1.Classificação *INPE-COM.9/RRE*

2.Período *August 1975*

4.Critério de Distribuição:

interna ☐

externa ☒

3.Palavras Chave (selecionadas pelo autor)

5.Relatório nº *INPE-718-RRE/023*

6.Data *August 1975*

7.Revisado por - WGonzalez *W.D. Gonzalez*

8.Título e Sub-Título

MORPHOLOGY OF THE MESOSPHERIC SODIUM LAYER AT 23^{o}S

9.Autorizado por -

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Director

10.Setor *CEA* Código *4.01*

11.Nº de cópias - *30*

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14.Nº de páginas - *28*

15.Preço

13.Assinatura Responsável

16.Sumário/Notas

17.Observações *To be presented at IAGA Meeting in Grenoble, France.*

MORPHOLOGY OF THE MESOSPHERIC SODIUM LAYER AT 23^{o}S

by

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ABSTRACT

Laser radar observations of the night-time mesospheric sodium layer have been made at São José dos Campos (23^{o}S, 46^{o}W) from 1972 to 1975. The average height of the peak of the layer is found to be 93.5 km, the average centroid height is 92.2 km and the thickness 11 km. The average abundance is $5.0 \times 10^{13} m^{-2}$ and the average peak sodium concentration is $4.2 \times 10^{9} m^{-3}$. The total abundance of sodium shows a strong seasonal variation, with a maximum of $6.7 \times 10^{13} m^{-2}$ in winter, and a minimum of $3.3 \times 10^{13} m^{-2}$ in summer. The seasonal variation in the height of the layer is not greater than 1 km, with a possible minimum in summer. Below 82 km the scale height is less than 1 km, and above 100 km it is about 1.3 km. Profiles averaged over a few hours or less show considerable vertical structure to the layer; this structure is frequently observed to propagate downwards through the layer with a vertical velocity of about 1km hr^{-1}. Some of the implications of these results are discussed.

1. INTRODUCTION

We have been observing the mesospheric sodium layer at São José dos Campos (23^{o}S, 46^{o}W) since March 1972. Some preliminary results of these measurements were presented by Kirchhoff and Clemesha (1973). In this paper we present a considerably more complete study, based on measurements made up to August 1975.

The observations have been made using a laser radar tuned to the sodium D_2 line. The main characteristics of the radar are given in Table 1.

TABLE 1

SPECIFICATIONS OF THE LASER RADAR

Transmitted energy	20 mJ
Pulse duration	1 microsecond
Repetition rate	600 per hour
Wavelength	588.996 nm
Transmitted bandwidth	10 pm
Receiver area	0.39 m^2
Receiver bandwidth	1 nm
Receiver efficiency	2%
Height interval	2 km

Calibration of the sodium return is done by comparison with the Rayleigh scattering from a height in the 20 to 30 km range. Simultaneous observations of the scattering profile of this region allow us to choose a height free from aerosol scattering. Both the total laser energy, and the fraction of the output within the sodium resonance line (measured with the aid of a sodium vapour scattering cell) are monitored on a shot to shot basis. This information, together with a knowledge of the laser bandwidth (obtained by sweeping the laser frequency through the D_2 line and measuring the scattering cell output as a function of wavelength), provides a reliable calibration of the sodium returns. The laser is kept tuned to the D_2 line by an automatic tuning system (Clemesha et al., 1975).

2. GENERAL FEATURES OF THE LAYER

In Figure 1(a) we show a typical profile averaged for just over one hour of observation. The double peaked structure seen in Figure 1(a) is quite common in profiles averaged over short time periods. On occasions as many as three peaks may be maintained for several hours, but never over an entire night. In this respect our results are quite similar to those of Gibson and Sandford (1971), working in England at a latitude of 54°N.

An average profile for a period of seven hours, including the period covered by Figure 1(a), is shown in Figure 1(b). It may be seen that when averaged over the longer time period the distinct peak at 88 km is no longer present, although a ledge can be seen at this height. The

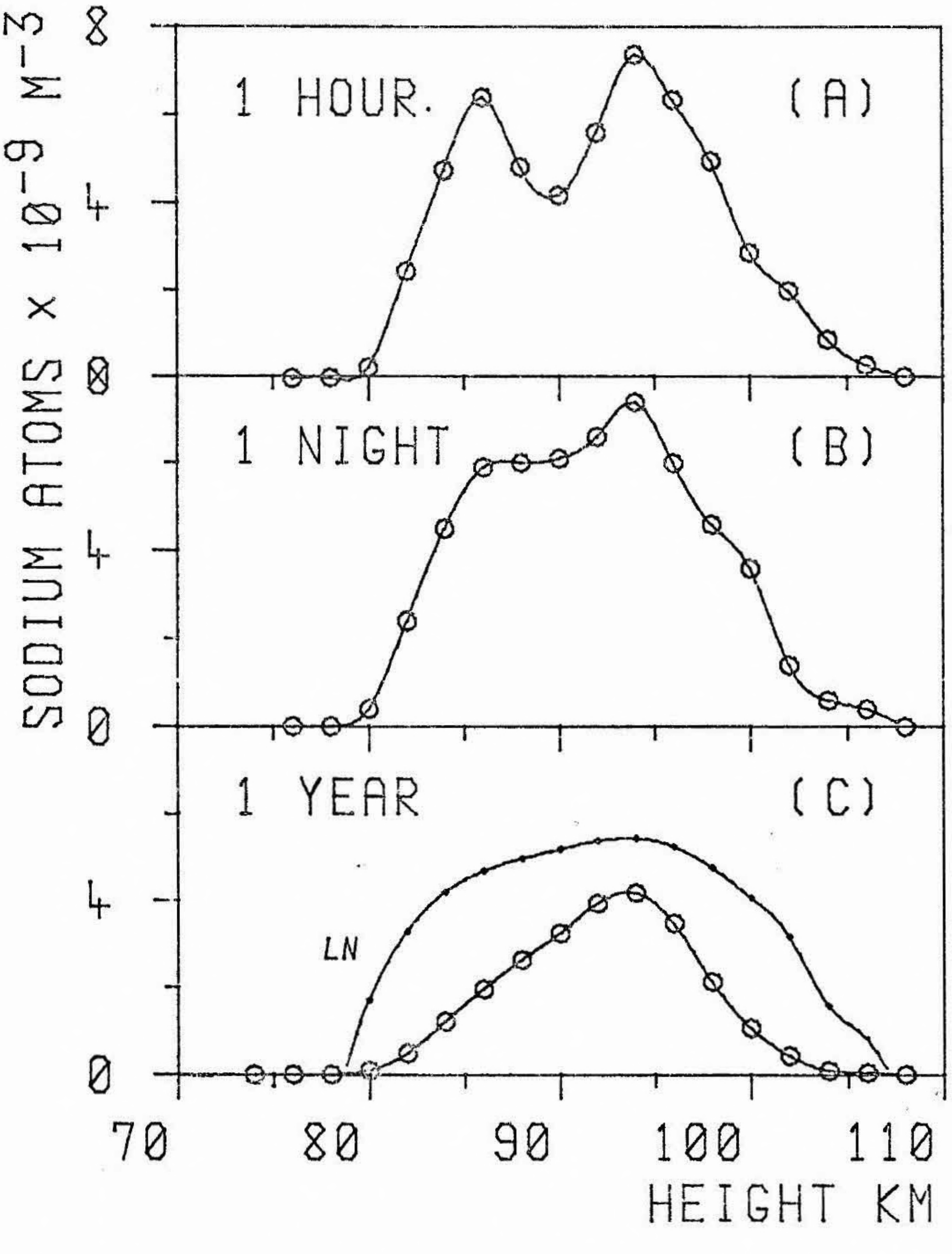

FIG 1 SODIUM DENSITY AVERAGED OVER VARIOUS TIME PERIODS

existance of a ledge at heights around 85 to 88 km is a very common feature of profiles averaged over a complete night. A slight indication of this feature is even present in the overall average profile shown in Figure 1(c).

