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ScienceDirect
Advances in Space Research 38 (2006) 2388–2393
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

In situ observations of small scale neutral and plasma dynamics in the mesosphere/lower thermosphere at 79°N

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Received 1 November 2004; received in revised form 7 March 2005; accepted 7 March 2005

Abstract

From June 29 to July 6 2003, the German-Norwegian ROMA-SvalRak campaign (ROMA = Rocket borne Observations in the Middle Atmosphere) took place at the SvalRak rocket range, Ny-Ålesund (78.9°N, 11.9°E; Spitzbergen). The main scientific aim of this campaign was to study polar mesosphere summer echoes (PMSE) and mesospheric turbulence. During this campaign a total of three instrumented sounding rockets was launched. In addition, ground based observations with a VHF radar and a potassium lidar at Longyearbyen complemented the in situ measurements. All three sounding rockets were equipped with the CONE (COmbined sensor for Neutrals and Electrons) instrument to measure small scale structure of neutral air and electron density, and neutral temperature. The PIP (positive ion probe) instrument was used to measure small scale structure of the positive ion density. Furthermore, two cold plasma probes were flown to measure electron temperature, and a particle detector was employed to detect signatures of charged aerosols. During the first launch, an electric field experiment was also incorporated, while during the other two launches, Faraday rotation experiments yielded absolute electron number densities. During all three rocket flights a PMSE was observed by the VHF radar, whereas the potassium lidar detected a noctilucent cloud (NLC) only during the second launch. Signatures of charged particles forming the PMSE and NLC layers were recorded by the onboard particle detectors.

Keywords: Arctic mesosphere; Turbulence; Plasma instability; NLC; PMSE; In situ measurements

1. Introduction

From 29 June to 6 July 2003, the European sounding rocket campaign ROMA-SvalRak (Rocketborne Observations of the Middle Atmosphere at the SvalRak facilities) took place at Ny-Ålesund (Spitzbergen, geographical coord. 78.92°N, 11.93°E; geomagnetic coord. 76.26°N, 110.98°E). The main scientific aim of this campaign was the study of small scale processes related to neutral and plasma dynamics in the upper mesosphere and lower thermosphere/ionosphere, including turbulence, polar mesosphere summer echoes (PMSE), and noctilucent clouds (NLC). A total of three sounding rockets was launched while ground based measurements were performed with a VHF radar monitoring polar mesosphere summer echoes, a potassium lidar for the detection of noctilucent clouds, and magnetometers which gave evidence for disturbances of the auroral electrojet. The distinctive feature of this campaign is that it is the first summer sounding rocket campaign devoted to the investigation of the mesospheric small scale structuring at such high northern latitudes.

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doi:10.1016/j.asr.2005.03.097

Different instruments onboard the sounding rockets provided simultaneous and high resolution measurements of neutral air density and temperature, electron density and temperature, and positive ion density. The radar observations were continuously conducted throughout the entire campaign period while the potassium lidar was always operated whenever weather conditions permitted.

In the present paper, we give an overview of this comprehensive campaign. The purpose of the paper is not to discuss the results in depth, but to give an impression of the in situ and ground based observations. In the following section, we start with an overview of the different experimental techniques applied. Experimental results are then shown in Section 3. In Section 4, we summarize the campaign results.

2. Experimental technique

2.1. Rocketborne instruments

The PIP (positive ion probe) sensor mounted in the front of the payload is an electrostatic positive ion probe, developed by the Norwegian Defence Research Establishment (FFI). It allows to measure minute ion density fluctuations at a high spatial resolution. This makes it possible to detect ion irregularities on spatial scale as small as ten centimeters. Together with the radio propagation experiment, the PIP sensor further allows us to derive absolute ion densities. For a detailed description of the PIP instrument, the reader is referred to Blix et al. (1990).

In the rear, the payload was equipped with the CONE instrument (see Giebeler et al., 1993 for more details). Basically, the CONE sensor is a combination of an ionization gauge for the measurement of neutral density and a fixed biased Langmuir probe to measure electron number density.

