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Observations of the lower thermospheric neutral temperature and density in the DELTA campaign

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The rotational temperature and number density of molecular nitrogen (N_2) in the lower thermosphere were measured by the N_2 temperature instrument onboard the S-310-35 sounding rocket, which was launched from Andøya at 0:33 UT on 13 December 2004, during the Dynamics and Energetics of the Lower Thermosphere in Aurora (DELTA) campaign. The rotational temperature measured at altitudes between 95 and 140 km, which is expected to be equal to neutral temperature, is much higher than neutral temperature from the Mass Spectrometer Incoherent Scatter (MSIS) model. Neutral temperatures in the lower thermosphere were observed using the auroral green line at 557.7 nm by two Fabry-Perot Interferometers (FPIs) at Skibotn and the Kiruna Esrange Optical Platform System site. The neutral temperatures derived from the look directions closest to the rocket correspond to the rotational temperature measured at an altitude of 120 km. In addition, a combination of the all-sky camera images at 557.7 nm observed at two stations, Kilpisjärvi and Muonio, suggests that the effective altitude of the auroral arcs at the time of the launch is about 120 km. The FPI temperature observations are consistent with the in situ rocket observations rather than the MSIS model.

Key words: The DELTA campaign, the lower thermosphere, temperature and density

1. Introduction

The dissipation of energy originating in the magnetosphere and lower atmosphere plays an important role in the energy budget controlling the temperature of the polar lower thermosphere (Fujiwara *et al.*, 2004). However, correspondence of the time-varying energy dissipation rates to the resulting temperature structure is presently not well investigated. In addition, the vertical structure of temperature is also important for the dynamics in this region. Studies on instability formation and turbulence generation in the neutral wind field require observations of the temperature structure in the background atmosphere. Recent rocket observations in the polar lower thermosphere showed the neutral wind jet with large wind shears during disturbed conditions (Larsen *et al.*, 1997), but the mechanisms responsible for generating the jet is still unclear.

In spite of the importance of temperature observation in the lower thermosphere, it is difficult to obtain reliable temperatures from both in situ and remote sensing measurements. The low atmospheric density in this region makes direct measurements difficult, and most techniques infer neutral temperature from Doppler temperature, ion temperature, and rotational temperature on the assumption that the ions, the light-emitting particles, and the rotational state of the molecules, respectively, are in thermal equilibrium with the neutral atmosphere. The Fabry-Perot Interferometer (FPI) derives the neutral temperature from the Doppler width of airglow and auroral emissions, such as green (OI 557.7 nm) and red (OI 630.0 nm) lines. In polar regions, the effective emission altitude of auroral green line varies depending on the precipitating electron energy. Since vertical temperature gradients in the lower thermosphere are generally steep, there are difficulties in quantitative analysis of the neutral temperature derived from the auroral green line measurement by the FPI. However, the green line temperature measurement is potentially useful in estimating an auroral energy deposition (Holmes *et al.*, 2005).

One of the objectives of the Dynamics and Energetics of the Lower Thermosphere in Aurora (DELTA) campaign was to measure temperatures by a rocket-borne instrument, ground-based FPIs, and the European Incoherent Scatter (EISCAT) radar during the auroral disturbances. This paper reports the in situ observations of rotational temperature and number density of atmospheric molecular nitrogen (N_2) by the N_2 temperature instrument (NTV) onboard the sounding rocket. The N_2 rotational temperature is expected to be equal to the neutral temperature in the lower thermosphere as described in Sec. 2.1, thus this experiment provides the vertical structure of the neutral temperature. The results were used to verify quantitatively the FPI temperature measurements.

2. Experiment

2.1 Instrumentation

In situ temperature and density measurements were made with the NTV onboard a sounding rocket during the DELTA campaign. Rocket experiments using this instrument have been successfully carried out twice in Japan (Kawashima *et al.*, 1997; Kurihara *et al.*, 2003). This is an active experiment using the Electron Beam Fluorescence (EBF) technique, and the instrument consists of an electron gun to excite and ionize the ambient N_2 and a spectrometer to detect the fluorescence of the N_2^+ first negative (1N) system. An electron beam with an energy of 1 keV and a current of 10 mA is continuously emitted from the electron gun in a direction perpendicular to the rocket axis, and the excitation-ionization of N_2 and the subsequent fluorescence of the N_2^+ occur along the electron beam. A measurement volume of the NTV is located at an intersection of the electron beam and the field of view of the spectrometer and is 0.2 m away from the payload. The fluorescence spectrum of the N_2^+ 1N system between 380 and 460 nm, including the 1N(0,0) band at 391.4 nm, 1N(1,2) band at 423.7 nm, and 1N(0,1) band at 427.8 nm, is detected by a linear image sensor in the spectrometer. The exposure time for each spectrum is 245.76 ms. The analysis of the fluorescence spectrum provides properties of the initial state of the N_2 molecules: rotational temperature, vibrational temperature, and number density of N_2. The rotational temperature is determined by fitting a synthetic spectrum to the measured spectrum of the 1N(0,0) band, and the vibrational temperature is determined by measuring the relative intensities of the 1N(0,1) and 1N(1,2) bands. The number density is calculated from the intensity of the 1N(0,0) band. The detailed description of the instrument and measurement method is presented by Kurihara and Oyama (2005).

