Negligible long-term temperature trend in the upper atmosphere at 23°S

Barclay R. Clemesha, Dale M. Simonich, and Paulo P. Batista
Instituto Nacional de Pesquisas Espaciais, São José dos Campos, Brazil

Tomas Vondrak and John M. C. Plane
School of Environmental Sciences, University of East Anglia, Norwich, UK

Received 13 October 2003; revised 5 January 2004; accepted 13 January 2004; published 2 March 2004.

[1] Measurements of the vertical distribution of atmospheric sodium, made at São José dos Campos (23°S, 46°W) from 1972 to 2001 show a negligible net long-term trend in the layer over this time period. In view of the fact that cooling of the upper atmosphere, as indicated by some experimental studies and predicted by models, would be expected to influence the vertical distribution of sodium, this result can be used to estimate the limits of such cooling. In order to investigate the sensitivity of the sodium layer to changes in the atmospheric temperature profile, and thus estimate an upper limit to the changes it should be possible to detect, we have used a comprehensive model for the mesosphere and lower thermosphere (65–110 km) that includes all species and reactions thought to be relevant to the sodium chemistry. On the basis of this study we find that the sodium layer observations are consistent with model calculations for the global effects of increased CO_2 but are not consistent with many of the experimental studies, which show cooling trends much larger than expected from theoretical studies. *INDEX TERMS:* 0317 Atmospheric Composition and Structure: Chemical kinetic and photochemical properties; 0350 Atmospheric Composition and Structure: Pressure, density, and temperature; 0340 Atmospheric Composition and Structure: Middle atmosphere—composition and chemistry; 1610 Global Change: Atmosphere (0315, 0325); *KEYWORDS:* global trend, atmospheric sodium layer

Citation: Clemesha, B. R., D. M. Simonich, P. P. Batista, T. Vondrak, and J. M. C. Plane (2004), Negligible long-term temperature trend in the upper atmosphere at 23°S, *J. Geophys. Res.*, *109*, D05302, doi:10.1029/2003JD004243.

1. Introduction

[2] Modeling studies suggest that the observed long-term increase in the concentration of greenhouse gases in the atmosphere should lead to atmospheric cooling at heights above the tropopause. A number of workers have attempted to model such an effect. These studies have generally aimed at the so-called "doubled CO_2 scenario." One of the earliest of such studies was that of *Roble and Dickinson* [1989]. For a doubling in the concentration of atmospheric CO_2, *Roble and Dickinson* [1989] found a temperature decrease of 15 K at 50 km and more than 50 K at 400 km.

[3] In recent years a number of workers have developed more detailed atmospheric models allowing predictions to be made for the effect of increased greenhouse gas concentrations. *Brasseur et al.* [1990] presented a chemical-dynamical-radiative model that includes Rossby wave absorption and gravity wave breaking. For the doubled CO_2 scenario they found maximum cooling at around 50 km, with temperature changes between −16 K at the winter pole to −8 K at the equator. This model gave a small increase in temperature below 20 km, and zero effect at 70 km. *Akmaev and Fomichev* [2000] have modeled the effects of the increase in CO_2 known to have occurred over the past 3–4 decades. For a change in CO_2 concentration from 331 to 360 ppm, they found temperature changes going from 0 at 20 km to about −10 K at 180 km. The trend did not increase monotonically with height, and was close to zero at 120 km. The trend modeled by *Akmaev and Fomichev* [2000] provides a convenient basis for comparison with measured trends. *Portmann et al.* [1995] studied the effects of including dynamical feedbacks in the *Garcia and Solomon* [1985] two-dimensional model. They found that such feedbacks have a major effect, especially at the summer pole, where the doubled-CO_2 scenario produced net heating of about 14 K without feedbacks, but cooling of around 6 K with. Portmann et al. obtained typical trends, with dynamical feedbacks included, of 0 K at 20 km to −25 K at 110 km.

[4] Experimental studies aimed at detecting long-term trends in the MLT region have been made using various techniques. Rocket measurements [see, e.g., *Keckhut et al.*, 1999] suggest trends of as much as −5 K/decade at 70 km. Rayleigh lidar [see, e.g., *Keckhut et al.*, 2001] indicate a few degrees per decade at heights between 50 and 70 km. Satellite measurements by *Aikin et al.* [1991] suggest a cooling of 3.5 K per decade. These measurements were from the SSU 47X channel, corresponding to about 0.4 mB,

0148-0227/04/2003JD004243

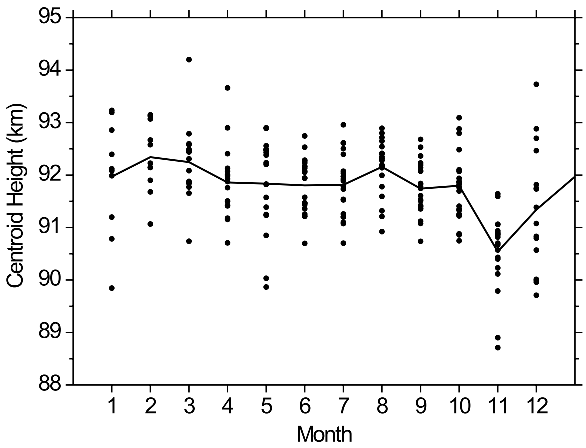

Figure 1. Annual variation of the Na layer centroid height.

or 55 km. OH rotational temperature measurements, which refer to about 87 km, indicate trends that vary from −10 K/decade [*Golitsyn et al.*, 1996] to zero [*Bittner et al.*, 2002]. Measurements of the reflection height of VLF radio signals have been interpreted by *Taubenheim et al.* [1997] as indicating a −6 K/decade trend in the mesosphere. These measurements refer to the "column mean temperature between the stratopause and 81.8 km."

