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Lightning as a space-weather hazard: UK thunderstorm activity modulated by the passage of the heliospheric current sheet

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Key Points:

- UK lightning is enhanced when the Earth intersects the heliospheric current sheet
- Lightning rates depend on the polarity of the heliospheric magnetic field
- Associated changes in the energetic particle populations are complex

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Abstract Lightning flash rates, R_L, are modulated by corotating interaction regions (CIRs) and the polarity of the heliospheric magnetic field (HMF) in near-Earth space. As the HMF polarity reverses at the heliospheric current sheet (HCS), typically within a CIR, these phenomena are likely related. In this study, R_L is found to be significantly enhanced at the HCS and at 27 days prior/after. The strength of the enhancement depends on the polarity of the HMF reversal at the HCS. Near-Earth solar and galactic energetic particle fluxes are also ordered by HMF polarity, though the variations qualitatively differ from R_L, with the main increase occurring prior to the HCS crossing. Thus, the CIR effect on lightning is either the result of compression/amplification of the HMF (and its subsequent interaction with the terrestrial system) or that energetic particle preconditioning of the Earth system prior to the HMF polarity change is central to solar wind lightning coupling mechanism.

1. Introduction

Lightning is of interest to a wide range of disciplines from atmospheric chemistry to studies of aviation hazards and forest fire management. It has long been speculated that there exists a (causal) link between solar activity and terrestrial thunderstorm activity [*Brooks*, 1934; *Stringfellow*, 1974]. The prime focus has been on long-term trends (months to years), in particular a covariance between lightning rates and the solar cycle, although both in-phase [*Stringfellow*, 1974; *Schlegel et al.*, 2001] and antiphase [*Chronis*, 2009; *Pinto Neto et al.*, 2013] relations have been reported, which may be a result of lightning in different geographic locations responding differently to solar variations or other solar modulations of the climate system. Lightning rates have traditionally been compared with sunspot number or galactic cosmic ray (GCR) intensity at Earth. Recently, rapid modulation (hours to days) of lightning by solar wind conditions has been reported. *Scott et al.* [2014] demonstrated an increase in daily means of UK lightning following the passage of corotating interaction regions (CIRs) in near-Earth space. CIRs form when fast solar wind encounters slower wind ahead of it and compresses the solar wind plasma and heliospheric magnetic field (HMF). CIRs can also be associated with moderate solar energetic particle (SEP) acceleration [e.g., *Mason et al.*, 1999] and modulation of higher energy GCRs [e.g., *Richardson*, 2004; *Rouillard and Lockwood*, 2007]. *Scott et al.* [2014] speculated that the increase in lightning activity was the result of the observed variations in SEP and GCR flux incident on Earth following the passage of CIRs, potentially through changes to the atmospheric conductivity, and hence, atmospheric electric circuit [e.g., *Wilson*, 1921]. *Owens et al.* [2014] also looked at UK lightning but as a function of the heliospheric magnetic field (HMF) polarity. They reported a large (~50%) difference in average lightning rates between days when the HMF was pointing toward from the Sun compared to days when it pointed away. They speculated that this trend was the result of different HMF polarities perturbing the atmospheric electric circuit through both changing the local ionospheric potential and shifting the atmospheric foot points of various magnetospheric energetic particle precipitations.

In this study we use high resolution (hourly) measurements of UK lightning flash rates to investigate the degree to which the *Owens et al.* [2014] and *Scott et al.* [2014] results may be manifestations of the same physical mechanisms. Regions of opposing HMF polarity are separated by the heliospheric current sheet (HCS) which is nominally located within the band of slow solar wind [e.g., *Owens and Forsyth*, 2013]. Thus, the HMF polarity typically reverses within a CIR. Here we investigate the occurrence of lightning relative to the passage of the HCS past Earth, separating out toward-to-away and away-to-toward HMF transitions in order to determine whether solar wind, heliospheric magnetic field, or energetic particle variations are principally responsible.