An equilibrium between rotational and translational degrees of freedom for $\mathrm{N_2}$ is immediately established in the lower thermosphere. Relaxation time for attaining the equilibrium, τ_{RT}, is given by

$$\tau_{\mathrm{RT}} = Z_{\mathrm{RT}}\,\tau_0, \tag{1}$$

where Z_{RT} is the number of collisions needed for the rotational relaxation and τ_0 is the mean free time between collisions. Values of Z_{RT} for $\mathrm{N_2}$–$\mathrm{N_2}$ collisions in the temperature range of 200–1000 K obtained in the laboratory experiments are 4–14 (Capitelli *et al.*, 2000). The rotational relaxation time τ_{RT} for the $\mathrm{N_2}$ gas is calculated to be $\sim 10^{-3}$ s at 95 km altitude and $\sim 10^{-1}$ s at 140 km. Thus, the rotational temperature of $\mathrm{N_2}$ is expected to be equal to the neutral temperature in the lower thermosphere.

2.2 Rocket experiment

The NTV was installed on the top of the S-310-35 sounding rocket, which was launched northward from Andøya (69.3°N, 16.0°E) at 0:33 UT on 13 December 2004. The temperature and density measurements by the NTV were conducted in 97–140 km altitude in the ascent of the rocket flight, and after stopping the electron beam emission for 10 s to get the background spectra, the measurements were restarted 140–95 km altitude in the descent. After that, the temperature and density could not be obtained because the fluorescence spectra were saturated due to the higher atmospheric density. The rocket was separated into mother/daughter payloads at 106.6 km altitude during the ascent. The purpose of the separation is to electrically isolate the other plasma instruments such as a fast Langmuir probe (FLP) and an impedance probe (NEI) on the mother payload from the NTV on the daughter payload, because the electron beam emission by the NTV causes significant charging of the rocket body.

The experimental conditions for the NTV in the DELTA campaign were different from that in the previous experiments at the midlatitude because of auroral emissions. During the rocket flight, the passages of several auroral arcs were observed by the all-sky camera (ASC) at Kilpisjärvi in the

