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First mesopause temperature profiles from a fixed southern hemisphere site

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Abstract. The INPE sodium lidar was recently modified so as to enable measurements to be made of the Doppler temperature of the Na atoms in the atmospheric sodium layer. Measurements have been made on a total of 15 nights from July to October, 1998, providing temperature profiles between heights of about 83 and 105 km. Almost all measurements showed a mesopause temperature structure strongly perturbed by oscillations which appear to be caused by gravity waves and/or tides, with peaks in sodium density occurring at almost the same height as the temperature maxima on the bottom side of the sodium layer. The lowest temperatures, between 170 and 200 K, typically occur above 100 km, and the average profile for all our measurements is similar to the winter profile seen at mid-latitudes, with a mesopause temperature of 190 K at 103 km.

Introduction

Over the past few years our knowledge of the temperature structure of the mesopause region has been greatly improved by lidar measurements of the Doppler temperature of metallic atoms of meteoric origin in the 80 - 110 km region. Before the development of Doppler lidar, only rocket-based techniques provided profiles with good height resolution, limiting the measurements to a small number of specific experimental campaigns (see, for example, *von Zahn and Meyer*, 1989). Although limb-scanning satellite measurements have the advantage of global coverage, they have limited height resolution and, at least until recently, have not covered the upper part of the height range in question. The most extensive climatological data set available, from the SME satellite [*Clancy and Rusch*, 1989] has a height resolution of 4 km and does not extend beyond 92 km. The Doppler lidar technique, using scattering from sodium, iron or potassium atoms, has made it possible to make long-term measurements up to about 110 km with better than 1-km height resolution, leading to a greatly improved knowledge of the climatology of this region of the Earth's atmosphere (see, for example, *Yu and She*, 1995). On the basis of such observations it has been found that the temperature structure of this part of the atmosphere is significantly different to that previously accepted from rocket measurements. Extensive lidar measurements of the mesopause temperature structure have been made at mid-northern latitudes by a number of workers (*Senft et al.*, 1994; *Yu and She*, 1995; von *Zahn and Hoffner*, 1996; *She and von Zahn*, 1998), but the only observations reported from low latitudes and from the southern hemisphere up till now are from a shipboard campaign by *von Zahn et al.* [1996]. In this paper we report the results of Doppler temperature measurements made at São José dos Campos (23° S, 46° W) between July and October, 1998.

Experimental technique

Although the measurement of the Doppler broadening of the hyperfine structure of the D2 sodium line was first demonstrated 20 years ago by *Gibson et al.* [1979], it is only during the past decade that the technique has been used to obtain routine measurements. Lidars designed for this sort of measurement normally use a rather sophisticated laser system to generate a single line output which is used to probe the hyperfine structure of sodium or other metal. This typically involves the use of a single-frequency CW ring laser followed by suitable pulsed amplifiers, with a total cost of around US$ 400,000 (see, for example, the system used by *She et al.*, 1992). This high cost is, no doubt, the main reason for the small number of locations using the technique. To overcome the cost problem we decided to adopt a technique which, although less efficient, is very much cheaper. This technique, which has been described *by Clemesha et al.* [1997], uses a fairly simple modification to the dye laser transmitter of a sodium lidar to produce a multi-line output consisting of a comb of narrow lines spaced by 1.98 pm. This spacing is exactly equal to the separation of the two groups of hyperfine lines in the sodium D2 line spectrum.. By changing the gas pressure in the Fabry-Perot interferometer which produces this line structure, it is possible to switch between a laser output where the lines exactly coincide in wavelength with the Na D2 hyperfine lines, and one where the central laser line is exactly equidistant from the D2 lines. Using an automatic pressure control system, it is possible to switch between the two wavelengths in a few seconds.

