Evidence for lightning-associated enhancement of the ionospheric sporadic $E$ layer dependent on lightning stroke energy

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Abstract In this study we analyze the lightning data obtained by the World-Wide Lightning Location Network (WWLLN) and hourly ionospheric data observed by ionosondes located at Sanya and Beijing, to examine the changes in ionospheric electron density in response to the underlying thunderstorms and to investigate the possible connection between lightning discharges and the enhancement of the ionospheric sporadic $E$ ($E_s$) layer. We identify a statistically significant enhancement and a decrease in altitude of the $E_s$ layer at Sanya station, in agreement with the results found at Chilton, UK. However, the lightning-associated modification of the $E_s$ layer investigated using the same approach is not evident at Beijing station. Furthermore, we compare the responses to weak and strong lightning strokes using WWLLN-determined energies at Sanya in 2012. The lightning-associated enhancement of the $E_s$ layer is predominantly attributed to powerful strokes with high stroke energy. A statistically significant intensification of the $E_s$ layer with higher-energy strokes at Sanya, along with the statistical dependence of lightning-associated enhancement of the $E_s$ layer on stroke energy, leads us to conclude that the magnitude of the enhancement is likely associated with lightning stroke energy.

1. Introduction

Variation in ionospheric electron density has been predominantly attributed to the influence of solar radiation, geomagnetic activity, and thermospheric composition which are regarded as the main drivers in numerous ionospheric models [Rishbeth, 1979, 1998; Anderson et al., 1998; Hajj et al., 2004; Bilitza et al., 2011]. Meteorological processes including mesoscale convective weather and thunderstorms in the lower atmosphere can affect the ionosphere [Bishop et al., 2006; Kelley, 1997] as a result of energy transfer from the troposphere mainly through wave activity (i.e., gravity waves (GWs) and infrasonic waves [Blanc, 1985; Chimonas, 1971; Sentman et al., 2003]) as well as electrical effects associated with brief optical emissions known as red sprites and gigantic jets that have been reported to propagate upward to around 90 km [Pasko et al., 2002; Lu et al., 2011, 2013]. Modeling work indicated that elves can even extend to greater altitudes, which is associated with ionospheric enhancements expected in response to electromagnetic pulses (EMPs) [Rodger et al., 2001].

A superposed epoch analysis (SEA) using the ionospheric parameters and the times of lightning discharges by Davis and Johnson [2005] revealed a significant enhancement of the ionospheric sporadic $E$ layer ($E_s$) in response to the lower lightning activity passing through the ionospheric monitoring station at Chilton, UK, with peaks in $\delta f$, observed about 6 h and 36 h after the lightning. Recent studies showed that GWs originating from large underlying thunderstorms clearly affect the electron distribution on the $D$ layer ionosphere [Lay and Shao, 2011] and total electron content (TEC) [Lay et al., 2013]. Furthermore, the electron density in the lower ionosphere with even a small thunderstorm can be disturbed by underlying lightning discharges [Shao et al., 2013].
Table 1. Description of the Ionosonde Network and WWLLN Lightning Data

<table>
<thead>
<tr>
<th>Location</th>
<th>Ionosonde Network</th>
<th>Sanya</th>
<th>Beijing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data source</td>
<td>IGG, CAS</td>
<td>IGG, CAS</td>
<td></td>
</tr>
<tr>
<td>Data coverage</td>
<td>Oct 2007 to Dec 2012</td>
<td>Jun 2006 to Dec 2012</td>
<td></td>
</tr>
<tr>
<td>DPS-4D</td>
<td>Jan 2010 to Dec 2012</td>
<td>Apr 2011 to Dec 2012</td>
<td></td>
</tr>
<tr>
<td>WWLLN Lightning Data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latitude</td>
<td>17.3°N–19.3°N</td>
<td>39.3°N–41.3°N</td>
<td></td>
</tr>
<tr>
<td>Longitude</td>
<td>108.6°E–110.6°E</td>
<td>115.2°E–117.2°E</td>
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<tr>
<td>Number of lightning discharges</td>
<td>258,341</td>
<td>48,796</td>
<td></td>
</tr>
<tr>
<td>Number of events</td>
<td>8,089</td>
<td>3,006</td>
<td></td>
</tr>
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</table>