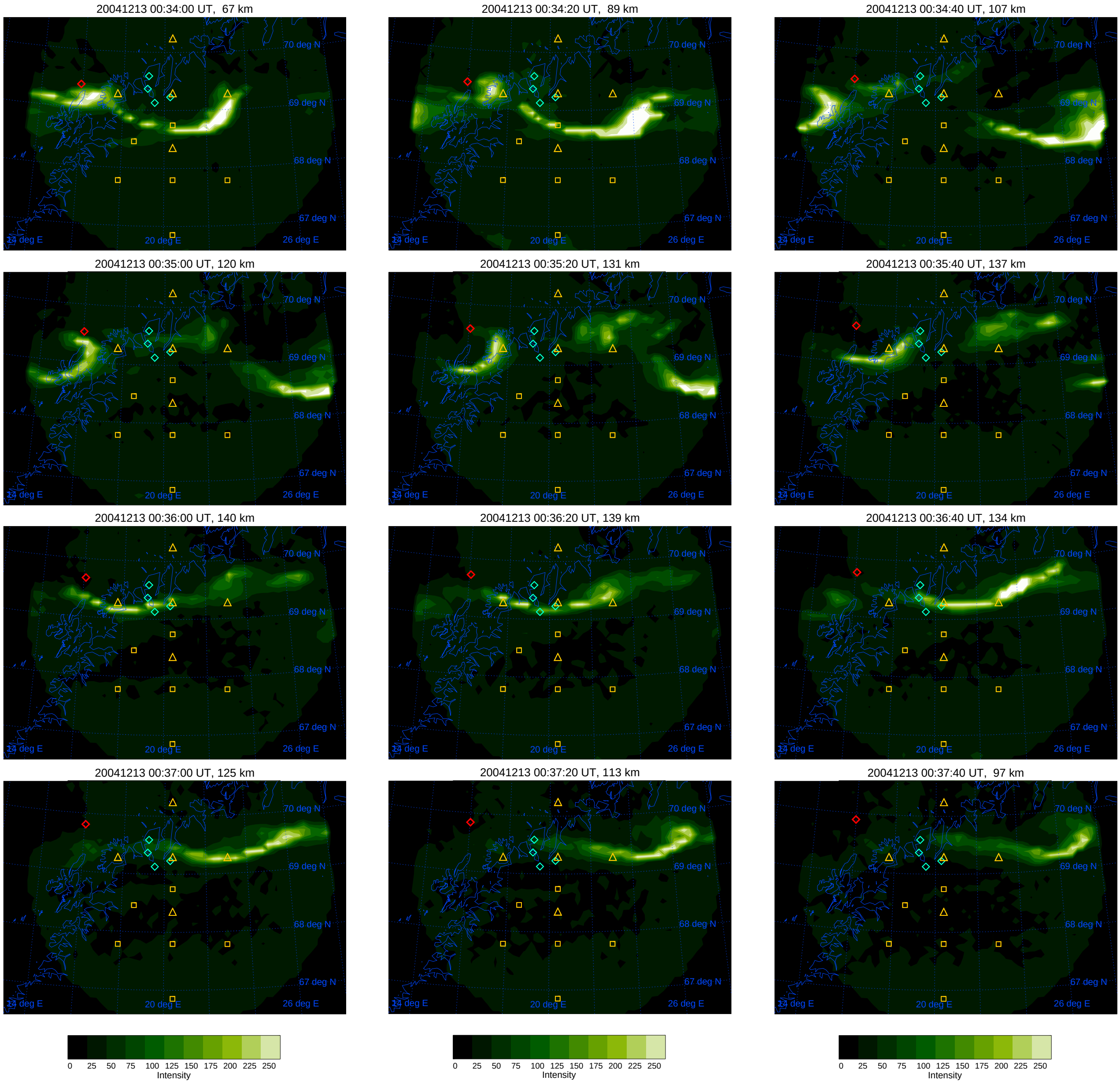

Fig. 1. The green line emissions observed by the ASC at Kilpisjärvi at intervals of 20 s during the rocket flight. The UT time and the corresponding rocket altitude are indicated at the top of each image. The projection altitude of the ASC images, the rocket positions (red diamonds), the EISCAT CP-2 beam positions (cyan diamonds), and the sampled volumes for the Skibotn FPI (yellow triangles) and KEOPS FPI (yellow boxes) is 110 km.

MIRACLE network as shown in Fig. 1. The ASC acquired the images at 557.7 nm with a sampling rate of 20 s. Under such auroral condition, the background auroral emission can contaminate the spectra observed by the NTV, because the N_2^+ 1N system induced by the EBF technique is commonly seen in auroral spectra. Figure 2(a) and (b) show the spectra observed by the NTV spectrometer during the ascent at 99.7 km and 84.9 km altitude, respectively. Note that the electron beam emission started at

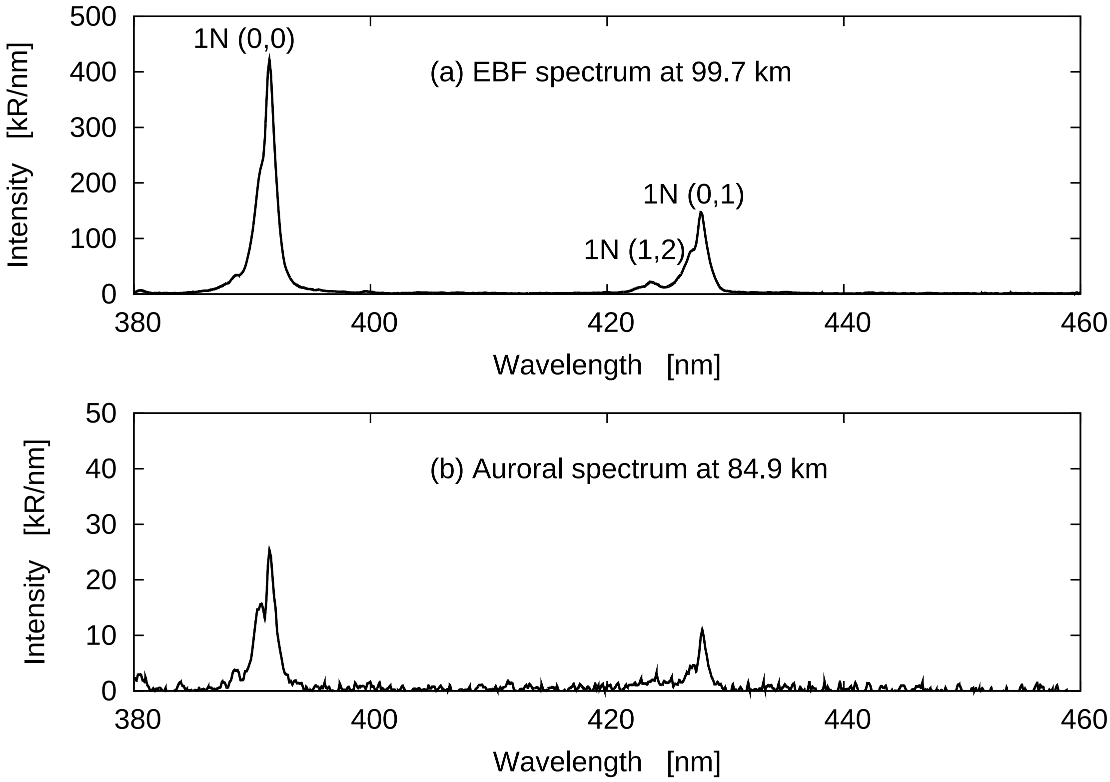

Fig. 2. Spectra from the NTV spectrometer observed at (a) 99.7 km and (b) 84.9 km altitudes. The N_2^+ 1N bands in (a) are the fluorescence mainly induced by the EBF technique, and the same bands in (b) are the background auroral emissions.

97.3 km during the ascent. The spectra obtained below 97.3 km are not the fluorescence induced by the EBF technique but the background emissions. In Fig. 2(a), the N_2^+ 1N(0,0), (0,1), and (1,2) bands are predominantly strong, and other spectral features are not recognized. Figure 2(b) shows an example of the background auroral emissions, and identifiable bands in Fig. 2(b) are the same as in Fig. 2(a). It is therefore difficult to eliminate the auroral contamination from the observed spectra. The observed intensity of the background auroral emissions changes with altitude and also with look direction of the spectrometer because of the transient and localized nature of the auroral arc as observed simultaneously by an auroral green line photometer (AGL) onboard the rocket (Iwagami *et al.*, 2005 in this issue). At around 100 km altitude during the ascent, the intensity of the background auroral emission was at least an order of magnitude lower than the intensity of the fluorescence by the EBF technique. However, since the intensity by the EBF technique decreases rapidly with altitude in proportion to the N_2 number density, the auroral emissions can be a significant source of error in the temperature and

