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THE DIURNAL VARIATION OF ATMOSPHERIC SODIUM

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ABSTRACT

Continuous measurements of the vertical distribution of atmospheric sodium, made over a number of complete diurnal cycles, show the existence of strong semidiurnal oscillations in total abundance and height. The amplitude of the abundance variation, about 15% of the mean, is about twice that predicted for the 2,2 mode of the semi-diurnal tide, and its phase, with maxima at 0400 and 1400 LT, is in good agreement with tidal theory. The vertical oscillation, with an amplitude of 2 km at a height of 100 km, is about 3 times the expected amplitude, and the measured vertical wavelength of 38 km is in good agreement with theory, although the phase is not. A strong diurnal oscillation, observed only at heights below 82 km, is interpreted as being the result of photochemical reactions between sodium and other atmospheric constituents. The lack of any appreciable 24-hour component in the total abundance variation implies either a residence time for total sodium of more than 3 days, or source and sink functions whose diurnal variations, unless identical, are very small.

INTRODUCTION

The development of the laser radar technique has enabled a great deal of information about the vertical distribution of sodium and its nocturnal variations to be obtained. (Gibson and Sandford, 1971; Megie and Blamont, 1977; Simonich et al., 1979). Unfortunately, almost all of the lidar measurements have been restricted to nighttime, measurements during the day being much more difficult to make because of the high noise level produced in the lidar receiver by scattered sunlight. The only daytime data published so far is that of Gibson and Sandford, 1972, who presented the results of seven daytime measurements made in 1971 and 1972. These workers found no significant difference between mean daytime and nighttime abundances, in contrast to the dayglow results of Blamont and Donahue (1964), which were interpreted as showing a large daytime increase in abundance. It should be pointed out that Chanin and Gautail (1975) have shown that the large diurnal increase in sodium derived from the dayglow results could at least partly result from an inadequate consideration of the effects of the earth's albedo. Gibson and Sandford (1972) presented only one profile of the daytime distribution of sodium, and did not discuss the variation of this distribution over a 24-hour period. The purpose of this paper is to present the results of 24-hour measurements made over a period of 10 days in May 1981 at São Josẽ dos Campos (23^{o}S, 46^{o}W), and to discuss the diurnal variation revealed by these observations.

OBSERVATIONS

The basic laser radar used for our measurements has been described by Simonich et al (1979). In order to reduce the background noise to a level where daytime measurements were possible, the angular beamwidth was reduced from 1 mR to 0.2 mR, and the receiver bandwidth was reduced from 2 nm to 30 pm. The beamwidth reduction was achieved by using 30 cm collimator optics in the transmitter, and the reduction in the receiver bandwidth was obtained by means of a piezo-electrically tuned Fabry Perot interferometer having a free spectral range of

800 pm and a finesse of 27. The interferometer, used in conjunction with an 800 pm bandwidth interference filter, was tuned to the D_2 line by adjusting it to the minimum of the solar Fraunhoffer line. A further increase in signal to noise ratio was obtained by increasing the laser energy from 30 mJ to 60 mJ. Specifications for the lidar are given in the following tabulation.

Parameter	Nighttime value	Daytime value
Transmitted energy	30 mJ	60 mJ
Pulse duration	2 μs	2 μs
Repetition rate	0.4 s^{-1}	0.4 s^{-1}
Wavelength	589 nm	589 nm
Total transmitted bandwidth	10 pm	12 pm
Receiver area	0.39 m^2	0.39 m^2
Receiver bandwidth	800 pm	30 pm
Transmitter beamwidth	0.15 mR	0.15 mR
Receiver beamwidth	0.4 mR	0.2 mR
Receiver efficiency	2.4 %	0.7 %
Height interval	1 km	1 km

The lidar signal for 50 shots was accumulated in 33 range-gated 1 km intervals from 76 to 109 km. The signal from 109 to 119 km was recorded to provide the noise level to be subtracted from the signal, and the scattering from the lower atmosphere was recorded in 2 km intervals from 10 to 44 km. It should be noted that the transmitter and receiver beams of our lidar are almost coaxial, so there is no problem of lack of beam overlap in the lower atmosphere when using the 0.2 mR beamwidth. Details of the calibration procedure which takes into account variations in the laser output and the atmospheric transmission are given in Simonich et al (1979).

