An arch in the UK

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1 Dunstanburgh Castle, Northumberland, silhouetted by an auroral display on 16 February 2015.

An arch in the UK

Mike Lockwood and **Luke Barnard** report on a new catalogue of auroral observations made in the British Isles and Ireland.

Arches, streamers, polar lights, merry dancers… just a few of many names used to describe the *aurora borealis* (figure 1) in historical documents in the UK. We have compiled a new catalogue of 20591 independent reports of auroral sightings from the British Isles and Ireland for 1700–1975 using observatory yearbooks, the diaries of amateur observers, newspaper reports and the scientific literature. Our aim is to provide an independent data series that can aid understanding of long-term solar variability, alongside cosmogenic isotope data and historic records of geomagnetic activity and sunspots.

The most time-consuming part of this task has been sorting the newspaper reports: a search of the British Newspaper Archive (compiled in partnership with the British Library) for the term *aurora borealis* revealed 13673 articles. We have had to sift out those relating to: racehorses and ships of the same name; travelogues about the polar regions; articles about scientific theories; articles and letters proposing false associations with the weather; descriptions of light shows, paintings and works of literature; and advertisements for fireworks. We here define a "sighting" as a night on which aurora was observed before dawn; observations after midnight but before dawn are given the date of the start of the night before midnight. We have, so far, found 3090 newspaper reports of auroral sightings, the most useful being regular monthly meteorological reports. The years after 1923 have yet to be analysed, but are well reported in observatory yearbooks.

The yield from newspapers compares with 5278 reports from the scientific literature and 2034 from amateur observers. However, the largest contribution comes from observatory yearbooks and reports, which yielded 9239. Parish and county archives have proved difficult to exploit (our survey contains just 26 such reports); these are not widely available in electronic form. We have added these to 2958 reports of sightings from the British Isles listed in previous international surveys, in particular those by Fritz (1873, 1881) and Lovering (1868).

This total of 20591 reports contains duplicates of the same observation and so we have stored details, wherever possible, such as the observer's name, the source and the location, to help identify these. The location of a reported sighting tends to be generalized as it is copied from one catalogue to another. For example, many early sightings come from King's Lynn (by Martin Folkes and William Rastrick) but this is sometimes generalized to "Norfolk" or even to "England": hence, one sighting can lead to three or more, apparently different reports. Also, place names change: King's Lynn has been referred to as Lynn, Lun, Lenn, Lenne Regis, Lynn Regis, Len Episcopi and Bishop's Lynn. Metadata is also particularly valuable in identifying observations that have been duplicated because of the confusion between Julian and Gregorian dates. In Britain, the transition to the Gregorian calendar was made on 25 March 1752 and so a correction of 11 days is needed for reports between 1700 and 1752, many of which were published in *Philosophical Transactions*. However, for other reports the correction has already been made; care must be taken not to apply it twice.

After removal of duplicates the dataset contains 17761 independent reports from known locations between 1705 and 1950 on 7640 auroral nights (an average of 2.33 per auroral night). For 1951 to 1975 we do not, at the time of writing, have the coordinates of individual sightings but we do have summaries of the totals as a function of latitude; adding these allows us to identify 10390 auroral nights between 1705 and 1975.