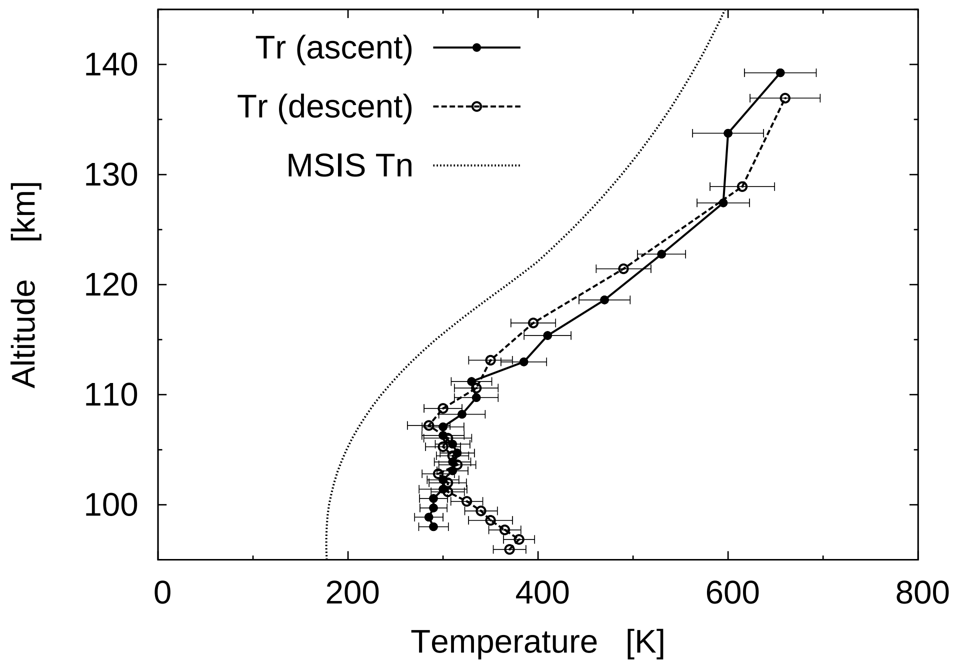

Fig. 3. Observed N_2 rotational temperature profiles during the ascent (solid line) and the descent (dashed line) compared with neutral temperature profile predicted by the MSISE-90 model (dotted line).

density measurements at the upper part of the observation, as discussed later.

3. Observational Results

3.1 Rotational temperature and number density of molecular nitrogen

Altitude profiles of the observed N_2 rotational temperature during the ascent and descent of the rocket flight are shown in Fig. 3. The uncertainty in the rotational temperature determination from each spectrum increases with altitude because the signal to noise ratio of the spectrum decreases with a decrease in density. In order to reduce the uncertainty, the spectra are grouped into altitude bins so that the integrated spectra have comparable intensities. As a result, the altitude resolution of the rotational temperature data in Fig. 3 varies from 1 km at 95 km altitude to 6 km at 140 km. The uncertainty in Fig. 3 is estimated from the signal to noise ratio of the spectrum using the results of the laboratory experiment and increases with altitude from 15 K at 95 km to 40 K at 140 km.

The profiles in the ascent and descent in Fig. 3 agree well above 102 km. Below this altitude, the rotational temperature in the descent is significantly higher than that in the ascent. This enhancement is caused by aerodynamic effects resulting from supersonic motion of the rocket. The temperature of the airflow around the sounding rocket is enhanced by compression depending on the attitude of the rocket (Gumbel, 2001). As mentioned previously, the measurement volume of the NTV is located in the vicinity of the payload, the rotational temperature measurement can be affected by the translational temperature enhancement around the rocket. Kurihara *et al.* (2005) used the Direct Simulation Monte Carlo (DSMC) method to study the flow around the sounding rocket and the aerodynamic effects on the NTV measurement. They showed that the measurement volume is less than 1 m downstream from the shock front during the ascent. Atmospheric molecules in the flow travel the distance from the shock front to the measurement volume in $\sim 10^{-3}$ s at the flow speed of ~ 1 km. Considering this travel time t and the rotational relaxation time τ_{RT} in Eq. (1), the rotational temperature can be higher than the background neutral temperature below 110 km where $t \simeq \tau_{\mathrm{RT}}$. Above 110 km, the rotational temperature is free from the aerodynamic effects, because the supersonic flow arrives at the measurement volume in a much shorter time than τ_{RT}.

The neutral temperature profile predicted by the Mass Spectrometer Incoherent Scatter (MSISE-90) model (Hedin *et al.*, 1991) is also plotted in Fig. 3. The MSISE-90 model is an empirical model to predict expected values of the atmospheric parameters as a function of local time, latitude, longitude, UT, $F_{10.7}$, and A_p. The observed rotational temperature is much higher than the neutral temperature from the MSIS model in all altitudes, and the differences between the rotational temperature and the neutral temperature are 70–140 K above 110 km.

