Sudden Sodium Layers: Their Appearance and Disappearance

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Abstract Temperature variation has been proposed to play an important role in the formation of the sporadic sodium layers (SSLs or NaS) in subtropic area, based on the observed significant correlation between SSLs and high temperatures. The icy-dust particle, which could form in the extremely cold conditions and act as absorbers of sodium species, was proposed to be a possible candidate for the sodium reservoir of the SSLs. In this study, the University of Science and Technology of China temperature/wind lidar and the sodium fluorescence lidar at a subtropic station Hefei (31°N, 117°E), China, were used to observe sodium density, temperature, and wind profiles simultaneously throughout the SSL events. Based on the observations of two SSLs occurring on 12 and 13 May 2013, the possibility of an icy-dust layer existing and acting as the sodium reservoir is tested for the first time in details. Both events experienced an extremely cold temperature (<150 K) several hours before the onset of SSLs, followed by a subsequently fast production of sodium atoms during a large temperature enhancement (>40 K). An empirical model including two main steps is then proposed: first, sodium species are collected by an icy-dust reservoir and stored during the extremely cold phase; second, free sodium atoms could be released from the reservoir by a possible trigger. As a result, this kind of SSLs could possibly be regarded as a quasi-continuous phenomenon caused and modulated by temperature variations with an icy-dust model that can exhibit intermittent time variations related to the water vapor concentration.

Plain Language Summary Temperature variation, rather than through the mechanism of cooccurrence of sporadic E layer (ES), has been proposed to play an important role in the formation of the sporadic sodium layers (SSLs or NaS) in subtropic area based on the observed significant correlation between SSLs and high temperatures. But the detailed process and mechanism are still unclear. The icy-dust particle, which could form in the extremely cold temperature conditions and as absorbers of sodium species, was proposed by previous studies to be a possible candidate for the sodium reservoir of the SSLs. However, this most promising scenario has not yet been evaluated in those earlier studies owing to a lack of the relevant observations. In this study, the University of Science and Technology of China temperature/wind lidar and the sodium fluorescence lidar at a subtropic station Hefei (31°N, 117°E), China, were used to observe sodium density, temperature, and wind profiles simultaneously throughout the SSL events and activities. Based on the observations of two SSLs occurring on 12 and 13 May 2013, the possibility of an icy-dust layer existing at the mesopause and acting as the sodium reservoir is tested and verified for the first time in details.

1. Introduction

Existing observations show that sporadic sodium layers (SSLs or NaS) have obvious regional distinctions in occurrence frequency, duration, peak height, and seasonal and diurnal distributions, all of which indicate a diversity of mechanisms for SSL formation and maintenance in different latitudes and altitudes (Beatty et al., 1988; Clemesha, 1995; Collins et al., 2002; Cox et al., 1993; Daire et al., 2002; Gardner et al., 1995; Qiu et al., 2015; Zhou et al., 1993). Up to now, three mechanisms have been widely studied: the dust theory (suggesting the release of free sodium atoms from dusty surfaces by the energetic
auroral particle bombardment; von Zahn et al., 1987), the ES theory (supporting the recombination of sodium ions from a series of downward ES; Collins et al., 2002; Cox & Plane, 1998), and the temperature-controlled theory (suggesting the triggering of sodium atoms by some means through temperature enhancement in a narrow altitude region due to energy damping during gravity wave breaking; Zhou et al., 1993; Zhou & Mathews, 1995). However, none of these three viable proposals seems to be able to explain the rather wide variety in specific characteristics of SSLs all over the world: Some SSLs observed at high latitude occurring during the temperature minimum phase (Hansen & von Zahn, 1990; Østerpart, 2011), SSLs occurring in a subtropic area were accompanied by no ES (Dou et al., 2009; Gong et al., 2002; Miyagawa et al., 1999), and a decrease in sodium density was also observed during auroral activity (Heinselman et al., 1998; Tsuda et al., 2013), all of which indicate a particular mechanism for different SSLs.

In general, the occurrence of SSLs observed in subtropical latitudes, from 20°N to 35°N, has a weak correlation to ES activities (Dou et al., 2009; Gong et al., 2002; Miyagawa et al., 1999; Qiu et al., 2015, 2016). These SSLs, usually lasting for a long period and locating near the centroid height of normal sodium layer at 92 km, are often detected accompanied by large temperature enhancements (Gardner et al., 1995; Li et al., 2005; Qian et al., 1998; Qiu et al., 2015, 2016). Thus, the temperature-controlled theory, instead of the ES theory, seems to be more appropriate for explaining the subtropical SSLs (Qiu et al., 2015, 2016).