[5] These various experimental studies suffer from a variety of deficiencies. For example, many are based on comparatively short data series, less than 10 years in the cases of some of the satellite and Rayleigh lidar measurements. The rocket measurements involve changes in instrumentation that are difficult to allow for accurately, the OH rotational temperature measurements are based on small changes in the relative strength of the components of the rotational spectrum, and are thus sensitive to small changes in instrumentation. Nevertheless, a majority of the measurements do appear to indicate a negative trend in the temperature of the MLT region. In view of the implications of this fact, it is clearly important to investigate any long-term data series that have bearing on the subject.

2. Atmospheric Sodium Profile

[6] The sodium layer has its origin in the ablation of meteors in the upper atmosphere, liberating free sodium atoms which subsequently participate in a complex chemistry, both neutral and ion. The net result of this chemistry, together with the ablation profile and eddy diffusion transport, is to produce a layer peaking at about 90 km, with densities falling to zero at about 105 km on the topside and 80 km on the bottom. The exact shape of this distribution depends on the vertical distribution of other atmospheric constituents, both major and minor. Minor constituents such as atomic oxygen and ozone play a major role in the chemistry of atmospheric sodium, and the major constituents, molecular oxygen and nitrogen, are important not only to the chemistry, but also to the ablation profile. It should be pointed out that the major constituents distribution is important not only in the region of the sodium layer, but at all heights below it, since it will influence the atmospheric density at the height of the layer. The instantaneous distribution of sodium is also strongly influenced by atmospheric waves, including internal gravity waves, tides and planetary waves, but these effects can be expected to cancel out when averages are taken over long time periods. Long-term changes in wave amplitudes would, however, affect the eddy transport and consequently the sodium profile. Since the sodium profile depends on the vertical distribution of atmospheric constituents, both major and minor, it is to be expected that any changes in these distributions resulting from long-term global change might result in corresponding changes in sodium. Since we have sodium data taken over the past 30 years, we can search for such an effect.

[7] Lidar measurements of the vertical distribution of atmospheric sodium have been made at São José dos Campos since May 1972. Although numerous changes have been made to the equipment used for these measurements over the years, the determination of the relative vertical distribution of sodium is a straightforward measurement that does not depend on any difficult calibration process, and is thus independent of equipment changes [*Clemesha et al.*, 1992]. Determination of the absolute abundance of sodium is a much more difficult process, and we do not believe that our calibration of the absolute sensitivity of the lidar is reliable enough for us to detect small long-term changes. For this reason, we restrict this study to the normalized vertical distribution of sodium.

[8] In two earlier papers we showed long-term trends in the centroid height of the sodium layer from 1972 to 1986 [*Clemesha et al.*, 1992] and 1972 to 1994 [*Clemesha et al.*, 1997], respectively. In the first paper we found a linear trend of -49 ± 12 m yr^{-1}, and in the second this reduced to -37 ± 9 m yr^{-1}. In both analyses the trend is statistically significant, but it should be noted that extending the period studied from 15 to 23 years resulted in a considerable decrease in the trend obtained.

[9] The sodium layer shows significant diurnal and seasonal variations, and these effects must be taken into account when searching for any long-term trend. The average diurnal variation shows a peak-to-peak oscillation of about 2 km in the height of the centroid of the layer [*Clemesha et al.*, 1982]. This variation can be allowed for either by appropriately displacing individual height profiles before including them in the long-term average or by restricting the analysis to a relatively short local time interval, over which the layer is known not to show a strong variation. In our 1992 paper we tried both these methods and found them to give almost the same final trend for the centroid height. In subsequent work, including this paper, we have simply restricted our analysis to the time interval 1900–2200 local time. See our earlier papers for details of this aspect of the analysis.

[10] In the two earlier papers cited above we did not take into account the seasonal variation in the height of the sodium layer. This is because we were analysing many years of data, so that the seasonal variation should not significantly affect the derived long-term trend. This, however, is not entirely true because the annual distribution of our data varies from year to year, and to obtain an average profile that truly reflects the long-term mean, the seasonal variation should be taken into account. The annual variation in the centroid height of the sodium layer observed at São José dos Campos is shown in Figure 1. Although there is

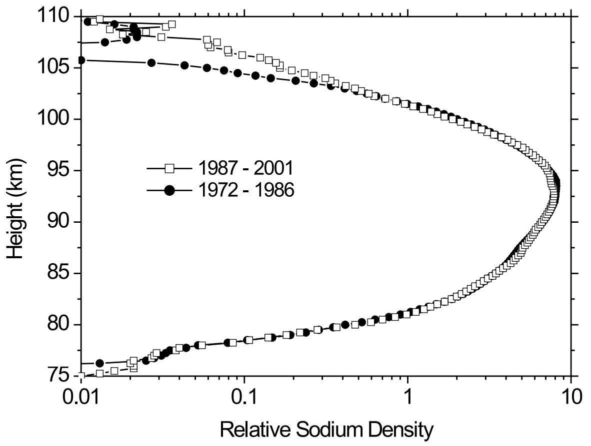

Figure 2. Mean sodium profiles for 1972–1986 and 1987–2001.

little variation in the mean centroid height over most of the year, the November average is significantly different, indicating that correction should be made for the annual variation. In order to take this effect into account the data, consisting of normalized one-month average profiles for measurements made between 1900 and 2200 hours local time, for March 1972 to December 2001, were analyzed as follows. We first calculated monthly averages for all available data, irrespective of year; in other words, all available data for a given calendar month were averaged to give an average profile for that month. These monthly means were then averaged to give an annual mean profile. We then calculated, for each calendar month, and for each 0.25-km height interval from 75 to 110 km, the differences between the monthly and yearly averages. These differences were then used to adjust the individual one-month average profiles so as to compensate for the annual variation, leaving us with a set of normalized one-month averages, from 1972 to 2001, compensated for the annual variation.