Following *Clemesha et al.* [1997], the lidar response, $R(\lambda_o-\lambda_l)$, from sodium atoms for an emission of this sort is given by

$$R(\lambda_0-\lambda_1)=C\frac{1}{\sqrt{\Delta}}\sum_{n=-\infty}^{n=\infty}\left\{\left[A\exp-\frac{(\lambda_0-\lambda_1-nS)^2}{\Delta^2+\delta_1{}^2}+B\exp-\frac{(\lambda_0-\lambda_2-nS)^2}{\Delta^2+\delta_1{}^2}\right]\left[\exp-\frac{(\lambda_0-\lambda_1-nS)^2}{\delta_2{}^2}\right]\right\} \quad (1)$$

Where C is a constant, λ_o the center wavelength of the laser, S the line spacing, δ_1 the 1/e half bandwidth of each laser line, δ_2 the 1/e half bandwidth of the envelope of the laser spectrum, $\Delta^2 = 2kT\lambda^2/mc^2$, k is Boltzmann's constant, T the temperature and m the mass of the sodium atom, c the velocity of light, and A and B are proportional to the strengths of the D2a and D2b hyperfine components, centered on λ_1 and λ_2 respectively. Note that S is made equal to λ_1 - λ_2 The maximum response occurs when $\lambda_o = \lambda_1$, and as a first approximation we assume $\delta_2 >> S$, so that the first minimum occurs when $\lambda_o = (\lambda_1 + \lambda_2)/2$. It is then a simple matter to compute the ratio between the on-line and off-line responses. This ratio is a sensitive function of temperature, changing from a value of 2.3 at 230 K to 3.9 at 170 K, making it possible to determine the temperature from the experimentally determined ratio. The main disadvantage of this technique, when compared to the single frequency method used by other workers, is that much of the laser energy is wasted in lines which have little or no interaction with the atmospheric sodium atoms. Apart from its simplicity and low cost, a minor advantage of the technique is that maximum response always corresponds to the situation where the laser emission is exactly centered on the D2 hyperfine lines, and the minimum response always corresponds to that where the central laser line is located exactly mid-way between the

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centers of gravity of the two hyperfine line groups. This means that tuning for maximum or minimum response is independent of the temperature of the sodium atoms, which is not the case for a single frequency laser.

Ideally, the on-line and off-line responses would be measured simultaneously, but in practice this is not possible. In general our measurements were made in a 3 minute cycle, with 200 laser shots on-line being followed by 500 shots off-line. The larger number of off-line shots compensates for the reduced off-line signal. The data were then low-pass filtered and interpolated at constant intervals to give time-coincident estimates of the on-line and off-line signals. The filter cut-off used depends on two factors. Poor signal to noise ratio, resulting from low atmospheric transmission, makes it necessary to increase the averaging period to compensate for high statistical noise. Rapid variations in sodium density, caused by strong short-period gravity wave activity, also mandate the use of longer averaging periods to prevent such variations from producing false variations in the derived temperature. As a result of these two effects it was frequently necessary to use filter cut-off periods as high as 1 hour although, under good conditions, it was sometimes possible to use values as low as 10 min. Variations in the transmission of the lower atmosphere were compensated in the usual way by normalizing the sodium layer signal to the Rayleigh scattering signal from the 35 km to 45 km height range (*Bowman et al.,* 1969). The INPE lidar uses a dye laser tuned to 589 nm producing 300 mJ pulses at 5 pps. The receiver has an area of 0.38 m^2, a quantum efficiency of 2%, and a height resolution of 250 m.

The precision of the measurement is influenced by a number of factors including shot noise and geophysical noise, as discussed above. Major contributions to the errors in the absolute temperature come from uncertainties in the bandwidths of the individual laser lines and their envelope function, and in the center wavelength of the envelope. Since all these quantities must be known in order to convert the measured on-line/off-line ratios to temperatures, the uncertainties result in temperature errors. This systematic error is not strongly dependent on temperature, so the main effect is a displacement of the entire profile. Space limitations prohibit a detailed discussion of these effects, but we estimate that, under good conditions, the net result is an uncertainty of about $\pm$ 7 K in the absolute temperatures, and $\pm$ 2 K in the relative temperatures when the data are averaged over about 10 minutes.

