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Initial Spring Temperature Profiles of the Mesopause Region over Fort Collins, CO, Measured by the Colorado State Na Temperature Lidar

J. R. Yu, J. W. Huang, H. Latifi*, and C. Y. She

Physics Department, Colorado State University, Fort Collins, CO 80523, USA (Fax: +303 491-7947)

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Abstract. After its first measurement in late August, 1989, the new Na temperature lidar has been in operation during springs 1990 and 1991 at Fort Collins, CO. A total of nine nights (over 2600 profiles) of mesopause temperature measurements, each for a period longer than 4 hours, have been taken. We present these high quality initial profiles which demonstrate the effectiveness of the new two-frequency narrowband lidar technique for mesopause temperature measurements. The average temperature profiles suggest that the spring mesopause temperatures range from 168 K to 205 K. The mesopause heights are around 88 km before the midnight and around 99 km after the midnight. The nightly averaged temperature profiles in the mesopause region display considerable variability. The richness in new geophysical information obtainable with a Na temperature lidar is made evident by noting strong perturbations in a short time scale (15 min) in the data taken on March 11, 1990 and March 18, 1991.

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Broadband Rayleigh lidars with large receiving apertures can be used routinely to measure atmospheric density and temperature profiles from about 25 to 80 km in altitude [1]. To measure atmospheric profiles with high accuracies and resolution beyond 80 km, a more efficient method is needed. Since Na fluorescence cross-section is more than 14 orders higher [2] than the Rayleigh scattering cross-section at 589 nm, broadband Na fluorescence lidar has been used for the past two decades to probe atmospheric dynamics in the mesopause region [3]. The sodium D_2 fluorescence spectrum consists of two groups of lines, D_{2a} and D_{2b}, separated by 1.772 GHz due to the hyperfine splitting of the Na ground-state; its Doppler-broadened fluorescence spectrum is temperature-dependent. Thus, if the sodium D_2 fluorescence is induced by a narrowband laser at different frequencies, the mesopause temperature can be determined. This idea was first applied by Gibson et al. [4] who were able to deduce the temperature near the peak of the sodium layer. More recently, Fricke and von Zahn [5] have obtained Na temperature profiles with 1 km resolution, using an excimer pumped dye laser system and the Bonn group has published several lidar studies of the mesopause region above Andoya [6, 1]. We have developed a two-frequency lidar for measuring Na temperature profiles. By comparing the Na D_2 fluorescence excited by two different frequencies at $v_a = -656.7$ MHz, and $v_c = 203.9$ MHz relative to the center of the fluorescence spectrum, the first mesopause temperature profiles at a mid-latitude was measured over Fort Collins, CO (40.6° N, 105° W), in collaboration with the Illinois group in August 1989 [8]. The Colorado State Na Temperature Lidar has since been operated on an irregular basis in the spring of 1990 and 1991, conducting the first sets of mesopause temperature profiling measurements in the mid-latitude. During this period, the lidar has been shown to be reliable and information on temperature and gravity wave dynamics in the mesopause region have been obtained [9, 10]. This paper briefly discusses the Colorado State Na Temperature Lidar, and presents preliminary analysis of atmospheric temperature measurements in the mesopause region over Fort Collins, CO, during this initial period of observation. Regular temperature measurements over Fort Collins began June 1991; these results will be analyzed for future publications.

1 The Colorado State Na Temperature Lidar

A schematic of the narrowband lidar transmitter is shown in Fig. 1. The laser beam starts from a tunable cw single-mode dye laser which is pumped by a cw argon-ion laser. Its output is amplified by a pulsed dye amplifier, which is pumped by an injection-seeded doubled YAG laser at a pulse rate of 20 Hz. The output of this system consists of tunable, megawatt, narrowband beam of pulses, with a measured FWHM of roughly 4.2 ns. The bandwidth of the output pulses is nearly Fourier-transform limited, giving a

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* Present address: Department of Physics, University of Shadid Beheshhty, Teheran, Iran

