The location of lightning affecting the ionospheric sporadic-E layer as evidence for multiple enhancement mechanisms

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[1] We present a study of the geographic location of lightning affecting the ionospheric sporadic-E (Es) layer over the ionospheric monitoring station at Chilton, UK. Data from the UK Met Office's Arrival Time Difference (ATD) lightning detection system were used to locate lightning strokes in the vicinity of the ionospheric monitoring station. A superposed epoch study of this data has previously revealed an enhancement in the Es layer caused by lightning within 200km of Chilton. In the current paper, we use the same data to investigate the location of the lightning strokes which have the largest effect on the Es layer above Chilton. We find that there are several locations where the effect of lightning on the ionosphere is most significant statistically, each producing different ionospheric responses. We interpret this as evidence that there is more than one mechanism combining to produce the previously observed enhancement in the ionosphere. **Citation:** Johnson, C. G., and C. J. Davis (2006), The location of lightning affecting the ionospheric sporadic-E layer as evidence for multiple enhancement mechanisms, *Geophys. Res. Lett.*, *33*, L07811, doi:10.1029/2005GL025294.

1. Introduction

[2] *Davis and Johnson* [2005] compared data from the ionospheric monitoring station at Chilton, UK with data from the Arrival Time Difference (ATD) lighting detection system of the UK Meteorological Office [*Lee*, 1989] and revealed an enhancement of the ionospheric sporadic-E (Es) layer in response to lightning. An Es layer can be characterised by three parameters; the critical frequency of the layer, foEs, is a measure of the maximum radio frequency each layer can reflect. This value is, in turn, related to the peak electron concentration within the layer by $f = 8.98 \times \sqrt{Ne}$ where f is the radio frequency of the sounding pulse (in Hz) and Ne is the electron concentration per cubic metre. The blanketing frequency, fbEs, is a measure of the lowest radio frequency that the Es layer can reflect and is a measure of the weakest patches of ionisation within the layer. The virtual height, h'Es, is estimated from the time-of-flight of the radio pulse. This is not a true height since interaction with underlying ionisation artificially increases the apparent, or "virtual" height of the layer. Since photo-ionisation is the dominant production mechanism for ionisation within the Es layer, the electron concentration of this layer exhibits strong diurnal and seasonal variation. In order that these cyclic variations did not dominate the subsequent analysis, monthly median values were subtracted from each parameter (creating variables denoted as δfoEs, δh′Es and δfbEs) before events were combined in a superposed epoch study using the occurrence of lightning as the trigger event. It was found that, on average, there was an enhancement in δfoEs at six and thirty hours after a lightning stroke, an enhancement in δfbEs thirty hours after a lightning stroke and a decrease in δh'Es six hours after a lightning stroke. It is difficult to use the observed time delays to infer much about the mechanisms involved, however, as this response is modulated by a residual diurnal variation in the data which results from the non-random distribution of lighting strokes throughout the day (most lightning in the UK occurring on summer afternoons). A first, simplified, method used at the time revealed no direction dependence and a weak distance dependence for lightning strokes causing this enhancement. We present here a more thorough analysis of the effect the position of a lighting stroke has, relative to the ionospheric sounder, on the magnitude of the enhancement seen in the same ionospheric parameters and discuss evidence for several possible mechanisms that may be at work.

