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Thermal structure of the winter middle atmosphere observed by lidar at Thule, Greenland, during 1993–1994

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Abstract—Lidar measurement of the atmospheric temperature in the 30–70 km height region have been carried out from Thule, Greenland, through winter 1993–1994, with increased frequency during January 1994. The lidar profiles are in agreement with radiosonde measurements in the overlapping region. Comparison of the lidar data with the CIRA model indicates that the January temperature is consistently below the model value throughout the middle stratosphere. The profiles show large variability, as expected for the high latitude winter middle atmosphere. The evolution of the temperature has been related to minor warming events. The stratopause height and temperature vary considerably during the evolution of the phenomenon. The temperature variations in the stratosphere and mesosphere appear to be negatively correlated. Two 'quiet layers' are observed, and their altitudes correspond to the extrema and the nodes of Quasi-Stationary Planetary Wave 1. This confirms the prominence in January 1994 of the Planetary Wave 1 oscillations in the middle atmosphere temperature variations during winter at high latitudes. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

The high latitude middle atmosphere is particularly disturbed in winter; the winter warmings are amongst the large disturbances, which perturb the thermal structure of the stratosphere and mesosphere. These disturbances are associated to the vertical propagation of planetary waves, thus dynamically coupling the troposphere and the middle atmosphere. The vertical propagation of the planetary waves is allowed by the westward circulation associated to the winter polar vortex (see Schoeberl, 1978; Labitzke, 1981). The strongest disturbances, called major warmings, produce the break-up of the polar vortex, with the increase of the temperature along the meridian toward the Pole, and the reversal of the zonal winds. Weaker disturbances, called minor warmings, have a reduced hemispheric impact and are not able to modify the winter circulation substantially. A large increase of the middle and upper stratospheric temperature is generally associated with the warming events; correspondingly a decrease of the mesospheric temperature occurs. In the lower stratosphere a consistent increase of the temperature is observed during major warmings, while a small perturbation is expected during minor warmings.

Studies of the winter middle atmosphere have been conducted in the past mainly by means of rockets and satellite data. Lidar measurements of the temperature profile in the absence of aerosol are currently used at mid-latitudes. This paper reports observations by a ground-based Rayleigh lidar of the thermal structure of the high latitude middle atmosphere: the data show that a detailed study of the temperature in the 30–70 km height range is possible at a reduced cost, with respect to rocket measurements, with a good temporal resolution, even with a simple, relatively low-power lidar instrument.

LIDAR SYSTEM

The results reported here were obtained with a lidar in Thule, Greenland (76°32′N, 68°47′W). The lidar was originally set up for lower stratospheric aerosol measurements. The transmitter is based on a two-stage Nd-YAG laser with a second harmonic generator emitting at 532 nm, a repetition rate of 4 Hz, and an energy of 300 mJ per pulse. The beam is sent vertically through a beam expander, with an outgoing divergence of 0.15 mrad. The receiver includes a 0.8 m diameter Cassegrain telescope and a photon counter. A rotating disk (chopper) protects the photomultiplier from overloading due to the intense signal from the lowest levels.

The signal is recorded in 1024 successive channels, each temporal bin being of the duration of 1 μs. Successive profiles are added to improve the signal-to-noise ratio, with a 30 min integration period. Subsequently the 30 min profiles have been added together, thus obtaining an integration time equal to the full duration of the measurement.

TEMPERATURE RETRIEVAL

The backscattered signal is collected into height bins of thickness $\Delta z = 150$ m. The number of counted photoelectrons is corrected for the discriminator dead-time, and the background is subtracted. The relative density of the layer at height z_i is then calculated:

$$d_{\mathrm{rel}}(z_i) = N(z_i) z_i^2 e^{2\tau(z_i, z_1)} \tag{1}$$

where N is the number of counts, z_1 is the lowest level where the temperature is calculated, and $\tau(z_i, z_1)$ is the optical depth of the layer in the height range (z_1, z_i). The optical depth (< 0.0025 between 35 and 75 km) is calculated by taking into account the Rayleigh scattering from the molecular atmosphere and the ozone absorption, using suitable atmospheric models.

In the absence of aerosols, the relative density is directly proportional to the molecular air density:

$$\rho(z_i) = K d_{\mathrm{rel}}(z_i) \tag{2}$$

where K, denoted as the lidar constant, accounts for pulse energy fluctuations, receiver efficiency, and extinction in the height range $(0, z_1)$. Normalization of the data at 36 km with the CIRA 1986 model (Barnett and Corney, 1985) yields the value of the lidar constant.

