Sporadic sodium layer: A possible tracer for the conjunction between the upper and lower atmospheres

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Abstract. In this research, we reveal the inter-connection between lightning strokes, reversal of the electric field, ionospheric disturbances, and a trigger of sporadic sodium layer event (Na_S), based on the joint observations by three lidars, an ionosonde, an atmospheric electric mill, a fluxgate magnetometer, and World Wide Lightning Location Network (WWLLN). Our results suggest that lightning strokes would probably have an influence on the ionosphere and thus give rise to the occurrence of Na_S, with the overturning of electric field playing an important role. Statistical results reveal that the sporadic E layers (E_S) could hardly be formed or maintained when the atmospheric electric field turns upward. A conjunction between the lower and upper atmospheres could be established by these inter-connected phenomena, and the key processes could be suggested as follows: lightning strokes→overturning of electric field→depletion of E_S/generation of Na_S.

Keywords: sporadic sodium layers, sporadic E layers, atmospheric circuit, lightning stroke, electric field

1 Introduction

The upper mesosphere-lower thermosphere (MLT) region, is the junction for momentum and energy exchanges between the Earth's low atmosphere and outer space. However, on account of the limitations of detection methods, this region remains the least known part of our planet. Fortunately, the metal layers (especially the sodium layer), which located

5   between about 80 ~ 110 km, could possibly act as a window to detect the MLT parameters by means of fluorescence resonance lidars. With an active chemical property and high abundance of sodium species, the sodium layer has been widely observed and studied all over the world. The sporadic sodium layer (SSL or Na_S), with the neutral sodium density that could double within several minutes, is the most fantastic phenomenon observed from the sodium layer. Since first reported in 1978 [*Clemesha et al.*, 1978], many mechanisms, involving meteor injection [*Clemesha et al.*, 1980], dust reservoir [*von*

10   *Zahn et al.*, 1987], recombination of ions and electrons in sporadic E layer (E_S) [*Cox and Plane*, 1998], and high temperature theory [*Zhou et al.*, 1993], have all been proposed. Because the Na_S is suggested to have a connection to so many atmospheric parameters, the metric or phenomenon could be appropriate to act as a tracer for studying inter-connection between the middle and upper atmospheres. Up to now, a large quantity of observations exhibit a diversity of the Na_S features, and the exact mechanism for Na_S is probably still uncertain [*Collins et al.*, 2002; *Cox et al.*, 1993; *Daire et al.*, 2002;

15   *Gardner et al.*, 1995; *Qiu et al.*, 2015; *Zhou and Mathews*, 1995; *Zhou et al.*, 1993].

Among all the candidates, the E_S theory is supported by abundant observations and numerical simulation results [*Cox and Plane, 1998*; *Daire et al., 2002*; *Dou et al., 2009*; *Dou et al., 2010*; *Gardner et al., 1993*; *Gong et al., 2002*; *Kane et al., 2001*; *Kane et al., 1993*; *Kane et al., 1991*; *Kirkwood and Nilsson, 2000*; *Kwon et al., 1988*; *Mathews et al., 1993*; *Miyagawa et al., 1999*; *Nagasawa and Abo, 1995*; *Nesse et al., 2008*; *Shibata et al., 2006*; *Williams et al., 2006*]. The key process of E_S

20   theory is the recombination of ions and electrons in the E_S layer while descending to lower altitudes [*Cox and Plane, 1998*; *Daire et al., 2002*]. The E_S layer is mainly influenced by the vertical wind shear [*Abdu et al.*, 2003; *Clemesha et al.*, 1998; *Haldoupis et al.*, 2004; *Mathews*, 1998; *Šauli and Bourdillon*, 2008; *Wakabayashi and Ono*, 2005] and the electric field [*Abdu et al.*, 2003; *Damtie et al.*, 2003; *Haldoupis et al.*, 2004; *Kirkwood and Nilsson*, 2000; *Kirkwood and von Zahn*, 1991; *Macdougall and Jayachandran*, 2005; *Matuura et al.*, 2013; *Nygren et al.*, 2006; *Parkinson et al.*, 1998; *Takahashi et al.*,

25   2015; *Voiculescu et al.*, 2006; *Wakabayashi and Ono*, 2005; *Wan et al.*, 2001; *Wilkinson et al.*, 1993]. In the Northern Hemisphere, the E_S layer would descend to a lower altitude during southward electric field [*Abdu et al.*, 2003; *Damtie et al.*, 2003; *Haldoupis et al.*, 2004; *Kirkwood and Nilsson*, 2000; *Kirkwood and von Zahn*, 1991; *Macdougall and Jayachandran*, 2005; *Nygrén et al.*, 2006; *Parkinson et al.*, 1998; *Takahashi et al.*, 2015; *Voiculescu et al.*, 2006; *Wakabayashi and Ono*, 2005; *Wan et al.*, 2001; *Wilkinson et al.*, 1993], and observations in the polar cap suggest the electric field reversal have an

30   influence on the E_S occurrences [*Macdougall and Jayachandran*, 2005].