Under the temperature theory, sodium density is thought to be influenced by a set of temperature-dependent ion-molecule gas-phase reactions (Zhou et al., 1993). The most rapid reaction for creating sodium atoms in the mesopause, according to our knowledge, is the recombination of sodium ligand complex with free electrons (Collins et al., 2002; Cox et al., 1993),

\[
\text{Na}^+ \cdot X + e^- \rightarrow \text{Na} + X (X = \text{O}, \text{N}_2, \text{CO}_2, \text{H}_2\text{O}),
\]

where \( k \) is the reaction rate coefficient. However, this recombination rate is in fact inversely dependent on temperature, which means the reaction rate would decrease with a temperature increase. At the same time, the diffusion coefficient of sodium (\( k_{\text{Diffusion}} = 152 \times (300/T)^{-1.85} \text{torr cm}^2 \cdot \text{s}^{-1} \); Cox et al., 2001) had a direct, positive dependence on temperature. So the sodium density will probably decrease during the temperature enhancement episode. Therefore, it is simply difficult to invoke only the temperature dependence for chemical reactions to explain the relatively fast generation of sodium atoms during SSLs. Such an interpretation is in accord with some observations and model simulations showing that the maximum temperature had only a weak relationship with the Na peak density (Qian et al., 1998) and the Na density could even have a negative correlation to temperature above 96 km due to the dominance of ion-molecule chemistry there (Plane et al., 1999). In fact the scenario for a gas-phase reservoir responsible for generating sodium atoms was rejected earlier on by Cox et al. (1993). And even Zhou et al. (1993), who first deduced the temperature theory, supported the temperature enhancement only as a trigger for the release of sodium from a preexisting reservoir.

The existence of a solid sodium reservoir (e.g., dust/smoke particles) for the SSLs was proposed by increasingly more research works and papers (Cox et al., 1993; Gu et al., 1995; Nesse et al., 2008; von Zahn et al., 1987). It was widely accepted that dust could act as a major sink of sodium atoms (Cox et al., 1993; Hunten et al., 1980). The dust particles, usually with a radius about several nanometers, had a sufficient number density of hundreds to thousands particles per cubic centimeter from rocket-borne measurements or model simulation results (Brattli et al., 2009; Fentzke et al., 2009; Jensen & Thomas, 1991; Lynch et al., 2005; Megner et al., 2008, 2006; Robertson et al., 2009). These particles could be concentrated into a narrow layer by appropriate wind shear when the particles are charged (Nesse et al., 2008; von Zahn et al., 1987). However, in these studies, the suggested trigger responsible for the release of free sodium atoms from the dusty surfaces was the energetic auroral particle bombardment, which might factually be unfeasible for subtropical SSLs. On the other hand, the formation of SSLs occurred near 95 km were often observed to be related to wave-like structures (Tsuda et al., 2011) and wave dissipation phenomenon (Li et al., 2005).
We propose that the supposed sodium reservoir should contain some specific properties: it needs to have efficient adsorption ability to store enough sodium sources, it has a fast release mechanism, and lastly, the release process is related to a warming temperature enhancement; it might have no correlation to Es or auroral activities. Recently, Qiu et al. (2015) and Qiu et al. (2016) observed the following empirical scenario for typical subtropical SSLs: extremely low temperatures below 150 K have always occurred several hours before the SSLs and most of these SSLs were formed or generated with a temperature maximum over 190 K. These statistical results showed that the occurrence of low temperature and the corresponding subsequent temperature increase is a specific character of these SSLs. According to these results, formation of icy-dust particles, which could form in the extremely cold weather condition and then adsorbs and accumulates sodium species, and could also sublimate in the hot mesospheric weather to release free sodium atoms, was proposed as a candidate for the sodium reservoir (Qiu et al., 2015, 2016). However, no final conclusion was made in these two earlier studies, because simultaneous temperature observational records were not available at that time.

Fortunately, in this work we can use the University of Science and Technology of China (USTC) T/W lidar (Li et al., 2012), as well as the sodium fluorescence lidar (Dou et al., 2009) at Hefei site (31°N, 117°E), to observe sodium density, temperature, and wind profiles simultaneously throughout the SSL formation (see section 2). Based on the observations of two SSLs found occurring on 12 and 13 May 2013, the possibility of an icy-dust layer existing at the mesopause and acting as the sodium reservoir is experimentally tested for the first time in details. An empirical (and comprehensive) model containing two main steps of the formation progression of SSL formation and maintenance is elaborated in section 3. These results indicate that the SSLs could possibly be described as a quasi-continuous phenomenon formed through temperature variations. And our research essentially pointed out that for the formation of SSLs, three simultaneous conditions need to be met, that is, a zonal wind shear, the temperature, and the water vapor cycle. If any is not met then a layer does not form, or, if a layer is present, and one or more of the three elements changes, then the layer disappears, hence the reasons for intermittency. The conclusion is summarized in section 4.

2. Observations and Results

On 12 and 13 May 2013, two SSLs were detected by the USTC lidar, respectively. Figures 1a and 1b show the sodium density contour images for the two events: Figure 1a shows the sodium lidar operated from 11:49 UT to 20:44 UT on 12 May, and the SSL was maintained from 17:53 UT to 20:44 UT (with no ending of the event seen before the lidar stopped operating/observing), and Figure 1b shows the sodium lidar operated from 11:59 UT to 20:39 UT on 13 May, with the SSL lasting from 16:55 UT to 19:13 UT. Figures 1c and 1d show the peak density profiles for the two events: the solid black curve in Figure 1c shows the peak height of the SSL on the night of 12 May located at 93.2 km, with a maximum density of 5,740 cm\(^{-3}\) and an intensity factor, f (i.e., f = peak density/background density of the whole night), of about 4.0, timed around 18:38 UT. The dotted black line shows the fitted sodium density profile for the background sodium layer through the whole night. Figure 1d shows similar results for 13 May event reaching its peak density of 4,300 cm\(^{-3}\) (with f = 3.5) at 94.7 km altitude timed around 17:16 UT.