2. Data

High time resolution (1 day and below), long-term studies of thunderstorm activity are best performed using data from a radio network. The UK Met Office's Arrival Time Difference (ATD) network of radio receivers in Western Europe [*Lee*, 1989] detects the very low frequency (~3–30 kHz) component of broadband emission from lightning and uses the relative timing between antennas to determine location. The ATD system is primarily sensitive to cloud-to-ground lightning over Europe but does detect lightning worldwide with reduced sensitivity. As in *Scott et al*. [2014] and *Owens et al*. [2014], the lightning data used here have been restricted to events within a radius of 500 km of central England in order to ensure uniformity of measurements and enable more direct comparison with the independent UK-based thunder-day data. Ongoing development of radio detection systems also influences the stability of lightning detection thresholds. Between September 2000 and May 2005, however, the ATD system was not subject to any modifications affecting its sensitivity. During May 2005–May 2007, there were only minor changes, increasing the average lightning flash rate by around 50%. As in *Owens et al*. [2014], we include latter period in this study by normalizing flash rates after May 2005 by 0.64, the observed scaling factor in the annual mean lightning flash rates in 10 January 2001–10 January 2004 and 5 January 2005–5 January 2007. (We note that our results are largely unchanged whether these later data are included or not.) As an independent estimate of UK thunderstorm activity, we also use records of audible thunder from manned UK Met Office stations. While this is a low time resolution and low dynamic range measurement, it serves as a vital validation of radio observations which is not subject to the ionospheric effects that could potentially affect lightning flash rates measured by radio networks [e.g., *Reuveni and Price*, 2009].

Figure 1 summarizes the hourly lightning flash rates, R_L, used in this study (i.e., over the period September 2000 to May 2007). Figures 1a and 1d clearly show a strong seasonal variation, peaking strongly in June–August. Figure 1f shows the seasonal trend in $R_{\mathrm{TH},}$ the fraction of manned UK Met Office stations which recorded thunder on a given day. This lower resolution and lower dynamic range measurement of thunderstorm activity shows the same basic seasonal trend as R_L. Both R_L and R_{TH} exhibit a drop in thunderstorm activity around early July (i.e., day of year ~190). This is not currently well understood and merits further study but is likely to be the result of a period of increased atmospheric stability over the UK, relative to the early June regime of cold airflow from a cold sea over an increasingly warm land and the late July regime of more organized storms when the land is at its warmest. Increasingly stable measurement networks will allow this feature to be investigated climatologically.

Figures 1a and 1b show that, in common with other locations, UK thunderstorm activity exhibits a strong diurnal variation, peaking in midafternoon/early evening as a result of peak surface heating and hence convective available potential energy (CAPE) in the atmosphere [e.g., *Dwyer and Uman*, 2014, and references therein]. The early morning rise in $\mathrm{R_L}$ around 5 A.M. in the summer months could be an artifact of the ATD system being affected by detection efficiency changing between night and sunlit hours, as a result of radio wave reflection by the ionosphere [*Bennett et al*., 2011]. In the *Scott et al*. [2014] and *Owens et al*. [2014] studies, issues of natural diurnal variations and ATD detection efficiency were not relevant to the daily means of the ATD lightning flash rates used.

Heliospheric magnetic field (HMF) and solar wind parameters are taken from OMNI data set of near-Earth spacecraft observations [*King and Papitashvili*, 2005]. Times of near-Earth heliospheric current sheet (HCS) encounters are obtained from the catalog of *Thomas et al*. [2014]. They manually identified "clean" HCS crossings, in which there is a clear, sharp transition in HMF polarity from a Parker spiral configuration [*Parker*, 1958] pointing toward (T) the Sun to away from the Sun (A) or vice versa. They excluded polarity reversals which take the form of an extended, slow rotation in magnetic field direction, such as when the HCS is accompanied by a coronal mass ejection [*Crooker et al*., 1998]. In the 2000.7 to 2007.3 interval used in this study, there are 141 such HCS crossings, approximately 1.5 per solar rotation. Sixty-six of these HCS crossings are transition from T to A polarity (i.e., $B_Y < 0$ to $B_Y > 0$), while 75 A to T transitions. For both sets of HCS crossings, there is a uniform distribution of occurrence time as a function of both time of day and day of year; thus, there is little risk of aliasing with the known R_L and R_{TH} variations.

