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Resonance Lidar studies of Mesospheric Sodium at a tropical station

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ABSTRACT :
We present the structure and dynamics of the sodium and its characteristics in the mesosphere in the altitude range from 80 to 110 km during 2005 and 2006, a tropical station, using resonance fluorescence lidar system located at the National Atmospheric Research laboratory (NARL), Gadanki. The sodium density is maximum in March and also in October and shows clearly a semi-annual oscillation. There are no clear seasonal variations of the layer width but there is a distinct decrease of the centroid height by about 1km in February and March when the abundance is maximum. The observed nighttime variation could be the manifestation of semidiurnal variation in the sodium layer. The database showing more than 63 Sporadic Sodium Layer (SSL) events makes it clear that we are dealing with a complicated and puzzling phenomenon. The analysis has shown that sporadic sodium layers are observed during 42 % of the time. The most prominent sporadic layer, which formed on 12 February 2005 exhibited a peak density of 64344 Na atoms/cm^3 around 92 km and it was nearly twice the peak density reported from elsewhere using ground-based observations. A downward motion of the peaks is observed in the majority of the events.

1. Introduction

The middle atmosphere or mesosphere is a region of complex photochemical and dynamic interaction. Stretching from roughly 50 to 90 km altitude, it is the transition region between the stratosphere and thermosphere, and it is the least understood region of the earth's atmosphere. Resonance fluorescence lidar is a unique experimental technique, which provides the vertical distribution of sodium with good resolutions and accuracies. Resonance fluorescence lidar systems have been used to study the chemistry and dynamics of the mesospheric metals. The mesosphere is characterized by a variety of interesting and important features. A variety of layered structures are found in the mesosphere including noctilucent clouds, the polar mesospheric dust layer, the airglow layers, and the alkali metal layers of sodium, lithium, potassium, and calcium. Meteoric ablation is believed to be the dominant source of all the mesospheric metal layers.

It is well known that metallic sodium atoms exist in theneutral state in the upper part of the atmosphere (Slipher,1929). Ablation of meteorites and comet dusts is believedtobethedominantsourcefortheformationof sodium (Na)and other metal layers in the mesosphere (Alpers *et al.,* 1993). Themesospheric Na layer generally appears in the altitude rangeof80to110kmwithapeakclosetothemesopausewhere the Na number density is of the order of 10^3 to $10^4 cm^{-3}$(Richter*etal.,*1981). Since the mesospheric region is difficult to measure, being too low for satellites and too high for balloons androcketflightsaretooinfrequent,moststudiesrelyonremote-sensing techniques.Over the past three decades,resonance lidar systems have been used to study most ofthe alkaline metals and dynamics of the mesopause region.The metal layers are useful for remote sensing as they canbe excited at specific wavelengths to emit resonance fluorescence.For sodium the resonant wavelength is 589 nm,bright orange in color, which matches the frequency of Na atomic transition from the ground state to the first-excitedstate.The resonance scatter occurs when the absorbed radiationisre-emittedbytheNaatoms.Therescatteringisoneofthemof sufficientscatteringprocessesintheatmosphere. It is noted that the Rayleigh backscatter cross-section at 589 nm wavelength is about $3x10^{-31}$ m^2 (Nicolet, 1984), while the Na-resonance cross-section of the D_2lineisabout10^{-15}-$10^{-16}$$m^2$(FrickeandvonZahn,1985). This showsthatthe Nacross-sectionis about15-16orders of magnitude larger than the Rayleigh or molecular cross-section. Because of this reason, the mesospheric sodium hasbecome the most frequently studied metallic component oftheEarth'satmosphere.

Resonance lidar observations of the atmospheric sodiumlayer have been made by numerous groups at different locations.These studies show that the mesospheric sodiumlayer is subject to seasonal and shorter term variations,which differ significantly from location to location (Clemesha*et al.,*1999;Kane *et al.,*2001;Yi *et al.,*2002).Thesodium layer is also an excellent tracer of the atmosphericwavemotion.Much of the information about the mesospheric atomicsodium layer has been obtained from lidar measurementsaround the globe. However, the measurements in the tropicalregionarerelativelysparseincomparisontothoseavailableatmidandhighlatitudes.The main objective of this study is to understand the structure and dynamics of the sodium and its characteristics in the mesosphere. The work concerning the observations made on the mesospheric sodium such as sodium layer characteristics, sporadic sodium layers (SSLs) in the altitude range from 80 to 110 km during 2005 and 2006 using resonance fluorescence lidar system located at the National Atmospheric Research laboratory (NARL), previously known as NMRF, Gadanki near Tirupati, India.

