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SEASONAL AND NOCTURNAL VARIATIONS OF THE MESOSPHERIC SODIUM LAYER AT STARFIRE OPTICAL RANGE, NEW MEXICO

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Abstract The seasonal variations of the mesospheric sodium layer structure over Starfire Optic Range (SOR: 35°N, 106.5°W), New Mexico are characterized using 46 night data of Na wind/temperature lidar observations collected from Jan. 1998 to May 2000. The column abundance has a mean value of $5.06 \times 10^9 \text{ cm}^{-2}$ and strong annual oscillations with a maximum in November and a minimum in June and July. The annual mean rms width of the sodium layer is 4.30 km and the mean centroid height is 91.60 km. Semiannual oscillations are evident in seasonal variations of the rms width and the centroid height. Their mean nocturnal variations show effects of tides. The photo-ionization during daytime and recombination processes of Na at night, as well as tidal dynamics, induce strong nocturnal variations in the sodium abundance with a minimum just before midnight and a maximum just before sunrise.

Key words Sodium layer structure, Seasonal variations, Na Wind/Temperature lidar.

1 INTRODUCTION

The mesospheric sodium layer that exists in 80~105 km altitude range with a peak density near 92 km of about $10^9 \sim 10^{10} \text{ m}^{-3}$ originates from meteor ablation. Because of sodium's long lifetime, it is an excellent tracer of the chemistry and dynamics in the mesosphere. Lidar observations of the sodium layer since late 1960s^[1] have been used to study the layer structure. Long term sodium lidar observations revealed the general features of the seasonal and nocturnal variations of this layer, as reported by Gibson and Sandford^[2] at Winkfield, England (51°N, 1°W), Megie and Blamont^[3] at Haute Provence, France (44°N, 6°E), Simonich et al.^[4] at Sao Paulo, Brazil (23°S, 46°W), Gardner et al.^[5] at Urbana, U.S. (40°N, 88°W), Kane and Gardner^[6] at Urbana and Plane et al.^[7], respectively. States and Gardner^[8] presented seasonal and diurnal variations of the sodium layer structure at Urbana using a lidar with daytime measurement capabilities. These results show that the seasonal variations of the layer structure depend on latitudes.

The University of Illinois Na wind/temperature lidar was installed at SOR, New Mexico in 1994. The data have been used to investigate the spectrum of gravity waves and to calculate the dynamical cooling rate associated with the vertical transport of heat by dissipating gravity waves^[9]. In this paper the lidar data available from January 1998 to May

2000 are used to study the seasonal and nocturnal variations of the sodium layer to enrich our knowledge of its features at different latitudes.

2 LIDAR EXPERIMENT

The University of Illinois Na wind/temperature lidar is interfaced with the 3.5 m diameter steerable telescope that is operated by the Air Force Research Laboratory, Directed Energy Directorate at SOR near Albuquerque, NM. The telescope is steered between zenith and 10° off zenith to the North, East, South and West to make nighttime measurements of all three wind components between about 82~104 km altitudes as well as temperatures and Na densities.

Na profiles measured at the zenith beam have a vertical resolution of 96 m and an accumulation time of about 2 min, while the profiles at the off-zenith beams have a corrected vertical resolution of a little less than 96 m. Totally 46 night data are available from January 1998 to May 2000. Six nights with sporadic sodium layers and one night with strong meteor echoes, are excluded from analysis of the Na layer structure in this paper.

3 DATA ANALYSIS TECHNIQUE

The sodium layer structure can be well described with a Gaussian function

$$\rho_z = \frac{C_s}{\sqrt{2\pi}\sigma_s} \exp \left[-\frac{(z - z_s)^2}{2\sigma_s^2} \right], \quad (1)$$

where ρ_z is the sodium density at z level, C_s is the column abundance, z_s is the centroid height, and σ_s is the rms width. The detailed method of calculating these three parameters with the sodium density data was given by Gardner et al.^[5]. After C_s , z_s and σ_s are estimated, their mean values and standard deviations for each night can be computed. Their seasonal variations are deduced from the nightly mean values.

Similar to Plane et al.^[7], a harmonic fit function is applied to these nightly mean data to determine the annual and semi-annual oscillations

$$x = A_0 + A_1 \times \cos[2\pi(t - d_1)/365] + A_2 \times \cos[4\pi(t - d_2)/365], \quad (2)$$

where x represents one of the three structure parameters, t is the time of observation, A_0 is its annual mean value, $A_1(A_2)$ is amplitude of annual (semi annual) oscillations, $d_1(d_2)$ is phase of annual (semi annual) oscillations.