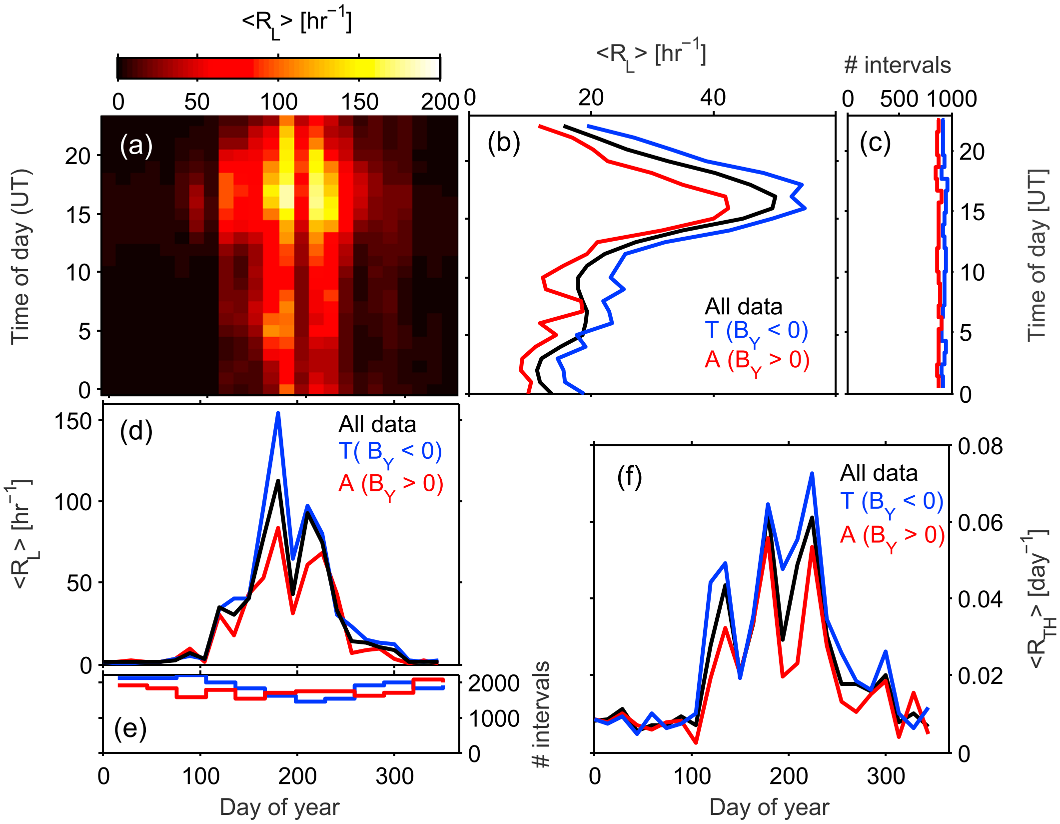

Figure 1. Climatology of hourly ATD lightning flash rates (R_L) over the interval 2000.7 to 2007.3, within 500 km of central England. (a) A color map of $<R_L>$ as a function of time of day and day of year; (b) $<R_L>$ as a function of time of day, in hourly bins. Black shows all data, blue shows hourly intervals with $B_Y < 0$ (toward polarity), red shows $B_Y > 0$ (away polarity); (c) The occurrence of T and A intervals as a function of time of day; (d)$<R_L>$ as a function of day of year, in approximately 15 day bins, in the same format as Figure 1b; (e) The occurrence of T and A intervals as a function of day of year; (f) the fraction of manned UK stations reporting thunder (R_{TH}), in the same format as Figure 1d.

3. Results

In order to demonstrate the suitability of hourly R_L for the study of space effects, we first repeat the analysis of *Owens et al.* [2014] with these data, separating individual hours into either toward (T, taken to be $B_Y < 0$ in geocentric solar ecliptic coordinates) or away (A, taken to be $B_Y > 0$) polarity heliospheric magnetic field. We find the mean R_L for all data to be 25.3 h^{-1}, while the mean R_L for A and T intervals is 20.2 and 30.1 h^{-1}, respectively. (We note that if the data are divided into two equal halves, these trends persist.)