In this paper, we use the lightning data obtained by the World-Wide Lightning Location Network (WWLLN) and hourly ionospheric data observed by ionosondes located at Sanya and Beijing to investigate the possible connection between lightning discharges and the enhancement of the $E_s$ layer. Section 2 discusses the data and analysis method used in our research. Section 3 explains the statistical results, and section 4 shows the discussion and conclusions of this paper.

2. Data and Method

WWLLN is a network of global stations to monitor the radio emissions from lightning discharges in the very low frequency (VLF) bands (3–30 kHz) and is regarded as one of the currently best suited networks to study the occurrence and impacts of high peak current lightning (>50 kA) on the upper atmosphere for global coverage and for regional studies in areas that lack other accessible lightning networks [Rodger et al., 2006; Jacobson et al., 2006].

The $E_s$ layer is a narrow ionization layer with thin and patchy plasma and can be characterized by the critical frequency ($f_cE_s$) and the virtual height ($h'_{E_s}$) from the observation of ionosondes. The critical frequency, $f_cE_s$ (in Hz), is related to the peak electron concentration of the $E_s$ layer, $N_e$ (in m$^{-3}$), by the formula $f_cE_s = 8.98\sqrt{N_e}$. Here the digisondes located at Sanya (18.3°N, 109.6°E) and Beijing (40.3°N, 116.2°E) operated by the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGG, CAS) are used to obtain the $f_cE_s$ and $h'_{E_s}$, which were manually scaled with a time resolution of 1 h. The ionograms were manually scaled using the SAO Explorer software developed by the University of Massachusetts Lowell to avoid unpredictable poor automatic scaling [Reinisch et al., 2005]. At each station, two types of digisondes, namely, the Canadian Advanced Digital Ionosonde (CADI) and the Digital Portable Sounder 4D (DPS-4D), perform routine ionospheric vertical sounding. Concurrent operation has shown that these two digital ionosondes employ different antenna arrays and digital signal processing techniques yet nevertheless are closely related instruments [Morris et al., 2004]. More detailed description about the CADI and DPS-4D ionosondes can be found in the relevant literature [e.g., MacDougall et al., 1995; Reinisch et al., 2008]. The description of the two stations and the temporal coverage of the digisondes data used in this study are summarized in Table 1.

In our study, the same method of superposed epoch analysis (SEA) [Davis and Johnson, 2005] was performed to the ionospheric parameters $f_cE_s$ and $h'_{E_s}$ of the $E_s$ layer and the times of lightning discharges in thunderstorms. We included the WWLLN lightning data within ±1° of latitude and longitude of each ionosonde station, i.e., Sanya and Beijing. The region under investigation was chosen because Davis and Johnson [2005] revealed that the response of the lower ionosphere to thunderstorms was pronounced and insensitive to distance for lightning within ~100 km, decreasing with distance >100 km. The time resolution of ionospheric data was 1 h, so the lightning discharges that occurred within a 1 h time period were deemed as one lightning event to ensure uniformity of the lightning with ionospheric data. A total of 8089 lightning events was available at Sanya and 3006 at Beijing for the period of interest in this study. The details of lightning events...
are summarized in Table 1. The trigger times for the SEA approach were the times of lightning events, and the average behavior of two ionospheric parameters was investigated for 200 h before and after the lightning. This method is commonly used to analyze geophysical data to determine repeatable but weak responses to a certain phenomenon [Samson and Yeung, 1986]. In this way, the influence of the lightning discharges on $f_{o}E_s$ and $h^\prime E_s$ of the $E_s$ layer will be reinforced while other randomly distributed influences (geomagnetic activity, tidal waves, meteors, etc.) will be ruled out. Considering that most lightning occurs on summer afternoons, we defined $\delta f_{o}E_s$ and $\delta h^\prime E_s$ to subtract the 30 day median values of each ionospheric parameter $f_{o}E_s$ and $h^\prime E_s$ to minimize the effects of the diurnal trend. Then we calculated the average response of the ionospheric $\delta f_{o}E_s$ and $\delta h^\prime E_s$ to lightning. In this way, the analysis becomes sensitive to deviations from the diurnal and seasonal trends. Meanwhile, the background variability of the $E_s$ layer can be excluded.

