THE SEASONAL VARIATION OF NIGHT-TIME SODIUM LAYER AT 33°N

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Abstract: Measurements of the night-time mesospheric sodium layer have been performed since 1977, using a dye lidar at Fukuoka (33.4°N, 130.2°E). The results measured during 1983 are presented in this paper. The annual average in abundance ($4.2\times10^{13}/m^2$) is in good agreement with twilight observation made at Kitt Peak (32°N) and lidar measurements at São José dos Campos (23°S). The annual average of peak height is 93 km. Averaging the measurements every three months except for the value on the peak day of the shower, the sodium abundance shows seasonal variation by a factor of 2 with maximum ($5.3\times10^{13}/m^2$) in winter and with minimum ($2.6\times10^{13}/m^2$) in spring. The abundance increased on the night during the Perseids meteor shower, which is remarkable, since such correlative increment to permanent meteor shower has not been seen at low latitudes by lidar or twilight observations.

1. Introduction

Since the first lidar measurements of the night-time sodium layer were taken by BOWMAN *et al.* (1969), several research groups have observed the seasonal variation of the night-time sodium layer (GIBSON and SANDFORD, 1971; MEGIE and BLAMONT, 1977; SIMONICH *et al.*, 1979; CERNY and SECHRIST, 1980). Unfortunately, almost all of the lidar measurements have been restricted to middle latitude in the northern hemisphere. The only lidar measurement at low latitude is that at São José dos Campos (23°S, 46°W) (SIMONICH *et al.*, 1979). These workers indicated that large day-to-day variations are observed, but the average over a large number of measurements consistently shows an annual variation by a factor of 2 in the sodium abundance with maximum in local winter. SIMONICH *et al.* pointed out that twilight observation made at Tamanrasset (23°N) shows no significant seasonal variation, which is surprising since one would expect to see a seasonal effect similar to that at 23°S, with a 6-month phase lag. Moreover, no significant seasonal variation of the sodium content was observed at our latitude in the northern hemisphere as shown by the results obtained at Kitt Peak, Tuscon (32°N) (HUNTEN, 1967). These twilight technique is, of course, restricted to sunset and sunrise, moreover to coarse height resolution due to uncertain assumption. Hence, lidar will be necessary to observe the seasonal variation of sodium layer at low latitude in the northern hemisphere, in order to make clear the puzzling information mentioned above. The purpose of this paper is to present the results measured during 1983 at Fukuoka (33°N) and to discuss the seasonal variation revealed by these observations.

2. Observation

The Kyushu lidar uses a flashlamp pumped dye laser tuned to the sodium D_2 line (589.0 nm) as a transmitter. The dye laser used in the Kyushu lidar system has been described (NAGASAWA *et al.*, 1980; NAGASAWA, 1983). The parameter of the Kyushu lidar system are presented in Table 1.

Table 1. Performances of the lidar system.

Laser		Receiver	
Wave length	589.0 nm	Area	0.19 m^2
Energy	1.0 J/pulse	Field of view	10 mrad
Line width	10 pm	Band width	1.0 nm
Pulse width	2 μs FWHM	Counter gate	10 μs
Repetition rate	0.25 Hz		
Beam divergence	0.5 mrad		

Following CERNY and SECHRIST (1980), an expression relating the number of photocounts originating from a specific altitude range Z_i to the sodium density ρ_i is given by

$$\rho_i = \frac{\sigma_r(\pi)(Z_i + \Delta Z/2)^2 \rho_r}{\sigma_{\mathrm{eff}} Z_r^2 T_{\mathrm{u}} T_{\mathrm{d}}} \frac{N_i}{N_r},$$

where

Z_i; altitude of the i-th range bin
ΔZ; thickness of the range bin
Z_r; normalizing altitude
ρ_r; air molecule density at Z_r
$\sigma_r(\pi)$; Rayleigh scattering cross section at Z_r
σ_{eff}; effective resonant scattering cross section
N_i; the number of received photocounts returned from Z_i
N_r; the number of received photocounts returned from Z_r
ρ_i; average sodium density at Z_i
T_{u}, T_{d}; upwards, downwards transmission through the sodium layer.

