Responses to Reviewer 1

We would like to thank the reviewer for the valuable comments and constructive suggestions. We have studied all comments carefully and revised the manuscript accordingly. We marked all the changes in red fonts in the revised manuscript. The point-by-point answers to the comments are given below in blue fonts.

This paper describes a study of sporadic sodium layers (Nas) and their possible relationship with strong lightning discharges causing the overturning of the electric field in the upper atmosphere. An impressive range of instruments was used for the study: two Na lidars in Hefei, one of which also measured wind and temperature; a third Na lidar in Wuhan; and an ionosonde and electric field mill in Wuhan. An Nas layer was observed by the Hefei lidars (though not by the Wuhan lidar?), which coincided with an overturning of the vertical electric field. Strong lightning was observed in the region, and the authors postulate that highly charged clouds led to the overturning of the electric field, and that this may be causally linked to the appearance of the Nas. While the possible link with the overturned electric field and lightning is an interesting idea and certainly worth investigating, I am not sure that a link with the overturned electric field is needed to explain the observed Nas. Figure 1(d) shows a very clear shear in the zonal wind, which descends below 100 km around 1330 hrs. This coincides with the observed descent of the Es layer to 100 km (Figure 2b), after which it disappears and the Nas appears (Figure 1a and 1b). The Na density in the Nas layer peaks around 1.2e4 cm^{-3}. The strength of the Es layer as it descends to 100 km is around 4 MHz, corresponding to an electron density of 2e5 cm^{-3}. Most of the metallic ions in the Es layer would be Fe^+ and Mg^+, with a smaller amount of Na^+. Assume all the Na^+ ions were neutralised when the Es layer descended below 100 km and the ion-molecule chemistry becomes very fast (the theory proposed quantitatively by Plane). Then, if you divide the peak Na density in the Nas layer by the Es electron density, this implies that the fraction of Na+ in the Es layer was around 6%, which sounds sensible (see the results of rocket-borne mass spectrometers flown by E. Kopp, for example). What this exercise shows is that the Nas can be explained by the sporadic E layer descending below 100 km. The authors therefore need to explain what the additional effect of the overturned electric field might be. If it is not needed to explain the appearance of the Na layer, then the two phenomena could be quite unrelated to each other.

In fact, the statistics summarized in Table 1 indicate that the overturned electric field is often associated with the termination or significant decrease in Es layers (80% of the time). So the question is what is the link? Does the reversal of the electric field accelerate the Es downwards, leading to its destruction through fast ion-molecule chemistry and the appearance of Nas?

Thanks for the important comment. First, we would like to explain the locations of lidars. The two stations at Hefei and Wuhan locate about 350 km apart. Unfortunately, there was no observations by Wuhan lidar on June 3rd, otherwise the results would be far more convincing. However, previous statistical analyses show that Na_S often observed simultaneously at both stations: "Among all 19 cases, 16 cases, including 9 SSL cases and 7 TeSL cases, occurred almost simultaneously over Hefei and Wuhan without a time delay. Seven TeSLs and four out of the nine SSLs were accompanied by ionospheric sporadic *E* (*E*s)" (see Ma et al., 2019). So we could possibly assume and infer that the horizontal scale of Na_S is large enough.

Second, we would like to discuss the possible link between electric field and E_S, as suggested by the kind reviewer. Since the recombination of $Na^+ + e^- \rightarrow Na + h\nu$ is inefficient to generate Na_S, Na^+ ion is believed to first form a ligand $Na^+ \cdot N_2$ through the recombination reaction:

$$Na^+ + N_2 + M \rightarrow Na^+ \cdot N_2 + M, \qquad (1)^*$$

with a rate coefficient of $k_1 = 4.8 \times 10^{-30}(T/200)^{-2.2}$ cm^6 $molecule^{-2}$ s^{-1} (Cox and Plane, 1998). $Na^+ \cdot N_2$ can either switch with CO_2 (which will undergo dissociative electron recombination to form Na), or O (which reforms Na^+)(Cox and Plane, 1998). The key factor of Professor Plane's E_S mechanism depends on the ratio of [O]/ [CO_2]. Recombination of $Na^+ \cdot CO_2$ and e^- will increase rapidly as [O]/ [CO_2] decreases below the value of 100 (Cox and Plane, 1998). Then the sodium atoms could be formed directly from the following chemical reaction:

$$Na^+ \cdot CO_2 + e^- \rightarrow Na + CO_2. \qquad (2)^* \text{ (Cox and Plane, 1998)}$$

The chemical reaction rate (*v*) for this second-order reaction could be calculated using the following equation:

$$v = k[Na^+ \cdot CO_2]N_e, \qquad (3)^*$$

The reaction rate coefficient k_2 for the chemical reaction is experimentally measured to be:

$$k_2 = 1 \times 10^{-6}\sqrt{\frac{200}{T}} \quad (cm^6\ molecule^{-2}\ s^{-1}) \qquad (4)^*$$

(Collins et al., 2002; Cox and Plane, 1998; Daire et al., 2002), and the electron density N_e can be calculated using the following equation:

$$N_e = 1.24 \times 10^4 foE_S^2 (cm^{-3}) \qquad (5)^* \text{ (Bittencourt, 2004).}$$

Overall, this E_S mechanism is most widely accepted, if we neglect k_1 as being too small with an order of 10^{-30}. A possible adaptation is to assume a plenty quantity of pre-existing $Na^+ \cdot N_2$ / $Na^+ \cdot CO_2$ in the sodium layer, and the E_S just needs to provide enough additional electrons.

On the other hand, a link between the reverse electric field and E_S variations could be established through the acceleration of electrons. Normally, positive particles will move along the direction of electric field, and negative particles do the opposite (Griffiths, 1999). Since metal ions are much heavier than electrons, the ions would drag electrons in order to move/drift together, this process is called the bipolar diffusion (Griffiths, 1999). In the initial stage, ions and electrons descend gradually under the southward electric field (Fig. 1*(a)). In a partially ionized plasma, the characteristic frequencies for ions and electrons are associated with the collisions of the plasma particles with stationary neutrals (e.g., the electron–neutral collision frequency ν_{en} and the ion–neutral collision frequency ν_{in}). The collision frequency ν_{sn} for scattering of the plasma species *s* by the neutrals is given by

$$\nu_{sn} = n_n \sigma_s^n V_{Ts}\,, \qquad (6)^*\ \text{(Shukla and Mamun, 2002)}$$

where n_n is the neutral number density,

σ_s^n is the scattering cross section (which is typically of the order of 5×10^{-15} cm^2 and depends weakly on the temperature Ts),

and $V_{Ts} = (k_B T_s/m_s)^{1/2}$ is the thermal speed of the species *s*.

So the relaxation times $\tau = \frac{1}{\nu}$ for ions and electrons are different in a partially ionized plasma, and electrons would respond much faster than the heavier sodium ions do (since $m_i \gg m_e$). At the moment when the electric field reverses, electrons will be rapidly accelerated by the northward electric field, and ions would be regarded as essentially remaining northward or unchanged. If we could possibly assume that $Na^+ \cdot CO_2$ is always excessive (we see can below it just needs a number density of 100 cm^{-3}, but regrettably there is no direct measurements and detections even up till now), we only need to consider the amount of electrons. When the reactant concentration for R(2)* is increased (e.g., when a concentrated electron layer accelerated downward below 100 km), this reaction will shift to the right side of R(2)*.