On the other hand, the atmospheric electric circuit is a closed loop [*Driscoll et al.*, 1992; *Jánský and Pasko*, 2014; *Lv et al.*, 2004; *Roble and Hays*, 1979; *Rycroft and Harrison*, 2012; *Rycroft et al.*, 2000; *Suparta and Fraser*, 2012; *Tinsley*, 2000], like a capacitor with a positive plate (e.g., the ionosphere) and a negative panel (e.g., the ground), and dielectric medium

between them (e.g., the neutral atmosphere). Then the global atmospheric electric circuit formed in the capacitor, with the lightning phenomena generating an upward current (with the atmospheric electric field intensity E<0) and returning a downward current (E>0) under fair weather condition. Nowadays increasing and emerging evidences are pointing to the close link between the upper atmosphere (e.g., the positive plate) and lower atmosphere (e.g., the negative plate) [*Harrison et al.*, 2010; *Rycroft*, 2006]. For example, thunderstorm occurring in the lower atmosphere is suggested to have a direct impact on the E_S layer based on recent observational results [*Bortnik et al.*, 2006; *Christos*, 2018; *Cummer et al.*, 2009; *Curtius et al.*, 2006; *Davis and Johnson*, 2005; *Davis and Lo*, 2008; *England et al.*, 2006; *Fukunishi et al.*, 1996; *Girish and Eapen*, 2008; *Haldoupis et al.*, 2012; *Immel et al.*, 2013; *Kumar et al.*, 2009; *Kuo and Lee*, 2015; *Lay et al.*, 2015; *Mangla et al.*, 2016; *Maruyama*, 2006; *Pasko et al.*, 2002; *Rodger et al.*, 2001; *Rycroft*, 2006; *Sátori et al.*, 2013; *Sentman and Wescott*, 1995; *Shao et al.*, 2013; *Sharma et al.*, 2004; *Su et al.*, 2003; *Surkov et al.*, 2006; *Yu et al.*, 2015] or even the sodium layer [*Yu et al.*, 2017]. The possible carriers or phenomena connecting the thunderstorm to the upper atmosphere are suggested to be atmospheric tides [*England et al.*, 2006; *Haldoupis et al.*, 2004; *Immel et al.*, 2013], planetary waves [*Lv et al.*, 2004], gravity waves [*Davis and Johnson*, 2005; *Kumar et al.*, 2009; *Lay et al.*, 2015; *Shao et al.*, 2013], transient luminous event (TLEs) [*Cummer et al.*, 2009; *Fukunishi et al.*, 1996; *Haldoupis et al.*, 2012; *Pasko*, 2008; *Pasko et al.*, 2002; *Sentman and Wescott*, 1995; *Sharma et al.*, 2004; *Su et al.*, 2003], the solar activity [*Zhang et al.*, 2020], and also the electric fields [*Bortnik et al.*, 2006; *Davis and Johnson*, 2005; *Davis and Lo*, 2008; *Immel et al.*, 2013; *Kuo and Lee*, 2015; *Maruyama*, 2006; *Rycroft*, 2006; *Sátori et al.*, 2013; *Shao et al.*, 2013].

In this research, we apply five joint observations for our case studies and statistical works: (1) Three lidars (with one sodium lidar at Wuhan (30.5°N, 114.6°E) and two lidars at Hefei (31.8°N, 117.2°E), providing observations of sodium density, mesopause temperature and zonal wind; (2) An ionosonde in Wuhan (30.5°N,114.6°E), detecting the E_S and ionospheric echoes in different modes; (3) An atmospheric electric mill (30.5°N, 114.5°E), giving simultaneous electric field variations; (4) A fluxgate magnetometer (30.5°N, 114.5°E), probing the H, D, and Z magnetic field components; and (5) The World Wide Lightning Location Network (WWLLN), observing the location and power of a lightning stroke. The purpose of this study is to examine the possibility of Na_S acting as a practical robust tracer for the conjunction between the upper and lower atmospheres. Our results suggest that lightning strokes may have an influence on the lower ionosphere leading to the occurrence of Na_S, with the atmospheric electric field probably playing an important role.

2 Observations and results

2.1 An Na_S event during the overturning of electric field

A sporadic sodium layer is detected on the night of June 3rd, 2013, by both the USTC sodium lidar [*Dou et al., 2009*] and the nearby T/W lidar [*Li et al., 2012*] (in Fig. 1a and 1b, the same Na_S event detected with different resolutions). Results of the broadband sodium lidar focus on the details of sodium density with high resolution, while the narrowband T/W lidar could afford observations of simultaneous temperature, wind shear, and less-precision sodium density. This Na_S event occurs

much higher above the centroid height of sodium layer (normally at about 92 km). Both Fig. 1a and 1b show the sodium density begins to increase at about 13:20 UT, while the largest intensity of sodium enhancement occurs from about 14:20 UT, with a peak density of more than 12000 cm^{-3} on 97.75 km at 14:40 UT. The simultaneous temperature observation by the T/W lidar reveals this Na$_S$ occurs in a cold region (Fig. 1c), so the high temperature mechanism appears to be invalid for this

5   event.

