LETTERS

Lightning-induced intensification of the ionospheric sporadic E layer

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A connection between thunderstorms and the ionosphere has been hypothesized since the mid-1920s[1]. Several mechanisms have been proposed to explain this connection[2–7], and evidence from modelling[8] as well as various types of measurements[9–14] demonstrate that lightning can interact with the lower ionosphere. It has been proposed, on the basis of a few observed events[15], that the ionospheric 'sporadic E' layer—transient, localized patches of relatively high electron density in the mid-ionosphere E layer, which significantly affect radio-wave propagation—can be modulated by thunderstorms, but a more formal statistical analysis is still needed. Here we identify a statistically significant intensification and descent in altitude of the mid-latitude sporadic E layer directly above thunderstorms. Because no ionospheric response to low-pressure systems without lightning is detected, we conclude that this localized intensification of the sporadic E layer can be attributed to lightning. We suggest that the co-location of lightning and ionospheric enhancement can be explained by either vertically propagating gravity waves that transfer energy from the site of lightning into the ionosphere, or vertical electrical discharge, or by a combination of these two mechanisms.

The Arrival Time Difference system of the UK Meteorological Office[16] was used to identify lightning that occurred within the field of view of the ionospheric monitoring station at Chilton, UK, between 1993 and 2003. The system identifies broadband radio noise emitted by lightning discharges known as sferics, and is able to estimate the position of lightning to within 5 km over the UK. Hourly ionospheric measurements are made using a digital ionospheric sounder (digisonde)[17] from which a series of short-wave radio pulses are transmitted (typically 1–15 MHz in 100-kHz steps). Reflection occurs when the plasma frequency of the ionospheric electrons matches the radio frequency. The plasma frequency, f_p (in MHz) is related to the number density of the electrons, N_e (in m^{-3}), by the formula $f_p = 8.98\sqrt{N_e}$.

The most common cause of sporadic E (E_s) ionization at mid-latitudes is through meteoric metal atoms that are deposited over a broad range of heights around 100 km (refs 18, 19). The small fraction of these atoms that become ionized are relatively long-lived[19] (several hours), so it is possible for them to be concentrated by tidal forces and wind shears into thin, dense layers[18]. The localized nature of the meteor showers means that these layers are often patchy. The intensity of an E_s layer is parameterized in two ways: by the peak plasma frequency (ordinary mode), f_{oEs}, which is a measure of the densest patches of ionization within the layer, and the blanketing frequency, f_{bEs}, which corresponds to the lowest frequency that can penetrate the layer and is therefore a measure of the electron number density in the weakest patches. The height of an E_s layer (obtained from the flight time of the radio signal, assuming it is travelling through free-space), h'_{Es}, is inferred from the time-of-flight of the radio pulse. This apparent or 'virtual' height can be artificially increased by up to about 2 km if underlying ionization delays the propagation of the radio pulse.

For the period of the current study, 3,874 hours were identified in each of which there was at least one lightning event. The average behaviour of three ionospheric parameters was investigated for 160 hours either side of the lightning events in a superposed epoch analysis. This technique is frequently used with geophysical data to identify repeatable but weak responses to a given phenomenon[20,21]. E_s ionization exhibits strong seasonal and diurnal trends[18], which are likely to be much larger than any effect due to lightning. These trends