[11] *Clemesha et al.* [2003] presented the results of the above analysis in the form of monthly average centroid heights for 1972 to 2001. A regression analysis of these monthly averages gave a linear trend of 9.3 ± 5.3 m yr^{-1}, practically indistinguishable from zero. On this basis we concluded that although a clear negative trend is observable in the first half of our 30-year data set, this has been compensated for by a positive trend in more recent years, indicating almost no net long-term trend associated with global change. The present paper is an attempt to use our data to put an upper limit on any change that might have occurred in the upper atmosphere at our location. The near-zero trend observed in the centroid height suggests that negligible change must have occurred, but it is possible that the vertical distribution of sodium might have changed without altering the centroid height. To examine this possibility we have divided our seasonally adjusted data set into the intervals 1972–1986 and 1987–2001, and have computed average profiles for each of these two 15-year periods. Thus we obtain the two 15-year average profiles, separated by 15 years, shown in Figure 2. It is clear from Figure 2 that the two profiles are almost identical over most of the height range. In Figure 3 we have plotted the difference in height between the two average profiles as a function of height, showing that over most of the height range this difference is of the order of 0.1 km. Near to the peak of the layer, where the vertical gradient in sodium density is small, the height difference becomes meaningless, and is therefore not shown in Figure 3. We conclude that there was no systematic change in the shape of the sodium profile over the 15-year period in question.

3. Model Calculations

[12] Cooling of the upper atmosphere will lead to long-term subsidence of the constant density levels. On a simplistic basis this should lead to a corresponding lowering of the atmospheric sodium layer. This, however, ignores the effects of the changes on the chemistry of the layer. For this reason we have used a comprehensive model to estimate the effects of a trend in the atmospheric temperature profile on the sodium distribution.

3.1. Description of the Model

[13] The UEA mesospheric model is one dimensional, extending from 65 to 110 km with a resolution of 0.5 km. It contains a full treatment of the odd oxygen and hydrogen chemistry in the mesosphere, with rate coefficients taken from the NASA/JPL compilation [*DeMore et al.*, 1997] (http://jpldataeval.jpl.nasa.gov/). The vertical eddy diffusion coefficient is taken off-line from a 2D global model [*Garcia and Solomon*, 1994]. This model also supplies the H_2O, H_2 and CO_2 mixing ratios at the lower boundary of the model (65 km). Parameterized photolysis codes for the photolysis of O_3, H_2O, HO_2, H_2O_2, and O_2 at Lyman-α, and in the Schumann-Runge continuum, are taken from *Shimazaki* [1985] and *Brasseur and Solomon* [1986]. The photolysis of O_2 in the Schumann-Runge bands is calculated using the formalism of *Koppers and Murtagh* [1996]. Profiles of NO^+, O_2^+ and e^- are input off-line for the appropriate year and time-of-day from the International Reference Ionosphere 2001 (http://nssdc.gsfc.nasa.gov/space/model).

[14] The sodium reaction scheme in the model is illustrated in Figure 4. Rate coefficients are taken from *Plane* [2002]. The annual average ablation flux of Na was set to 4.5×10^3 atom cm^{-2} s^{-1}, with a diurnal and seasonal

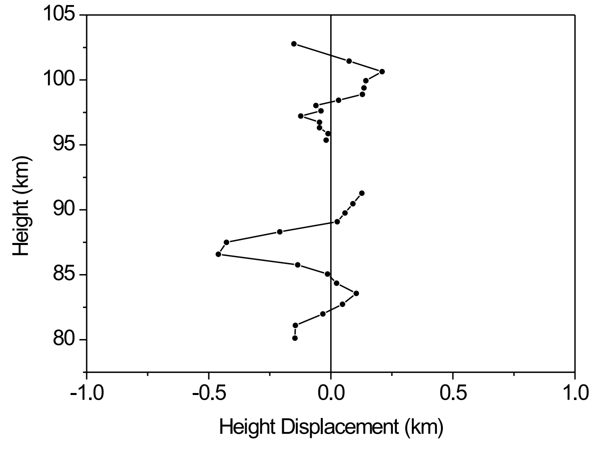

Figure 3. Height difference between the two profiles shown in Figure 2.

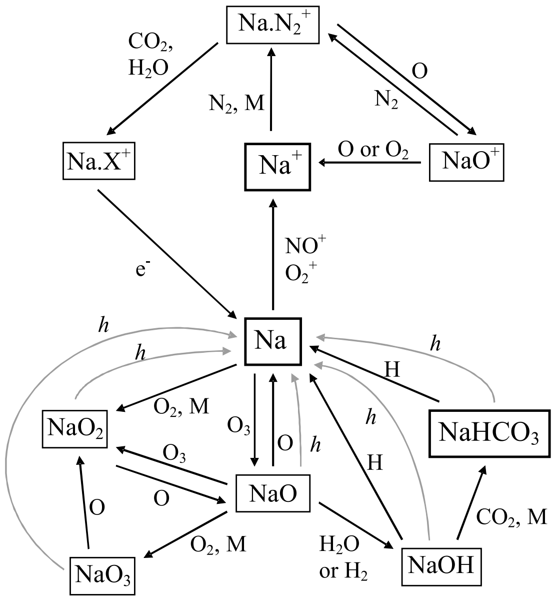

Figure 4. Schematic diagram of the gas-phase chemistry of sodium in the upper mesosphere/lower thermosphere region [*Plane*, 2002]. Grey arrows indicate photodissociation pathways.

dependence taken from *Yrjola and Jenniskens* [1998]. The meteoric ablation profile is calculated using the ablation equations given by *Hunten et al.* [1980], and assuming a meteoroid size and velocity distribution from the Long Duration Exposure Facility experiment [*McBride et al.*, 1999]. The sodium compounds, principally $NaHCO_3$, are removed on meteoric smoke particles with an uptake coefficient of unity. The height profile of these particles is calculated for a monodisperse aerosol of radius 1.3 nm, using the treatment of *Hunten et al.* [1980]. The inclusion of removal on meteoric smoke is necessary in order to model the diurnal behaviour of the Na layer correctly (J. M. C. Plane, A new time-resolved model of the mesospheric sodium layer: Constraints on the meteor input function, submitted to *Atmospheric Chemistry and Physics*, 2003).