Next, we test our null hypothesis that the two A and T distributions of lightning rates are in fact subsamples of the same underlying distribution and that the difference in mean lightning rates is merely the result of chance sampling. We use an autoregressive model [*Wold*, 1954] to produce a random B_Y time series with the observed autoregressive properties out to 130 h, where the observed autoregression first becomes insignificant. This random time series is used to define new T and A periods, from which new mean R_L values are computed. Taking a Monte Carlo approach, this process is repeated 1000 times. Of these random samplings, only 38 exhibit a larger difference in A and T mean R_L than that observed; thus, the null hypothesis has $p = 0.04$ and can be rejected at the 95% confidence level. The two-sample, nonparametric Kolmogorov-Smirnov test also finds $p < 0.05$ for the null hypothesis. This is in general agreement with the results of *Owens et al.* [2014] based on daily means, though this significance is slightly lower owing to the better treatment of autoregression in the data. Figure 1b shows that the T intervals (blue) show higher R_L than the data set as a whole (black), throughout the day. Similarly, the A intervals show lower R_L than the data set as a whole. Figure 1c shows there are no systematic trends in the occurrence of T and A intervals throughout the day, suggesting the difference in T and A lightning rates is not simply the result of ATD detection efficiency.

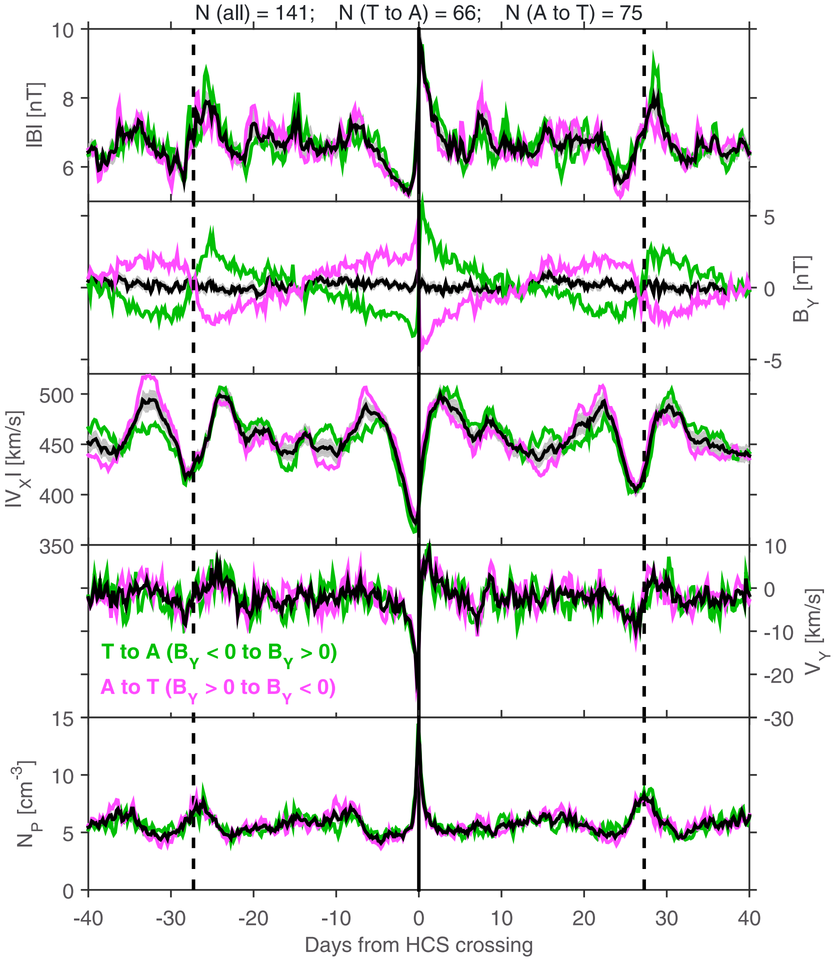

Figure 2. A superposed epoch analysis of solar wind properties about heliospheric current (HCS) crossings in the interval 2000.7 to 2007.3. All 141 events are shown in black, with grey-shaded regions showing one standard error on the mean. Green lines show HCS crossings in with the heliospheric magnetic field (HMF) transitions from toward to away polarity (i.e., $B_Y < 0$ to $B_Y > 0$). Pink shows A to T transitions. Vertical dash lines show 27.27 days from the HCS crossing. Figures show, from top to bottom: The HMF intensity, the HMF B_Y, and the solar wind flow speed, the V_Y component of the flow and the solar wind density.