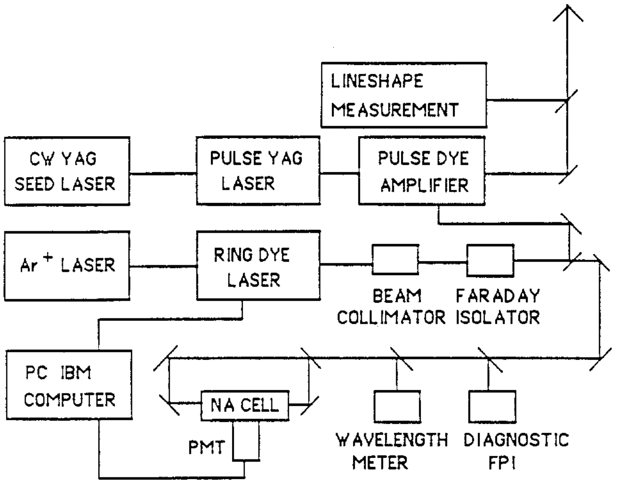

Fig. 1. The transmitter of the Colorado State Na Temperature Lidar

FWHM of roughly 130 MHz. The typical energy per pulse has been measured to be 30 mJ. A Fresnel lens, 1.22 m in diameter, is used to receive the scattered photons. The characteristics of the lidar transmitter and receiver is summarized in Table 1. In order to determine the characteristics of this laser system, several monitoring devices are used. Setting of the center frequency is done by tuning the cw single-mode dye laser, first monitored with a wavelength meter for rough wavelength selection and then with Doppler-free fluorescence spectroscopy for accuracy. The wavelength meter searches for the Na D_2 line. The saturated Doppler-free fluorescence spectroscopy technique, referenced to a vapor cell, can be used to set the absolute frequency of the cw single-mode dye laser to within ±10 MHz. To determine the laser lineshape function of the pulsed output, a small portion of the output is sent through a Fabry-Perot etalon to measure the lineshape. During data acquisition, the laser is first tuned to the D_{2a} peak at $v_a = -656.7$ MHz and the photon returns from a fixed number of laser shots (typically 600) is accumulated. The laser is then tuned to the cross-over resonance at $v_c = 203.9$ MHz and photon returns from the same number of laser shots is accumulated. Alternating between the two frequencies, consecutive photon profiles are recorded from which Na temperature and density profiles are calculated. The temperature accuracy at the Na layer peak (edges) is estimated to be ±4 K (±8 K) with a vertical resolution of 1 km and an integration period of 2.5 min. The details of this procedure have been described elsewhere [11].

2 Observational Results

After the initial demonstration of the new technique in August 1989, Na temperature and density profiles in the mesopause region over Fort Collins, CO (40.6° N, 105° W), have been taken irregularly during two intervals associated with cooperative campaigns: (1) ALOHA '90 lead by C. S.

Table 1. Characteristics of the Na temperature lidar

Transmitting system		Receiving system	
Wavelength	589 nm	Telescope	1.22 m dia. Fresnel lens
Pulse energy	30 mJ (typ.)	Aperture area	1.17 m^2
Pulse rate	20 pps	Field of view	3 mrad
Average power	600 mW	Optical bandwidth	20 Å FWHM
Beam divergence	1.0 mrad FW	Range resolution	75 m
Polarization	4° ± 5° linear to magnetic north		

Table 2. Measured parameters of the mesopause over Fort Collins in springs 1990 and 1991

Date	Time UT	Abundance [10^9 cm^2]	Centroid km	Mesopause Height [km]	Mesopause Temperature [K]
3/03/90	4:10–7:30	4.8	93.3	87.8	185.1
	7:31–11.02	5.4	92.7	98.9	191.2
3/11/90	5:22–12:43	7.7	91.1	98.6	197.6
3/17/90	3:07–7:36	3.5	92.1	88.9	186.8
4/17/90	4:18–6:10	5.1	92.5	85.7	167.7
	8:55–12:24[a]	4.2	92.7	92.3	187.2
2/25/91	8:51–12:39	5.4	93.0	100.7	179.6
2/26/91	7:31–11:09	11	92.3	97.9	193.9
3/14/91	8:55–12:34[b]	5.7	92.0	99.7	183.4
3/18/91	6:49–12:43	4.3	92.0	99.5	205.2
3/19/91	4:47–7.30	3.5	92.8	89.8	188.3
	7:31–12:39	4.0	92.8	101.6	180.2
3/21/91	3:58–8:46	4.4	92.9	87.1	191.7