Profiles for different nights are averaged at a fix local time to investigate the mean nocturnal variations of the sodium layer structure. Each sodium density profile is averaged over 1 km in vertical direction and re-distributed from 75.5 km to 109.5 km with 0.5 km intervals. Then these profiles are temporally averages for every 0.5 h bin. Annual mean nocturnal sodium layer variations are finally obtained.

4 SEASONAL VARIATION OF THE SODIUM LAYER STRUCTURE

Seasonal variations of parameters C_s , z_s and σ_s are shown in Fig. 1. The column abundance has a maximum of $12.15 \times 10^9 \text{ cm}^{-2}$ on Nov. 12, 1999 and a minimum of $2.17 \times 10^9 \text{ cm}^{-2}$

on June 27, 1998. This is consistent with observations at other latitudes in the northern hemisphere. The annual mean value of the centroid height in Fig. 1b is 91.60 km. Its maxi-

Fig. 1 Seasonal variations of the sodium layer structure parameters
(a) column abundance; (b) centroid height;
(c) rms width. The vertical bars denote their variations ranges, the thick solid curves are fit functions, and thin solid curves are standard deviations.

mum is 92.90 km on August 12, 1999 and its minimum 89.90 km on January 5, 2000. The mean value of the rms width in Fig. 1c is 4.29 km. The maximum of σ_s is 5.38 km on November 15, 1999 and the minimum is 3.55 km on September 9, 1999.

Fig. 1 suggests that annual oscillations dominate C_s and semiannual oscillations dominate the z_s and σ_s . This is also confirmed by the fit parameters for C_s , z_s and σ_s , given in Table 1. Since observational nights are distributed randomly through the year in Fig. 1, the accuracies of parameters fitting should be high.

The C_s annual mean value of $5.06 \times 10^9 \text{ cm}^{-2}$ is the largest one among $4.26 \times 10^9 \text{ cm}^{-2}$ at 40°N and 41°N ^[7], $3.71 \times 10^9 \text{ cm}^{-2}$ at 40°N ^[8], and $4.4 \times 10^9 \text{ cm}^{-2}$ at 23°S ^[4]. It is close to $5.28 \times 10^9 \text{ cm}^{-2}$ at 40°N ^[6] within its error range. The 91.60 km mean value of z_s is close to values reported by Gardner et al.^[5], Kane and Gardner^[6], States and Gardner^[8] and Plane et al.^[7]. The 4.30 km mean value of σ_s is also close to those reported by Gardner et al.^[5], Kane and Gardner^[6] and Plane et al.^[7], but less than the value of 4.91 km at 40°N reported by States and Gardner^[8]. The reason for this difference may be that they used 24h data of sodium densities to estimate the rms width.

Table 1 Parameters of annual and semiannual fits to the sodium layer

Quantities	A_0	Annual oscillations		Semiannual oscillations		Residual rms
		A_1	d_1/d	A_2	d_2/d	
$C_s/(10^9 \text{ cm}^{-2})$	5.06 ± 0.26	2.80 ± 0.37	349.7 ± 7.2	0.98 ± 0.36	144.7 ± 10.5	1.415
z_s/km	91.60 ± 0.13	0.26 ± 0.16	87.4 ± 42.4	0.41 ± 0.18	58.2 ± 12.5	0.698
σ_s/km	4.30 ± 0.06	0.18 ± 0.09	349.7 ± 27.3	0.39 ± 0.08	160.1 ± 6.5	0.340

C_s has large annual oscillations. z_s and σ_s have relative large semiannual oscillations. Amplitudes of A_1 and A_2 for C_s are greater than those at 40°N reported by Plane et al.^[7] and State and Gardner^[8]. Their phases are close to those of State and Gardner^[8] but

different from those of Plane et al.^[7]. One interesting point in Table 1 is that annual and semiannual oscillations of C_s are almost in phase with those of σ_s respectively, and ahead of z_s by about $\pi/2$.