Figure 1d shows T intervals have enhanced R_L relative to A throughout the year. Figure 1e shows the occurrence of T and A intervals throughout the year. Unlike the daily data, there is a weak trend in these hourly data, but for fewer T intervals during the summer months, when R_L is enhanced. This further suggests the difference in thunderstorm activity in T and A HMF is not simply a result of aliasing between T and A occurrence and the seasonal variation in thunderstorm activity. The same trends in the independent R_{TH} data (Figure 1f) support this interpretation.

We now use these hourly data to investigate the behavior of thunderstorm activity as the heliospheric current sheet (HCS) passes through near-Earth space. Figure 2 shows a superposed epoch analysis of key near-Earth solar wind parameters about the HCS crossing times. The close association of the HCS with corotating interaction regions (CIRs) is clear: the magnetic field intensity and solar wind speed and density show a sharp rise at the zero epoch time, resulting from fast solar wind compressing the slow solar wind ahead of it. The solar wind flow direction is also deflected in the manner expected. Note that the magnitude of this flow deflection is smaller than was reported by *Scott et al.* [2014] for the same interval, as superposing the data about the magnetic field structure somewhat smears out this plasma signature. It is also possible that some of the large flow deflections in the *Scott et al.* [2014] study were the result of fast coronal mass ejections [*Owens and Cargill*, 2004], which have been specifically excluded from the present study. It can clearly be seen from

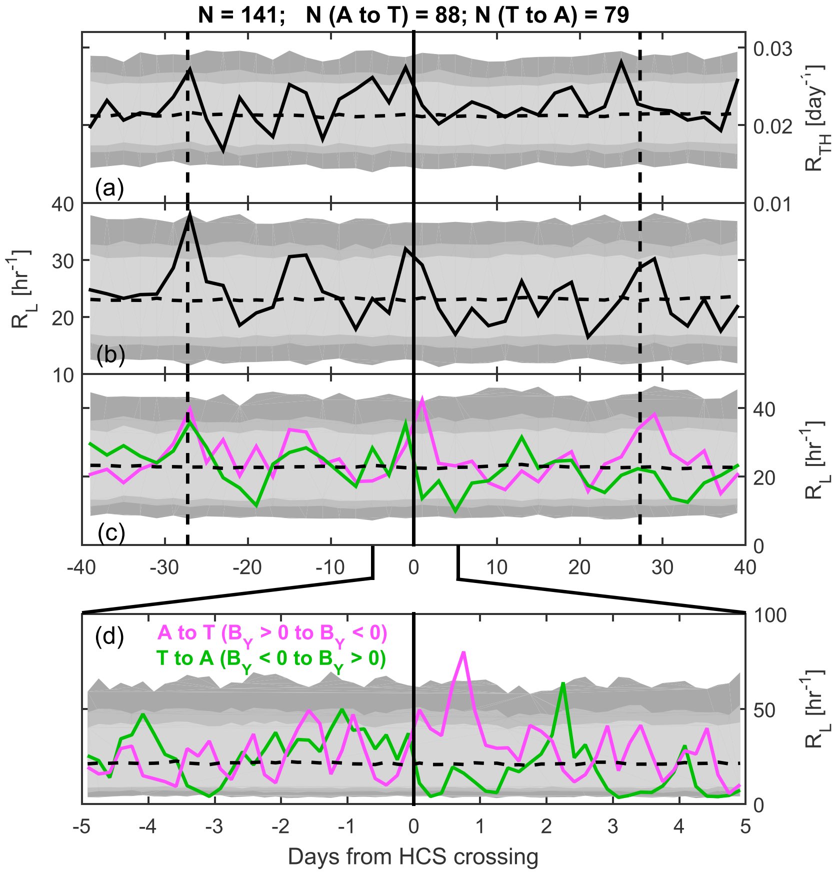

Figure 3. Superposed epoch plots of thunderstorm activity about HCS crossings for the period 2000.7 to 2007.3. Grey-shaded regions show 90%, 95%, and 99% confidence intervals from a Monte Carlo sampling of data, with the median shown as a near-horizontal black dashed line. Vertical dashed lines show ±1 synodic solar rotation period (27.27 days). (a and b) R_{TH} and R_L for all HCS crossings. (c and d) HCS crossings into A to T (pink) and T to A (green) transitions. Figures 3a to 3c use daily bins; Figure 3d uses hourly bins.