In addition, we carried out the superposed epoch analysis many times using random trigger events with the same number as real lightning events during the same period of the study at each station, respectively. The probability of whether a statistical response exceeds that expected by chance can be judged after calculating the 95th and 99th percentiles of these random responses. The statistical significance of each response was given explicitly with the method of Davis and Johnson [2005]. Therefore, the magnitude of each response can be compared quantitatively. Besides, the significance of the ionospheric parameter response can be further investigated by comparing the distributions of points used to calculate mean values at a range of times before and after time zero using a two-sample Kolmogorov-Smirnov test [Wang et al., 2003].

3. Results

3.1. Variation of the Lightning-Associated Responses of the $E_s$ Layer at Two Stations

Figure 1 shows the results of the SEA for the ionospheric changes in response to lightning at Sanya and Beijing. The time bin is 1 h. As shown in Figure 1a, a significant enhancement in $\delta f_{o}E_s$ for Sanya with its maximum peak value of 0.533 MHz is observed, approximately 34 h after lightning, which is indicated by the red vertical dashed line. Relative to the null hypothesis, the enhancement in $\delta f_{o}E_s$ is significant at the 99.95 ± 0.05% level. The grey area, in this and subsequent plots, represents the standard error in the mean calculated from the standard deviation of each mean value divided by the square root of the number of points within each time bin of the composite analysis. The null values, where there were no $\delta f_{o}E_s$ or $\delta h^\prime E_s$ values, were not included in calculating the mean and the error. The number of data points included in each time bin of the composite analysis is 2613 ± 20 (of 8089 lightning events) with no bin containing fewer than 1899 data points, ensuring a distribution containing sufficiently large number of points and obtaining a meaningful mean. Except for the enhancement at approximately 34 h after lightning, there are no other changes in $\delta f_{o}E_s$ that greatly exceed the 95th and 99th percentiles of the data, represented by cyan and blue dashed lines, respectively. There are some peaks in $\delta f_{o}E_s$ up to 200 h prior to the lightning event, whereas only one peak around 160 h before lightning is slightly significant (just above the 95th percentile but below the 99th percentile). The enhancement is significant at the 98.30 ± 0.29% level. It may occur by chance or be caused by the long-period amplitude modulation related to the planetary wave-like oscillations in $f_{o}E_s$ [Haldoupis et al., 2004], included in $\delta f_{o}E_s$. Also, possibly some undesired recurrence of lightning events before time zero would contaminate the result in the SEA, as a case in Davis and Lo [2008]. So it is necessary to calculate the significance levels, and any enhancement in the SEA can then be compared with these levels in order to determine its significance. The percentiles were calculated by repeating the SEA 100 times using the same number of trigger times extracted at random from the period of this study. From these analyses a range of values can be determined for each time bin that represents random fluctuations in the data. By ordering these values in each bin, it is possible to generate the 95th and 99th percentiles against which the true data can be compared. Further, the significance of the enhancement in $\delta f_{o}E_s$ can be investigated by conducting a Kolmogorov-Smirnov test comparing the distributions of points over 3 days before and after time zero. The two-sample Kolmogorov-Smirnov test is a nonparametric hypothesis test that evaluates the difference between the cumulative distribution functions of the distributions of the two-sample data and determines whether the two distributions are indeed statistically different or if they represent subgroups from the same population [Wang et al., 2003]. The advantage of the Kolmogorov-Smirnov test is that it is independent of the shape of the distribution so that it is useful in a SEA for hypothesis testing [Scott et al., 2014]. The observed difference of $\delta f_{o}E_s$ values in 3 days before and after lightning is highly significant to confidence levels >99.9% ($p = 0.0002 < 0.001$). The mean and error values of the distribution are 0.413 ± 0.004 MHz before lightning and 0.434 ± 0.004 MHz after lightning. In Figure 1d, the number of data points included in each time bin of the composite analysis is 1138 ± 9 (of 3006
Figure 1. Results from superposed epoch analyses 200 h before and after the lightning at Sanya (18.3°N, 109.6°E) and Beijing (40.3°N, 116.2°E). The mean values of $\delta f_0 E_s$ and $\delta h' E_s$ are shown as black lines, the standard error in these mean values as a grey area around the line, while cyan and blue dashed lines correspond to the 95% and 99% levels of data set, respectively. The standard error was calculated from the standard deviation of each mean value divided by the square root of the number of points in that mean. (a–c) The statistical response in $\delta f_0 E_s$ and $\delta h' E_s$ to lightning and the distribution of lightning events at Sanya. (d and e) The statistical response in $\delta f_0 E_s$ and $\delta h' E_s$ to lightning at Beijing. (f) The associated distribution of lightning events at Beijing.