Figure 2 shows the temperature profiles and distributions throughout the two nights. Figures 2a and 2b show the temperature variations detected by the zonal (Tu) and meridional (Tv) beams on 12 May. The mesopause went through a cold phase from the beginning of the observation till the onset of the SSL. Temperature kept below 160 K for almost 6 hr, with a minimum of 134.4 K ± 1.5 K for Tu at 95 km timed around 14:44 UT. Sounding of the Atmosphere with Broadband Emission Radiometry (SABER) swept Hefei at 13:41 UT, detecting a temperature minimum of 142.8 K at 96.8 km (29.6°N, 114.7°E), confirming the extremely cold mesospheric weather on that day. On the other hand, from about 18:00 UT to 20:00 UT, we observed the appearance of a hot phase with large temperature enhancement in the altitude ranges between 90 and 98 km. We noted that the temperature was raised above 190 K in this range, reaching a maximum of 202.2 K ± 0.1 K for Tv at 97 km timed around 18:59 UT. The hot phase area overlapped the SSL region, in terms of both duration and altitude. Similar to the situations on 12 May, Figures 2c and 2d show temperature variations on 13 May, with a cold phase from 12 UT to 15 UT between 92 and 96 km altitude and a hot phase from 17 to 19 UT between 92 and 98 km region. The duration and location of temperature enhancement for this 13 May event are also in accord to the SSL activity on 12 May.
The near-simultaneous $E_S$ activities observed using a nearby ionosonde in Wuhan (30°N, 114°E) on 12 and 13 May are shown in Figures 3a and 3b, respectively. The black squares stand for the virtual height of the echoes ($h_{ES}$) detected. These $E_S$ echoes were selected if the $f_{oES}$ ($E_S$ layer’s critical frequency) values were greater than zero. On 12 May, a sequence of downward $E_S$ sustained from 07:00 UT to 13:00 UT. However, only two scattered $E_S$ signals, at 17:30 UT and 17:45 UT, were recorded between 13:00 UT and the onset of the SSL. The two $E_S$ echoes had a time interval of more than 4 hr to the termination of the downward $E_S$ series, indicating a disconnection of SSL formation from $E_S$ activities. Furthermore, $E_S$ were not active at all on 13 May, with no $E_S$ echoes detected during the 4 hr before the SSL.

These two SSLs have similar characteristics from the lidar profiles: the peak altitude locating near the centroid height of the normal sodium layer (usually 92 km in subtropical area), lasting for a relatively long duration of over 2 hr, having a large peak density and strong intensity (with $I > 3$), and in particular, the onset time for both SSL events began soon after about 17:00 UT. The corresponding temperature profiles and distributions also exhibit a similar character, with an extremely cold phase before the onset of the SSL and an overlapping of temperature enhancement during the SSL. On the other hand, $E_S$ echoes remained at zero values several hours before the SSLs. All these similarities probably imply the same mechanism for these SSLs’ formation processes.
3. Discussions

3.1. Possible Influences by the $E_5$ Activities

Figure 3a and 3b show the $E_5$ echoes detected by Wuhan ionosonde, which exhibits no $E_5$ echoes during the 4 hr before the onset of the SSLs (the grey vertical lines mark the onset time of the SSLs). The simultaneous wind profiles observed by the USTC T/W lidar east beam and north beam on 12 and 13 May are shown in Figures 4a and 4b, respectively. The positive velocity corresponds to the eastward wind. For both events, the zonal wind shear, covers an altitude ranges from about 80 to 100 km and a time ranges from 12 UT till the onset of the SSL, had an opposite polarization to the required wind shear (which needs a westward wind locating above and an eastward wind below, Kirkwood & von Zahn, 1991) for gathering sodium ions through the $\vec{v} \times \vec{B}$ drifts in Northern Hemisphere, also indicating an inefficient condition for gathering metal ions for the formation of $E_5$ layers. On the other hand, the formation of SSLs on 13 May 2013 observed by both USTC sodium lidar and T/W lidar completely overlapped with the temperature enhancement region. This result is consistent with our previous studies, which suggested that SSLs in this subtropical station usually had weak correlation to $E_5$, but a close relationship to temperature variations (Dou et al., 2009, 2010; Qiu et al., 2015, 2016).

In contrast, another SSL observed on 3 June 2013 by the USTC lidar and T/W lidar shows distinct characters. The sodium density contour image and peak density profile for this comparative event are shown in
Figures 5a and 5b, respectively. Temperature profiles from the USTC T/W lidar exhibit the formation of SSL on 3 June occurring during a particular cold weather (Figure 5c), quite different from the cases on 12 and 13 May. The peak altitude locates at 97.7 km at the top of the sodium layer. Distinctly different from 12 and 13 May, from 06:00 UT to 13:15 UT on 3 June, a sequence of E₅ layers descends downward from above 120 to 100 km, getting closer to the altitude where the SSL occurs (Figure 6).