2. Method

[3] The original data set of 3874 lightning events is here extended to 5142 by the inclusion of data from the year 2000 which was previously unavailable. The magnitude of the effect in the ionosphere for each lightning stroke was characterised by the difference between δfoEs values averaged over 48 hours before each lightning stroke and the corresponding averages of δfoEs values measured for 12-hour periods after each lightning stroke. By measuring the average response in δfoEs at a series of time delays (averaging from 0–12 hours, 6–18 hours, 12–24 hours etc., after each lighting stroke) and noting the geographic position of each lightning stroke, it was possible to build up a picture of the location - in both time and space - of those lightning strokes which caused an effect on the Es layer above Chilton. If the time resolution is increased, the number of data points used to calculate the magnitude of the response becomes too small and increased noise causes the response to become statistically less significant. While the difference between δfoEs values before and after a lighting stroke gives an indication of the magnitude of the effect, it does not take into account the variability caused by other means within the δfoEs time series. The significance of each response will depend on the background variability of the data: given two responses of identical magnitude, the one which deviates most from the background variability observed during the event ought to be considered the more significant. The magnitude of each response was therefore compared with the distribution of the δfoEs data 160 hours either side of the lightning event in order to calculate the

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significance of the response in terms of the number of standard deviations from the mean. These values can be stated in terms of a significance value between 0.01 and 0.99 using the cumulative Gaussian probability function, the normality of the data having been checked using the Lilliefors normality test.

[4] The data were then combined in bins of equal area according to the position of the lightning stroke. Lightning strokes measured by the ATD system are accurate to within a horizontal position of 5 km over the UK [*Lee*, 1989]. A similar technique was also used to calculate the significance of responses in the other two parameters.

3. Results

[5] Figure 1 contains a series of maps, showing the position of lightning strokes relative to the position of the ionospheric measurement, with the significance of the resulting change in δfoEs, δfbEs and δh'Es represented in colour, corresponding to time intervals of twelve hours separated by six hours (from 0–12 hours - 6–18 hours, 12–24 hours after lightning etc (with time after lightning increasing down the page). The position of lightning is given relative to the Chilton monitoring station which is located in the middle of each plot. Each bin is represented by a coloured block, representing an area of 1650 km^2. The maps extend to 400 km from Chilton and are not symmetrical as a result of the limits of the data set, which covered only mainland UK. While the initial study by *Davis and Johnson* [2005] was limited to those lightning strokes occurring within the (200 km radius) field of view of the ionosonde, extending this to the limits of the data set reveals that lightning beyond this limit can also have a direct effect on the ionosphere above Chilton.

[6] Within the first twelve-hour bin, it can be seen that there are two distinct regions in which lightning has the most significant effect on the ionosphere above Chilton. To the north-west, lightning occurring at distances greater than 200 km is responsible for a significant early rise in δfoEs at times within 18 hours of the lightning event. At the same time, a region extending from directly below the ionospheric measurement and extending to the south and east is also responsible for a rise in δfoEs but in this region, the lightning responsible for the maximum ionospheric response is located within 100 km of Chilton. At 12–24 hours after lightning, the effect of lightning to the north-west and east begins to fade, while influence of the region extending from directly above Chilton to the south remains. By 24–36 hours after the lightning, this region appears to migrate northward, leaving an isolated patch to the south which gradually fades.

[7] δfbEs does not show such a strong response initially. It is only after 12–24 hours that a strong increase is seen, closely matching the area seen in the response of δfoEs extending from above the sounder to the south east. At the same time, lightning to the north is associated with a decrease in δfbEs but this response fades by 18–30 hours after lightning.

[8] The most significant response in δh'Es is an initial decrease in response to lightning from a broad region to the far north west (and to a smaller extent to the far south east) which fades by 12–24. This is then replaced by a decrease in δh'Es in response to lightning to the south west of Chilton by 18–30 hours, after which, most of the lightning to the east of Chilton causes a significant decrease in δh'Es. In contrast, a small region of lightning generates an initial increase in δh'Es over Chilton which by 12–24 hours has faded to be replaced by an increase in response to lightning to the far north. This, in turn, fades to be replaced by an increase due to lightning from the south east by 30–42 hours.