Four 50 shot profiles per hour were taken whenever weather conditions permitted from May 5th to May 15th, 1981. To facilitate subsequent data analysis these were averaged in approximmately 1 hour periods and interpolated to give regular hourly profiles. During the first week, early morning cloud cover prevented us from obtaining continuous 24-hour data, but during the second week continuous measurements were possible over a period of 100 hours.

RESULTS

The noise level for daytime measurements, is, of course, much higher than that for nighttime, with a consequent loss of precision in the profile obtained. In Figure 1a we show a typical daytime profile for 200 laser shots taken between 1430 and 1530 LT. The error bars in Figure 1a refer to the statistical uncertainty in the photon counting process in the usual way. Profiles taken closer to noon were generally noisier than that shown, and, conversely, closer to sunrise or sunset the profiles were less noisy.

In Figure 2 we show the results of the continuous run from May 11 to May 15. In Figure 2a, which shows the contours of constant sodium density between 79 and 107 km, a consistent diurnal variation in sodium distribution can be seen. At the lowest heights, around 80 km, a 24-hour period is noticeable, with maximum density occurring at sunset. This is particularly obvious on the 11th and 12th. On the topside of the layer a predominantly semidiurnal oscillation is visible, with density maxima at around 0600 and 1800 LT. The periodicities of these oscillations are more clearly visible in Figures 2b and 2c, where we have plotted the centroid height and the abundance respectively. The continuous lines in Figures 2b and 2c are 5 hour running means. The centroid height clearly shows both diurnal and semidiurnal oscillations, with minimum height occurring shortly after noon, and a total excursion of about 2 km. The abundance oscillation is mainly semidiurnal and has a peak amplitude of about 30% of the mean abundance. The phase of the abundance variation is somewhat variable, with maxima between 0200 and 0600 LT and between 1400 and 1800 LT.

In order to show the diurnal behaviour of the sodium layer more clearly we have plotted in Figure 3 averages for the periods May 5-8 and May 11-15. In Figures 3a and 3b we show contour plots of the average 24 hour variations. In Figure 3b maximum densities at the peak of the layer can be seen to occur at about 0300 and 1400 LT. At all heights between about 85 km and 100 km a semidiurnal oscillation in the height of the sodium isopleths can be seen to show a downward phase propagation. Below 82 km the oscillation is mainly diurnal, with maximum densities occurring at about 1800 LT. The measurements made between May 5 and 8 show similar variations, although less clearly, probably because of the data gap between 0300 and 0900 LT. The oscillations in centroid height and abundance are shown in Figures 3c and 3d respectively. From Figure 3c it can be seen that the centroid height starts to fall about 2 hours after sunrise, reaching a minimum at about 1500 LT, and subsequently rising rapidly to reach the nocturnal level about 2 hours after sunset. For a screening height of 30 km, sunrise and sunset at 90 km occur almost exactly at 0600 and 1800 LT respectively for our location in early May. A subsidiary minimum in the centroid height occurs at 0200 LT, and the maximum excursion is about 1 km. The abundance variation, shown in Figure 3d, is strongly semidiurnal, with maxima at 0400 LT and 1400 LT, and with a maximum excursion of about 30%.

DISCUSSION

The profile shown in Figure 1b is averaged over exactly 4 diurnal cycles, and thus any diurnal variations should cancel out. It is interesting to note that this profile does not differ significantly from the nocturnal average which we presented in Simonich et al. (1979). In particular the tendency for a secondary peak, or ledge, to form at around 85 km is apparent. When the observations are averaged over only 12 hours, as was the case in

Simonich et al. (1979), layer structure could be the result of diurnal tidal modes, expected to have fairly short vertical wavelengths. In the 96 hour average of Figure 1 b, however, any such tidal structure should cancel out, so we must conclude that the shape of the layer must be a result of the source distribution, the sink distribution or photochemistry. Model calculations by Kirchhoff et al (1981) do in fact confirm that a subsidiary peak in the sodium distribution can be produced by photochemical effects.