Thus, the sodium density is deduced by normalyzing N_i with N_r. Accordingly, it is important to select Z_r adequately. Then, there are two criteria to be considered. First, the photocounts returns from normalizing altitude must be due to Rayleigh scattering. Secondly, a small amount of laser pulse is attenuated by aerosol as it propagates from Z_r to the bottom of the sodium layer, but Z_r must be high enough to neglect it. Since we can anticipate the amount of aerosol above about 30 km from our Nd–YAG lidar observation, Z_r can be selected so as to satisfy these criteria. Z_r=30–35 km is usually selected.

Figure 1 shows the mean column number density of sodium for each night on which observations were made. The average density is $4.2 \times 10^{13}/\mathrm{m}^2$. The layer has less abundance during March–May, and more abundance during August–October and December–January. The variation in abundance during the Perseids meteor

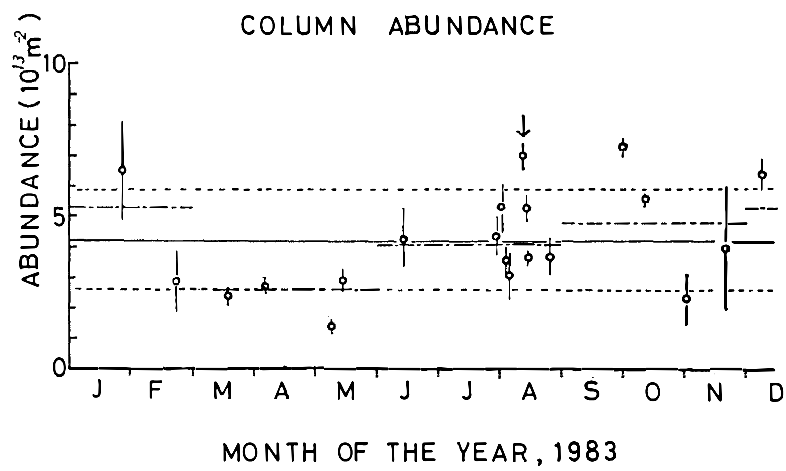

Fig. 1. Seasonal variation of Na total column abundance (1983). The arrows correspond to anomalous values correlated with the Perseids meteor shower. The solid line represents the average, the dashed lines are one standard deviation above and below the average and the dashed-and-dotted lines are the average over three months.

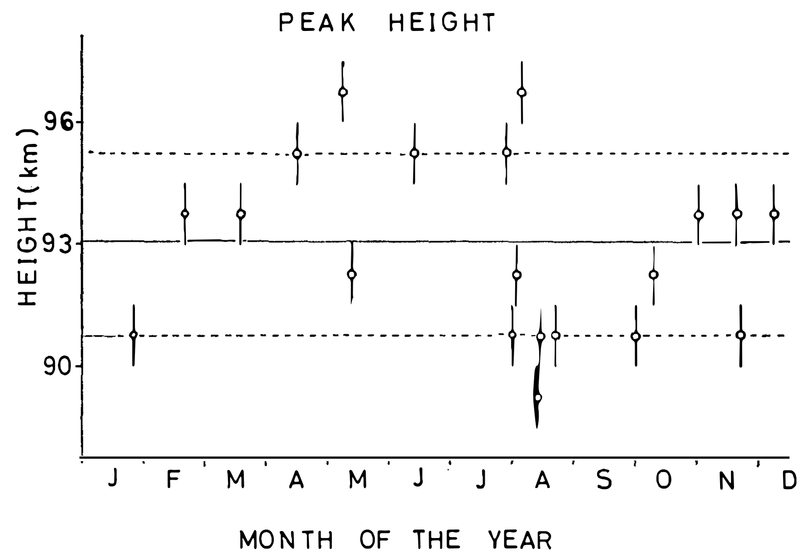

Fig. 2. Seasonal variation of the height of the maximum density. The solid line represents the average and the dashed lines are one standard deviation above and below the average.