[9] It is important to make sure that the observed responses are not the result of some unseen bias in the data. *Davis and Johnson* [2005] have already shown that the average response seen in the ionospheric data is not dominated by one large event but is instead the consistent

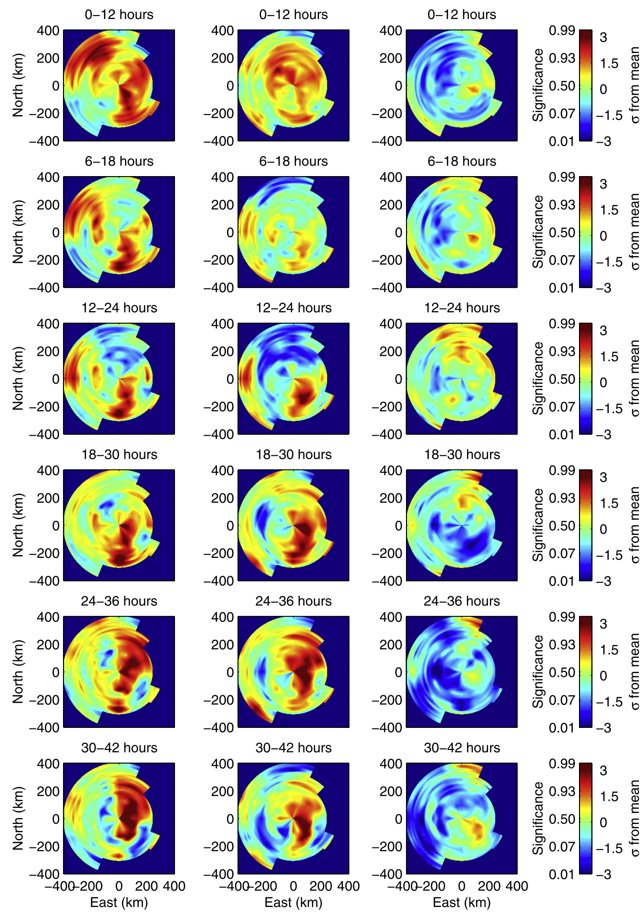

Figure 1. The geographic position of lightning strokes producing significant responses in Es parameters over Chilton, UK. The colour scale denotes "number of standard deviations from the mean" and extends from −3 (denoting a decrease in the parameter) to +3 (for an increase). This scale is also marked in the equivalent significance values ranging from 0.01 (a significant negative response) through 0.5 (no significant response) to 0.99 (a significant positive response). Each map represents an area 800 km square, centred on the ionospheric monitoring station at Chilton (51.7 N, 1.3 W). The left hand column denotes changes in δfoEs, the middle column δfbEs and the right hand column δh'Es. The data are presented in 12 hour bins at intervals of 6 hours. Time after lightning increases down the page.

signature of many smaller responses. There could also be a bias due to the number of lightning events across the field of view but the distribution, while not uniform, does not bear any resemblance to the position of the most significant lightning events.

[10] The spatio-temporal distribution of lightning strikes is non-uniform due to the localisation of storm clouds. This has the effect of introducing a dependence in the significance values of nearby spatial bins. To test this, the Chilton ionosonde data was replaced with data from an ionosonde in Stanley (Falkland Islands) and the significance of responses calculated using the same UK lightning data: a null result is obviously expected. The result showed some dependence between significances in adjacent spatial bins, caused by the non-uniform nature of the lightning strikes; however, the significances were much lower than for Chilton data (within expected values) and, unlike the Chilton data, showed no large-scale spatial features. We can conclude from this that the effect of a non-uniform lightning distribution on the significance plots is small.

4. Discussion

[11] Several mechanisms have been suggested to explain ionospheric enhancement due to energy transfer from the troposphere, from wave activity - both gravity and infrasonic [*Chimonas*, 1971; *Shesthra*, 1971; *Blanc*, 1985] - through to electrical effects associated with observed optical signatures (electro-magnetic pulses, electrical discharge or relativistic electrons) [e.g., *Wilson*, 1925; *Sentman et al.*, 2003; *Rodger et al.*, 2001; *Lehtinen et al.*, 1999]. Each of these mechanisms has distinct signatures in both the location and the nature of the resulting ionospheric enhancement and so this information can be used to distinguish between them.