The lack of a diurnal variation in the total abundance of sodium has a number of implications with respect to the possible source and sink mechanisms for sodium in the upper atmosphere. Free sodium might enter the upper atmosphere either by direct evaporation from ablating meteors, or by sublimation from mesospheric aerosols. In either case the source should show a strong diurnal variation. In the case of meteor ablation the source will be modulated by the diurnal variation in meteor rates. According to Gadsden (1969) this modulation should amount to about 50% of the mean production rate. In the case of sublimation from aerosols Fiocco et al (1974) have shown that production should occur almost exclusively during the day, when the temperature of the particles would be raised by solar radiation to a point where sublimation could occur. In this case there would be an almost 100% modulation of the production rate. Unless the source variations are accompanied by similar variations in the sink, a diurnal variation in the sodium abundance would ensue, the amplitude of which depends on the residence time for sodium in the region of the layer. By residence time we mean the time between the first appearance of a sodium atom and its irreversible loss from the layer. Our results show that any diurnal variation has an amplitude of less than 5% of the mean, which, for a 100 % diurnally modulated source and a constant sink, implies a residence time greater than 3 days.

In view of the foregoing discussion, the observed lack of a diurnal variation in abundance appears to be in conflict with the sodium model recently proposed by Hunten (1981), in which sodium is produced by evaporation during metor ablation, and lost by photoionization. The ionization rates and ion drift velocities used by Hunten imply a residence time of about 12 hours, so a large diurnal variation in abundance should ensue. Apart from the effects of the variation in meteor rate, the virtual cessation of ionization at night would result in an approximately 60% increase in the sodium abundance between dusk and dawn. A possible way out of this problem would be to assume sublimation from aerosols as the source, instead of direct evaporation during ablation; in this case the production and loss terms would vary in a similar way over the 24 hour cycle.

The predominantly semidiurnal nature of the oscillations in the sodium layer strongly suggests that their origin is tidal. If we assume that the abundance variations are the direct result of tidal density oscillations then they are indicative of the presence of the 2,2 semidiurnal mode, whose vertical wavelength, according to an analysis of the sort presented by Chapman and Lindzen (1970), is much greater than the thickness of the layer, and whose phase is such that maximum density at all heights should occur close to 0300 and 1500 LT. The peak-to-peak amplitude of our measured abundance variation, amounting to about 30% of the mean, is about twice that which would be predicted by tidal theory.

The contour plots of Figure 3 suggest the presence of a tide induced vertical oscillation of the entire layer. In order to examine this oscillation in more detail we have plotted, in Figure 4, the relative density oscillation for various heights. To produce this figure we first normalized the 24 hour density variations for fifteen 2 km height intervals by dividing by the 24 hour density average of each interval. The data were then smoothed by taking a 5 hour running mean in time, and a 2 point (4 km) running mean in height. A clear downward phase propagation, indicated by broken lines, can be seen in Figure 4, with negative excursions from the mean above the layer peak corresponding to positive excursions below the peak, and vice versa, as would be expected for a vertical oscillation. Note that for visual continuity we have repeated the 24 hour variation in the figure.

The observed downward phase propagation does not agree with the predictions of Chapman and Lindzen (1970), who find negligible phase change in the semidiurnal tide over the height range in question. The work of Lindzen and Hong (1974), however, which takes into account mode coupling, predicts a phase progression, shown in Figure 4 as a continuous line representing the hour of maximum vertical wind. The agreement in vertical wavelength is good,our results suggest a value of about 38 km, as compared with around 32 km for the theoretical computations, but the phase does not agree. We should expect maximum vertical wind to occur about 3 hours before the maximum height of the layer, but in practice this does not occur. It should be noted that the theoretical predictions of Lindzen and Hong show little seasonal variation in the phase.

If the density variations shown in Figure 4 result mainly from vertical displacements of the layer, then we should expect the height at which the phase reversal occurs to coincide with that height at which the scale height of sodium is equal to the scale height of the major atmospheric constituents, i.e. where there is no vertical gradient in mixing ratio. Using the U.S. Standard Atmosphere for 15^{o}N (U.S. Standard Atmosphere Supplements, 1966) and our average sodium profile for the period in question, this height comes out to be 96 km, in excellent agreement with Figure 4. It would appear, then, that the major cause of the observed density variations is vertical motion of the layer induced by the semidiurnal tide. That this is not the only tidal effect, however, is evidenced by the existence of the semidiurnal oscillations in abundance which appears to be a result of the atmospheric density oscillations associated whith the semidiurnal tide.