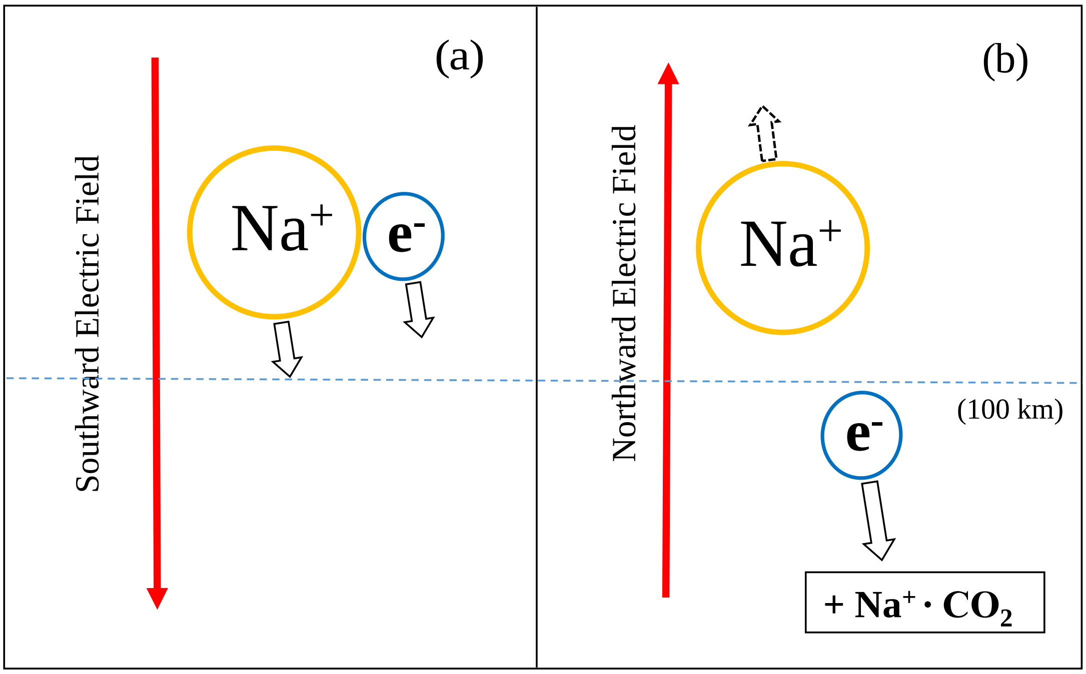

Fig. 1* A sketch to illustrate what happened before (a) and after (b) the overturning of atmospheric electric field: (a) The ions and electrons descend gradually under the southward electric field. (b) At the moment when the electric field reverses, the electrons will be rapidly accelerated by the northward electric field, and the heavier ions would be regarded as essentially remaining northward or unchanged.

To calculate the chemical reaction rate, we assumed a pre-existing concentration of 100 cm^{-3} for $[Na^+ \cdot CO_2]$, and used the observed value of 3.1 MHz for foE_S (which means $N_e = 1.2 \times 10^5$ cm^{-3}), and 170 K for T. The calculated rate is

$\nu = 13$ $cm^{-3}s^{-1}$, in accord with the required source strength of sodium atoms of 3 sodium atoms $cm^{-3}s^{-1}$ for the formation of Na_S (Cox et al., 1993). If we deduct some influences by eddy diffusion and loss of sodium atoms, this chemical rate can generate one Na_S within several minutes. So no matter how many Na^+ ions are contained in E_S, the electrons in E_S are always sufficient to produce Na_S. Perhaps that is why we often observed that even a very weak E_S is always accompanied by Na_S (Dou et. al., 2010).

We have added a new section 3.2 to discuss the E_S and Na_S described in this reply in details for our revised manuscript.

Other matters to address:

1. The Na lidar measurements in Figure 1(a) and 1(b) have concentrations varying by a factor of 2, even though co-located in Hefei. This cannot be correct. Even if the lidars have different vertical resolutions, the integrated Na density across the Nas layer should be the same.

Thanks for another valuable comment. We first apologize for the confusions and imprecisions in the data analysis. We have now thoroughly checked the raw data files of the wideband fluorescence resonance lidar and the temperature/wind lidar. We have learnt more about the data reduction/inversion methods for both lidars. The key conflict could possibly derived from the wideband lidar. Fig. 2* (a) shows the lidar system operated poorly after the midnight. But the first author made a reckless mistake in handling the bad data files (i.e., she accidentally deleted the bad file). Yet we can note that the signal to noise ratio (SNR) in the first half of the night is 10, still larger than the limitation of 2.

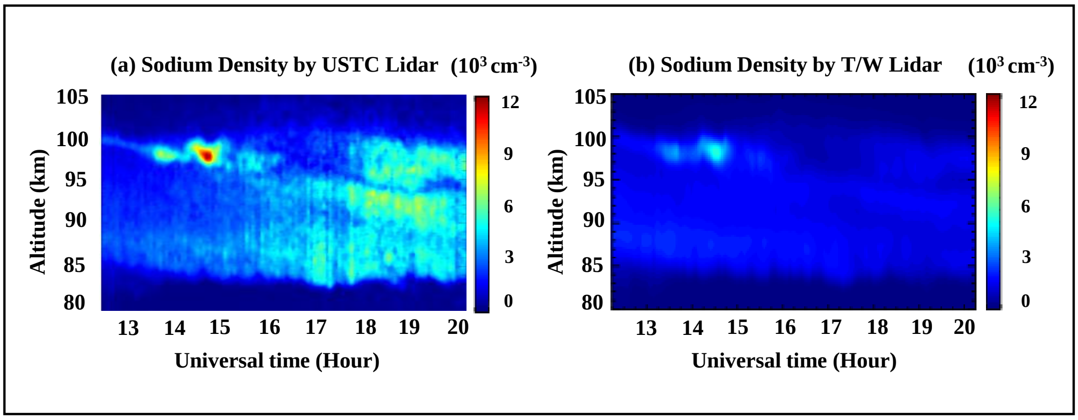

Fig. 2* (a) The entire sodium density profile observed by the wideband lidar on June 3rd, 2013. (b) The sodium density profile by T/W lidar.

For the wideband sodium fluorescence resonance lidar, the inversion formula for the sodium number density N at an altitude of z is given as follows:

$$N = \frac{\sigma_R n_a(z_0)}{\sigma_{Na}} \cdot \frac{(P(z)-P_B)z^2}{(P(z_0)-P_B)z_0^2} , \qquad (7)^* \qquad \text{(Xue, 2007)}$$

where σ_R is the Rayleigh backscatter cross section,

$n_a(z_0)$ is the atmosphere density at a reference altitude, given by atmospheric model,

σ_{N_a} is the effective sodium backscatter cross section,

$P(z)$ is the number of photons detected in the range interval (z-Δz/2, z+Δz/2),

P_B is the expected photon count per range bin due to background signal and dark counts, calculated through the averaged background signal above 130 km, and,

$P(z_0)$ is the Rayleigh photon count at 30 km altitude, estimated by averaging the measured photon count over a 5-km range interval centered at 30 km (Gardner et al., 1986).

Among all the parameters, the variables are σ_R, $P(z)$, P_B, $P(z_0)$, and z (means $N = f(\sigma_R, P(z), P_B, P(z_0), z)$. The error transfer formula of N equals to:

$$\frac{\Delta N}{N} = \left|\frac{\partial \ln f}{\partial \sigma_R}\right| \Delta \sigma_R + \left|\frac{\partial \ln f}{\partial P(z)}\right| \Delta P(z) + \left|\frac{\partial \ln f}{\partial P_B}\right| \Delta P_B + \left|\frac{\partial \ln f}{\partial P(z_0)}\right| \Delta P(z_0) + \left|\frac{\partial f}{\partial z}\right| \Delta z. \quad (8)^*$$

The fourth term, $\left|\frac{\partial \ln f}{\partial P(z_0)}\right| \Delta P(z_0) = \left|\frac{1}{P(z_0) - P_B}\right| \Delta P(z_0)$, makes the final error inversely proportional to the absolute value of $P(z_0) - P_B$. The averaged photon count $P(z_0)$ at 30 km is given by:

$$P(z_0) = \eta T_A^2 \frac{\lambda J}{hc} \frac{A_R}{4\pi z_0^2} \sigma_R \Delta z n_a(z_0), \quad (9)^*$$

where η is the overall system efficiency and,

T_A one-way atmospheric transmittance of the lower atmosphere;

λ optical wavelength, 0.589×10^{-6} m;

J laser pulse energy, J;

h Planck's constant, 6.63×10^{-34} J s;

c velocity of light, 3 × 108 m/s;

A_R receiver aperture area, m^2;

$n_a(z_0)$ the atmosphere density at z_0 (Gardner et al., 1986).

