SMALL-SCALE STRUCTURES IN NEUTRAL AND PLASMA SPECIES IN THE MIDDLE ATMOSPHERE AS OBSERVED DURING THE ECOMA ROCKET CAMPAIGNS

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ABSTRACT

The ECOMA project (Existence and Charge state Of Meteoric smoke particles in the middle Atmosphere) led by the Leibniz Institute of Atmospheric Physics, Germany, and the Norwegian Defence Research Establishment, Norway, comprises rocketborne in situ measurements as well as ground-based observations with radars and lidars to study meteor smoke particles and their atmospheric and ionospheric environment. The prime instrument of the ECOMA payload is a new particle detector which combines a classical Faraday cup design with a xenon flash lamp for the active photoionization of mesospheric aerosol particles and the subsequent detection of corresponding photoelectrons. All these instruments yield measurements with very high resolution and precision and allow us to study small-scale structures in both neutral and plasma species in detail. In particular, the neutral air density measurements yield turbulence parameters which, in turn, allow us to derive the Schmidt numbers, Sc, from the plasma density measurements. We present results of in situ measurements of small-scale structures in neutral and plasma species in the middle atmosphere as observed during the ECOMA sounding rocket campaigns. We also present an estimate of the Schmidt numbers, Sc, for the charged aerosols that utilizes in situ measured small-scale density fluctuations of charged aerosols and both in situ and radar turbulence measurements.

Key words: ECOMA, Schmidt number.

1. INTRODUCTION

Mesospheric ice particles and meteoric smoke particles (MSP) in the mesosphere/lower thermosphere (MLT) region have recently been in the focus of several experimental studies [HTB+96, GLK+98, LGK+05, RHS+05, SRS+09b]. It is believed that these particles play a key role in MLT phenomena like polar mesosphere summer echoes (PMSE) and noctilucent clouds (NLC). Under the conditions of the extremely cold summer polar mesopause these particles may act as nuclei for building large ice particles and, therefore, better knowledge of them is important for understanding the microphysics of these phenomena [e.g. RT06]. Both MSPs and ice particles are often referred to as aerosols. In the MLT these aerosols are surrounded by the ionospheric plasma and gain a charge because of electron and ion capture processes. As initially proposed by [KFR87] and later extended by [CHK92] and [RL03], charged aerosols should ultimately reduce the diffusivity of free electrons. In turbulence theory, this reduced diffusivity can be expressed in terms of high Schmidt numbers $Sc = \nu/D$, a dimensionless number defined as the ratio of momentum diffusivity (viscosity) and mass (molecular) diffusivity.

The ECOMA project (Existence and Charge state Of Meteoric smoke particles in the middle Atmosphere) led by the Leibniz Institute of Atmospheric Physics, Germany, and the Norwegian Defence Research Establishment, Norway, with contributions from Sweden, Austria and the US, comprises rocketborne in situ measurements as well as ground-based observations with radars and lidars to study meteor smoke particles and their atmospheric and ionospheric environment. In the frame of the ECOMA project several sounding rocket campaigns have taken place at the North-Norwegian Andøya Rocket Range [69°N, see RSS+08, RS09, for details].

In this paper we present recent results of the in situ measurements of small-scale structures in neutral air and charged aerosols obtained during the ECOMA-2008 sounding rocket campaign and compare it with the results of the ECOMA-2007 rocket campaign. These measurements allow us to derive Schmidt numbers for the charged aerosols utilizing both in situ and radar turbulence measurements and high resolution in situ density measurements of the charged aerosols.

2. INSTRUMENTATION

The instrumentation of the ECOMA payload employed during the ECOMA-2007 sounding rocket campaign is described in detail in [SRS+09b]. As further described in

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detail in [RSS+08], the ECOMA-2007 sounding rocket campaign was supported by numerous ground-based observations. The same ground-based instrumentation was also employed during the ECOMA-2008 sounding rocket campaign. Regarding the two rocketborne instruments that provided the data for the current paper, the ECOMA payloads used in 2007 and 2008 may be considered as identical. Here we briefly describe the instruments which were the main data sources for this paper.