Assuming the vertical oscillation which we observe in the sodium layer to be the direct result of the vertical tidal wind, we can use our results to estimate the amplitude of this wind. The sodium isopleths would not be expected to simply follow the vertical motions of the atmosphere because of density changes which result from vertical displacements of an air parcel in an exponential atmosphere. The parameter which should be conserved in vertical motion is the mixing ratio of sodium to the main atmospheric constituents. We have plotted this parameter, derived by dividing the densities of Figure 3b by the U.S. Standard Atmosphere for 15^{O}N in Figure 5. The vertical oscillations of the contours of Figure 5 should now represent movements of the atmosphere as a whole. It can be seen from the figure that the amplitude of the semidiurnal oscillation increases from 1 km at 89 km height to 2 km at 101 km. These amplitudes imply vertical semidiurnal tidal velocities of 15 cm s^{-1} and 30 cm s^{-1} respectively, somewhat higher than the predictions of Lindzen and Hong (1974) who calculated about 2.5 cm s^{-1} for the lower height and 10 cm s^{-1} for the upper level.

At 80 and 82 km the variation in sodium density visible in Figure 4 is mainly diurnal, with maximum density just before sunset, after which time the density falls rapidly. The effect of the build-up of sodium on the bottom-side of the layer during the day can also be seen in Figure 3c, in the form of a lowering of the centroid height. Some daytime loss of sodium on the topside, probably caused by ionization, also contributes to this height change. The much smaller semidiurnal oscillation in the centroid height is presumably the result of the tidal oscillation. Earlier nocturnal measurements (Simonich et al, 1979) have shown that the density at 80 km falls by an order of magnitude during the night. It seems probable that this large variation is photochemical in origin, rather than tidal. In most photochemical studies of the sodium layer, the most successful of which appears to be that of Liu and Reid (1979), sodium is oxidized, mainly by ozone, and reduced by atomic oxygen and hydrogen. An increase in sodium density during the day would be expected because of the decrease in ozone brought about by photolysis, and the consequent increase in atomic oxygen and hydrogen. The Liu and Reid (1979) treatment, which has been investigated in more detail by Kirchhoff et al (1981), would result in a rapid change in sodium density by more than an order of magnitude at a height of 80 km during the day-night transition, owing to the rapid change in ozone predicted by models such as that of Shimazaki and Laird (1972), and confirmed by observations of the hydroxyl emission (Moreels et al, 1977). Our experimental results clearly show that this rapid change does not happen. Modifications to the Liu and Reid model to bring it into better agreement with these new observations will be discussed elsewhere.

CONCLUSIONS

A series of twentyfour-hour observations of the atmospheric sodium layer made at S. José dos Campos confirm the conclusion of Gibson and Sandford (1972) that there is no significant day-night variation in the total abundance of atmospheric sodium. Our observations show the existence of a semidiurnal abundance oscillation whose phase is in good agreement with that predicted for the 2,2 solar semidiurnal density oscillation, and whose amplitude is approximately twice as large as the predicted amplitude.

The observations show the existence of a semidiurnal vertical oscillation in the sodium layer. It seems reasonable to suppose that this oscillation is the result of a vertical oscillation of the atmosphere produced by the vertical semidiurnal tidal wind. This appears to be the first direct measurement of the vertical displacement produced in the mesosphere and lower thermosphere by vertical winds. If our interpretation is correct, the amplitude of the semidiurnal vertical wind is of the order of 30 cm s^{-1} at a height of 100 km, approximately 3 times the amplitude predicted by Lindzen and Hong (1974). The vertical wavelength of the oscillation is about 38 km, in good agreement with Lindzen and Hong's predictions, which take into account mode coupling, but the phase does not agree with the theory.

The lack of a diurnal variation in the sodium density, except at the lower extreme of the layer, shows that either the residence time for total sodium in the 80-100 km region is greater than 3 days, or , unless they vary in phase,the source and sink functions have no large diurnal variations. By "total sodium" here we mean sodium and its compounds and ions with which it is in equilibrium, including aerosols only if sublimation of sodium from such particles occurs.