To minimize shot noise, $P(z_0)$ at 30 km altitude is estimated by averaging the measured photon count over a 5-km range interval centered at 30 km (Gardner et al., 1986). Because the atmospheric density decreases approximately exponentially with altitude, the average photon count at 30 km is computed by first subtracting the estimated background count, multiplying the result by z^2, taking the natural logarithm and then averaging over the range 27.5 km to 32.5 km (Gardner et al., 1986). We can see $P(z_0)$ is therefore sensitively influenced by the background atmosphere and lidar system conditions.

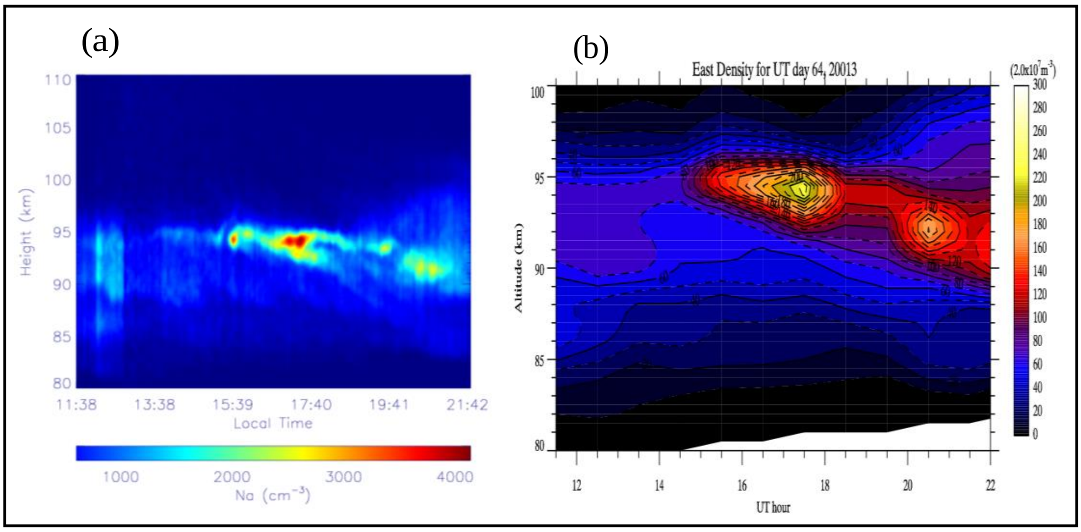

Fig. 3* (a) Sodium density profile detected by the wideband lidar on May 5th, 2013. (b) Sodium density profile detected by the T/W lidar on that day.

In comparison, we show that the sodium density profile detected on May 5th, 2013, by the wideband lidar is close to that by the T/W lidar (Fig. 3* (a) and (b)). Both profiles exhibit a peak density of about 4000 cm^{-3}.

Then we check the raw data files on June 3rd (the case we have chosen in the manuscript) and May 5th, 2013 (for comparison). Through $h = c \times t/2$, the reference height of $z_0 = 30km$ is equivalent to $t \approx 0.2ms$ (marked by the light line at .2000ms). On June 3rd, $P(z_0) = 106$ (highlighted by the red circle in Fig. 4* (a)), and the expected photocount at 130 km equals to 18 (not shown in Fig. 4*(a), but could be read from the data file). On May 5th, $P(z_0) = 501$, and $P_B = 7$ (Fig. 4*(b)). Since the error term is inversely proportional to the absolute value of $P(z_0) - P_B$, a much smaller $|P(z_0) - P_B|$ (about 5.6 times less) would cause the deduced sodium number density N to increase.

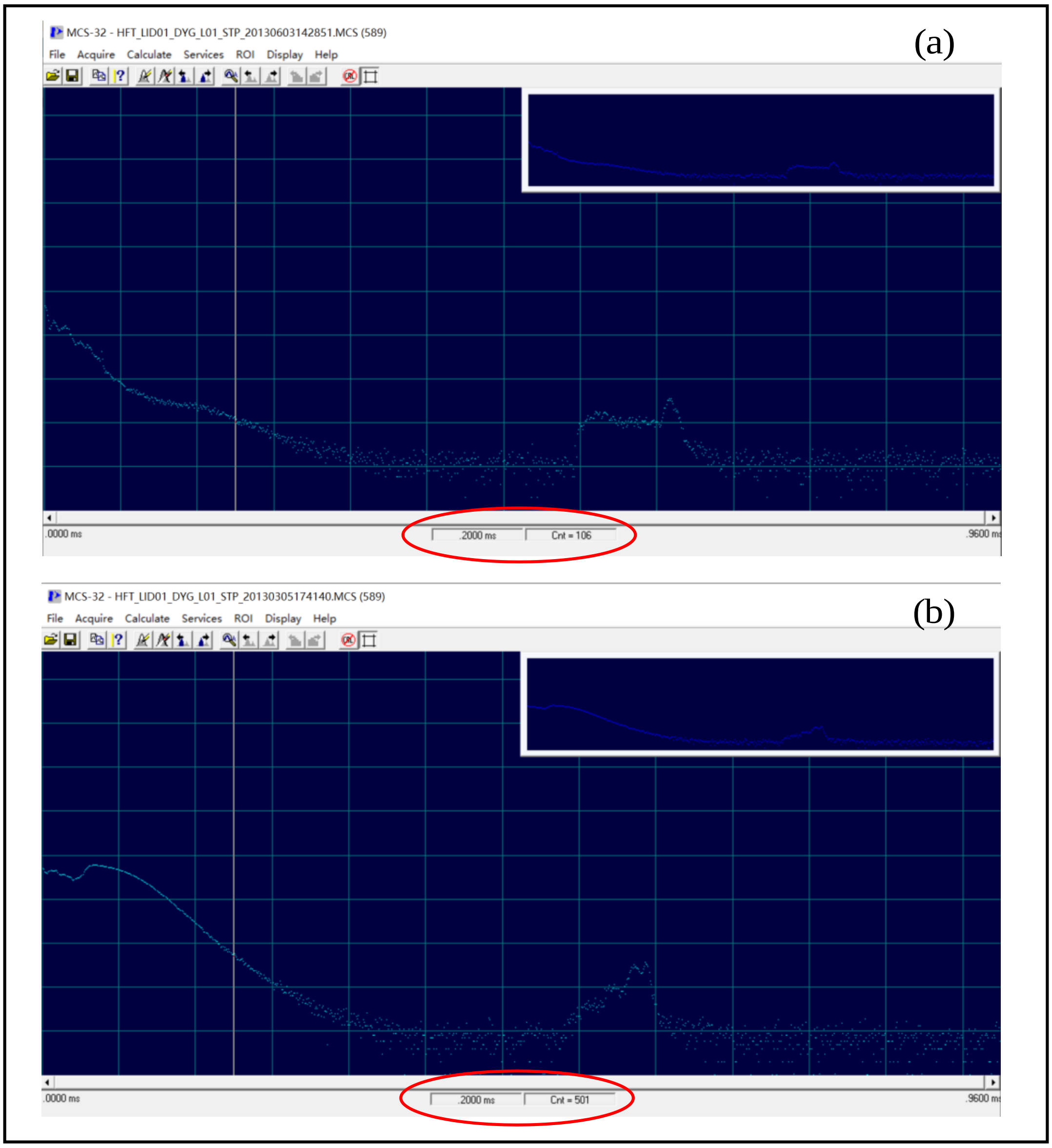

Fig. 4* (a) The raw data file at 14:28 UT on June 3rd. $P(z_0) = 106$ (highlighted by the red circle), and the expected photon count at 130 km equals to 18. (b) The raw data file at 17:41 UT on May 5th, 2013. $P(z_0) = 501$, and $P_B = 7$.

