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JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 97, NO. D5, PAGES 5981–5985, APRIL 20, 1992

The Annual Variation of the Height of the Atmospheric Sodium Layer at 23°S: Possible Evidence for Convective Transport

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On the basis of a long series of lidar measurements made at São José dos Campos, it is found that the centroid height of the atmospheric sodium layer is about 1 km lower in November than during the rest of the year. Photometric measurements of the OH(9,4) and OI 557.7 nm airglow intensities, observed at a nearby location, show that these emissions have maximum values at this time of the year. The hydroxyl emission shows a sharp increase in intensity by about 20% in November, and the atomic oxygen emission has a broader peak in October, November, and December. There is a strong inverse correlation between the seasonal variations in sodium layer centroid height and the OH intensity, with a correlation coefficient of 0.86 and a regression coefficient of -89 ± 16 Rayleighs km^{-1}. It is suggested that the anticorrelated variations in sodium layer height and airglow intensity could be the result of seasonal changes in convective transport in the lower thermosphere.

INTRODUCTION

The layer of meteoric metals at around 100 km is unique in the context of minor constituent layers in that it is produced by input from an external source, unlike other layers, which are produced by chemical or ionization processes. Despite many years of study of atmospheric sodium (the easiest of the meteoric layers to observe) we still do not have a clear picture of the processes involved in its formation. Photochemical models in which the sodium, after entering the atmosphere, undergoes production and loss via reduction and oxidation by other atmospheric constituents, have been analyzed by many workers. Recent models of this sort [*Sze et al.*, 1982; *Swider*, 1986; *Kirchhoff*, 1986] have involved the three-body reaction $Na + O_2 + M \rightarrow NaO_2 + M$, as the main loss process. Production is assumed to occur during meteor ablation, although there is no detailed picture of just how free sodium atoms enter the atmosphere. Apart from purely chemical processes, a number of other loss mechanisms have been suggested, including the formation of cluster ions [*Richter and Sechrist*, 1979*a*, *b*; *Jegou et al.*, 1985*a*, *b*; *Granier et al.*, 1985] and attachment to aerosols [*Hunten et al.*, 1980; *Hunten*, 1981].

Independent of the detailed processes involved, it is possible to make an estimate of the lifetime of sodium in the atmosphere on the basis of its measured abundance and the estimated rate of meteor deposition. Calculations of this sort give a value of several days. This long lifetime makes it possible to use sodium as a tracer of atmospheric motions and, in this context, extensive studies have been made of atmospheric gravity waves [*Kwon et al.*, 1987; *Shelton et al.*, 1980; *Gardner and Voelz*, 1987; *Kwon and Gardner*, 1990] and tides [*Clemesha et al.*, 1982; *Batista et al.*, 1985, 1990; *Kwon et al.*, 1987] in the 80-100 km region. In this paper we investigate the seasonal variation of the height of the sodium layer at São José dos Campos (23° S, 46° W), and conclude that the observed variation provides evidence for the influence of convective winds on the vertical distribution of minor constituents in the lower thermosphere.

In an earlier paper [*Simonich et al.*, 1979] we presented a morphology of the atmospheric sodium layer observed by laser radar at São José dos Campos. The limited data set available at that time was insufficient to determine a meaningful seasonal variation of the layer height. In this note we analyze a much longer data set, from 1972 to 1986, which enables us to determine a consistent annual variation in the height of the centroid of the layer. Although the determination of sodium density by lidar involves a difficult calibration problem, measurement of the centroid of the layer is independent of this calibration. Lidar measurements of the sodium layer use a photon counting receiver in which the numbers of detected photons are accumulated in range-gated bins. The timing of the bins is controlled by a crystal-controlled oscillator which, in our case has a precision of a few parts in 10^6, corresponding to less than a meter in height. The accuracy of the centroid height determined in any given measurement, however, is limited by the quantum noise in the photon counts rather than the precision of the timing. In our measurements this photon noise typically results in an error of less than 50 m in the nightly average. In this context it is important to note that the width of the height bins used to accumulate the signal photons has only a very small influence on the precision of the measurement. This parameter has a significant effect on the calculated centroid height only when the profile contains strong peaks which are narrower than the bin width.