Figure 2 that HCS crossings and the associated solar wind structures repeat with an approximately 27.27 day periodicity. Other than the B_Y variation (and associated B_X variation, not shown), which is used to classify the sense of HMF polarity change at the HCS crossing, the T to A transitions do not show any significant differences to the A to T transitions in magnetic field intensity, solar wind flow speed or deflection, or solar wind density.

Figure 3 shows the same analysis for UK thunderstorm activity. Figures 3a and 3b show daily bins of thunder and lightning rates, respectively, about the 141 HCS crossings within the 2000.7–2007.3 period. The R_{TH} data are noisier than R_L, as expected, but in both cases there is a peak in thunderstorm activity around the time of the HCS crossing. This peak is localized to within 1–2 days around the zero epoch time. A similar enhancement is seen approximately 27 days before and after the HCS crossing, as in Figure 2. There is also a smaller peak around 13 days. This is likely the result of solar wind stream structure or HCS crossings resulting from "two sector" HMF (whereby the HCS is encountered twice per solar rotation) expected from a simple dipolar solar magnetic field, which is only present during limited periods, as three and even four sector HMFs are also possible [e.g., *Owens and Forsyth*, 2013, Figure 5].

Next we test the null hypothesis that the thunderstorm variations about times of HCS crossings have occurred by chance. Again, we perform a Monte Carlo sampling of the data, using 1000 random samplings of 141 epoch times constructed from the observed waiting time distribution of HCS crossings. From these random sets of epoch times, 141 superposed epoch series are produced, and we determine the range of values which contain 90, 95, and 99% of the values, shown as the grey-shaded areas in Figure 3. Thus, the null hypothesis has $p = 0.05$ and can be rejected at around the 95% confidence level. (If the data are split into two