2.Equipmentsetup

Astate-of-theartRayleighandMiebackscatteringlidars(Bhavani Kumar *et al.,* 2000, 2001, 2006) were set up atGadanki (13.5°N, 79.2°E) in 1998 under the Indo-Japanesecollaboration programme. The lidar system wasaugmentedwiththe capability of probingthemesospheric sodium, and also to study the aeronomy of the mesopause region overthis tropicallow-latitudesiteonregularbasis.Usingthelidar system,wehaveobservedNalayerataltitudesbetween80 and 105 km during January 2005 for the first time overtheIndiansub-continentandalsoobservedsporadicformation of thin dense layers of sodium during late night hours.The broadand Na lidar system at Gadanki wasset up in a mono-static configuration.The power-apertureproductofthelidarsystem.35W-m^2. The transmitter consists of a tunable pulsed dye laser pumpedbyafrequency-doubledNd:YAG-laser.Thepulseddye laser is tuned to the D_2

resonant absorption line of Naata wavelength near589nm. The dye laser ispumpedwith 200 mJ at 532 nm to get anoutput pulse energy of 30 mJ at 589 nm.TheNa density profiles are obtained with a vertical resolutionof 300 m and a time sampling of 120 s. The detailed system and method of themesospheric Nanumberdensitycomputationandthestatistical error from the NARL sodium lidar is given elsewherebyBhavaniKumar*etal.*(2007). Inthis study,wepresenttheobservations made during 2005 and 2006.

3. Mean Nocturnal variations of the Sodium Layer

The mean nocturnal variations of the sodium layer for the period of two years i.e. from January 2005 to December 2006 over Gadanki are shown in Figure 1. The most prominent feature of the density contour plot in Figure 1 is the peak of the layer reaching a maximum density of about 7300 cm^{-3} at 93.8 km around 0430 LT. It is also clear that the increase of sodium above 95 km and a decrease below 83 km during the night.

The structure of the mesospheric Na layer can be characterized by the column abundance (C_0), Centroid height (Z_0), and rms layer width (σ_0). The layer parameters are calculated from different moments of the mesospheric Na layer as given by Gardner *et al.,* (1986b). Figure 2 shows the temporal variations of the column abundance, centroid height and rms width of the average nocturnal sodium layer during the period of January 2005 to December 2006 over Gadanki. In Figure 2, the total Na content is found to vary between $1.54 \cdot 10^{10}$ and $7.18 \cdot 10^{9}$ atoms cm^{-2}. It shows a variation of abundance over the night is more than 200% and the average abundance is $8.51 \times 10^{9} cm^{-2}$. The abundance curve shows an increasing trend through the middle of the night from a minimum at 2300 LT to a peak about 0500 LT, and then a subsequent decrease linearly morning hours.

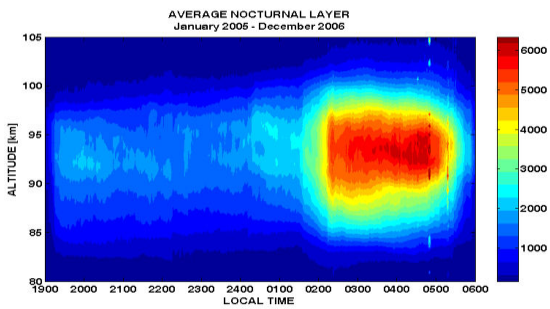

Figure 1. Contour plot for the averagenocturnal sodium layer at NARL

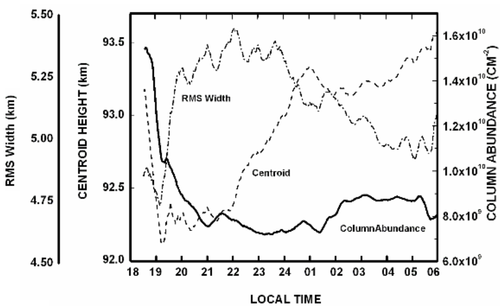

Figure 2, Temporal variations of the column abundance, centroid height and rms width of the average nocturnal sodium layer