The fact that the ledge in sodium density which we observe at 85 km is apparent in profiles averaged over a number of 24-hour cycles indicates that it does not result from tidal perturbations of the layer, and is therefore most probably photochemical in origin.

The fact that the sodium layer appears to follow the tide induced vertical motions of the atmosphere suggests that 24-hour sodium measurements could provide an important tool for studying tides in the 80-105 km height region.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Fig. 1 - Vertical distribution of atmospheric sodium: (a) 1430-1530 LT, May 14, 1981; (b) Average for 0800 LT, May 11 to 0700 LT, May 15, 1981.

Fig. 2 - Sodium variations for period May 11-15, 1981. Density isopleths are in units of m^{-3}. The continuous curves in (b) and (c) are 5-hour running means.

Fig. 3 - Average 24-hour sodium variations: (a) May 5-8, (b) May 11-15, (c) and (d) show the centroid heights and abundances respectively; broken lines are for the period May 5-8 and continuous lines are for May 11-15.

Fig. 4 - Normalized average 24-hour sodium density variations for the period May 11-15, 1981. The broken lines show the phase propagation. Continuous line indicates the hour of maximum vertical wind from Lindzen and Hong (1974).

Fig. 5 - Sodium mixing ratio isopleths, 24-hour average variations for May 11-15, 1980.

REFERENCES

Blamont, J.E. and T.M. Donahue, Sodium dayglow: observation and interpretation of a large diurnal variation. J. Geophys. Res., 69, 4093-4127, 1964.

Chanin, M.L. and J.P. Goutail, Diurnal variation of the sodium dayglow, J. Geophys. Res., 80, 2854-2858, 1975

Chapman, S. and R.S. Lindzen, Atmospheric Tides, D. Reidel, Dordrecht, 1970.

Fiocco, G., D. Fua, and G. Visconti, Origin of the upper atmospheric Na from sublimating dust; a model, Ann. Geophys., 30, 517-528, 1974.

Gadsen, M., Antartic twilight observations 2. Sodium emission at 90^{o}S, Ann. Geophys., 25, 721-730, 1969.

Gibson, A.J and M.C.W. Sandford: The seasonal variation of the nightime sodium layer. J. Atmos. Terr. Phys., 33. 1675-1684. 1971.

Gibson, A.J. and M.C.W. Sandford. Daytime laser radar measurements of the atmospheric sodium layer, Nature, 239, 509-511, 1972.

Hunten, D.M., A meteor-ablation model of the sodium and potassium layers, Geophys. Res. Lett., 8, 369-372, 1981

Kirchhoff, V.W.J.H., B.R. Clemesha and D.M. Simonich, The atmospheric neutral sodium layer I, recent modeling compared to measurements, J. Geophys. Res., 86, 6892-6898, 1981.

Lindzen. R.S. and S. Hong, Effects of mean winds and horizontal temperature gradients on solar and lunar semidiurnal tides in the atmosphere, J. Atmos. Sci., 31, 1421-1446, 1974.

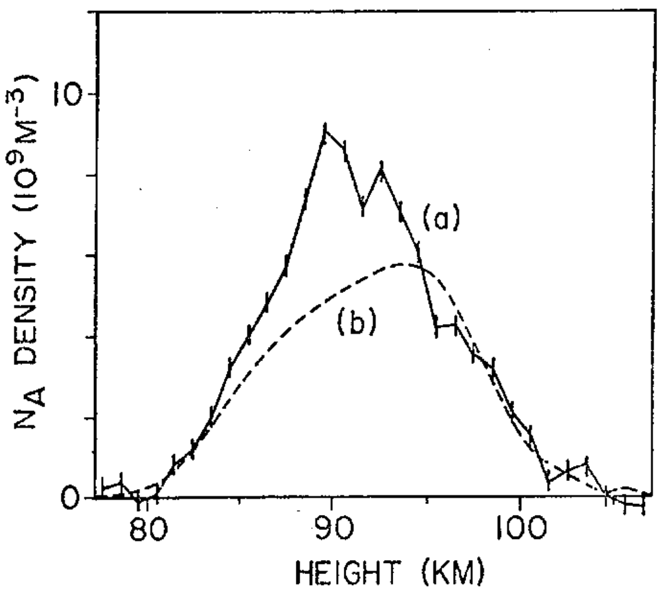
Liu, S.C. and G.O. Reid, Sodium and other minor constituents of meteoric origin in the atmosphere. Geophys. Res. Lett., 6, 283-286, 1976.