lightning events) with no bin containing fewer than 837 data points, and there are multiple peaks in $\delta f_0 E_s$ values at Beijing station. However, the peak at approximately time zero, i.e., $t = 0$ is just above the 95th percentile, and there is no significant enhancement in $\delta f_0 E_s$ that exceeds the 99th percentile. The lightning-associated enhancement at Beijing station is significant at the 98.90 ± 0.23% level, so it seems not as evident as that at Sanya station.

Figures 1b and 1e show the changes in $\delta h' E_s$ for Sanya and Beijing in response to lightning, and the numbers of data points included in each time bin of the composite analyses are 2494 ± 19 and 1139 ± 9, respectively. Davis and Johnson [2005] observed a decrease in $\delta h' E_s$ of ~1 km at Chilton. In our study, the response of an evident decrease at the 99.85 ± 0.09% level in $\delta h' E_s$ for Sanya (Figure 1b) indicated by the red vertical dashed line (exceeding the 99th percentile) appeared at approximately 62 h after lightning (later than the occurrence of the increase in $\delta f_0 E_s$), which passed a Kolmogorov-Smirnov test at >99.9% comparing the distributions of points over 3 days before and after time zero. The mean and error values of the distribution are 1.455 ± 0.022 km before lightning and 1.418 ± 0.022 km after lightning. However, there is not such an evident decrease (exceeding the 99th percentile) in $\delta h' E_s$ for Beijing in Figure 1e.

The diurnal nature of storms can be seen in the wings of the number of lightning events as shown in Figures 1c and 1f. Davis and Johnson [2005] also showed the distribution of lightning with a 24 h recurrence of lightning discharges and additional lightning strokes around time zero, quite similar to Figures 1c and 1f.
The fact that the distributions before and after lightning pass the Kolmogorov-Smirnov test in spite of this cross contamination of points further strengthens the statistical significance of the results above.