From a long-term observation at Hefei, we have learned from experience that SSLs occurring at a lower altitude (most likely below 96 km) often had a feature like the case on 12 and 13 May, and the higher altitude SSLs (usually above 96 km) appeared more like the cases on 3 and 13 June (Qiu et al., 2016). Therefore, the SSLs locating below 96 km may have a different mechanism from those appearing above 96 km. The different characters between the SSL on 3 June and the two typical SSLs discussed lead us to believe and propose that the formation for the case on 3 June probably has an E₅-related formation mechanism, while the current studied cases on 12 and 13 May may have a close relationship to temperature variation mechanism.

3.2. The Possibility of Icy-Dust Mechanism

As discussed above, seeking out the previously undetected, preexisting sodium reservoir is the key observational constraint on the low-temperature phase of the model. One of the possible sodium reservoirs identified in previous studies was thought to be the dust/smoke/aerosol particles originated from meteoric ablation (Cox et al., 1993; Nesse et al., 2008; von Zahn et al., 1987). The existence of dust reservoir was confirmed by the simultaneous occurrence of dust layer and sporadic metal layer detected by joint airborne rockets and ground-based lidars (Gelinas et al., 1998, 2005). For example, a 5-km-thick positively charged dust layer was found in the vicinity of the SSL by Gelinas et al. (1998). Another research detected strong correlations between the dust density and neutral Fe profile during four flights, suggesting that dust particles could serve as a reservoir for atomic metals (Gelinas et al., 2005).
In our previous studies, we supposed that the dust reservoir to be mainly icy-dust particles and was assumed primarily because of the possibility of icy-dust layer existing at the subtropical mesopause zone (Qiu et al., 2015). This supposition was based on the observed anticorrelation between metal layer densities and the occurrence of mesospheric ice-related phenomena (e.g., polar mesospheric cloud and polar mesosphere summer echo) during high-latitude summer when the mesopause temperature fell below 150 K (Lübken & Hoffner, 2004; Plane et al., 2004; She et al., 2006; Thayer & Pan, 2006). The icy-dust particles were able to adsorb metal atoms on the surface as a thin metal film (Bellan, 2008; Fan et al., 2007; Plane et al., 2004; Raizada et al., 2007; Thayer & Pan, 2006) or packet metal species as nuclei (Olofson et al., 2009; Plane, 2000), which were determined by rocket-borne measurements and numerical modeling results (Brattli et al., 2009; Havnes et al., 1992, 1996; Robertson et al., 2009). The icy-dust particles, as a result, could act as an effective sink of metal layer through scavenging metal species around (Gardner et al., 2005; Plane et al., 2004; She et al., 2006; Thayer & Pan, 2006). The final fate of the icy-dust particles/layer is to sublimate under the warm mesospheric weather condition and leaving behind a concentrated layer of residual metal species (Plane et al., 2004), which

![Figure 5](image-url)

**Figure 5.** A comparative case on 3 June 2013. (a) Sodium density variations, with the SSL lasting from 13:26 UT to 14:49 UT. (b) Peak density profile for the SSL, with the peak located at 97.7 km at the top of the sodium layer. (c) Temperature profiles on 3 June showing that the entire formation of the SSL maintains in a temperature minimum region. (d) Zonal wind profiles observed by the USTC T/W lidar on 3 June.

![Figure 6](image-url)

**Figure 6.** Es activities observed by the Wuhan ionosonde, for the comparative SSL case on 3 June 2013. The grey circle stands for the altitude of the SSL and the vertical line marks the onset of the SSL.
could probably be regarded as a seed or initial phase of sporadic metal layer. Our statistical results show that in the subtropical station over Hefei, low temperatures below 150 K always appeared before the characteristic SSLs and most of these SSLs occurred during the phase with large temperature enhancements (Qiu et al., 2015, 2016). The water vapor mixing ratio near 93 km, discussed in our case studies, showed a sharp decrease before the typical SSL but soon after a recovery to normal levels during the SSL (Qiu et al., 2015, 2016). The variations of both temperature and water vapor concentration implied a possibility of the coagulation and sublimation of the supposed icy dust over the subtropical mesopause region (Qiu et al., 2015).

The water vapor variations from 11 to 14 May are shown in Figure 8. The water vapor concentration maintains relatively high content on 0511, with an obvious peak of over 3 ppmv at about 93 km. So the supposed icy-dust particles could form during the cold phase before the 12 May NaS (e.g., during 11 May). As discussed by previous studies, ice particles could coagulate and grow when the water vapor saturation became greater than 1 (Thomas, 1996). The degree of saturation, \( Sa \), can be expressed as (Thomas, 1996)

\[
Sa = \frac{w(H_2O)p}{\exp\left(28.548 - \frac{6077.4}{T}\right) - \frac{6077.4}{T}} = \frac{w(H_2O)p}{e^{\frac{6077.4}{T}} - e^{\frac{6077.4}{T}}}.
\]  