[15] The model is integrated with a 10 min time step using a time-implicit integration scheme [*Shimazaki*, 1985]. The concentrations of the major sodium species, Na, Na^+ and $NaHCO_3$, are integrated explicitly. All the other sodium species shown in Figure 4 are put in steady state, because they are short-lived intermediates. All the model runs shown here were integrated for 20 days, and show the average concentration between 1900 and 2100 hours for the conditions of midwinter at 23°S.

3.2. Results and Discussion of the Model Runs

[16] In order to examine the effect on the sodium layer of cooling in the upper atmosphere, we have used a simple approach based on the studies of *Portmann et al.* [1995] and *Akmaev and Fomichev* [2000]. We assume a temperature change of zero below 20 km, and a uniform cooling of ΔT from the midstratosphere (30 km) to the lower thermosphere (110 km). The temperature change between 20 and 30 km is then interpolated linearly from zero at 20 km to ΔT at 30 km. In this we are, of course, making an arbitrary choice but, in view of the wide range in published model results, there is no reason to do otherwise. Figure 5a shows the modeled Na layer profiles for $\Delta T = 0, -2, -4, -10, -15$ and -20 K. Figure 5b shows the centroid height as a function of ΔT. The relationship is approximately linear, yielding the relationship

$$\text{Centroid height/km} = 92.4 + 0.15\Delta T \qquad (1)$$

Note that the modeled centroid height of 92.4 km in the absence of cooling is in good accord with the lidar observations (Figure 2). The reduction in centroid height when $\Delta T < 0$ arises because the Na layer forms at a constant density level ($\approx$ 0.15 Pa at 200 K), and cooling of the atmosphere lower down results in hydrostatic contraction and subsidence. There are three reasons that the Na layer occurs around this density level. First, the source of the Na is meteoric ablation, and the height in the atmosphere at which meteoroids ablate is governed by the rate of collisions with air molecules, and hence by the density profile. Second, Figure 4 shows that the molecular sodium reservoirs are converted back to Na by atomic O and H. Hence the underside of the Na layer is shaped by the falloff

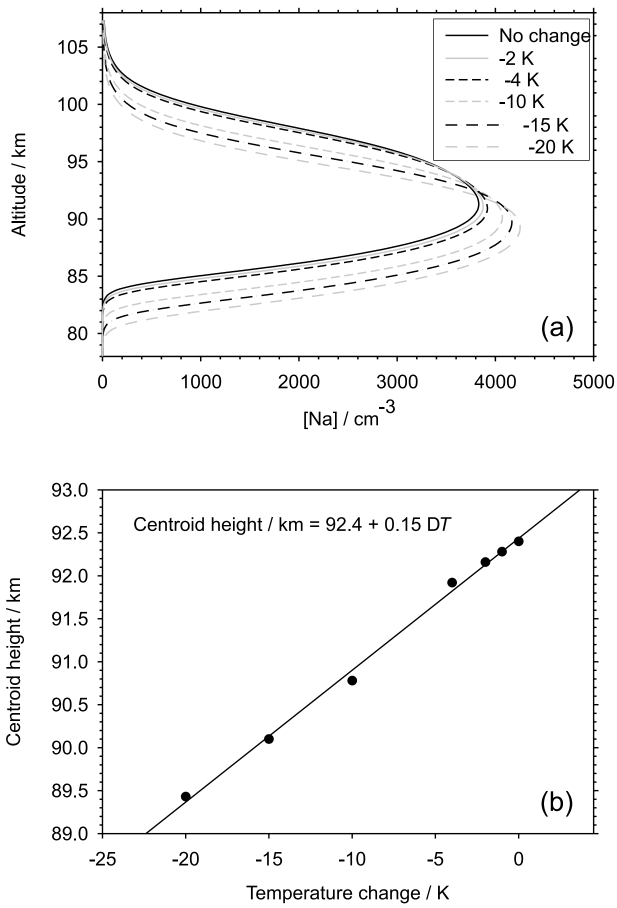

Figure 5. (a) Modeled height profiles of the atomic Na layer, for a range of temperature changes between 20 and 110 km (see text). (b) Plot of the Na layer centroid height against temperature change between 20 and 110 km. Conditions: January, 23°S, averaged between 1900 and 2200 hours local time.

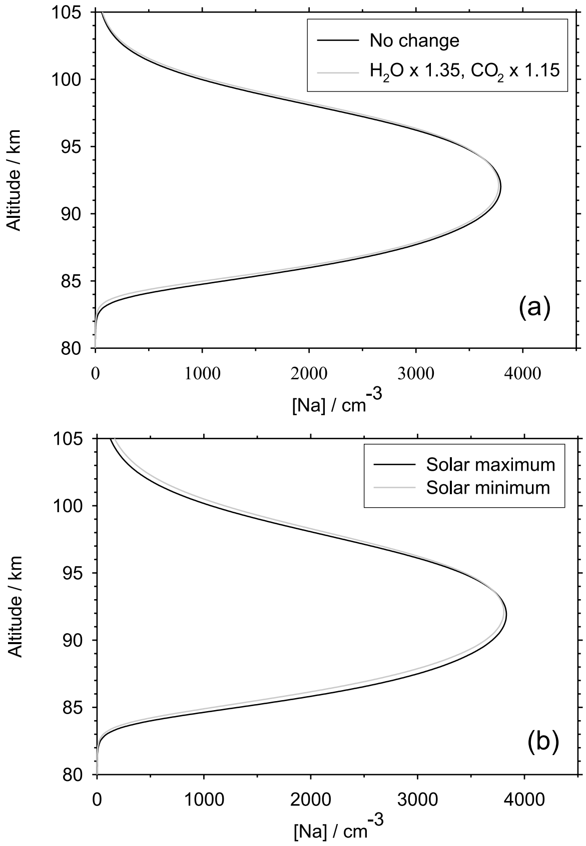

Figure 6. Modeled height profiles of the atomic Na layer showing (a) the effect of increases in H_2O and CO_2 between 1972 and 2001 and (b) the effect of the solar cycle. Note that in both cases only chemical effects are considered. Conditions: January, 23°S, averaged between 1900 and 2200 hours local time.