A running average on the relative density profile is carried out in order to smooth the final temperature curve, degrading the vertical resolution to 4.5 km.

The temperature, T, is computed assuming that the atmosphere obeys the perfect gas law and is in hydrostatic equilibrium, with the method described by Hauchecorne and Chanin (1980) and Jenkins *et al.* (1987):

$$T(z_i) = \frac{M g(z_i) \Delta z}{R \ln(1 + x)} \tag{3}$$

where R and M are the perfect gas constant and the mean molecular weight, respectively, $g(z_i)$ is the acceleration due to gravity at height z_i,

$$x = \frac{d_{\mathrm{rel}}(z_i) g(z_i) \Delta z}{\dfrac{p_2}{K} + \sum_{j=i+1}^{i_2} d_{\mathrm{rel}}(z_j) g(z_j) \Delta z}, \tag{4}$$

p_2 is the pressure at height $z_2 = z_{i2}$ obtained from the CIRA model, and z_2 is the altitude of the highest level where the temperature is calculated.

We have conservatively chosen $z_1 = 32$ km, being the aerosol confined to the underlying layers; z_2 is taken at the level where the signal-to-noise ratio reduces to 2.5.

The use of a model only affects the result through the ratio p_2/K in equation (4). This influence decreases with decreasing height, as the sum in the denominator increases, and the retrieved temperature becomes almost independent from the model used about 10 km below z_2. A reasonable doubt exists about the reliability of the measurements in the upper part of the profiles, since the signal-to-noise ratio decreases and the p_2/K value affects the result considerably. In what follows, however, the entire profiles are shown, since their sequence produces a coherent evolution; sensitivity tests indicated that even for a $\pm 5\%$ variation of p_2 the T curve remains within the measurement error, σ.

RESULTS

Thirty-two data sets, corresponding to a total of 94 h of observations, were collected between November 1993 and March 1994. More than half of the profiles were obtained during two weeks in January.

The data are shown in Fig. 1, together with the radiosonde temperatures measured on the same location (not always simultaneously) by the Danish Meteorological Institute (DMI). The $T \pm \sigma$ profiles are also displayed. For comparison, the CIRA model for the month (linearly interpolated for latitude) is also depicted. The maximum altitude in the derived temperature profile depends on the integration time, the background noise and the possible presence of clouds in the troposphere. Agreement between lidar and radiosonde temperatures is generally good when radiosonde data reach altitudes above 32 km, and the two profiles appear easily joinable even when the balloon data stop at heights as low as 25 km.

The measured temperatures show a large variability, as expected for the winter middle atmosphere at high latitudes (e.g. Labitzke, 1981). Part of the observed variations may be attributed to relatively fast transient phenomena like gravity waves, in some cases detected from the analysis of the lidar-derived density profiles.

Some features of the temperature profiles may be related to the dynamical evolution of the stratosphere and mesosphere. Naujokat *et al.* (1994) reported a detailed description of the evolution of the dynamical circulation in the middle atmosphere during winter 1993–1994: no major warming occurred, but several minor warming events took place. The strongest