(3)

where \( p \) is the total gas pressure in N/m\(^2\) and \( w(H_2O) \) is the water vapor mixing ratio. The frost-point temperature \( T_f \), the temperature at which \( Sa = 1 \), could be deduced as (Thomas, 1996)

\[
T_f(K) = 6077.4 \left[ 37.759 - \log_e(w(ppm)) - \log_e(p(mb)) \right].
\]  

(4)

where \( w(H_2O) \) is expressed in units of parts per million (ppm) and \( p \) (mb) is in hPa units. Using these equations, the saturation of water vapor and the critical temperature could be estimated based on direct

Figure 7. (a) Zonal wind velocity variations, by Wuhan meteor radar covering the 12–13 May interval. (b) Temperature profile, similar to Figure 2a and 2c, but now in the same corresponding time interval with zonal wind data given above in Figure 7a.
observations. On 12 May, for \( p = 0.001 \) hPa (corresponding to 93 km altitude), assuming \( w(H_2O) = 3 \) ppm, the calculated critical temperature \( T_0 = 139.5 \) K. The observed temperature minimum during the cold phase was 134.4 K ± 1.5 K at 95 km, lower than \( T_0 \). So under the temperature minimum condition, the environment could become over saturated for a sustained duration, suggesting a possibility for icy dust to grow.

However, it is worth noting that even for the lowest temperature of 134 K, the calculated saturation degree of \( Sa \) was only 6.0, not so extremely larger than 1. In fact, the estimated frost temperature and saturation degree are highly uncertain because the imprecision in the values of total gas pressure and water vapor mixing ratios may add some uncertainties to the calculated values. Most previous studies, including direct observations and simulation results, support an upper limit of 150 K for ice particles in the mesopause (Aschbrenner et al., 2008; Baumgarten & Thomas, 2006; Bellan, 2008; Berger & von Zahn, 2002; Chandran et al., 2010; Chu et al., 2001, 2004; Gerdig et al., 2007; Herrig et al., 2001; Jensen & Thomas, 1994; Lübken et al., 2002; Latteck et al., 2008; Merkel et al., 2009; Murray & Plane, 2003, 2004; Plane, 2000; Rapp & Lübken, 2004; Rapp et al., 2002; Taylor et al., 2002; Thomas, 1991, 2003; von Savigny et al., 2007; von Zahn, 2003; von Zahn & Berger, 2003), or even 154 K (Kirkwood et al., 1998). Even at temperatures larger than 150 K, say at 155 K, it takes tens of minutes for a 10 nm particle to evaporate assuming a reasonable water vapor mixing ratio (Lübken et al., 2002). So the lowest temperature of 134 K detected by the T/W lidar is indeed much lower than the upper limit of 150 K. On the other hand, studies on ice particles also show that the existence of ice depends on several parameters and conditions. The number density of seed nuclei may be the most important condition for ice grains, followed by water vapor and then temperature (Rapp & Thomas, 2006). Results from Fentzke et al. (2009) indicate a large number density of tiny dust particles over Arecibo (18.3°N, 67.3°W), which may act as the seed ice nuclei. If such an amount of tiny dusts could also exist over Hefei, the nucleation time needed will be much shorter than previously supposed.

Furthermore, in previous studies, the ice particles are thought to must have been nucleated within 2 hr (Berger & von Zahn, 2007), which is probably not quite a long duration of cold weather. So the environment during the cold phase could indeed be suitable to support the formation and maintenance of icy dust, though these ice particles probably only grow to subvisible particles with tiny size. Furthermore, our T/W lidar could only operate at night, so we must necessarily have missed the opportunity to document a long period of extremely low temperatures when we start operating our equipment during the night hours. Take the case on 12 May 2013 for instance: We observed a cold temperature at the beginning of our observation, which probably did not start simultaneously with our turning on of the instruments. By contrast, the whole-day observation by T/W lidar over Fort Collins, Colorado (41°N, 105°W), shows that the cold temperature
coincided well with the eastward wind and persisted as long as the eastward wind phase continued (see Figures 1a and 1c of Li et al., 2007). Figure 7a shows the zonal wind observed by the nearest meteor radar at Wuhan, indicating an eastward wind lasting from 16 UT on 11 May to 18 UT on 12 May (marked by red oval in Figure 7a). So the corresponding cold temperature might reasonably persisted for a much longer duration (time covered by the red dashed oval in Figure 7b) than is shown by our T/W lidar nighttime observation in Figure 2a.