in O and H between 80 and 85 km [*Plane et al.*, 1999], which results from termolecular recombination reactions (e.g., $O + O_2 + N_2 \rightarrow O_3 + N_2$) that are dependent on the square of the density. Third, the topside of the layer is controlled by ion-molecule chemistry (Figure 4); the rate at which Na^+ ions are neutralized is governed by the termolecular reaction $Na^+ + N_2 + N_2$ [*Cox and Plane*, 1998], which again is highly dependent on atmospheric density.

[17] Other long-term changes to consider are the increasing concentrations of CO_2 and H_2O in the mesosphere. Between 1972 and 2001 the CO_2 mixing ratio has increased from about 325 to 370 ppm. As shown in Figure 4, the role of CO_2 in sodium chemistry is to convert sodium hydroxide (NaOH) into sodium bicarbonate ($NaHCO_3$), the stable reservoir for Na below the layer [*Plane et al.*, 1999]. Thus an increase in CO_2 converts more Na to $NaHCO_3$ on the underside of the layer, raising the centroid height. Our model indicates that a 15% increase in CO_2 raises the centroid height by 110 m, equivalent from equation (1) to a warming of $\Delta T = 0.72$ K.

[18] The mesospheric H_2O mixing ratio at 83 km is believed to have increased from about 2.8 to 3.7 ppm over the same period [*Olivero and Thomas*, 2001]. However, H_2O plays a more complex role in sodium chemistry. It is required to convert sodium oxide (NaO) into NaOH, the precursor of $NaHCO_3$ (Figure 4). Thus an increase of H_2O should raise the centroid height of the layer, as in the case of CO_2. However, the Lyman-α photolysis of H_2O produces atomic H, which reacts with NaOH and $NaHCO_3$ to regenerate Na (Figure 4). Atomic H also catalytically destroys odd oxygen (O and O_3), which are involved in several reaction steps in the Na cycle (Figure 4). These different effects of H_2O on the sodium chemistry largely cancel, so that a 35% increase in H_2O results in an increase in the centroid height of only 80 m, equivalent to a warming of 0.6 K. Figure 6a shows that the increases in CO_2 and H_2O over 30 years produce a centroid height increase of 190 m, equivalent to $\Delta T = 1.3$ K. Note that the lidar data is averaged into two blocks whose midpoints are separated by15 years, so the expected change in the centroid heights of the lidar profiles would be 95 m, i.e., $\Delta T = 0.65$ K.

[19] The effects of the 11-year solar cycle also need to be considered. The Lyman-α flux increases by a factor of 1.6 from solar minimum to maximum [*Tobiska et al.*, 2000], and this has two significant effects on the Na layer. On the topside of the layer there is about a 2.4-fold increase in the major lower *E* region ions NO^+ and O_2^+. These convert Na to Na^+ by charge transfer (Figure 4), leading to a lowering of the topside of the layer, as shown in Figure 6b. On the underside of the layer below 90 km, increased Lyman-α causes an increase in atomic H from the photolysis of H_2O. This leads to increasing production of Na from $NaHCO_3$, and a lowering of the underside (Figure 6b). The combined effect is to lower the centroid height by 300 m, equivalent to $\Delta T = -2.0$ K.

[20] However, the solar cycle is also believed to cause variations in the temperature structure of the MLT region. Estimates of the magnitude of the solar cycle variation in temperature vary widely. On the basis of rocket borne thermistor probe measurements at Heiss Island, *Labitzke and Chanin* [1988], for example, reported a 25 K solar cycle variation in the temperature at 80 km. The reliability of these measurements, however, is questionable for a number of reasons. Eighty kilometers was the upper limit for the rockets, and correction for dynamic heating of the thermistor sensor was very problematic at this height. Also, there were several changes in instrumentation during the approximately 25-year measurement period. In contrast to the rocket measurements, the OH rotational temperature measurements of *Bittner et al.* [2000] at Wuppertal, which refer to a height of about 87 km, show no measurable solar cycle effect over a period of nearly 20 years. OH rotational temperature measurements made over a period of 14 years at Cachoeira Paulista, about 100 km from our lidar station, show a peak-to-peak sunspot cycle variation of 12 K [*Clemesha et al.*, 2004]. Any relative warming of the middle mesosphere during solar maximum will raise the Na layer, and thus counteract the chemical effects of the Lyman-α increase shown in Figure 6b. In our 1997 paper we fitted a 10-year oscillation to our 1972–1994 data series, but found the amplitude too small to be considered significant. We have tried fitting periodic functions to our 30-year series and find the best fits for 7- and 14-year cycles. Figure 7 shows the monthly average centroid heights, together with a harmonic fit of 7- and 14-year components, with amplitudes of 182 ± 95 m 145 ± 94 m, respectively. It is clear that these

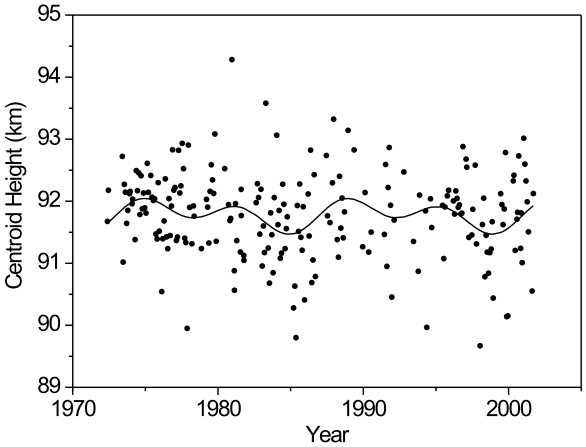

Figure 7. Monthly sodium layer centroid heights, 1972–2001. The smooth curve is a fit of 7- and 14-year components.

oscillations are not related to the solar cycle. In any case, the average Lyman-α fluxes over the periods 1972–1986 and 1987–2001 were essentially the same: 4.5×10^{11} and 4.7×10^{11} photons cm^{-2} s^{-1}, respectively [*Tobiska et al.*, 2000], so solar cycle effects should have had a negligible influence on the averaged lidar profiles in Figure 2.

