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First mesopause temperature measurements using sodium lidar observations in the Antarctic region

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Abstract: The mesopause temperature structure was observed using a sodium temperature lidar system at Syowa Station (69°00′ S, 39°35′ E), beginning in February 2000. The laser transmitter was newly developed and included two injection-seeded Nd: YAG lasers. Regular observations were performed using the two-frequency technique as demonstrated by C.Y. She *et al.* (Geophys. Res. Lett., **17**, 929, 1990), with a spatial resolution of about 1 km and a temporal resolution of 6 min. The temperature structures of the 85 km to 105 km region of the upper atmosphere were measured by Na D_2 Doppler profile-fitting as well as the two-frequency technique. Temperatures derived from the two techniques agreed well and were consistent with the MSIS 90 model temperature structure. Night-time temperature variations over a 15-hour period were measured in May 2000. A large temperature fluctuation with an interval of about 4 hours, and an amplitude of 60 K (probably caused by gravity waves) was observed. From the average night temperature profile, the mesopause was determined to be located at 102 km, and have a temperature of 180 K. These values are similar to wınter values observed in the northern hemisphere.

1. Introduction

In the past few years, narrowband resonance lidar observations have drastically changed our knowledge in temperature structures of the mesopause region (80 km–110 km). Before the application of the lidar technique, temperature data for this region could only be obtained by rocket observations. The temperature in this region was well known to be much colder in summer than in winter, especially in the polar region (Andrews *et al.*, 1987). Fricke and Von Zahn (1985) first applied the lidar technique to measure temperature structures at Andoya, Norway (69°N, 16°E). Later, Lubken and Von Zahn (1991) reported the presence of a 'bistable' mesopause region: from autumn to spring, the mesopause was located at a high altitude (98 km) and was relatively warm (192 K); in early summer, however, the mesopause was located at a lower altitude (88 km) and was colder (129 K).

In the 1990's, a new sodium (Na) temperature observation method lidar was developed using a two-frequency measurement technique (She *et al.*, 1990; Bills *et al.*, 1991). This technique enabled an absolute temperature accuracy of better than ±3 K to be obtained at the Na layer peak, with a vertical resolution of 1 km and an integration period of approximately 5 min (Bills and Gardner, 1993). Using the same system, She *et al.* (1993) revealed two distinct levels of temperature minima using measurements performed at Fort Collins (41°N, 105°W). Yu and She (1995) reported the seasonal statistics showing two temperature minima in the nightly mean annual temperature profiles. A mobile potassium lidar observation system was developed (Von Zahn and Hoffner, 1996), and measurements from a ship were performed between 71°S and 54°N from April to July 1996 (Von Zahn *et al.,* 1996). These latitudinal observations suggested that only two distinct worldwide mesopause levels are present at altitudes of either 100±3 km or 86±3 km. A sharp transition in mesopause altitude was observed at 24°N. The winter level (100±3 km) extended from 71°S to 23°N, while the summer level (86±3 km) extended from 24°N to 54°N. She and Von Zahn (1998) also summarized their temperature data set obtained at Fort Collins (41°N, 105°W) and Kuhlungsborn, Germany (54°N, 12°E) for the same 1996/1997 period. Based on the average temperature structure over the winter season, the mesopause was found to maintain a nearly constant temperature of about 180 K, independent of latitude. The summer temperature decreases drastically as one moves from mid-latitudes toward the poles.

The first lidar temperature measurements in the southern hemisphere were performed at Sao Jose dos Campos (23°S, 46°W), Brazil, and were reported by Clemesha *et al.* (1999). The average of all their temperature profiles from July to October is similar to the winter profile seen at mid-latitudes, with a mesopause temperature of 190 K at 103 km. In the Antarctic region, Lubken *et al.* (1999) reported *in situ* temperature measurements for the summer mesopause that were obtained using rocket-borne falling spheres that were launched from Rothera (68°S, 68°W). They reported that the mesopause temperature was 129 K at 87 km, which is close to the northern hemispheres mean summer values. However, routine observations in the Antarctic region are still sparse, especially for the winter season.

In February 2000, lidar observations of the temperatures in the Antarctic mesopause region were initiated at Syowa Station (69°S, 39°E). The main objective was to examine the mechanism of energetic interactions between the lower thermosphere and the upper mesosphere through the mesopause region. In addition to lidar observations, MF radar measurements and other optical techniques were also performed. In this paper, we discuss the first temperature profiles that we have obtained and compare them with the MSIS 90 model and the observations of previous investigators.

2. Wavelength control

The transmitter consists of two Nd:YAG oscillators that produce 1064 and 1319 nm pulse lasers. The two phase-matched, spatially and temporally overlapping pulse lasers produce a 589 nm beam by sum frequency mixing (SFM) through a BBO crystal. Seeders for 1064 and 1319 nm are applied to generate single-wavelength, narrowband lasers. The full-width at half-maximum (FWHM) of the Doppler broadened Na D_2 spectrum is about 3 pm. The laser linewidth is less than 0.1 pm, which is sufficiently narrow for the required temperature measurements. A wavemeter (WA-1500 NIR, Burleigh) is used to monitor the 1319 nm and 1064 nm seeder wavelengths. The detailed specifications of this lidar system have been reported in previous papers (Kawahara *et al.*, 1998; Kitahara *et al.*, 1999).

Our temperature measurement method is the same as that proposed by research groups at Colorado State University and the University of Illinois. A detailed description of this method can be found in the paper by She *et al.* (1992). The method requires a narrowband laser and a high degree of laser tuning accuracy between the Na D_{2a} peak and the adjacent minimum in the middle of the Doppler-broadened spectrum. By collecting lidar photocount profiles with a narrowband lidar at each of these two wavelengths and calculating the ratio of the photocounts collected at each altitude, the vertically resolved temperature structure throughout the Na layer region can be derived.

To monitor the wavelength at 589 nm, previous investigators used a Na vapor cell kept at about 50°C as a reference. When the two counterpropagating 589 nm cw seeders are simultaneously illuminated at a saturated intensity, the Na fluorescence spectrum emitted by the cell exhibits Doppler-free features at the D_{2a} ($f_a = -648.8$ MHz) and D_{2b} ($f_b = +1066.9$ MHz) peaks and at the crossover resonance ($f_c = +200.3$ MHz) between the peaks. Each frequency denotes the offset from the Na D_2 center frequency ($= c/589.1583$ nm, c is speed of light in a vacuum). In previous reports, the laser frequencies were shifted between fa and fc by monitoring the cell. The fluorescence of sharp, Doppler-free features requires a very narrow laser linewidth (*e.g.* less than 0.001 pm), such as the cw 589 nm laser. The 589 nm pulse laser has a wider linewidth of about 0.1 pm FWHM, so no apparent Doppler-free features were seen. In our system, the SFM wavelength was calculated from the seeder wavelengths of 1064 nm and 1319 nm by monitoring a wavemeter. The wavemeter were a He-Ne laser in as a wavelength reference, and the wavelength accuracy in the near-infrared region is 0.1 pm. The wavelength is adjusted to 589 nm by changing the 1064 seeder wavelength between 1064.6221 nm and 1064.6187 nm and fixing the 1319 nm seeder wavelength at 1319.2012 nm. The corresponding theoretical wavelength shift varies from 589.1589 nm (D_{2a} peak) to 589.1578 nm (near the crossover resonance). All wavelength adjustments are controlled by a personal computer.

3. Observation and results

Scattered light was collected by a 0.5 m diameter Dall-Kirkham Cassegrain telescope (Kiyohara Optical Lab.). The measurements were performed in the photon-counting mode with a cooled photomultiplier (R943-02, Hamamatsu Photonics). Samples of the signal intensity ranges are shown in Figs. 1a and 1b. The laser wavelength was tuned at 589.1589 nm near the D_{2a} peak and at 589.1580 nm near the minimum between the peaks. The accumulation time was 100 s (1000 laser shots), and the height resolution was 96 m.

Before performing routine observations using the two-frequency technique, we compared the measured temperatures with those from a Na D_2 Doppler profile-fitting procedure to confirm their consistency. The Na D_2 profiles were obtained by measuring backscattered signal intensity while shifting the wavelength by 0.3-pm steps. The height resolution was 1 km. Figure 2 shows the measured Doppler profiles at each altitude range. The estimated fitting error was ± 3 K. To adopt the two-frequency

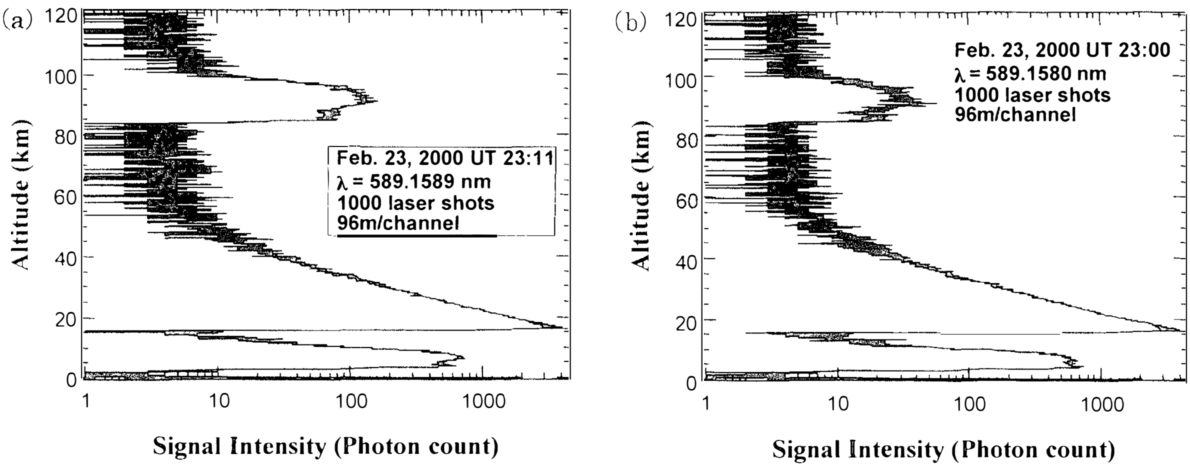

Fig. 1. Backscatter signal received by a photomultiplier. The laser wavelength was tuned (a) at λ $=589.1589$ nm near the sodium D_{2a} peak, and (b) at $\lambda=589.1580$ nm near the minimum between the D_{2a} and D_{2b} peaks.

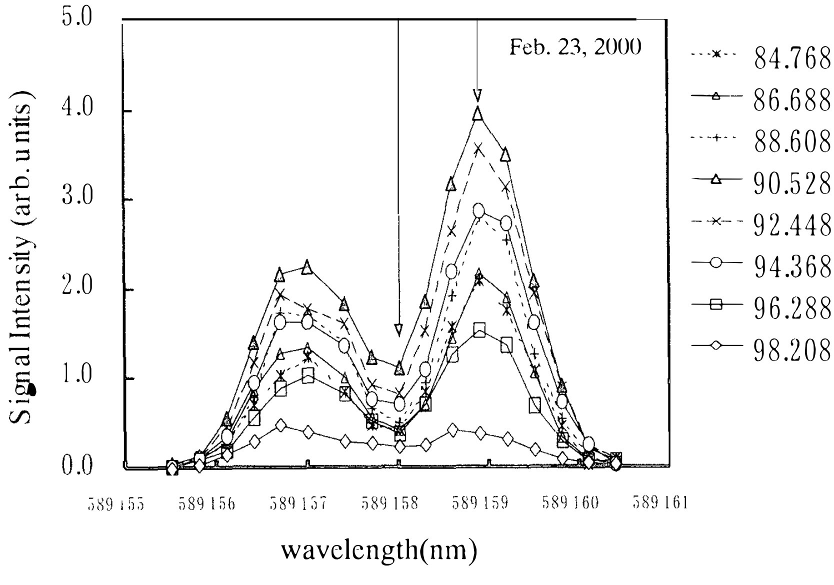

Fig 2. Backscatter signal intensity from the sodium D_2 Doppler-broadened absorption spectrum. The arrows indicate the data used for the two-frequency method.

technique, photocount data at 589.1589 nm (near the D_{2a} peak) and 589.1580 nm (near the crossover resonance) were selected, as indicated in Fig. 2. A simple running mean of the photocount data resulted in the same height resolution (about 1 km). Figures 3a and 3b display examples of the temperature profiles (solid line), the results obtained from the D_2 Doppler profile-fitting procedure (#), and the MSIS 90 model temperature (dashed line). The two temperature measurements were made on the nights of February 23 and April 20, 2000, respectively. Errors in the two-frequency technique are predominantly the result of the photon counting statistics. In Fig. 3a, the error is ± 9 K for the 84 km to 96 km region and increases with height to ± 45 K at 100 km. For Fig. 3b, the error is ± 8 K for the 82 km to 95 km region and increases to ± 16 K at 98 km.

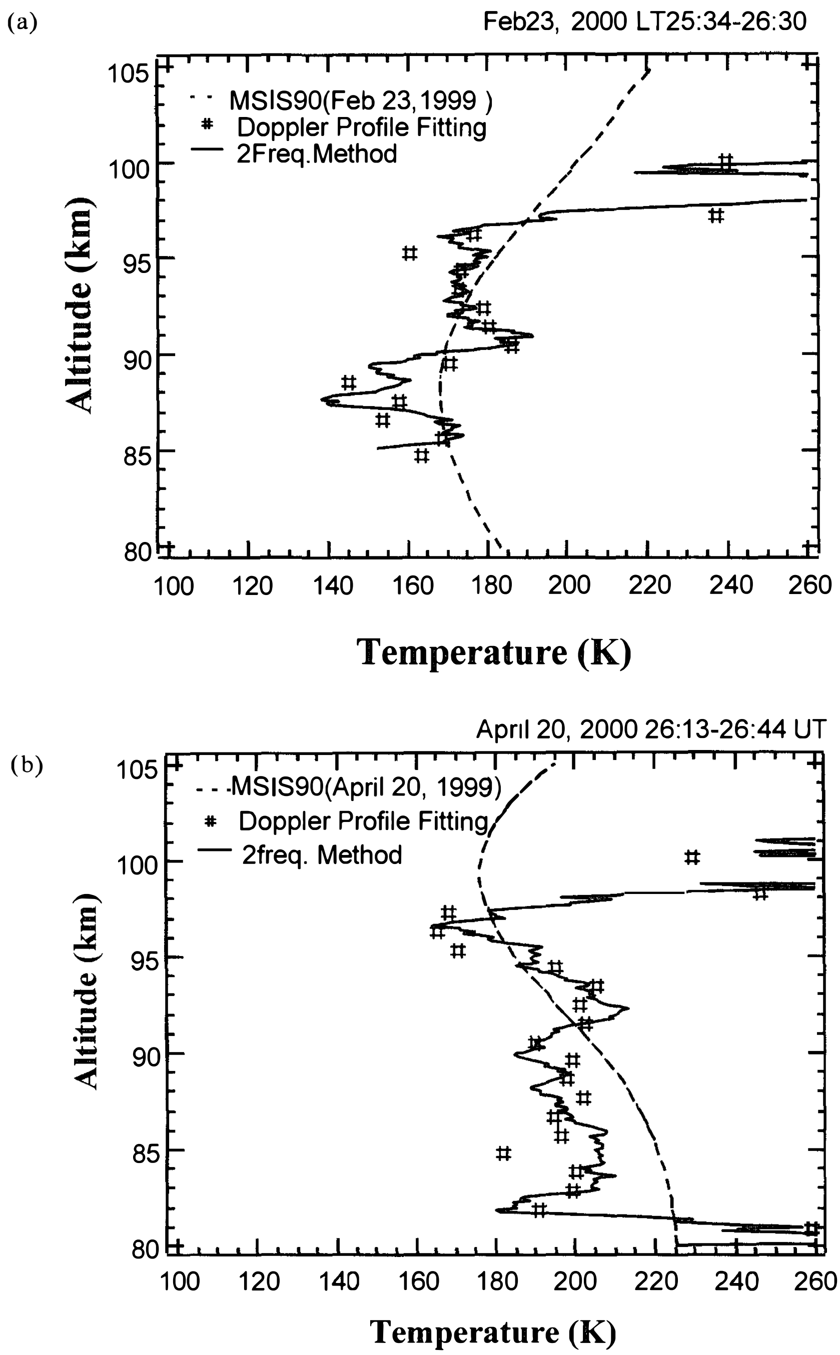

Fig. 3. Temperature structures in the mesopause region. The solid line and mark (#) denote the structures obtained by the two-frequency method and the sodium D_2 fitting procedure, respectively. The dashed line indicates the MSIS 90 model temperature. The data was obtained on (a) Feb. 23, 2000 and (b) April 20, 2000.

Hourly temperature variations for long periods were successfully measured in May 2000 (Fig. 4). Data was obtained over a 15-hour period from 1700 LT (May 27) to 0840 LT (May 28) using the two-frequency technique. The laser shot number at each wavelength was 1500 (/150 s) for this observation period. The temporal gate width was 0.64 μm, corresponding to a height resolution of 96 m. For the data processing, a

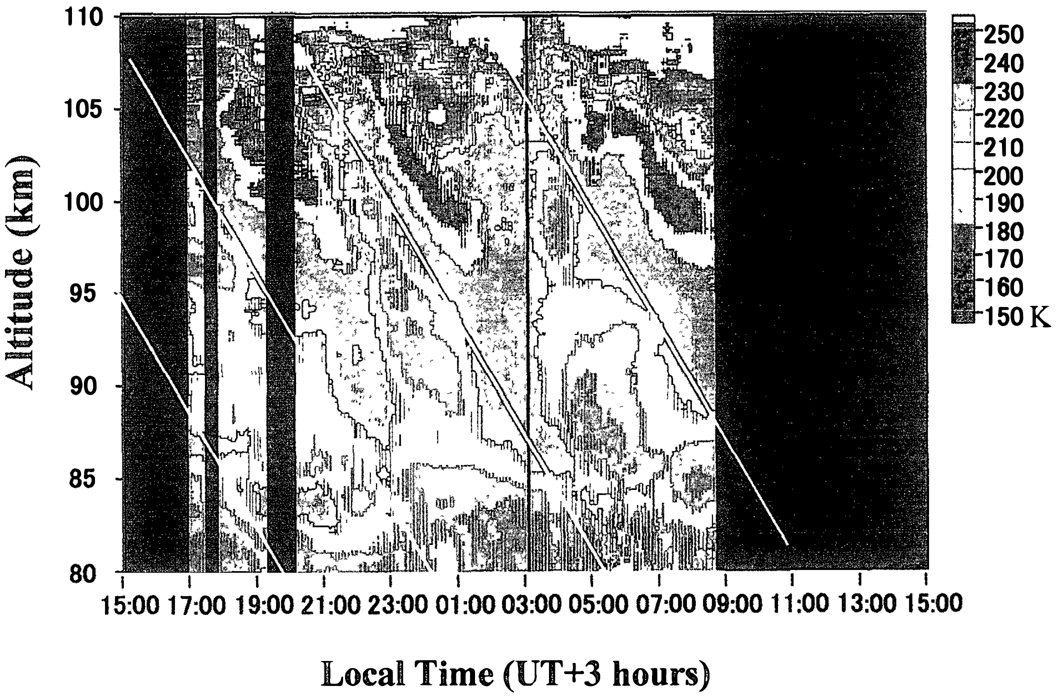

Fig. 4. Temperature variations over a 15-hour observation period on May 27–28, 2000.

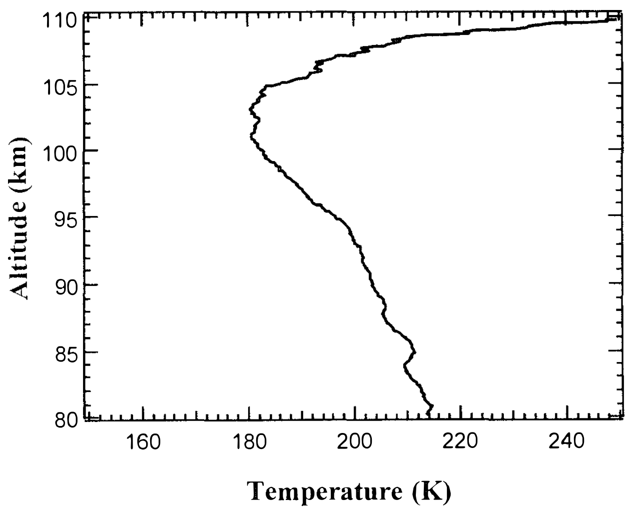

Fig. 5. Average night temperature profile for May 27–28, 2000.

running mean procedure using 11 gate channels (corresponding to ~1 km) was employed in the height direction. In the temporal direction, the running mean procedure was performed using 30 min intervals. In Fig. 4, quasi-monochromatic wave propagations are clearly visible. The wave parameters for these measurements are as follws: observation period $\simeq$4 hours, $v_z = \sim 1$ m/s, and $\lambda_z = \sim 15$ km. The waves dynamically disturbed temperature readings during the observation period, *e.g.* from ~170 K to ~230 K at 98 km. Figure 5 shows the average temperature structure for the 15-hour observation period. The nightly mean mesopause was found to be located at 102 km and have a minimum temperature of 180 K.

4. Discussion

Over the past 10 years, rapid progress has been made in the use of sodium lidars for measuring temperature. The development of the two-frequency technique was crucial for measuring the thermal structure of the mesopause region with a high degree of spatial and temporal resolution. Laser wavelength switching between two wavelengths is the key to this procedure. With a 589 nm pulse laser, the laser wavelength cannot be accurately determined, so the wavelengths of both seeder lasers must be monitored. The uncertainty between the SFM wavelength and the absolute wavelength was examined using the measured Na D_2 Doppler spectrum, as shown in Fig. 2. By fitting the theoretical Na D_2 spectrum to the measured profile, the absolute wavelength was experimentally scaled from the D_{2a} and D_{2b} peak wavelengths. By comparing this wavelength with the calculated wavelength at 589 nm from the wavemeter values, the disagreement was found to be less than 0.1 pm. Note that this value is the same as the wavemeter accuracy. This result allowed us to use the wavemeter to control the generated 589 nm laser wavelength without using the cell.

In Figs. 3a and 3b, the temperature errors of the two-frequency technique are mainly caused by small backscatter photocounts. As seen in the Figs. 1a and 1b, the photocounts at the two wavelengths are low (about 200 and 50) because of the short integration time (100 s). The small counts result in the large temperature errors of ± 9 K, as shown in Fig. 3a, even at a Na density peak altitude of 95 km. In contrast, the error of the line-fitting procedure, ± 3 K, showed almost no altitude dependence. Within the error bar, the structures are in good agreement. The disagreement between the temperature structures is partially due to the difference in temporal resolutions. As shown in Fig. 4, the wave dynamics drastically changed the temperature value, even within a 30-min period. The Doppler profile measurements required 30 min to record a data point. In contrast, the temporal resolution of the two-frequency technique was 7 min in these experiments. Therefore, the wave/tide activities may have changed the temperature structures within the observation period. The MSIS 90 model temperature was calculated for the corresponding time and location, as indicated by the dashed line in each figure. The measured temperature structures agree well with the model temperature. Thus, the validity of the measured temperature structures was confirmed.

Temperature variations over a 15-hour observation period on May 27–28 are shown in Fig. 4. Four downward structures resolting from waves/tides were observed in 15 hours (0.26 events/hour). Nomura *et al.* (1989) also reported an average number of wave events, of 0.26 events/hour observed on lidar observations at Syowa Station from March to October in 1985. To obtain the background temperature structure, the average nightly temperature was obtained, as shown in Fig. 5. The results indicate that the mesopause was located at 102 km and that the temperature was 182 K. She and Von Zahn (1998) reported that two mesopause altitudes are present worldwide, one near 100 km during the winter and the other around 88 km during the summer. In the northern hemisphere, the mesopause is near 100 km and the temperature is about 180 K at all latitudes during the winter. Our result is close to the winter mesopause for the northern hemisphere. The Antarctic summer mesopause observed by Lubken *et al.* (1999) showed a temperature of 129 K at 87 km. Their observation site, Rothera

(68°S, 68°W), and Syowa Station (69°S, 39°E) are at almost the same latitude. If the mesopause temperature has no longitudinal dependence, the summer mesopause temperature at Syowa Station should be similar to that at Rothera. However, seasonal variations in the temperature structures must be clarified. Our temperature data for the Antarctica will contribute to the extension and improvement of simulation models. This should lead to a better understanding of the thermal structures in the Antarctic region.

5. Conclusion

The first observation of mesopause temperature profiles in the Antarctic region was conducted using a new Na lidar at Syowa Station. The validity of the measured temperature structures was confirmed by a Na Doppler profile-fitting procedure and the two-frequency method. Within the error bars, the measurements are in good agreement and consistent with the MSIS 90 model temperatures. Temperature variations over a 15-hour period were measured in May 2000. Temperatures varied considerably (as much as 60 K) over a 4 hour interval, probably as a result of gravity waves. Based on the average daily temperature, the mesopause was determined to be located at 102 km and have a temperature of 180 K. There values are similar to the winter values for the northern hemisphere reported by She and Von Zahn (1998).

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