IN SITU DENSITY, TEMPERATURE, AND TURBULENCE MEASUREMENTS IN THE MIDDLE ATMOSPHERE DURING ECOMA 2010

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ABSTRACT

From the 19th of November to the 18th of December 2010 the fourth and final ECOMA rocket campaign was conducted at Andøya Rocket Range (69 °N, 16 °E) in northern Norway. All the ECOMA payloads were equipped with a CONE instrument to measure neutral air density, with very high altitude resolution and precision. CONE measurements yield absolute neutral air densities in the height range from 70 to 110 km from which a high resolution temperature profile can be retrieved assuming hydrostatic equilibrium. In addition, CONE allows to investigate small-scale structures in neutral density and retrieve turbulence parameters. During the last ECOMA flight labeled ECOMA09 the CONE temperature measurements reveal two inversion layers. At the same time, turbulence measurements show very high energy dissipation rates right above the temperature inversions. The observed upper inversion layer between 86 and 89 km was associated with turbulent heating rates of about 200 K/day which are thought to be sufficient for producing temperature inversions.

Key words: CONE, neutral temperature, temperature inversion, turbulence.

1. INTRODUCTION

Since first observed by [11], temperature inversion layers have been routinely observed in the mesosphere and lower thermosphere (MLT). A recent review of both theory and observations has been provided by [8]. These authors have pointed out that despite the considerable progress that has been made in recent years the formation mechanisms of mesospheric inversions remain poorly understood. Numerous observations show that temperature inversions are often associated with a near adiabatic lapse rate above the inversion layer, which is clearly indicative of turbulence activity in those regions. However, numerical simulations showed that only vigorous turbulence with heating rates of $\sim$10 K/day is capable of producing temperature inversions. Such strong turbulence has rarely been observed [5], which apparently is in contrast to the temperature inversion layers, which are a common phenomena.

A common tool to study temperature inversion layers experimentally in the MLT is lidar observations. The advantage of the lidar measurements is that they deliver continuous (or at least long duration) observations of the temperature field and allow us to distinguish between strong gravity waves and weak temperature inversions that both create similar signatures in single altitude-profiles. However, those techniques do not allow to measure turbulence parameters directly and must rely on numerical simulations for this particular purpose [see e.g., 15, 3].

Making use of in situ measurements in the MLT, i.e. employing sounding rockets, it is possible to directly measure both temperature and turbulence parameters simultaneously and in the same volume. Motivated by the need to gain a better understanding of mesospheric aerosol properties and related processes, the German-Norwegian-led ECOMA sounding rocket program was started in 2006 and involved the launching of nine instrumented rockets for studying properties of mesospheric aerosols and related phenomena from the north-Norwegian Andøya Rocket Range (69°N; 16°E). For a review of the entire project and obtained major results the reader is referred to [10]. All the ECOMA payloads were also equipped with a CONE instrument [1] to measure density and temperature of neutral air with very high spatial resolution. The CONE instrument also yields turbulence parameters based on spectral analysis of measured neutral density fluctuations [4, 13].

The final ECOMA sounding rocket campaign was conducted in December 2010 during the Geminid meteor shower and focused on the study of the influence of an enhanced meteor influx on the properties of meteor smoke particles (MSP) in the mesosphere. Three sounding rockets were launched on 4, 13, and 19 of December respectively. In this paper we focus on experimental results obtained during the rocket flight of the ECOMA project labeled ECOMA09. First, we present density and temperature measurements which were obtained with CONE which describes the background atmosphere. Then we discuss in situ measurements of small-scale structures in neutral air and its connection to the temperature profile.

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2. INSTRUMENT DESCRIPTION

The data analyzed and discussed in this paper was obtained with the CONE instrument (COmbined sensor for Neutrals and Electrons). Briefly, the CONE instrument is a combination of an ionization gauge and a fixed biased Langmuir probe for electron density measurements [1]. CONE measurements are capable to resolve small-scale structures in neutral air density down to some centimeters. These small scale structures are caused by neutral air turbulence. On the ECOMA payload CONE was mounted on the rear deck and, therefore, was in a favorable (for most precise density measurements) aerodynamical condition during the downleg of the trajectory of this spin-stabilized sounding rocket [9]. Making use of laboratory calibrations, CONE measurements yield absolute neutral air densities in height range from 70 to 110 km from which a high resolution temperature profile can be retrieved assuming hydrostatic equilibrium.