shower had the maximum $7.0\times10^{13}/m^2$ (nocturnal average) on August 12, 1983. After the Perseids meteor shower, the abundance went back to monthly mean on the following day. Averaging the measurements every three months except for the peak value of the meteor shower day, the sodium abundance shows seasonal variation by a factor of 2 with maximum ($5.3\times10^{13}/m^2$) in winter and with minimum ($2.6\times10^{13}/m^2$) in spring (Fig. 1). The variation of the altitude of the peak of the layer during the year is shown in Fig. 2. The average peak height is 93 km. The peak is higher in February–July, and lower in August–October. The variation of the density of the peak during the year is shown in Fig. 3. The average peak density is $3.3\times10^9/m^3$. It increased in September–October, decreased in March–May. Figure 4 shows top side scale height

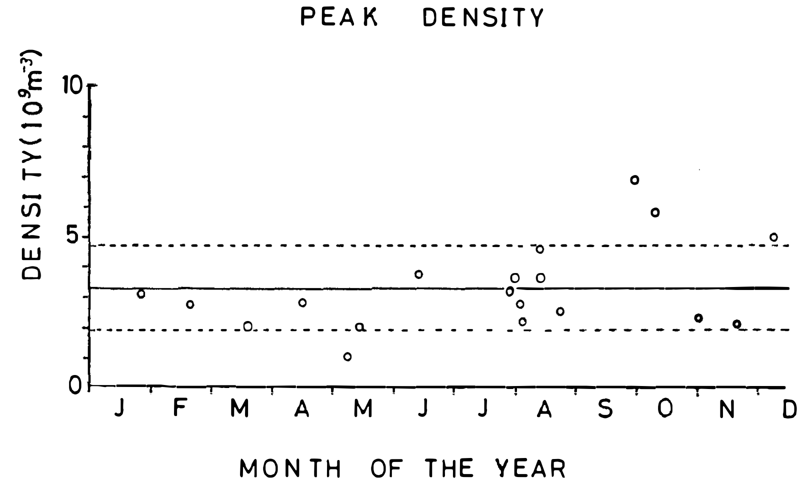

Fig. 3. Seasonal variation of the maximum density of the Na layer. See also the caption of Fig. 2.

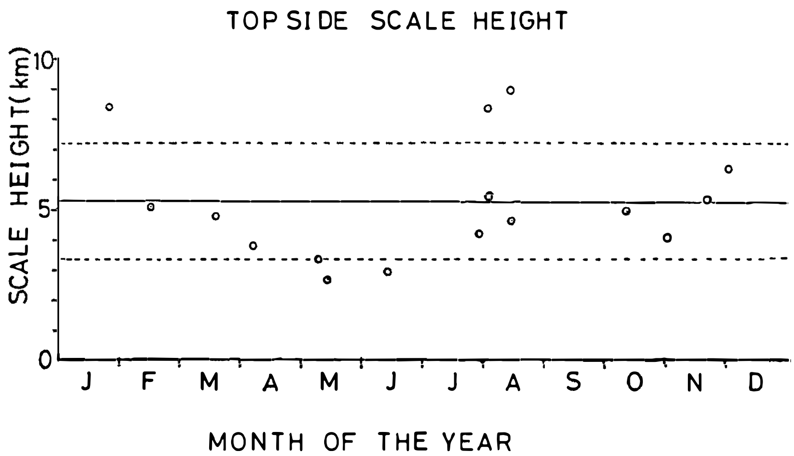

Fig. 4. Seasonal variation of the top side scale height. See also the caption of Fig. 2.

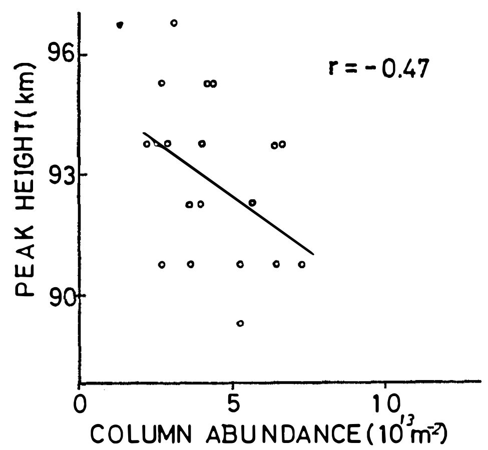

Fig. 5. Correlation between the column abundance and the peak height.