The profile shown in Figure 1(c) is the average of the 12 monthly profiles shown in Figure 10, and discussed in section 4.2. It shows a well defined peak at 93.5 km, with the sodium concentration falling off rather more rapidly on the topside than on the bottom. The overall average abundance determined from this profile is 5.0 x $10^{13}m^{-2}$, the centroid height is 92.2 km and the width of the layer between points where the sodium concentration falls to half of the peak value is 11 km. Almost all of the sodium is contained within the region between 80 and 104 km. Scale heights are most clearly seen from the logarithmic plot included in Figure 1(c). Below 82 km the scale height is less than 1 km, and above 100 km it is about 1.3 km, so that although close to the peak, the density falls off more rapidly on the topside, at the extremities of the layer the decrease is most rapid on the bottomside. Even smaller scale heights than these may be observed over integration times of the order of one hour or less. On occasions the sodium density changes by more than one order of magnitude over a height range of 2 km.

3. NOCTURNAL AND DAY TO DAY VARIATIONS

3.1 Typical nocturnal variation

Figure 2 shows a sequence of profiles taken at 10 minute

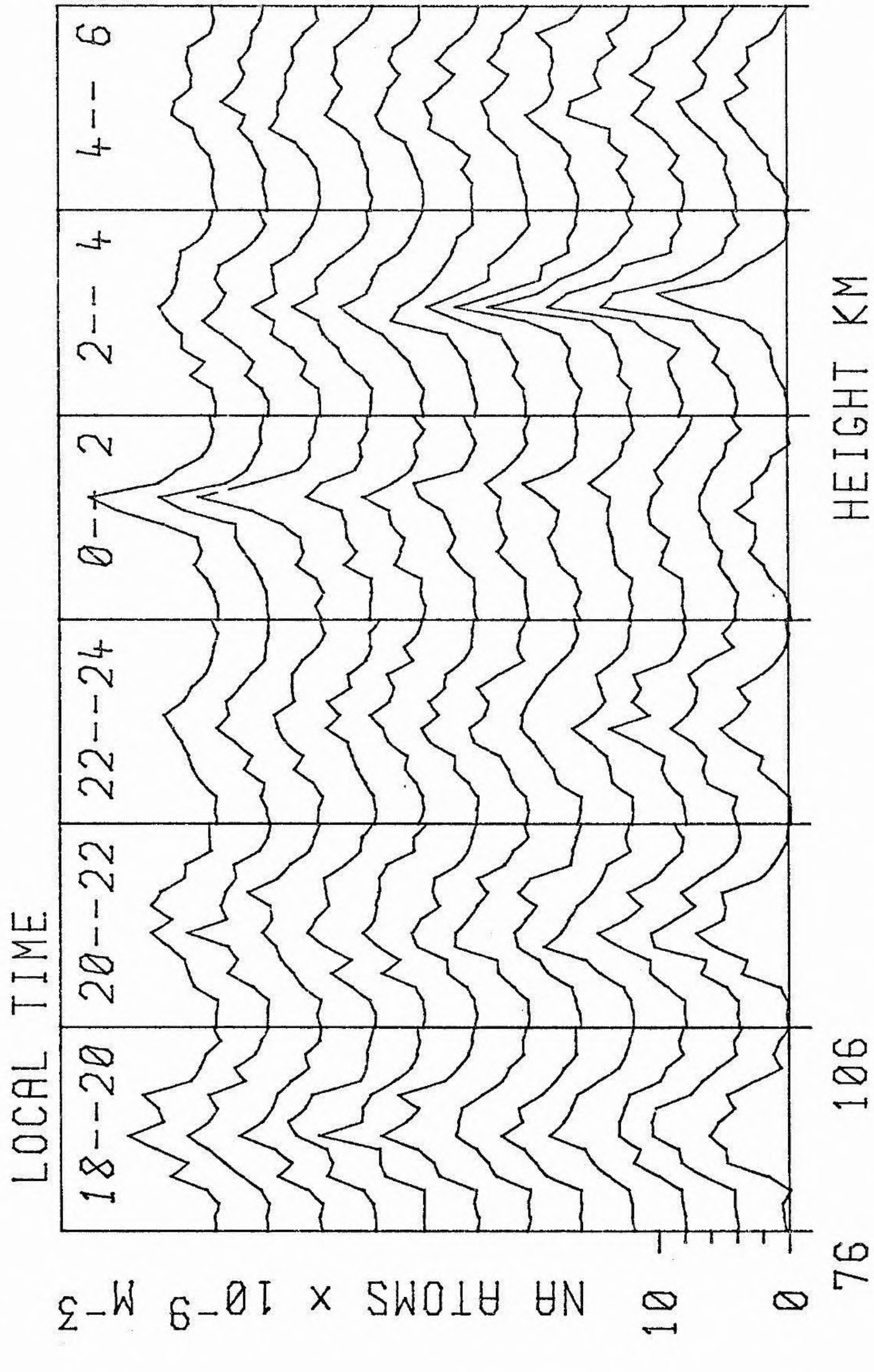

FIG 2 DENSITY VARIATIONS. JULY 23-24. 1975

intervals over a period of 12 hours on the 23rd/24th of July 1975. Although part of the fluctuation observed from profile to profile is due to photon counting statistics, it is quite clear that the layer undergoes very considerable modifications during the course of the night. Not only does the structure vary between single, double and triple-peaked forms, but the total abundance varies by more than a factor of 2, as may be seen from Figure 3, where the abundance is plotted as a function of time. In the average profile for the entire night, shown in Figure 4, the density varies fairly smoothly with height, with a slight ledge at 85 km. Although the narrow peak seen at around 0200 hours on the 24th of July is somewhat unusual, both the general variation in structure and the factor of 2 change in abundance are quite common.

In Figure 5 we have plotted the height variations observed during the course of the night. In this figure the values plotted as points represent the centroid height, and those plotted as crosses represent the peak height. Since the height resolution of our lidar is 2 km it is difficult to estimate the height of the peak of the layer to better than ±0.5 km, hence the apparent quantisation of this parameter. It is interesting to note that although the centroid height increases steadily throughout the night at a rate of a little more than 0.1 km per hour, with a superimposed short period oscillation having an amplitude of about 0.5 km, the peak height behaves quite differently, remaining close to 90 km until midnight, and changing almost discontinuously to about 96 km just after midnight. In the second half of the night the peak falls fairly regularly at a little more than 1 km per hour.