Figure 2 also shows the mean nocturnal variation of the centroid position of the layer for January 2005 to December 2006. The movement of the sodium layer centroid is a very important parameter to consider for understanding the layer dynamics. The layer mean centroid position alters between 92.11 and 93.57 km. The centroid curve shows an increase of the centroid height throughout the night. The average centroid height for the period of observation is 92.9 km. The average rate of variation is around 10 cm sec^{-1}, which is a typical amplitude of semidiurnal wind reported in the layer (Batista et al., 1985). The rms width curve shows an increasing trend from sunset through the middle of the night and then subsequent decrease from midnight to the early morning hours. The mean rms widths of the layer vary between 4.72 and 5.44 km. The mean layer width has a peak-to-peak variation of about 700 m. The average rms width of the layer for the whole data set is 5.14 km. It appears that the layer width has an in-phase relation with the sodium column abundance, but an anti-phase relation with the centroid height (Gardner *et al.,* 1986b). However, there is a significant wave nature appeared in mean layer width variation. Due to short and long period wave activity such as gravity waves and tides, the structure of the nocturnal layer changes substantially throughout the night.

4. ObservationofSporadicNalayer

An interesting and topic of interest with the mesosphericNalayer isthesporadicoccurrenceofthinlayersofenhanced number density superposed on the regular back-ground layer. These sporadic layers generate sharp sodiumabundance peaks of full width at half maximum (FWHM)typically between several hundred meters and less than afew km thick with number density equal to or greater thantwice that of the background Na layer. These layers persistfor periods a few minutes to several hours. These sporadiclayers appear to be related to the ion layers known as sporadic E, or Es,and for this reason are sometimes referredto as Na_slayers.

Figure3.shows a typical SSL event for 02 January 2006 (dashed curve) with the maximum density of 36874 cm^{-3} at an altitude of 97 km with a peak width of 3.2 km. A special SSL event is identified on 12 February 2005 (shown in the figure as solid curve). During this event, the sodium density over Gadanki peaks to the greatest ever observed value of 64344 atoms/cm^3. The peak density occurs at an altitude of 92 km with a peak width (FWHM) of 2.2 km. These profiles show that occurrence of SSL events are highly variable in altitude, density and peak width.

The Na density profiles measured at the start of the SSL, SSL reached maximum density,decayof the SSL and normal Na layer profile are plotted in Figure 4(a-d). These profiles were observed during the late evening of January 15 2005.The layer formed with the short period of 1 hour and 09 minutes between 21:15 and 22:24 LT at altitudes between 94.8 and 95.4 km. They were very narrow and very dense, and they formed and decayed quickly. The shortest-lived layer formed at 22:04 LT, was observed in only one profile (figure 4(b)) and had a peak density of 15445 cm^{-3}at an altitude of 94.5 km with a peak width of 1.2 km .The Sporadic sodium layer that formed near 94.8 km at 21:15 LT reached a maximum density that was approximately 12 times larger than the normal density of the Na layer at this same altitude. At 22:30 LT, the SSL was decayed at an altitude of 95.4 km. In figure 4(d). shows the normal Na density profile observed at 05:30 LT.

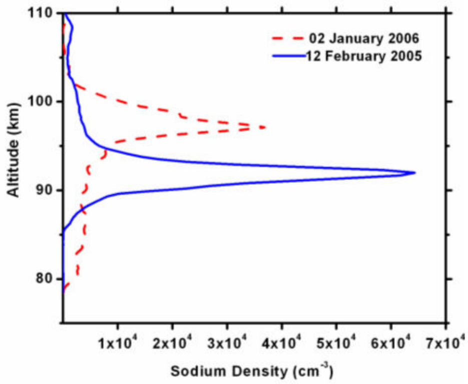

Figure3. Two examples of SSL profiles on 12 February 2005 (solid) and 02 January 2006 (dashed).