Although a statistically significant enhancement and a decrease in altitude of the $E_s$ layer at Sanya station have been found, additional statistics of the changes in the distribution of $\delta f_o E_s$ values for 25–48 h around the day of the peak as well as the changes in the distribution of $\delta h' E_s$ values for 49–72 h around the day the minimum occurs before and after lightning were conducted. It can distinguish the possibility that such a statistical result was generated by a few large and specific responses or small and consistent responses. Figure 2 shows any difference in bins between the approximately Gaussian distributions of ionospheric parameters before and after lightning. The difference between the distributions before and after lightning shows up well when an increase in $\delta f_o E_s$ and a decrease in $\delta h' E_s$ occur, respectively, as shown in Figure 2. The positive bins represent an increase of such $\delta f_o E_s$ and $\delta h' E_s$ values correlated with the occurrence of lightning, and vice versa. So it can present a change due to lightning. Figure 2a therefore shows that previous negative bins of $\delta f_o E_s$ between $-2.0$ and $1.0$ MHz are enhanced to positive bins between $1.0$ and $3.5$ MHz. The total number of $\delta f_o E_s$ values observed before lightning is 1.02% higher than the total number after lightning, bringing about the sum of negative bins being slightly larger than the sum of positive bins. On the other side, it may indicate that the $E_s$ layers are existing and enhanced instead of generated by lightning. Again, it can be seen in Figure 2b that $\delta h' E_s$ values are reduced. Previous negative bins of $\delta h' E_s$ between 4 and 16 km decrease to positive bins around 0 km after lightning. The total number of $\delta h' E_s$ values observed before lightning is 0.98% higher than the total number after lightning, and it is the possible reason why the bins of $\delta h' E_s$ between $-8$ and 0 km are slightly negative instead of positive. The changes in the distribution of $\delta f_o E_s$ around the day of the peak as well as the changes in the distribution of $\delta h' E_s$ values around the day the minimum occurs agree with the result of Davis and Johnson [2005].

In order to investigate whether a diurnal variation in the superposed epoch distributions could result in an artifact of the data or not, the histogram of the total number of lightning events versus local time at Sanya station is shown in Figure 3a. Although the number of lightning events of this study varies with local time with the maximum number that occurred between 15 and 17 LT, there are sufficient statistics at all hours of the day (mostly >3% or 243 events in each hour). As shown in Figure 3b, the mean values of $f_o E_s$ reach the maximum at about 13 LT, consistent with the diurnal variation of $f_o E_s$, which is observed by the digisonde at Fuke station (the distance to Sanya is about 140 km) [Wang et al., 2012]. Even though the lightning occurrence is locked to local afternoon so that the trigger times might introduce a diurnal bias of $f_o E_s$ values, the enhancement due to the diurnal bias should occur every afternoon in the local time other than the only observed enhancement 34 h after lightning (about midnight). Besides, 30 day running monthly medians were subtracted from $f_o E_s$ for each hour of the day (the resolution of the data) to minimize the effects of the diurnal trend, so the enhancement of the $\delta f_o E_s$ values is associated with lightning events, not an artifact caused by a diurnal variation in the superposed epoch distributions.
Figure 3. (a) The diurnal variation of the occurrence of lightning events and (b) the diurnal variation of the mean values of $f_{\text{Es}}$ for the period of this study at Sanya.

From the above, we interpret the statistically significant enhancement by the SEA as a statistically reliable ionospheric response to lightning.

In addition, the blanketing frequency of the $E_s$ layer, $f_{\text{Es}}$, is also a useful ionospheric parameter which corresponds to the lowest frequency that can penetrate the layer and is a measure of the weakest patches of ionization within the layer. As a result of the lack of the ionospheric parameters $f_{\text{Es}}$ in our manually scaled data, we used the automatically scaled $f_{\text{Es}}$ data by the DPS-4D ionosonde (no equivalent data were available for the CADI at Sanya and Beijing stations). As shown in Figure 4, there are no evident responses in $\delta f_{\text{Es}}$ (exceeding the 99th percentile) at Sanya and Beijing stations.

3.2. Variation of the Lightning-Associated Enhancement of the $E_s$ Layer With Lightning Stroke Energy

The peak current of lightning stroke is associated with the radiation field amplitude regarded to determine the level of ionization in the $E_s$ layer. Since 2012, WWLLN has been expanded to record the root-mean-square (RMS) electric field value of the sferic waveform between 6 and 18 kHz in a 1.33 ms time window and to measure radiated VLF lightning stroke energies [Hutchins et al., 2012a]. The strokes used in this study were from the WWLLN lightning data in 2012, which recorded lightning stroke energy data and located within ±1° latitude and longitude of the ionosonde location.