On the other hand, the zonal wind exhibits a suitable wind shear for creating those sporadic E layers, with a westward wind above and an eastward wind below (Fig. 1d). The E$_S$ layer is predicted to form around the border of the wind shear. Actually, observations by the ionosonde at Wuhan show active sporadic E layers on that day (Fig. 2a and b). The E$_S$ series keep travelling/propagating downward starting around 6:30 UT, and then disappear at last while the Na$_S$ occurs coincidently

10   on about 13:20 UT. So this Na$_S$ prefers the E$_S$ mechanism than the high temperature theory, in accord with our previous results shown that a Na$_S$ higher than 96 km tends to be controlled by the E$_S$ mechanism [*Qiu et al.*, 2016]. Although the content of sodium ions in E$_S$ layers is sometimes implied insufficient [*von Zahn et al.*, 1989], it is also proposed that the ions could be concentrated by the wind shear effectively [*Clemesha et al.*, 1999; *Cox and Plane*, 1998; *Nesse et al.*, 2008]. On the other hand, laboratory results show that the ligand complexes of Na$^+$·X would form and thus speed up the recombination of

15   ions in the mesopause condition [*Collins et al.*, 2002; *Cox and Plane*, 1998; *Daire et al.*, 2002]. The calculated reaction rate suggests the formation of cluster ions is enhanced at lower temperature, in accordance with the cold region observed in Fig. 1c where the sporadic sodium layer occurs.

More details about the atmospheric parameters are shown in Fig. 3. The time series of sodium density on the peak height display a sharp enhancement from 14:20 UT (pointed out by the vertical red dashed line in Fig. 3a). The atmospheric

20   electric field detected by the mill exhibits an overturning at around 14:20 UT, alternating from downward direction to upward (Fig. 3b). It can be clearly observed that the enhancement of sodium density occurs coincidentally with the overturning of electric field, as highlighted by the vertical red dashed line in Fig. 3. A nearby fluxgate magnetometer provides the horizontal magnetic field H (nT) (Fig. 3c), showing disturbances at 14:15 UT. The total magnetic intensity B could be deduced by the H, Z, and D components ($B = \sqrt{H^2 + D^2 + Z^2}$) from fluxgate magnetometer observations (the

25   calculated values are plotted in Fig. 3d).

It is worth noting that the overturning of atmospheric electric field discussed here is theoretically rough, since the electric field at the lower ionosphere will be modulated as well (e.g., with a value of several mV/m [*Seyler et al.*, 2004]). Nevertheless, model simulations from the electrodynamics show that the upward electric field in upper atmosphere is proportional to the source current in the troposphere [*Driscoll et al.*, 1992], and that the upward current would continue

30   transmitting to the heights of 100~130 km of the dynamo region where E$_S$ occurs most frequently [*Rycroft et al.*, 2012]. The model, based on the rocket observations, shows that the atmospheric electric field has a similar scale and the same polarity from the ground to the altitude of ionosphere [*Abdu et al.*, 2003]. So the electric field detected by a ground-based mill could reasonably be a reflection of the actual situation in the lower ionosphere, at least for the trends of variations.

2.2 Statistical results of the E_S and overturning of electric field

A statistical correlation between the overturning of electric field and E_S variations is shown in Table 1. The foE_S values refers to the Critical Frequency, at which the reflection starts while the radio frequency equals the plasma frequency ($foE_S = \omega_{pe} = \left(\frac{n_e e^2}{m_e \varepsilon_0}\right)^{\frac{1}{2}} \approx 9\sqrt{10^{-6} n_e}$, with foE_S in MHz and n_e in cm^{-3}). From 2012 to 2014, in the summertime season (from May to August, when the E_S layers occur frequently), there are 242 days with effective observations of E_S and electric field with the overturning feature. Among all the cases, for about 155/242 days the foE_S get interrupted during the overturning of electric field, while the foE_S decreases on 39/242 days. In comparison, foE_S appears only for 6/242 days, and increases for 26/242 days. Another 28/242 days show no distinguishing features of the E_S during an overturning of the electric field. These ratios are overlapped, since sometimes there are more than one overturning on a single day. So in general, these results suggest that E_S could hardly be formed for upward electric field situations and that indeed the overturning of electric field causes a depletion of E_S. This statistical result may also give an implication that the electric field variations detected by ground based mill have a feasible link with the lower ionosphere. It is worth mentioning that there is indeed no one-to-one correspondence between the electric field overturning and E_S depletion, since the E_S is also influenced by other key parameters and phenomena including wind shears, tides and gravity waves. Sometimes the overturnings recover quickly, without sufficient time for producing an obvious effect on E_S. Therefore a deeper analysis will be needed in future statistical studies.