Results

Figure 1 shows a temperature profile for August 19, 1998, using data obtained between 2218 and 2248 LT. The error bars in this figure are based on photon counting statistics, and do not include any systematic error of the sort discussed above. The first point of interest in Figure 1 is that minimum temperature occurs at around 103 km, with a strong secondary minimum at 92.5 km. The height of the principal minimum at 103 km is well above that given by the CIRA standard atmosphere at our latitude, which is about 95 km. As we shall show later, this high mesopause is a characteristic of all our measurements. The second point of interest is the similarity between the structures in the vertical distributions of temperature and sodium density. Both profiles show a pronounced minimum at 92.5 km, with maxima above and below this height, the temperature maxima coming a few km below those of the sodium concentration. The similarity in the structure in the density and temperature profiles could result from temperature dependent sodium chemistry and/or dynamical effects It is interesting to note that 3 hours later on the same night (Figure 2), the strong vertical oscillations in both temperature and density are absent, although there still appears to exist minor wave modulation of both the temperature and density profiles, with a vertical wavelength of about 7 km. Almost all our data sequences show correlated wave-like perturbations in the temperature and density profiles, which we assume to be the result of internal gravity waves and/or tides.

In Figure 3 we show the average of all our measurements, corresponding to data taken over the 4-month period between July and October, 1998. This figure was produced by averaging nightly means, so each night's measurement is equally weighted, independently of the length of the data run. The horizontal bars in Figure 3 show the standard deviation of the measurements. These standard deviations include, of course, both measurement noise and day-to-day variations in the temperature at a given height. The rapid increase in the standard deviations above 104 km and below 83 km reflects the low sodium densities at such heights, with consequently

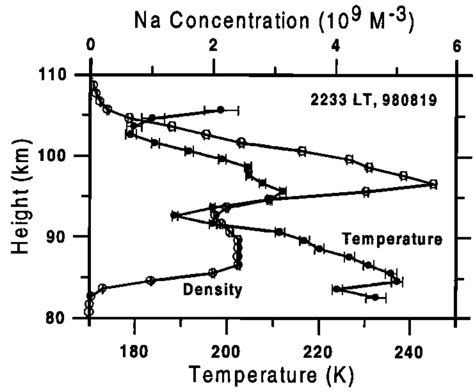

Figure 1. Vertical distributions of sodium concentration and temperature averaged over 30 minutes centered on 2233 LT, August 19, 1998.

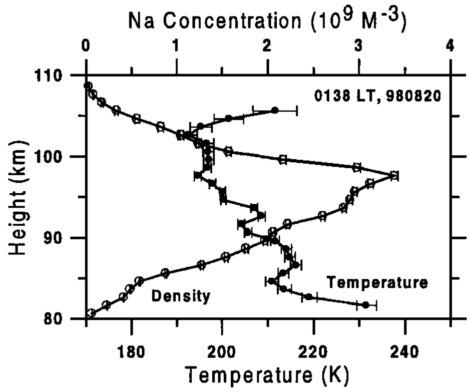

Figure 2. As for Figure 2, but 3 hours later.

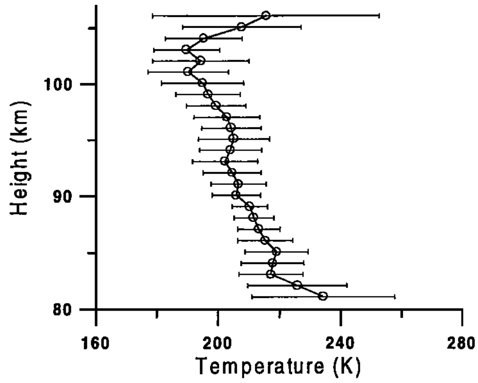

Figure 3. Average temperature profile for all measurements, July - October, 1998.

high measurement noise. Within the 83 to 104 km height range we believe the standard deviations represent a real estimate of the day-to-day variations in the atmospheric temperature profile. With respect to this average profile it must be remembered that all the measurements were made at night, mostly between 1900 and 2400 LT, so it is quite possible that the profile shown in Figure 3 is influenced by tidal oscillations.

Discussion

Average Profile. On the basis of their shipboard measurements of the Doppler temperature of atmospheric potassium, von *Zahn et al.* [1996], suggested that the mesopause level occurs around either 86 ± 3 km or 100 ± 3 km worldwide, that the lower level is generally associated with summer conditions, and the upper with winter. Further support for this behavior is provided by measurements at Fort Collins [*She and von Zahn,* 1998]. The latter workers suggest that between 23° S and 23° N the mesopause is probably always located at the "winter" level. With the limitation that our observations so far are restricted to winter through spring equinox conditions, our results tend to confirm this conclusion. In Figure 4 we compare our average profile with other measurements. The São José dos Campos average profile agrees very closely with the December average profile for Fort Collins, taken from *Yu and She* [1995], providing strong support for the conclusions of *von Zahn et al* [1996] and *She and von Zahn* [1998]. Consistent with this is the recently published data from the UARS HRDI instrument [*Ortland et al.,* 1998] showing a mesopause around 100 km throughout the year at the equator.