[a] No data between 10:05 and 11:13, UT
[b] No data between 9:52 and 11:36, UT

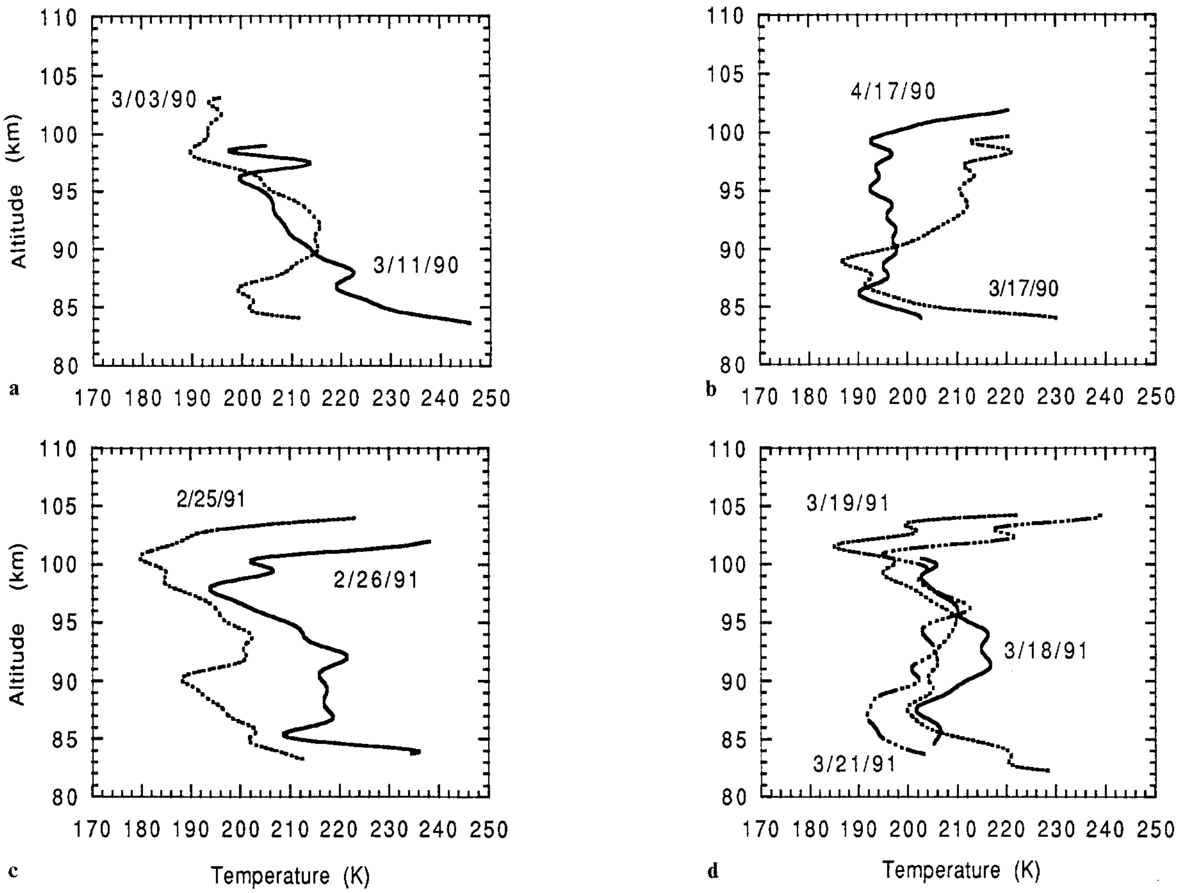

Fig. 2a–d. Nightly average temperature profiles in the mesopause region over Fort Collins, CO (40.6° N, 105° W), **a** for March 3, and 11, 1990; **b** for March 17, and April 17, 1990; **c** for February 25 and 26, 1991; **d** for March 18, 19, and 21, 1991. The temperature profiles are terminated at altitudes where the average Na density is 5% of the corresponding peak value