On the other hand, for the narrowband T/W lidar, the number of photons received by telescope from the range (z-Δz/2, z+Δz/2) is given by:

$$N(z,\nu_L,T,V) = \left(\frac{E_L}{hc/\lambda}\right) \times (\eta T_A^2) \times \left(\rho_{N_A}(z)\sigma_{SB}(\nu_L,T,V)\Delta z\right) \times \left(\frac{A_R}{z^2}\right) \times (T_\uparrow T_\downarrow) + N_B,$$

where (10)* (Li, 2005)

ν_L Transmitter laser frequency;

T Temperature (K);

V Wind velocity (m/s);

E_L	Transmitted laser pulse energy (J);
η	System efficiency;
$\rho_{N_A}(z)$	Na number density (m^{-3});
$T_\uparrow$	Upward transmission in the Na layer;
$T_\downarrow$	Downward transmission in the Na layer.

Different from the wideband lidar, the deduced sodium number density $\rho_{N_A}(z)$ here is independent on the atmospheric conditions at a relative altitude z_0. Perhaps that is the reason why they establish a necessary T/W lidar nearby.

We have added more detailed explanation on the discrepancy of the peak densities, around lines 5 to 18 on page 4. We have redrawn Fig. 1(a) on page 20 of the revised manuscript.

2. The statement on page 6 (line 28): "Thus, we conclude that the ionospheric echoes and the lightning activities exhibit an obvious synchronous behaviour." Presumably Es layers are observed over Wuhan in the absence of lightning activity. So the implication of this statement is that whenever strong lightning is present Es is observed – is that correct?

Thanks for the comment. From a lot of references, we can propose that lightnings causing influences on the ionosphere. However, we cannot make a definitive claim that lightnings would cause Es all the time, based on our current case study. More statistical work is needed for the further studies. Therefore, we have modified the absolute descriptions around lines 14 to 15 on page 7.

Minor issues:

page 2, line 4: I don't think the MLT is the "least known part of our planet" – what about the deep oceans? I think you mean "our planet's atmosphere".

Thanks for the comment. We have modified it to "our planet's atmosphere", and added a reference accordingly, around lines 3 to 4 on page 2. This part is indeed worth our lifetime of learning and relearning.

page 2, line 6: changed "sodium species" to "sodium atoms", since that is the form of Na that can be observed from the ground.

Thanks for the comment. We have changed "sodium species" to "sodium atoms", around line 7 on page 2.

page 2, lines 15-30: in this discussion there is no mention of the magnetic field, which is part of the classical $V \times B$ mechanism for sporadic E formation

Thanks for the comment. We have added the influences on E_S by geomagnetic field around lines 23 to 24 on page 2.

page 4, line 10: "prefers the Es mechanism" implies that the Nas is an intelligent being that can make a choice! I would rephrase "is better explained by the Es mechanism"

Thanks for the comment. We have modified it to "this Na_S is better explained by the E_S mechanism" around lines 28 to 29 on page 4.

page 4, line 16: "suggests"

Thanks for the comment. We have modified it to "suggests" around line 1 on page 5 in the revised manuscript.

page 5, line 4: provide a citation for the equation

Thanks for the comment. We have added the citation of this equation around line 24 on page 5 in the revised manuscript. On page 10 of Bittencourt (2004), the electron plasma frequency is given by

$$\omega_{pe} = \left(\frac{n_e e^2}{m_e \epsilon_0}\right)^{1/2}, \qquad (11)^*$$

where n_e

m_e

ϵ_0

When ω_{pe} equals to the critical frequency detected by the ionosonde (foEs), $n_e = \frac{m_e \epsilon_0}{e^2}\omega_{pe}^2 = \frac{m_e \epsilon_0}{e^2} foE_S{}^2 = 1.24 \times 10^4 foE_S^2 (cm^{-3})$.

page 5,line 29: the phrase "could be supported by a classic electrodynamics textbook" should be omitted. Either this is very well understood by the community, or you should provide reference to such a textbook.

Thanks for the comment. We have added citation of the textbook around lines 17 to 18 on page 6.

page 6, line 6: I cannot believe that the energy of this lightning stroke is known to 7 significant figures!

Thanks for the comment. We are so sorry for the misunderstanding of unit. We have checked the data description for WWLLN, and the unit of the power of one lightning stroke must be kW (reshown below as a screenshot). So these lightning strokes might be powerful enough to make contributions to ionospheric disturbances. We have modified the unit for lightning energy to be in kW throughout the manuscript.

Format of data files:
Files are ascii text files labeled with the date and time of the data such as A20100203.loc for data from 2010/02/03. All data in UTC sample:

2012/4/4,00:00:01.369657, 14.9924, -091.3758, 25.1, 8, 1109.25, 295.14, 6
2012/4/4,00:00:01.479687, 14.7209, -087.7137, 10.1, 5, 1243.98, 431.82, 5
2012/4/4,00:00:01.444158, 06.0155, 097.2494, 03.9, 5, 1004.87, 249.15, 3
2012/4/4,00:00:01.534491, -17.6947, 040.8280, 16.2, 6, 5534.23, 4172.98, 3
...

Year/Mo/Da,Hr:Mn:Sec.fract, Lat , Long, Resid, Nsta, power (kW), power uncertainty (kW), nstn power

page 6, line 12: the shading in the figure is too faint to see.
Thanks for the comment. We have redrawn Figure 4. We hope the current figure would be better.

page 6, line 17: the statement "such an idea/picture has been proposed long time ago" must be referenced.
Thanks for the comment. We have added the references around line 4 on page 7.

page 6, line 30: the statement "The Sodium ions and electrons recombine much faster during the overturning period, leading to a depletion of the Es" needs further discussion. As I state above, I think this can only happen if the Es descends rapidly. Another possibility is that somehow the Es becomes compressed so that the plasma concentration increases – that seems unlikely.
Thanks for the comment. We wholeheartedly agree with this accelerated descending mechanism. We have added a new section 3.2 to discuss the mechanism in the revised manuscript.

page 7, line 12: change "consequential occurrence" to something like "consequent production"
Thanks for the comment. We have changed it around line 22 on page 9.

page 9, line 5: the journal requires that the data is archived and accessible to the reader. Not through writing to someone.
Thanks for the comment. We have changed it to "National Space Science Data Center, National Science & Technology Infrastructure of China (http://www.nssdc.ac.cn)".

page 19. Figure Caption 3: change "another Nas companying" to "another Nas being produced" Figure 4 should be redrawn. The site of the electric mill is hidden. The units of power are W, not J, and these "powers" contain too many significant figures. The map and shading are too faint to read.
Thanks for the comment. We have changed the unit for power to kW. We have

redrawn Figure 4.

Figure 5. The legend in the figure needs to be explained in the figure caption.
Thanks for the comment. We have added the description in the figure caption of Fig. (5).

Cited References for this Reply:

Collins, S. C., Plane, J. M. C., Kelleya, M. C., Wright, T. G., Soldán, P., Kanee, T. J., Gerrarde, A. J., Grime, B. W., Rollason, R. J., and Friedman, J. S.: A study of the role of ion-molecule chemistry in the formation of sporadic sodium layers, Journal of Atmospheric & Solar Terrestrial Physics, 64, 845-860, 2002.

Cox, R. M., and Plane, J. M. C.: An ion-molecule mechanism for the formation of neutral sporadic Na layers, Journal of Geophysical Research Atmospheres, 103, 6349-6359, 1998.

Gardner, C. S., Voelz, D. G., Sechrist, C. F., and Segal, A. C.: Lidar studies of the nighttime sodium layer over Urbana, Illinois: 1. Seasonal and nocturnal variations, Journal of Geophysical Research Space Physics, 91, 13659-13673, 1986.

Dou, X. K., Xue, X. H., Li, T., Chen, T. D., Chen, C., and Qiu, S. C.: Possible relations between meteors, enhanced electron density layers, and sporadic sodium layers, Journal of Geophysical Research: Space Physics, 115, A06311, 2010.