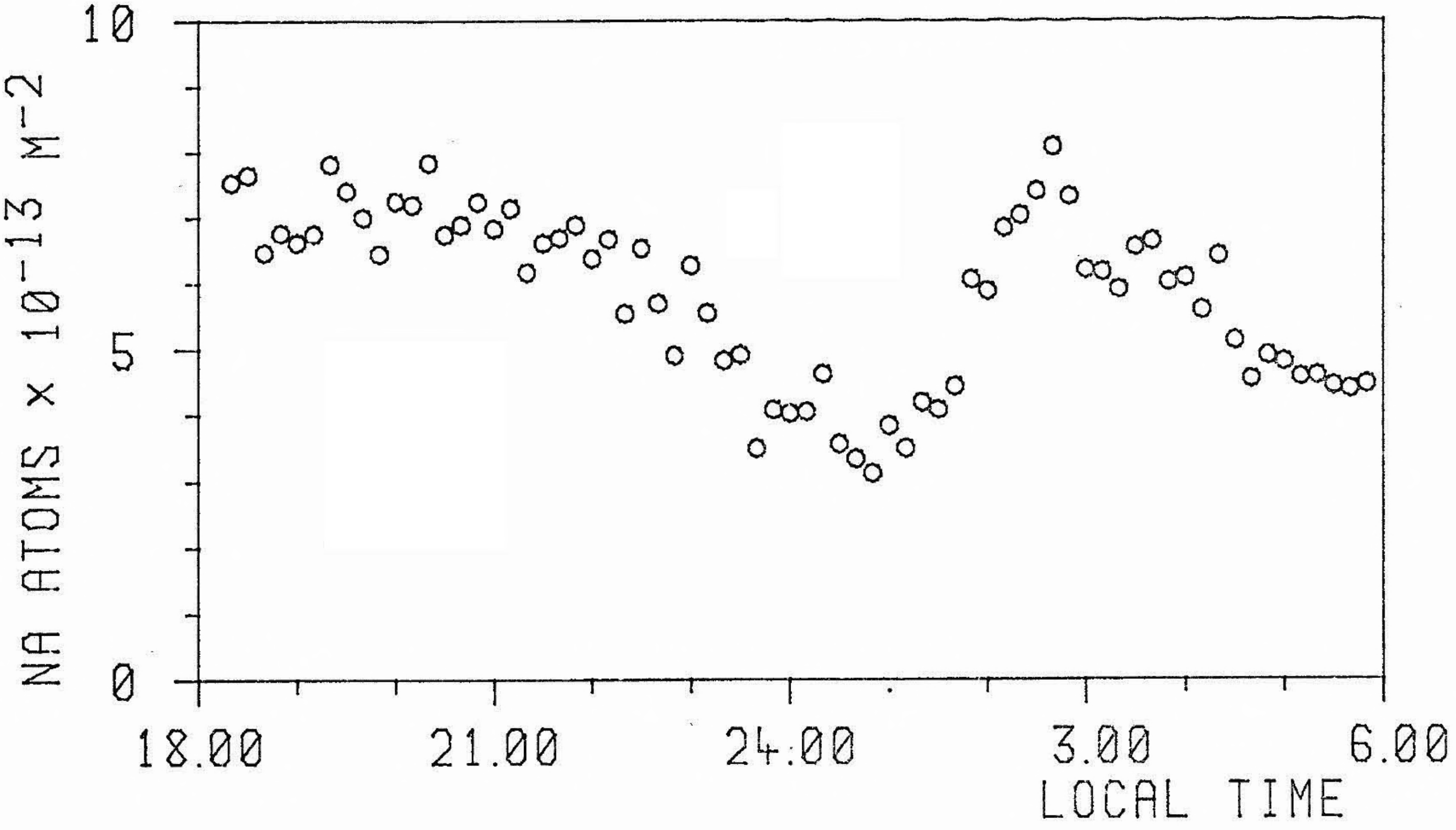

FIG 3 ABUNDANCE VARIATIONS, JULY 23-24, 1975

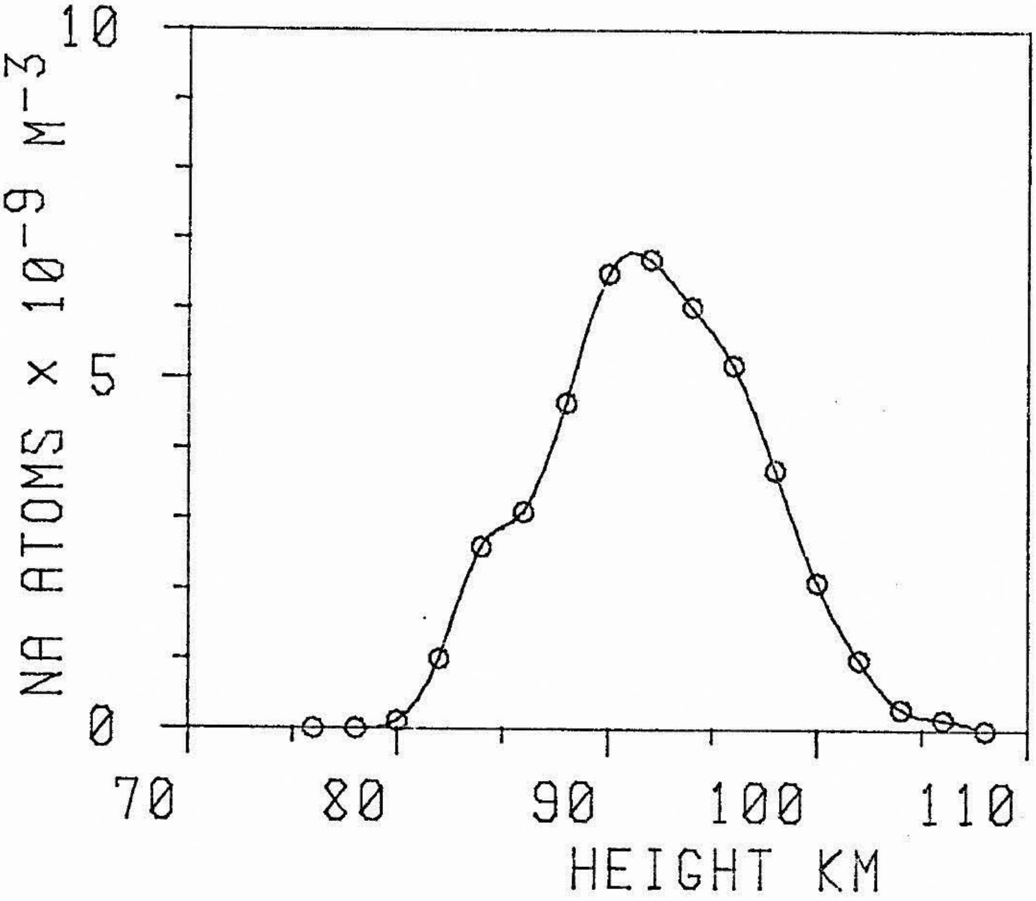

FIG 4 AVERAGE PROFILE. 23-24 JULY 1975

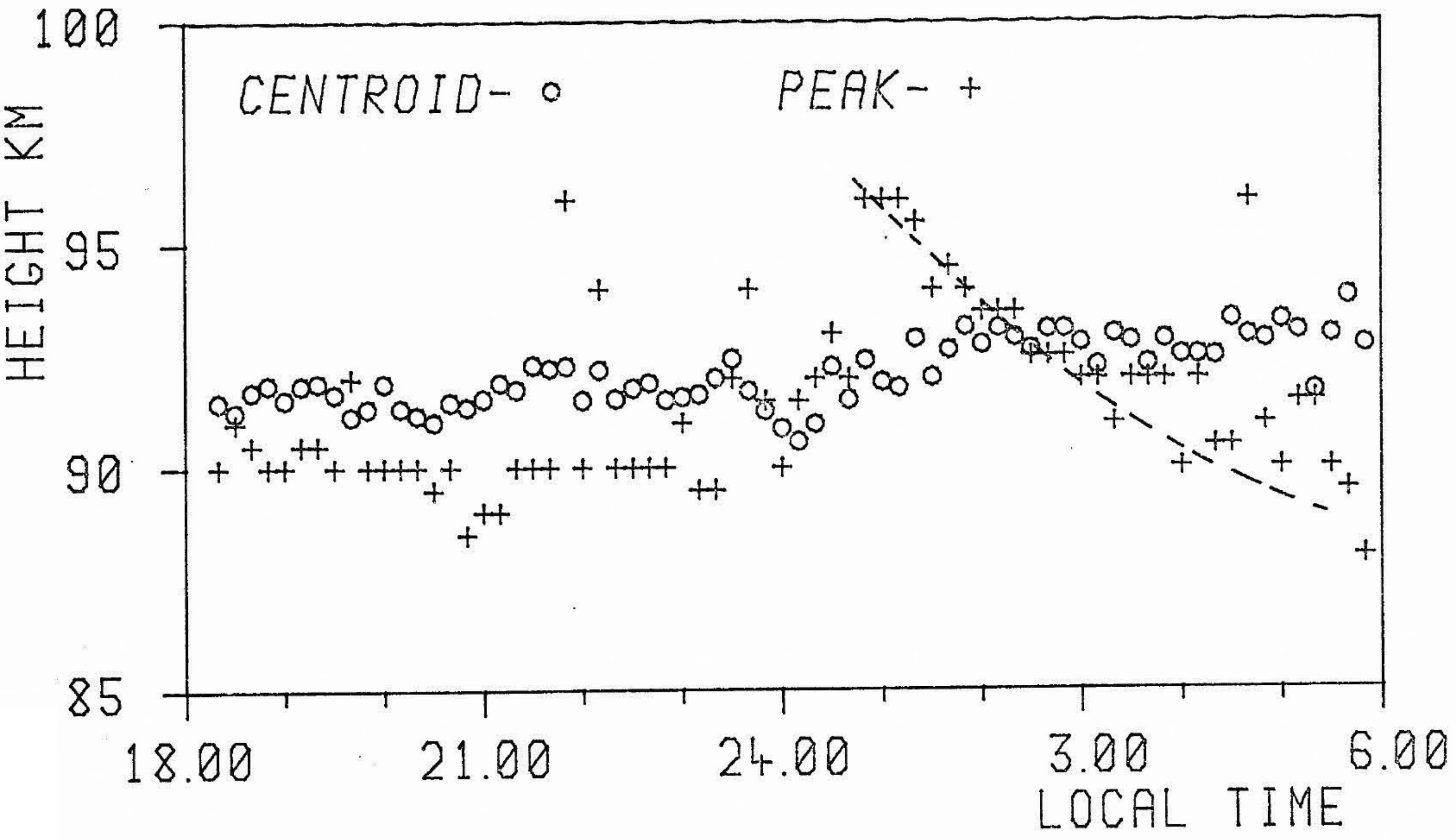

FIG 5 HEIGHT VARIATIONS, JULY 23-24, 1975

The steady increase in the centroid height throughout the night is not a consistent feature of the layer. As will be described in section 3.3, we do not observe any consistent trend during the night. The rapid decrease in the peak height observed to occur between midnight and 0600 hours on this occasion, is, however, frequently seen, although not at any fixed time. The variation observed on the 23rd/24th of July is unusually clear because of the uncommonly large amplitude of the descending peak. It is frequently possible to identify peaks which descend in height at a rate of about 1 km per hour, although such peaks may not necessarily constitute the principal peak of the layer throughout their existence.

3.2 Day to day variations

It is unfortunate that weather conditions and logistic considerations make it difficult for us to obtain measurements on many consecutive days. We do, however, have a number of sequences of measurements on consecutive or alternate days, lasting for a week or more. Two such sequence are shown in Figure 6. In each of these sequences it is clear that although considerable changes in abundance occur from night to night, involving more than a factor of two on some occasions, there exists a correlation both in total abundance and layer structure over a period of days. It should be noted that the time period over which measurements were made was not the same for each night in the sequence shown, and that the changes in abundance might well be smaller if always averaged over a full night. On the other hand, the 40% fall in abundance observed between the 23rd and 24th of July is undoubtably genuine, the measurements having