2.1. Rocketborne instruments

The prime instrument, the ECOMA particle detector, is mounted on the front deck of the payload, and is designed to measure aerosol properties. For the detailed description of the ECOMA instrument the reader is referred to [RS09]. Briefly, the ECOMA particle detector is a Faraday cup with two shielding grids that are negatively and positively biased to reflect electrons and ions, similar to the one first used by [HTB+96]. Heavy aerosols pass through the biased grids and, if they carry a charge, produce a current which can be measured by a sensitive electrometer. Measurements of this current are analyzed in this article. Measurements with the novel photoelectron channel of the same instrument are described in [RSS+09]. Note, that the here employed technique is only sensitive to the charged fraction of the aerosols. Also, because of aerodynamical effects, this method only allows to measure particles with radii larger than $\sim$2 nm [HGWR99, RHS+05, HGR07].

In the rear, the payload was equipped with the CONE (COmbined measurements of Neutrals and Electrons) instrument [see GLN93]. Basically, the CONE sensor is a spherical ionization gauge for the measurement of neutral density surrounded by two shielding grids biased positively and negatively to shield the gauge from ambient plasma. The CONE measurements are made at very high spatial resolution and high precision (i.e., altitude resolution $\approx$10 cm; precision better than 0.1 %). Hence these measurements allow for the detection of small scale fluctuations that arise due to neutral air turbulence [LRH02]. In addition, the height profile of neutral number densities can be integrated assuming hydrostatic equilibrium to yield a temperature profile at $\sim$200 m altitude resolution and an accuracy of $\sim$3 K [RGL01, RLM+02].

2.2. Ground-Based instruments

The ALWIN MST radar [LSB99] operating at 53.5 MHz is located close to the rocket launch site at the Andøya Rocket Range. The radar is operated continuously throughout the whole year to study the dynamics and structure of the troposphere/lower stratosphere and PMSE. PMSE observed by ALWIN with high temporal and spatial resolution were used as rocket launch criteria throughout the both ECOMA campaigns. During the rockets flights radar measurements of the PMSE power, radial velocity, and spectral width were obtained with a time resolution of 14 s and a height resolution of 50 m.

3. EXPERIMENTAL RESULTS

In situ measurements preformed during the ECOMA flights provided simultaneous and high-resolution measurements of neutral temperature, turbulence, density of neutral air and heavy charged particles. Also, simultaneous ALWIN radar measurements allow us to derive turbulence energy dissipation rates from the volume co-located with the ascending part of the rocket trajectory. In the next sections we focus on the first rocket flight during the ECOMA-2008 campaign labelled ECOMA-04 that was launched on 30 June, 2008 at 13:22:20 UTC. In section 3.4 we also compare the new presented results with those derived during the ECOMA-2007 campaign (flight ECOMA-03) as discussed in detail in [SRS+09a].

3.1. Temperature

In Fig. 1 we present the temperature profile derived from the CONE measurements. We see a gravity wave-disturbed mesopause around 85 km height with minimum temperatures between $\sim$120 and 130 K. Comparing this profile with the frost point temperature (Fig. 1, dashed line) derived using the water vapor saturation pressure formula from [MM93] and vapor mixing ratio from [KS01], we see that the air was supersaturated at altitudes between $\sim$80 and 89 km. This thermal structure measured by the in situ instrument (Fig. 1) at the mesopause heights is consistent with the PMSE display observed by the ground-based radar technique that observed a double-layer structure around the time of the rocket launch. For more details about these measurements see [ESL+09].

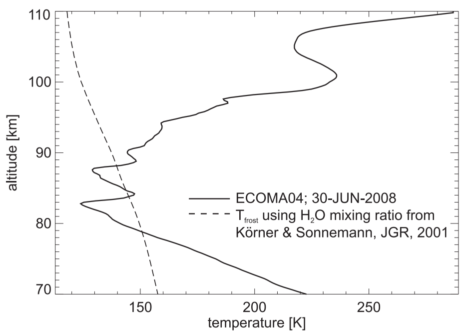

Figure 1. Temperature measurements with the CONE instrument during ECOMA-04 flight (solid profile). The dashed line shows frost point temperature derived using water vapor mixing ratios from [KS01].