Griffiths, D.J..: Introduction to Electrodynamics, 3rd ed., Prentice- Hall, Upper Saddle River, New Jersey, 1999.

Li,T.: SODIUM LIDAR OBSERVED VARIABILITY IN MESOPAUSE REGION TEMPERATURE AND HORIZONTAL WIND: PLANETARY WAVE INFLUENCE AND TIDAL-GRAVITY WAVE INTERACTIONS, Ph.D. thesis, Colorado State University, Fort Collins, Colorado, 48-50pp, 2005.

Ma, J., Xue, X., Dou, X., Chen, T., Tang, Y., Jia, M., Zou, Z., Li, T., Fang, X., and Cheng, X.: Large-Scale Horizontally Enhanced Sodium Layers Coobserved in the Midlatitude Region of China, Journal of Geophysical Research: Space Physics, 124, A026448, 2019.

Shukla, P. K. and Mamun, A. A.: Introduction to Dusty Plasma Physics, Institute of Physics Publishing, 2002.

Williams, B. P., Berkey, F. T., Sherman, J., and She, C. Y.: Coincident extremely large sporadic sodium and sporadic E layers observed in the lower thermosphere over Colorado and Utah, Annales Geophysicae, 25, 3-8, 2007.

Xue, X.H.: Studies on Geoeffectiveness of Coronal Mass Ejections and Near-Earth

Space Environment, Ph.D. thesis, University of Science & Technology of China, Hefei, China, 85-92pp, 2007.

Responses to Reviewer 2

General comments:

A reasonable mechanism of Nas layer enhancement in MLT region by lower atmospheric electric field was proposed in this manuscript, based on the observation date of several kinds of detection tools. This paper also provided a detail process how lower atmospheric electric field influences the ionized and neutral components in the upper atmosphere. This research is so novel and the similar reports are quite little up towards now. Consequently this manuscript fitted the scope of ACP at the moment in my point of view, however the mechanism of Nas layer enhancement in this manuscript needs to be further analyzed in the proceeding steps.

We would like to thank the reviewer for the valuable comments and constructive suggestions. We have studied all comments carefully and revised the manuscript accordingly. We marked all the changes in red fonts in the revised manuscript. The point-by-point answers to the comments are given below in blue fonts.

Specific comments:

1. In Fig.1a, the peak density of Nas is more than 12000 cm^{-3} on 97.75 km at 14:40 UT (line 142). But it can be seen from Fig.1b, the peak density of Nas at the same time is only about 5000 cm^{-3}. Although the sodium density in Fig.1a and Fig.1b were given by two different kinds of lidars, the large difference of the density is difficult to be understood as these two lidars almost located at the same site. Is this large difference caused by the different resolutions or reversion methods? Authors should re-calculate the density in Fig.1a and Fig.1b, and give reasonable values.

Thanks for this valuable comment. We apologize on the confusions and imprecisions in the data analysis. We have now thoroughly checked the raw data files of the wideband fluorescence resonance lidar and the temperature/wind lidar. We have learnt more about the data reduction/inversion methods for both lidars. The key conflict could possibly come from the wideband lidar. Fig. 1*(a) shows the lidar system operated poorly after the midnight. But the first author made a reckless mistake in handling the bad data files (i.e., she accidentally deleted the bad file). Yet we can note that the signal to noise ratio (SNR) in the first half of the night is 10, still larger than the limitation of 2.

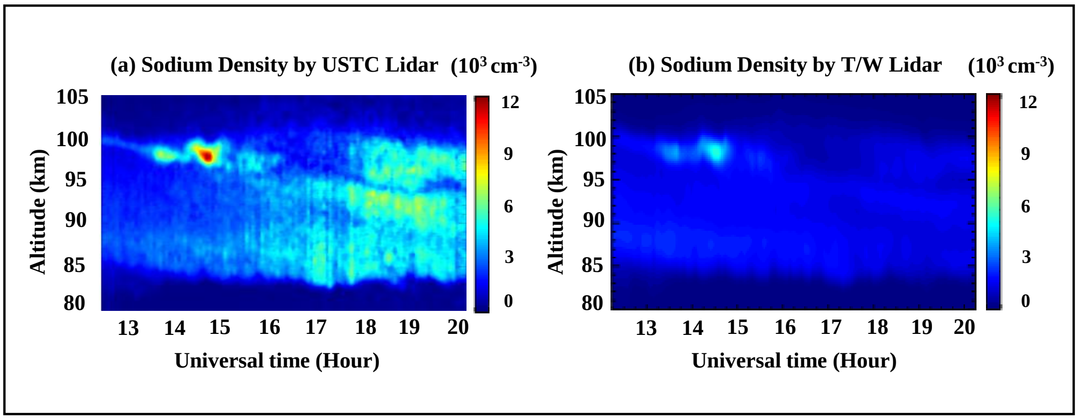

Fig. 1* (a) The entire sodium density profile observed by the wideband lidar on June 3rd, 2013. (b) The sodium density profile by T/W lidar.

For the wideband sodium fluorescence resonance lidar, the inversion formula for the sodium number density *N* at an altitude of *z* is given as follows:

$$N = \frac{\sigma_R n_a(z_0)}{\sigma_{N_a}} \cdot \frac{(P(z)-P_B)z^2}{(P(z_0)-P_B)z_0^2}\ , \qquad (1)^* \qquad \text{(Xue, 2007)}$$

where σ_R is the Rayleigh backscatter cross section,

$n_a(z_0)$ is the atmosphere density at a reference altitude, given by atmospheric model,

σ_{N_a} is the effective sodium backscatter cross section,

$P(z)$ is the number of photons detected in the range interval (z-Δz/2, z+Δz/2),

P_B is the expected photon count per range bin due to background signal and dark counts, calculated through the averaged background signal above 130 km, and,

$P(z_0)$ is the Rayleigh photocount at 30 km altitude, estimated by averaging the measured photon count over a 5-km range interval centered at 30 km (Gardner et al., 1986).

Among all the parameters, the variables are σ_R, $P(z)$, P_B, $P(z_0)$, and *z* (means $N = f(\sigma_R, P(z), P_B, P(z_0), z)$. The error transfer formula of *N* equals to:

$$\frac{\Delta N}{N} = \left|\frac{\partial \ln f}{\partial \sigma_R}\right| \Delta\, \sigma_R + \left|\frac{\partial \ln f}{\partial P(z)}\right| \Delta P(z) + \left|\frac{\partial \ln f}{\partial P_B}\right| \Delta\, P_B + \left|\frac{\partial \ln f}{\partial P(z_0)}\right| \Delta P(z_0)\ + \left|\frac{\partial f}{\partial z}\right| \Delta z. \qquad (2)^*$$

The fourth term, $\left|\frac{\partial \ln f}{\partial P(z_0)}\right| \Delta P(z_0) = \left|\frac{1}{P(z_0)-P_B}\right| \Delta P(z_0)$, makes the final error inversely proportional to the absolute value of $P(z_0) - P_B$. The averaged photon count $P(z_0)$ at 30 km is given by:

$$P(z_0) = \eta T_A^2 \frac{\lambda J}{hc} \frac{A_R}{4\pi z_0^2} \sigma_R \Delta z n_a(z_0), \qquad (3)^*$$

where η is the overall system efficiency and,

T_A one-way atmospheric transmittance of the lower atmosphere;

λ optical wavelength, 0.589×10^{-6} m;

J laser pulse energy, J;

h Planck's constant, 6.63×10^{-34} J s;

c velocity of light, 3 × 108 m/s;

A_R receiver aperture area, m^2;

$n_a(z_0)$ the atmosphere density at z_0 (Gardner et al., 1986).