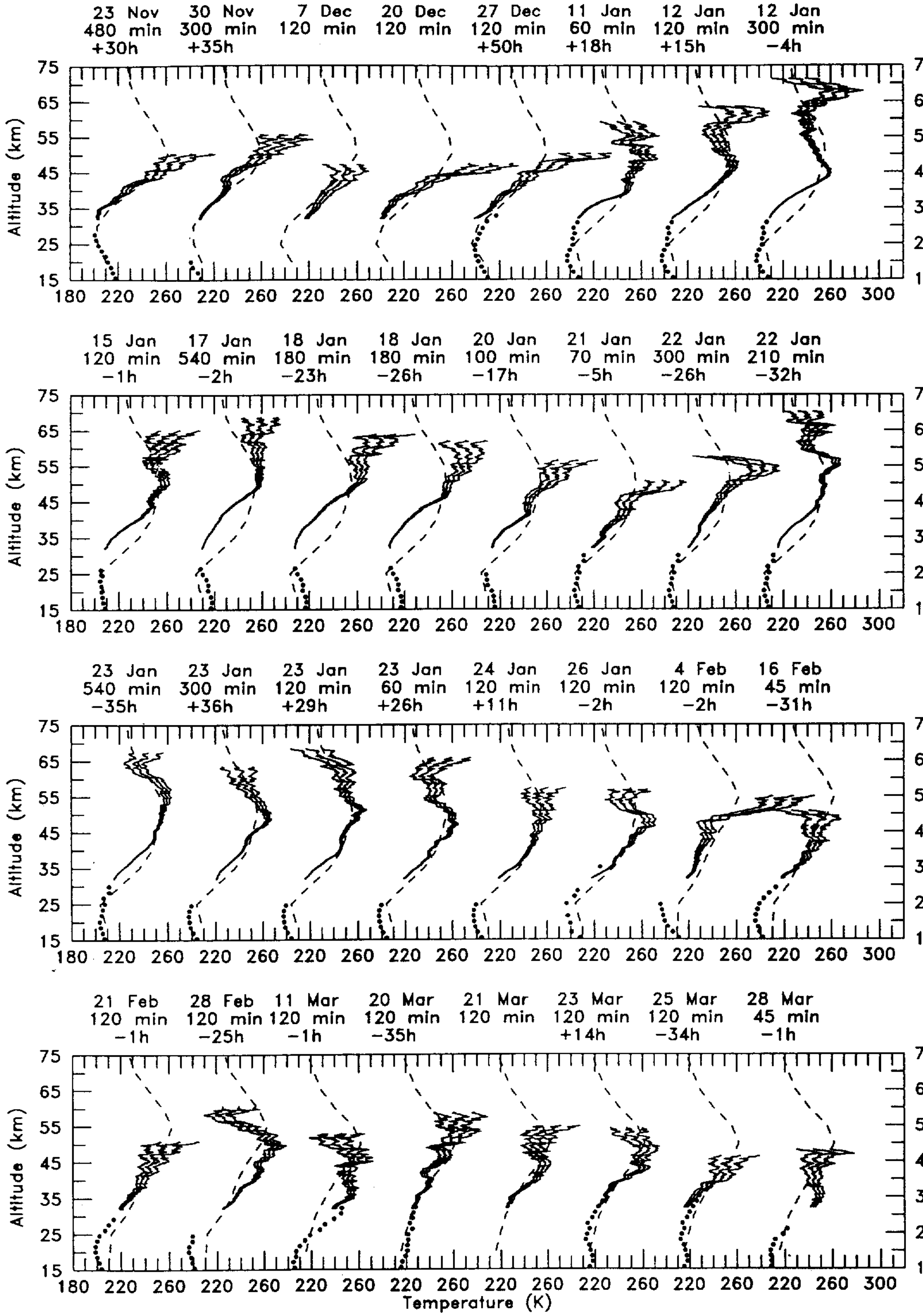

Fig. 1. Temperature profiles for winter 1993–1994. The $T \pm \sigma$ curves are also shown. The dashed line represents the CIRA model for the month. The dots in the lower part are the closest in time radiosonde's data (omitted if the elapsed time between lidar measurement and radiosonde is more than 50 h). Below the date the integration time in min and the time difference between the lidar and the radiosonde measurements are reported.

minor warming was recorded in late December–early January, and other pulses occurred during January, mainly over northeastern Asia, Alaska, Canada (a weaker warming occurred over Europe around 14 January 1994), and also over Europe in February. Two pulses in early and late March led to the final reversal of the temperature gradient between 60°N and 90°N, and to the break-up of the polar vortex, that took place in April.

Some indications of the strong minor warming of late December may be obtained from the profiles of 20 and 27 December 1993, when temperatures as high as 280K were observed at 40–50 km.

Intensive observations were carried out between 11 and 26 January 1994. Unfortunately, weather conditions prevented measurements on 13 and 14 January, in correspondence with the European warming. However, large temperature changes were recorded in the stratosphere and the mesosphere above Thule both before and after these days. Between 32 and 40 km the temperature was always quite low in the period 11–24 January, reaching 25K below the CIRA values. An intensive cooling took place in the upper stratosphere (30–50 km) between 11 and 18 January: on 11 January temperatures lower than the CIRA were encountered below 40 km, and below 47 km on the 18th. On 20 January at these altitudes the temperature started to rise again, and values close to the CIRA were reached on 24 January. The stratopause was located at 44 km on 12 January and at 56 km 10 days later. In the height region 50–65 km a progressive warming occurred from 12 to 22 January; 275K was reached at 55 km on 20 January, and 283 K at 52 km on 22 January. On 17 January, T was approximately constant between 47 and 65 km; a positive vertical gradient of T was observed throughout the 32–60 km height range on 18, 20 and 21 January. A distinct stratopause, warmer than indicated in the CIRA model, reappeared on 22 January. The stratopause altitude decreased on the following day (four profiles), its temperature still higher than the CIRA. On 24 January the T profile followed the CIRA model approximately. As shown more clearly later, in the period 11–18 January a cooling took place between 35 and 45 km, while a warming was observed above 50 km. The lower stratosphere (at radiosonde heights) also warmed up in the same period. The upper stratosphere thus appears to be anticorrelated to both the lower stratosphere and the mesosphere.