3.3. An Empirical Model for the Typical SSLs

The temperature distributions for the two cases in May exhibit a similar character: a cold phase before the NaS and a huge enhancement of temperature during the NaS phase. Figure 8 also shows that the water vapor concentration repeats a depletion-enhancement and recovery cycle for the two cases. And ES were not active at all on either 12 or 13 May. Based on the observations and discussions above, we conclude that this kind of subtropical SSLs might possibly have similar characteristics and hence indicate a similar mechanism: these SSLs yielded no convincing relation or connection to ES, but instead, we found a clearer specific relationship with temperature variations. The two events were observed to undergo two main steps throughout the formation: first, an extremely cold weather persisting several hours before the onset of sodium increase, and second, a large temperature warming enhancement (>40 K of temperature increase) during the fast generation of sodium atoms. Except for the strong correlation between the release of sodium atoms and the enhancement of temperature, the only point of these progressions that could be experimentally determined was the temperature variations. However, as discussed in the introduction, the rate coefficient of the most rapid chemical reactions for generating sodium atoms in the mesosphere have inverse dependence on temperature with the eddy diffusion having a positive and direct correlation to temperature. So as the temperature is raised, the generation speed of the chemical reactions would be slowed and the diffusion of Na atoms would be strengthened, which should indeed lead to an overall reduction of the sodium density. Therefore, it seems difficult to explain the sharp burst of sodium atoms by temperature enhancement alone. Then it may be proposed that the observed enhancement of sodium density during the high-temperature phase is probably caused by sodium atoms being released relatively quickly from an unknown sodium reservoir via a trigger.

3.3.1. The Cold (Low-Temperature) Phase

The SSLs observed on 12 and 13 May both went through an extremely cold temperature before their onset and with a subsequent large temperature enhancement after are both shown in Figure 2. Figure 8 shows that the water vapor concentration repeats a depletion-enhancement and recovery cycle, especially exhibiting an obvious reduction of water vapor density on 12 May and a recovery by 13 May. The water vapor concentration maintains a relatively high concentration on 0511. So the supposed icy-dust particles could form during the cold phase before the 0512 NaS, and as a result the water vapor concentration later exhibits a depletion on 0512. At 05:26 UT on 0513, there is an obvious peak of water vapor. The temperature pattern and water vapor cycle are well in accord with the icy-dust reservoir description proposed recently by Qiu et al. (2015) and Qiu et al. (2016). Once the icy-dust particles have formed, an updraft will allow the particles to stay for a longer time in an altitude (Reid, 1975). As a result, during the cooling phase, the tiny icy-dust particles can counteract the gravitational settling effects by the upward motion and therefore achieve buoyancy in a small height range, hence effectively permits accumulation within a narrow layer.

The capability of the adsorption of sodium atoms on the icy-dust surface during a cold phase can be estimated through the collision rate. The sodium density variations throughout the cold phase before the SSLs on the nights of 12 and 13 May are shown in Figures 9a and 9b, respectively. Figure 9a (dashed line) shows the difference of sodium density between at 13: 59 UT and at 13: 00 UT in the region from 94 to 100 km, with the negative values standing for a reduction of sodium density; the solid line indicates the difference of sodium density between at 15:01 UT and at 13: 00 UT. Both curves show a sodium reduction of about 400 cm\(^{-3}\) during the cold phase compared with the initial state of the observation. Figure 9b (dashed line) shows the deviation between sodium densities at 14:46 UT and 12:03 UT, with a maximum density difference of 300 cm\(^{-3}\); the solid line shows the deviation between sodium density at 16:01 UT and 12:03 UT, with a maximum density difference of up to 900 cm\(^{-3}\). From Figures 1c and 1d, the sodium densities of the background (dash-dotted line with asterisk symbol overlaid) for both nights at...
corresponding altitudes were nearly 1,500 cm\(^{-3}\), so the density reduction amplitude varied from about 20% to as high as 60% throughout the cold temperature phases. This result indicates the possibility that the cold phase could be interpreted as a collection step, under which the sodium atoms would be efficiently collected and accumulated from a yet undetected sodium reservoir, representing a substantial reduction of sodium density during this first phase.

The collision rate \( k_f \) of a sodium atom with dust surface area per unit volume \( A \) is

\[
k_f = \frac{\tau A}{4}
\]

where \( \tau = \sqrt{\frac{8kT}{\pi m}} \) is the mean thermal velocity of the sodium atom, \( k \) is the Boltzmann constant, \( T \) is the environmental temperature, and \( m \) is the mass of sodium atom (Hunten et al., 1980).

For \( m = 23 \text{ amu} \), \( 1 \text{ amu} = 1.66 \times 10^{-27} \text{ kg} \), and assuming the average temperature during the cold phase of interest equaling to 150 K, the value of \( k_f \) could be calculated. From Figure 5 of Hunten et al. (1980), the total dust surface was \( A \approx 5 \times 10^{-10} \text{ cm}^{-2} \) near 95 km, so the collision rate

\[
k_f = A \sqrt{\frac{kT}{2\pi m}}
\]

\[
= 5 \times 10^{-10} \text{ (cm}^{-1}) \times \sqrt{\frac{1.38 \times 10^{-23} \times 150 \times 10^4 (\text{kg s}^{-2} \text{ cm}^{-2})}{2 \times 3.14 \times 23 \times 1.66 \times 10^{-27} (\text{kg})}}
\]

\[
= 4.65 \times 10^{-6} \text{ s}^{-1}
\]

When the average background sodium density was 1,500 cm\(^{-3}\), the total equivalent collision rate is about

\[
1500 \times 4.65 \times 10^{-6} = 6.98 \times 10^{-3} \text{ cm}^{-3} \text{ s}^{-1}.
\]