Megie, G. and J.E. Blamont, Laser sounding of atmospheric sodium: Interpretation in terms of global atmospheric parameters, Planet. Space, Sci., 25, 1093-1119, 1977.

Moreels, G., G. Megie, A. Vallance-Jones and R.L. Gattinger, An oxygen-hydrogen atmospheric model and its applicaton to the OH emission problem, J. Atmos. Terr. Phys., 39, 551-570, 1977.

Shimazaki, T., and A.R. Laird, Seasonal effects and distribution of minor neutral consitituents in the mesosphere and lower thermosphere, Radio Sci., 7, 23-43, 1972.

Simonich, D.M., B.R. Clemesha and V.W.J.H. Kirchhoff, The mesospheric sodium layer at 23^{o}S: Nocturnal and seasonal variations, J. Geophys. Res., 84. 1543-1550, 1979.



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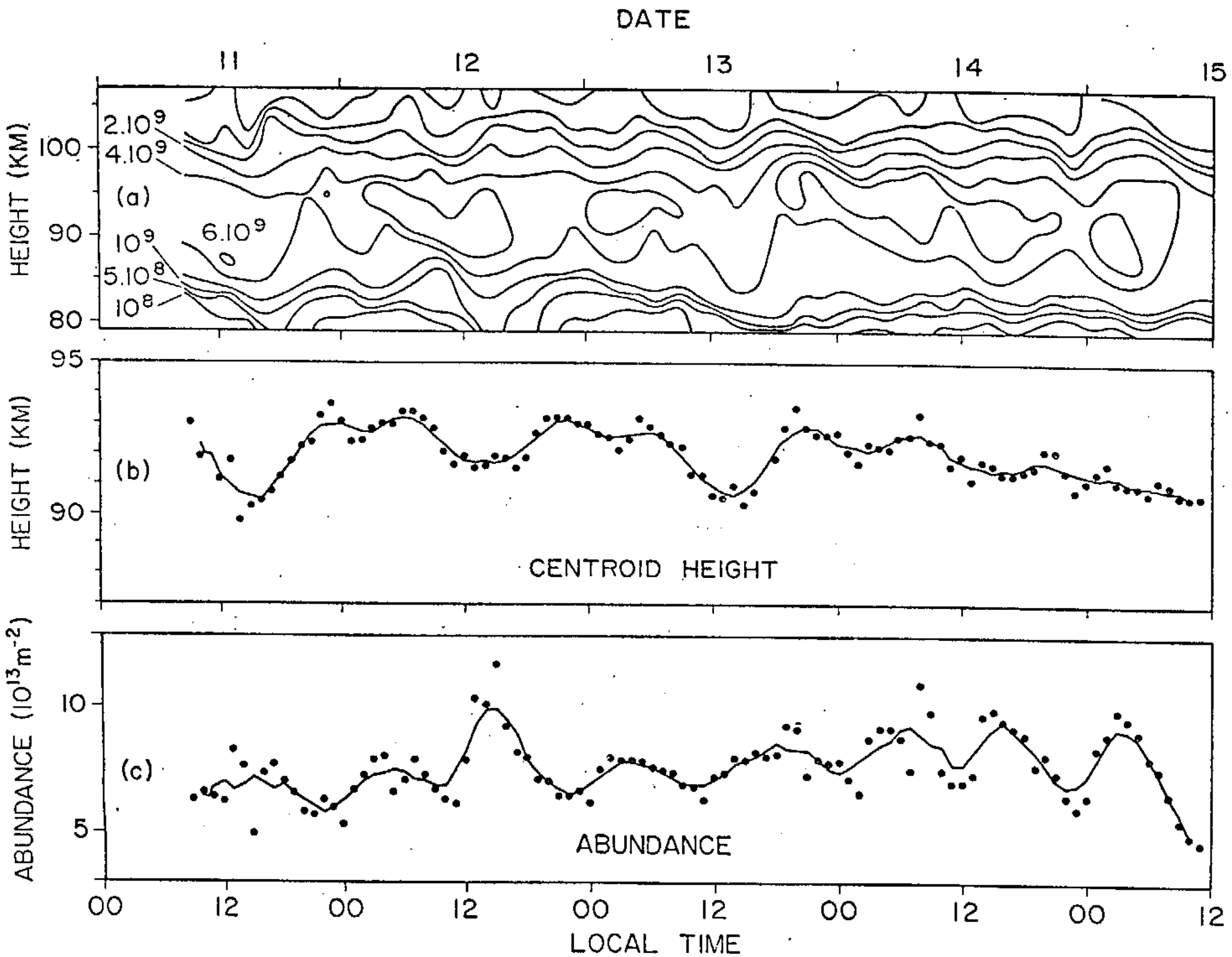