The measurements with the PIP and CONE instruments are both performed at very high spatial resolution and high precision (i.e., altitude resolution $\geqslant$10 cm; precision better than 0.1%). Hence, these measurements allow to detect small scale fluctuations in both species that arise due to processes like neutral air turbulence (Lübken et al., 2002) or plasma instabilities (see below and e.g. Blix et al., 1994). 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 (Rapp et al., 2001, 2002).

The radio wave propagation experiment yields a highly accurate electron density measurement. The theoretical basis and practical application of this technique are described elsewhere (e.g. Smith, 1986). The combination of this technique with high resolution measurements (PIP and CONE instruments) yields the fine scale absolute ion and electron density profiles.

The cold plasma probe (CPP), also mounted on the forward deck of the payload, is a swept Langmuir probe. A description of the principle of operation of such probes can be found for example in Thrane (1986). Most important for our application, this technique allows one to derive the electron temperature. A more detailed description of the CPP instrument and its operation during the ROMA-SvalRak campaign will be presented in an upcoming paper.

Finally, the particle detector, developed at the University of Colorado at Boulder, and mounted flush with the rocket skin is a magnetically shielded electrometer, which detects signatures of charged heavy particles (Smiley et al., 2003).

2.2. Ground based measurements

The SOUSY-Svalbard radar is a VHF radar operating at a frequency of 53.5 MHz and is primarily used for the study of PMSE. The SOUSY radar was continuously operating throughout the ROMA-SvalRak campaign and provided measurements of the PMSE power, radial velocity, and spectral width. This radar is located near Longyearbyen which is approximately 100 km to the south-east of the rocket launch site at Ny-Ålesund. Technical details of this radar can be found in Czechowsky et al. (1984).

The mobile potassium resonance lidar of the Leibniz Institute of Atmospheric Physics (IAP) is capable of measuring mesospheric temperatures and noctilucent clouds under full daylight conditions (von Zahn and Höffner, 1996, 2002). The lidar was placed also at Longyearbyen, that is $\sim$100 km to the south-east of the launcher place. Temperatures were deduced from the spectral width of the Doppler broadened K-D1 resonance line at 769.9 nm, whereas the NLC was detected as an enhanced signal relative to the background noise. A detailed description of the instrument and first results on NLC were published by Höffner et al. (2003).

The Tromsø Geophysical Observatory is running a continuously operating magnetometer at Ny-Ålesund which monitors the Earth magnetic field at 10 s time resolution. The magnetometer provides the horizontal and vertical magnetic field intensity and the angle between magnetic and geographic north. Similar magnetometers are also operated at Longyearbyen (geographical coord. 78.20°N, 15.83°E; geomagnetic coord. 75.31°N, 111.88°E) and Hopen (geographical coord. 76.51°N, 25.01°E; geomagnetic coord. 73.12°N, 115.01°E). A detailed description of these instruments is available on the internet (http://geo.phys.uit.no/map.html).

3. Results

3.1. PMSE and NLC conditions

As expected based on previous observations by Rüster et al. (2001) at such northern latitudes (79°N), PMSE were continuously observed all the time throughout the entire campaign. In Fig. 1 we show scientific conditions for all three flights during the ROMA-SvalRak campaign. The vertical red line marks the rocket launch time in each case. The rocket flights are labeled RO-MI-01, RO-MI-02, and RO-MI-03, respectively. The grey scale contours in Fig. 1 show the signal-to-noise ratio (SNR) registered by the SOUSY radar during the days of the rocket launches, i.e., July 1st, 4th, and 6th.

The thick blue contour lines show the NLC observed by the IAP lidar. The shown contour lines indicate the volume backscatter coefficient (BSC) of 2×10^{-10}/(m sr) at a wavelength of 770 nm.

As one can see, NLC events were registered only on the days of the second and third rocket launch and only the second rocket was launched exactly at the time when strong backscattering from the mesospheric ice layers was observed by the potassium lidar.