3 Discussions

The atmospheric electric circuit is formed by the ionosphere and ground surface with the dielectric medium (e.g., the neutral atmosphere) sandwiched between them [*Driscoll et al.*, 1992; *Harrison*, 2020; *Jánský and Pasko*, 2014; *Lv et al.*, 2004; *Roble and Hays*, 1979; *Rycroft and Harrison*, 2012; *Rycroft et al.*, 2000; *Rycroft et al.*, 2012; *Rycroft et al.*, 2007; *Suparta and Fraser*, 2012; *Tinsley*, 2000]. The lightning phenomena and thunderstorms, acting as the electric generator for the circuit, drive an upward current to the ionosphere. In fair weather regime, the electric field directs downward to the earth surface (E > 0), making a closed global electric circuit (see Fig. A1 in Appendix). The electric field could vary through two distinct ways. The first one is the changing magnetic field explained by the Faraday's law (e.g. , $\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$). However, observations by the fluxgate magnetometer show that there is just a small disturbance of magnetic field during the overturning of electric field. The other way is the electrostatic induction following the Coulomb's law ($\vec{E} = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}\hat{r}$). The connection between the lightning stroke and the overturning of electric field could be explained by a classic thunderstorm charge model through the electric imaging method based on the Coulomb's law (i.e., this model could be supported by a classic electrodynamics textbook, and modified in Appendix A). A typical thundercloud (e.g., pairs of (Q_1, $-Q_2$) or ($-Q_3$,

Q_4) in Fig. A1), with a dipole of positive charge located above a negative charge part, would produce an upward electric field toward the ionosphere (see more details in Appendix A).

According to the observations from WWLLN, we find two regions (circles A and B in Fig. 4) with heavy lightning activities during the period of the Na$_S$. Before the Na$_S$ occurrences, there were only a few powerful lightnings detected within about (25.1ºN ~ 35.8ºN) and (113.8ºE ~ 118.1ºE) during the period of 12 UT to 13:15 UT (just one strong stroke with a power of 43720.25 J happening on 12:17 UT, at 25.7229ºN and 117.3955ºE). The continuous strongest lightnings with a power larger than 10^4 J occur from 13:19 UT to 15:43 UT, mainly concentrating in two areas centered around (35.8ºN, 118.1ºE) and (25.1ºN, 113.8ºE). After 15:45 UT, no strong strokes were detected again within this area. Thus, the pairs of (Q_1, —Q_2) and (—Q_3, Q_4) could be referred to the lightning area of part A and B in Fig. 4. Since thunderstorms could trigger the breakdown process within a rather large area [*Leblanc et al.*, 2008] and influenced the ionosphere with around more than 800 km range horizontally away from the lightning center [*Johnson and Davis*, 2006; *Johnson et al.*, 1999], the whole area above might get a breakdown easily around $Q_1 \sim Q_4$ (e.g., the whole shadow zone in Fig. 4, involving the two strongest lightning areas and the two observing stations).

In previous studies, lightning strokes in lower atmosphere were reported to cause a reduction of electrons of the ionosphere [*Shao et al.*, 2013], and in reverse an enhancement of sodium density in the metal layer [*Yu et al.*, 2017]. Those two scenarios are in accord with our current results presented above, with a depletion of E$_S$ and a consequential occurrence of Na$_S$. Although such an idea/picture has been proposed long time ago, this is the first time that one can apply the imaging method for observing thunderstorms to explain the link between upper and lower atmospheres through an overturning of upward electric field.

Furthermore, the results from different channels of Wuhan ionosonde exhibit extraordinary echoes in different modes during the lightning period (Fig. 5a to 5l). (a) ~ (c): From 13:15 UT to 13:45 UT, the echoes gradually increase. Note that the powerful lightning period begins on 13:15 UT as well, with the sodium density enhancement and the E$_S$ depletion occurring on about 13:20 UT. (d) ~ (g): Most intense echo signals occur during 14:00 UT to 14:45 UT, while the largest intensity of sodium enhancement begins at 14:20 UT and the sodium density peaks at 14:40 UT. The overturning of electric field also occurs at 14:20 UT. (h) ~ (j): From 15:00 UT to 15:30 UT, the signals weaken gradually; (k) ~ (l): The echoes vanish after 15:45 UT. Afterwards, no strong stroke detected again within the discussed area. Meanwhile, the ionospheric echoes diminish after 15:45 UT, and the overturning of electric field also recovers at about 15:30 UT. Thus, we conclude that the ionospheric echoes and the lightning activities exhibit an obvious synchronous behavior.

Based on the above observations and calculations, a possible mechanism for Na$_S$ could be suggested by three steps: (1) Strong lightning strokes produce an upward atmospheric electric field toward the ionosphere; (2) The Sodium ions and electrons recombine much faster during the overturning period, leading to a depletion of the E$_S$; (3) The depleted E$_S$ layers generate the formation of Na$_S$. Thus there would probably be a connection between the lightning strokes, overturning of the electric field, ionospheric disturbances, and also the Na$_S$. Therefore a link between the lower and upper atmospheres could be established by carefully studying and examining these phenomena. However, it is worth noting that the key process during

step (2) is still quite uncertain. A more in-depth model concerning both plasma and neutral molecules is needed in the future work.