After 26 January the soundings were obtained discontinuously; remarkable features in the 50–60 km height region were observed on 4 February ($T = 295$K at 53 km) and 28 February ($T = 220$K at 58 km). Indications of a warm mid-stratosphere appeared on 11 and 28 March, corresponding to the two warming pulses of early and late March reported by Naujokat *et al.* (1994).

Temperature changes of opposite sign in the stratosphere and mesosphere, reported in the past (Labitzke, 1972b; Houghton, 1978), and observed by lidar at mid-latitudes (Hauchecorne and Chanin, 1983), appear also in Fig. 2. This figure shows the evolution of the temperature at fixed altitudes for the period 11–27 January. The data for the three lowest layers are obtained from the European Centre for Medium-range Weather Forecasts (ECMWF), and are relative to the 50 mbar, 30 mbar isobaric surfaces and 700K potential temperature level, corresponding respectively to approximately 19, 23 and 27 km. The data for the other layers are obtained from the lidar data. The average T for each level is indicated.

Oscillations of period approximately equal to the time window of the observations (15 days) appear at all levels; four different layers are identified:

- layer 1, between 20 and 27 km, with a temperature maximum around 19 January and minima at the extremes of the time interval.
- layer 2, 35–45 km, with a minimum around 18 January and maxima around 11 and 26 January; this layer is thus approximately 180° out of phase with layer 1.
- layer 3, corresponding to the stratopause region (50–55 km), is approximately 90° out of phase with layer 2.
- layer 4, 57–65 km, is approximately 90° out of phase with layer 3, thus almost 180° out of phase with respect to layer 2 and approximately in phase with layer 1.

Two 'quiet layers' can also be identified at levels 32.6 km and 47.6 km. The identification of the altitude of the first 'quiet layer' is uncertain, since lidar derived T values are obtained only above 32 km, and the closest available ECMWF data are relative to 27 km.

The existence of 'quiet layers' in the middle atmosphere, i.e. height regions where the atmosphere does not experience wide T variations, while the levels below and above show evident oscillations, has been emphasized by Offermann *et al.* (1987) and Bittner *et al.* (1994). They describe the temperature variations of the winter atmosphere as harmonic oscillations: the same periods apply to all height levels, but amplitude and phase differences for each harmonic apply to different levels. At certain levels the amplitude of the oscillations reduces to zero and the phase changes abruptly. Offermann *et al.* (1987) ascribe this peculiarity to the nodes of standing waves. Bittner *et al.*