The analysis presented in this paper is based on mean daily profiles, typically averaged over at least 3 hours of measurements. Such average profiles almost never show height structures having dimensions less than a few km. As a result of this, the fact that our measurements were made using a comparatively wide height interval (2 km up to June, 1980, and 1 km after that date) does not influence the precision of the centroid determination. In fact, the day-to-day fluctuations in the centroid height are many times greater than the error in the measurement, i.e. the geophysical noise is much more important than the measurement noise. Details of the Instituto Nacional de Pesquisas Espaciais (INPE) lidar and

Paper number 91JD03146.
0148-0227/92/91JD-03146 $05.00

the data reduction technique used can be found in *Kirchhoff and Clemesha* [1973], *Simonich et al.* [1979], and *Batista et al.* [1985].

DATA ANALYSIS AND DISCUSSION

Care must be taken in using our observations to derive average characteristics of the sodium layer because the available data are biased toward certain times of day and certain seasons of the year. More specifically, the data are strongly biased toward winter nighttime conditions, with a maximum frequency for the early evening hours. The presence of a strong diurnal variation in the centroid height of the sodium layer at our latitude [*Clemesha et al.*, 1982; *Batista et al.*, 1985] could thus lead to an apparent seasonal variation. This would occur if the average time of measurement was not the same for all seasons. There are two ways of avoiding this problem: (1) use a mean diurnal variation to adjust the heights to a fixed hour; (2) analyze only data for a given time of day. To implement the first technique, we adjusted our hourly average sodium profiles to the mean diurnal centroid height variation shown in Figure 1. This variation is based on a total of 59 days of 24-hour measurements made between the months of April and November. The use of a single average diurnal variation to adjust all data is justified by the fact that our 24-hour measurements do not show a significant seasonal change in the diurnal variation of the centroid. The adjustment involved a height displacement of each hourly profile by an amount equal to the difference in centroid height between the corresponding hourly average and the diurnal mean of the 24-hour measurements. After making this adjustment, daily mean centroid heights were calculated for the 710 days for which good quality data are available. These daily means were then used to determine means, standard deviations and standard errors for each month of the year.

We have also tried the second technique by averaging only those profiles obtained between 1900 and 2200 hours. The results of these analyses are shown in Figure 2. The monthly mean centroid heights plotted in Figure 2 show that for most of the year the height remains close to 92.5 km, except in November, when it falls sharply by more than 1 km. The error bars, representing the standard error of the estimate (standard deviation divided by the square root of the number of measurements), make it clear that the November minimum represents a real departure from the annual mean, rather than a statistical fluctuation. The fact that both analysis techniques give similar results adds weight to this conclusion. The local maximum in centroid height in August also appears to represent a consistent trend.

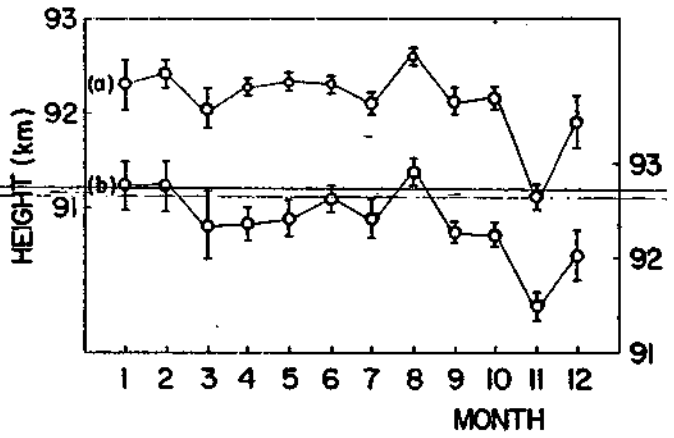

Fig. 2. Seasonal variation in the centroid height of the sodium layer based on (a) Seasonally adjusted data and (b) data for 1900-2200 LT.

Why should the sodium layer be about 1 km lower in November than during the rest of the year? In attempting to answer this question the first point to consider is whether the effect results from a change in shape or from a simple lowering of the entire layer. To investigate this point we have calculated, separately, the average profiles for November and for the remaining 11 months of the year. To eliminate the effects of the diurnal variation, we have used only those data obtained between 1900 and 2200 LT. The profiles are plotted in Figure 3, which makes it clear that most of the change in height corresponds to a simple lowering of the entire layer. Note that the profiles shown in Figure 3 have been normalized to a constant abundance in order make the height shift easier to discern. It might be expected that the seasonal height variation should bear some relationship to the variation in abundance, but this is not the case, as can be seen from Figure 4, where we show the seasonal variation in abundance based on all our data. Minimum abundance occurs in December, and the November abundance is also greater than that for January, February, and March.