4 Conclusions

5   In this research, we study the conjunction between the lower and upper atmospheres, through the phenomena and processes of lightning strokes, overturning of the atmospheric electric field, ionospheric disturbance, plasma drift velocity reversal, and the formation and dissipation of sporadic sodium layer. The main findings of our results are summarized as follows:

1. The Na_S event discussed in the present case study shows a close relationship with E_S activities rather than conforming with

10   the prescriptions from high temperature theory.

2. The atmospheric electric field exhibits an overturning, opposite to the fair weather downward field in circuit, in coincident with the depletion of E_S and the consequential occurrence of Na_S.

3. A statistical result shows the E_S could hardly be formed or maintained when the atmospheric electric field is directed upward.

15   4. A typical thunderstorm with a positive charge located above a negative charge layer, is shown to produce an upward electric field toward the ionosphere. Two regions with heavy lightning activities nearby are found during the overturning of the atmospheric electric field.

5. Observations by the ionosonde exhibit extraordinary echoes during the lightning period and the temporal property of the echoes behaved synchronously with lightning activities.

20   Our results support a physical connection between the lightning strokes, overturning of the electric field, ionospheric disturbances, and also possibly the Na_S phenomenon. A link between the lower and upper atmospheres could be established by the monitoring of Na_S and related phenomena as follows: lightning strokes→overturning of electric field→depletion of E_S/generation of Na_S.

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Appendix A: Calculations for the induced upward electric field in the global electric circuit
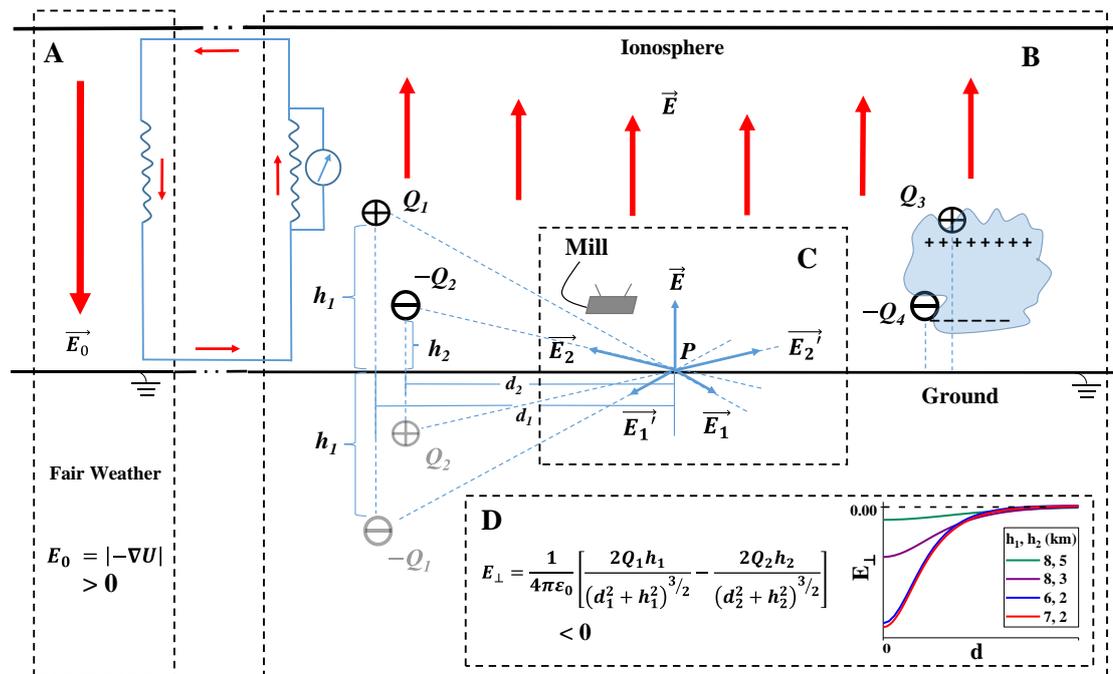
Figure A1: A diagram illustrates the global electric circuit. Part A: The atmospheric electric field under fair weather with a downward field returning from the ionosphere. Part B: The dynamo area, with thunderstorms generating an upward electric field towards the ionosphere. The electric field intensity $E_\perp$ could be deduced through the electric imaging method. Part C: The deduced vertical electric field intensity at any point P within the thundercloud. Part D: The calculated $E_\perp$ based on the electric imaging method.

Suppose there is positive charge Q_1 at the top of a thunderstorm, with a distance of d_1 above the ground; and a negative charge $-Q_2$ at the bottom with a distance of d_2. Since the ground surface could be regarded as an infinite conducting plane, it would generate an induced charge. The boundary conditions here is:

$$U = 0 \quad \text{at } z=0$$

$$U \rightarrow 0 \quad \text{at infinity}$$

Under the uniqueness theorem, we can remove the ground surface if we put the postulated image charges of $-Q_1$ and Q_2 to the corresponding mirror points. Then for an arbitrary point P near the boundary, the vertical electric field equals to the following expression according to the Coulomb's law:

$$E_\perp = \frac{1}{4\pi\varepsilon_0}\left[\frac{2Q_1 h_1}{(d_1^2+h_1^2)^{3/2}} - \frac{2Q_2 h_2}{(d_2^2+h_2^2)^{3/2}}\right] \qquad (A1)$$

In the simplest case, when Q_1 equals to Q_2 and $d_1=d_2=d$, $\boldsymbol{E_\perp}$ varies with the distance d. If Q_2 is larger than Q_1 ($Q_2 > Q_1 > 0$), and the negative charge $-Q_2$ is more closed to the observing point P ($d_2 < d_1$), $\boldsymbol{E_\perp}$ would acquire negative values (e.g., with the upward direction). A brief simulation result is shown by part D, exhibiting a persistent negative values for $\boldsymbol{E_\perp}$.

