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Observations of peculiar sporadic sodium structures and their relation with wind variations

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ABSTRACT

Resonance lidar observations of sodium density in the upper mesosphere region over Gadanki (13.5°N, 79.2°E) rarely show complex structures with rapid enhancements of sodium density, completely different from normal sporadic sodium structures. The hourly averaged meteor radar zonal winds over Trivandrum (8.5°N, 76.5°E) show an eastward shear with altitude during the nights, when these events are formed. As suggested by Kane et al. [2001. Joint observations of sodium enhancements and field-aligned ionospheric irregularities. Geophysical Research Letters 28, 1375–1378], our observations show that the complex structures may be formed due to Kelvin–Helmholtz instability, which can occur in the region of strong wind shear.

1. Introduction

In the upper mesosphere and lower thermosphere (UMLT) region (80–110 km), metallic atoms, namely, sodium, potassium, lithium, iron, etc. are formed due to ablation of meteors. The lidars based on resonance fluorescence principle have been used to study the vertical distribution of sodium atoms, because of their largest cross-section than other metals (Bowman et al., 1969). The profiles of sodium density sometimes show enhancement by a factor of 2 or more than the normal layer in a narrow altitude region of 2 km and on these occasions, they are called sporadic sodium layer, or briefly Ns (Clemesha et al., 1978). These sporadic sodium layers are believed to be related to sporadic E or briefly Es, as wind shear is believed to be responsible for both sporadic E (Axford, 1967; Kane et al., 1993) and sporadic sodium layer by the neutralization of metals ions (Clemesha, 1995). They in general decrease in height with time (Batista et al., 1989; Clemesha et al., 1999; Vishnu Prasanth et al., 2007). Recently, Kane et al. (2001) observed a new, but a rare type of sporadic sodium layer over Arecibo (18.3°N, 66.8°W). They suggested that these structures could be related to the occurrence of field-aligned ionospheric irregularities. The structures are quite complex and they are different from normal sporadic sodium layers. They extend over several kilometers in height and last for about 1 or 2 h. The structures quite often resemble the letter C and hence they are called as C-structures by Clemesha et al. (2004). Clemesha et al. (2004) presented a few examples of these structures and they noticed the evolution and decay of these structures quite different from each other. In some examples, there is a rapid increase in sodium density over a limited height range. Sometimes, they split into two with one part rising with time and other one falling. In other examples, multiple structures form in a short time. As there has been limited evidence for the relation between these structures and sporadic E, wave breaking or Kelvin–Helmholtz instabilities, Clemesha et al. (2004) suggested that these structures could be the result of the advection of a spatial structure over the lidar site. They studied the correlation between these structures and tidal wind profiles obtained with meteor radar winds over Cachoeira Paulista (23°S, 45°W). In the present study, we present a few examples of similar sporadic sodium structures, which are quite different from the normal sporadic descending layers. The altitude profiles of hourly winds observed by all-sky meteor radar at Trivandrum (8.5°N, 76.5°E) are examined on those nights, when these structures are formed. They, in turn are compared with the wind structure during a few nights, when regular sporadic descending layers are formed.

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2. Observations and data analysis

2.1. Resonance sodium lidar

An Nd:YAG lidar was set up at Gadanki (13.5°N, 79.2°E) under the Indo-Japanese collaboration programme in 1998 (Bhavani Kumar et al., 2000). The lidar system was augmented with capability of probing the mesospheric sodium in January 2005. The system details are described in detail by Bhavani Kumar et al. (2007a). Briefly, the broadband Na lidar system at Gadanki was setup in a mono-static configuration with the power-aperture product of 0.35 W m^2. The transmitter consists of a tunable pulsed dye laser pumped by a frequency-doubled Nd:YAG laser. The pulsed dye laser is tuned to the D_2 resonant absorption line of Na at a wavelength near 589 nm. The dye laser employs a dual grating system that is controlled by a computer that enables a rapid selection of transmitted wavelength. The line width of the laser is about 2 pm. The dye laser is pumped with 200 mJ at 532 nm to obtain output pulse energy of 25 mJ at 589 nm. The dye laser uses Kiton Red as the laser medium. The laser beam is expanded and transmitted into the atmosphere. The receiving system uses a 750-mm Newtonian telescope with field optics and an interference filter. The photomultiplier tube (PMT) is used for photon detection and the output pulses of the PMT are amplified by a broadband amplifier and then fed into a PC-based photon-counting multi-channel scalar (MCS). The MCS counts the pulses in successive time bins. Each time bin is set to 2 μs, corresponding to a vertical resolution of 300 m. The photon counts are accumulated for 2400 shots, corresponding to a time resolution of 2 min. As the laser FWHM spectral width is 2 pm (about 1.7 GHz), the effective cross-section of the Na atom, which is a function of the laser spectral width, is estimated to be 5.17×10^{-16} m^2. Then, using this value in the equation for the concentration of sodium, given in Gardner (1989), the sodium concentration profiles are derived (Bhavani Kumar et al., 2007a). The first lidar observations of the sodium layers from Gadanki were reported by Bhavani Kumar et al. (2007b) and sporadic sodium layers by Vishnu Prasanth et al. (2007). The sodium layer parameters, namely, column abundance, RMS width and centroid height are estimated using the method given by Gardner (1989).