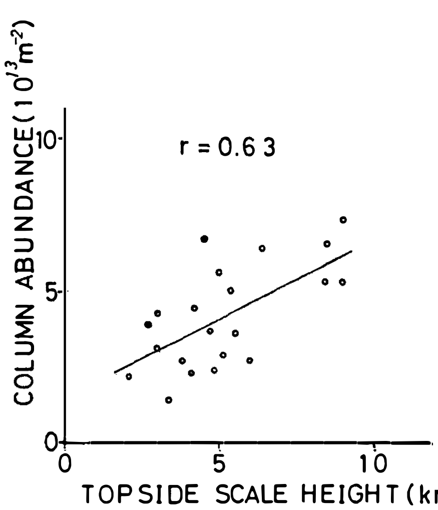

Fig. 6. Correlation between the top side scale height and the column abundance.

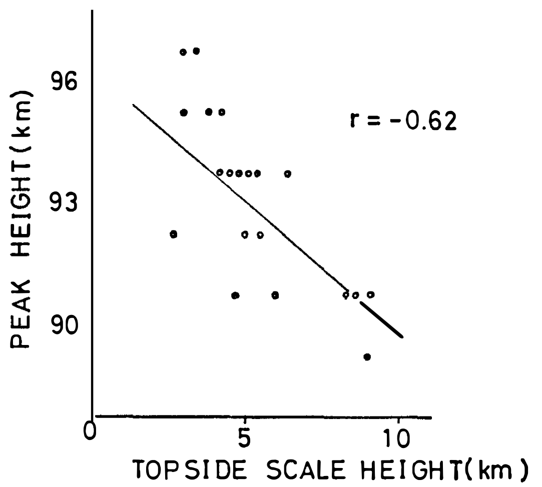

Fig. 7. Correlation between the top side scale height and the peak height.

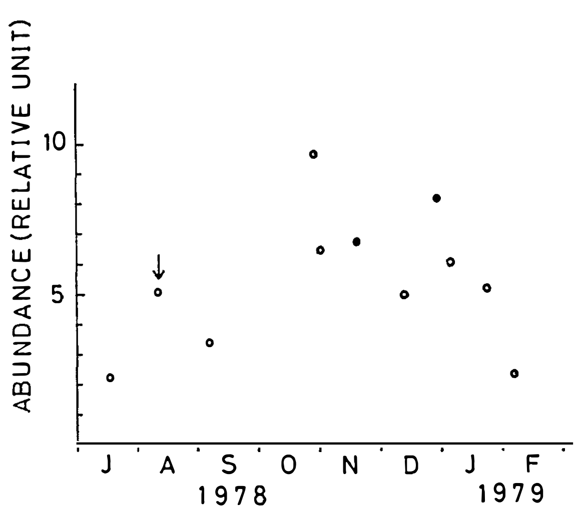

Fig. 8. Seasonal variation of Na total column abundance (relative unit) (1978–79). The open circles indicate good tuning and the closed circles are bad tuning. The arrows correspond to anomalous values correlated with the Perseids meteor shower (after NAGASAWA et al., private communication, 1979).

of the layer. The average top side scale height is 5.3 km, with maxima in August and January. The peak height of the layer has been plotted *versus* the column abundance in Fig. 5. The correlation coefficient is -0.47. Also Fig. 6 shows the correlation between the top side scale height and the column abundance, and the correlation coefficient is 0.63. This means, indeed, that the abundance increases in accordance with breadth of the layer. And the correlation coefficient between the height and the top side scale height shown in Fig. 7 is -0.62. Hence we conclude that the peak height has a good correlation with the top side scale height. Furthermore, this correlation between the top side scale height and the peak height is in good agreement with the results obtained at 44°N (MEGIE and BLAMONT, 1977). This correlation shows that the lower the peak height is located, the larger the top side scale height tends to be. This means that throughout the year there is a height where the layer is cut off due to chemical reactions and/or other processes. Three correlations mentioned above which give consistent relations, seem to be useful to estimate the validity of a sodium model. Although, a present, our results are obtained only for one year, the only other observation which is currently available is that made in 1978 (Fig. 8). This figure shows winter maximum. The analysis of data observed from 1980 to 1981 will be given in a later paper.