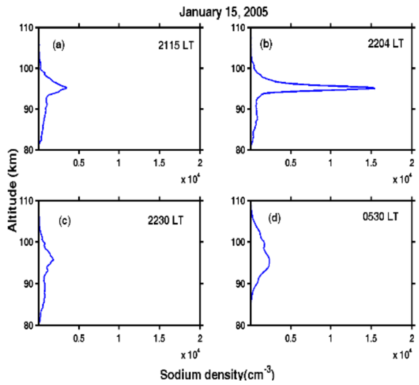

Figure 4. Density profiles of the Na layer observed on January 15, 2006 (a) Start of the SSL (b) Maximum Peak of the SSL (c) After decay of the SSL (d) Normal Na density profile

5.Thermospheric Sporadic Sodium Layer

The sporadic sodium layers which occurred between 90 and 100 km can be called as Mesospheric sporadic sodium layers or Mesospheric Na_s while the layers occurred between 100 and 110 km are known as Thermospheric sporadic sodium layers or Thermospheric Na_s. The thermospheric sporadic layers had peak concentrations of less than one-tenth the concentration at the peak of the background Na layer, while the mesospheric Na_s layers had peak concentrations up to 10 times the peak concentration (Hansen and von Zahn, 1990). Figure 5 shows the altitude/temporal variation of the thermospheric/mesospheric Na_s layer during the night of October 05, 2005. The observation period on this night was 0243 LT - 0502 LT. On this night, we observed both mesospheric and thermospheric sporadic sodium layers. The themospheric Na_s occurred between 99.5 and 103 km. A strong themospheric Na_s started at 0300 LT at about 100 km and the density reached the maximum of 8135 cm^{-3} at 0408 LT at 101.3 km altitude, decreasing slowly afterwards. The layer has a FWHM of 2 km. The strength factor of this event was 4.6. This thermospheric Na event continued at least until 0500 LT when lidar observation was interrupted. During this night, a strong mesospheric Na_s also observed between 0243 LT and 0502 LT. This layer varies between 91 km and 93 km. At 0440 LT, the peak number density reached a maximum of about 23628 cm^{-3} at 92.6 km. The peak width of this layer was 4.2 km. Figure 6 shows the temporal behavior of themospheric/mesospheric Na_s layer at Gadanki on 05 October 2005. We can see themospheric Na_s layer between 0300 and 0502 LT and mesospheric Nas layer between 0243 and 0502 LT.

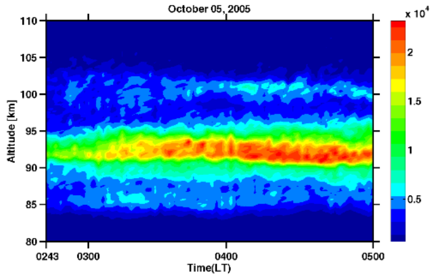

Figure 5. Contour plot for the sporadic sodium layer observed on October 05, 2005

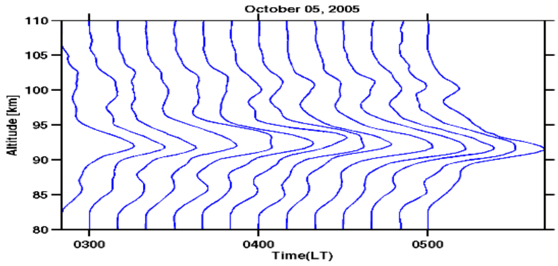

Figure 6. Sequence of sporadic sodium layer observed at Gadanki in the night of 05 October 2005 showing the occurrence of SSL event