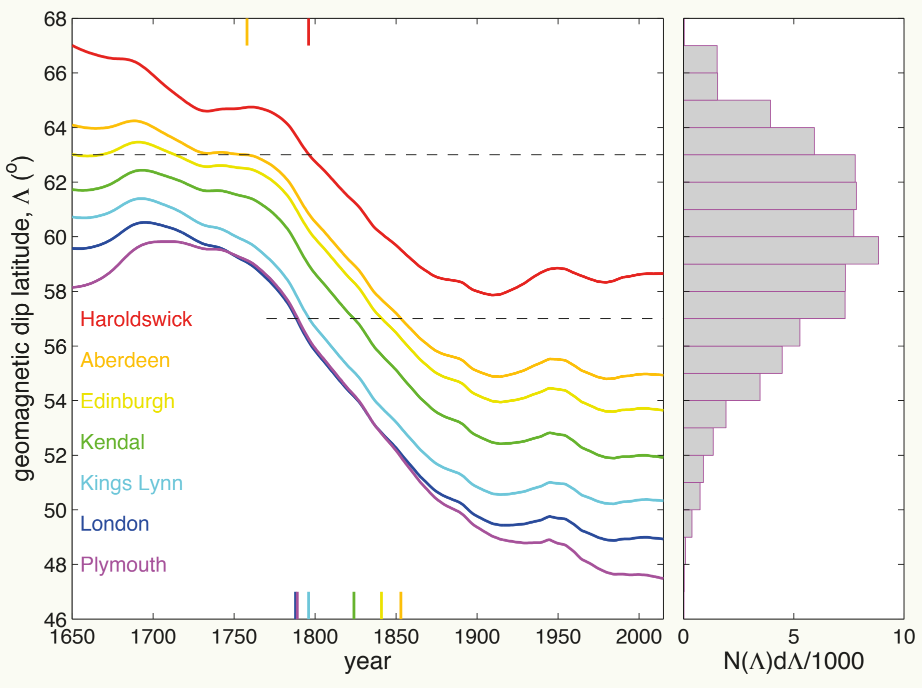
> **"The dataset contains 17761 reports from known locations from 1705 to 1950"**

Geomagnetic latitudes

A feature of the British Isles is that they cover a wide range of geomagnetic latitudes – about 9° in all. The secular change in the geomagnetic field makes this spread of latitudes a major advantage. To find the geomagnetic latitude of each location at a given date we here use a spline of the International Geomagnetic Reference Field (IGRF) and the gufm1 geomagnetic field models (Jackson *et al.* 2000), with some smoothing to remove small discontinuities between the two at 1900. These models are used to compute the field inclination, i, which is converted into a "dip" geomagnetic latitude, Λ, using the formula $\tan(\Lambda) = \tan(i)/2$. Values of Λ were evaluated at grid points with spacing 1° in latitude and 2° in longitude and 2-dimensional interpolation was used to derive Λ for the coordinates of each observation. The left-hand panel of figure 2 shows Λ as a function of date for various sites important in the history of auroral observations in the British Isles. The right-hand panel shows the distribution in magnetic latitudes of auroral observations from known sites (computed in the same way) in seven catalogues from the northern hemisphere from 1650 to 1950. The catalogues used are by Fritz (1873, 1881) and Lovering (1868) (both global), Silverman (New England), Silverman (all USA; see Silverman 1992), Rubenson (1879, 1882; Sweden), Nevanlinna (1995; Finland) and the new catalogue described here (British Isles and Ireland). The distribution shows a marked peak at Λ between 57° and 63° (the two dashed lines in the left-hand panel). The decay at $\Lambda < 57°$ with decreasing Λ is probably accurate because throughout the period there were many available observers at these latitudes. However, the decay at higher Λ may be influenced by a decrease in the available observers with increasing Λ. We here refer to the band of peak occurrence at $57° \le \Lambda \le 63°$ as the "auroral oval".

The large changes in Λ with time for a given site are caused by the secular changes in the geomagnetic field associated with the motions of the magnetic pole. The red line shows Λ for Haroldswick, on the Island of Unst in Shetland, which was poleward of the auroral oval at the start of the interval but has been within it since 1796. Aberdeen was also poleward of the oval initially, but "moved" to lower Λ such that it was within it for 1783–1853. Edinburgh was initially close to the poleward edge of the oval but moved equatorward of it in 1841. Kendal, King's Lynn, London and Plymouth were all within the oval at the start of the interval, but moved equatorward of it (leaving the oval in 1824, 1796, 1788 and 1789, respectively). As sites moved equatorward of the oval in the geomagnetic reference frame, the occurrence frequency of auroral sightings there fell. At the end of the Maunder minimum (1715), centres of population such as London, Plymouth and King's Lynn were ideally placed to observe aurorae.