Gardner of Illinois [12] in March-April, 1990, and (2) a simultaneous co-located airglow/lidar temperature measurements in February-March 1991 with B. Lowe's group of Western Ontario. As a result, four nights of temperature and Na density profiles in 1990 and five nights in 1991 with a total of some 2600 profiles were taken. Since there are at least 4 hours of observation each night, meaningful nightly average can be taken. Figures 2a–2d show the nightly average profiles with a spatial resolution of 1 km for the springs of 1990 and 1991. The wave structure is quite evident even though more than 4 hours of average have been taken for each profile. The characteristics for the profiles of these nine nights along with those taken on March 14, 1991, for a period of two hours are summarized in Table 2 for clarity and comparison. The column abundance ranges from 3.5×10^9 to $1.1 \times 10^{10}\,cm^{-2}$ and the centroid of the Na layer is located between 91.1 and 93.0 km as expected [3]. The temperature profiles are terminated arbitrarily, but conservatively, at altitudes where the average Na density is 5% of the corresponding peak value. Since the Na profiles rise more quickly at the bottom and drop slower in the top, the temperature profiles terminate at varied heights near the layer top as shown in Fig. 2. In general, the mid-latitude spring temperatures in the mesopause region clusters between 190 K and 220 K; they are warmer than the late summer values by about 20 K [8]. Other than the range of comparable temperatures, the temperature profiles show considerable variability. This is due to the prevailing wave activity in the mesopause region. Comparing the profiles of February 25, 1991, to that of February 26, 1991, for example (Fig. 2c), one sees similar wave perturbation, yet in one day the Na layer is lowered by 1 km and the average temperature is raised by 20 K across the entire mesopause region. For those nights where enough data were taken both before and after the midnight, we treat them separately in Table 2. The mesopause temperature is seen to range from 168 to 205 K. We note that the mesopause heights are around either 88 km or 99 km in altitude. It is near 88 km for data taken before the midnight (7:00 h, UT), and near 99 km for data taken after the midnight. This agrees with the high mesopause of late August 1989, which was deduced from data taken after the midnight [8]. More data should be taken to check this assertion and to evaluate its geophysical implications.

To investigate the temporal variation through the night, we prepared Figs. 3, 4, and 5. The temperature at the centroid averaged over 15 min and ±2.5 km, termed the centroid temperature, is plotted as a function of time, in UT, in Fig. 3. Shown in Figs. 4 and 5 are, respectively, the corresponding Na column abundance and centroid. There are strong perturbations in the centroid temperature in March 11, 1990, and March 18, 1991, as high-lighted in Fig. 3a and respectively. Temperature changes of more than ±30 K are seen in a time scale of 15 min. Ignoring these sharp variations, the centroid temperature for six out of the nine nights shows a

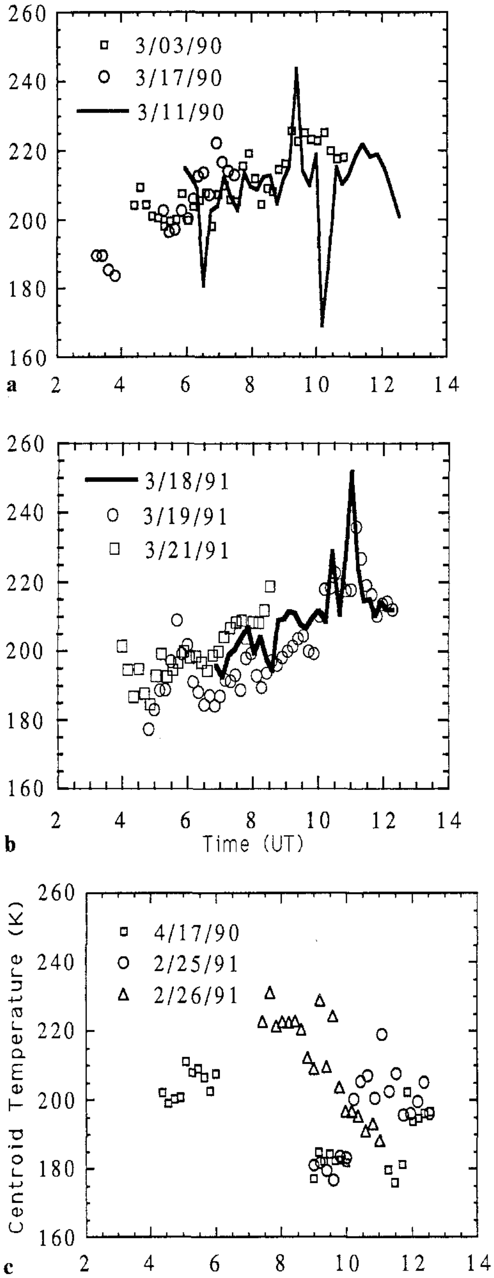

Fig. 3a–c. Temporal variations of centroid temperature as a function of time, in UT. **a** for March 3, 11 and 17, 1990; **b** for April 17, 1990, and February 25 and 26, 1991; **c** for March 18, 19, and 21, 1991. The centroid temperature here is the average temperature at the centroid over 15 min and +2.5 km. High-lighted are profiles for March 11, 1990 and March 18, 1991, which show unusually strong perturbations in the centroid temperature in a short time scale (15 min) with temperature changes of more than ±30 K. Ignoring these sharp variations, the centroid temperature shows a gradual increase of about 3 K/h for the six nights shown in **a** and **c**