The relationship between the annual variations in height distribution and total abundance measured at our location is quite different to that seen at northern mid-latitudes. Data for Winkfield (51° N), published by *Gibson and Sandford* [1971], show that the annual winter maximum in abundance observed at that latitude results mainly from increased sodium on the bottomside of the layer, implying that maximum abundance occurs together with minimum centroid height. *Megie and Blamont* [1977] observed a sharp max-

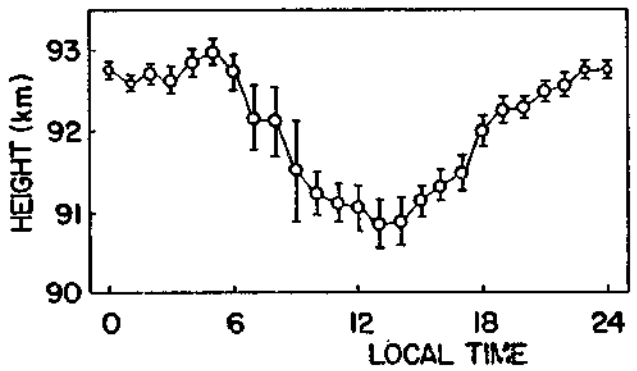

Fig. 1. Diurnal variation in sodium layer centroid height.

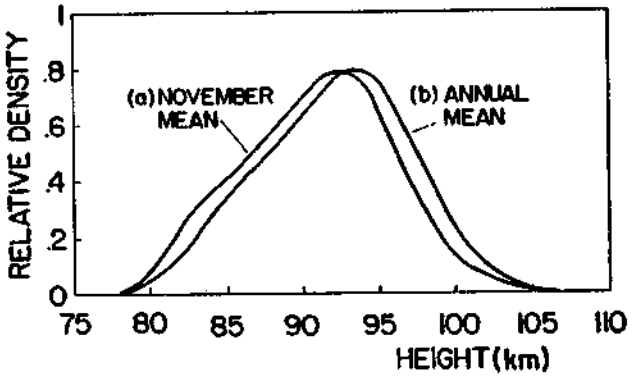

Fig. 3. Vertical distributions of atmospheric sodium.

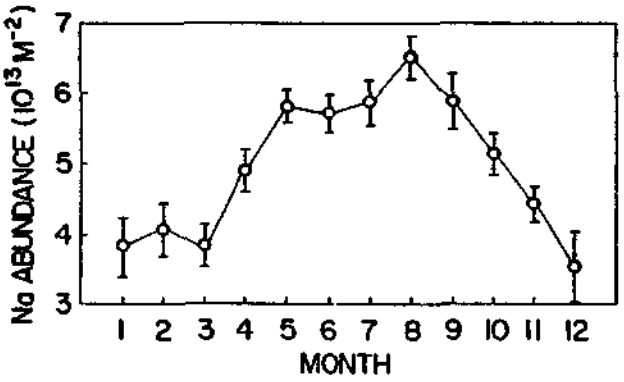

Fig. 4. Seasonal variation of sodium abundance.

imum in abundance in November and December at Haute Provence (44° N), with some indication of a lowering of the layer in winter. *Gardner et al.* [1986], working at Illinois (40° N), found maximum abundances between November and January, but their centroid height variation appears to show a semi-annual variation with minima in June and December. In view of this diversity, it is difficult to believe that the winter lowering of the centroid height observed at northern mid-latitudes bears any relationship to our November minimum.