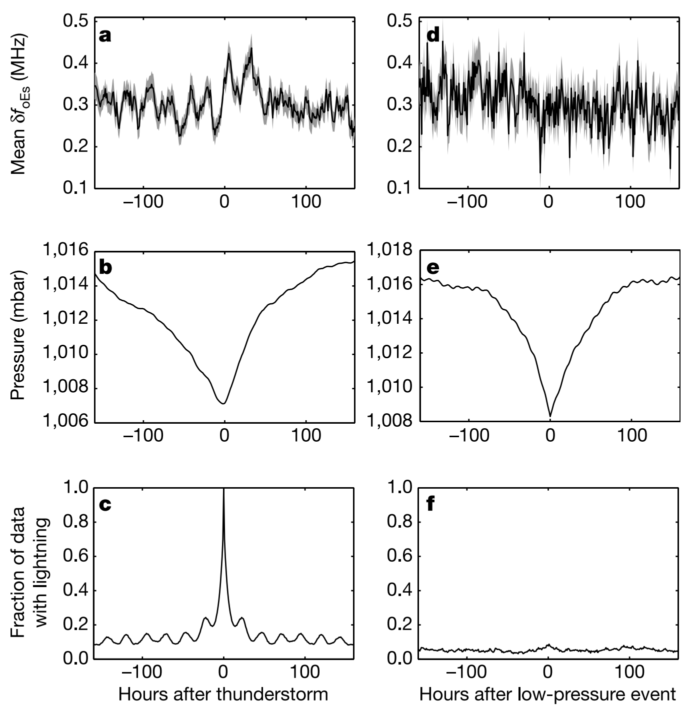

Figure 1 | Superposed epoch analyses for lightning and low-pressure events. Mean δf_{oEs} values are shown in **a** and **d** as a black line, with the standard error in these mean values (calculated from the standard deviation of each mean divided by the square root of the number of points in that mean) represented by the width of the grey shaded area about this line. When calculating δf_{oEs}, it is desirable to subtract the 30-day median rather than the 30-day mean, because it is less sensitive to outliers. The resulting δf_{oEs} values are positive because the median is less than the mean for the f_{oEs} distribution, because the distribution has large positive outliers. The average drop in pressure shown in **b** and **e** is of the order of 7 mbar (corrected to sea level). The fraction of data containing lightning in each hourly bin is shown in **c** and **f**. The number of hours containing lightning data was restricted for each pressure event, resulting in a flat distribution of lightning events (**f**).

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would dominate the study, especially as the lightning events are not randomly distributed in time (most lightning occurs on summer afternoons). To minimize the effects of these trends, therefore, the parameters δf_{oEs}, δf_{bEs} and $\delta h'_{Es}$ were defined. These are the difference between any hourly values of f_{oEs}, f_{bEs} and h'_{Es} and the median value for that hour (calculated from 30 days of data around each data point). In this way, the method becomes sensitive to deviations from the diurnal and seasonal trends rather than to the trends themselves.

Figure 1a shows the average response in δf_{oEs} to lightning. An enhancement in δf_{oEs} is seen 6 hours after lightning and again after 30 hours (the exact time of the ionospheric response may be masked by the residual diurnal variation in the data). Relative to the null hypothesis, these enhancements are significant at the 98.1% and 99.65% levels, respectively (that is, the probability that these enhancements arose by chance are 0.019 and 0.0035, respectively). The average atmospheric pressure associated with the lightning (Fig. 1b) decreases by 7 mbar. Figure 1c displays the fraction of data containing lightning in each hourly bin. Thunderstorms rarely occur in isolation, and although the data have been arranged so that there will always be a lightning strike at time zero, additional strikes may occur either side of this. A 24-hour recurrence of thunderstorms can clearly be seen in Fig. 1c.

Some previous studies have investigated the relationship between air pressure and E_s enhancements, with conflicting results[4,5,22,23]. To test whether E_s enhancements seen over Chilton are caused by the passage of low-pressure systems, 1,331 such events were identified in atmospheric pressure readings taken at Chilton. The subsequent response of E_s was then studied in a second superposed epoch analysis. To ensure that the effects of lightning did not dominate any ionospheric response to the pressure events, the number of lightning strikes coincident with each pressure event was restricted to fewer than 29 within 64 hours of each event. No significant response in δf_{oEs} (Fig. 1d) is seen as a result of low-pressure events, despite the average pressure variation (Fig. 1e) closely matching that associated with lightning (Fig. 1c). Wilson[1] speculated that the ionospheric electric field generated by a large rain cloud may be sufficient to induce ionization at ionospheric altitudes without lightning. The fact that there is no noticeable enhancement in E_s for low-pressure events without lightning is evidence that lightning is necessary to enhance the E_s layer significantly. It is interesting to note that the residual diurnal variation in δf_{oEs} (Fig. 1d) is not as strong as for the E_s response to lightning (Fig. 1a). Even when the pressure events in Fig. 1e were limited to times with a distribution similar to that of thunderstorm occurrence (most occurring during summer afternoons), no obvious diurnal component in δf_{oEs} emerged, despite the non-uniform diurnal distribution of pressure events. It is therefore reasonable to conclude that the diurnal variation seen in Fig. 1a is, at least in part, caused by the 24-hour recurrence of thunderstorms within the data (Fig. 1c) rather than by pressure.