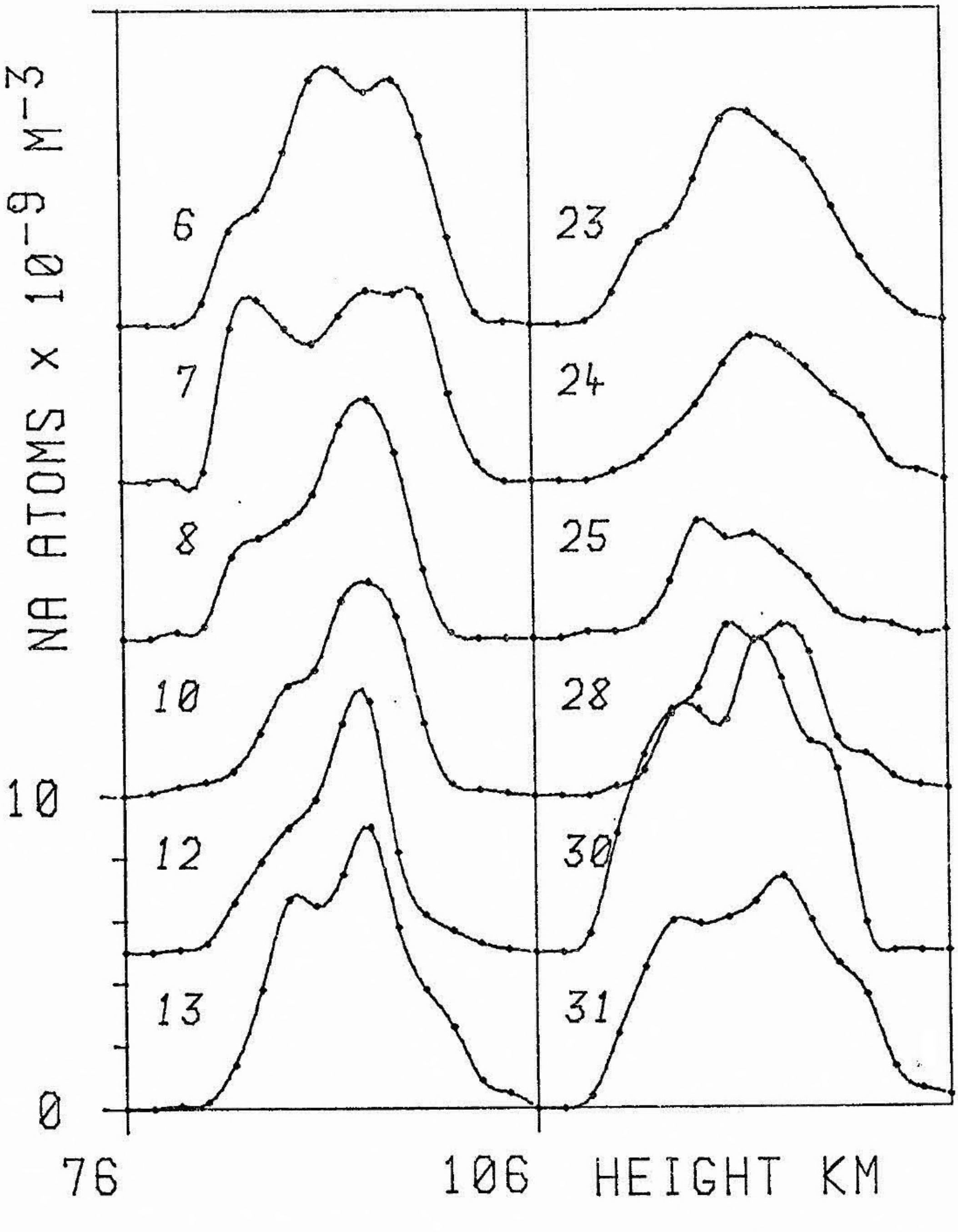

FIG 6 DAY TO DAY VARIATIONS

JULY 1975

been made over periods of 12 hours and 10 hours respectively on these particular days.

3.3 Average nocturnal variation

In order to look for a possible average trend in the structure or abundance during the night we have grouped our data into 4 time periods: (1) 1800 - 2059, (2) 2100 - 2359, (3) 0000 - 0259 and (4) 0300 - 0559. Data for individual days were then normalised by dividing by the mean monthly abundance and multiplying by the overall average abundance in order to remove the seasonal trend discussed in the next section. All available data in each time period were then averaged to give mean profiles for the 4 intervals. The profiles plotted in Figure 7 for periods 1, 2, 3 and 4 are the average of 125, 112, 24 and 7 profiles respectively. It is clear that there is no significant variation between periods 1 and 2. The difference in total abundance between the two periods is less than 5%, and the layer shape is almost identical. A considerably larger change occurs between periods 2 and 3 and 3 and 4, but considering the greatly reduced number of profiles obtained during these periods it is doubtful if the differences are significant.

4. SEASONAL VARIATIONS

Mean monthly profiles were calculated by averaging the mean profiles for all available 3 hours data periods for each month of the year. In Table 2 we show the number of profiles averaged for each month. and the number of days over which the profiles were taken. Note that measurements

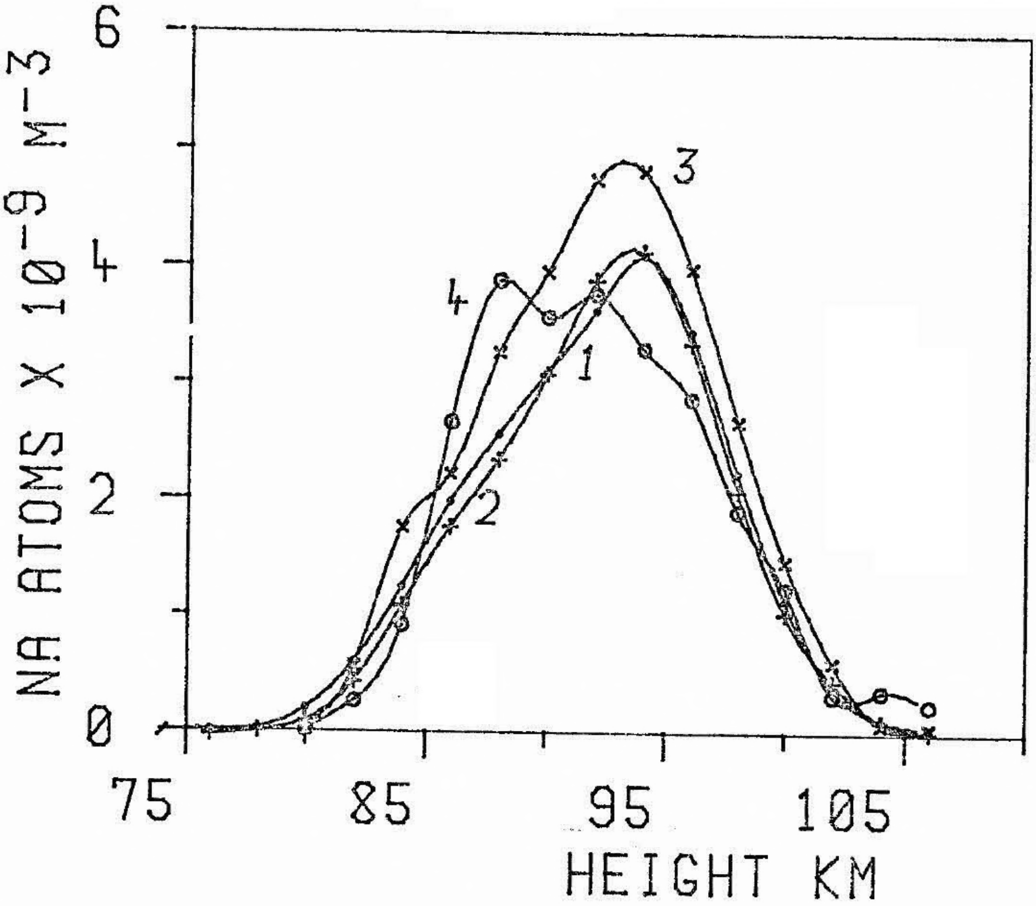

FIG 7 AVERAGE PROFILES. (1) 18-21. (2) 21-24. (3) 00-03 (4) 03-06.

were not always made over the entire three hour period, so that the total number of hours of observation is less than three times the number of profiles. Equal weight was given to each three hour period for which data are available, irrespective of the length of time over which observations were made within the period.

TABLE 2

DATA SUMMARY

MONTH	No. OF PROFILES	No. OF DAYS	TOTAL HOURS
January	13	7	14.7
February	42	20	55.2
March	4	2	6.5
April	21	13	22.5
May	50	29	72.2
June	22	17	28.5
July	49	29	83.0
August	16	14	17.6
September	8	6	5.9
October	16	10	13.0
November	18	10	24.7
December	8	4	8.6

Note that only 4 profiles taken on 2 days in 1972 are used to form the March average. Further data from March 1975 are available, but have not yet been included in the analysis.