3. Discussion

The annual average in abundance observed at Fukuoka ($4.2\times 10^{13}/m^2$) is in good agreement with the twilight observation made at Kitt Peak (32°N) (HUNTEN, 1967) and the lidar measurements at São José dos Campos (23°S) (SIMONICH *et al.*, 1979).

The details of the seasonal variation are, however, rather different among these low latitude observations. HUNTEN found no significant seasonal variation at Kitt Peak. The twilight observations made at Tamanrasset (23°N) also show no significant seasonal variation. Middle and high latitude observations, however, indicate the distinct winter maximum. Hence HUNTEN concluded that there is a striking winter maximum at latitude above 50°, it is still noticeable at 40°, but has almost disappeared at 32°, according to the Kitt Peak data, and that phase reverses in the southern hemisphere (HUNTEN, 1967). On the other hand, our observations do not show such a pronounced winter maximum, because the layer has less abundance in November 1983. Here, it should be noted that normalizing altitude Z_r is high enough to exclude the effect of the stratospheric aerosol layer. Averaging over three months does, however, show variation by a factor of 2 with maximum in winter and with minimum in spring. Furthermore, although the Kitt Peak data show similar results that revealed minimum abundance in November 1965, the results revealed no significant seasonal variation in 1964 (HUNTEN, 1967). To be noted is the difference of the year when sodium observations were made. Such discrepancy is probably caused by the year-to-year variation in sodium abundance at low latitudes. These year-to-year variations in abundance are scarcely seen at middle or high latitudes in the northern hemisphere. Further sodium lidar measurements for a long period at 33°N can be expected to shed light on the cause of this variation. Furthermore, TOMITA *et al.* (private communication, 1983) indicated that the seasonal variation shows a conspicuous winter maximum in Tohoku (39°N). Therefore, it appears that a conspicuous winter maximum in sodium abundance tends to break from out latitude (33°N) in the northern hemisphere as the degree of latitude decreases. Likewise, averaging over a large number of measurements, SIMONICH *et al.* (1979) indicated a gradual annual maximum from early autumn to late spring at 23°S, without significant seasonal variation in the vertical distribution of sodium.

First of all, meteor ablations should be mentioned to be one of the sources by which winter maximum take place. The increment in sodium abundance during the permanent meteor shower indicates that meteor ablation is a source of sodium layer, as shown in some observations (HAKE *et al.*, 1972; MEGIE and BLAMONT, 1977). Thus, it is generally believed that the sodium is partly extraterrestrial in origin. However, annual variation in meteor rates does not appear to be right phase, since it shows a maximum influx in summer–autumn rather than in winter in the northern hemisphere according to radio meteor studies (SIMONICH *et al.*, 1979; HAWKINS, 1956). Our observational results on the enhancement during the Perseids meteor shower will be described in detail in a later paper.

Next, the origin of sodium also has been attributed partly to sublimation from dust. Then FIOCCO and VISCONTI (1973) accounted for the observed winter maximum owing to developed theory based on an evaporation model of sodium atoms from deposited particles. However, MEGIE *et al.* (1978) showed the abundance ratio of sodium to potassium atoms varies between a low summer value (~ 10) and a high winter value (~ 50) by lidar observations. Thus, the evaporation mechanisms have to vary independently for Na and K during the year, in order to explain the variation of the ratio of Na to K. Hence, if one assumes similar mechanism for Na and K, the model does not explain well the variation of the ratio of Na to K.

In this connection, MEGIE *et al.* (1978) concluded that two different origins can be assumed for the alkalis in the upper atmosphere: a meteoric one constant over the year and a terrestrial source due to the vertical transport of particles at high latitude which only works in winter. The hypotheses of a terrestrial origin generally assume that the major source of the materials is particulate matter from evaporated sea spray, carried to high altitudes. These workers suggested thus that the dust layer hypothesis is the only one fit to the observed data, when two different origins are assumed for alkalis. There are, however, two essential problems in order to reinforce this hypothesis: (a) Vertical transport of marine aerosol is theoretically improbable (to these altitude, at least); (b) if transport is feasible, there is still a lack of mechanism for dissociation of sodium chloride, probably coated with sulfate (ALLEN, 1970).

