mentioned above is less accurate for TOTAL than for CONE.

An important result comes from a comparison of columns 2 and 4 in Table 1: Only a fraction of the upper mesosphere where S>0.5 is actually filled with PMSE. Ignoring the NLC-91 flights (see above) we conclude from Table 1 that PMSE covers less than half of the altitude range where ice particles can exist. The reason for this absence could be that the water vapor concentration is much smaller than the standard value, for example because the freeze drying effect has removed the water vapor from these altitudes, or that other physical mechanisms required for PMSE, e. g., the mechanism creating small scale fluctuations in the electron gas, are missing.

Table 1. Altitude ranges of PMSE and the degree of saturation, the latter derived from high resolution temperatures measurements on sounding rockets. The second column gives the altitude range where PMSE is observed. The third column gives the altitude range within the PMSE layer where the degree of saturation S is larger than 0.5. The fourth column gives the total altitude range where S>0.5, and the last column gives the percentage of the altitude range where S>0.5 relative to the altitude range of PMSE, i. e., the ratio of columns 2 and 4.

flight label	Δz PMSE [km]	Δz(S>0.5) in PMSE [km]	Δz(S>0.5) total [km]	[%]
NAT13	4.5	3.0	3.8	118
NBT05	5.5	2.9	4.0	135
SCT03	4.0	2.8	9.4	42
SCT06	4.0	3.9	7.5	54
ECT02	7.0	6.9	8.6	82
ECT07	3.5	3.5	10.1	35
ECT12	3.0	2.9	7.3	41

4. TEMPERATURES AND TURBULENCE

Mixing of the neutral atmosphere by turbulence tends to create an adiabatic lapse rate of temperatures (Γ =9.81 K/km) since the turbulent motions can in first order be considered as an adiabatic process. If turbulence is acting persistently so that other processes affecting the temperature profile, such as molecular heat conduction or horizontal advection are of minor importance, we expect to observe a temperature profile similar to that sketched in Fig. 3. Within the turbulent layer the temperature profile should show a tendency for dT/dz$\sim$ Γ [*Hill et al.*, 1999].

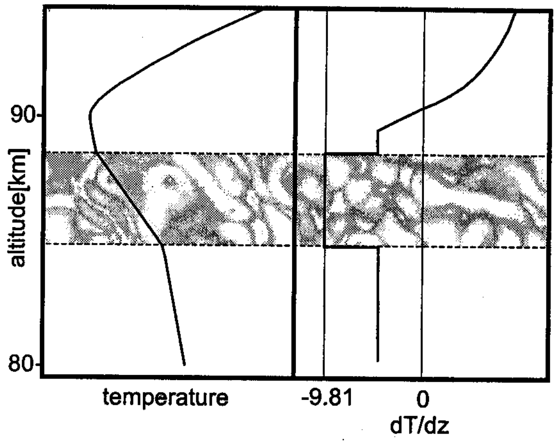

Figure 3. Sketch of a temperature profile being modified by a persistent turbulent layer. Within the layer turbulent mixing leads to an adiabatic lapse rate, i. e., dT/dz$\sim$-9.81 K/km.

In Fig. 4 a high resolution temperature profile and the corresponding lapse rates are shown for flight ECT12 launched on August 12, 1994, at 00:53 UT during the ECHO campaign from the Andøya rocket range. A comparison of the PMSE layer observed during that flight (right panel in Fig. 4) with the temperature gradients (middle panel in Fig. 4) shows no tendency for adiabatic lapse rates within in PMSE layer. This conclusion is supported by the results from the other flights: In none of the PMSE layers have we found a temperature gradient close to Γ (see Table 3 in *Lübken et al.* [2001]).