2.2. Meteor radar

The SKiYMET (all Sky interferometric METeor) radar installed at Trivandrum (8.5°N, 76.5°E) is a VHF radar with 40 kW peak power and operating at a frequency of 35.25 MHz in pulsed mode to detect meteor trails (Deepa et al., 2006, Kumar et al., 2007). The pulse length is 13.3 μs corresponding to 2 km resolution and the pulse repetition frequency is 2144 Hz. A detailed description of this kind of radar and the meteor detection algorithm can be found in Hocking et al. (2001). A three-element crossed Yagi antenna is used for transmission, and two-element crossed Yagi antenna is used for reception. Five separate receivers are used for data acquisition, one for each antenna. This allows interferometry to be performed in order to determine the position of the meteor trail in the sky, without ambiguities in the angle of arrival. The location of meteors with angular accuracies of $\pm$1–2° can be achieved. By observing meteor trail drifts, deductions can be made about the speed and direction of the atmospheric wind at the altitude at which the meteor was observed. The instrument detects a sufficient number of meteor echoes throughout the day, to derive a comprehensive picture of the wind field (Kumar et al., 2007). Radial velocity can be measured with an accuracy of 5% or better.

3. Results

3.1. Sporadic sodium structures

Out of 800 h of sodium observations over Gadanki, the peculiar sporadic structures are observed only on four nights. They are 25–26 January 2006, 18–19 December 2006, 9–10 February 2005 and 27–28 November 2005. The altitude–time cross-section of

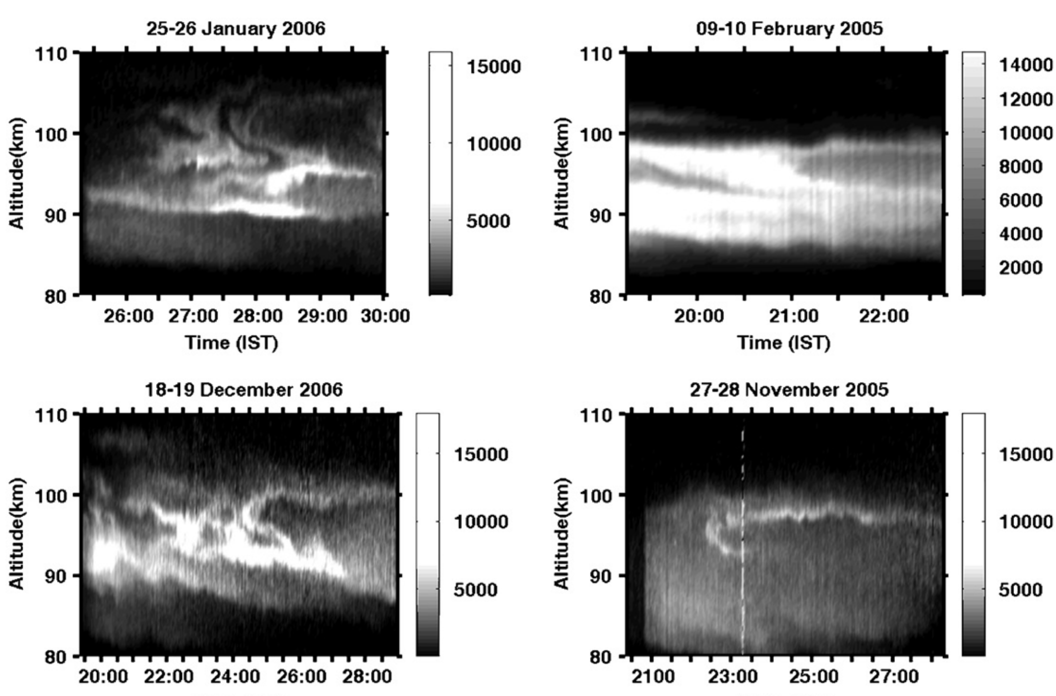

Fig. 1. Altitude–time cross-section of sodium concentration over Gadanki on the nights of 25–26 January 2006 (top left panel), 18–19 December 2006 (bottom left panel), 09–10 February 2006 (right top panel) and 27–28 November 2005 (right bottom panel).

sodium density over Gadanki on 25–26 January 2006 during 25:16–30:00 h (01:16–06:00 IST on 26 January 2006 and IST is Indian Standard Time, which is $5\frac{1}{2}$ h ahead of U.T.) is shown in the top left panel of Fig. 1. A group of C-shaped structures can be observed in the figure between 26:30 and 29:00 h. An enhancement of sodium density is observed at 26:30 h (02:30 IST on 26 January 2006) at two different height regions 95–98 km and 101–103 km. A part of the upper layer falls down with time and joins with the nearly steady lower one at 27:15 h (03:15 IST on 26 January 2006). Because of the joining of two layers, there is a considerable enhancement of sodium density observed in the height region 95–98 km. As time progresses, the joined layer in the height region 95–98 km falls with time, whereas the another part of the upper layer rises with height to above 105 km. The bottom layer survives with more density than the top layer, which disappears at around 28:15 h (04:15 IST on 26 January 2006). Two more C-structures are formed after about 10 min. The bottom layer of these two structures join together and survive with larger density until the end of observation period. The top layer also survives, however, with less density until 30:00 h (06:00 IST on 26 January 2006). The normal sporadic sodium layer is also found at the height 90–93 km and it survives between 01:30 and 05:00 IST. On 18–19 December 2006, the dense sodium clouds are observed in the altitude region 90–95 km and though there are irregular variations within the cloud, a slow descending structure is observed. At 24:30 h (00:30 IST on 19 December 2006), the sodium layer divides into two and the upper part is nearly steady with time, whereas the lower part continues to descend with time. Similar bifurcation of sodium layer is observed on 09–10 February 2005 at 21:00 IST. On 27–28 November 2005, dense cloud of sodium density is not observed before the bifurcation of sodium layer, which occurs at 22:15 IST is not observed. In this case, the upper part with more density is nearly steady with time till the end of the observation period, whereas the descending structure in the lower part is observed only for a short time until 23:15 IST.