In searching for other geophysical parameters which might be related to the sodium layer we have examined the annual variations of a number of airglow emissions measured at our latitude. The OI 557.7 nm, Na D 589.0 nm and OH (9,4) band emissions have been monitored at Cachoeira Paulista (23° S, 45° W) for many years, and reliable mean annual variations are available for these parameters. The seasonal variations of the airglow intensities are shown in Figure 5. This figure is based on 10 years of data obtained between 1977 and 1986. The photometer used was a multichannel tilting filter type instrument, operated for 15 nights each month, around the new moon period, whenever weather conditions permitted. Regular calibrations were carried out, using a radioactively excited phosphor light source and an incandescent substandard. The photometer sampled each emission intensity at 10 min intervals, and nightly mean intensities were calculated by averaging these values. Averages of all the nocturnal means for each month were used to obtain the mean seasonal variations shown in Figure 5. Note that the OI 557.7 nm intensities have been compensated for the F region component by subtracting 20% of the simultaneously measured OI 630.0 nm intensity. Details of the measurement and data reduction techniques employed can be found in *Takahashi and Batista* [1981] and *Takahashi et al.* [1984]. Both the OH and OI intensities show maximum values in November. It is not surprising that Na D shows a maximum earlier, in October, because the sodium abundance is decreasing rapidly at this time of the year. The similarity between the annual variations in OH intensity and sodium layer centroid height is remarkable. A regression analysis of the monthly mean values, shown in Figure 6, gives a regression coefficient of -89±16 Rayleighs km^{-1}, with a correlation coefficient of -0.86. It is interesting to note that the only other southern hemisphere OH observations available, for Zeckooegat, located at 33° S, 22 ° W [*Weins and Weill*, 1973] also show a November maximum in the OH(9,3) emission intensity.

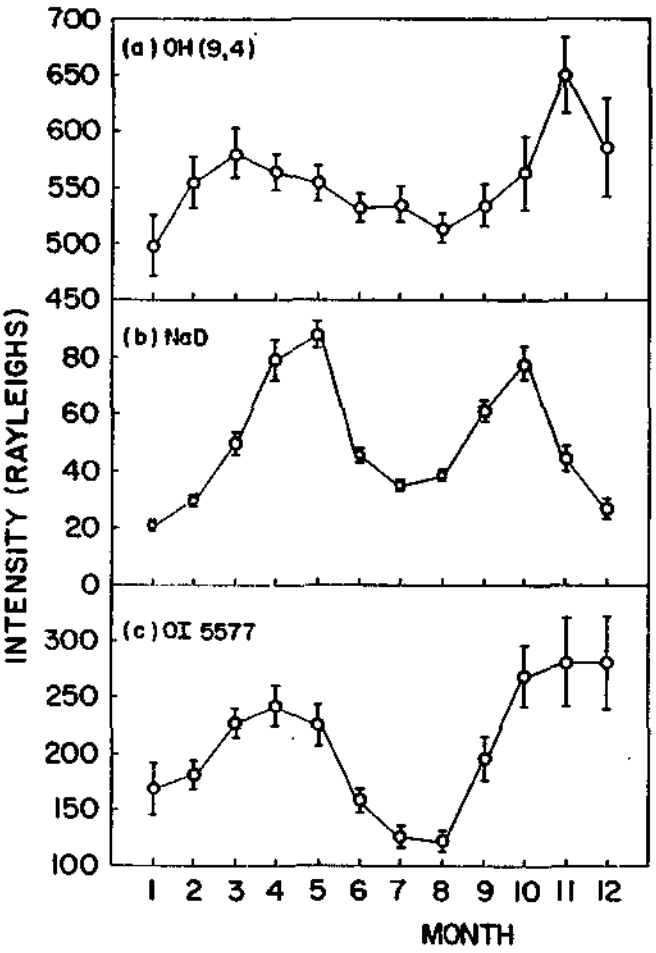

Fig. 5. Seasonal variations of airglow emissions: (a) OH(9,4) band, (b) Na D line, and (c) OI 557.7 nm.

A lowering in the height of the sodium layer could result from changes in meteoric input or chemistry, or from dynamical effects. It seems probable that the November minimum in the height of the sodium layer is related to the November maxima in OH and OI emission intensities, making it unlikely that changes in meteor flux should be responsible. The most plausible explanation for a simultaneous lowering of the sodium layer and increase in atomic oxygen and hydroxyl emissions appears to be a vertical wind in the lower thermosphere. A downward directed vertical wind should result in increased atomic oxygen at all heights, because the mix-