5. DISCUSSION AND CONCLUSION

From the comparison of small scale insitu density measurements with PMSE observations we conclude that there is no apparent correlation between PMSE and turbulence. Occasionally, some turbulence is observed within the PMSE layer but in the majority of the flights the turbulent energy dissipation rate is actually zero. We note that significant turbulence is frequently observed above the PMSE layer. From these measurements alone we would not be able to judge whether or not the occasional coincidence of turbulence and PMSE is accidental or in fact demonstrates a close physical coupling. However, the high resolution temperature measurements indicate that turbulence cannot have been active for a substantial time period since this would result in temperature gradients close to the adiabatic lapse rate, opposite to observations. In nearly all flights PMSE

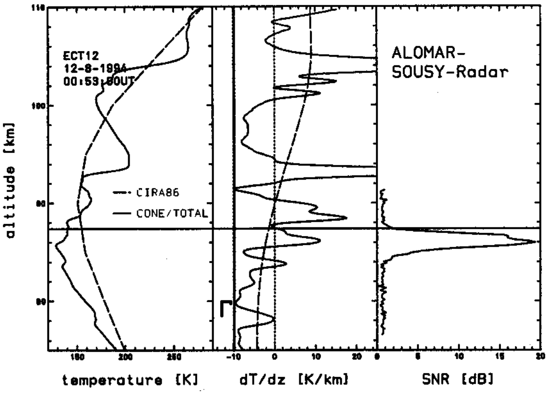

Figure 4. Temperature profile (solid line in left panel) derived from CONE measurements during flight ECT12 and the PMSE profile measured during that flight (right panel). The CIRA-1986 profile is shown for comparison[Fleming et al., 1990]. The temperature lapse rate (dT/dz) is shown in the middle panel. The adiabatic lapse rate (Γ=-g/c$_p$) and the isothermal case (dT/dt=0 K/km) are shown for comparison (thick and thin dotted lines, respectively).

was present for more than an hour at the time of the rocket launch, i. e., if PMSE were related to turbulence it had acted persistently enough to leave its footprint in the thermal structure. We conclude, that the occasional occurrence of turbulence at PMSE layers is presumably accidental. Probably the only common physical ground is the background temperature profile which supports the creation of ice particles (since temperatures are very low), thereby provides an important prerequisite for PMSE, and which provokes the breaking of gravity waves and creation of turbulence since the temperature gradient changes at the mesopause [*McIntyre*, 1989].

The question is of course why some of the earlier measurements showed a nice agreement between Schmidt numbers derived from turbulence theory and Schmidt numbers derived from microphysical calculations (both taken from insitu measurements within a PMSE layer). We presume that PMSE is created by an yet unidentified process and that turbulence acts on top of this mechanism. This idea is supported by measurements of the spectral spectral broadening of the received radar signal which sometimes shows a dynamically quiet situation which suddenly turns to very disturbed conditions (see Figure 5 in *Cho and Röttger* [1997]). This suggests that the fine structures in the plasma (which are caused by the unidentified process) lead to PMSE and act as passive tracers for turbulence.

We find that within the PMSE layer temperatures are generally low enough for water ice particles to exist or grow (i. e., the degree of saturation S is larger than unity). It is interesting to note that a substantial altitude region can exist with S>1 but no PMSE layer exists at these heights. In some flights the PMSE layer covers only less than half of the altitude range where the condition for the existence of water ice particles is fulfilled. We repeat our assumption about a water vapor mixing ratio [H_2O] of 4 ppmv independent of altitude. However, the degree of saturation is much more dependent on temperatures than on [H_2O]. We conclude that the non-occurrence of PMSE cannot automatically be attributed to temperatures being too high as is sometimes done in the literature [*Balsley et al.*, 1993; *Huaman and Balsley*, 1999]. Low enough temperature seem to be a necessary but not sufficient condition for PMSE to occur. Other processes, in particular a mechanism to create small scale fluctuations in the plasma are also required.

Polar mesosphere summer echoes is an intriguing phenomenon in the upper polar atmosphere which is somehow related to the background temperature profile and to charged aerosols. It is important to understand the mechanism(s) creating PMSE since ground based observations are an important tool to better understand the physical and chemical processes acting in the upper atmosphere. In this paper we have shown that neutral air turbulence, which for a long time was believed to be the prime mechanism, plays a minor role in creating PMSE. Furthermore, we found that low enough temperatures are a necessary but not sufficient condition for PMSE. Further experimental and theoretical efforts are required to fully understand PMSE and its complicated dependence on background conditions.

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