[21] Finally, we consider the question of whether changes in the dynamics could offset the effects considered above. For instance, a change in turbulent mixing (parameterized as the vertical eddy coefficient, K_{zz}) might occur if the gravity wave spectrum originating from lower in the atmosphere were to change. To show the effect of this, we consider two cases where K_{zz} is halved and doubled, at all heights between 65 and 110 km. (Note that these changes in K_{zz} would correspond to the same change in the energy dissipation rate, ε, since $K_{zz} = 0.8\ \varepsilon/\omega_B^2$, where ω_B is the Brunt-Vaisala frequency). As shown in Figure 8, changing K_{zz} has a significant effect on the Na layer. The 4-fold increase in K_{zz} leads to a decrease in the Na column density by a factor of 1.59, because of more rapid downward transport of the ablated Na into the middle mesosphere. The scale heights on the top and bottom of the layer also increase significantly with greater vertical mixing. The fact that we observe no change in the scale heights makes it clear that changes in eddy diffusion of this magnitude could not have occurred. When K_{zz} is doubled, the centroid height decreases from 92.4 to 92.1 km. This is mostly caused by increased concentrations of atomic O below 85 km, resulting in more rapid conversion of sodium reservoir species into Na (see Figure 4). The O has been transported more rapidly downward from above 90 km. In contrast, when K_{zz} is halved, there is much less effect on the atomic O profile and hence the underside of the Na layer (Figure 8). The centroid height only increases 0.1 km. Even a tenfold reduction in K_{zz} leaves the centroid height essentially unchanged. Therefore, while an increase in vertical mixing causes the centroid height to decrease, the reverse is not the case. There is therefore little potential for a change in vertical mixing to offset the potentially large decrease in the centroid height over the last 30 years that would have arisen from the reported atmospheric cooling rates of around 5 K $decade^{-1}$.

[22] In summary, the lidar data show a centroid height change of -9.3 ± 5.3 m yr^{-1}. Over the 15 years that separate the two average profiles, the upper limit to the decrease in centroid height is therefore 219 m. This would be explained by $\Delta T = -1.5$ K, which should be increased by -0.65 K to take account of the offsetting effect of increasing CO_2 and H_2O levels. Hence the upper limit to the temperature change in 15 years is -2.1 K, or -1.4 K $decade^{-1}$. The corresponding lower limit is -0.7 K $decade^{-1}$, and our best estimate of the cooling trend is close to 1 K $decade^{-1}$.

4. Discussion

[23] Our analysis of the sodium layer observations made over a period of 30 years at São José dos Campos, together with the model calculations presented above, suggests that any long-term negative trend in atmospheric temperature in the MLT region over the past 30 years has not been greater than about 1.4 K $decade^{-1}$. This is of the same order of magnitude as the trend obtained by *Akmaev and Fomichev* [2000] in their model calculations for the effect of the observed increase in atmospheric CO_2. Thus our results are not inconsistent with model calculations. They are, however, inconsistent with many of the published experimental studies, which, as described in the introduction, often show trends much larger than those predicted by the models. As an example of this we can take the recent reanalysis of the rocket data from Thumba (8°N), by *Beig and Fadnavis* [2001], which gives a trend that varies from zero at 20 km to -5.5 K $decade^{-1}$ at 70 km, the maximum height for which the rocket data was analyzed. *Clemesha et al.* [2002] estimate that this trend would correspond to a subsidence of the constant density levels by about 0.7 km $decade^{-1}$ at 90 km, which is much larger than the minimum change detectable by our lidar measurements. *Dunkerton et al.* [1998] have analyzed rocketsonde data from a number of low-latitude and midlatitude locations, from 8.6°S to 37.5°N, where regular launches were made between 1963 and 1991, and found an average trend of

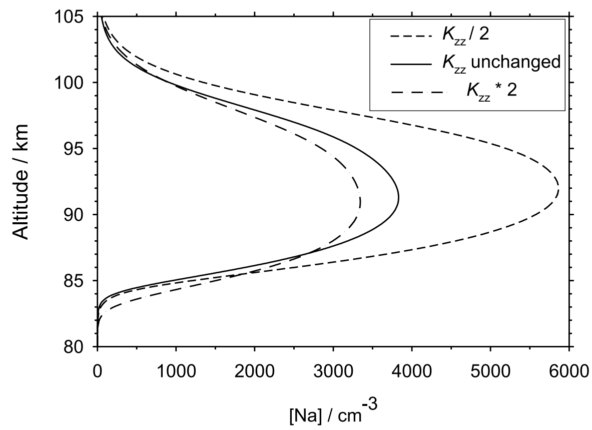

Figure 8. Modeled height profiles of the atomic Na layer showing the effect of changing the vertical eddy diffusion coefficient, K_{zz}, by a constant factor between 65 and 110 km. Conditions: January, 23°S, averaged between 1900 and 2200 hours local time.

-1.7 K decade^{-1} for the 30- to 60-km height range, reaching about -5 K/decade at 60 km. If the 60-km trend continues to greater heights then this is appreciably larger than our minimum detectable trend. The data analyzed by *Dunkerton et al.* [1998] do not appear to show a large latitudinal dependence, so the difference cannot be explained on this basis. One of the longest data series studied is the VLF radio reflection height, measured at Kühlungsborn (50.7°N), by *Taubenheim et al.* [1997]. Interpreting a decrease in the reflection height observed over a period of 33 years as being the result of long-term atmospheric subsidence, these workers find a temperature trend of about -6 K decade^{-1} at 80 km. This is about 4 times our upper limit, although here the latitude difference must be borne in mind.