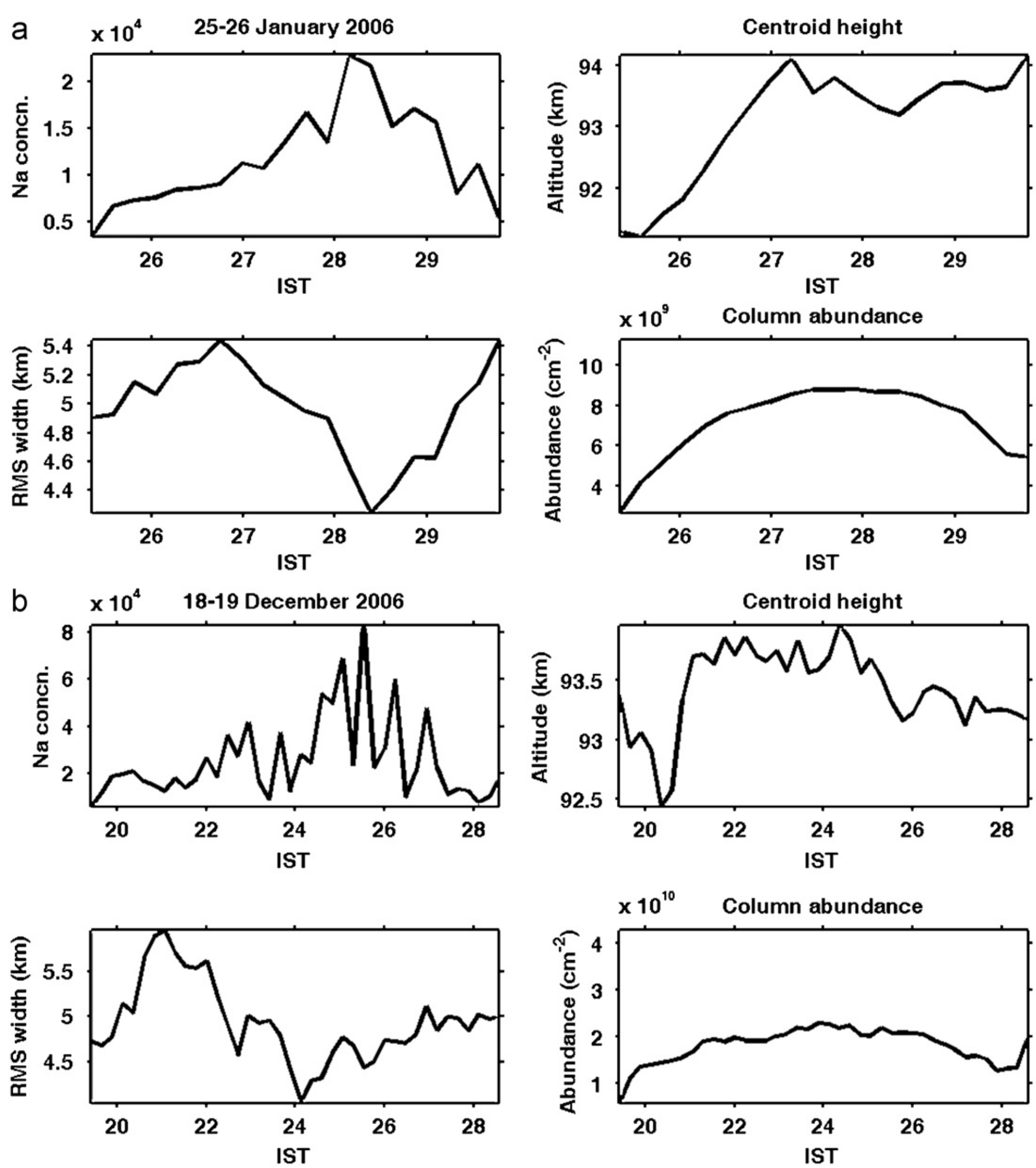

Fig. 2. (a) Time variation of sodium layer properties, namely, centroid height (top right panel), RMS width (left bottom panel) and column abundance (right bottom panel) for 25–26 January 2006. The time variation of peak sodium density is also shown in the top left panel, (b) same as Fig. 2a but for 18–19 December 2006, (c) same as Fig. 2a but for 09 December 2005, (d) same as Fig. 2a, but for 27–28 December 2005.

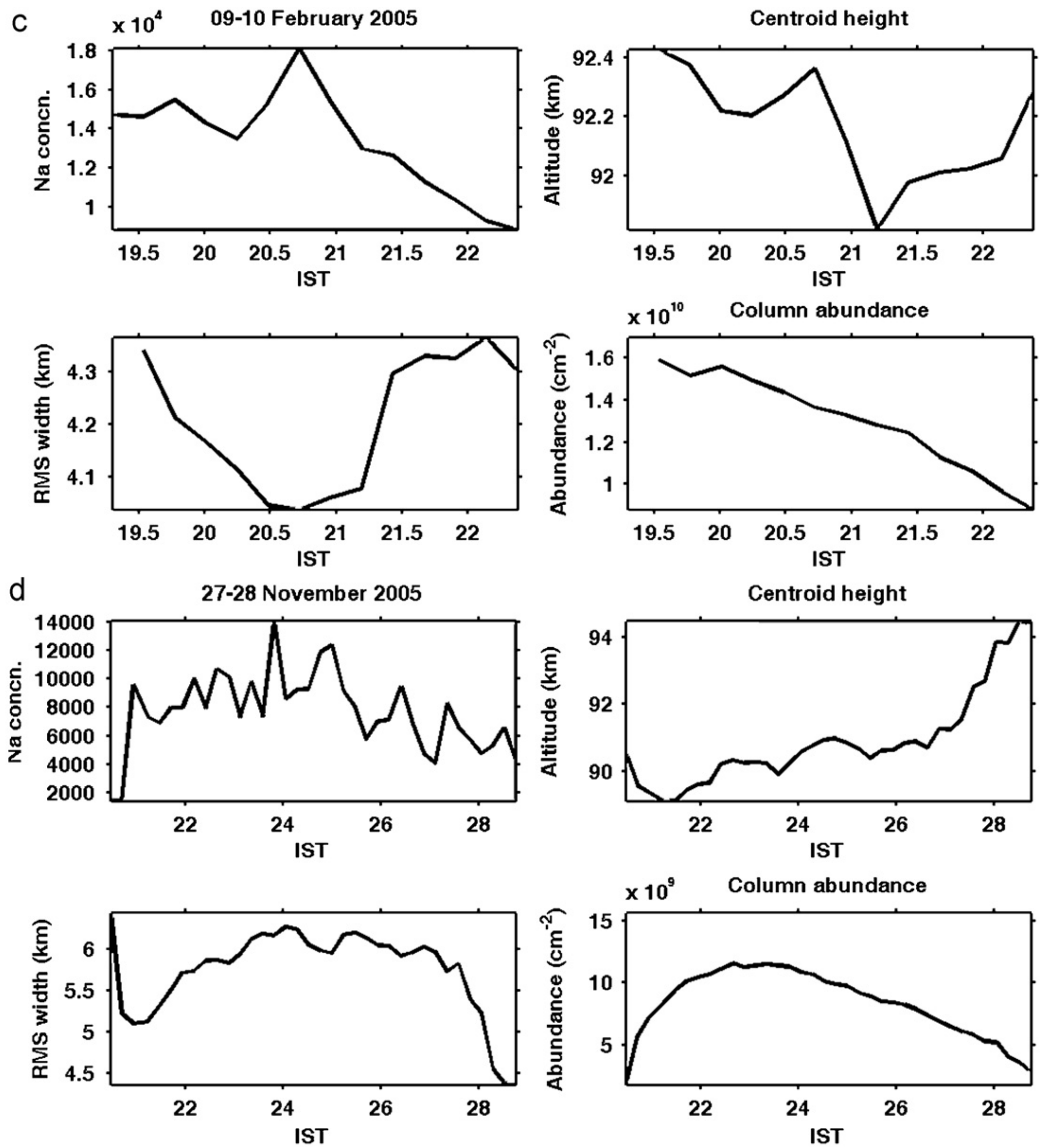

Fig. 2. (*Continued*)

3.2. Sodium layer parameters

The sodium layer parameters, namely, centroid height, RMS width and column abundance are estimated for all the four cases considered here and the time variation of these parameters are plotted in Fig. 2a–d. The width and centroid height variations are nearly out of phase with each other in all the cases. On 25–26 January 2006, the increase in centroid height before the formation of C-structures reveals that there is relatively an increase in the sodium occurrence on the top side of the layer. The maximum centroid height of 94.1 km is observed at ~27:30 h (03:30 IST on 26 January 2006), just before the formation of C-structures. On 18–19 December 2006, the centroid height increases from 92.4 km at 20:30 IST to 94 km at 21:45 h. The increase in the centroid height suggests an abundant increase in sodium on the top side of the layer. The dense clouds of sodium can be formed by excess sodium deposition due to meteoric ablation (Kirchoff and Takahashi, 1984). It is found that the RMS width decreases prior to the formation of C-structures and increases after its formation. In both these cases, RMS width decreases from 5.45 to 4.24 km (26 January 2006) and 5.97 to 4.04 km (18–19 December 2006), just before and during the formation of these structures. Though decrease of RMS width and increase of centroid height are also noted on 9 February 2006, they are not clearly observed on 27 November 2005.

3.3. Relationship with wind shears

The altitude–time cross-section of sodium density over a site represents time history of the vertical distribution of sodium over the site and they incorporate both temporal variations and changes resulting from the advection of the layer containing horizontal gradients (Clemesha et al., 2004). The horizontal structures are translated into temporal variations by the wind. In order to see wind variations during this time, the UMLT wind observed by the all-sky meteor radar over Trivandrum (8.5°N, 76.5°E), which is located south of Gadanki (13.5°N, 79.2°E) are used. As the sites are not well separated in longitude, the local time difference is small. The altitude profiles of hourly averaged zonal winds over Trivandrum is plotted in Fig. 3 for 26 January 2006, 18–19 December 2006, 9 February 2005 and 27 November

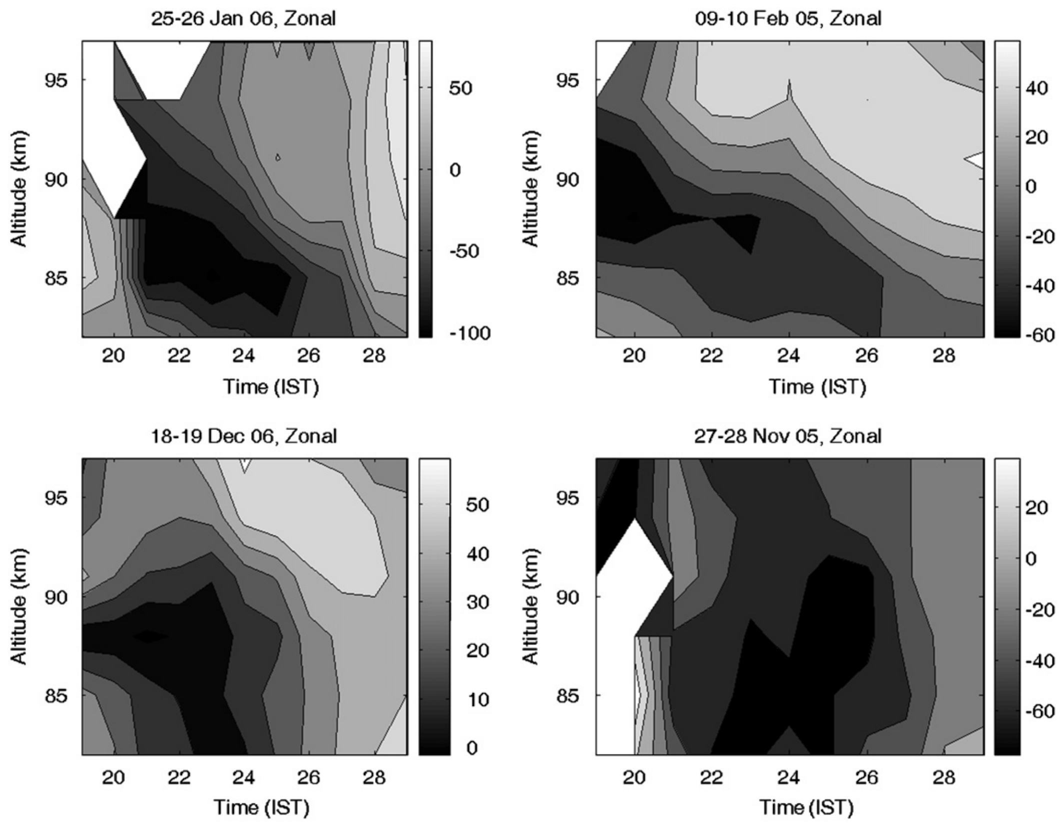

Fig. 3. The altitude profiles of hourly mean zonal winds on 26 January 2006 (top left panel), 18–19 December 2006 (bottom left panel), 09 February 2005 (top right panel) and 27 November 2005 (bottom right panel) over Trivandrum (8.5°N, 76.5°E).

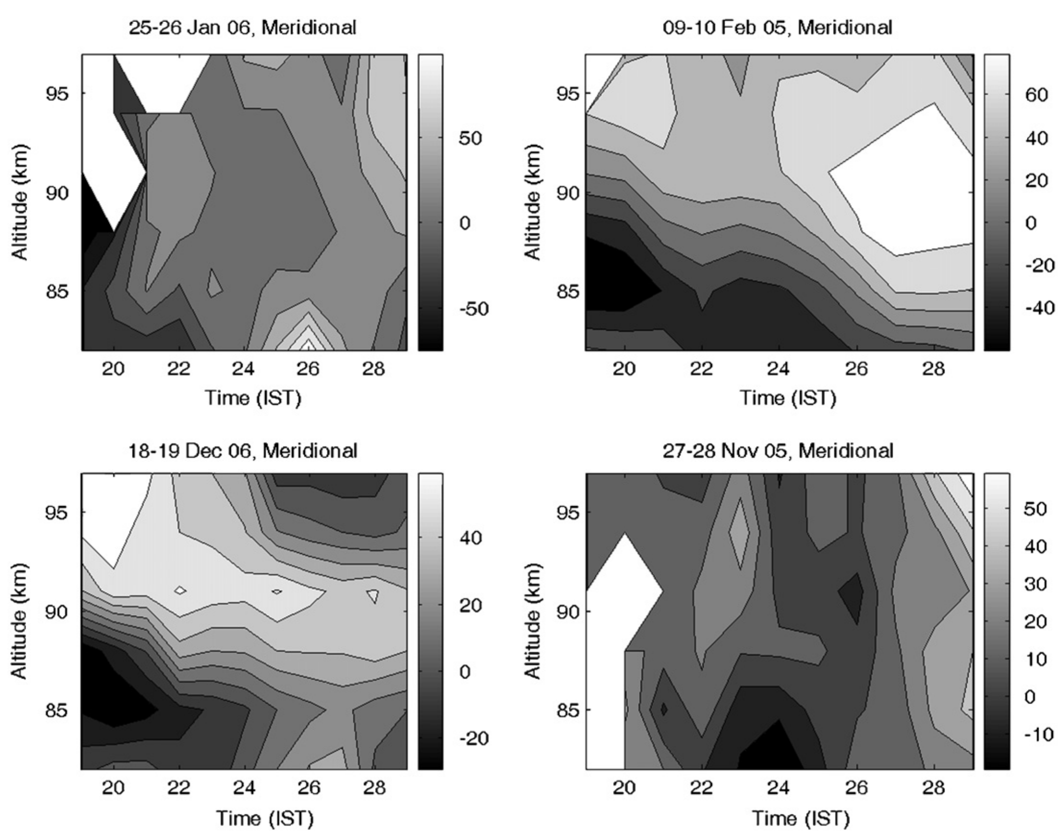

Fig. 4. Same as Fig. 3 but for meridional winds.

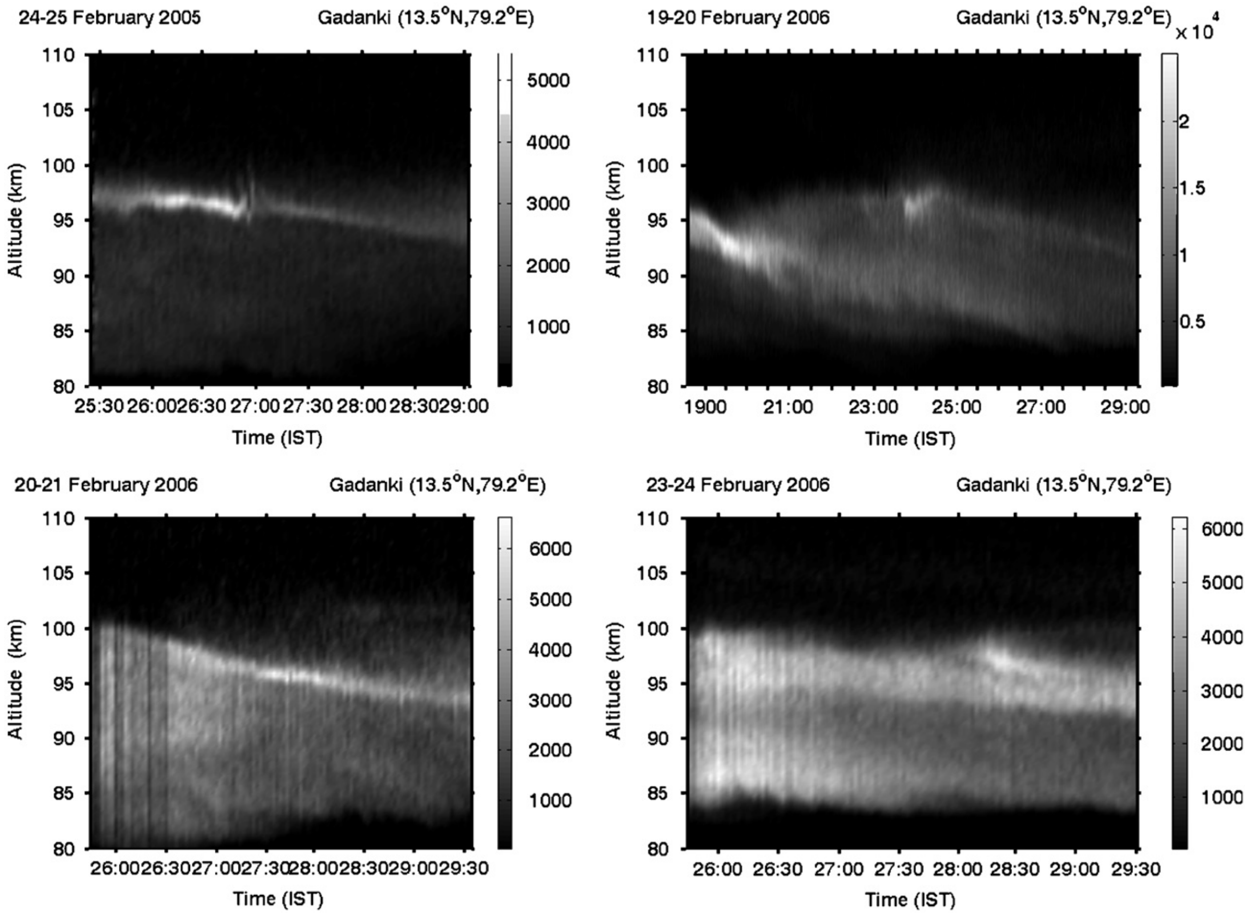

Fig. 5. Altitude–time cross-section of sodium concentration over Gadanki on the nights of 24–25 February 2005 (top left panel), 20–21 February 2006 (bottom left panel), 19–20 February 2006 (top right panel) and 23–24 February 2006 (bottom right panel).

2005. On 25–26 January 2006, winds are more westward (~80–100 m/s) at lower heights (~82–90 km) and eastward at higher heights (>90 km) during late evening hours (19:00–24:00 IST). The eastward wind shear continues to persist during 24:00–30:00 h also, with weak westward winds at lower heights and large eastward winds at higher heights. The eastward shear with height can also be observed on 18–19 December 2006, 9 February 2005 and 27 November 2005 also. Fig. 4 shows time–altitude cross-section of meridional winds for the same days shown in Fig. 3. The meridional wind profiles do not show any consistent pattern among the cases considered.

We investigate the wind profiles during normal sporadic events. Fig. 5 shows a few examples of normal sporadic sodium profiles over Gadanki for the nights of 24–25 February 2005, 19–20 February 2006, 20–21 February 2006 and 23–24 February 2006. All the profiles show regular descending structures with time. On 19–20 February 2006, though there is a bifurcation at ~20:00 h, the original descending structure, which starts at ~19:00 h at the altitude of ~95 km continues to further descend with time to lower altitudes (85 km) and persists till the end of the observation period. On 23–24 February 2006, there are two separate peaks in the altitude profiles of sodium concentration and they descend slowly with time. Fig. 6 shows the altitude–time cross-section of hourly mean zonal winds for the nights mentioned above. It may be noted that during 19:00–24:00 h, winds are westward at higher heights and weakly westward or eastward at lower heights. However, on the days, when peculiar sporadic structures are formed, the winds are westward at lower heights and eastward at higher heights. Through simultaneous measurements of meteor winds and sporadic sodium layers, Clemesha et al. (2001) observed that the descending structures were closely related to similar structures in meridional wind profile. They observed a clear tidal signature in the sodium layer with a vertical wavelength corresponding to that in winds. On 19–20 February 2006, the sodium observations over Gadanki are for about 10 h. The rate of descending of the peak of sodium layer is faster during the beginning of the observation period. It descends at the rate of about 3.5 km/h until 21:00 h. After 21:00 h, it descends relatively slowly at the rate of 1 km/h. Fig. 7 shows the altitude–time cross-section of meridional winds for all the normal nights considered in the present work. The meridional winds over Trivandrum also shows faster descending rate during 19:00–21:00 h. Then it descends relatively slowly during the rest of the period as shown in the figure. These observations are consistent with the observations by Clemesha et al. (2001).

4. Discussion and conclusion

We presented four cases of peculiar sporadic structures of sodium density observed by sodium lidar at Gadanki along with the time variations of the layer parameters, namely, column abundance, RMS width and centroid height. These structures, in the altitude–time cross-section of sodium densities, do not look like normal sporadic structures, which appear to be quasi-horizontal structures descending with time. These structures are quite complex and they sometimes develop vertically to form C-shaped structures. On some occasions, sodium density peak

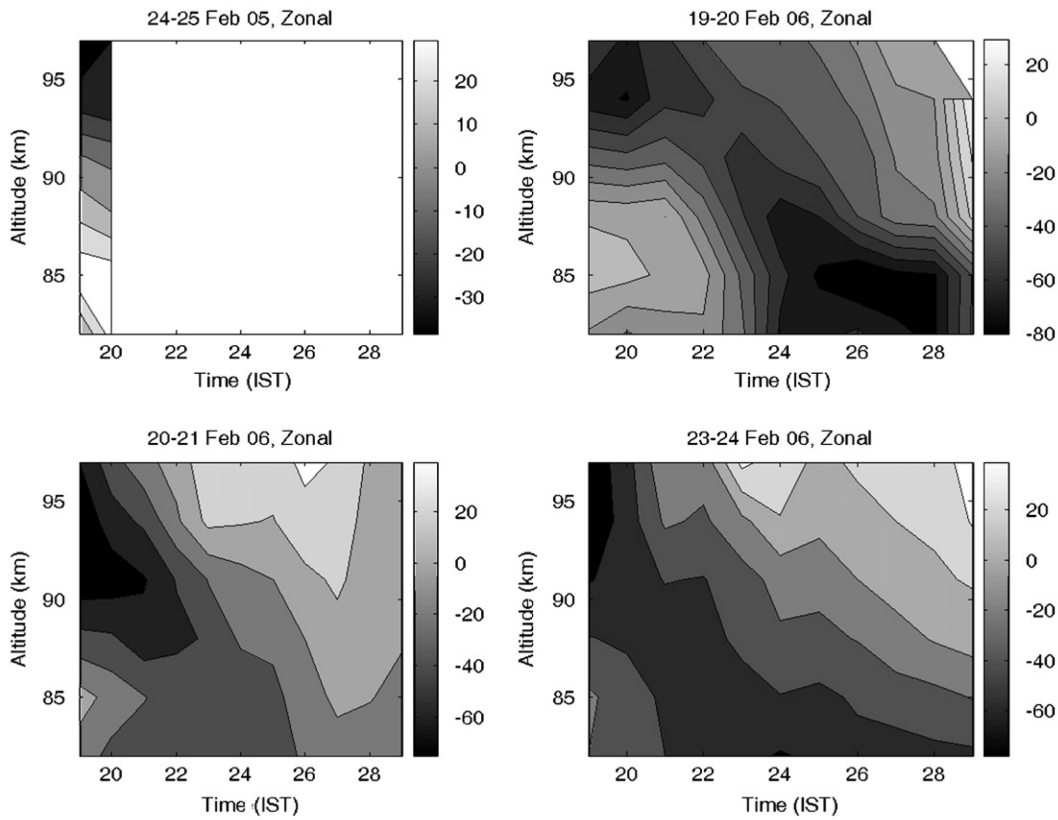

Fig. 6. The altitude profiles of hourly mean zonal winds on the nights of 24–25 February 2005 (top left panel), 20–21 February 2006 (bottom left panel), 19–20 February 2006 (top right panel) and 23–24 February 2006 (bottom right panel).