2.1. Data description

The ECOMA-2010 campaign took place between the 19 November 2010 and the 18 December 2010. During this campaign three rockets were launched, namely: ECOMA07 on the 4th of December 2010 (before the maximum activity of the Geminids Meteor Shower), ECOMA08 on the 13th of December 2010 (during maximum activity of Geminids Meteor Shower) and ECOMA09 on the 19th of December 2010 (after the maximum activity of Geminids Meteor Shower). Unfortunately, the CONE data were not reliable for the first two flights, so in this paper we will concentrate on the CONE data obtained during the ECOMA09 flight. The ECOMA09 rocket was launched on 19th of December 2010 on 02:36:00 UTC. The ALOMAR RMR Lidar was measuring for several hours before and after the rocket launch and yielded temperature measurements up to 87 km height.

3. ANALYSIS TECHNIQUE

The current measured with the CONE instrument is proportional to local neutral density and can be converted to absolute densities applying a laboratory calibration. The calibration is performed in a vacuum chamber where simultaneous measurements by both CONE and an absolute pressure standard, e.g. a baratron, are made at different pressures. The pressures are converted to number-densities using the temperature of the calibration chamber applying the ideal gas equation.

Due to the shock front that appears because of the high speed of the sounding rocket ($\sim$1000 m/s), a ram correction must be applied to the measured densities which is obtained using the Direct Simulation Monte Carlo technique. [9].

Assuming hydrostatic equilibrium, i.e., $dp = -\rho(z)g(z)dz$, where p and ρ are the atmospheric pressure and mass density, z is height and g is the acceleration of gravity, and taking into account the ideal gas law $p(z) = \rho(z)\dfrac{R}{M}T(z)$, where T is temperature, R and M are the gas constant and mean molar mass, one can obtain the equation to derive a temperature profile from measured densities:

$$T(z) = T(z_0)\frac{\rho(z_0)}{\rho(z)} - \frac{1}{\rho(z)}\frac{M}{R}\int_{z_0}^{z} \rho(z')g(z')dz' \quad (1)$$

Because the density measurements by CONE are done with very high spatial resolution (down to 10 cm) and also precision (~ 0.1 %), we are able to extract tiny density fluctuations from the CONE measurements. These fluctuations are a good tracer for turbulence [4]. The CONE turbulence measurements are based on the spectral model method introduced by [4] and [5] and extended by [13]. In short, the turbulence energy dissipation rate, ε, is derived as the best fit value after fitting the theoretical model of [2] or [14] to the measured spectra of the relative density fluctuations of neutral air. From the best fit of the theoretical spectra of turbulence the inner scale, l_0, can be derived. This is the scale where inertial forces and viscous forces are in equilibrium. Then, using the formula [6] $l_0 = 9.90\sqrt[4]{\dfrac{\nu^3}{\varepsilon}}$ we can obtain the turbulence energy dissipation rate ε, which is the rate at which turbulent kinetic energy is dissipated into heat at small scales.

4. MEASUREMENTS

In situ measurements performed during the downleg of the ECOMA09 flight provided simultaneous and high-resolution measurements of neutral air density, temperatures, and turbulence parameters.

4.1. Background atmosphere

The results of the neutral density measurements at heights between 70 and 110 km are shown in Fig. 1 as the black profile. The measured densities are comparable to the CIRA-86 and MSISE-90 climatologies (blue and green lines, respectively) in the range from 70 to 80 km and are slightly lower by up to a factor of 2 for the higher altitudes.

The temperature profile obtained using the CONE sensor between 70 and 110 km is shown in Fig. 2 in black. The lowest temperatures of $\sim$175 to 190 K appear at heights between 79 and 84 km. The measured temperature profile reveals two pronounced inversion layers at heights between 72 and 73 km and between 86 and 89 km, respectively. The amplitude of the upper layer, i.e. at 86 to 89 km, reaches values of about 40 K, also the layer is at