[12] Gravity waves launched by lightning are expected to enhance foEs by concentrating existing ionisation in localised patches. Such waves have a small vertical component compared with their horizontal velocity and so would need to propagate for many hundreds of kilometres horizontally before reaching an altitude of 100 km where Es layers form. East-west gravity waves are expected to favour the formation of low Es layers, while northerly waves would be expected to favour the formation of higher Es layers [*Chimonas*, 1971].

[13] Both infrasonic waves, direct electrical discharge (in the form of sprites) and electro-magnetic pulses (EMPs, associated with elves) would be expected to act vertically from the thundercloud top to the ionosphere [*Blanc*, 1985; *Sentman et al.*, 2003; *Rodger et al.*, 2001]. Infrasonic waves would generate an increase in foEs by concentrating existing ionisation (either directly or by depositing energy thereby enhancing the wind-shear necessary to form an Es layer). Electrical discharge would increase foEs by creating more long-lived metal ions from the ambient population of meteoric metal atoms found at these altitudes. Sprites only extend to around 70km however, and are rarely seen over continental Europe, making enhancement due to direct electrical discharge unlikely.

[14] Elves are a more likely candidate since they extend to greater altitudes and recent modelling work has shown that the associated EMP can cause significant increases in the electron concentration of the lower ionosphere over a wide area above a lightning storm [*Rodger et al.*, 2001].

[15] While all these mechanisms could potentially enhance the local Es layer and therefore δfoEs values, they will have different effects on the background density of the Es layer, characterised by the blanketing frequency, fbEs. Localised enhancement of the layer by wave action would gather up existing ionisation into patches, weakening the background layer and so δfbEs values would be expected to decrease. A localised enhancement of the wind-shear by wave action or the deposition of energy by infrasonic waves at ionospheric altitudes would increase δfoEs values while leaving the peak density of adjacent weaker areas of the layer unaffected. Under these circumstances, δfbEs would remain unchanged. An electrical discharge would both increase δfoEs values locally by creating additional ionisation which, given the long life-times of metallic ions [*Plane et al.*, 2003], would eventually diffuse into the weaker patches of the layer, increasing the background ionisation of the layer and enhancing δfbEs. A very similar result would be expected for an EMP-induced enhancement, although the initial increase in δfoEs could occur over an extended area.

[16] While sprites themselves do not reach sufficient altitudes to directly affect the Es layer, gravity waves generated by sprites have been observed at an altitude of 70 km and such waves would be expected to reach an altitude of 100 km within 15 km horizontal distance of the source [*Sentman et al.*, 2003].

[17] Modelling work [*Lehtinen et al.*, 1999] carried out to explain observations of gamma rays produced in the Earth's atmosphere [*Fishman et al.*, 1994] suggest that relativistic electrons, released from cloud tops as a result of lightning discharge, travel upward from the top of the thundercloud where they emit gamma rays. This work suggests that the region of the upper atmosphere most affected would be to the south of the thundercloud in the northern hemisphere, due to the electrons being columnated by the magnetic field. If such excitation were also responsible for the ionisation of long-lived metal atoms, we would expect to see an enhancement in the Es layer to the south of the thundercloud.

[18] Applying these expected effects to our data, the mechanism for lightning strokes influencing the Es layer from a distance of several hundred kilometres is most likely to be gravity waves. Eastward propagating gravity waves from distant lightning to the north-west of Chilton would also be expected to influence the height of the Es layer. This is indeed what we see, with little or no influence on δh'Es from the lightning strokes seen above or to the south-east of Chilton until the influence of the lightning strokes to the north west has faded (after 16–22 hours). Gravity wave action would result in either a decrease or no change in δfbEs in association with the lightning strokes to the north-east and this is what we see, even initially when δfoEs values are strongly enhanced by strokes in this region.