[24] It should be pointed out that not all experimental studies have shown large negative trends. *Lübken* [2000] compared falling sphere measurements made during the nineties with rocket grenade measurements from the sixties. Most of the measurements were made from the Andoya range at 69°N. Lübken found no significant trend over the entire height range from 50 to 95 km. Applying a statistical analysis to all heights lumped together they find a trend of -0.24 ± 0.14 K decade^{-1}, indistinguishable from zero. Although this result is derived by comparing two separate data sets, obtained by different techniques, it is probably more reliable than the rocketsonde measurements. Both the rocket grenade and the falling sphere techniques are relatively straightforward methods, and do not involve difficult calibrations. At midlatitudes (Wuppertal, 51°N), *Bittner et al.* [2002] found no long-term trend in OH rotational temperature over a period of 19 years. The Wuppertal measurements were made with a carefully calibrated grating spectrometer and probably represent the most reliable long-term series of rotational temperature observations available.

5. Conclusions

[25] Measurements of the vertical distribution of atmospheric sodium, made at São José dos Campos over a period of 30 years, show an almost negligible net trend in the profile over this time period, although significant changes were observed on shorter timescales. We have simulated the expected effect on the sodium layer of long-term cooling of the upper atmosphere and find that a trend of greater than 1.4 K decade^{-1} between 20 km and 90 km would have produced a detectable change in the observed profile. In view of the fact that the lidar technique involves no difficult calibration problems and that the relative vertical distribution is determined from a highly accurate time of flight measurement, we believe this to be an extremely robust result. This appears to be in conflict with the results of many studies using other techniques, such as rocketsondes, the Russian OH rotational temperature measurements, and VLF reflection heights. These studies have been made at a number of locations, including low latitudes such as Thumba (8°N), for which trends much greater than our limit of detection have been derived. On the other hand, our best estimate of 1 K decade^{-1} cooling is in sensible accord with the cooling trend of 0.8 K decade^{-1} for the lower mesosphere obtained in model studies by *Akmaev and Fomichev* [2000]. It is also compatible with the rocket measurements analyzed by *Lübken* [2000] and the OH rotational temperature measurements of *Bittner et al.* [2000]. It should be noted that neither of the two techniques used by *Lübken* [2000] involve difficult calibration problems, unlike the rocket-borne temperature sondes used in the Thumba measurements. Bittner et al.'s OH rotational temperature measurements should also be reliable in that the same instrumentation was used throughout. It is difficult to avoid the conclusion that many of the published experimental studies may have exaggerated the cooling trend in the upper atmosphere, either as a result of calibration difficulties or because they were based on relatively short periods of time. In this respect it should be pointed out that when we first analyzed the long-term trend in the sodium centroid height, on the basis of 15 years of data, we found a significant negative trend [*Clemesha et al.*, 1992]. Subsequent analysis, with more data, showed that this negative trend has been compensated for by a positive trend in recent years, with the result that the net trend over the past 30 years is negligible. It is interesting to note that our conclusion is consistent with that reached by *Beig et al.* [2003], through an evaluation of a wide range of existing data relevant to global change in the mesosphere.

[26] **Acknowledgments.** We gratefully acknowledge the financial support of the Programa de Núcleos de Excelência (Pronex), the Fundaço de Amparo a Pesquisa do Estado de São Paulo (FAPESP), and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq).

References

Aikin, A. C., M. L. Chanin, J. Nash, and D. J. Kendig (1991), Temperature trends in the lower mesosphere, *Geophys. Res. Lett.*, *18*, 416–419.
Akmaev, R. A., and V. I. Fomichev (2000), A model estimate of cooling in the mesosphere and lower thermosphere due to the CO_2 increase over the last 3–4 decades, *Geophys. Res. Lett.*, *27*, 2113–2116.
Beig, G., and S. Fadnavis (2001), In search of greenhouse signals in the equatorial middle atmosphere, *Geophys. Res. Lett.*, *28*, 4603–4606.
Beig, G., et al. (2003), Review of mesospheric temperature trends, *Rev. Geophys.*, *41*(4), 1015, doi:10.1029/2002RG000121.
Bittner, M., D. Offermann, and H. H. Graef (2000), Mesopause temperature variability above a midlatitude station in Europe, *J. Geophys. Res.*, *105*, 2045–2058.
Bittner, M., D. Offermann, H.-H. Graef, M. Donner, and K. Hamilton (2002), An 18-year time series of OH rotational temperatures and middle atmosphere decadal variations, *J. Atmos. Terr. Phys.*, *64*, 1147–1166.
Brasseur, G., and S. Solomon (1986), *Aeronomy of the Middle Atmosphere*, D. Reidel, Norwell, Mass.
Brasseur, G., M. H. Hitchman, S. Walters, M. Dymek, E. Falise, and M. Pirre (1990), An interactive chemical dynamical radiative two-dimensional model of the middle atmosphere, *J. Geophys. Res.*, *95*, 5639–5656.
Clemesha, B. R., D. M. Simonich, P. P. Batista, and V. W. J. H. Kirchhoff (1982), The diurnal variation of atmospheric sodium, *J. Geophys. Res.*, *87*, 181–186.
Clemesha, B. R., D. M. Simonich, and P. P. Batista (1992), A long-term trend in the height of the atmospheric sodium layer: Possible evidence for global change, *Geophys. Res. Lett.*, *19*, 457–460.
Clemesha, B. R., P. P. Batista, and D. M. Simonich (1997), Long-term and solar cycle changes in the atmospheric sodium layer, *J. Atmos. Terr. Phys.*, *59*, 1673–1678.
Clemesha, B. R., P. P. Batista, and D. M. Simonich (2002), Comment on "In search of greenhouse signals in the equatorial middle atmosphere" by Gufran Beig and S. Fadnavis, *Geophys. Res. Lett.*, *29*(16), 1810, doi:10.1029/2002GL015097.
Clemesha, B. R., P. P. Batista, and D. M. Simonich (2003), Long-term variations in the centroid height of the atmospheric sodium layer, *Adv. Space Res.*, *32*, 1707–1711.
Clemesha, B. R., H. Takahashi, D. M. Simonich, D. Gobbi, and P. P. Batista (2004), Experimental evidence for solar cycle and long-term changes in the low-latitude MLT region, *J. Atmos. Sol. Terr. Phys.*, in press.
Cox, R. M., and J. M. C. Plane (1998), An ion-molecule mechanism for the formation of neutral sporadic Na layers, *J. Geophys. Res.*, *103*, 634–641.