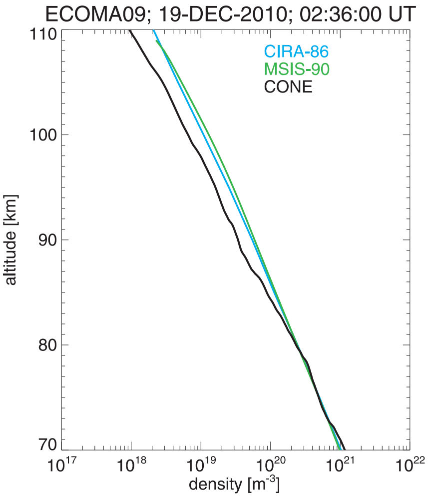

Figure 1. Neutral densities measured during ECOMA09 flight (black line). Climatologies MSISE-90 and CIRA-86 are shown as green and blue, respectively.

least 4 km thick. The lower inversion layer is somewhat weaker, i.e. it has an amplitude of ∼20 K and a thickness of ∼2 km. The entire temperature profile, including regions with the inversion layers, also reveal clear signatures of gravity waves.

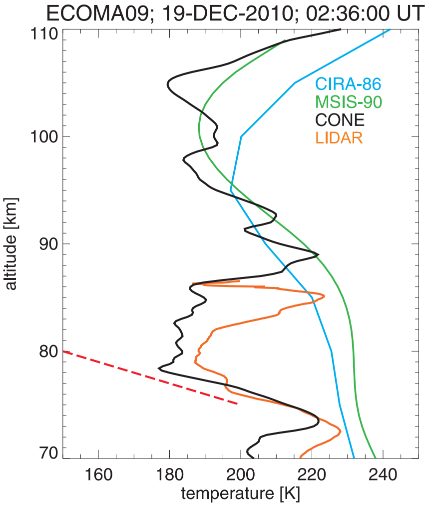

Figure 2. Neutral temperatures measured during the ECOMA09 flight (black line). Climatologies MSISE-90 and CIRA-86 are shown as green and blue, respectively. Additionally, ALOMAR RMR-lidar measurements are plotted with orange line. The dashed red line shows adiabatic lapse rate (see text for details).

Two reference profiles from CIRA-86 and MSISE-90 are shown in Fig. 2 in blue and green, respectively. Additionally, we compare the CONE measurements with temperatures obtained using the ALOMAR RMR-lidar [12]. The latter is shown as the orange profile in Fig. 2. The lidar measurements reveal very similar wave structures to those measured by the CONE. The difference between the lidar and in situ temperature measurements can be explained by a horizontal distance of ∼50 km between the lidar beam, that was pointing to the direction of the rocket's ascent, and the volume probed by CONE on the descending part of the trajectory.

At heights between 74 and 79 km, i.e. right above the lower inversion layer, the temperature profile reveals an adiabatic to super-adiabatic lapse rate (compare with the adiabatic lapse rate shown by the red dashed line in Fig. 2). Also, above the upper inversion layer, i.e. at heights between 89 and 95 km, the measured temperature profile reveals adiabatic gradients. These gradients are clearly indicative of turbulence activity in those regions.

4.2. Turbulence

Next, in Fig. 3 we present results of measurements of the turbulence energy dissipation rates, ε in the altitude range from 60 to 100 km. The derived ε-values are shown by dark blue crosses with error bars in orange. Whenever a continuous turbulence layer was detected, the single crosses are connected by a dark blue line. The energy dissipation rate can be converted to the heating rate as $\partial T/\partial t = \varepsilon/c_p$, where c_p is the heat capacity of air at constant pressure ($c_p \sim 1\ J/K \cdot g$). The resulting heating rates are represented by the upper axis in Fig. 3. Two reference profiles shown by red and blue lines represent in situ measured mean ε-values for summer [7] and winter [5], respectively.

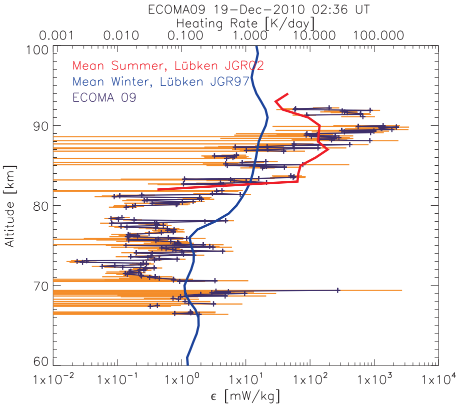

Figure 3. Turbulent energy dissipation rates measured in situ during ECOMA09 flight are shown with dark blue crosses. The single crosses are connected whenever a continuous turbulence layer was detected. The error bars for each point are shown by orange line. Mean summer and winter profiles taken from [7] and [5] are shown in red and blue, respectively. The corresponding heating rate is shown on the upper axis.