Data availability

The data sets of sodium fluorescence lidar at Hefei and three kinds of instruments at Wuhan (the ionosonde, electric mill and the fluxgate magnetometer) are publicly available from the Chinese Meridian Project database at http://data.meridianproject.ac.cn/. The access to the sodium density and temperature data by the USTC T/W lidar is referred to Professor Tao Li (*litao@ustc.edu.cn*). The lightning location and power data can be downloaded from the World- Wide Lightning Location Network (http://wwlln.net/).

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Contributions

Shican Qiu conceived this study and wrote this manuscript. She also prepared Fig. 2~5 in the main text and Fig. A1 in the Appendix.

Ning Wang performed data analysis.

5   Willie Soon was in charge of the organization and English polishing of the whole manuscript.

Gaopeng Lu added some materials about thunderstorms and lightning strokes.

Mingjiao Jia prepared Fig. 1 and gave some useful comments on the content.

Xiankang Dou conceived this study and provided the data usage of Chinese Meridian Project.

10   **Competing interests**

The authors declare no conflict of interest.

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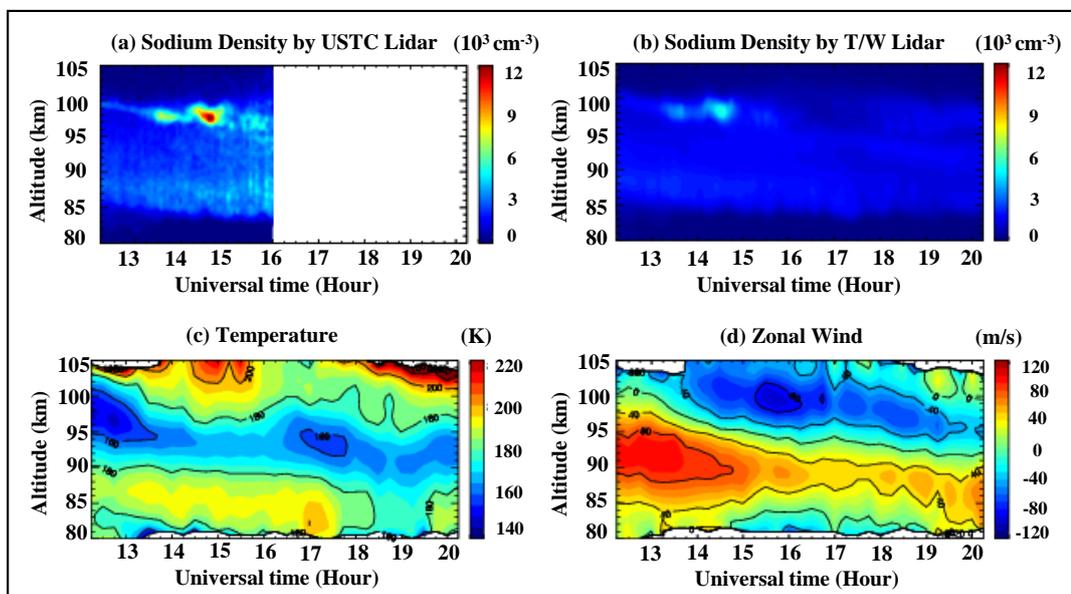