3.2. Turbulence

The CONE turbulence measurements are based on the spectral model method introduced by [LGB+94] and extended by [SRL03]. In short, the turbulence energy dissipation rate, ε, is derived as the best fit value after fitting the theoretical model of [Hei48] or [Tat71] to the measured spectra of the relative density fluctuations of neutral air. The derivation of energy dissipation rates from the ALWIN radar measurements is described in detail in [ELS+05]. Basically, that technique goes back to [Hoc83] who applied a correction for beam and shear broadening based on the background wind field measurements, applied to the measured signal.

The results of the turbulence measurements by both in situ and radar instruments during the ECOMA-04 flight are shown in Fig. 2. Two reference profiles shown by dotted and dashed lines are the minimum and the mean ε-values, respectively, representing turbulence climatology for polar summer MLT [see SRL03, for more details]. Within the PMSE height region (i.e. 82 to 92 km) we

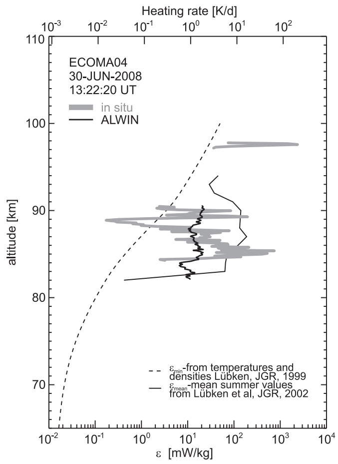

Figure 2. Turbulence measurements during ECOMA-04 flight. The bold grey profile shows results of in situ measurements with the CONE instrument. The thin black line shows ε-values derived from the ALWIN radar measurements.

see a double layer of turbulence activity measured in situ and a relatively uniform turbulence layer derived from the radar measurements. It is interesting to note that a thin layer of turbulence activity was detected in situ at heights of $\sim$98 km. For the PMSE height region our in situ technique yielded a continuous profile of the energy dissipation rates with values ranging from very weak (0.17 ± 0.07 mW/kg) to very strong (746 ± 223 mW/kg) turbulence for those heights. The mean ε-value derived from the in situ measurements is equal to 62 ± 20 mW/kg. In contrast, the turbulence layer detected by the ALWIN radar reveals moderate values of the energy dissipation rates which are 15 mW/kg on average and only vary between 7 and 23 mW/kg within the entire altitude range between $\sim$82 and 90 km. Note that the in situ turbulence measurements were done during the downleg, that is about 50 km to the north-west of the volume probed by the ALWIN radar. Also the radar observations are representative of an average turbulence activity over a spatial region of about 10 km in diameter at 85 km height whereas the CONE measurements can be considered as a point measurement.

3.3. Small-scale signatures in the particle measurements

The ECOMA particle detector measures, among other things, current which is proportional to the number density of charged particles [DC-channel measurements, see RS09, RSS+08, for more details]. Those measurements are done with a sufficiently high altitude resolution making it possible to perform a spectral analysis and derive Schmidt numbers of the charged aerosols inside the PMSE layer [see SRS+09a, for more details].

In the left panel of Fig. 3 we show the ECOMA DC-channel measurements, that is the current produced by the charged aerosols. The right panel of Fig. 3 shows a wavelet power spectrum of the measured signal derived using Morlet-12 wavelet function. This figure shows that the charged particles were highly structured between $\sim$82.5 and 89 km, that is in the height range where turbulence structures were observed by both in situ and radar techniques.