Figure 4. The responses in $\delta f_{\text{Es}}$ from superposed epoch analyses 200 h before and after the lightning at Beijing and Sanya.
Figures 5a and 5b show the distributions of lightning stroke energy in 2012 at Sanya and Beijing. The median stroke energy is indicated by the red vertical dashed line. There are relatively more high energy strokes at Sanya station with a larger median and mean stroke energy of 1142.30 J, 2132.34 J than 632.38 J, 2128.47 J at Beijing station. The stroke energies >2000 J are 26.5% at Sanya station while 19.3% at Beijing station. Similarly, there are relatively more low energy strokes at Beijing station than at Sanya station. The stroke energies <400 J are 13.1% at Sanya station while 34.4% at Beijing station. Note that Sanya is a coastal area, and Chilton is also a station ∼150 km from the coast where the enhancement of \( E_s \) associated with lightning was first reported [Davis and Johnson, 2005]. Lightning strokes over the ocean were also found to be stronger on average than those over land with a sharp boundary along coastlines [Hutchins et al., 2013]. Therefore, it is a possible explanation for the more significant lightning-associated enhancement of \( E_s \) at Sanya that there are more high energy strokes in stronger thunderstorms over the coastal area than the continental area. Next, we investigate our hypothesis that the magnitude of the ionospheric response is associated with the lightning stroke energy.

The WWLLN-determined energy is not the absolute energy of the lightning strokes but rather can be used to measure the energy of the strokes from the RMS electric field in the 6–18 kHz band, to estimate the return stroke peak current, and to distinguish between weak and strong strokes. A study was conducted to investigate variations in the intensification of the \( E_s \) layer in response to lightning with stroke energy using the SEA approach. Figure 6 shows the average responses in \( \delta f_o E_s \) and \( \delta h' E_s \) at Sanya for the five stroke energy levels, i.e., all lightning events and the events with energies <400 J, <600 J, >3000 J, and >6000 J, respectively. The numbers of lightning events are relatively consistent in two pairs of weak and strong strokes, i.e., 678 (<400 J), 676 (>6000 J) lightning events and 966 (<600 J), 967 (>3000 J) lightning events, respectively. All responses in \( \delta f_o E_s \) in 2012 at Sanya with the maximum peak value of 0.63–0.75 MHz around 34 h after lightning (Figures 6a, 6d, 6g, 6j, and 6m) are consistent with the result at Sanya between 2007 and 2012 (Figure 1a).
Figure 7. Results from superposed epoch analyses 200 h before and after the lightning and the distributions of lightning events in 2012 at Sanya for the five stroke energy levels, i.e., (a–c) all lightning events and the events with energies (d–f) < 400 J excluding > 6000 J, (g–i) < 600 J excluding > 3000 J, (j–l) > 3000 J, and (m–o) > 6000 J.

whereas greater stroke energy corresponds to greater magnitude of $\delta f_{o}E_{s}$. The peaks in $\delta f_{o}E_{s}$ with higher stroke energy (> 3000 J, > 6000 J) greatly exceed the 99th percentile, and these enhancements are both significant at the 99.70 ± 0.12% level. The peak with the low stroke energy (< 400 J) is at 99.00 ± 0.22% level, and the peak with the stroke energy (< 600 J) is at 99.65 ± 0.13% level. The average responses of $\delta h^{'2}E_{s}$ for all lightning event and each subset (Figures 6b, 6e, 6h, 6k, and 6n) present a decreasing trend in height when $\delta f_{o}E_{s}$ reaches the maximum peak value. Since WWLLN preferentially detects strong strokes due to a detection efficiency effect [Hutchins et al., 2012b], the results of higher stroke energy are more reliable. Compared with the responses of higher stroke energy (Figures 6j, 6k, 6m, and 6n), the enhancements in $\delta f_{o}E_{s}$ around 34 h and the decreasing trend in $\delta h^{'2}E_{s}$ are preserved. Besides, there is another evident peak significant at the 99.50 ± 0.16% level about 60 h after lightning in Figure 6m. Strong strokes mostly occur with weak ones in minutes, while the resolution of ionospheric data is only 1 h. So it is difficult to distinguish the different ionospheric responses to strong and weak lightning strokes completely.