3.2. Small scale plasma observations

In Fig. 2, we further present the results of both the remote sensing techniques and the in situ measurements of the ionospheric plasma species.

Fig. 2(a) represents in situ measurements of charged particles (black oscillating profile) plotted over the PMSE (light grey shaded area) and NLC (thick dark grey contours) performed during the flight RO-MI-02 on 4 July 2003 at 8:20 UT. An additional axis at the bottom of Fig. 2(a) shows current values in nA for the black profile. Note that in situ measurements were performed by the particle detector onboard the sounding rocket launched at Ny-Ålesund, whereas the ground based instruments (radar and lidar) were located at Longyearbyen. The vertical solid line in Fig. 2(a) shows zero current level. This zero point was slightly changing during

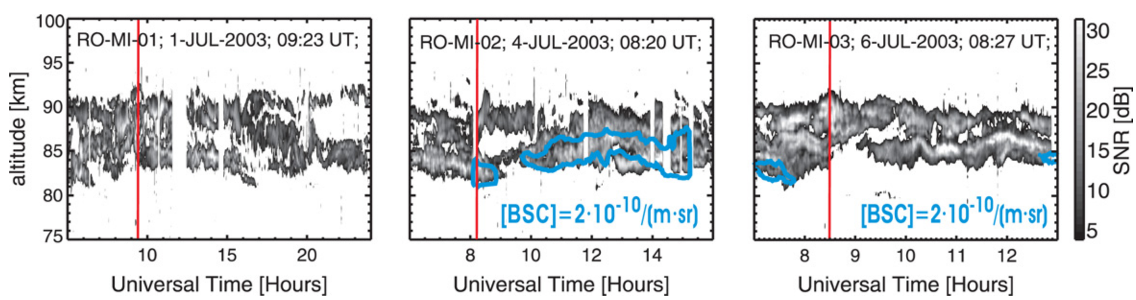

Fig. 1. PMSE and NLC conditions for the ROMA-SvalRak campaign registered at Longyearbyen (78.20°N, 15.83°E). Grey scale contours show the SNR in dB recorded by the SOUSY-Svalbard radar during the days of the rocket launches. The names, dates and times of launches indicated in the figure. The time of rocket launch is also marked by the vertical line in all cases. The blue thick contour line shows the NLC registered by the potassium lidar.