To minimize shot noise, $P(z_0)$ at 30 km altitude is estimated by averaging the measured photon count over a 5-km range interval centered at 30 km (Gardner et al., 1986). Because the atmospheric density decreases approximately exponentially with altitude, the average photon count at 30 km is computed by first subtracting the estimated background count, multiplying the result by z^2, taking the natural logarithm and then averaging over the range 27.5 km to 32.5 km (Gardner et al., 1986). We can see that $P(z_0)$ is therefore sensitively influenced by the background atmosphere and lidar system conditions.

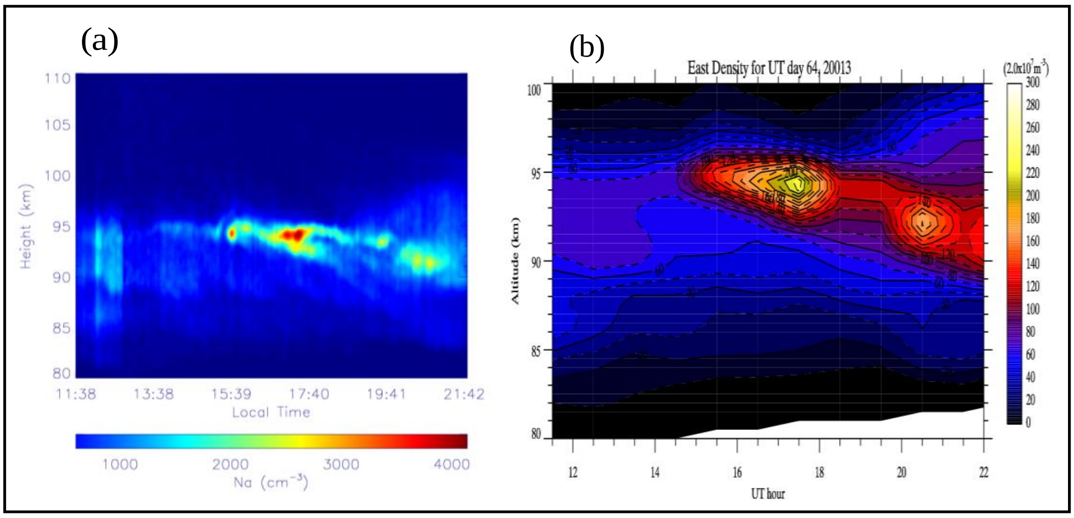

Fig. 2* (a) Sodium density profile detected by the wideband lidar on May 5th, 2013. (b) Sodium density profile detected by the T/W lidar on that day.

In comparison, we show that the sodium density profile detected on May 5th, 2013, by the wideband lidar is close to that by the T/W lidar (Fig. 2* (a) and (b)). Both profiles exhibit a peak density of about 4000 cm^{-3}.

Then we check the raw data files on June 3rd (the case we have chosen in the manuscript) and May 5th, 2013 (for comparison). Through $h = c \times t/2$, the reference height of $z_0 = 30km$ is equivalent to $t \approx 0.2ms$ (marked by the light line at .2000ms). On June 3rd, $P(z_0) = 106$ (highlighted by the red circle in Fig. 3* (a)), and the expected photocount at 130 km equals to 18 (not shown in Fig. 3*(a), but could be read from the data file). On May 5th, $P(z_0) = 501$, and $P_B = 7$ (Fig. 3*(b)). Since the error term is inversely proportional to the absolute value of $N(z_0) - N_B$, a much smaller $|P(z_0) - P_B|$ (about 5.6 times less) would cause the deduced sodium number density N to increase.

On the other hand, for the narrowband T/W lidar, the number of photons received by telescope from the range (z-Δz/2, z+Δz/2) is given by:

$$N(z, \nu_L, T, V) = \left(\frac{E_L}{hc/\lambda}\right) \times (\eta T_A^2) \times \left(\rho_{N_A}(z)\sigma_{SB}(\nu_L, T, V)\Delta z\right) \times \left(\frac{A_R}{z^2}\right) \times (T_\uparrow T_\downarrow) + N_B,$$

where (4)* (Li, 2005)

ν_L Transmitter laser frequency;

T Temperature (K);

V	Wind velocity (m/s);
E_L	Transmitted laser pulse energy (J);
η	System efficiency;
$\rho_{N_A}(z)$	Na number density (m^{-3});
$T_\uparrow$	Upward transmission in the Na layer;
$T_\downarrow$	Downward transmission in the Na layer.

Different from the wideband lidar, the deduced sodium number density $\rho_{N_A}(z)$ here is independent on the atmospheric conditions at a relative altitude z_0. Perhaps that is why they establish a necessary T/W lidar nearby.

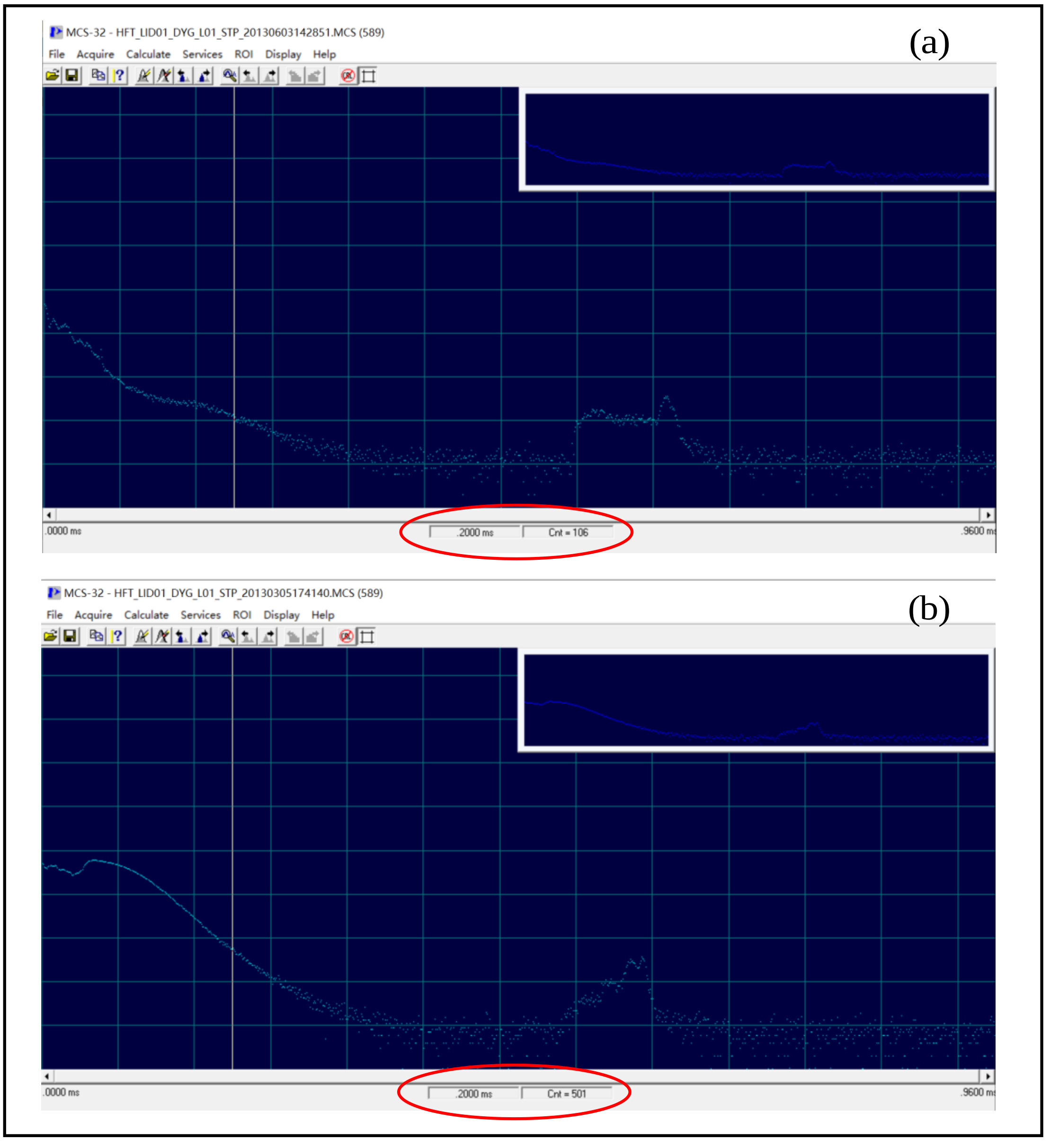

Fig. 3* (a) The raw data file at 14:28 UT on June 3rd. $P(z_0) = 106$ (pointed out by the red

circle), and the expected photocount at 130 km equals to 18. (b) The raw data file at 17:41 UT on May 5th, 2013. $P(z_0) = 501$, and $P_B = 7$.