For the SSL event on 12 May, a sodium density reduction of 400 cm\(^{-3}\) was detected during about 2 hr. In theory, the duration of absorption for these sodium atoms can be estimated to be about:

\[
t_1 = \frac{400 \text{ cm}^{-3}}{6.98 \times 10^{-3} \text{ cm}^{-3} \text{ s}^{-1}} \approx 15.9 \text{ hr}.
\]

For the SSL event on 13 May could also be deduced. For a reduction of 900 cm\(^{-3}\) from a time period from 12:03 to 16:01 UT, the theoretical duration estimate is about

\[
t_2 = \frac{900 \text{ cm}^{-3}}{6.98 \times 10^{-3} \text{ cm}^{-3} \text{ s}^{-1}} \approx 35.8 \text{ hr}.
\]

The calculated time has a similar order of magnitude to the observed during for the extremely cold period of about 2 hr. The discrepancy could be explained by the uncertainties in the model of Hunten et al. (1980) that the available dust surface at 95 km might be much larger than 5 \times 10^{-10} \text{ cm}^{-2} (Cox et al., 1993). The suggested dust density above 90 km was in the order of 100 cm\(^{-3}\) by Hunten et al. (1980), but recently, model simulations show that the deduced dust number density was likely to be as large as 1,000 cm\(^{-3}\) at 95 km (Megner et al., 2006) or even up to 10^5 cm\(^{-3}\) (Balsiger et al., 1996). And it was supposed that the total dust surface would be much greater if the particles were not regularly spherical (Raizada et al., 2007). On the other hand, the wind shear would affect the falling motion of charged dust significantly (Cox et al., 1993; Havnes et al., 1992). As a result, dust below 90 km, with greater concentrations of sodium species coated, could conceivably be transported to above 95 km by an upward wind. Furthermore, Nadykto and Yu (2003) suggested that the uptake of neutral molecules by charged particles is much more effective for tiny particle under very cold temperature conditions (Nadykto & Yu, 2003). So the actual absorption process might be much shorter than the theoretically calculated time duration.
3.3.2. The Hot (High-Temperature) Phase

The observation results of multiple metal atom and ion layers, exhibiting an altitude sequence (the NaS was highest, the FeS was some meters lower than the NaS, while the CaS was a few hundred meters lower than the FeS, and the CaS\(^+\) was lowest, e.g., NaS > FeS > CaS > CaS\(^+\)), which coincided well with the boiling point-dependent differential ablation under the thermal ablation theory (Yi et al., 2013). This scenario further suggested that these metal species were directly released at the same time from a preexisting reservoir through evaporation/sublimation process.

The observed strong temperature and wind perturbations during the SSLs suggested that gravity waves play an important role in the formation of SSLs, although the exact role still remains unclear (Qian et al., 1998). The supersaturated gravity wave energy must dissipate in a vertical distance of the order of the wavelength, resulting in an enhanced divergence of the vertical flux of horizontal momentum and enhanced wave drag in the same region (Fritts, 1989). The most likely mechanism for gravity wave saturation is via a shear instability in the generation of turbulence (Fritts, 1989). Dynamic stability was characterized by the Richardson number \(Ri\), which was defined as

\[
Ri = \frac{N^2}{S^2},
\]

(9)

where \(N\) was the buoyancy frequency defined as

\[
N^2 = \frac{g}{T} \left( \frac{\partial T}{\partial z} + \frac{g}{C_p} \right),
\]

(10)

g is the gravitational acceleration with a value of 9.5 m/s\(^2\) in the mesopause region, \(T\) is the atmospheric temperature, and \(C_p\) is the specific heat at constant pressure with the value of 1,004 J · K\(^{-1}\) · kg\(^{-1}\), and \(S\) is the total vertical wind shear represented by

\[
S^2 = \left( \frac{\partial u}{\partial z} \right)^2 + \left( \frac{\partial v}{\partial z} \right)^2.
\]

(11)

\(u\) and \(v\) are the zonal and meridional wind velocities, respectively (Li et al., 2007; Sarkhel et al., 2012; Sherman & She, 2006).

So \(Ri\) represents the ratio of the production or suppression of turbulence kinetic energy by buoyant forces (\(N^2\)) to the mechanical production of turbulence kinetic energy by shear forces (\(S^2\); Nappo, 2013). \(Ri > 0.25\) is considered a sufficient condition for dynamics stability, where if the fluid is disturbed by a small vertical
displacement, it will return to the initial state (Nappo, 2013). Dynamic instability would occur over the range $0 \leq Ri \leq 0.25$, and the condition for convective instability is for $Ri < 0$ (Nappo, 2013).