Meteor ablation does not have strong seasonal variations. The temperature dependant chemistry was widely used to explain seasonal variations of the column abundance. A high temperature in winter, relative to a low temperature in summer in mesopause regions, tends to interrupt conversion of Na to the bicarbonate reservoir such as NaHCO_3 . This mainly accounts for seasonal variations. States and Gardner^[8] showed a good correlation between the seasonal Na abundance and the sodium layer weighted temperature. Other aspects including variations of O_3 and other minor species evolved in main chemical reactions of Na in the atmosphere also contribute to variations in Na abundance.

There are no explanations on seasonal variations of the centroid height and the rms width yet. McNeil et al.^[10] proposed a model to calculate seasonal variations of sodium layer structure. Their calculations of seasonal variations of the column abundance agreed with observations. However, calculations of the rms width show an annual oscillation with minimum in winter and maximum in mid summer, which does not agree with the above observations.

5 NOCTURNAL VARIATIONS OF THE SODIUM LAYER

Fig. 2 shows the annual mean nocturnal variations of the sodium layer. The horizontal axis is the universal time, which is 7h ahead of the local time at SOR. The numbers of profiles used for averaging within each time bin are plotted in Fig. 3.

Fig. 2 Contours of annual mean nocturnal variations of the sodium layer (unit: m^{-3})

Fig. 3 Numbers of profiles used in obtaining the averaging contours in Fig. 2

Several features of the nocturnal variations are obvious in Fig. 2. Two large peaks located approximately at 00:30UT and 12:00UT suggest an evident semi-diurnal oscillation, which can also be found in the annual mean nocturnal abundance variations in Fig. 4a. The column abundance has a minimum at 3:30UT (20:30LT) and a maximum at 12:00UT (5:00LT) near sunrise.

Fig. 4 Annual mean nocturnal variations of the sodium layer structure parameters (a) the column abundance; (b) the peak height; (c) the rms width; (d) the centroid height.

Fig. 4b gives annual mean nocturnal variations of the peak height, which shows a clear incline throughout the night. This is probably associated with the neutralization of ions Na^+ , which results in the pre-sunrise maximum near 90 km (see Fig. 2). The annual mean centroid height shown in Fig. 4d remains almost unchanged except for a low value at 00:30UT, which may be due to a small number (only 3) of profiles used for its estimations. The annual mean rms width nocturnal variations in Fig. 4c show a similar behavior to the column abundance.

The above results are generally consistent with the observations at 40°N ^[6,8]

It has been shown that the dynamics (gravity waves and tides) can have a strong influence on the sodium layer. The sodium layer perturbations can result from a distortion due to wind divergence and displacement of the layer due to the vertical winds^[5]. Because that their phases varied randomly through the year, it is difficult for gravity waves to show in the annual mean nocturnal variations of the sodium layer. But tides with relatively steady phases may have influences on its annual mean nocturnal variations. The 12-hour oscillations in Fig. 2 and the incline of peak height in Fig. 4b show effects of tides. Tidal effects can also be seen in the annual mean temperature nocturnal variations in Fig. 5. Similar to sodium

Fig. 5 Contours of annual mean nocturnal variations of atmospheric temperatures (unit:K)

densities, the mean nocturnal temperature variations have a downward phase structure. The peak-to-peak value of temperatures at 90 km is about 20 K, which is close to the seasonal temperature variations.

Besides the dynamics, States and Gardner^[8] proposed that sodium's photoionization during the daytime and recombination during the nighttime may dominate the diurnal abundance variations. Although the chemical time constants for most important Na reactions are sufficiently long, the temperature may play a significant role in the diurnal Na layer variations.

6 CONCLUSIONS

The seasonal variations and annual mean nocturnal variations of the sodium layer structure at 35°N are analyzed using lidar data at SOR, NM. The column abundance has a maximum in winter and a minimum in summer with a mean value of $5.06 \times 10^9 \text{ cm}^{-2}$. The mean rms width is 4.30 km and the mean centroid height is 91.60 km. Semiannual oscillations exist in the seasonal variations of the rms width and the centroid height.

Annual mean nocturnal variations of the sodium layer show 12-hour oscillations with a maximum at 12:00UT near sunrise. The annual mean nocturnal column abundance shows a minimum at 4:00UT and a maximum in 12:00UT near sunrise. The rms width variations are similar to those of the column abundance.

The temperature dependant chemistry is the main reason of the seasonal variations of the sodium layer structure. Tidal dynamics and photo-ionization and recombination processes mainly account for the mean nocturnal variations of the sodium layer.

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