With respect to (a), HUNTEN and GODSON (1967) indicated that, according to results of an epoch analysis correlating sodium abundance at Saskatoon with stratospheric warmings above the Canadian Arctic, the sodium abundance shows a significant peak at the warmings. Hence, these workers suggested that the material is raised in the form of small dust or salt particles, which have a greater tendency to fall out when vertical mixing is not unusually strong. Stratospheric warmings, however, do not appear to be solely responsible for the variations in sodium abundance at Saskatoon and at Victoria (RUNDLE and SULLIVAN, 1972). On the other hand, according to lidar measurements at low latitudes, averaged measurements show a variation by a factor of 2 in abundance with maximum in winter (23°S and 33°N). In particular, at 23°S, stratospheric warmings are not likely to take place. Accordingly, stratospheric warmings are not solely likely to participate in the vertical transport of sodium compounds, though it is not clear whether amplification of planetary waves gives rise to enhancement of vertical transport of tracers or not. Further study is still necessary to make clear this point.

In the meantime, PERRY *et al.* (1980) showed that sodium is likely to exist as compounds of NaOH, NaCl, $NaNO_3$, $NaHCO_3$ in the stratosphere. Consequently, sodium likely exists as a form of aerosols and ion compositions which contained sodium or sodium compounds, rather than sodium vapor, in the stratosphere. Therefore, there must be the material originated from sea in the stratosphere, if the material rises up to the mesosphere. Nevertheless, the mixing ratio height profiles for Si, Na and K measured by DELANY *et al.* (1974) up to 18 km show distinct minima just above the tropopouse level ($\sim$13 km) which suggests the Na/Si and Na/K mass ratios measured near 18 km are closer to those found in meteor than those found in tropospheric aerosol. Recently, *in-situ* positive ion composition measurement using rocket-borne mass spectrometer reveals the newly detected NPH's (ARNOLD and VIGGIANO, 1982). From their studies, ARNOLD and VIGGIANO (1982) concluded that the NPH's are probably formed from PH's by trace gas reactions, and suggested that the reactant trace gases do not originate in lower atmosphere but are rather mixed downward from the region above 81 km. Therefore, at present, there seems to be no evidence that reinforces the presence of sea salt or small dust originated from sea in the stratosphere.

In addition, the seasonal variation of the mesospheric sodium is considered to be explained, as is pointed out by SIMONICH *et al.* (1979), by the seasonal temperature variation in this region. From temperature data at 90 km (U.S. Standard Atmosphere Supplement, 1966), they estimated the ratios of Na to NaO in winter and summer at 23° and 51° latitude based on the two main photochemical reactions of sodium. The ratios account for the observed winter maximum at 23° and 51° latitude. However, according to a recent model (THOMAS *et al.*, 1983), a small fraction of the sodium is in a form of the sodium oxide, so that changes in the [Na]/[NaO] ratio would have little effect on abundance. Thus, estimation mentioned above must take account of the feature of the model, that is, a large fraction of the sodium is in a form of the sodium dioxide or the sodium hydroxide below the sodium peak, in order to make clear sensitivity to temperature.

Hence, at present, the reason of winter maximum in sodium abundance is inconclusive.

4. Conclusion

Measurements of the night-time mesospheric sodium layer have been performed since 1977, using a dye lidar at Fukuoka. The results measured during 1983 are presented in this paper. The annual average in abundance ($4.2\times10^{13}/m^2$) is in good agreement with twilight observation made at Kitt Peak (32°N) and lidar measurements at São José dos Campos (23°S). The annual average of peak height is 93 km. Averaging the measurements every three months except for the peak value of the Perseids meteor shower, the sodium abundance shows seasonal variation by a factor of 2 with maximum ($5.3\times10^{13}/m^2$) in winter and with minimum ($2.6\times10^{13}/m^2$) in spring. It is worthwhile to observe annual variation in abundance at low latitude in order to investigate transport mechanisms of trace gases.

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