4.1 Seasonal variation in the total abundance

For each mean monthly profile, calculated in the manner described above, the total abundance and centroid height were determined. Abundances for individual three hour periods were also calculated, and are mass plotted in Figure 8, along with the monthly means. Although the three hour averagesshow a very wide spread, the monthly means show a clear seasonal trend with winter maximum abundance of about 6.7×10^{13} m^{-2}, and a summer minimum of $3.3 \times 10^{13} m^{-2}$. The scatter of points in Figure 7 may be exagerated by short term fluctuations in the spectral output of our laser. The scattering cell monitoring system mentioned in section 1 was not installed until early 1975, so data taken prior to this date may contain total abundance errors of up to about 40%. We believe, however, that monthly averages based on the earlier data should not be in error by more than 20%.

4.2 Seasonal variations in the height distribution

In Figure 9 we have mass plotted the centroid heights measured for each available 3 hour period, and have also included the centroid height of the mean monthly profile. A minimum centroid height of 91.2 km is observed in November. In view of the very large scatter in the individual values, and the fact that only the November height is appreciably outside the range of the apparently random month to month changes, it is difficult

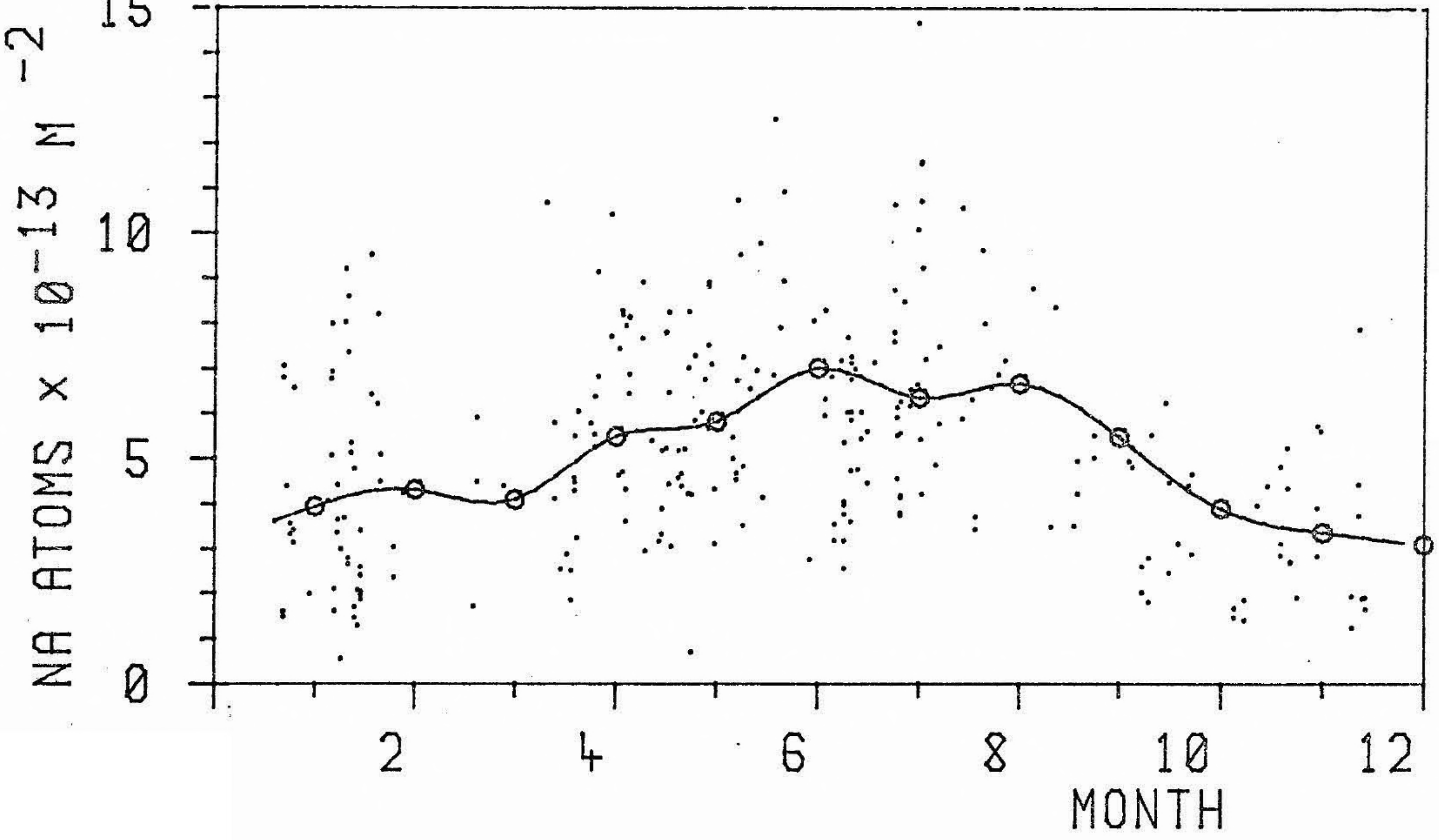

FIG 8 SEASONAL VARIATION IN ABUNDANCE

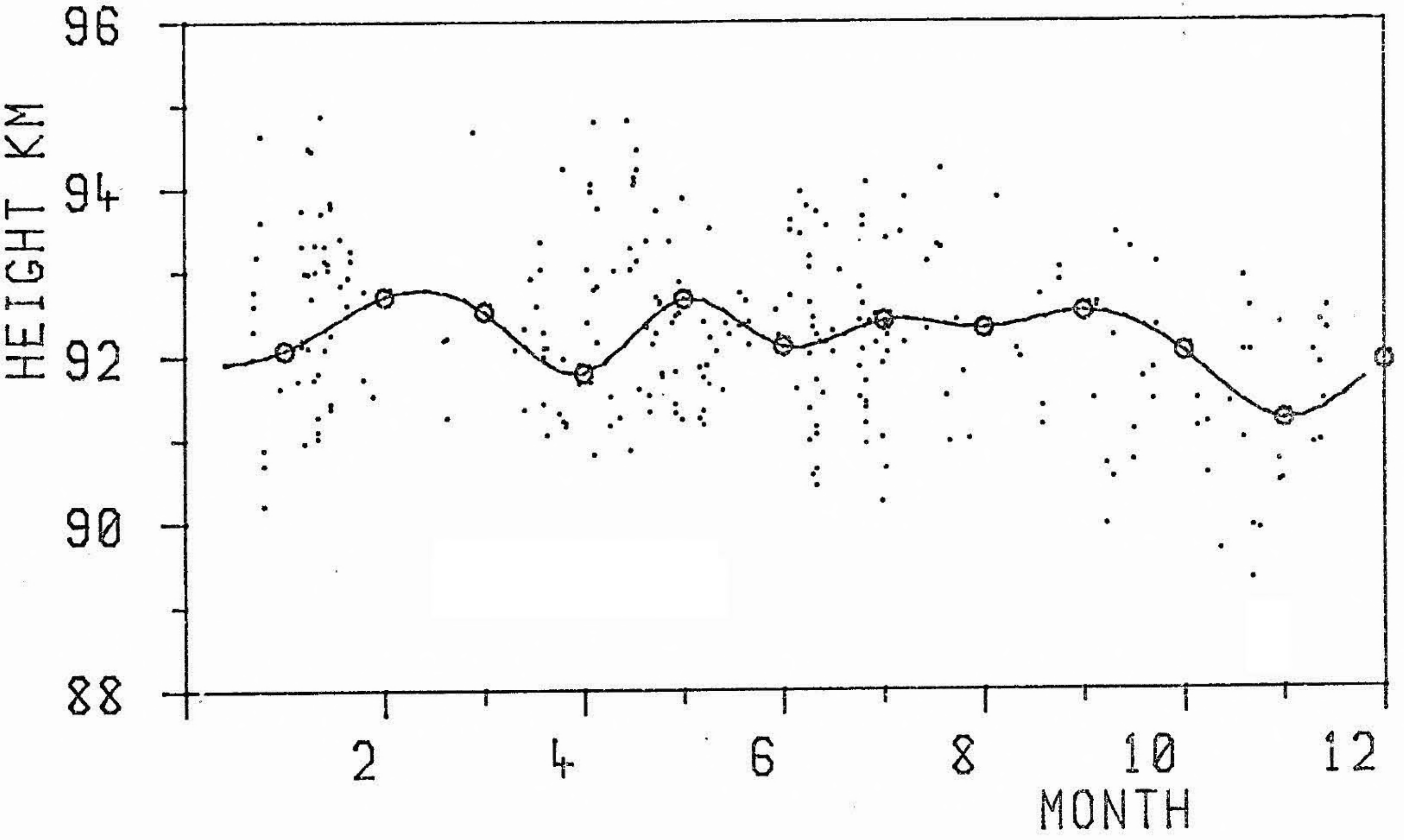

FIG 9 SEASONAL VARIATION IN CENTROID HEIGHT

to assign much significance to the variation.

The mean monthly profiles from January through December are plotted in Figure 10. Examination of these profiles shows that the increase in abundance from January to May is almost entirely due to the growth of a narrow peak of sodium extending from about 90 to 98 km. The months of maximum abundance, June, July and August show a wide peak, and from September to December the trend observed between January and May is reversed. It is interesting to note that the ledge at heights close to 88 km, referred to in section 2, is clearly visible on most of the mean monthly profiles.

