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Perspective

Thunder and lightning—what determines where and when thunderstorms occur?

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Abstract
Where and when thunderstorms occur is a topic of considerable practical importance for human society on which some meteorologists and atmospheric and space scientists carry out research. Owens *et al* (2104 *Environ. Res. Lett.* **9** 115009) have found that the occurrence of lightning over the UK is up to ~50% greater than usual when the magnetic field outside the Earth's magnetosphere, in interplanetary space, points towards the Sun rather than away from it. But why this happens is not yet totally clear.

The occurrence of thunder and lightning has fascinated humankind for aeons, as we know from both the written word[1,2,3] and classical music[4,5,6]. The frightening dangers of being exposed to lightning were first explored scientifically by Benjamin Franklin during the 1750s and 1760s. With kites he investigated charged thunderclouds, 'drawing lightning from the heavens'; he also invented the lightning conductor to be attached to important buildings to prevent these from being struck by lightning (Krider 2006). Lightning also starts wildfires; lightning occurrence over the USA is predicted to increase by ~12% for each degree Celsius of global warming (Romps *et al* 2014).

So what is lightning? In most lightning discharges, a small part of the charge of ~−100 C near the bottom of a thundercloud is transferred to the Earth's surface; this constitutes the bright and powerful return stroke (Rakov and Uman 2003). In such a negative cloud-to-ground (−CG) discharge a high current (typically 30 kA) flows for $\sim 10^{-4}$ s. In a minority of discharges, positive charge is transferred to ground (+CG discharges); the peak current in the short duration return stroke is again typically ~30 kA, but there is also a continuing current (~1 kA) lasting up to $\sim 10^{-2}$ s. Intra-cloud discharges are three times more frequent that −CG discharges, which are ten times more likely than +CG discharges; the global average number of lightning discharges is 44 s^{-1} (Christian *et al* 2003). Lightning occurs mostly over tropical land masses during the local afternoon and evening hours (Rycroft and Harrison 2012, Price 2013). From optical observations made aboard NASA satellites, we know that the number of lightning flashes is largest in the summer time, up to 70 $km^{-2}\,yr^{-1}$ in the tropics, but only about 1 $km^{-2}\,yr^{-1}$ over and around the UK (Christian *et al* 2003).

[1] Holy Bible (King James version) Revelation **4**, 5 'And out of the throne proceeded lightnings and thunderings and voices'.
[2] Shakespeare W 'Where shall we three meet again in thunder, lightning, or in rain?' Macbeth, Act 1, Scene 1, and 'First let me talk with this philosopher—what is the cause of thunder?' King Lear, Act 3, Scene 4.
[3] Thomas D M 'Though wise men at their end know dark is right, Because their words had forked no lightning they Do not go gentle into that good night'.
[4] Third movement, Summer, in The four seasons, written by Antonio Vivaldi in 1725.
[5] Fourth movement, Pastoral symphony, number 6, written by Ludwig van Beethoven in 1808.
[6] Thunder and lightning polka, written by Johann Strauss II in 1868.

The UK Met Office operates a network of very low frequency (3–30 kHz) radio receivers in Western Europe which locates the atmospherics (known as 'sferics') radiated by the impulsive current of the lightning discharge, to an accuracy of 5 km over the UK. These data sets have been analysed by Scott *et al* (2014) and by Owens *et al* (2014). Scott *et al* (2014) found a remarkable increase in lightning occurrence over the UK according to specific conditions in interplanetary space just outside the Earth's magnetosphere. This happened about two weeks after a high speed solar wind stream arrived at Earth, when the flux of >1 MeV solar protons was up to 50% greater than normal. Abnormal space weather conditions, and their effects on different regions of the Earth's environment, are the subject of much research in Europe (especially with Framework 7 programmes) and around the world today.

In this issue, Owens *et al* (2014) have shown that this increase of lightning activity is related to the orientation of the interplanetary (or heliospheric) magnetic field outside the magnetosphere, in particular whether this field is pointing towards or away from the Sun. Analysing data for six years, from 2001 to 2006, they found significantly more lightning, about 50% more, in the toward sectors than the away ones. The effect appears in every month of the year, and in all but one of the six years. This result is significant at the 3 sigma level.