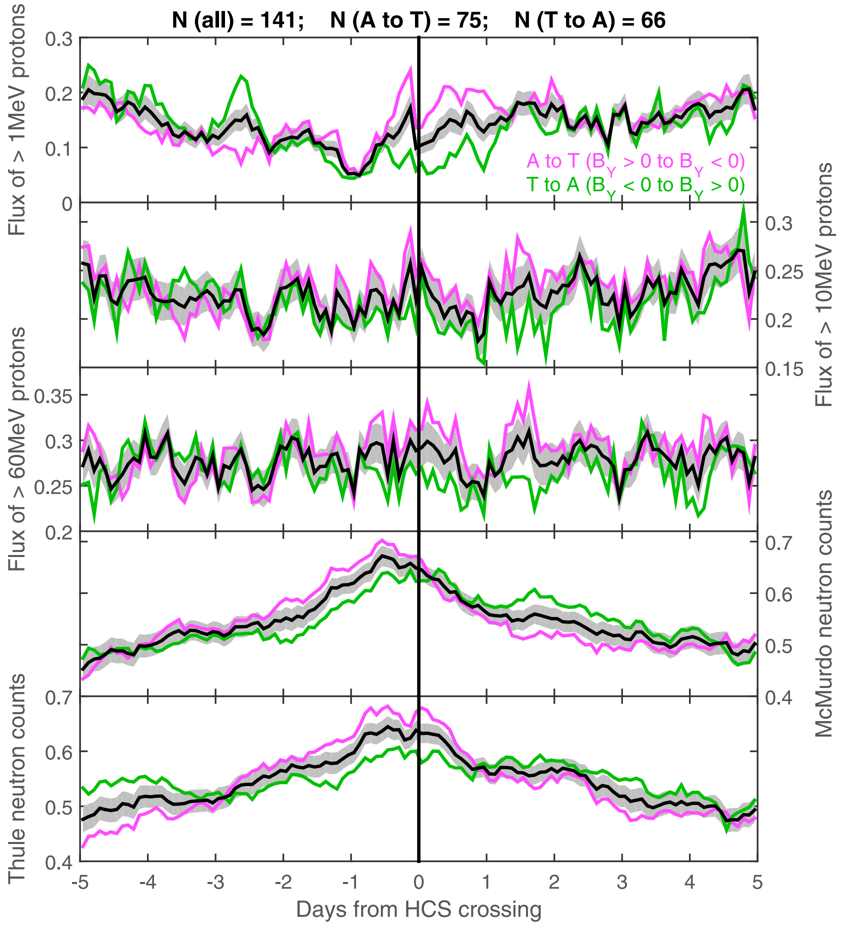

Figure 4. A superposed epoch plot of energetic particle variations about HCS crossings, in the same format as Figure 2. All data have been normalized to the maximum and minimum values in the 10 day window, to remove longer-term trends. Figures, from top to bottom, show the >1, >10, and >30 MeV proton flux from the OMNI data set, and the McMurdo (Antarctica) and Thule (Greenland) neutron counts.

equal halves, these features remain, though obviously the statistical significance is reduced.) The probability of a causal link between the HCS passage and UK thunderstorm activity is further supported by the enhancements around ±1 synodic solar rotation period, as is seen in solar wind conditions (Figure 2). Figures 3c and 3d separate the HCS crossings by the sense of HMF polarity change. A to T transitions (pink) show a highly significant ($p < 0.01$) enhancement in R_L beginning at the HCS time and peaking within a day. Similarly, the T to A transitions show a decrease at the time of the HCS, lasting for around a day ($p < 0.05$). These trends are in agreement with those seen in Figure 1 and *Owens et al.* [2014] that T polarity magnetic field is generally associated with enhanced thunderstorm activity.

In order to investigate possible physical mechanisms, Figure 4 shows the same superposed epoch analysis for a range of energetic particle fluxes incident on the terrestrial system. Lower energy particles, >1, >10, and >60 MeV protons, are measured by the GOES satellite and stored as part of the OMNI data set. Fluxes of higher energy particles, typically >2 GeV galactic cosmic rays (GCRs), are monitored by ground-based neutron monitors. Here we consider the polar monitors from McMurdo (Southern Hemisphere) to Thule (Northern Hemisphere) [*Krüger et al.*, 2008]. All data are normalized to the maximum and minimum values in the 10 day window, so as to ensure, the trends are not dominated by a single large solar energetic particle (SEP) event in the case of the lower energy particles and to remove long-term trends in the case of the GCR particles. The lower energy protons do not exhibit strong ordering about the time of the HCS passage. We do note, however, that they show elevated fluxes after the T to A HCS crossings relative to A to T crossings. This is in the same sense as the R_L enhancement. Unlike R_L, however, the proton flux enhancement begins 1–2 days prior to the HCS crossing. Neutron counts show stronger ordering about the HCS in rough agreement with the solar wind structure “sweeping up” GCRs in the inner heliosphere. Neutron counts do show different fluxes in T to A and A to T transitions, in approximate agreement with higher neutron counts in A sectors, as has been reported elsewhere [*Owens et al*., 2014; *Thomas et al*., 2014]. But unlike the R_L variations, these differences are most pronounced in the 1–2 days prior to the HCS crossing.

4. Discussion and Conclusions

Two recent studies have used daily means of UK thunderstorm activity to demonstrate a modulation associated with both corotating interaction regions (CIRs) and the polarity of the heliospheric magnetic field (HMF). CIRs are strongly associated with the heliospheric current sheet (HCS), where the polarity of the HMF reverses; thus, it is likely these two thunderstorm effects are the result of the same physical phenomenon.

In this study, we have used hourly measurements of UK lightning flash rates. Despite the strong diurnal variation in thunderstorm activity and, potentially, ATD detection efficiency, we are able to reproduce the results of *Owens et al*. [2014], demonstrating that these higher temporal resolution data can be used to investigate the causes of solar wind modulation of lightning, as long as caution is taken to assess possible aliasing between data sets. Using an existing catalog of HCS crossings, both radio measurements of lightning flash rates and audible thunder measurements are found to show a significant enhancement at the time of the HCS crossing, as well as one solar rotation before/after that time. The thunderstorm activity enhancement is focussed to within 1–2 days of the time of the HCS passage, rather than an extended enhancement in thunderstorm activity ~10–20 days that was found following the passage of CIRs [*Scott et al*., 2014]. Ordering the thunderstorm data by heliospheric current sheet crossings also shows evidence of 13 and 27 day recurrence in thunderstorm activity, which wasn’t present in the *Scott et al*. [2014] analysis which ordered the data by solar wind plasma signatures.