Figure 1: Observations on June 3rd, 2013, by the USTC sodium lidar and T/W lidar. (a) The sodium density detected by the USTC lidar. A moderate increase of sodium density appears at about 13:20 UT, while the largest intensity of sodium enhancement begins at about 14:20 UT. The sodium density peaks at 14:40 UT around 97.75 km. (b) The sodium density profile by T/W lidar, with a different resolution. (c) Temperature profile observed by the nearby T/W lidar, showing a cold region where the Na$_S$ occurs. (d) The zonal wind detected by the T/W lidar, exhibiting a suitable wind shear for the creation or formation of E$_S$.
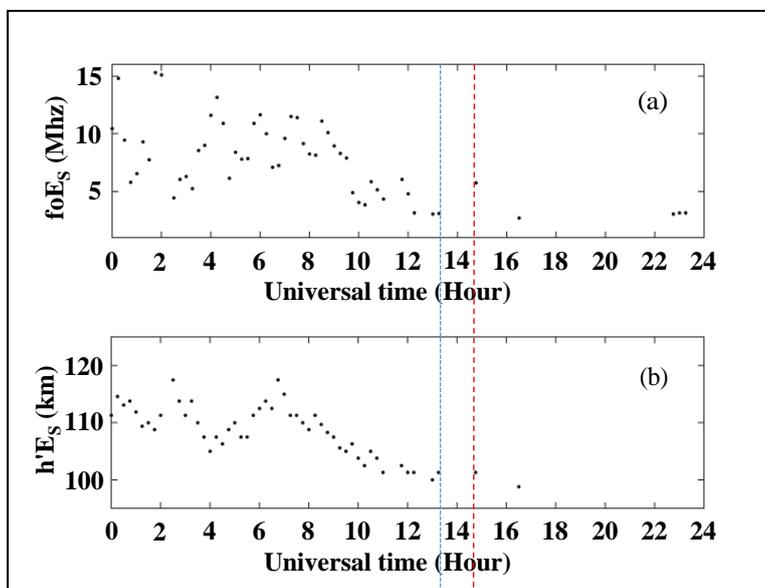
Figure 2: Sporadic E layers observed by the ionosonde at Wuhan (30.5°N, 114.6°E). (a) The time series of the critical frequency for Es (foEs). The Es layers travel/propagate downward starting around 6:30 UT, and deplete altogether at about 13:20 UT. (b) The visual height of Es (h'Es). The vertical blue dotted line annotates the beginning of the Nas around 13:20 UT, and the vertical red dashed line points out the time when the most intense sodium enhancement starts on 14:20 UT.
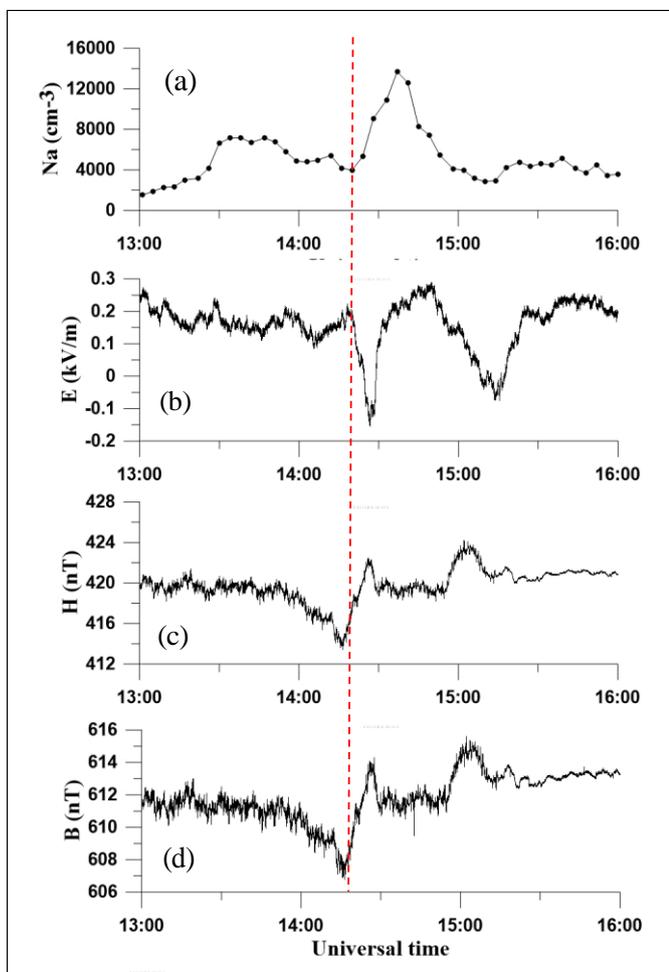
Figure 3: Observations of some atmospheric parameters and some deduced results. (a) Time series of sodium density variations at peak height 97.75 km. The sodium density begins to increase at about 14:20 UT. (b) Atmospheric electric field