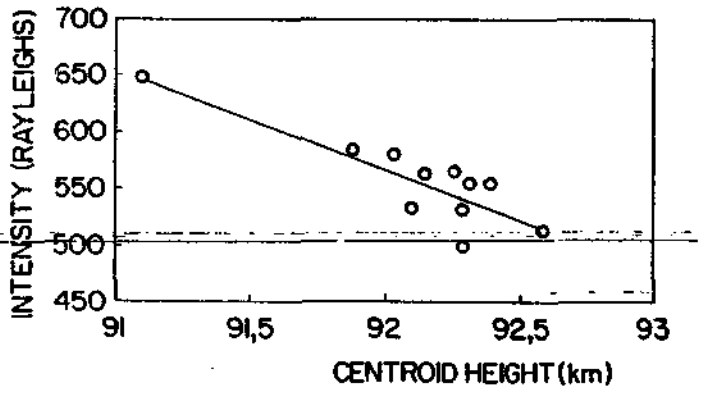

Fig. 6. Monthly averages of OH(9,4) band intensity versus sodium layer centroid height.

ing ratio of atomic oxygen increases with height throughout the region in question. The magnitude of such an increase would depend on the vertical velocity, the vertical mixing ratio gradient and the chemical lifetime of atomic oxygen, greater than one day at all heights above 85 km [*Allen et al.*, 1984]. As a result of this long lifetime, a significant effect should be seen in both the OI 557.7 nm and the OH(9,4) emissions, of which the former is expected to be proportional to somewhere between the square and the cube of the atomic oxygen concentration [*McDade et al.*, 1986], and the latter linearly proportional [*Good*, 1976].

With regard to the effect of a vertical wind, it should be remembered that this is quite different to that of eddy diffusion. In the case of atomic oxygen, increased eddy diffusion would ultimately result in a decrease in the concentration of this constituent because of its more rapid transport to the sink region, where it is lost via the three-body ozone producing reaction at heights below 85 km. *Garcia and Solomon* [1985] have analyzed a model, in which they parameterize eddy diffusion in terms of breaking gravity waves, and show that the equinoctial maxima in the OI 557.7 nm emission observed at mid-latitudes are consistent with reduced turbulent transport of atomic oxygen at this time of the year. As pointed out above, the fact that the mixing ratio of atomic oxygen increases with height implies that a downward wind would cause an increase in the atomic oxygen concentration at all heights. The existence of a prevailing downward vertical wind in a given height region would imply a horizontal convergence at greater heights, i.e. such a wind must be part of a large-scale cell. It is this convergence which would provide the additional input of atomic oxygen needed to sustain the greater chemical loss caused by its increased concentration at all heights. In other words, assuming a meridional circulation cell to be involved, the increased atomic oxygen would actually be supplied by horizontal transport from other latitudes, where the vertical component of the wind would be upward, and where the the atomic oxygen concentration would be depleted..

It is interesting to estimate what sort of vertical velocity is required to produce the observed effects. In view of the considerable uncertainty concerning the factors which control the vertical distribution of atmospheric sodium, there would appear to be little point in doing this via the analysis of a complete model. There are at least three fundamentally different types of model for the sodium layer available, and their responses to changes in atmospheric parameters are quite different. Although there is some experimental evidence which suggests that photochemical models of the sort published in the past should be rejected [*Clemesha et al.*, 1992] there is still no one model which can be accepted with any degree of confidence. However, we can make an order of magnitude estimate of the required velocity on the basis of the estimated lifetime of atmospheric sodium. Estimates of the meteoric influx of sodium give values in the region of 10^4 cm^{-2} [*Hughes*, 1975], and the total abundance of free sodium is about 3×10^9 cm^{-2}. These values suggest a lifetime of about 3 days, so the vertical velocity needed to produce a 1 km lowering of the layer is about 0.3 km d^{-1}, or 3 mm s^{-1}.

The rapid increase in the chemical lifetime of atomic oxygen with height complicates the problem of estimating the effect of a vertical wind on this constituent. Above about 90 km the distribution of atomic oxygen is controlled by transport, and to estimate the effect of a wind, the latter must be included in the flux divergence term in the continuity equation, where it contributes a term $n\nabla \cdot \boldsymbol{V} + \boldsymbol{V} \cdot \nabla n$, where n is the minor constituent concentration and $\boldsymbol{V}$ is the vector velocity. For a height independent vertical wind, w, and no horizontal density gradients, this becomes $w(n/H + dn/dz)$, where H is the atmospheric scale height, and dn/dz is the vertical gradient in minor constituent density.