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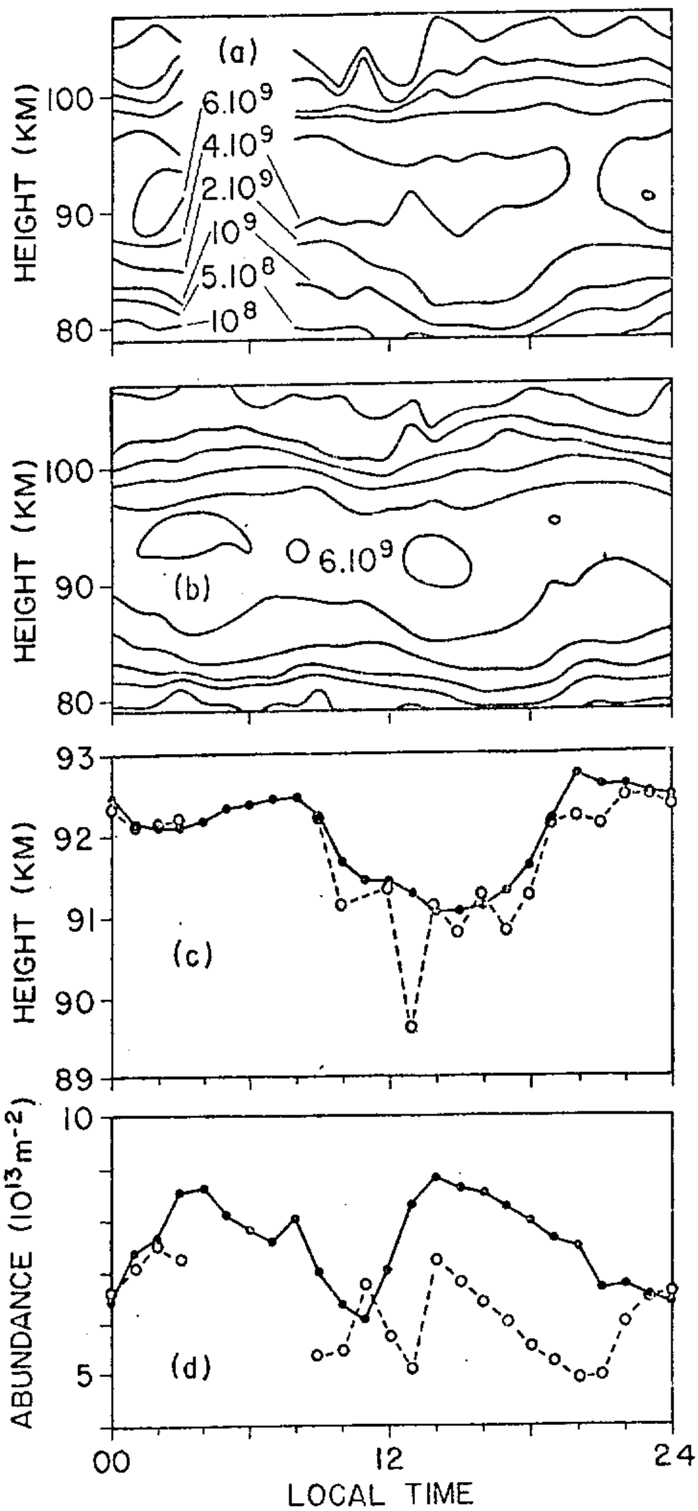