6. Observation of meteoric induced enhanced Na layer

It is generally believed that the ablation of meteoroids is the only source of metal atoms at the mesopause altitude region. The invention of resonance lidars has made it possible to measure the densities of different metal atoms quantitatively with high vertical and temporal resolutions, even inside the trail of an individual meteoroid (Kane and Gardner, 1993; Grime et al., 1999; von Zahn et al., 1999; Drummond et al., 2001, 2002). In our observations, on the night of January 12 2005, four narrow layers of atomic sodium enhancement observed with in a time interval of 3 hours, between 0200 and 0500 LT, as shown in Figure 7. However, short lifetime, about 4 to 6 minutes, is found as the characteristic of these layers. The altitudes of peak number density appeared between 93 and 96 km. We understood that the formation of these narrow layers in short period, such as a few seconds to a few minutes, probably due to advection of meteor trails across the lidar field of view (FOV). In particular, observations during meteor showers such as the prominent Leonids have widely been used to demonstrate the influence of single meteors on the local metal layer (Höffner et al., 1999, 2000; Kruschwitz et al., 2001). From such experiments it has become clear that single meteoroids can, in many instances, have large impacts for a short period on the local metal layers.

In order to show the formation and decaying of sodium layers, we present in Figure 8 two examples, in which the durations of the SSL events are different. In the figure, the sodium density profiles are plotted in steps of every 20 minutes for 11 January 2005 and in steps of every 6 minutes for 15 January 2005. It can be observed that, a thin dense Na layer is superposed on the normal Na layer during 0232-0534 LT. The thickness of this layer (FWHM) is about 1.8 km. The duration of the event shown in the 15 January 2005 is relatively shorter (about 70 minutes), as the dense Na layer appears during 2115-2222 LT. The thickness of the layer is about 1.2 km. In both cases, both evolution and decaying of the SSL events can be observed. It can be noted that the evolution of the SSL event in both cases is slower, when compared to its decaying phase. This result is in contrast with the earlier reports, namely, Batista et al. (1989) from low-latitude and Gong et al. (2002) from mid-latitude.

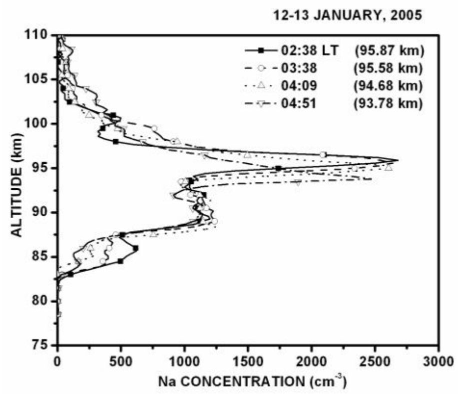

Figure 7. Observation of narrow sodium layer formation on the night of 12 January 2005 due to meteorite ablation.

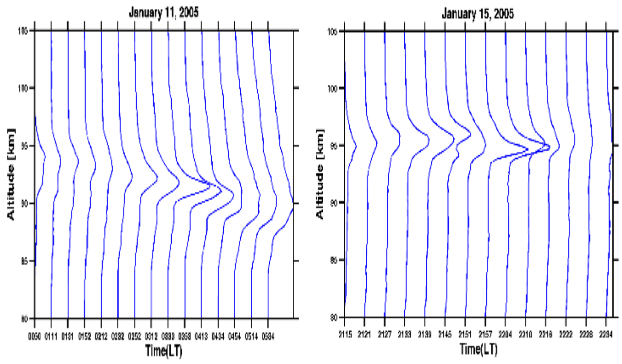

Figure 8. Successive profiles of sodium density showing evolution and decay of an SSL event on 11 January 2005 and 15 January 2005.

7. Statistics for the SSL events

A statistical analysis of a few important parameters estimated for the available SSL events is carried out and the results are shown in Figure 9(a-d). Though there are, in total, 63 events available, to bring out the statistics, we selected the SSL events for which beginning, evolution and ending of the events can be detected within the observation period and by this way, we could get only 35 events. The distribution of the SSL peaks with height is shown in Figure 9(a). From the figure, we can infer that most of the SSL events are located in the altitude range of 91-98 km with maximum occurrence of 6 events each at 92 and 93 km. It may be noted that the SSL event appears in one case, even at altitudes as low as 88 km..Figure 9(b).shows the histogram of the layer thickness (FWHM i.e., peak width of all 35 SSL events) versus number of events. In some SSL events (about 10), the peak width is around 1.5-2 km and in some other events, it is around 4-5 km. It may be recalled that the maximum FWHM is limited to 5 km in one of the criteria; we adopted to identify an SSL event.