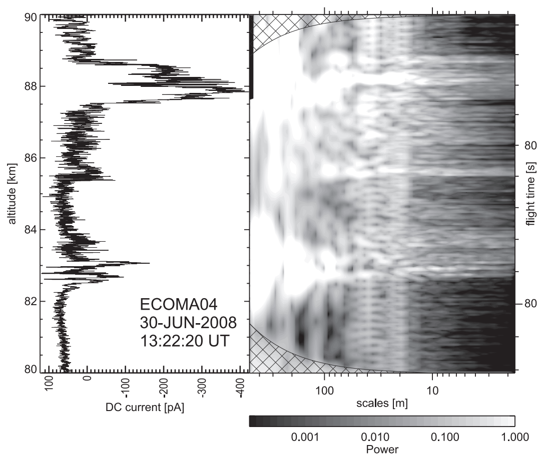

Figure 3. DC-current measured by the ECOMA instrument (left panel) and its wavelet power spectrum (right panel).

In Fig. 4 we compare the radar power from the vertical beam (grey dashed) measured close to the rocket launch time with the profile of the $PSD(\Delta N_{aerosol},\ 2.8\ m)$ in dB (black) derived as a slice of the spectrogram from Fig. 3 at 2.8 m. We also show absolute electron density profile (grey bold) measured by the radio wave propagation technique. It is interesting to note that the residual structuring in the charged aerosol density data (black profile) is strongest at the top and the bottom of the entire region, that is inside the PMSE layers. However, in contrast to the radar observations, the in situ data also show

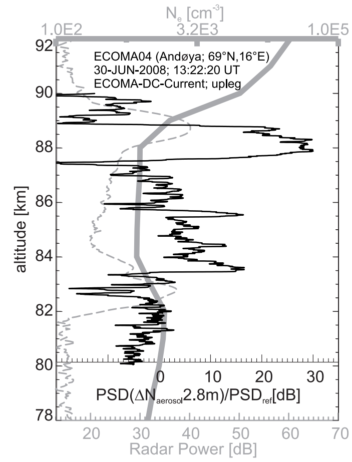

Figure 4. Comparison of radar power and charged aerosol density fluctuations. Grey dashed profile: ALWIN radar power from vertical beam observed near ECOMA-04 launch time. Black solid profile: Charged aerosol density fluctuations at ALWIN's Bragg scale (2.8 m) in dB. Grey bold profile: Absolute electron density measured by the radio wave propagation technique.

significant fluctuations inside the entire height region between 83 and 89 km, that is between the PMSE layers observed by the ALWIN radar (dashed grey profile). There is, however, no contradiction between those in situ and radar data. As it is seen from the measurements (Fig. 4, bold grey profile), there was a 'bite-out' in the electron densities observed in situ during the ECOMA-04 flight. This is very similar to the results of the ECOMA-03 flight discussed in [SRS$^+$09a]. As shown by [RGLL02], there is lower electron density threshold for PMSE observations that is readily explained in terms of the standard theory of the scattering of the VHF radio waves. These authors found that at least a few hundreds electrons/cm^3 are required for a detectable PMSE. Hence, in our case there were too few electrons between ∼84 and ∼88 km to lead to detectable radar backscatter.

3.4. Schmidt numbers

Similar as for the case of the neutral density fluctuations, one can also fit a theoretical model to the spectra shown in Fig. 3. The model has to account for a presence of charged aerosols that, as mentioned above, reduce diffusivity of free electrons leading to enhanced Schmidt numbers ($Sc \gg 1$). By using turbulence energy dissipation rates independently derived for the same volume where the plasma (charged aerosols in our case) fluctuations were observed we can derive the Schmidt numbers. [LGB$^+$94] and [LRBT98] first derived Schmidt numbers from high resolution in situ measurements of plasma (electron) density fluctuations and resulted in values between ∼6 and 500. Following their work, [SRS$^+$09a] fitted the model of [DK85] to the relative density fluctuations of the charged particle density measured during the ECOMA-2007 sounding rocket campaign (flight ECOMA-03). The latter yielded large Sc-values of up to 4500 being in agreement with another independent Sc-estimates by [RSL$^+$08] derived from simultaneous radar measurements at different frequencies.