The magnitude of the enhancement is likely associated with lightning stroke energy, and the ionospheric response to strong lightning strokes is much clearer (significant at the 99.70 ± 0.12% level) than the response to weak lightning strokes (significant at the 99.00 ± 0.22% and 99.65 ± 0.13% levels). A complication in trying to distinguish the different ionospheric responses to lightning stroke energy is that the strong lightning strokes are mostly accompanied by the weak ones within minutes. A study of the ionospheric response to weak lightning strokes may be contaminated by the more evident response to strong lightning strokes within the relatively low time resolution hourly ionospheric data. In order to separate the effect of the strong lightning strokes from the ionospheric responses to the weak lightning strokes, the superposed epoch studies of the weak lightning events (< 400 J and < 600 J) were repeated but this time excluding any events in which there were strong lightning stroke events (> 6000 J and > 3000 J, respectively) within 1 h of the trigger event. The results of this study are shown in Figure 7. In Figure 7, most of the panels (first, fourth, and fifth columns) are the same as in Figure 6, only second and third columns are different to determine the ionospheric response to weak lightning strokes. The numbers of independent weak lightning events, 363 (< 400 J excluding > 6000 J) and 311 (< 600 J excluding > 3000 J), are dramatically lower than previous ones, 678 (< 400 J) and 966 (< 600 J). Due to the reduced event number, the standard error increases to ~0.1 MHz, 1.5 times that of previous ones. However, the evident trending can be seen that the magnitude of the ionospheric response is associated with the lightning stroke energy. Both the responses to weak lightning strokes in $\delta f_{o}E_{s}$ are much weaker, and the enhancements in $\delta f_{o}E_{s}$ around 34 h were significant at the 63.02 ± 1.08% and 74.31 ± 0.98% levels, much less significant than the 99.00 ± 0.22% and 99.65 ± 0.13% levels shown in Figures 6d and 6g.

The analyses subdividing the lightning events by the lightning stroke energy presented above provide evidence that the magnitude of the lightning-associated enhancement of the ionospheric sporadic $E$ layer is likely associated with lightning stroke energy.
4. Discussion and Conclusions

In this paper, we have observed variation of the lightning-associated responses of the ionospheric sporadic $E$ layer at Sanya and Beijing stations. Both a statistically significant intensification and a decrease in altitude of the $E_s$ layer due to lightning at Sanya were observed through a superposed epoch analysis, consistent with the result of Davis and Johnson [2005]. However, the lightning-associated enhancement at Beijing was not evident. Different responses in $\delta f_o E_s$ and $\delta h'E_s$ to lightning at the coastal and continental stations and the statistical dependence of lightning-associated enhancement of the $E_s$ layer on stroke energy provide potential evidence that there could be a relation between the magnitude of the lightning-associated enhancement of the $E_s$ layer and the lightning stroke energy.

There is evidence that multiple mechanisms play a combined role in reinforcing the $E_s$ layer, and they will have different effects on the blanketing frequency, $f_o E_s$ [Johnson and Davis, 2006]. Localized $E_s$ enhancement of wave action would gather up existing ionization into patches, weakening the background layer with a decrease in $\delta h'E_s$. A localized enhancement of wind shear by wave action or the deposition of energy by infrasonic waves at ionospheric altitudes would increase $\delta f_o E_s$ values, leaving the peak density of the adjacent, weaker, areas of the $E_s$ layer unaffected. Thus, the $\delta f_o E_s$ would remain unchanged. A direct electrical discharge or an EMP-induced enhancement would result in an initial increase in $\delta f_o E_s$ values followed by a subsequent increase in $\delta f_o E_s$ values as any created ionization is redistributed into the layer. Applying these expected effects above to our result that there is no evident response in $\delta f_o E_s$ (exceeding the 99th percentile) in Figure 4a, the wave action may be one of the mechanisms for lightning strokes influencing the $E_s$ layer and playing a role in the enhancement of $E_s$ layer in response to lightning at Sanya.