To define the strength factor we use the same definition as that used by von Zahn and Hansen (1988). According to them, it is the ratio between the sodium peak density at the maximum SSL evolution, and density of the average layer at the same height before the start of the enhancement. From the histogram shown in Figure 9(c)., we can infer that the strength factors of all 35 SSL events are distributed with a more frequent value of 2- 4, which is similar to that reported by Gong et al., (2002). Batista et al., (1989) have also shown that most of the events have strengths between 2.5 and 3. Figure 9(d). shows the distribution of sporadic sodium event duration. Most of the events continued for a few minutes to one hour. Some SSL events last for 2-4 hours. Our observations could find one special event, which continued for about 7 hours.

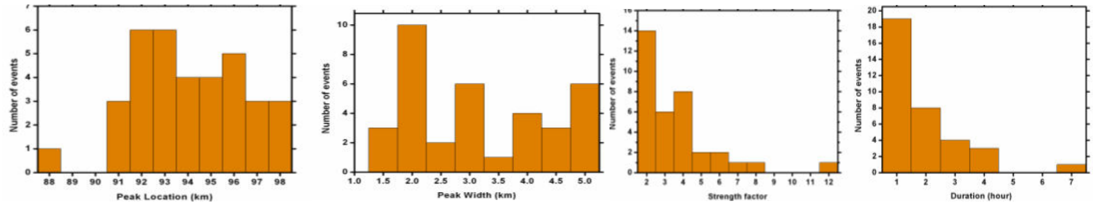

Figure 9. Histograms of (a) Peak location (b) Peak width (c) Strength factor and (d) duration of 35 SSL events observed.

8. Summary

The sodium lidar data used in this study were collected over 159 nights during the period January 2005 to December 2006.The sodium density is maximum in March and also in October. It shows clearly a semi annual oscillation. The magnitude of sodium density in March is less than the magnitude of sodium density in October. The maximum sodium density occurred in all the months is approximately at a height of 95 km. During the year 2005, the column abundance value shows primary maxima of 2.04 x 10^{10} cm^{-2} during September and October and Secondary maxima of 1.08 x 10^{10} cm^{-2} during February and March and minima is 4.55 x 10^{9} cm^{-2} during winter i.e. November, December and January. The layer centroid has an average value for the layer of approximately 92.5 km. The average rms width is approximately 4.75 km. There are no clear seasonal variations of the layer width but there is a distinct decrease of the centroid height by about 1km in February and March when the abundance is maximum. The minimum layer width was 3.74 km measured on December 27,2005, and the maximum was 6.66 km on February 05,2005.

The total Na content decreases during the night and reaches a minimum value during midnight and reaches a maximum at early hours over Gadanki. The observed nighttime variation could be the manifestation of semidiurnal variation in the sodium layer. The layer mean centroid position alters between 92.11 and 93.57 km. The amplitude of the centroid movement is 1.46 km over the average nocturnal period of measurement during January 2005 to December 2006. The average nocturnal centroid shows an increase of the centroid height throughout the night. The average nocturnal centroid height for the period of observation is 92.9 km. The mean nocturnal rms width of the layer varies between 4.72 and 5.44 km.

The analysis of this database showing more than 63 SSL events makes it clear that we are dealing with a complicated and puzzling phenomenon. The analysis has shown that sporadic sodium layers are observed during 42 % of the time. The most prominent sporadic layer, which formed on 12 February 2005 exhibited a peak density of 64344 Na atoms/cm^3 around 92 km and it was nearly twice the peak density reported from elsewhere using ground-based observations. The peak altitude of the SSL events are located in the altitude range of 91-98 km with maximum occurrence of 92 and 93 km. The strength factors of all SSL events are distributed with a more frequent value of 2- 4. Most of the SSL events continued for a few minutes to one hour. The average rise time in all SSL events is around 48 minutes and is longer than the average fall time, which is found to be around 30 minutes. A downward motion of the peaks is observed in the majority of the events.

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