In general our results do not confirm earlier measurements and models for our latitude at the appropriate time of the year. As commented by von *Zahn et al.* [1996] "Model atmospheres have so far not anticipated a bimodal behavior of the mesopause altitude". Below 100 km the CIRA 86 temperatures are around 20 K cooler than ours. The SME satellite measurements published by *Clancy et al.* [1994] also show much lower temperatures, and suggest a mesopause level at around 80 km, at least 20 km lower than that derived from the lidar observations. The SME profile shown in Figure 4 is an interpolation for 23° S of the average of the July through October profiles from *Clancy et al's.* Table 1. The analysis of the SME data involves the assumption of a starting point pressure at the top end of the profile. Any error in the "educated guess" used for this pressure will reflect in the derived temperatures for a few scale heights below this point, but this should not be significant below 80 km. The fact that the SME temperature profiles are derived from limb-scanning measurements, integrated over about 5 degrees of latitude, should not have any substantial effect on the derived mesopause height. For this reason it is difficult to explain the large discrepancy between the SME and the lidar results. We have included in Figure 4 an average temperature profile derived from TOVS satellite infrared radiometer data for the same time period as our lidar data, and for locations within ± 2° of our latitude and longitude. This profile only reaches 65 km, corresponding to the 0.1 mB TOVS level but, within this limitation, appears to be in agreement with our lidar measurements, in that a straight line, joining the lowest point on the lidar profile with the highest TOVS point, provides a plausible extrapolation of both sets of observations.

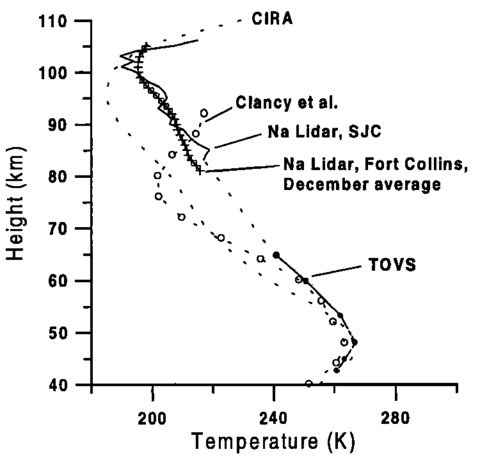

Figure 4. Comparison between mean temperature profile for 23° S (SJC) and other profiles.

Wave Perturbations. As we have already mentioned, it is frequently observed that peaks in the vertical distribution of temperature are accompanied by similar peaks in sodium concentration. As pointed out by other workers (*Bills and Gardner,* 1993, for example), it is expected that wave-induced oscillations in temperature and density should be in the same phase on the bottomside of the layer, and in anti-phase on the topside. The basic reason for this is that whereas the sign of the temperature change induced by the quasi-adiabatic vertical displacement of an air parcel depends only on the direction of the displacement, the sign of the sodium density change at a given height depends on the direction of the gradient in its mixing ratio. In an Eulerian frame of reference, on the bottomside of the layer, the rapid increase in sodium mixing ratio with height causes small vertical displacements to produce large changes in Na concentration, with an upward displacement producing a decrease in concentration. Well above the sodium layer peak, the mixing ratio gradient reverses, so that an upward displacement results in an increase in mixing ratio. Since an upward displacement must always produce a decrease in temperature, the concentration and temperature variations should be positively correlated below the Na peak, and negatively correlated above the height where the mixing ratio gradient changes sign.