Altitude profiles of the observed N_2 number density are shown in Fig. 4. The ascent and descent data are offset to ease comparison. Unlike the rotational temperature determination, number densities are calculated from each spectrum with a high time resolution of 245.76 ms. Spin periods of the rocket measured by an onboard geomagnetic aspectmeter are $\sim$ 870 ms during the observation, and hence about four density data are obtained per spin. For this reason, the density profiles in Fig. 4 show clear spin modulation caused by the aerodynamic effect. This spin modulation in the density

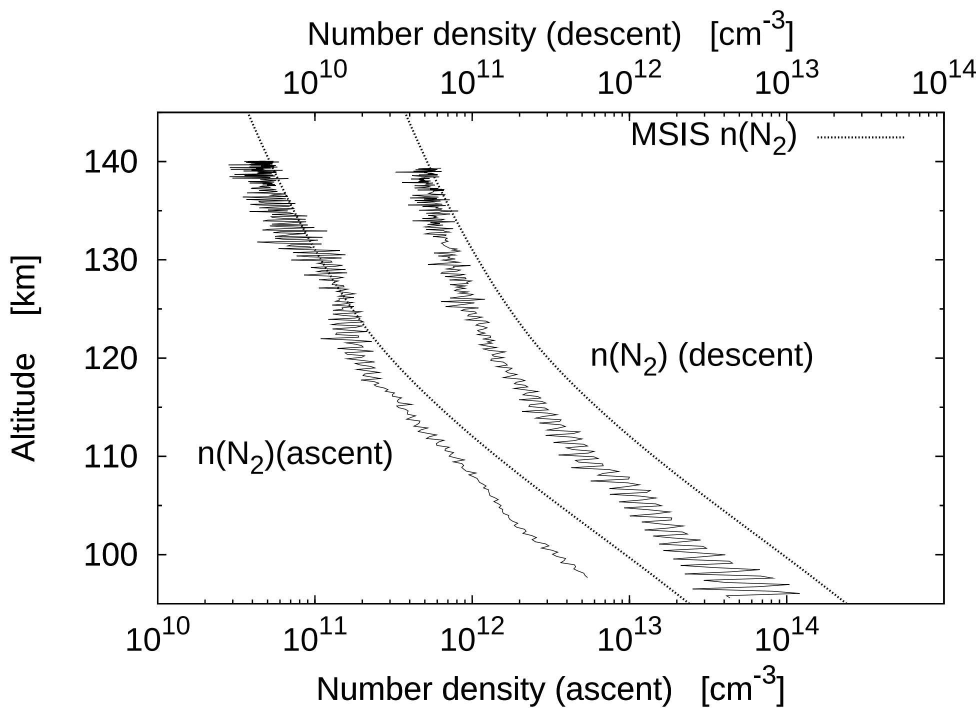

Fig. 4. Observed N_2 number density profiles during the ascent (lower scale) and the descent (upper scale) compared with N_2 number density profile predicted by the MSISE-90 model (dotted lines).

profiles is a ram/wake modulation, which is caused by the compression/rarefaction, typically observed by side-looking instruments (Gumbel, 2001). Similar spin modulation observed in the previous NTV experiment at the midlatitude was quantitatively analyzed by Kurihara *et al.* (2005). The amplitude of the spin modulation during the decent is larger than that during the ascent, particularly in the lower altitudes, because an angle of attack of the rocket is larger during the descent.

As in the case of the rotational temperature profiles, the density profiles during the ascent and descent indicate a similar tendency. However, at 120–135 km altitude, the density during the ascent is higher than that during the descent. This is mainly attributed to the auroral contamination of the observed spectra. The projections of the auroral arcs observed by Kilpisjärvi all-sky camera in Fig. 1 show that the auroral arc was located just on the south side of the rocket during the ascent and moved eastward during the descent. The AGL onboard the rocket also detected larger slant emission rates of the green line during the ascent (Iwagami *et al.*, 2005 in this issue).

In order to estimate the auroral contamination in the NTV spectra, the difference of the density

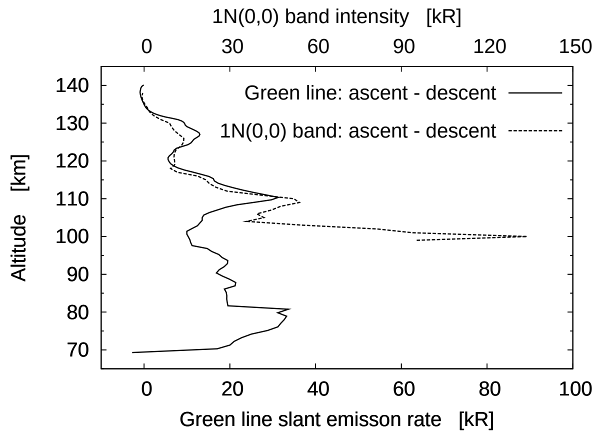

Fig. 5. Slant emission rate of the green line observed by the AGL (solid line) and the 1N(0,0) band intensity observed by the NTV (dashed line). Both are differences of the spin-averaged profiles between the ascent and descent.

profiles between the ascent and descent is converted to the original 1N(0,0) band intensity and compared with the slant emission rate of the auroral green line observed by the AGL in Fig. 5. Although the AGL was installed on the daughter payload, the AGL and NTV look in approximately the same direction away from the rocket axis. The angles between the rocket axis and the line of sight of the AGL and NTV are 60.0 and 67.5 degrees, respectively. The 1N(0,0) band intensity and the slant emission rate of the green line in Fig. 5 are shown as differences of the spin-averaged profiles between the ascent and descent. The 1N(0,0) band profile is similar to the green line above 105 km. This result implies that most of the density difference between the ascent and descent is due to the auroral contamination and that the true density profiles during the ascent and descent are very similar. The dissimilarity between the 1N(0,0) band and the green line emission profiles below 105 km in Fig. 5 results from the large spin modulation on the density profile during the descent. Kurihara *et al.* (2005) performed the numerical simulation of the spin modulation on the density measured by the NTV in the previous experiment and showed that the simple running average of the spin modulation deviates from the true background atmospheric density when the amplitude of the spin modulation is large.