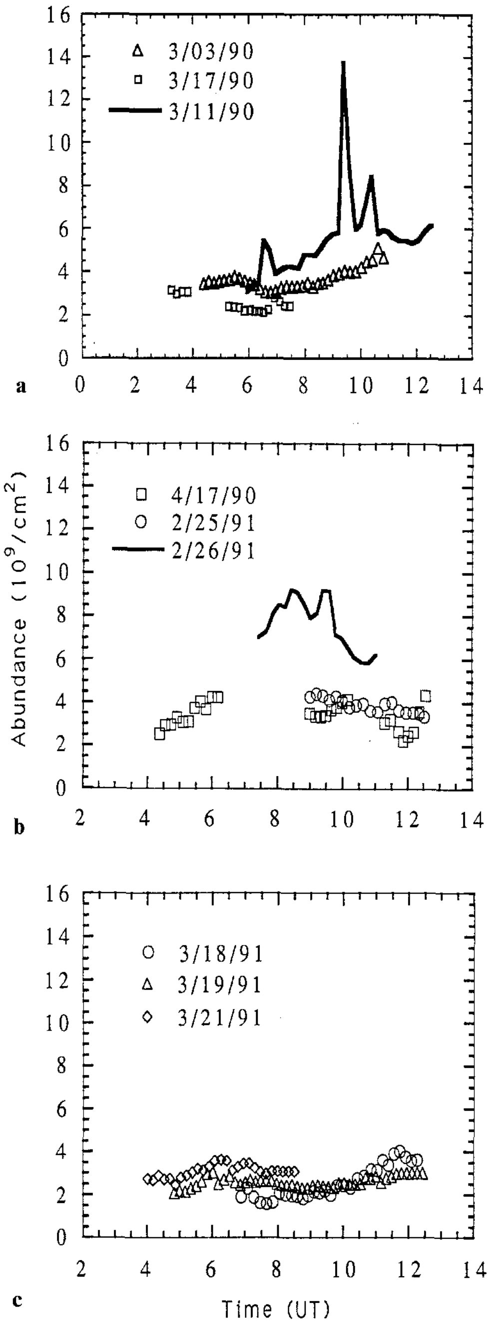

Fig. 4a–c. Temporal variations of Na column abundance as a function of time, in UT. **a** for March 3, 11 and 17, 1990; **b** for April 17, 1990, and February 25 and 26, 1991; **c** for March 18, 19, and 21, 1991. High-lighted are profiles for March 11, 1990 and February 26, 1991, which show unusually strong variation in column abundance. Ignoring these large variations, the Na abundance varies mildly between 2 to 4×10^9 cm^{-2}

gradual increase of about 3 K/h, Fig. 3a and c. In the case of column abundance, we note unusual variations in March 11, 1990, Fig. 4a, and in February 26, 1991, Fig. 4c. In March 11, 1990, there are sharp increase in Na abundance up to a factor of 2.5 in a 15 min time scale, while in February 26, the Na abundance first increases by a factor of two and then decreases to its original value in 5 h. Ignoring these large variations again, the Na abundance varies mildly between 2 to 4×10^9 cm^{-2}. Two very different data sets (March 11, 1990 and March 18, 1991) are again high-lighted in Fig. 5a and c, where the centroids are plotted as a function of time. Between 7:00 h and 12:00 h, the centroid of March 11, 1990, is lowered steadily by 2 km while that of March 18 is nearly constant, yet both data sets show huge centroid tempera-