Audible records of thunder heard at manned UK Met Office stations were also analysed; this study confirmed the results obtained by radio, even though the thunder does not propagate nearly so far from the thunderstorm as the VLF radio signals do. Thunder is the acoustic wave generated by the expansion of the rapidly heated lightning channel which propagates through the atmosphere away from the thunderstorm (Rakov and Uman 2003).

How may these results be explained? Whatever the mechanism is, it does not require that thunderstorm activity is directly regulated by the effects of solar activity in interplanetary space, but rather that the lightning produced in a given set of convective storms varies with those effects. One possibility is as follows. In the GSE right-handed coordinate system used by Owens *et al* (2014), when the interplanetary magnetic field **B** is in a toward sector pointing towards the Sun, the dawn-to-dusk component of the magnetic field, $\mathbf{B_y}$, is negative. This means that the electric field **E** associated with the solar wind flowing radially outwards from the Sun, along the—x axis, at $\mathbf{v} \sim 500\,\mathrm{km\,s^{-1}}$ (at times of a fairly active Sun), $\mathbf{E} = -\mathbf{v} \wedge \mathbf{B}$, is directed along the—$z$ axis, from North to South (Tinsley and Zhou 2006, Tinsley 2008). This electric field maps down to the ionosphere along geomagnetic field lines, and causes the ionospheric potential at Northern high latitudes to be ~6.5 kV less than its usual potential of ~250 kV with respect to the Earth's surface (Rycroft and Harrison 2012, Rycroft *et al* 2012). At Southern high latitudes, it will be ~6.5 kV greater. These values are obtained for a reasonable value of $B_y = 4\,\mathrm{nT}$, so that $E_z \sim 2\,\mathrm{mV\,m^{-1}}$; therefore, over two Earth radii plus twice the height of the ionosphere, E_z is ~−13 kV.

This constitutes an extra 'battery' powering the global atmospheric electric circuit in addition to the thunderstorm 'battery' which generates an upward vertical electric field, as first postulated by Wilson (1924). Each of the thousand or so thunderstorms active at any instant is a generator which drives an upward current of ~1 A, to maintain the ionosphere as an equipotential surface at ~+250 kV. In regions remote from thunderstorms, a downward current of $\sim 2\,\mathrm{pA\,m^{-2}}$ flows through the weakly conducting atmosphere, due to ionization produced by galactic cosmic rays. Due to this small conduction current there is a downward electric field of $\sim 130\,\mathrm{V\,m^{-1}}$ at the Earth's surface (Harrison 2013, Tacza *et al* 2014). Nicoll and Harrison 2014 and Elhalel *et al* (2014) have shown interesting space weather effects on this conduction current density.

Rycroft and Odzimek (2010) modelled a thunderstorm battery inside a thundercloud, where the charge resides on ice particles rather than on more mobile molecules of air, so that the electrical conductivity was a factor of 5 less than that in the surrounding free air. Their figure 3 shows that this factor has to be 5.2 to charge the ionosphere to 256.5 kV in order to overcome the extra B_y field-induced potential. How might a 4% stronger thunderstorm driver cause an increase of lightning activity by up to 50%? And how can its effect last so long, up to two weeks? Do increased fluxes of solar energetic charged particles cause significant conductivity increases either in the thunderclouds or in the surrounding air (Nicoll and Harrison 2014), or even in both? And how may these effects influence the currents flowing in the global atmospheric electric circuit which is so very sensitive to changes of the conductivity of the air (Rycroft and Harrison 2012)?

Further research is clearly required in this area. Besides exploring all possible physical mechanisms whereby space weather effects in the heliosphere can be connected to the troposphere on a global scale, it is necessary to investigate what triggers a lightning discharge. Are galactic cosmic rays involved? Or do more particles in the energetic tail of the solar charged particle spectrum penetrating the atmosphere down to thunderstorm altitudes make the initiation of lightning easier? Do the greater numbers of lightning discharges in toward sectors have generally smaller return stroke currents than in their usual distribution, or do they have the same distribution with the same mean current? Another rather obvious question is: what was the interplanetary magnetic field geometry on the days before thunderstorms were especially active over the UK? In particular, it could be worthwhile to investigate the interplanetary situation on the days preceding 22–23 July 2013 and 17–18 July 2014.

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