[19] A direct electrical discharge or enhancement by a lightning induced EMP would result in an initial enhancement of δfoEs followed by a subsequent enhancement in δfbEs as any newly created ionisation is redistributed into the layer. It is this behaviour which most closely matches the response to lightning strokes in the region extending south from directly above the ionospheric sounder. The

more likely occurrence of elves over Europe combined with the extended nature of this region favours an EMP as the likely cause although the extended region could also be the result of a northward wind subsequently blowing ionisation into the field of view of the ionospheric sounder.

[20] There are no thunderstorms to the north of the ionospheric measurements which significantly enhance the sporadic E layer there (in other words, there are no storms creating an enhancement to the south) as would be expected for excitation by relativistic electrons [*Lehtinen et al.*, 1999]. A neutral wind could account for this difference but such a systematic wind field over ten years' worth of data is unlikely. The distribution of terrestrial gamma ray flashes observed by the RHESSI spacecraft shows very few at the high latitudes of the UK. The combination of these two factors makes it unlikely that this mechanism is the cause of any of the observed ionospheric enhancements.

[21] While the results presented above provide evidence that both gravity waves and EMPs act to influence the ionospheric Es layer in response to lightning, it does not rule out a role for other potential mechanisms such as direct electrical connection, infrasound or ionisation by relativistic electrons. It is possible to observe changes in Es layer ionisation with routine hourly measurements because of the long lifetimes of metal ions in the layers but higher time resolution measurements are desirable in order to resolve the difference between mechanisms with an instantaneous response and those where a specific time delay is expected. While the majority of Es layers observed with the Chilton ionosonde are likely to be within a few tens of kilometres, information regarding the relative position of the Es layer within the field of view of the ionosonde would remove this ambiguity. Similarly, information about the mesospheric and thermospheric wind-field throughout the period of study would help to deconvolve any systematic effect they may introduce, particularly if the formation of Es layers takes several hours.

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References

Blanc, E. (1985), Observations in the upper atmosphere of infrasonic waves from natural or artificial sources: A summary, *Ann. Geophys.*, *3*, 673–688.

Chimonas, G. (1971), Enhancement of sporadic E by horizontal transport within the layer, *J. Geophys. Res.*, *76*, 4578–4586.

Davis, C. J., and C. G. Johnson (2005), Lightning induced intensification of the ionospheric sporadic *E* layer, *Nature*, *435*, 799–801.

Fishman, G. J., et al. (1994), Discovery of intense gamma-ray flashes of atmospheric origin, *Science*, *265*, 1313–1316.

Lee, A. C. L. (1989), Ground truth confirmation and theoretical limits of an experimental VLF arrival time difference lightning flash location system, *Q. J. R. Meteorol. Soc.*, *115*, 1147–1166.

Lehtinen, N. G., et al. (1999), Monte Carlo simulation of runaway MeV electron breakdown with application to red sprites and terrestrial gamma ray flashes., *J. Geophys. Res.*, *104*, 24,699–24,712.

Plane, J. M. C., et al. (2003), Laboratory studies and modelling of mesospheric iron chemistry, *Adv. Space Res.*, *32*, 699–708.

Rodger, C. J., et al. (2001), Lower ionosphere modification by lightning-EMP: Simulation of the night ionosphere over the United States, *Geophys. Res. Lett.*, *28*, 199–202.

Sentman, D. D., et al. (2003), Simultaneous observations of mesospheric gravity waves and sprites generated by a midwestern thunderstorm, *J. Atmos. Sol. Terr. Phys.*, *65*, 537–550.

Shesthra, K. L. (1971), Sporadic-*E* and atmospheric pressure waves, *J. Atmos. Terr. Phys.*, *33*, 205–211.

Wilson, C. T. R. (1925), The electric field of a thundercloud and some of its effects, *Proc. Phys. Soc.*, *37*, 32–37.

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