The observed density profiles are also compared with the density profile from the MSIS model. The observed N_2 number density profiles both during the ascent and descent are lower than the N_2 number density predicted by the MSISE-90 model at all altitudes as shown in Fig. 4. The observed density during the descent, which is much less affected by the auroral contamination, gradually approaches the MSISE-90 density with altitude from $\sim$ 30% at 95 km to $\sim$ 90% at 140km.

3.2 Neutral temperature

The two ground-based FPIs at Skibotn (69.3°N, 20.4°E) and the Kiruna Esrange Optical Platform System (KEOPS) site (67.8°N, 20.4°E) sampled the auroral green line emission at 557.7 nm and provided neutral temperatures and line of site wind velocities. Both FPIs operated a normal scan of cardinal directions plus zenith but the KEOPS FPI had one extra direction of Northwest towards the rocket trajectory as shown in Fig. 1. The detailed description of the instruments and observations is presented by Griffin *et al.* (2005) in this issue. The neutral temperatures measured from the two directions closest to the sounding rocket, the Skibotn West and the KEOPS Northwest, at the period from 23:00 UT on 12 to 2:00 UT on 13 December 2004 are shown in Fig. 11 of Griffin *et al.* (2005). The temperatures from two directions are in very good agreement at $\sim$ 500 K just before the launch time. The Skibotn West data show a temperature jump of 150 K at 0:36:37 UT just after the launch and return to the former 500 K level at the next data point in 7.5 minutes. The KEOPS Northwest temperature gradually increases after the launch time up to $\sim$ 600 K and drops to $\sim$ 300 K after 1:15 UT. The data from the other directions show a temperature of around 500 K during the rocket flight.

3.3 Auroral emission height

The two ASCs at Kilpisjärvi (69.0°N, 20.9°E) and Muonio (68.0°N, 23.5°E) in the MIRACLE network acquired the green line emissions simultaneously. A combination of the two ASC images can be used to determine the altitude of auroral arcs by a stereo imaging technique. Figure 6 shows the combined ASC images for different projection altitudes at 0:34 and 0:37 UT on 13 December 2004. The two ASC images from Kilpisjärvi and Muonio are combined on the middle line between the two stations. The combined images for the projection altitude of 120 km show better connections of the continuous arc at the seam of the two ASC images than those for 110 and 130 km. These results suggest that the effective altitude of the auroral arc at around the time of the launch is about 120 km.