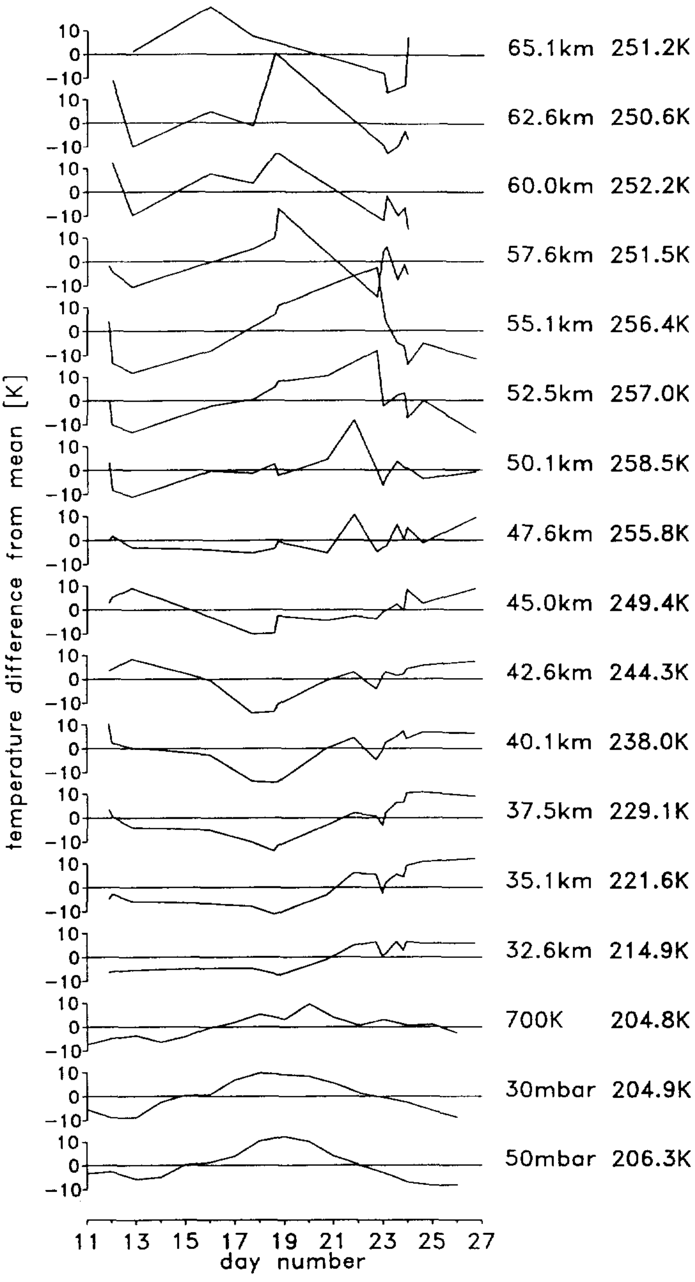

Fig. 2. Temperature variations at fixed height levels, as measured by lidar, for 11–27 January 1994. Also shown are the lower stratosphere values at the 50 and 30 mbar pressure surfaces and at the 700K potential temperature surface. The rightmost number is the mean temperature at each level.

(1994) show that the quiet layers generally correspond to the regions where the CIRA Quasi-Stationary Planetary Wave No. 1 has zero T amplitude (type 1 quiet layer) or has a minimum or a maximum (type 2 QL). For Thule (69°W) the CIRA type 1 quiet layer is located between 45 and 50 km, and the type 2 quiet layer at ~ 35 km. The observed values of 32.6 and 47.6 km are thus in agreement with the CIRA model and with the attribution of prominence to Planetary Wave No. 1. This seems to be consistent with the data of Naujokat *et al.* (1994), indicating that in this period the Planetary Wave No. 1 is dominant. By adding the

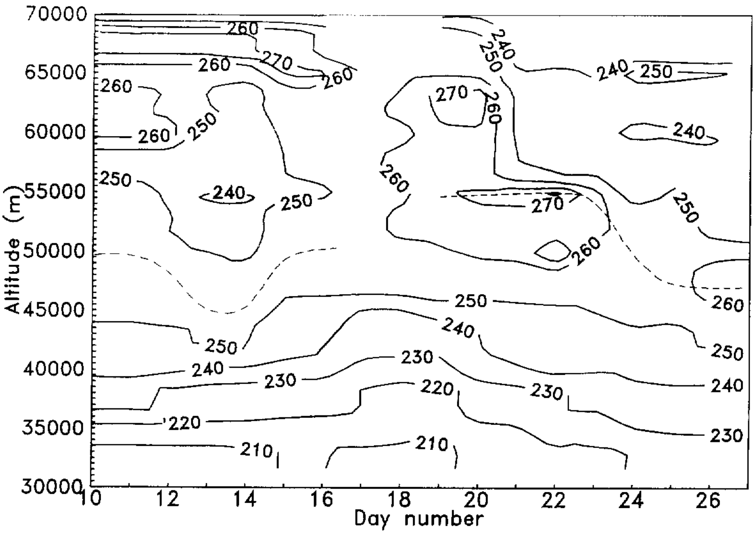

Fig. 3. Time–height temperature contour map for the two-week period of intensive measurements in January. The thin dashed line indicates the height of the stratopause.

quiet layers observed at Thule to the graph obtained for the DYANA campaign at high latitudes (Bittner *et al.*, 1994; Fig. 17b, altitude levels of quiet layers vs longitude), a more consistent pattern is obtained.

Figure 3 shows the evolution of the temperature as a function of time and height in the period 11–26 January. The thin dashed line indicates the position of the stratopause as derived from the T profiles; when the T profile did not show a definite maximum, i.e. between 18 and 20 January, this line was interrupted. The most relevant features are the large variations of the stratopause height (from approximately 45 km on 13 January to 57 km on 20 January) and temperature (from 255K to 282K); these variations seem to be related to the 15-day period of the oscillations shown in Fig. 2, i.e. to the evolution of the planetary waves. Naujokat *et al.* (1994) show that an increase of the Stratospheric Sounding Unit radiances on channels 26 and 27 (corresponding to pressure levels of approximately 4 and 1.7 mbar, respectively) over the North Pole was observed between 18 and 25 January; they reported also an increase of the zonal mean temperature at 30 mbar between 14 and 19 January, and easterly zonal mean winds between 4 and 18 January northward of approximately 75°N at 30 mbar. These observations indicate that the evolution of the temperature profile over Thule is the result of phenomena acting on a relatively large scale, including a small minor warming event in mid-January.