As described above, however, the CONE turbulence measurements are only available from the downleg, whereas the charged aerosol data shown in Fig. 3 were measured during the upleg. This leads to an uncertainty because the turbulent structures are most probably not as homogenous to reveal the same strength over ∼50 km extent. The radar turbulence measurements, however, where done around the rocket launch time and are representative of a mean turbulence strength of a large volume that was located close to the rocket trajectory. That is, we may also use the ε-values derived from the ALWIN measurements that observed turbulent structures in the same height range as the in situ soundings.

Thus, we fitted the spectra shown in Fig. 3 (right panel) in the altitude range between 82 and 90 km with 100 m altitude resolution. The resultant Schmidt numbers are present in Fig. 5 where the results shown by the thin solid black line utilize the ALWIN radar ε-measurements and the Sc-values shown by the bold grey line were derived using in situ ε-measurements (Fig. 2). In this plot we also compare the derived Schmidt numbers with those derived by [SRS$^+$09a] for the ECOMA-03 flight (dashed profiles) that also utilize both the radar and in situ ε-measurements and shown by the dashed thin black and bold grey lines, respectively.

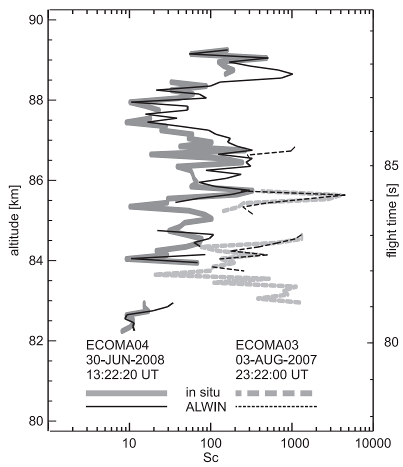

Figure 5. Schmidt number profiles. The bold grey profiles utilize results of in situ turbulence measurements with the CONE instrument. The black lines show Sc-values derived using the ALWIN radar turbulence measurements. The dashed and solid lines represent the ECOMA-03 and ECOMA-04 flight respectively.

The Sc-values derived for the ECOMA-04 flight are, in general, smaller than those derived for the ECOMA-03 flight. Similar to the results of the ECOMA-03 flight, the Schmidt numbers derived based on the radar turbulence measurements are close to those derived using in situ measured ε-values and the both derived Sc-profiles qualitatively agree (see Fig. 5). Even moderate changes of the energy dissipation rate from one case to the other (see Fig. 2) do not change the general range of Schmidt numbers derived from our measurements. Note also, that none of those profiles utilizes exactly simultaneous and co-located turbulence measurements. Due to the $\sim$50 km horizontal separation of neutral air and charged particle measurements, we do not expect to see an exact overlap of the structures in those data. Based on those measurements, we varied the strength of turbulence in a large range of values which, however, did not lead to significant change in the derived Schmidt numbers.

4. SUMMARY

In this paper we showed and discussed measurement results obtained during the ECOMA-04 flight of the ECOMA-2008 sounding rocket campaign. We presented results of in situ temperature measurements that suggest that around the mesopause heights there were favorable conditions for the existence of ice particles. This is consistent with the PMSE observations by the ground-based VHF radar. Also, small-scale structures in neutral air indicative of turbulence activity were detected within the PMSE height range by both in situ and ground-based radar techniques. The both rocketborne and radar measurements yielded turbulence energy dissipation rates at those heights. The ε-values derived based on the radar measurements are, in general, smaller and less variable than those derived from the in situ measurements. This might be a consequence of the averaging over a large volume and time in the radar technique and/or a spatial distance of about 50 km between both observations.

In the same height range in situ measurements with the ECOMA particle detector showed that charged aerosols were also highly structured at spatial scales down to few meters. These data together with the turbulence measurements allow us to derive the Schmidt numbers for the charged aerosols. The Sc-values derived based on the in situ turbulence measurements are very close to those ones derived based on the radar turbulence measurements. Importantly, the small changes of the energy dissipation rate from one case to the other do not change the general range of Schmidt numbers derived from our measurements. Hence, the derived range of values can be considered a robust result of our analysis. We also conclude that true common volume measurements of turbulence and tracer structures are needed to derive more robust results.

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