Although a significant ionospheric response to lightning has been found, such an average response could be generated by a small and consistent response or by a few large and dominant responses. To distinguish between these possibilities, the distribution of δf_{oEs} values in the two days before each lightning event was compared with that seen in the two days afterwards. Any difference between these two (approximately gaussian) distributions represents a change due to lightning. This difference shows up well if the pre-lightning distribution is subtracted from the post-lightning distribution as shown in Fig. 2. Any bins with negative totals represent a decrease of such δf_{oEs} values correlated with the occurrence of lightning. Conversely, bins with positive totals represent an increase in occurrence of such δf_{oEs} values. Figure 2 therefore shows that previously small values of $|\delta f_{oEs}| < 0.5$ MHz are enhanced to values between 0 and 2 MHz. The total number of f_{oEs} values observed after lightning is 2.1% higher than the total number before, indicating that, although existing layers are enhanced, few sporadic E layers are generated by lightning. A mechanism for intensifying the ionization, such as wind shear or wave action, must already be present.

We next investigated changes to the blanketing frequency, δf_{bEs}, and to the height of the E_s layer, $\delta h'_{Es}$, in response to lightning. The average responses of these parameters are shown in Fig. 3, along with histograms equivalent to those in Fig. 2. There is only one enhancement in δf_{bEs} (significant at the 99.2% level), about 30 hours after the lightning stroke (Fig. 3a). There is a decrease in $\delta h'_{Es}$ (Fig. 3c) of around 1 km, significant at the 99.5% level. This may represent an underestimate of the real drop in height, as any lightning-induced ionization below the E_s layer would retard the radio pulse used to estimate the layer height.

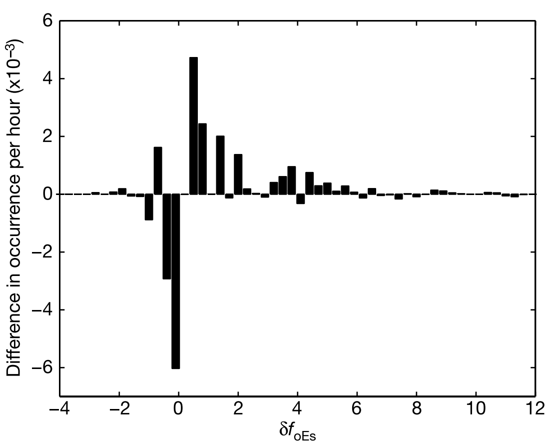

Figure 2 | Redistribution of δf_{oEs} values as a result of lightning. The distribution of δf_{oEs} values for the 48 hours before lightning events was subtracted from the distribution of δf_{oEs} values measured up to 48 hours after lightning events. The distributions were divided by the total number of hours examined (48 per thunderstorm for each distribution) to give occurrence per hour. A 2.1% rise in the occurrence of E_s after lightning results in the sum of positive bins being slightly larger than the sum of negative bins.