5. DISCUSSION

The results presented in this paper appear to represent the first detailed study of the mesospheric sodium layer at low latitudes. Twilight studies have been made at Tamanrasset (23°N) by Blamont and Donahue (1961) and at Kitt's Peak (32°N) by Hunten (1967), and absorption measurements have been made at Boca Raton (26°N) by Burnett et al (1972), but these measurements give only very limited information about the layer.

The observations referred to above all show negligible seasonal variation in abundance. The lowest latitudes at which such a variation has been observed being 44°N (Haute Provence-Blamont and Donahue (1964)) and 44°S (Christchurch-Tinsley and Valance Jones (1962)). The large seasonal variation which we observe is therefore unexpected, and worthy of some discussion. It would appear that there are a number of possible

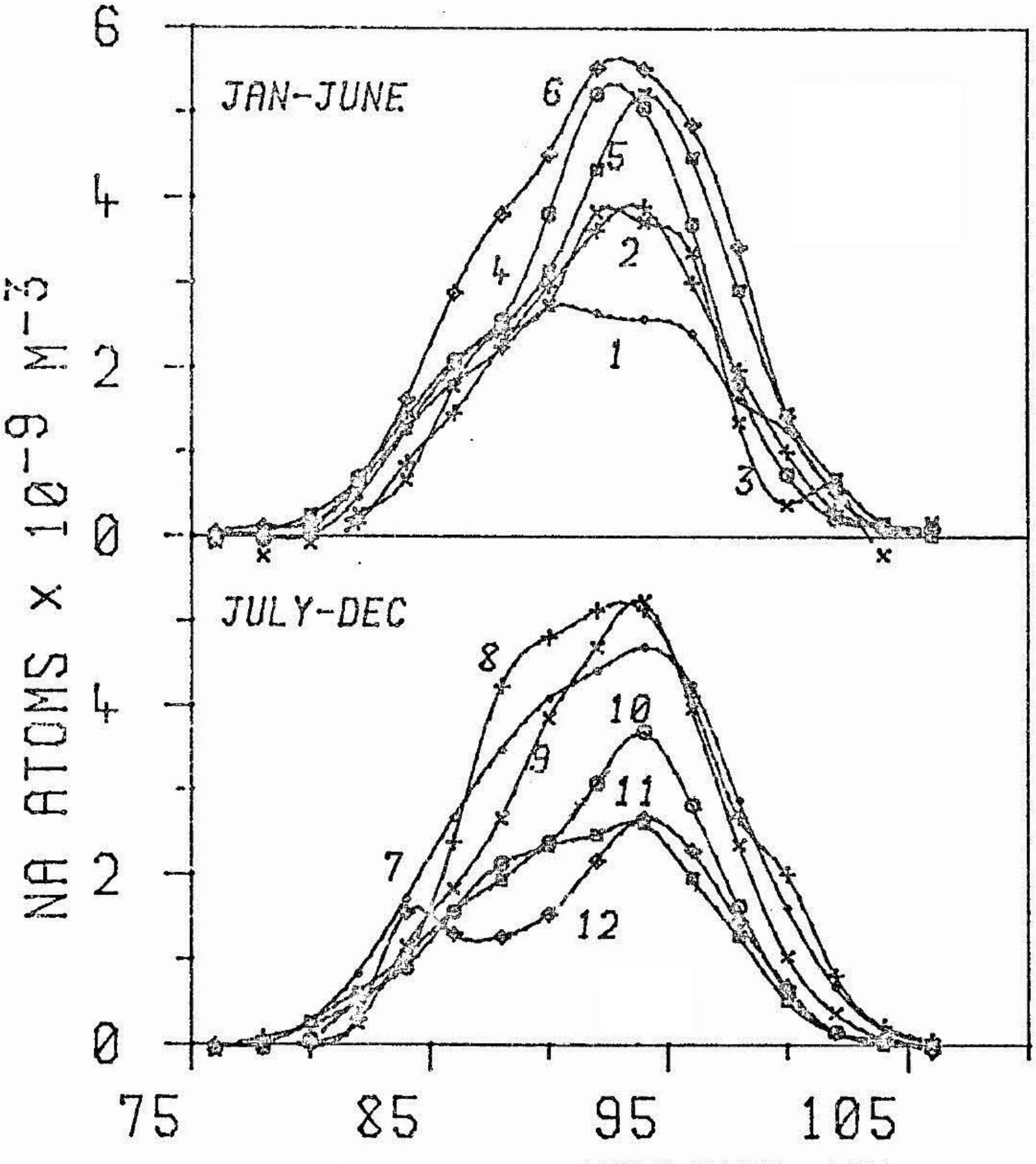

FIG 10 MEAN MONTHLY PROFILES

explanations of this discrepancy:

1. *Either the lidar observations or the twilight and absorption measurements are in error.* The possibility that the lidar measurements should be in error in such a manner as to show a large apparent seasonal variation during two consecutive years of observation is negligible. We believe that the absolute accuracy of any given measurement is better than ±20% for the 1975 results, and about ±40% for the earlier ones. Furthermore, we believe that the abundance averaged over many profiles is accurate to better than ±20% for the earlier measurements. The twilight and absorption techniques are intrinsically less accurate than the lidar, but, even so, it is difficult to believe that 3 separate sets of observations, using two different techniques, could be so much in error as to mask a factor of 2 seasonal variation.