The HCS crossings were subdivided on the basis of the HMF polarity change. Away (A) to toward (T) polarity HMF transitions are associated with a strong rise in lightning flash rates immediately following the HCS passage (i.e., during the T polarity HMF), while T to A transitions show a small decline in lightning following the HCS. Similarly, T to A transitions show a small enhancement in lightning immediately prior to the HCS (i.e., during the T polarity HMF). Given the HMF magnitude is enhanced around the time of the HCS, these trends suggest that CIRs primarily increase lightning by compressing the solar wind and amplifying the T polarity HMF, in agreement with the trends reported by *Owens et al*. [2014], that T polarity HMF is associated with more lightning than A, i.e., that the rise in lightning flash rates observed at HCS crossings in general and hence previously reported in CIRs is a result of the small drop in lightning associated with A polarity being outweighed by the large rise associated with T polarity. As the solar wind properties (enhanced HMF magnitude, solar wind flow speed, and density) associated with the two types of HCS crossing are identical, we suggest that the heliospheric magnetic field is the prime factor in modulating thunderstorm activity. Thus, our analysis is consistent with the idea that the effect of interplanetary magnetic field polarity of lightning rates found by *Owens et al*. [2014] has the same origin as the effect of corotating interaction regions reported by *Scott et al*. [2014].

We also investigated the energetic particle populations around HCS crossings, using spacecraft data for 1–60 MeV proton fluxes of primarily solar origin and neutron monitor data as a proxy for ~ GeV galactic cosmic ray intensity. While the data do not show strong trends, there are some systematic differences in these properties, primarily an enhancement of both solar and galactic particles around the time of A to T HCS crossings. Unlike the thunderstorm enhancement, particle fluxes differ up to 2–3 days prior to the HCS crossing and are thus unlikely to be directly related if the response time of the atmosphere to conductivity changes is assumed to be ~1 day. We note, however, the possibility that the enhanced energetic particle fluxes prior to A to T HCS crossings may in some way precondition the Earth system for the lightning response at the time of the HMF polarity reversal, though the mechanism by which this would occur is unknown. HMF polarity has also been shown to influence surface pressure at mid latitudes with <1 day time lag and to potentially influence planetary wave propagation [*Lam et al*., 2013], though, again, the robust statistical result lacks a physical explanation. Speculatively, this provides one possible explanation for the HMF-lightning link, since planetary waves affect the atmosphere’s level of stability which, in turn, has a strong role in thunderstorm development. HMF polarity does affect the local ionospheric potential and perturb the atmospheric footprint of various magnetospheric energetic particle populations [e.g., *Cowley et al.*, 1991] and hence atmospheric conductivity. Both these effects can, in turn, influence the atmospheric electric circuit [e.g., *Markson and Muir*, 1980; *Rycroft et al.*, 2000] which couples into weather forming regions.

Of course, the occurrence or otherwise of thunderstorm activity is primarily the result of meteorological conditions, not least surface heating which creates a convectively-unstable atmosphere, leading to the strong diurnal and seasonal variations in lightning flash rates. Indeed, there are a number of successful methods for forecasting lightning purely on the basis of meteorological conditions from numerical weather prediction schemes [*Deierling et al.*, 2008; *Finney et al.*, 2014; *Wilkinson and Jorge Bornemann*, 2014]. The influence of tropospheric environmental conditions on lightning flash rates was recently highlighted by *Fuchs et al.* [2015], demonstrating close correspondence of thunderstorm lightning flash rates with depth-normalized CAPE and cloud base heights. Thus, if the atmosphere is not meteorologically able to generate strong electrified convection, the solar wind cannot contribute to lightning rates. But from a forecasting perspective, the results presented here suggest that predictions of A to T HCS crossings, either from photospheric magnetic field observations [e.g., *Mikic et al.*, 1999; *Arge and Pizzo*, 2000] or even simple 27 day persistence forecasts [e.g., *Owens et al.*, 2013], could provide useful additional information to the forecasting of lightning flash rates for a given set of meteorological conditions.

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