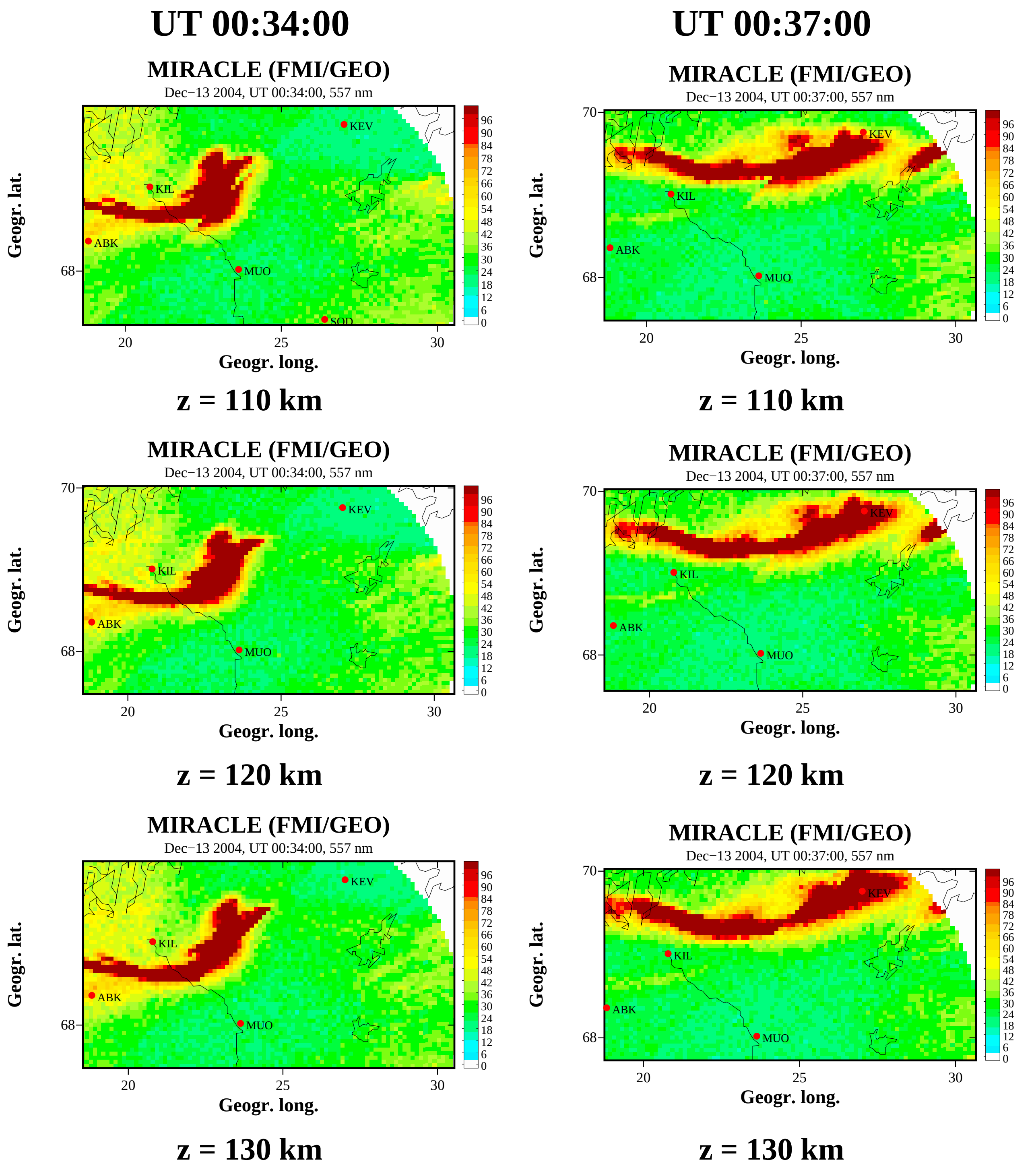

Fig. 6. Combined ASC images for the projection altitude of 110, 120, and 130 km at 0:34 and 0:37 UT on 13 December 2004. The two ASC images from Kilpisjärvi (KIL) and Muonio (MUO) are combined on the middle line between the two stations. The combined images for 120 km show smooth connections of the continuous arc than those for 110 and 130 km.

4. Discussion

The results of the observations of the rotational temperature and number density of N_2 in the DELTA campaign have features different from the MSIS model predictions. The observed rotational temperature is 40–140 K higher than the neutral temperature from the MSIS model above 110 km in the DELTA campaign. On the other hand, the observed N_2 number density is significantly lower than the MSIS model value especially in lower altitudes. However, the MSIS model is an empirical model based on the existing observational data, and the data coverage is the poorest at high latitudes in the upper mesosphere and lower thermosphere (Hedin *et al.*, 1991).

The temperature prediction by the MSIS model in the lower thermosphere is based on the assumption that the neutral temperature is equal to the ion temperature. The validity of this assumption during the geomagnetically disturbed period can be checked by comparing the rotational temperature with the ion temperature observed by the EISCAT radar during the DELTA campaign. A detailed comparison is provided in Nozawa *et al.* (2005) in this issue. The ion temperature retrieved from incoherent scatter spectra is influenced by the ion-neutral collision frequency. The ion-neutral collision frequency depends on the neutral density and composition, so that the large deviation of the observed N_2 number density from the MSIS model value can affect the estimation of the ion temperature. Maeda *et al.* (2005) discussed the effect of the assumed ion-neutral collision frequency on the ion temperature derived from the EISCAT-UHF radar at Tromsø and the ESR at Longyearbyen. They showed that the underestimate (overestimate) of the ion-neutral collision frequency resulted in the overestimate (underestimate) of the ion temperature around 100 km altitude particularly at the periods of strong electric fields. In addition, the change in the ion-neutral collision frequency can produce significant effects on the estimation of the E region neutral wind, conductivities, ionospheric current, and thereby the electromagnetic energy transfer rate, from the EISCAT measurements (Fujii *et al.*, 1998).

The large deviations from the MSIS model were also observed in the previous experiments at the midlatitude (Kawashima *et al.*, 1997; Kurihara *et al.*, 2003). The largest differences reached 150 K increase in temperature and 50% decrease in density at 115 km altitude. These deviations are comparable to those in the DELTA campaign. Contrastingly, above 130 km altitude in the midlatitude observations, the temperature and density were lower and higher, respectively, than the MSIS model.