After the strong mesospheric warming of 17 and 18 January, the stratopause region appears to be split in two maxima, the more pronounced being at higher altitude. A similar pattern was observed by Offermann *et al.* (1987) during a minor warming event in November–December 1980, from measurements carried out at ESRANGE and Andøya (69°N) in connection with the Energy Budget Campaign.

It is known that sudden stratospheric warmings are associated with the vertical propagation of planetary waves: the warming has been observed to proceed from the upper mesosphere toward the lower stratosphere, producing large changes in the altitude and temperature of the stratopause (Labitzke, 1972a Labitzke, 1981; Schoeberl, 1978). After a warming in the upper stratosphere the temperature has often been observed to be constant with height. Figure 3 shows that high temperatures are at first encountered in the mesosphere (see the large T increase between 60 and 70 km on 12 January in Fig. 1) and progressively propagate downward, eventually producing the large warming in the stratopause region of 21 and 22 January. After a large warming, the stratopause cools (by approximately 20K acclimation within 24 h) and descends. Figure 3 may be compared with Fig. 12 of the paper by Labitzke (1972a), where the time–height evolution of the temperature for a major mid-winter warming is shown. Several differences appear: the major warming phenomenon covers a longer time period (approximately 45 days), with the maximum occurring approximately 15 days after the large stratopause maximum ascent. Higher temperatures, exceeding 300K, are expected at the stratopause level during major warmings; moreover, a larger influence of the warming is observed also in the lower strato-

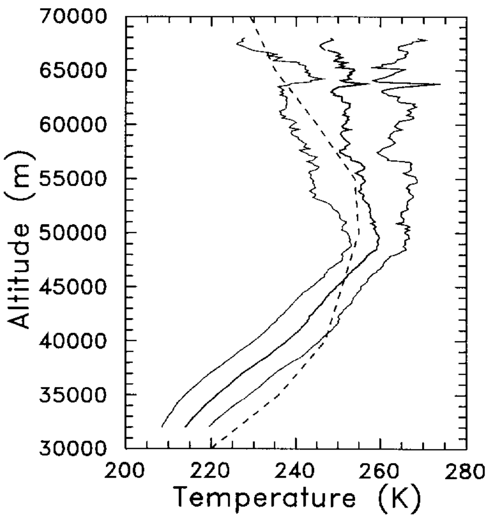

Fig. 4. Mean temperatures ($\pm\ \sigma$) for 11–26 January 1994, compared with the CIRA 1986 model values (dashed line) for January.

sphere. No evidence of a constant T profile before the peak of the warming was found.

The mean temperature profile for the month of January is shown in Fig. 4, together with the ± 1 standard deviation of the temperature variations. The large value of the standard deviation is due to the great variability of T described above. The CIRA model is included for comparison. Note that the monthly mean is lower than the model below 40–45 km, and the difference between the two curves exceeds the standard deviation of the mean. This difference may be attributed to the absence of major warmings and possibly to the intense cooling of the middle and upper stratosphere observed around 18 January. The stratopause and the region above 55 km appear to be warmer than the CIRA values.

CONCLUSIONS

The evolution of the temperature in the middle atmosphere above Thule, Greenland, has been studied with a ground-based Rayleigh lidar during winter 1993–1994. The obtained values are in general agreement with radiosonde measurements reaching 32 km. Intensive lidar observations were carried out mainly in the period 11–26 January 1994. The temperature profiles showed a large variability, and on occasions the vertical gradient above 50 km was found to be positive. A rapid and consistent change in the stratopause altitude occurred in connection with a minor warming event, reported over Europe around 14 January. The warming of the stratosphere was associated with a cooling of the mesosphere. Two quiet layers, i.e. altitudes where the variations of the temperature are small compared with the overlying and underlying regions, have been identified. These quiet layers correspond to the regions of minimum variability of Quasi-Stationary Planetary Waves No. 1 of the CIRA 1986 model. A comparison of the January average profile, as well as the single profiles, with the model shows that low temperatures were encountered in the middle stratosphere, and high temperatures in the mesosphere.

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