DeMore, W. B., S. P. Sander, D. M. Golden, R. F. Hampson, M. J. Kurylo, C. J. Howard, A. R. Ravishankara, C. E. Kolb, and M. J. Molina (1997), Chemical kinetics and photochemical data for use in stratospheric modeling: Evaluation 12, *JPL Publ.*, *97-4*.

Dunkerton, T. J., D. P. Delisi, and M. P. Baldwin (1998), Middle atmosphere cooling trend in historical rocketsonde data, *Geophys. Res. Lett.*, *25*, 3371–3374.

Garcia, R. R., and S. Solomon (1985), The effect of breaking gravity waves on the dynamics and chemical composition of the mesophere and lower thermosphere, *J. Geophys. Res.*, *90*, 3850–3868.

Garcia, R. R., and S. Solomon (1994), A new numerical model of the middle atmosphere: 2. Ozone and related species, *J. Geophys. Res.*, *99*, 12,937–12,951.

Golitsyn, G. S., A. I. Semenov, and N. N. Shefov (1996), Long-term temperature trends in the middle and upper atmosphere, *Geophys. Res. Lett.*, *23*, 1741–1744.

Hunten, D. M., R. P. Turco, and O. B. Toon (1980), Smoke and dust particles of meteoric origin in the mesosphere and stratosphere, *J. Atmos. Sci.*, *37*, 1342–1356.

Keckhut, P., F. J. Schmidlin, A. Hauchecorne, and M. L. Chanin (1999), Stratospheric and mesospheric cooling trend estimates from U.S. rocketsondes at low latitude stations (8°S–34°N), taking into account instrumental changes and natural variability, *J. Atmos. Terr. Phys.*, *61*, 447–459.

Keckhut, P., J. D. Wild, M. Gelman, A. J. Miler, and A. Hauchcorne (2001), Investigations on long-term temperature changes in the upper stratosphere using lidar data and NCEP analyses, *J. Geophys. Res.*, *106*, 7937–7945.

Koppers, G. A. A., and D. P. Murtagh (1996), Model studies of the influence of O_2 photodissociation parameterizations in the Schumann-Runge bands on ozone related photolysis in the upper atmosphere, *Ann. Geophys.*, *14*, 68–79.

Labitzke, K., and M. L. Chanin (1988), Changes in the middle atmosphere in winter related to the 11year solar cycle, *Ann. Geophys.*, *6*, 643–644.

Lübken, F.-J. (2000), Nearly zero temperature trend in the polar summer mesosphere, *Geophys. Res. Lett.*, *27*, 3603–3606.

McBride, N., S. F. Green, and J. A. M. McDonnell (1999), Meteoroids and small sized debris in low Earth orbit and at 1 AU: Results of recent modelling, *Adv. Space Res.*, *23*, 73–82.

Olivero, J. J., and G. E. Thomas (2001), Evidence for changes in greenhouse gases in the mesosphere, *Adv. Space Res.*, *28*, 931–936.

Plane, J. M. C. (2002), Laboratory studies of meteoric metals in chemistry, in *Meteors in the Earth's Atmosphere*, edited by E. Murad and I. P. Williams, pp. 289–310, Cambridge Univ. Press, New York.

Plane, J. M. C., R. M. Cox, and R. J. Rollason (1999), Metallic layers in the mesopause and lower thermosphere region, *Adv. Space Res.*, *24*, 1559–1574.

Portmann, R. W., G. E. Thomas, S. Solomon, and R. R. Garcia (1995), The importance of dynamical feedbacks on doubled CO_2-induced changes in the thermal structure of the meosphere, *Geophys. Res. Lett.*, *22*, 1733–1736.

Roble, R. G., and R. E. Dickinson (1989), How will changes in carbon dioxide and methane modify the mean structure of the mesosphere and thermosphere?, *Geophys. Res. Lett.*, *16*, 1441–1444.

Shimazaki, T. (1985), *Minor Constituents in the Middle Atmosphere*, Kluwer Acad., Norwell, Mass.

Taubenheim, J., G. Entzian, and K. Berendorf (1997), Long-term decrease of mesospheric temperature, 1963–1995, inferred from radiowave reflection heights, *Adv. Space Res.*, *20*(11), 2059–2063.

Tobiska, W. K., T. Woods, F. Eparvier, R. Viereck, L. Floyd, D. Bouwer, G. Rottman, and O. R. White (2000), The SOLAR2000 empirical solar irradiance model and forecast tool, *J. Atmos. Sol. Terr. Phys.*, *62*, 1233–1250.

Yrjola, I., and P. Jenniskens (1998), Meteor stream activity: VI. A survey of annual meteor activity by means of forward meteor scattering, *Astron. Astrophys.*, *330*, 739–752.

P. P. Batista, B. R. Clemesha, and D. M. Simonich, Instituto Nacional de Pesquisas Espaciais, CP515, São José dos Campos SP, Brazil. (clem@laser.inpe.br)

J. M. C. Plane and T. Vondrak, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK.