First report of sporadic Na layers at Qingdao (36° N, 120° E), China

Z. Ma1,2, X. Wang1,2, L. Chen1, and J. Wu2

1China Research Institute of Radiowave Propagation, Qingdao, Shandong, China
2National Key Laboratory of Electromagnetic Environment, Qingdao, Shandong, China

Correspondence to: Z. Ma (zh.zh.ma.7@gmail.com)

Received: 18 January 2014 – Revised: 25 May 2014 – Accepted: 27 May 2014 – Published: 2 July 2014

Abstract. This paper reports, for the first time, observational results of mesopause sporadic Na (Na\textsubscript{s}) layers by a ground-based lidar at Qingdao (36° N, 120° E), China. Based on ~430 h of observational data on 95 nights from December 2007 to June 2012, we have selected a total of 53 Na\textsubscript{s} layer events. It is found that characteristics of Na\textsubscript{s} layers over Qingdao have general similarity with those over nearby sites, Wuhan (30° N, 114° E) and Hefei (32° N, 117° E), but not those over the site Hachioji (35° N, 139° E) at nearly the same latitude as Qingdao. At the same time, parameters of sporadic E (E\textsubscript{s}) layers were recorded by an ionosonde. The fact that E\textsubscript{s} layer occurrence probabilities of 19, 22, and 18 % in time intervals before, during, and after the Na\textsubscript{s} layers are very close to the average occurrence ratio of the nocturnal E\textsubscript{s} layer (21 %), may reveal a general independence between Na\textsubscript{s} and E\textsubscript{s} layers over Qingdao. Only those strong Na\textsubscript{s} layers above the peak altitude of the main Na\textsubscript{s} layer might have a significant correlation with E\textsubscript{s} layers. In addition, a total of 11 high-altitude (above 105 km) Na\textsubscript{s} layer events have been surveyed specially. It is found that these high-altitude Na\textsubscript{s} layers were usually weak. And they possessed long-duration (>147 min) and broad-layer width (4.0 km) compared with Na\textsubscript{s} layers below 105 km (>96 min and 2.4 km). These characteristics are in accord with observational results at Wuhan. It is suggested that there is little correlation between this kind of Na\textsubscript{s} layers and E\textsubscript{s} layers. Finally, the summer topside enhancement phenomenon of Na atoms observed at Qingdao is in accord with several earlier observational results at different sites (18, 30, and 54° N) in the Northern Hemisphere.

Keywords. Atmospheric composition and structure (middle atmosphere – composition and chemistry)

1 Introduction

Free metal atoms are present in Earth’s mesopause region between 75 and 110 km. Among Na, Fe, K, and Ca, Na is most widely observed. Lidar measurements indicate that the number density profile of Na atoms roughly possesses the Gaussian shape with height and peaks at ~92 km normally. However, besides this normal layer (main layer), Na atoms can be sporadically enhanced within a narrow height range, which has been defined as a sporadic Na (Na\textsubscript{s}) layer (Hansen and von Zahn, 1990; Clemesha et al., 1999).

The characteristics of Na\textsubscript{s} layers have been widely surveyed. Despite the narrow height region (typically ~2 km full width at half maximum, FWHM) of Na\textsubscript{s} layers, they can exhibit horizontal sizes between 100 and 2000 km measured by multiple-point observations (Batista et al., 1991; Kane et al., 1991). The occurring altitude of Na\textsubscript{s} layers is generally higher than the peak of the main layer and normally falls with time (Clemesha, 1995). The decay period of Na\textsubscript{s} layers is normally longer than their formation period (Kwon et al., 1988; von Zahn et al., 1987). In addition, simultaneous and common volume lidar observations at 30° N showed that, 62 % of sporadic Na and Fe (Fe\textsubscript{s}) layers occurred in overlapping altitude ranges and moved following almost the same track (Yi et al., 2007). Occasionally, Na\textsubscript{s} layers could appear at extremely high altitude (above 105 km) (Collins et al., 1996; Yi et al., 2002; Gong et al., 2003; Ma and Yi, 2010; Dou et al., 2013). Through a statistics study, Ma and Yi (2010) have found that Na\textsubscript{s} and Fe\textsubscript{s} layers above 105 km at 30° N occurred mostly during summer and possessed long durations and broad layer widths.

However, the formation mechanism of Na\textsubscript{s} layers is still not very clear. Through simultaneous observations of sporadic E, Na, Fe, and Ca ion layers at Urbana, Illinois, Gardner et al. (1993) suggested that high-altitude Na\textsubscript{s} layers would
be formed by the neutralization of Na ion in an associated sporadic E (E_s) layer. A high correlation between the occurrences of Na_s layers and E_s layers has led to suggesting the neutralization of the Na ion reservoir in the E_s layers as a source of the neutral Na atoms (von Zahn and Hansen, 1988; Beatty et al., 1989; Kane and Gardner, 1993; Cox and Plane, 1998; Clemesha et al., 1999; Shibata et al., 2006; Williams et al., 2006, 2007; Delgado et al., 2012; Yuan et al., 2013; Dou et al., 2013). In addition, according to several chemical theoretical studies, the Na ion is converted into a Na atom at a height around or above 100 km (Cox and Plane, 1998; Hansen and von Zahn, 1990; Collins et al., 2002). Also, the observations indicated that, sporadic neutral atom (N_s) layers correlated with E_s layers were likely to appear around 100 km (Beatty et al., 1989; Friedman et al., 2000; Williams et al., 2007). Nevertheless, the correlation of N_s layers and E_s layers is not 1:1 (Clemesha, 1995). Observations at 69°N indicated that no E_s layer appeared within 2 h before and after the occurrence of some Na_s layers and Fe_s layers (Hansen and von Zahn, 1990; Alpers et al., 1994). Through the observations at different locations, Alpers et al. (1994) have found that the correlation between Fe_s and E_s layers exhibited obvious latitudinal variation. Through statistics work, it was found that the probability of a Na_s layer simultaneously appearing with the E_s layer was low (32%) at 69°N (Hansen and von Zahn, 1990). The geographical distribution characteristics of correlation between N_s and E_s layers are very obscure.

Another origin of Na_s layers may be direct meteoric injection, as source of metallic materials among the mesopause. The first report of a sporadic Na layer suggested that it resulted from meteor deposition (Clemesha et al., 1978). It has been suggested that the high-altitude sporadic metal layers might belong to a different population and have different origin (Hansen and von Zahn, 1990; Kane and Gardner, 1993; Clemesha, 1995). Höfchner and Friedman (2004, 2005) suggested a direct link between ablating meteoroids and topside metal layers. Through a statistical study, Ma and Yi (2010) suggested the Northern Hemisphere high-altitude sporadic layers occurring mostly during summer would come from enhanced micro-meteoroid influx.

In this study we present observational results of Na_s layers obtained by ground-based lidar at 36°N, as well as the statistical results of correlation between Na_s and E_s layers. In addition, high-altitude Na_s layers are surveyed.

2 Instruments

The multifunctional aerosol-temperature-sodium (ATS) lidar of the China Research Institute of Radiowave Propagation (CRIRP) can detect the lower atmosphere and aerosols by Mie and Raman scattering, as well as the middle atmosphere by Rayleigh and Na resonance fluorescence scattering. It first came into operation in June 2006 at Qingdao (36°N, 120°E), China. Observations are performed routinely at night and one of the operational modes is adopted roughly alternately for each night. The lidar parameters related with Na resonance fluorescence detection are given in Table 1.

The time bin length is 1 μs corresponding to the range bin length of 150 m. The time resolution of Na profiles is normally 250 s (5000 laser shots), and was adjusted to 300 s (6000 laser shots) from 20 February to 15 October 2009. The pointing of the transmitting beam is established by scanning the backscatter signal at 30 km along two perpendicular directions. The pointing of the laser beam is established by the trapezoidal method (Fiorani et al., 1998). The wavelength is tuned up by scanning the maximum backscatter signal strength of Na atom at 90 km. The Na atom number density is obtained by contrasting the resonance fluorescence scattering signal of Na atoms to the Rayleigh scattering signal of the atmosphere at 30 km.

The ionosonde of CRIRP is located at a horizontal distance of only ~30 m away from the lidar. Its frequency sweeps from 1 to 32 MHz in ~1 min, and the altitude uncertainty for sporadic E layers is ±5 km. This ionosonde operates every hour on the hour. Consequently, the data period of E_s layers cover all Na data. The ionograms are scaled according to the Manual of Ionogram Scaling by Wakai et al. (1987).

3 General overview of sporadic Na layers

Our observations of Na atoms by lidar were first performed in December 2007, and the data used in this study are up to June 2012. In order to ensure a good data quality, profiles with a threshold number density (the number density...
corresponding to one single photon in one range bin) above 40 cm\(^{-3}\) at 90 km have been excluded. Then we have obtained \(\sim 430\) h of Na number density data on 95 nights totally. Observation was performed at least three times in each month except in July.

To be classified as a sporadic layer, the peak Na density must be equal to or greater than twice that of the background Na density (Clemesha et al., 1999). In addition, the peak number density is required to reach 500 cm\(^{-3}\), and a sporadic layer should last at least for three successive profiles. According to these criteria, a total of 53 sporadic Na layer events have been selected from \(\sim 430\) h of data.

Through a statistical study of all these sporadic Na layer events, we have obtained their characteristics as exhibited in Table 2. For comparison, Table 2 also list characteristics of Na\(_s\) layers gained at another three lidar sites (Wuhan, Hefei, and Hachioji). Figure 1 is a map showing the relative positions of these four lidar sites. The distance between Wuhan/Hefei and Qingdao (\(\sim 900/500\) km) is nearer than that between Hachioji and Qingdao (\(\sim 1700\) km), whereas Hachioji (35°N) is nearly at the same latitude as Qingdao (36°N). As seen in Table 2, it is found that the occurrence rate and strength (average peak density, maximum peak density, average peak abundance and maximum peak abundance) of Na\(_s\) layers over Qingdao are all close to those over Wuhan. The average width and altitude of Na\(_s\) layers over Qingdao are close to those over Hefei. However, the strength (average peak density and maximum peak density) and average altitude of Na\(_s\) layers over Qingdao are much different with those over Hachioji. Overall, characteristics of Na\(_s\) layers over Qingdao have the general similarity with those over nearby sites, Wuhan and Hefei, but not with those over the site Hachioji, which is nearly at the same latitude as Qingdao. Thus the observations of Na\(_s\) layers over these four locations show little latitudinal dependence but are sensitive to longitude. Of course, we recognize that the data analysis and identification criteria of sporadic layers may have some difference for different observing locations.

In the next section, we will survey the temporal correlation between sporadic Na and E layers by both case and statistical studies. And we will further study the correlation between sporadic Na and E layers by surveying E\(_s\) layer occurrence probabilities in three different time intervals around Na\(_s\) layers in Sect. 5. Then Sect. 6 will pay attention to characteristics of high-altitude (above 105 km) sporadic Na layers.

4 Correlation between sporadic Na and E layers

The strength of a sporadic E layer detected by ionosonde is normally directly recorded by the plasma frequency, \(f_p\) (MHz), which is related to the electron concentration \(N_e = 1.24 \times 10^4 f_p^2 \text{ cm}^{-3}\). First of all, a proper strength criterion (threshold \(f_p\)) for judging the E\(_s\) layer event should be established. Based on the nighttime (19:00–05:00 LT – local time) data by ionosonde from December 2007 to June 2012, the calculated probabilities for \(f_p\) reaching 3, 4, and 5 MHz are 29, 21, and 14%, respectively. Thus we set the threshold \(f_p\) of E\(_s\) layers to 4 MHz (Dou et al., 2013), in order to ensure a similar ratio of event duration to total observation duration with Na\(_s\) layers (19 %, as seen in Table 2). Thus, a recognized E\(_s\) layer only represents one with \(f_p\) of or exceeding 4 MHz in the following.

4.1 Case studies

4.1.1 Case study 1 (3–4 May 2009)

Figure 2 shows the Na density contour plot and E\(_s\) layer parameters during the night on 3–4 May 2009. The color contour plot is the Na density with height and time. The two rows of values on the upper abscissa are plasma frequency (above) and virtual reflection height in kilometers, as recorded hourly by the ionosonde. The \(f_p\) in red color represents the occurrence of the E\(_s\) layer. We point out that the virtual height of an E\(_s\) layer will be slightly higher than its actual height due to the slowing of radiowave propagation in

Figure 1. A map showing the relative positions of four lidar sites.

Figure 2. Na density contour plot and E\(_s\) layer parameters during the night of 3–4 May 2009. For detailed explanation please see text. Notice the E\(_s\) layer occurred without any Na\(_s\) layer during the entire observation of Na layers.
Table 2. Statistical characteristics of Na<sub>s</sub> layers observed at different lidar sites in the midlatitude region.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Wuhan</th>
<th>Hefei</th>
<th>Hachioji</th>
<th>Qingdao</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latitude and longitude</td>
<td>30° N, 114° E</td>
<td>32° N, 117° E</td>
<td>35° N, 139° E</td>
<td>36° N, 120° E</td>
</tr>
<tr>
<td>Distance from Qingdao/km</td>
<td>∼900</td>
<td>∼500</td>
<td>∼1700</td>
<td>0</td>
</tr>
<tr>
<td>Number of observed Na&lt;sub&gt;s&lt;/sub&gt; layer</td>
<td>30</td>
<td>64</td>
<td>&gt;100</td>
<td>53</td>
</tr>
<tr>
<td>Occurrence rate/h&lt;sup&gt;−1&lt;/sup&gt;</td>
<td>1/6.5</td>
<td>1/14</td>
<td>20%</td>
<td>19%</td>
</tr>
<tr>
<td>Ratio of event duration to total observation duration</td>
<td>&gt;2.3</td>
<td>&gt;2.25</td>
<td>&gt;2.0</td>
<td>&gt;1.6</td>
</tr>
<tr>
<td>Average formation period/min</td>
<td>72</td>
<td>&gt;56</td>
<td>NA</td>
<td>19%</td>
</tr>
<tr>
<td>Average duration/h</td>
<td>&gt;2.3</td>
<td>&gt;2.25</td>
<td>&gt;2.0</td>
<td>&gt;1.6</td>
</tr>
<tr>
<td>Average peak density/cm&lt;sup&gt;−3&lt;/sup&gt;</td>
<td>7270</td>
<td>6170</td>
<td>&lt;2870</td>
<td>7510</td>
</tr>
<tr>
<td>Maximum peak density/cm&lt;sup&gt;−3&lt;/sup&gt;</td>
<td>41 760</td>
<td>17 380</td>
<td>8800</td>
<td>34 560</td>
</tr>
<tr>
<td>Average peak abundance/cm&lt;sup&gt;−2&lt;/sup&gt;</td>
<td>1.1 × 10&lt;sup&gt;9&lt;/sup&gt;</td>
<td>NA</td>
<td>NA</td>
<td>1.4 × 10&lt;sup&gt;9&lt;/sup&gt;</td>
</tr>
<tr>
<td>Maximum peak abundance/cm&lt;sup&gt;−2&lt;/sup&gt;</td>
<td>4.2 × 10&lt;sup&gt;9&lt;/sup&gt;</td>
<td>NA</td>
<td>NA</td>
<td>4.8 × 10&lt;sup&gt;9&lt;/sup&gt;</td>
</tr>
<tr>
<td>Average width (FWHM)/km</td>
<td>2.1</td>
<td>2.6</td>
<td>NA</td>
<td>2.4</td>
</tr>
<tr>
<td>Average altitude of maximum density/km</td>
<td>96.1</td>
<td>94.8</td>
<td>97.8</td>
<td>94.4</td>
</tr>
</tbody>
</table>

Figure 3. Na density contour plot and E<sub>s</sub> layer parameters during the night of 28–29 February 2008. Note an extremely strong Na<sub>s</sub> layer burst around 22:39 LT without any E<sub>s</sub> layer throughout the night.

Figure 4. Na density contour plot and E<sub>s</sub> layer parameters during the night of 16–17 May 2011. Note the temporally correlated sporadic Na and E layers occurring before midnight.

the E<sub>s</sub> layer. As seen from Fig. 2, during the observation period of Na layers, the E<sub>s</sub> layers appeared with f<sub>p</sub> of 5.1 and 4.3 MHz (N<sub>e</sub> = 3.2 × 10<sup>5</sup> and 2.3 × 10<sup>5</sup> cm<sup>−3</sup>) at 22:00 and 23:00 LT, respectively. The E<sub>s</sub> layers were also active within ∼2 h before and after the observation of Na layers. However, no Na<sub>s</sub> layer event could be found during the entire observation of lidar.

4.1.2 Case study 2 (28–29 February 2008)

As seen in Fig. 3, during the night on 28–29 February 2008, an Na<sub>s</sub> layer occurred near 95 km at 22:23 LT. It grew very rapidly and reached its maximum peak number density of near 21 600 cm<sup>−3</sup> near 91.8 km at 22:40 LT. Then this extremely strong Na<sub>s</sub> layer gradually decayed and finished at 01:34 LT. The layer was morphologically similar to Kelvin–Helmholtz billows (Kane et al., 2001), and it was the second strongest Na<sub>s</sub> layer during all 95 nights of observations. However, no corresponding E<sub>s</sub> behavior occurred around this time. In fact, the E region ionosphere was notably calm throughout the entire night, despite the appearance of this impressively strong Na<sub>s</sub> layer. By the way, the symbol “S” of virtual height means the occurrence of interference in ionosphere; no ionosonde echo by the E<sub>s</sub> layer can be received. In this situation, the corresponding f<sub>p</sub> recorded by the ionosonde represents the lowest frequency of undisturbed ionosonde echoes. Consequently, the real plasma frequency of the E<sub>s</sub> layer, which may exist, would only be less than the value of recorded f<sub>p</sub>.

4.1.3 Case study 3 (16–17 May 2011)

The above two cases represent the singly appearing E<sub>s</sub> and Na<sub>s</sub> layers. Now we show a case of temporally correlated sporadic Na and E layers on the night of 16–17 May 2011. As seen in Fig. 4, a Na<sub>s</sub> layer was already growing near ∼94.1 km when the observation began at 21:01 LT. It reached its maximum peak density of ∼7510 cm<sup>−3</sup> near 93.9 km at 22:24 LT. The Na<sub>s</sub> layer lasted...
for more than 2 h and finished at 23:14 LT. With respect to the $f_p$, it was more than 3.5 MHz from 20:00 to 23:00 LT. And the Eₚ event occurred at 23:00 LT with $f_p$ of 5.1 MHz. Then the $f_p$ suddenly fell below 1.6 MHz at 00:00 LT and never exceeded 1.7 MHz until dawn. Generally speaking, the period of this Naₐ layer covered the occurrence of the Eₚ layer. And the time difference between maximum Naₐ layer peak density and maximum $f_p$ was 36 min. By the way, the symbol “B” (at 05:00 LT) of virtual height means the occurrence of absorption in the ionosphere.

### 4.2 Statistics study

The correlation of Naₐ and Eₚ layers is normally confirmed by the difference of their occurrence time. Here we use $\Delta t$ to represent the difference of occurrence time for a Naₐ layer and an Eₚ layer. The confirmation of a pair of correlated Naₐ and Eₚ layers requires $\Delta t$ to be within ±2 h (Alpers et al., 1994; Hansen and von Zahn, 1990). Table 3 lists the detailed correlation of Naₐ and Eₚ layers at our site. The $\Delta t$ with a positive value means that an Eₚ layer lags behind its corresponding Naₐ layer, while the $\Delta t$ with a negative value means that an Eₚ layer occurs before its corresponding Naₐ layer.

As seen in Table 3, among a total of 53 Naₐ layer events, 26 (49 %) events possessed correlation with Eₚ layers. Furthermore, 17 (32 %) Naₐ layers occurred within ±1 h of their corresponding Eₚ layers. Figure 5 shows the height and peak number density distribution of all Naₐ layer events. The Naₐ layers occurring without Eₚ layers are drawn in hollow circles, and the others are drawn in solid symbols. Different solid symbols represent different value ranges of $\Delta t$. For further details, please see the figure annotation. As seen in Fig. 5, Naₐ layers correlated with Eₚ layers generally exhibit higher altitudes. In addition, with respect to Naₐ layers above 92 km, the stronger parts with peak densities greater than $1 \times 10^4$ cm⁻³ are all correlated with Eₚ layers.

### 5 Eₚ layer occurrence probabilities around Naₐ layers

As we know, a reliable correlation between one Naₐ layer and one Eₚ layer can only be established based on data with high enough temporal and spatial resolutions, such as the Naₐ and Eₚ layer pair evolving with the same track obtained by lidar and incoherent scatter radar on 16 January 1989 at Arecibo (Beatty et al., 1989). However, considering the comparably low resolutions (1 h and ±5 km) of Eₚ layer data obtained by our ionosonde, the claim of correlation between Naₐ and Eₚ layers obtained above is crude. The extent of correlation between Naₐ and Eₚ layers is still a mystery. Therefore, we will further study the correlation between Naₐ and Eₚ layers by surveying Eₚ layer occurrence probabilities in three different time intervals around a Naₐ layer. As seen in Fig. 6a, the first time interval is the period within 2 h before the Naₐ layer initiates. The second time interval matches the occurrence duration of the Naₐ layers. The third time interval is the period within 2 h after the Naₐ layer dissipates. Noticing that the ionosonde operates every hour on the hour, it operates twice in both the first interval and the third interval. Whereas, the number of ionosonde scans in the second interval is not fixed and could be several or none (Fig. 6b). As seen in Fig. 6c, a Naₐ layer could already exist when the lidar observation begins. In this case, the real beginning time point of a Naₐ layer has not been caught. Hence its first interval is not knowable and available. Similarly, the third interval could be unavailable if a Naₐ layer still exists when lidar observation stops (Fig. 6d).

Using these intervals to analyze all 53 Naₐ layers, we have obtained the total number of ionosonde operation times for each of the three time intervals. As seen in Table 4, the ionosonde made 70, 86, and 88 scans in the first, second, and third intervals, respectively. By calculation, occurrence probabilities of Eₚ layers in the same three time intervals are 19 % (13/70), 22 % (19/86), and 18 % (16/88). Very importantly, the advantage of introducing these three probabilities is their mathematical comparability with the average.
Figure 6. The definition of three time intervals around the Na<sub>s</sub> layer.

The definition of three time intervals around the Na<sub>s</sub> layer.

Figure 7. Na density contour plot and Es layer parameters during the night of 6–7 May 2009, which displayed a high-altitude Na<sub>s</sub> layer above 105 km. Notice the correlation between the Na<sub>s</sub> and Es layer events on this night seemed good.

6 Characteristics of high-altitude sporadic Na layers

Considering the fact that the detection ability of lidar decreases with increasing altitude, we have decreased the temporal resolution of Na data to 15 min by integrating several raw photon count profiles, in order to ensure a good data quality. Referring to our previous work, the high-altitude Na<sub>s</sub> layers are defined to match three criteria: (1) the altitude is above 105 km, (2) The peak density is greater than 50 cm<sup>-3</sup>, which is five times of corresponding detection threshold (10 cm<sup>-3</sup>) at 110 km, (3) The layer lasts for at least 45 min (three consecutive profiles).

6.1 Case studies

6.1.1 Case study 1 (6–7 May 2009)

In our previous work, we found a phenomenon that the high-altitude sporadic Na layers appeared on the same night (18–19 May) in two different years (2001 and 2006) at Wuhan (Ma and Yi, 2010). Interestingly, this reappearance phenomenon of high-altitude Na<sub>s</sub> layers also occurred at Qingdao.

Figure 7 displays a Na density contour plot during the night of 6–7 May 2009. A high-altitude sporadic Na<sub>s</sub> layer was distinguished around 115 km at 21:00 LT. Then it gradually descended and reached its maximum peak density of 128 cm<sup>-3</sup> near 110.7 km at 23:30 LT. At the same time, its FWHM and column abundance were 4.05 km and \( \sim 4 \times 10^7 \) cm<sup>-2</sup>, respectively. This Na<sub>s</sub> layer existed for about 5 h and finished after 01:45 LT when it merged with the main Na layer. With respect to the Es layer, it reached the plasma frequency of 6.4–6.5 MHz during the formation period of the Na<sub>s</sub> layer, and then was less than 4 MHz until the Na<sub>s</sub> layer finished. Generally speaking, the correlation between the Na<sub>s</sub> and Es layer events on this night seemed good.
First of all, a total of 11 high-altitude (above 105 km) Na layers have been selected from 95-night lidar data. Some characteristics of high-altitude Na layers over Qingdao as well as those over Wuhan are shown in Table 5. Notice that the sensitivity of lidar at Qingdao is higher than that at Wuhan due to the larger telescope aperture. By comparing the results in Tables 2 and 5, it is very obvious that high-altitude Na layers over Qingdao possessed long duration (>165 min) and broad layer width (4.0 km) compared with those over Wuhan as well as those over Qingdao are shown in Table 5. Note that the sensitivity of lidar at Qingdao is higher than that at Wuhan due to the larger telescope aperture. By comparing the results in Tables 2 and 5, it is very obvious that high-altitude Na layers over Qingdao possessed long duration (>165 min) and broad layer width (4.0 km) compared with those over Wuhan.

6.1.2 Case study 2 (6–7 May 2010)

As seen in Fig. 8, the high-altitude sporadic layers reappeared 1 year later (6–7 May 2010). This Na layer formed at 116 km around 23:45 LT and descended all along. It reached its maximum peak density of 71 cm\(^{-3}\) near 110.7 km at 23:45 LT. At the same time, its FWHM width and column abundance were 6.00 km and \(\sim 3 \times 10^7\) cm\(^{-2}\). This Na layer was still apparent when the lidar observation stopped at 00:15 LT. So it lasted for more than 165 min. However, with respect to an E\(_0\) layer, none occurred during the entire observation of the Na layer. Finally, notice both the high-altitude Na layers on the nights of 6–7 May in 2009 and 2010 possessed weak number density, broad layer width and long duration.

6.2 Statistics study

First of all, a total of 11 high-altitude (above 105 km) Na layers have been selected from 95-night lidar data. Some characteristics of high-altitude Na layers over Qingdao as well as those over Wuhan are shown in Table 5. Notice that the sensitivity of lidar at Qingdao is higher than that at Wuhan due to the larger telescope aperture. By comparing the results in Tables 2 and 5, it is very obvious that high-altitude Na layers over Qingdao possessed long duration (>147 min) and broad layer width (4.0 km) compared with Na layers below 105 km (>96 min and 2.4 km). These characteristics accord with the observational results at Wuhan.

Figure 9 has shown the seasonal distribution of high-altitude Na layers and their intensities (peak densities) have been denoted by solid circles with different colors. The cyan bars represent the total number of observation nights in each month. As seen from Fig. 9, high-altitude Na layers all occurred from April to August. This indicates that there exists a strong seasonal/annual distribution of high-altitude Na layers. The peak densities of these high-altitude Na layers were very small. Among a total of 11 Na layers, 9 and 4 of them had the peak densities of less than 200 and 100 cm\(^{-3}\), respectively. For the identical peak density threshold of 200 cm\(^{-3}\), the occurrence rates of high-altitude Na layers were 1/215 h\(^{-1}\) over Qingdao and 1/113 h\(^{-1}\) over Wuhan.

By a similar statistical work, E\(_0\) layer occurrence probabilities in the three time intervals around high-altitude Na layers are 33 % (4/12), 41 % (11/27), and 13 % (1/8), respectively. Nevertheless, it should be noticed that all high-altitude Na layers appeared from April to August. By calculation, the corresponding average occurrence rate of the E\(_0\) layer during the nights from April to August is 40 %. Hence, the fact that the E\(_0\) layer occurrence probabilities are less than or approximately equal to the corresponding average occurrence rate of E\(_0\) layers over Qingdao. Nevertheless, we point out that the numbers of ionosonde measurements are insufficient for a good statistical study.

Figure 10 draws the seasonal variation of the nocturnal mean Na atom density in which all sporadic layers have been retained. To preferentially show the Na atom number densities with small values, the density is drawn on a logarithmic scale. In addition, the red dots under the bottom of the panel
Seasonal distribution of peak altitudes for the high-altitude Na\textsubscript{s} layers over Qingdao (36° N). The peak densities are denoted by the color of solid circles. Cyan bars represent the night number of the lidar measurements in each month. Note that high-altitude Na\textsubscript{s} layers all occurred from April to August.

Figure 9. Na density at Qingdao (36° N) on logarithmic scales. For further explanation please see text.

7 Summary

We have surveyed the characteristics of sporadic Na layers based on lidar observations from December 2007 to June 2012 at Qingdao. A total of 53 Na\textsubscript{s} layers have been selected from \(\sim 430\) h of Na number density data on 95 nights. By comparison, it is found that the occurrence rate and strength of Na\textsubscript{s} layers over Qingdao are all close to those over Wuhan. And the average width and altitude of Na\textsubscript{s} layers over Qingdao are close to those over Hefei. However, the strength and average altitude of Na\textsubscript{s} layers over Qingdao are much different with those over Hachioji. Overall, the characteristics of Na\textsubscript{s} layers over Qingdao have a general similarity with those over nearby sites, but not with those over the site at nearly the same latitude as Qingdao.

Sporadic E layers were simultaneously observed by an ionosonde standing at only \(\sim 30\) m horizontal distance from the lidar. Among a total of 53 Na\textsubscript{s} layer events, 26 (49\%) events possessed temporal correlation with E\textsubscript{s} layers. Furthermore, 17 (32\%) Na\textsubscript{s} layers occurred within \(\pm 1\) h of their corresponding E\textsubscript{s} layers. However, considering the comparably low resolutions of E\textsubscript{s} layer data obtained by our ionosonde, we are unable to conclude that there is correlation between the Na\textsubscript{s} and E\textsubscript{s} layers obtained above. So we have further surveyed E\textsubscript{s} layer occurrence probabilities in three different time intervals around Na\textsubscript{s} layers. By calculation, E\textsubscript{s} layer occurrence probabilities in time intervals within 2 h before, during, and within 2 h after Na\textsubscript{s} layers are 19, 22, and 18\%, respectively. The fact that E\textsubscript{s} layer occurrence probabilities in these three time intervals are very close to the occurrence ratio of E\textsubscript{s} layers at night (21\%) should indicate the general statistical independence between Na\textsubscript{s} and E\textsubscript{s} layers over Qingdao. The subset of Na\textsubscript{s} layers with peak density above \(10^4\) cm\textsuperscript{-3} and altitude over 92 km have higher coincidence probabilities with E\textsubscript{s} layers: 67\% for E\textsubscript{s} occurring 2 h before Na\textsubscript{s}, 88\% for concurrent layers, and 40\% for E\textsubscript{s} within 2 h following Na\textsubscript{s}. These values are much higher than the average occurrence ratio of E\textsubscript{s} layers at night (21\%). Thus it might suggest that only those strong Na\textsubscript{s} layers above the peak altitude of the main Na layer have correlation with E\textsubscript{s} layers, although the number of events is still too small to reach a firm conclusion.

Na\textsubscript{s} layers at high altitude deserve special attention. It is found that high-altitude Na\textsubscript{s} layers over Qingdao possess long duration (> 147 min) and broad layer width (4.0 km) compared with normal ones (> 96 min and 2.4 km). These characteristics agree with our observational results at Wuhan. Similarly, the fact that E\textsubscript{s} layer occurrence probabilities during high-altitude Na\textsubscript{s} layers (33, 41, and 13\%) are less than or approximately equal to the corresponding occurrence rate of E\textsubscript{s} layers (40\%) suggests insignificant correlation between this kind of Na\textsubscript{s} layers and E\textsubscript{s} layers. Finally, the summer topside enhancement phenomenon of Na atoms observed at Qingdao is in accord with several earlier observational results at different sites (18, 30, and 54° N) in the Northern Hemisphere.
Acknowledgements. This research is supported by National Natural Science Foundation of China through grant 41104102. The authors appreciate Shaohong He, Xiaobing Wang and Zhengzheng Ma for their technical support in collecting ionosonde and lidar data. The authors also greatly appreciate the anonymous referees for enlightening and helpful comments.

Topical Editor C. Jacobi thanks two anonymous referees for their help in evaluating this paper.

References


Williams, B. P., Berkey, F. T., Sherman, J., and She, C. Y.: Coincident extremely large sporadic sodium and sporadic E layers ob-