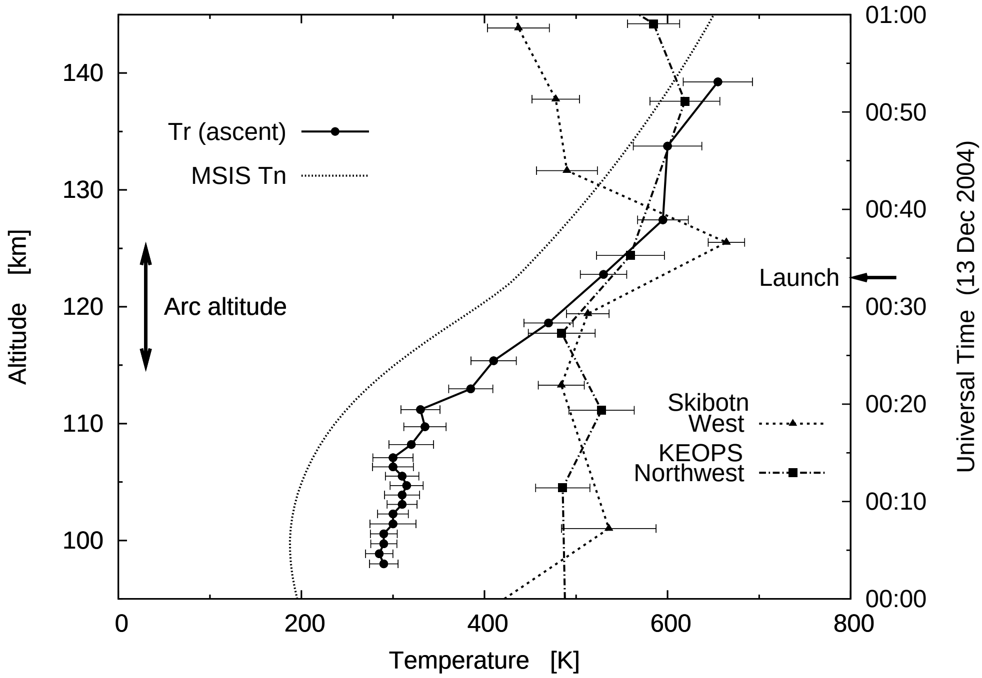

Fig. 7. Comparison of the in situ and FPI temperature observations. The rotational temperature from the NTV (solid line) and the neutral temperature from MSISE-90 model (dotted line) are plotted as a function of altitude (left scale), and the neutral temperatures from the Skibotn West (dashed line) and the KEOPS Northwest (dot-dashed line) directions are plotted as a function of universal time on 13 December 2004 (right scale). The effective altitude of the auroral arc determined from the combined ASC images and the time of the rocket launch are also represented by the arrows.

The results of the NTV experiments in the midlatitude and polar region show that the observed large deviations of the temperature and density from the MSIS model are less likely to be systematic errors inherent in the NTV experiment and are common in the lower thermosphere.

The auroral contamination in the observed spectra cannot be easily eliminated, but it becomes evident from the comparison with the green line emission measurement by the AGL that the density difference between the ascent and descent is mostly caused by the auroral contamination. In other words, the density profiles during the ascent and descent turned out to be very similar. It is not easy to estimate the effect of the auroral contamination on the rotational temperature measurement, but the actual differences of the observed rotational temperature between the ascent and descent are within the margin of uncertainty. Judging from the results of the in situ observations, the neutral atmosphere was fairly uniform at least along the rocket trajectory.

The rotational temperature from the in situ observation are compared with the neutral temperature from the ground-based FPI observations in Fig. 7. Only the altitude profile of the rotational temperature observed during the ascent is presented in Fig. 7 for simplicity. The effective altitude of the auroral arcs during the rocket flight is determined to be $\sim$ 120 km from the combinations of the two ASC images at Kilpisjärvi and Muonio in Fig. 6, and this altitude corresponds to the rotational temperature of $\sim$ 500 K at 120 km as shown in Fig. 7. The FPI neutral temperatures in Fig. 7 are limited to the observation of the two directions closest to the sounding rocket, the Skibotn West and the KEOPS Northwest, at the period from 0:00 UT on 12 to 1:00 UT on 13 December 2004. As described previously, the FPI neutral temperatures are at 500 K level except for the time just after the launch. The reason for this deviation is investigated in detail by Griffin *et al.* (2005) in this issue. As a result, the neutral temperature from the ground-based FPI observations is consistent with the observed rotational temperature rather than the MSIS model profile.

It should be noted that the temperature jump at the Skibotn West in the FPI observation is a reliable result with a small error bar. Griffin *et al.* (2005) discussed the temperature peaks from 23:00 on 12 to 2:00 UT on 13. It is difficult, however, to simply conclude that the temperature peaks are caused by either changes in the auroral emission height or some localized heating mechanisms, because the rocket trajectory and the sampled volumes of the FPIs are not ovelapped directly. Further studies including high spatial and time resolution simulations of a moving auroral arc are necessary to explain these observations.

5. Summary

The rotational temperature and number density of N_2 in the polar lower thermosphere were observed with the rocket-borne NTV in the DELTA campaign. The observed rotational temperature is 70-140 K higher than the MSIS model above 110 km, where the aerodynamical effects on the rotational temperature measurement are negligible. The observed N_2 number density during the descent, when the auroral contamination was sufficiently small, is much lower than the MSIS model and changes with altitude from 30% at 95 km to 90% at 140 km. This density reduction from the MSIS model density has a significant impact on the use of the ion-neutral collision frequency in the EISCAT observation and thereby the estimation of the ion temperature, neutral wind, ionospheric current, and electromagnetic energy transfer rate. The results of the NTV observation in the DELTA campaign and the previous midlatitude experiments show that large temperature and density deviations from the MSIS model are commonly seen in the lower thermosphere. The similarity of the profiles between the ascent and descent for both the rotational temperature and number density indicate that the neutral atmosphere was horizontally uniform along the rocket trajectory.

The results of the in situ observations are compared with the FPI temperature observation. The effective altitude of the auroral arcs during the flight are determined to be $\sim$ 120 km from the combined ASC images, because the combined images for the projection altitude of 120 km show better connections of the continuous arc at the seam of the two ASC images than those for 110 and 130 km. The neutral temperature of $\sim$ 500 K from the ground-based FPI observations just before the launch time is consistent with the observed rotational temperature at 120 km rather than the MSIS model profile. Further studies are needed to clarify the cause of the temperature peaks in the FPI observations after the lunch time, because the rocket trajectory and the sampled volumes of the FPIs are not overlapped directly.

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