To estimate the velocity needed to produce a 20% increase in the OH intensity we have analyzed a simplified time-dependent model. The model assumes production of atomic oxygen by photodissociation of O_2 and loss via $O + O_2 + M \rightarrow O_3 + M$, $O + O + M \rightarrow O_2 + M$ and $O + OH \rightarrow O_2 + H$. We used photodissociation coefficients and an eddy diffusion profile from Rodrigo et al. [1986], and reaction rates for $O + O_2 + M$ and $O + O + M$ from Kaufman and Kelso [1964] and Campbell and Thrush [1967], respectively. The lower boundary for the model set the oxygen density to zero at 60 km, and a constant downward flux of atomic oxygen was used as the upper boundary condition at 110 km.

The results of this simple model analysis are presented in Figure 7, where we show the calculated midnight profiles for atomic oxygen and relative OH emission intensity. On the basis of the fact that hydrogen plays a catalytic role in the destruction of ozone, the rate of production of OH^* was assumed equal to $[O][O_2][M]$. Since we are concerned only with the relative effect of a vertical wind, quenching of OH^* was neglected, and the emission intensity was assumed to be proportional to the excitation rate.

The integrated intensities corresponding to the emission profiles shown in Figure 7 indicate that a -1.5 mm s^{-1} vertical wind should result in an increase of 22% in the OH emission intensity. We find, then, that the vertical velocities needed to produce the observed effects on the OH emission intensity and the sodium layer height are within a factor of 2. In view of the very approximate nature of our estimates for the parameters involved, especially the sodium lifetime and the eddy diffusion profile, a closer agreement should not be expected.

An alternative explanation for the inverse correlation between OH intensity and Na centroid height would be that the atomic oxygen acts as a reducing agent for sodium compounds. Photochemical models for the atmospheric sodium layer [Sze et al., 1982; Swider, 1986; Kirchhoff, 1986] suggest that chemistry is much more important on the bottomside of the layer than on the top. If this is the case, reduction by

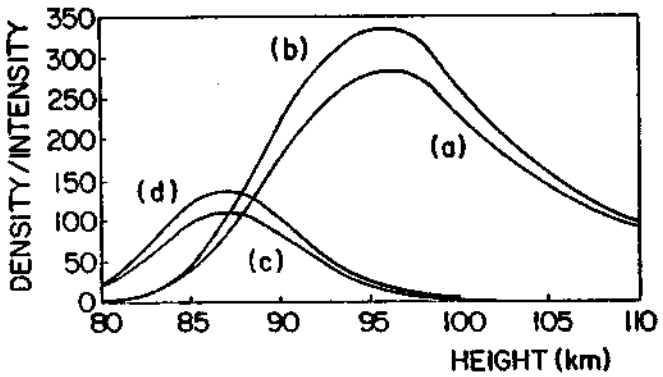

Fig. 7. Effect of a -1.5 mm/s vertical wind on atomic oxygen concentration and OH emission intensity: (a) density without wind and (b) with wind; (c) intensity without wind and (d) with wind. Arbitrary units.

increased atomic oxygen should preferentially increase the sodium density at lower heights, thus lowering the centroid of the layer. On the other hand, if such a chemical effect is taking place, the November peak in OH intensity would be expected to be accompanied by a maximum in the sodium abundance. No such effect is observed. Not only is there no significant change in the shape of the Na layer in November, but also the annual maximum in abundance, in August, coincides with a minimum in the OH intensity.

CONCLUSIONS

The analysis of a long time-series of measurements of atmospheric sodium and lower thermospheric airglow emissions shows a strong inverse correlation between the annual variations in the height of the sodium layer and the intensity of the OH(9,4) airglow emission. The most notable aspect of this correlation is a sharp November decrease in centroid height, accompanied by a sharp increase in the airglow emission. The increase in the airglow intensity is indicative of an increase in atomic oxygen concentration in the 85-90 km height range. The fact that the mixing ratio of atomic oxygen increases with height suggests that both effects could be caused by a downward vertical wind. We estimate that the wind velocity required is of the order of a few millimeters per second, well within the range expected for convective motions in the lower thermosphere.

Acknowledgment. This work was partially supported by the Fundo Nacional de Desenvolvimento Científico e Tecnológico (FNDCT) under contract FINEP-537/CT.

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(Received April 5, 1991;
revised December 2, 1991;
accepted December 5, 1991.)