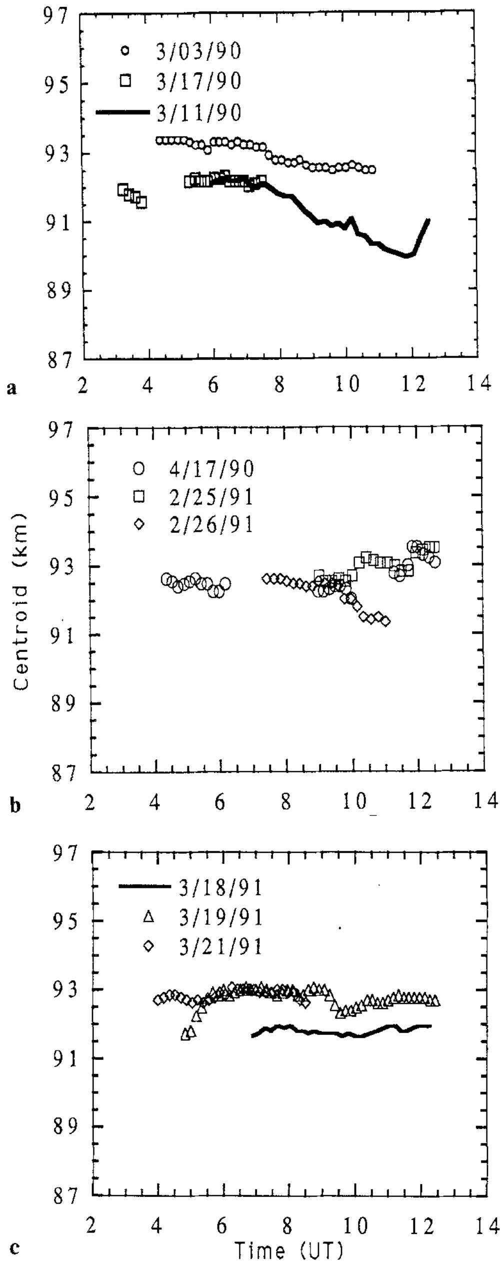

Fig. 5a–c. Temporal variations of the centroid height as a function of time, in UT. **a** for March 3, 11 and 17, 1990; **b** for April 17, 1990 and February 25 and 26, 1991; **c** for March 18, 19, and 21, 1991. Highlighted are profiles for March 11, 1990 and March 18, 1991. Between 7:00 h and 12:00 h, the centroid of March 11 is lowered steadily by 2 km while that of March 18 is nearly constant. Ignoring the data points of March 11, 1990 after 7 h, most centroids remain nearly constant through the night

ture variations in a short time scale (15 min). Ignoring the data points of March 11, 1990, after 7 h the average centroid location remains nearly constant through the night.

The dynamics in the mesopause region on March 11, 1990, as observed by the Colorado State Na Temperature Lidar, is unusually rich and appears to be very interesting. There exists an unusual gradient in nightly average temperatures with the top being 40 K cooler than the bottom of the Na layer as can be seen in Fig. 2a. An unusually steady dropping of the centroid, 2 km in 5 hs, is also seen, Fig. 5a. There exists in this night strong perturbations in the short time scale (15 min) in both centroid temperature and Na abundance in a correlated manner, as shown in Figs. 3a and 4a. Near 6.3 h, 9.4 h, and 10.2 h, respectively, the centroid temperature is increased by −30 K, +35 K and −45 K. At the same instants, the Na abundance is increased by 2×10^9, 8×10^9, and $2 \times 10^9\,\mathrm{cm}^{-2}$, respectively. These correlated strong short time variations suggest the presence of advective disturbances. On the other hand, no corresponding variations in Na abundance accompanies the strong short-time-scale perturbations observed in the centroid temperature of March 18, 1991. Temperature enhancements of long period gravity events of tidal origin have been noted recently with data from a giant Rayleigh lidar facility [13]. Indeed, the difference in mesopause heights before and after midnight as noted in Table 2 may be of tidal origin. Detailed analysis of these sets of lidar data in terms of gravity wave parameters in the mesopause region [10] should be interesting and will be pursued. The richness in new geophysical information obtainable from a Na temperature lidar, such as ours, is self-evident.

3 Conclusion

On irregular basis, the new Colorado State Na Temperature Lidar has been used to investigate temperature variations and gravity wave perturbations in the mesopause region over Fort Collins, CO. The initial temperature profiles have demonstrated beyond doubt that this lidar system is reliable and it can produce high quality data that match the richness of geophysics in the mesopause region. Starting June 1991, this lidar system is being operated on regularly basis for a systematic study to develop the climatology of the mesopause over Fort Collins, CO.

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