variations, exhibiting a synchronous overturning from 14:20 UT with the enhancement of sodium density (pointed out by the vertical red dashed line). Note that there is another overturning peaking at 15:15 UT, without another Na$_S$ companying, which could be explained by a depletion of ions in the E$_S$. The electric field recovers at about 15:30 UT. (c) Horizontal magnetic field observed by the fluxgate magnetometer. (d) The deduced magnetic induction intensity from observations of (H, D, Z) components by the fluxgate magnetometer ($B = \sqrt{H^2 + D^2 + Z^2}$).
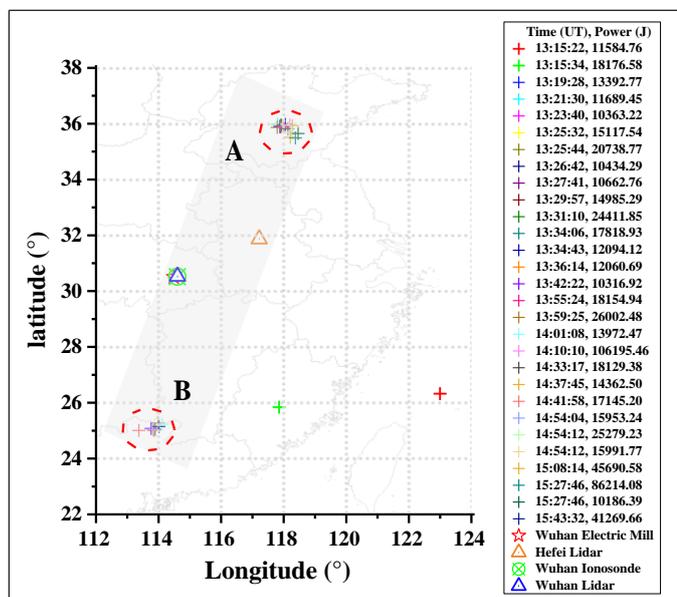
Figure 4: The lightning strokes are detected by WWLLN. The continuous strongest lightnings with a power larger than 10^4 J occur from 13:19 UT to 15:43 UT, mainly concentrating in two ranges about (35.8ºN, 118.1ºE) and (25.1ºN, 113.8ºE).
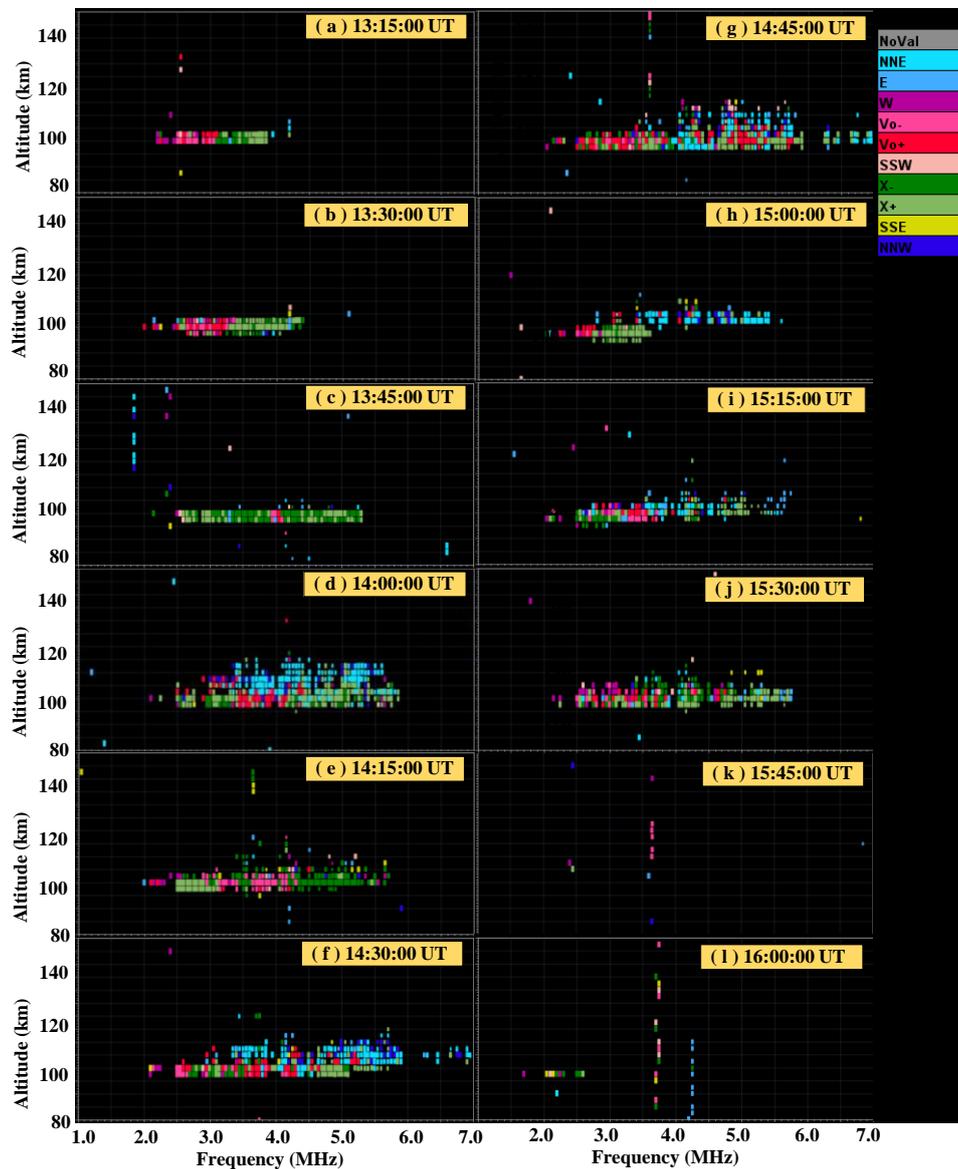
Figure 5: Extraordinary echoes by Wuhan ionosonde in different modes: (a) ~ (c): The echoes gradually increase; (d) ~ (g): Most intense echo signals occur; (h) ~ (j): The signals weaken gradually; (k) ~ (l): The echoes vanish.

Table 1 : The nature of foE$_S$ variations under the situations of the overturning of electric field

foE$_S$ Variations	Termination	Decrease	Generation	Increase	Others
Ratios **(Case days/Total days)**	155/242	39/242	6/242	26/242	28/242