The measured dissipation rates below 87 km reveal typical winter-values on average and almost continuously spread over the entire altitude range from ∼65 km up to 87 km, which is also typical for the polar winter mesosphere. However, above that region, between 87 and

93 km, the measured dissipation rates exhibit very large values, which even exceed average summer conditions.

It is interesting to compare the measured dissipation rate profile with the temperature profile. At heights of $\sim$75 and $\sim$90 km, i.e. just above the two observed inversion layers, turbulence exhibits local maxima. Especially the upper temperature inversion layer is accompanied by the extremely strong turbulence with a dissipation rate of up to $\sim$2 W/kg which is equivalent to a heating rate of 200 K/day. In Fig. 4 we show an example of a global wavelet spectrum for an altitude range from 89.9 to 90.0 km together with fitting results. The best fit of the Tatarskii model [14] is shown by the dashed blue line. The derived inner scale is marked by the vertical dash-dotted line and is equal to 32.4 m which corresponds to the energy dissipation rate of 1367.7 mW/kg or heating rate of $\sim$120 K/day. According to numerical simulations by [3], a heating rate of $\sim$10 K/day is sufficient for producing inversion layers.

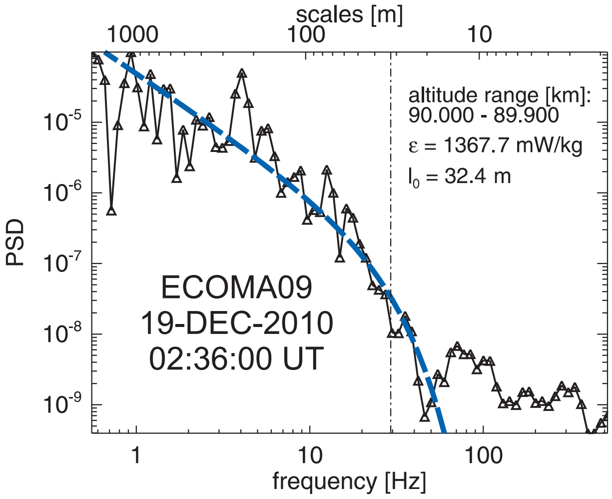

Figure 4. Example of measured spectrum close to 90 km height in black and fitting results. The blue dashed line shows the best fit of Tatarskii model and the dash-dotted line marks the derived inner scale. The derived turbulence energy dissipation rate $\varepsilon = 1368\ mW/kg$ which corresponds to heating rate of $\sim$120 K/day.

Note also, that our turbulence detection technique is not sensitive to turbulence in the regions where the temperature profile exhibits an adiabatic lapse rate and, therefore, can underestimate the actual ε-values. This implies that the turbulence dissipation above the inversion layers could be even stronger than what we observed with the CONE instrument.

As can be seen from Fig. 3, the measured energy dissipation rates exhibit large gradients. The ε-value often changes by an order of magnitude within one kilometer and, between 80 and 90 km by more than four orders of magnitude.

5. SUMMARY

The ECOMA09 flight provided real common volume in situ measurements of neutral densities, temperatures and turbulence. The measured neutral densities are comparable with the climatologies of CIRA-86 and MSISE-90 in the range form 70 to 80 km and are slightly lower for the higher altitudes. The neutral temperature profile shows a relatively cold atmosphere when compared to CIRA-86 and MSISE-90 climatologies. The temperatures obtained with the CONE sensor were also compared with the ground based lidar measurements. We observed the same temperature structure, although the lidar measurements exhibit larger temperatures. This may be explained by the fact that the lidar beam was pointing to the ascending part rocket trajectory, whereas the CONE measurements were done during the descent.

Turbulence was observed in a broad altitude range which is typical for winter. Turbulence was very strong (even for summer) around 90 km. The temperature profile reveals two inversion layers around the mesopause exactly at heights where turbulence revealed its strongest values, reaching heating rates of about 200 K/day. This implies that the inversion layers observed during the ECOMA09 flight were likely generated by local turbulent heating. Among the total of more than 20 successful CONE measurements since 1994 at least half of the retrieved temperature profiles reveal inversion layers. For the future, we aim to analyze in detail all the CONE measurements where simultaneous in situ turbulence and temperature measurements were conducted and where temperature inversions were observed.

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