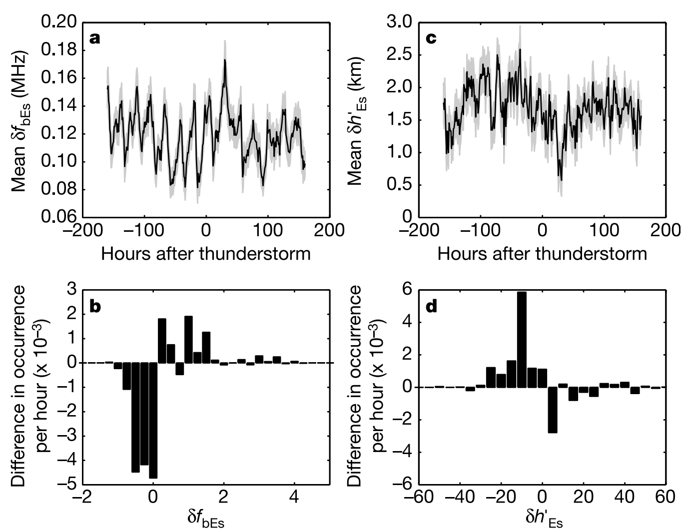

Figure 3 | Change in blanketing frequency and E_s layer height in response to lightning. The response to the same 3,874 thunderstorm events of the sporadic E blanketing frequency, δf_{bEs} (**a**, **b**), and the height of the E_s layer, $\delta h'_{Es}$ (**c**, **d**). The lines and shaded areas for **a** and **c** are the same as Fig. 1a, d but for values of δf_{bEs} and $\delta h'_{Es}$, respectively. The average δf_{bEs} value is enhanced 30 hours after lightning. **b**, **d**, Same as Fig. 2 but for changes in the distribution of δf_{bEs} and $\delta h'_{Es}$, respectively. Again, it can be seen that the average response to lightning is small but consistent, with no one event dominating either distribution.

Although gross pressure changes have been ruled out as the cause of the ionospheric enhancements seen in this study, lightning-associated wave activity could be responsible. A propagation time of six hours from cloud top to ionosphere represents a wave propagating at a velocity of around $5\,m\,s^{-1}$, which is typical for the vertical component of such a gravity wave generated in the troposphere[24]. Mesospheric wind measurements are known to exceed modelled predictions[25], and this is thought to be due to gravity waves transporting energy from the troposphere.

A method for producing localized intensifications in E_s through wave action has already been proposed[26]. If such a mechanism were solely responsible for localized enhancements in E_s through horizontal redistribution of existing ionization, no additional ionization would be created, and while δf_{oEs} would increase, δf_{bEs} may be expected to decrease as ionization from weaker patches within the layer was gathered up into the enhanced patches. No such decrease in δf_{bEs} was detected in the present study.

Because the horizontal wavelength is greater than the vertical wavelength in the mechanism[26] proposed above, waves modulating the ionosphere above Chilton would need to be generated in the troposphere beyond a horizontal distance of 100 km in order that the vertical component might reach ionospheric altitudes by the time the wave had reached Chilton. To find the optimum location for lightning to influence E_s above Chilton, δf_{oEs} data were binned according to the bearing and distance of the lightning. No significant direction dependence was found, and the ionospheric response was insensitive to distance for lightning within 100 km, decreasing with distance beyond 100 km. This indicates that this particular mechanism is unlikely to be responsible for the observed enhancement, although it does not rule out wave action completely. Convective instability above storm clouds can generate gravity waves that propagate vertically, and these have been observed in the mesosphere[27]. Instabilities have also been shown to be generated in the ionosphere by lightning modulating the ambient electric field there[28], and there is evidence that very-low-frequency waves launched by lightning can induce further lightning[29].

Optical emissions known as blue jets, associated with sferics[9], have been seen to propagate from cloud tops to an altitude of 70 km, and gravity waves associated with other upward-propagating optical features, called sprites, have been seen in the mesosphere[10]. Gravity waves launched from this altitude would take considerably less time to propagate 30 km vertically to the E_s layer. Measurements suggest[10] that such waves propagate upwards at an angle of around 27° and would therefore reach the E_s layer within a radius of 15 km from the thunderstorm, consistent with our observations.

Measurements of ionospheric electric fields above storm clouds (typically $20\,mV\,m^{-1}$)[13,14] have been significantly less than those estimated to be required for electrical discharge in the ionosphere[1] (in excess of $48\,mV\,m^{-1}$). This calculation[1] did not consider the presence of metallic atoms, which would undoubtedly lower the electric field necessary to cause electrical discharge, because their ionization potentials are significantly below those of gas species[30] (for example, 5.139 eV for Na compared with 12.06 eV for O_2).

The results presented here show a statistically significant enhancement of the ionospheric E_s layer due to lightning. The localized nature of this enhancement is evidence that the mechanism involved acts vertically, either through electrical discharge or wave action, or a combination of both. The fact that few E_s layers are created as a result of lightning is evidence that a wind shear must also be present. Indeed, gravity waves launched by lightning may even act to enhance this wind shear[29,30].

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