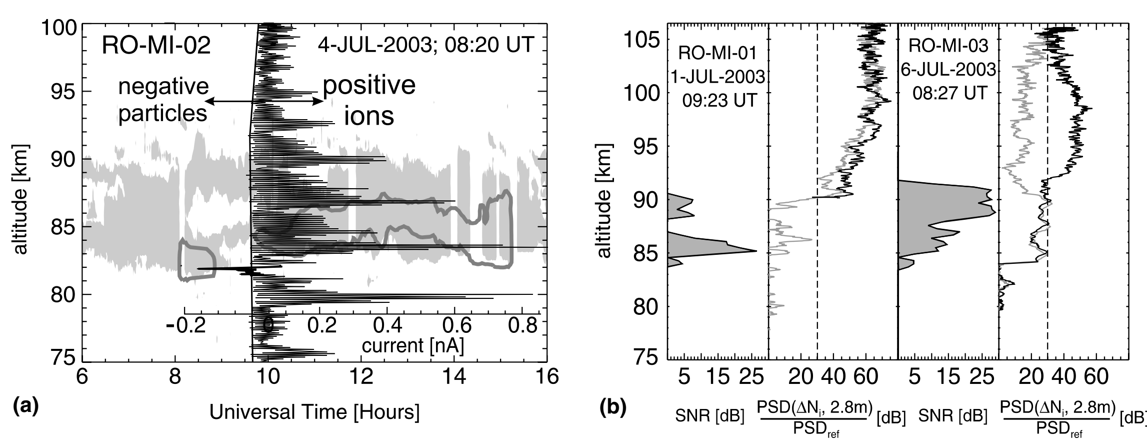

Fig. 2. In situ measurements of a small scale plasma irregularities compared to the observations by means of remote sensing techniques. (a) In situ measurements (performed by the particle detector) of charged particles (black oscillating profile) plotted over the PMSE (light grey shaded area) and NLC (thick dark grey contours) measurements performed during the flight RO-MI-02 on 4 July 2003 at 8:20 UT. The vertical solid line shows zero current level. To the left of this line we see signature of a negatively charged particles. (b) Grey shaded areas represent the mean of the PMSE measurements carried out with the SOUSY radar for the flights RO-MI-01 and RO-MI-03. Four profiles are the power spectral densities (PSD) of the absolute ion number density fluctuations (ΔN_i) at the Bragg scale of the SOUSY radar (=2.8 m), expressed in dB. Black profiles correspond to the upleg and grey to the downleg (PIP instrument).

this flight which does not affect measurements in the altitude region of our interest. It means that to the left of this line we see the signature of a negatively charged particles. It appears exactly within the altitude region where NLC was detected by the lidar. Note that the particle detector is sensitive only to the large particles ($\geqslant\sim 50$ nm) due to aerodynamics (Smiley et al., 2003). To the right of the zero current line one can see the signal modulated by the rocket spin and the coning of the payload. This oscillating signal was produced by positive ions which were collected by the sensor, indicating that the magnetic shielding does not properly work in the case of the collisionally dominating positive ions. The particle detector measures net current of charged species that penetrate through the magnetic shielding described in Robertson et al. (2004). It has been seen in the past, that this shielding does work for electrons, however, it does not work for positive ions which are pushed onto the electrode surface by collisions with the neutral gas molecules. Small negatively charged particles (with typical radii of the order of 2–10 nm), on the other had, do not reach the electrode but are pushed around the payload and electrode surface due to the prevailing shock front. This has been quantified in Horányi et al. (1999).

We did not observe any obvious signatures of negatively charged particles in the altitude range above the negative peak at an altitude of 82 km. The reason for this could either be that the aerodynamics of the payload did not allow particles smaller than a certain size to penetrate to the detector surface (Note that the payload experienced a pronounced coning motion during this part of the rocket flight), or it could be that the net charge of the particles was not negative so that the signal might be hidden in the positive currents dominated by positive ion collection.

Also, since the electron number density measurement failed in the relevant altitude range during the flight RO-MI-02, it is not possible to check whether the electron number density revealed a "biteout" within the NLC/PMSE hight region.

In Fig. 2(b), we present in situ measurements of a small scale plasma irregularity in the lower E-region. In this figure, we further compare the ground based PMSE observations with our small scale plasma density in situ measurements. The two left panels in this figure correspond to the flight labeled RO-MI-01, which took place on 1 July 2003 at 09:23 UT. The two rightmost panels represent the flight labeled RO-MI-03, carried out on 6 July 2003 at 08:27 UT.

The four profiles shown in Fig. 2(b) are the power spectral densities (PSD) of the absolute ion number density fluctuations ($\Delta N_{\rm i}$) at the Bragg scale of the SOUSY radar (i.e., the radar half wavelength $\lambda_{\rm Bragg} = \lambda_{\rm SOUSY}/2 = 2.8$ m). The black profiles were obtained during the upleg of the rocket flights and grey profiles during the downleg. The grey shaded area in this figure represents the mean of the PMSE measurements carried out with the SOUSY radar during $\sim$3.5 h after the rocket launch time. We consider such an extended time interval of PMSE observations in order to account for the horizontal distance of $\sim$100 km between the radar location and the rocket launch site (see Section 2). In this figure, both the radar and in situ measurements are expressed in dB and can be directly compared (see Strelnikov et al., 2004 for more details). The reference value $\mathrm{PSD_{ref}}$ was chosen as a mean over about 5 km just below the power enhancement caused by the PMSE that is at around the 82 km altitude.

As one can see, the SOUSY Svalbard radar detected strong, often double-layered PMSE at altitudes between 84 and 92 km. In situ measurements of ion density fluctuations show a similar power increase at the same altitudes with almost the same power values. The shape of the in situ measured profiles resembles very closely that of the radar observation.