2. *There is a long term change in the seasonal variation, either due to a sun spot cycle effect or due to a change in the seasonal variation in the input of sodium from meteorites or cometary dust.* The Tamanrasset observations were made in 1958, the Kitt's Peak in 1964 - 1966, the Boca Raton in 1967 - 1971 and ours were made in 1972 - 1975. It is conceivable that the observations are not directly comparable because they were made at different epochs. The sun spot cycle effect appears to be improbable because the Tamanrasset observations were made at sun spot maximum, whereas the Kitt's Peak measurements were made close to sun spot minimum. A secular change in the annual distribution of dust input to the upper atmosphere could possibly occur if an appreciable contribution were

due to dust recently released from comets.

3. The daytime and twilight abundances have a seasonal dependence different to that of the night-time abundance. This would imply a large difference between daytime and night-time. Observations of the sodium dayglow (see for example Gadson and Purdy (1970)) have indicated that the daytime abundance is much larger than the night-time, but the daytime lidar observations of Gibson and Sandford (1972) do not confirm this difference. These workers find a mean day/night ratio of 1.07 ± .06. Although the number of daytime lidar observations made was rather small, the intrinsically better accuracy of the lidar technique weighs heavily in its favour. Furthermore, since the abundance which we measure in winter is nearly twice that measured at Tamanrasset, the daytime density would have to be less than the night-time, rather than more. It would appear, then, that we cannot explain the difference between the northern and southern hemisphere results on the basis of a difference in the daytime and night-time abundances.

4. There is an annual variation in abundance in addition to a seasonal effect. If there were an annual variation with a maximum abundance in June/July, superimposed on the winter maximum, then they would reinforce each other in the southern hemisphere and it is possible that the two effects would approximately cancel at around 20 to 30°N. The seasonal variation observed by Tinsley and Vallance Jones (1964) at Christchurch (44°S) shows a ratio of about 4.6 between the winter maximum and the summer minimum. The same ratio for Haute Provence ($44^{o}N$), according to the results reported by Blamont and Donahue (1964), is about 2.8. It appears, then, that there is some evidence for a latitudinal assymetry in the seasonal variation in the required sense.

Of the four possibilities discussed above the last appears to us to be the most plausible. The required effect could result from an annual variation in the rate of accretion of sodium bearing extra-terrestrial material by the earth's atmosphere.

If our results are compared with those of Gibson and Sandford (1971), working at Slough ($54^{o}N$), a difference in the relationship between the height distribution and the total abundance can be noted. According to the Slough workers, the winter maximum is mainly due to an increase in the sodium density on the bottomside of the layer. We observe no such tendency, and in fact there is some indication that the layer is higher in winter than in summer, implying that the increase is greater on the topside.

If the seasonal variation in abundance observed by Gibson and Sandford is mainly caused by a seasonal variation in the distribution of the reacting species which give rise to the free sodium in the mesosphere, generally thought to be NaO, O and O_3, then the height variation in sodium would result from a seasonal change in the height distribution of these species. If, on the other hand, the winter maximum which we observe at $23^{o}S$ is largely due to a maximum in the input of sodium compounds to the atmosphere in June and July, we would not expect to see an appreciable height variation. It would appear, then, that the difference between the seasonal behaviour of the height distribution observed by us and that observed at 54°N could also be explained on the basis of an annual variation in sodium input to the atmosphere.

The general shape of the layer observed by us is similar to that reported by the Slough workers. In particular, we also observe a topside scale height of less than 2 km at heights above 102 km. Hanson and Donaldson (1967) have suggested that this unexpectedly small scale height, first observed in daytime rocket measurements (Hunten and Wallace 1967), could be due to a loss of atomic sodium on the topside by photoionization, balanced by an upward transport by eddy diffusion. Sandford and Gibson (1970) have pointed out that the small scale height measured at night does not support this theory unless the eddy diffusion coefficient at 100 km is much less than it is generally supposed to be. The scale heights, H, above 102 km for our mean profiles for the 1800 - 2059, 21 - 2359 and 0000 - 0259 hours local time periods lie between 1.2 and 1.7 km, and there does not appear to be a significant increase during the night. Assuming a typical diffusion coefficient, K, of 500 m^2 sec^{-1} the diffusion time, H^2/K, for these scale heights would be between 50 and 100 minutes. On this basis we would expect to see an appreciable increase in the topside scale height during the night, an increase which we do not in fact observe. In order for the scale height to be as small as 1.5 km, Hanson and Donaldson's theory would require the diffusion coefficient to be of the order of 50 m^2 sec^{-1}. The diffusion time would then be of the order of 12 hours, and the change in scale height during the night might be too small for us to detect.

In section 3.1 the considerable variation in the observed vertical structure of the layer which occurs during the course of a night was mentioned. These fluctuations were first observed by Sandford and Gibson (1970), who suggested that they might be due to irregularities of sodium density carried past the observation point by the horizontal motion of the atmosphere. Blamont et al (1972), noting that the vertical structure appears to exhibit a characteristic wavelength of about 6 km, similar to that observed in the mesospheric wind field, suggested gravity waves as its main source. Kirchhoff and Clemesha (1973), on the basis of an observed continuity in structure from night to night, and characteristic wavelengths of 6 to 12 km, suggested that the solar diurnal tide might be partially responsible. An interesting feature of our observations is the downward motion of the structure, clearly visible in figure 2. We believe that this motion provides strong support for the suggestion that the changes in structure are due to propagating atmospheric waves, rather than the horizontal drift of the layer. A detailed study of this aspect of our observations will appear elsewhere.

6. CONCLUSIONS

In this paper we have presented some results of a detailed study of the mesospheric sodium layer at a low latitude southern hemisphere station.

The seasonal variation in the total abundance of sodium shows a strong winter maximum, in contrast to the lack of seasonal change observed at low latitudes in the northern hemisphere. The most probable explanation of this behaviour appears to be that there is a maximum input of sodium to the earth's atmosphere in June/July. The lowering of the layer in winter, observed at 54°N is not observed at our latitude; this could also be explained by the supposition of a maximum sodium input in June/July.

The average scale height of the layer above 100 km is 1.3 km, and it does not vary appreciably during the night. If the topside of the layer is controlled by photoionization and eddy diffusion, then this implies that the diffusion coefficient is not greater than 50 m^2 sec^{-1}.

A downward propagation of the vertical structure of the layer with a velocity of about 1 km per hour is frequently observed. This is taken to imply that the structure is at least partially produced by atmospheric waves.

Although the total abundance may change by as much as a factor of 2 from one day to the next, both the abundance and the structure of the layer are correlated over periods of several days.

No consistent nocturnal trend in total abundance or layer height is observed.

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