The calculated time-dependent altitude distributions of dynamic (pink scatters) and convective instabilities (black scatters) from temperature and wind velocity observed by the USTC T/W lidar, as well as the locations of the SSLs, are shown in Figure 10. It is obvious that the dynamic instabilities (pink scatters) occur first, and then the convective instabilities (black scatters) appear followed by a SSL, though the approximation of $Ri_{z0}'$ may filter out some dynamic instabilities.
Figure 11 shows the zonal momentum flux changes before and after the SSL on 12 May. An obvious momentum flux between 90 and 95 km occur at 14:45 UT (Figure 11b), with a maximum absolute value of nearly 5 m²/s². This structure begins to dissipate at 17:45 UT (Figure 11h) and nearly disappeared after that, indicating a gravity wave breaking. The SSL occurred at 17:53 UT, after the dissipation of the wave. In the wave theory, the breaking gravity wave will deposit momentum into the mean flow and induce vertical heat flux, leading to wind acceleration/deceleration and temperature changes around the breaking region (Li et al., 2007; Liu & Hagan, 1998). This process can produce an inversion layer (or inversion layers) in the heating region(s) accompanied by cooling above and below (Li et al., 2007; Liu & Hagan, 1998). Simultaneous profiles of the peak density of the SSLs and temperature on 12 and 13 May 2013 are shown in Figures 1c and 1d, respectively. The temperature profiles are similar to those which are discussed by Li et al. (2007) and Liu and Hagan (1998). All of these results provide an experimental evidence that the gravity wave breaking may play a key role for the trigger of the SSLs.

### 3.3.3. An Empirical Model for the Formation of Typical SSLs Over Hefei

According to the discussions in sections 3.3.1 and 3.3.2, the formation processes for the typical subtropical SSLs such as two events on 12 and 13 May 2013, most likely composed of two main steps: the cold (low-temperature) phase, at which the sodium species were collected efficiently by a sodium reservoir; and the hot (high-temperature) phase, yielding a temperature-induced ablation rise for the release of sodium from the reservoir.

In the cold phase, the sodium density is sharply reduced under the low-temperature setting, indicating the collection of sodium atoms by some reservoir. The possible candidates for the sodium reservoir were proposed to be the icy-dust particles, which actually could be regarded as a particular kind of dust, collecting sodium species by packing them as nuclei or by surface absorption of sodium atoms.

During the hot (high-temperature) phase, even though there seemed to be inadequate sodium atoms generated directly through the temperature-controlled chemical reactions, the high temperature itself, or together with some other process accompanied by the temperature enhancement, might trigger the release of sodium atoms from the preexisting sodium reservoir formed during the initial cold phase. Observations on 12 and 13 May showed that these typical SSLs just occurred after the overturning of zonal wind (from east direction to west direction) and temperature (from cold phase to hot phase), indicating a nonnegligible correlation to the dynamical activities of tides and gravity waves. Calculations of the instabilities for different altitudes in section 3.3.2 (see Figure 10) show that instability occurred gradually near the SSL height before its onset, further supporting an important role of gravity wave breaking throughout the hot phase.

Thus, we propose that the so-called SSL, which was previously suggested to be mere stochastic coincidences or processes, is more likely to be a quasi-continuous phenomenon as a result of alternation of the temperature (heating and cooling) phase. The sodium reservoir acted as a core for the formation of SSLs: during the cold phase, the sodium reservoir collected sodium species, and then released the gathered sodium in the hot phase via triggers. However, as summarized by Gardner et al. (1995), the ultimate reality for reservoir is still to be determined based on an ever more increased innovation for direct detections. It is also worth noting that this ice-dust model may contain intermittent time variation because of the water vapor variations, such as the case on 0603, 2013, as discussed in section 3.1.

### 4. Conclusions and Outlook

On 12 and 13 May 2013, two typical SSLs were detected by a sodium fluorescent lidar and a nearby temperature/wind lidar at Hefei station. These two events had similar characters in duration (>2 hr), peak height (near 92 km), intensity (factor > 3), and the onset time (about 17 UT), all of which indicated an identical mechanism for them. Both events had experienced an extremely cold-temperature (<150 K) initiation condition with a density reduction several hours before the onset, compared with a relatively fast generation of sodium atoms during a large temperature enhancement (>40 K of temperature increase). Based on the observations, the possibility of an icy dust existing at the mesopause and acting as the sodium reservoir is experimentally tested for the first time in details and this scenario is ultimately confirmed for subtropical SSLs studied here. During the cold phase, the temperature minimum of 134.4 K was lower than the calculated frost-point temperature, indicating the nucleation and growth for the water vapor. The formed icy-dust particles may have a capability to adsorb enough sodium atoms in a given time period. So the SSLs were more
likely to be a subsequent phenomenon as a result of modulation of the temperature (heating and cooling) phase. An empirical model proposed in this study includes two main steps for subtropical SSLs studied here: first, sodium species were collected by a supposed reservoir and stored during the extremely cold phase; second, sodium reservoir would release free sodium atoms by a trigger, which is characterized by the temperature enhancement that is in turn caused by gravity wave breaking. Our overall finding suggests that such three important conditions regarding zonal wind shear, temperature, and water vapor cycle must be met in order for SSLs to form. Relatedly, if one or more of the three conditions changes, then the sodium layer disappears, which explains the occasional intermittency of the SSL phenomenon as observed.

However, since the entire model is based on the assumption that these SSLs were generated locally, the possibility of sodium atoms recombining from ions in $E_s$ layers in other places and being advected to this site could not be completely ruled out. So the future studies should further examine the following detailed points: (a) the $E_s$ mechanism and (b) the advection of sodium atoms.

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