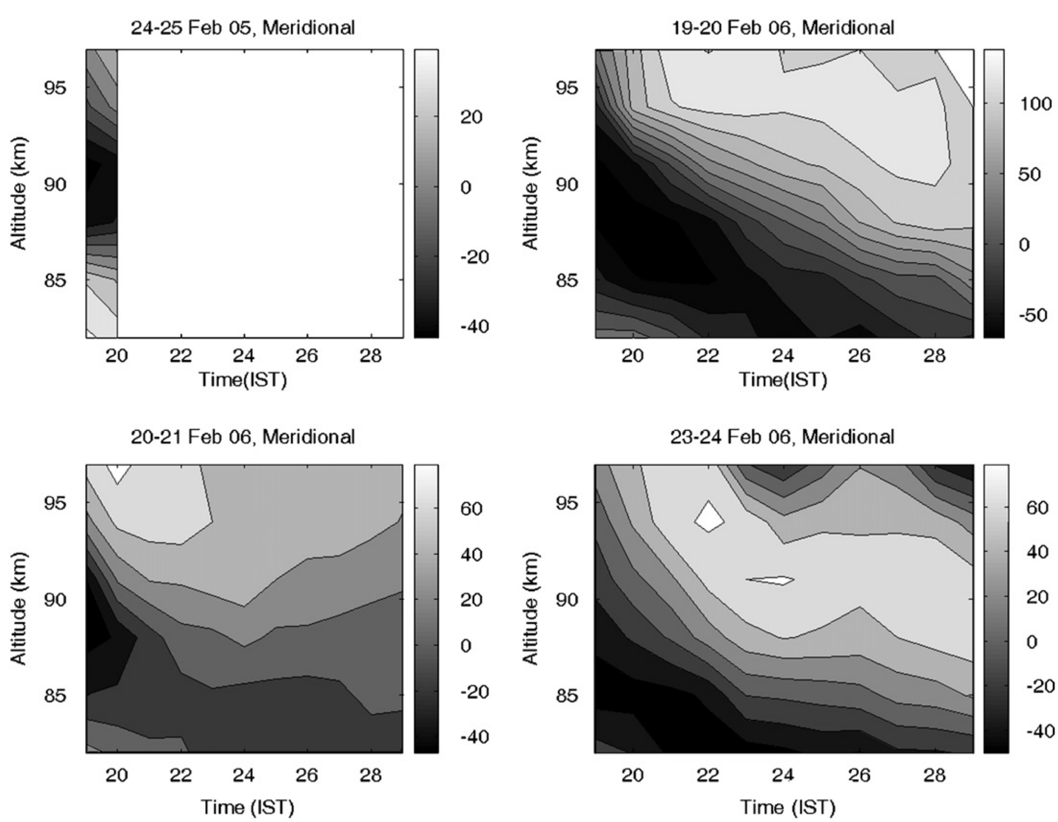

Fig. 7. Same as Fig. 6 but for meridional winds.

divide into two parts and the upper part is either ascending or stationary with time and the lower part shows normal sporadic descending structures. The C-structures, as Kane et al. (2001) first observed and recently by Clemesha et al. (2004) found to be a rare type of sporadic sodium layer. Out of 800 h of sodium observations over Gadanki during January 2005–December 2006, we also could get only four such events. All the events reported by Kane et al. (2001) and Clemesha et al. (2004) occurred during late evening hours. Our observations over Gadanki on 26 January 2006 show that they can also occur during early morning hours. It is found that just before and during the formation of these sporadic structures, decrease in RMS width and an increase in centroid height have been noted. An abundant increase in sodium density on the top side of the layer is inferred from the increase in the centroid height. The abundance of sodium density could be due to the formation of dense clouds by excess sodium deposition due to meteoric ablation (Kirchoff and Takahashi, 1984). The hourly averaged zonal winds over Trivandrum (8.5°N, 76.5°E) show an eastward wind shear on the nights when these complex structures are formed. Kane et al. (2001) suggested that these structures could be related to the occurrence of field-aligned ionospheric irregularities that cause VHF backscatter. Even though Indian MST radar (53 MHz) is located at Gadanki, unfortunately, there were no coherent scatter observations of field-aligned ionospheric irregularities on nights, when the peculiar sporadic events are formed. Kane et al. (2001) suggested two potential explanations for the sporadic Na and VHF connection. One is that lidar is observing mild sporadic Na associated with the Es layer and the VHF echo associated with the same Es. Another one is that if the sodium densities are tracers of an overturning wave, the resulting turbulence near an Es layer might induce the small-scale structure required to create the VHF backscatter (Gurevich et al., 1997). However, Kolmogorov microscale is too large to be detected by the 3 m radar. Clemesha et al. (2004) observed only some indications correlation of these structures with sporadic E. The week correlation of these structures with sporadic E, wave breaking or Kelvin–Helmholtz instabilities suggest that these structures may be due to winds. Clemesha et al. (2004) also suggested that they could be caused by the wind-shear distortion of an initial cloud of enhanced sodium concentration having horizontal dimensions of the order of 50 km and extending over a height range of upto 10 km.

The rocket measurements reported by Kane et al. (2001) showed large westward winds (nearly 85 m/s) at 92 km during the occurrence of these structures and the winds were nearly constant across the plasma layer (Larsen, 2000). Kagan and Kelley (1998) have suggested a neutral wind driven source for mid-latitude VHF radar echoes in which a westward wind induces instabilities on the top side of a plasma layer. Kane et al. (2001) observed high eastward winds above 100 km and suggested that the complex sporadic structures could be produced by Kelvin–Helmholtz instability in the region of a strong wind shear. Our observations show that on nights, when normal sporadic descending layers are formed, the winds are westward at higher heights and eastward at lower heights. This condition is favourable for the convergence of metallic layers to form sporadic sodium layers. On days, when observations are carried out only during early morning hours, the remnant Na layers are only observed by the lidar. However, the zonal winds show eastward shear with eastward winds at higher heights and weak eastward or large westward winds at lower heights on the nights, when the complex sporadic structures are formed. Our observations are in agreement with those by Kane et al. (2001) and support their hypothesis of Kelvin–Helmoltz instability for the formation of the complex sporadic structures. This study will be extended for more cases with joint observations of sodium lidar, coherent backscatter of radar field-aligned irregularities, ionosonde and meteor radar. Efforts are now made to upgrade the MST radar at Gadanki to active-phased array radar with interferometic capability so as to derive wind information in the UMLT region. The simultaneous local wind information will be useful to make more precise comparison with the sodium profile.

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