The temperature perturbations at a given height, resulting from the vertical displacement of an air parcel, should simply correspond to the adiabatic lapse rate, $dT/dz = (1-\gamma)T/H\gamma$, where T is temperature, z height, H is the scale height and γ is the ratio of specific heats, minus the unperturbed background atmospheric temperature gradient. The adiabatic lapse rate is of the order of -10 K km^{-1}, about an order of magnitude greater than the background temperature gradient, so the latter can be neglected. Relative changes in temperature are thus $(dT/T)_z \approx ((1-\gamma)/\gamma)(dz/H)$. Corresponding changes in mixing ratio, M, can be written as $(dM/M)_z \approx -(1/M)(dM/dz)dz$. Thus the ratio of the relative changes in mixing ratio to those in temperature is

$$R(z) = \left(\frac{dM}{M}\right)_z \Bigg/ \left(\frac{dT}{T}\right)_z \approx \frac{H}{M}\left(\frac{dM}{dz}\right)_z \frac{\gamma}{\gamma - 1} \qquad (2)$$

We have tried to test this by doing a linear regression analysis on corresponding experimental values of $(dM/M)_z$ and $(dT/T)_z$, determined as $(M_z - \overline{M}_z)/\overline{M}_z$ and $(T_z - \overline{T}_z)/\overline{T}_z$, where M_z and T_z are measured values of mixing ratio and temperature at height z, and $\overline{M}_z$ and $\overline{T}_z$ are their corresponding nightly means. To reduce the effects of measurement noise we used data from only 6 nights where we had at least 4 hours of continuous measurements, and took 20 minute averages. The results are plotted in Figure 5. In this figure the open circles are the slopes from the regression analysis, and the error bars represent the standard estimate of the slope error obtained from the same analysis. The filled circles in Figure 5 shows values of $R(z)$ computed from equation 2, using the average sodium concentration for the 6 nights of data to calculate the values of dM/M as a numerical derivative. As can be seen from the figure, although the switch from positive to negative correlation occurs at the same height for both the experimental and computed values of $R(z)$, the absolute values computed are much larger than the measured ones. This possibly reflects the

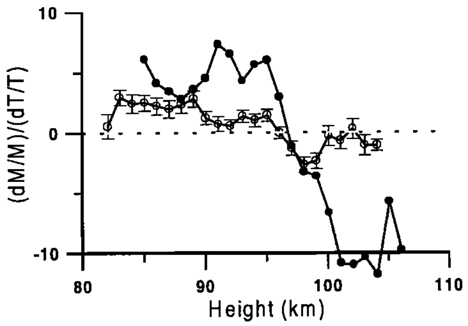

Figure 5. Fractional changes in Na mixing ratio v. fractional changes in temperature. The open circles with error bars show the results of a linear regression analysis of the observed variations, and the filled circles show values calculated from the average mixing ratio distribution.

fact that not all density changes result from vertical oscillations in the layer. There must exist horizontal irregularities in the sodium layer resulting from the sporadic nature of the meteor influx and the limited lifetime of sodium atoms in the 80 - 110 km region. These irregularities, advected by horizontal winds, would produce fluctuations in sodium density unrelated to temperature. It is interesting to note that Quian and Gardner [1995], using a rather different approach, also found a large discrepancy between calculated and measured values of $R(z)$.

Still on the subject of wave perturbations, *Helmer and Plane* [1993], on the basis of a photochemical model, find that temperature oscillations on the bottomside of the sodium layer should lead to corresponding concentration changes induced by the temperature dependence of rate coefficients. It appears that the value of $R(z)$ at 80 km would be around 10, but that it would fall rapidly with height, reaching a value around 1 at 85 km. Since the sodium concentration is normally too low at 80 km for us to be able to measure temperature, and a value of 1 at 85 km would be lost in the noise, our measurements do not permit us to check *Helmer and Plane's* [1993] analysis.

Conclusions

The first lidar measurements of the mesopause temperature profile from a fixed low-latitude southern hemisphere location show a temperature structure similar to the winter profile for mid-latitudes. The average profile for 15 nights between July and October shows a mesopause temperature of 190 K at a height of 102.5 km. Between 83 km and 100 km the measured temperatures were typically 20 K warmer than predicted by the CIRA 86 standard atmosphere for the corresponding time period at our location. Our average profile is very similar to the December average for Fort *Collins [She and von Zahn*, 1998], a fact that supports the suggestion of these workers that between 23° S and 23° N the mesopause is probably always located at the "winter" level.

The observed mesopause temperature profile almost invariably shows strong wave-modulation, closely correlated with similar modulation of the sodium density. As expected, maxima in sodium density correspond to maxima in temperature on the bottomside of the layer, and there is a negative correlation between temperature and density perturbations at heights above 96 km.

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