We have added more detailed explanation on the discrepancy of the peak densities, around lines 5 to 18 on page 4. We have redrawn Fig. 1(a) on page 20 of the revised manuscript.

2. In the Discussions, a clear causal chain is given by the authors: the lightning strokes induced the overturning of the electric field, and then induced the ionospheric disturbances, as well as Nas. However, it can be seen from Fig.2a: there is an enhancement in the Es layer from 13:20 to 14:20, and the origin of this enhancement was not explained or discussed in the manuscript. Is it caused by lightning as proposed by Johnson and Davis (GRL, 2006) ? As the main contribution of this manuscript is to propose a new mechanism of Nas layer enhancement by lower atmospheric electric field, I suggest that Authors could explain or discuss the enhancement in the Es layer from 13:20 to 14:20.

Thanks for the comment. We would like to explain the E_S enhancement through electron acceleration by the reverse electric field. Usually, the mid-latitude E_S layers would be brought down gradually by tidal fluctuations (Mathews, 1998). Professor Plane's E_S theory predicts that when a series of E_S layers descend below 100 km, they will be depleted through recombination of ions and electrons (Cox and Plane, 1998). Since the recombination of $Na^+ + e^- \rightarrow Na + h\nu$ is inefficient in generating Na_S, Na^+ is believed to first form a ligand $Na^+ \cdot N_2$ through the recombination reaction:

$$Na^+ + N_2 + M \rightarrow Na^+ \cdot N_2 + M, \qquad (5)^*$$

with a rate coefficient of $k_1 = 4.8 \times 10^{-30}(T/200)^{-2.2}$ cm^6 $molecule^{-2}$ s^{-1} (Cox and Plane, 1998). $Na^+ \cdot N_2$ can either switch with CO_2 (which will undergo dissociative electron recombination to form Na), or O (which reforms Na^+)(Cox and Plane, 1998). So the key factor of E_S mechanism depends on the ratio of [O]/ [CO_2]. Recombination of $Na^+ \cdot CO_2$ and e^- will increase rapidly as [O]/ [CO_2] decreases below the value of 100 (Cox and Plane, 1998). Then the sodium atoms could be formed directly from the following chemical reaction:

$$Na^+ \cdot CO_2 + e^- \rightarrow Na + CO_2. \qquad \text{(6)* (Cox and Plane, 1998)}$$

The chemical reaction rate (v) for this second-order reaction could be calculated using the following equation:

$$v = k[Na^+ \cdot CO_2]N_e, \qquad \text{(7)*}$$

The reaction rate coefficient k_2 for the chemical reaction is experimentally measured to be:

$$k_2 = 1 \times 10^{-6}\sqrt{\frac{200}{T}} \quad (\text{cm}^6\ \text{molecule}^{-2}\ \text{s}^{-1}) \qquad \text{(8)*}$$

(Collins et al., 2002; Cox and Plane, 1998; Daire et al., 2002), and the electron density N_e can be calculated using the following equation:

$$N_e = 1.24 \times 10^4 foE_S^2 (cm^{-3}) \qquad \text{(9)* (Bittencourt, 2004).}$$

Overall, this E_S mechanism is most widely accepted, if we neglect k_1 as being too small with an order of 10^{-30}. A possible adaptation is to assume a plenty quantity of pre-existing $Na^+ \cdot N_2$ / $Na^+ \cdot CO_2$ in the sodium layer, and the E_S just needs to provide enough additional electrons. Figure 4* (d) shows E_S descending near 100 km at about 13:20 (marked by the blue dashed line). Then the E_S depletes, and a moderate enhancement of Na occurs from 13:30 UT to 14:00 UT (pointed out by the green arrow in Figure 4*(a)). This sodium increase exhibits no obvious peak, which could probably be in accord with a normally descending E_S governed by tides. In comparison, the peak profile of the Na_S shows intense enhancement and sharp peak, indicating a distinct mechanism.

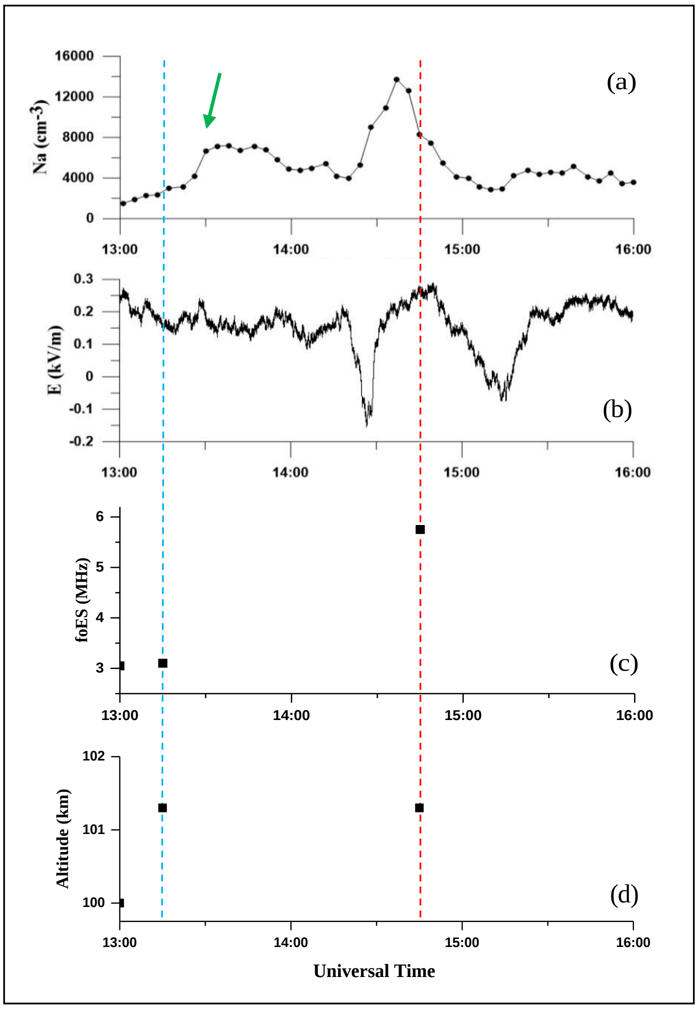

Figure 4* (a) Time series of sodium density variations. (b) Atmospheric electric field variations. (c) foE$_S$ variations from 13:00UT to 16:00 UT. (d) Altitudes of E$_S$. (Blue and red dashed lines and green arrow are discussed in this reply, see the text).

Furthermore, a link between the electric field reverse and E$_S$ enhancement at 14: 40 UT (marked by the red dashed line) could be established through the acceleration of electrons. Normally, positive particles will move along the direction of electric field, and negative particles do the opposite (Griffiths, 1999). Since metal ions are much heavier than electrons, the ions would drag electrons in order to move/drift together, this process is called the bipolar diffusion (Griffiths, 1999). In the initial stage, ions and electrons descend gradually under the southward electric field. In a partially ionized plasma, the characteristic frequencies for ions and electrons are associated with the collisions of the plasma particles with stationary neutrals (e.g., the electron–neutral collision frequency ν_{en} and the ion–neutral collision frequency ν_{in}). The collision frequency ν_{sn} for scattering of the plasma species s by the neutrals is

$$\nu_{sn} = n_n \sigma_s^n V_{Ts} , \qquad (10)^* \text{ (Shukla and Mamun, 2002)}$$

where n_n is the neutral number density,

σ_s^n is the scattering cross section (which is typically of the order of 5×10^{-15} cm^2 and depends weakly on the temperature Ts),

and $V_{Ts} = (k_B T_s / m_s)^{1/2}$ is the thermal speed of the species s.