Davis and Johnson [2005] found that the $E_s$ layer may be modulated by the lightning-associated GWs. Kumar et al. [2009] showed that the angle between the direction of the thunderstorm-generated GWs and the mean neutral wind flow is important for the effects of thunderstorms on the ionosphere. When the GWs sources are located in the direction antiparallel to the mean neutral wind flow, the effects of thunderstorms on the ionosphere are dominant. Thus, we reanalyzed the data by splitting the lightning strokes in two categories: those where the wind in the stratosphere primarily is from the lightning stroke toward the digisonde station and those where the wind in the stratosphere primarily is away, dependent on horizontal wind from the ERA-Interim reanalysis data produced with the European Centre for Medium-Range Weather Forecasts Integrated Forecast System [Dee et al., 2011]. The wind data in this study are the mean winds in the stratosphere in the vertical between 20 and 50 hPa at a spatial resolution of 1.5° × 1.5° and a temporal resolution of 6 h. The result of the SEA is shown in Figure 8. The enhancement in $\delta f_o E_s$ in Figure 8g, when the wind has a component antiparallel to the direction from the lightning stroke toward the digisonde station, is more evident and significant than that in Figure 8d. It is consistent with the background wind filtering effects that neutral wind in the stratosphere sharply limits the phase speeds of upward propagating gravity waves originating in the troposphere [Lindzen, 1981].

Davis and Johnson [2005] found that the ionospheric sporadic $E$ layer can be modulated by the lightning-associated GWs. Convective instability above storm clouds can generate GWs that propagate vertically, and these have been observed in the mesosphere [Sato, 1992]. It takes 34 h to observe the ionospheric response in the $E_s$ layer, so the lightning-associated enhancement of the $E_s$ at Sanya may not be due to a direct influence of lightning. Next, given that tides play a decisive role in forming $E_s$ layers [Wu et al., 2005], it is likely that an indirect lightning-associated GWs mechanism acts upon the $E_s$ layer, through the modulation of atmospheric tides. GWs can intervene and alter the regular tidal forcing of $E_s$-forming process in reinforcing or disrupting its course and therefore could be responsible for the irregular variability in $E_s$ [Haldoupis, 2012]. The sign of modulation of tides could be found from a significant peak of $\delta f_o E_s$ and a peak again after around 1 day in Figures 6m and 8g as well as a decrease in $\delta h'E_s$.

Clearly our results could provide potential evidence that the magnitude of the lightning-associated enhancement of the $E_s$ layer is likely associated with lightning stroke energy. Davis and Johnson [2005] pointed out that the ionization potentials of metal atoms are considerably lower than those of gas species, which makes it easier for any electrical discharge induced by lightning to affect the metallic ions within the $E_s$ layer. The formation of the $E_s$ layer is associated with the abundant meteoric metal in the mesosphere/lower thermosphere (MLT) being modulated by the wind shear theory [Whitehead, 1989; Plane et al., 2003; Kopp, 1997]. Studies have shown the temporal and spatial relationship between enhanced metal atoms and the $E_s$ layer [Gardner et al., 1993; Dou et al., 2010; Delgado et al., 2012; Dou et al., 2013].
Furthermore, over time, more WWLLN-determined energy data will be available to investigate the correlation between lightning stroke energy and lightning-associated enhancement of $E_s$ layer. The responses of the $E_s$ layer and the sporadic metal layer in MLT region as well as their dynamical process with the influence of lightning on a globe scale should be further studied in the future.

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