The next striking feature which is seen in Fig. 2(b) is the power increase measured by the PIP instrument above the PMSE signature. This power increase is caused by a two-stream plasma instability (Strelnikov et al., 2004). In situ measurements performed during the RO-MI-03 flight (Fig. 2(b), right panel) reveal high power values only on the upleg and not on the downleg. This feature was examined in Strelnikov et al. (2005) and can be explained as a time development of a modified two-stream instability due to the change of the ionospheric electric field during the rocket flight.

A very remarkable plasma instability event was detected during the flight RO-MI-01 on July, 1st (Fig. 2(b), left panels). The PSD profiles of the relative ion density fluctuations exhibit power values as high as 70 dB both during the upleg and downleg. It is worth saying here that the same PSD profiles of the relative *electron* density fluctuations derived for the RO-MI-01 flight show a similar power increase in the same altitude range (not shown here). To emphasize the strength of the fluctuations observed during this flight and to simplify orientation we mark the value of 30 dB (the x-range value of the panel showing the radar measurements) by the vertical dashed line for both flights.

3.3. Turbulence observations

In this section, we present the results of the first in situ turbulence measurements (Fig. 3) at latitudes as north as 79°N. In Fig. 3(a), we show the wavelet spectrogram of the relative neutral air density fluctuations, i.e., the power spectrum resolved both in frequency and altitude, performed during the flight RO-MI-03. In terms of turbulence it reveals a very quiet atmosphere. The white dashed line in Fig. 3(a) indicates the theoretical estimate of a minimum inner scale $l_0^{\rm min}$ and is plotted for comparison. The inner scale l_0 is the length