So the relaxation times $\tau = \frac{1}{\nu}$ for ions and electrons are different in a partially ionized plasma, and electrons would respond much faster than the heavier sodium ions do (since $m_i \gg m_e$). At the moment when the electric field reverses, electrons will be rapidly accelerated by the northward electric field, and ions would be regarded as essentially remaining northward or unchanged. So no matter how many Na^+ ions are in E_S, the electrons in the E_S are always sufficient to produce Na_S. Perhaps that is why we often observed that even a very weak E_S is always accompanied by Na_S (Dou et. al., 2010).

We have added a new section 3.2 to discuss the E_S and Na_S described in this reply in details for our revised manuscript.

3. From the progress of Nas in Fig.1a：The density of Nas increases with height drops after the Nas height lower than 100 km. A maximum of Nas is present at 97km around 13:30, and later the density of Nas decreases. But another maximum of Nas is present again around 14:20 (almost the same height), and the authors think that this Nas is produced by the overturn of low-altitude electric field. According to Plane’s theory, when the Es drops below 100 km, Na ions in the Es are rapidly neutralized to form Nas. As the height decreases, the rate of Na ion neutralization increases. And so there's Nas maximum at about 13:20 UT around 97 km. Later, the Nas gradually weakened due to excessive consumption of Na ions. But for the bigger Nas around 14:20, there needs to be an implicit condition if the ions in the Es contribute. That is, Na ions in the Es increased at 13:30. This may be due to the addition of surrounding sodium ions resulting in Es increase. So there may be a possible mechanism: A

reversal of the electric field adds sodium ions nearby, and these ions enhance Es. And then the sodium ions in the Es are neutralized to form Na atoms, with Es weakened.

Thanks for the comment. We agree with this enhancement mechanism described by the referee, except that we would like to replace the enhanced ions with electrons. We have added the possible mechanism in detail under the new section 3.2.

Technical corrections:

1. From line 22 to line 26 in the abstract: rewrite this long sentence.

Thanks for the comment. We have rewritten the sentence around lines 24 to 26 on page 1.

2. From line 47 to line 49, “the metal layers (especially the sodium layer), which located between about 80~110 km, could possibly act as a window to detect the MLT parameters by means of fluorescence resonance lidars.” please add the corresponding reference.

Thanks for the comment. We have added the references around line 6 on page 2.

3. And from line 49 to line 51 please also add the reference.

Thanks for the comment. We have added the references around line 8 on page 2.

4. At the end of Line 64, please consider the word “candidate” whether is proper or not.

Thanks for the comment. We have changed it to “proposed mechanisms”.

5. The author should pay much attention to the tense of the manuscript， the past tense shall be used when giving background information in the Abstract and Introduction, when describing methods used, and when presenting and discussing results. There are indeed quite a lot of such serious problems throughout all the manuscript. If possible, please ask a native speaker for help.

Thanks for the comment. We have tried our best to use appropriate tenses depending on the actual time of occurrences.

6. Line 137, please consider about the abbreviation “T/W lidar” as it appeared there for the first time.

Thanks for the comment. We have added the full name and a reference for the T/W lidar around line 4 on page 4.

7. Please change the line 162 as “in accord with our previous reports WHICH shown that an Nas higher than 96 km tended to be…

Thanks for the comment. We have modified this sentence around lines 28 to 29 on page 4.

8. Line 182, Based on the ABOVE observations

Thanks for the comment. We have modified it around line 5 on page 9.

9. Line 215 also POINTED out by the vertical red dashed line.

Thanks for the comment. We have rewritten the figure caption around line 4 on page 22.

10.Line 234 could be changed to “It is worth mentioned that…”

Thanks for the comment. We have changed it to “It is worth mentioning that” around line 32 on page 5.

11. Line 254 could be changed to “The electric field could change through within two distinct ways as below:”

Thanks for the comment. We have change it to “as below” around line 13 on page 6.

12.Line 291-292: “mainly concentrating in two ranges about (35.8ºN, 118.1ºE) and (25.1ºN, 113.8ºE).” please rewrite this sentence.

Thanks for the comment. We have modified this sentence in the figure caption 4 on page 23.

13.Line 302 could be changed to “Afterwards, no strong stroke WAS detected again in the discussed area.”

Thanks for the comment. We have modified this sentence around line 13 on page 7.

14.Line 311-313 the caption of Figure 5 (a)~(l): please unify the tense of verbs and pay attention to the English writing again as I remind.

Thanks for the comment. We have rewritten the caption of Fig. (5).

15.Lines 335-336, “similar to how moving cars will crash in a traffic accident in the car in front suddenly turns back or brakes” Please rewrite this sentence within much more scientific aspect.

Thanks for the comment. We have deleted this scenario in the manuscript.

16.Line 338, are you sure by three steps? Please check it.

Thanks for the comment. We have modified the legend to be four steps in total, around lines 4 to 9 on page 9.

Cited References for this Reply

Collins, S. C., Plane, J. M. C., Kelleya, M. C., Wright, T. G., Soldán, P., Kanee, T. J., Gerrarde, A. J., Grime, B. W., Rollason, R. J., and Friedman, J. S.: A study of the role of ion-molecule chemistry in the formation of sporadic sodium layers, Journal of Atmospheric & Solar Terrestrial Physics, 64, 845-860, 2002.

Cox, R. M., and Plane, J. M. C.: An ion-molecule mechanism for the formation of neutral sporadic Na layers, Journal of Geophysical Research Atmospheres, 103, 6349-6359, 1998.

Gardner, C. S., Voelz, D. G., Sechrist, C. F., and Segal, A. C.: Lidar studies of the nighttime sodium layer over Urbana, Illinois: 1. Seasonal and nocturnal variations, Journal of Geophysical Research Space Physics, 91, 13659-13673, 1986.

Dou, X. K., Xue, X. H., Li, T., Chen, T. D., Chen, C., and Qiu, S. C.: Possible relations between meteors, enhanced electron density layers, and sporadic sodium layers, Journal of Geophysical Research: Space Physics, 115, A06311, 2010.

Griffiths, D.J.: Introduction to Electrodynamics, 3rd ed., Prentice- Hall, Upper Saddle River, New Jersey, 1999.

Li,T.: SODIUM LIDAR OBSERVED VARIABILITY IN MESOPAUSE REGION TEMPERATURE AND HORIZONTAL WIND: PLANETARY WAVE INFLUENCE AND TIDAL-GRAVITY WAVE INTERACTIONS, Ph.D. thesis, Colorado State University, Fort Collins, Colorado, 48-50pp, 2005.

Ma, J., Xue, X., Dou, X., Chen, T., Tang, Y., Jia, M., Zou, Z., Li, T., Fang, X., and Cheng, X.: Large-Scale Horizontally Enhanced Sodium Layers Coobserved in the Midlatitude Region of China, Journal of Geophysical Research: Space Physics, 124, A026448, 2019.

Mathews, J. D.: Sporadic E: current views and recent progress, Journal of Atmospheric and Solar-Terrestrial Physics, 60, 413-435, 1998.

Shukla, P. K. and Mamun, A. A.: Introduction to Dusty Plasma Physics, Institute of Physics Publishing, 2002.

Williams, B. P., Berkey, F. T., Sherman, J., and She, C. Y.: Coincident extremely large sporadic sodium and sporadic E layers observed in the lower thermosphere over Colorado and Utah, Annales Geophysicae, 25, 3-8, 2007.

Xue, X.H.: Studies on Geoeffectiveness of Coronal Mass Ejections and Near-Earth Space Environment, Ph.D. thesis, University of Science & Technology of China, Hefei, China, 85-92pp, 2007.