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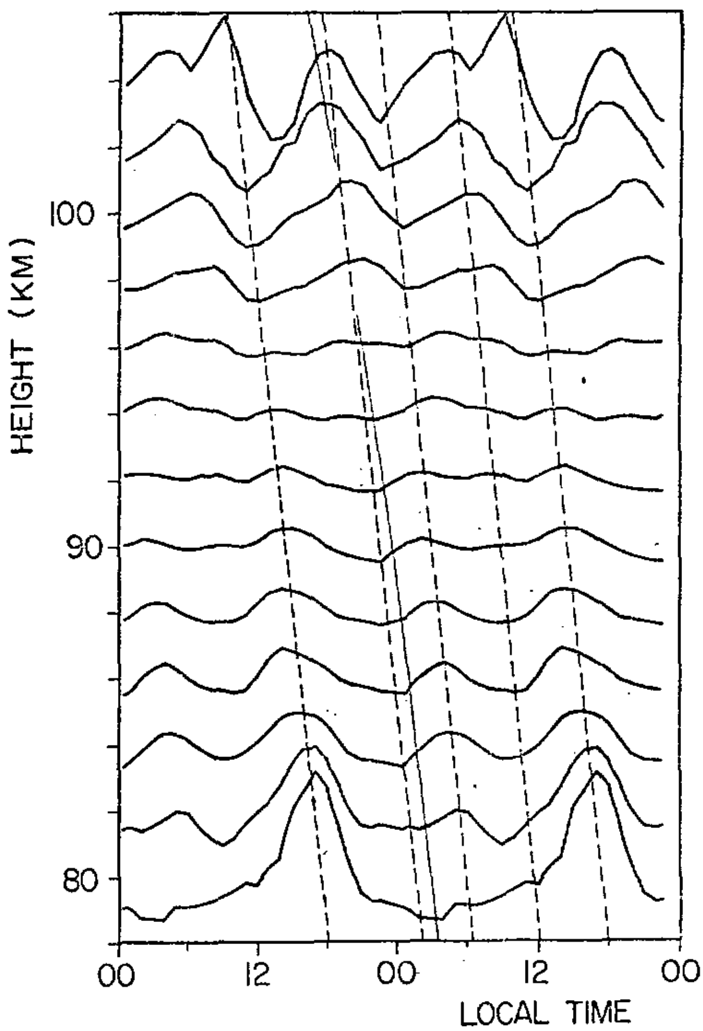

Figure 4 - Normalized average 24-hour sodium density variations for the period May 11-15, 1981. The broken lines show the phase propagation. Continuous line indicates the hour of maximum vertical wind from Lindzen and Hong (1974).

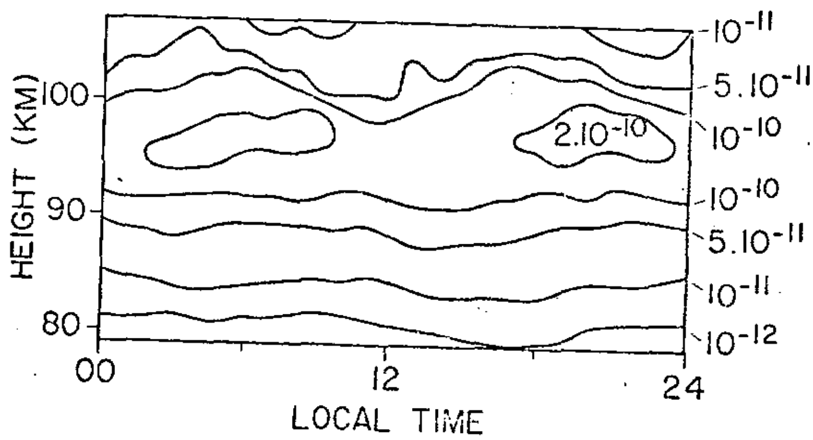

Figure 5 - Sodium mixing ratio isopleths, 24-hour average variations for May 11-15, 1980.