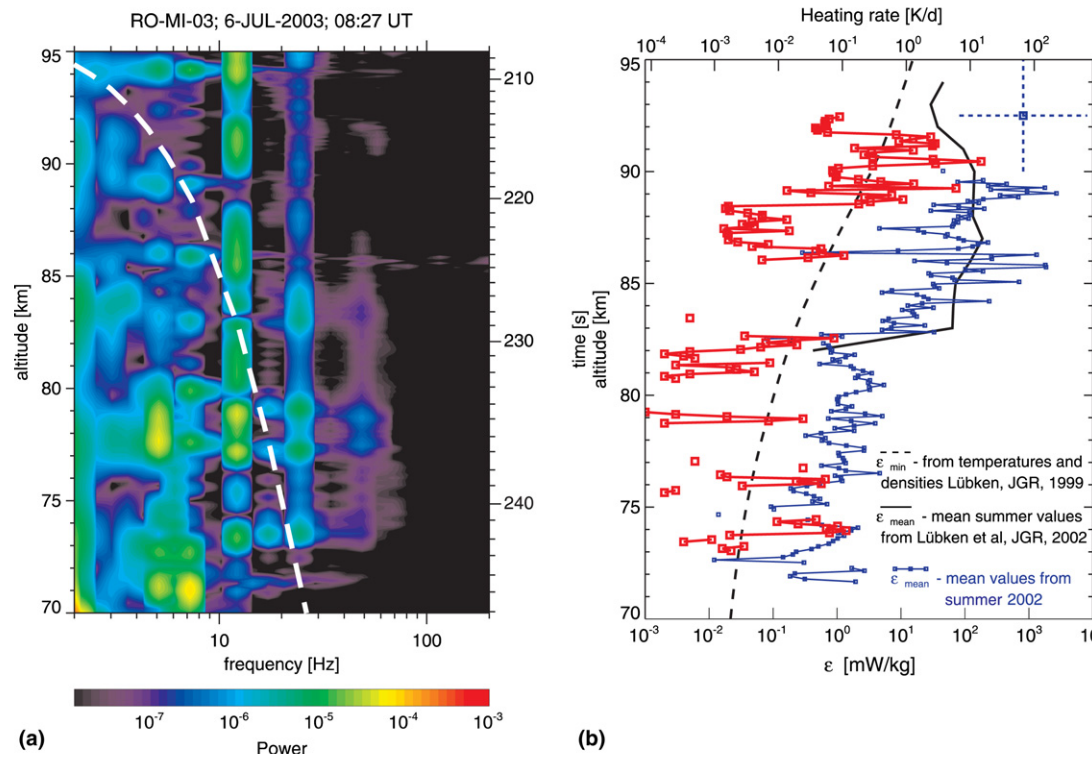

Fig. 3. Results of the neutral air turbulence measurements at Spitzbergen during the ROMA-SvalRak 2003 campaign at Spitsbergen, 79°N. Left panel (a): wavelet power spectra of the relative neutral air density fluctuations measured during the flight RO-MI-03. The dashed white line represents the theoretical estimate of the minimum inner scale (see text for details). Right panel (b): the mean over the three rocket flights turbulent energy dissipation rates, ε (red connected symbols). The black thick line is the mean ε-profile derived by Lübken et al. (2002). The blue connected squares represent the mean ε-profile derived from three rocket flights conducted from the Andøya (69°N, 16°E) during the summer 2002 (Strelnikov et al., 2003).

scale of a turbulent eddies at which transition between inertial and viscous energy subrange take place. So to be turbulent this spectrum must show $k^{-5/3}$ law to the left and k^{-7} power decay to the right of the white dashed line, where k is a wave number (Kolmogorov, 1941).

In Fig. 3(b), we present the mean turbulent energy dissipation rate (ε) for the three rocket flights conducted during the ROMA-SvalRak 2003 campaign, derived by means of the wavelet analysis technique. This method is based on fitting a Kolmogorov type spectrum to the measured spectrum and thereby determine the inner scale of turbulence, which in turn can be used to derive the energy dissipation rate (see Strelnikov et al., 2003 for more details). In Fig. 3(b), we also compare our measurements with the mean ε values derived by Lübken et al. (2002) and the mean ε profile derived for three flights conducted from Andøya (69°N, 16°E) during the summer 2002. That year a strong turbulence activity was detected in a wide altitude range (Rapp et al., 2004). The black dashed line in Fig. 3(b) represents the theoretical estimate of a minimum energy dissipation rate $\varepsilon_{\min}$ which is connected to the $l_0^{\min}$ as $l_0 = 9.9 \times \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}$, where ν is the kinematic viscosity.

As one can see, during the ROMA-SvalRak campaign 2003 at Spitzbergen, much weaker turbulence activity was detected compared to previous results which were obtained at Andøya, 69°N. This is especially the case for altitudes above 80 km. On the other hand, we do detect turbulence at lower heights, in accordance with the summer 2002 results. This is in contrast to the usual situation for heights below 80 km as described by Lübken et al. (2002).

4. Summary

In this paper, we have given an overview of a recent sounding rocket campaign supported by different ground based instruments which took place at Spitzbergen (79°N). We have presented some selected, but striking, results of small scale structures in both neutral air and plasma constituents. These can be summarized as follows:

- Signatures of charged particles have been detected in situ by the particle detector, and appear at altitudes where NLC was observed by the lidar.
- Small scale structuring in plasma species (ions and electrons) detected in situ reflects almost precisely the PMSE picture observed by the radar.
- Plasma instability events were registered in situ during all three flights during ROMA-SvalRak campaign

2003. Two different plasma instability events detected by the rocketborne instruments have been shown. Extremely strong fluctuations (up to 70 dB) in the E-region ion densities were detected during the flight RO-MI-01 (1 July, 2003). The time development of a plasma instability was observed during the flight RO-MI-03 (6 July, 2003). The latter has been examined in detail and the results described elsewhere (Strelnikov et al., 2004).
- Our turbulence measurements show less turbulent activity compared to previous observations at Andøya (69°N). We have presented the mean ε-profile over three rocket flights conducted during the ROMA-SvalRak campaign 2003. We have also presented evidence for a non-turbulent summer atmosphere around the mesopause region (about 87–88 km height) at 79°N (Fig. 3(a)), which has not been observed at 69°N.

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