So, for example, John Huxham, a physician with a mixed reputation (detailed in the intriguing biography by Schupbach 1981), observed and recorded aurorae on 122 nights between 1728 and 1748 from Plymouth (Herrick 1838). Between 1786 and 1793, John Dalton in Kendal (with his collaborator, Peter Crosthwaite in Keswick) recorded 240 auroral nights (Dalton 1834) and figure 2 shows that by this time the auroral oval had moved north such that Kendal was close to the magnetic latitude at which Huxham had made his observations half a century earlier. Kendal became equatorward of the oval in 1824; optimum observing locations moved poleward to Edinburgh, Aberdeen and eventually the Orkney, Hebrides and Shetland islands. Given that these areas are sparsely populated, one might have expected the rate of auroral recordings to fall. That they did not has much to do with an engineer called Robert Stevenson and his three sons David, Alan and Thomas who designed and built 55 lighthouses around Scotland between 1811 and 1886. Lighthouse keepers regularly reported aurorae until operations became mechanised in the second half of the 20th century. Between 1920 and 1950, there were 813 auroral observations from lighthouses constructed by the Stevensons and 1229 from all Scottish lighthouses.



2 (Left): The geomagnetic dip latitude Λ of various sites in the British Isles as a function of date. (Right): The distribution of auroral sightings with Λ (from well-specified locations taken from a basket of seven catalogues from various longitudes in the northern hemisphere and including the new catalogue presented here): the number of sightings during 1650–1950 at magnetic latitudes between Λ and Λ+dΛ, $N(\Lambda)d\Lambda$, is shown as a function of Λ for $d\Lambda = 1°$. All magnetic latitudes are computed in the same way from a spline of the IGRF and gufm1 models.

Amateurs and gentlemen scientists

Amateur observers also made vital contributions. Anthony Johnson reported 300 auroral nights between 1913 and 1930 from Haroldswick on Unst, Shetland and the Rev. Charles Clouston made an astonishing 875 reports of auroral nights between 1833 and 1882 from the manse in Sandwick, Orkney. Clouston was one of many clergymen who regularly observed and recorded natural phenomena. He was related by marriage to Balfour Stewart, who first postulated a conducting layer in the atmosphere (the ionosphere) as a cause of geomagnetic variations and after whom the Balfour Stewart Auroral Laboratory (BSAL) at the University of Edinburgh was named.

Other notable clergy observers in Scotland included: Rev. A C Henderson, who made observations from Whalsay in Shetland, then from Buckie and Forfar, between 1912 and 1918; and Rev. W M Dunbar of Applegarth Manse, Dumfries (observations 1838–1848). But clergymen looking to the heavens (in more than one sense) was far from a new phenomenon; there are many prior examples from further south including: nonconformist preacher William Rastrick (King's Lynn, 1722–1726); and Rev. William Derham (Upminster, Redbridge and Windsor, 1707–1728).

There were also a great many secular amateurs such as physician Thomas Hughes from Stroud, Gloucestershire, who recorded aurorae and meteorological information in his diaries from 1771 to 1813 (Harrison 2005). Those with inherited wealth were able to devote themselves to science. One such was Edward Joseph Lowe, who began his observations of natural phenomena in 1840 at the age of 15 at his family home of Highfield House, Nottinghamshire (now part of the University of Nottingham). A co-founder of the Royal Meteorological Society, Lowe gained the nickname The Big Snowflake on account of his impressive bushy white beard. Auroral sightings were part of his book *Natural Phenomena and Chronology of the Seasons* (1870) and have been included in several auroral catalogues. Lowe's own copy of his book was recently discovered in the Museum of Rural Life at the University of Reading and has proved to be valuable for its marginalia.

The first national network of amateur observers was assembled by George J Symons (1838–1900), who contacted, befriended and encouraged amateur observers, founding and managing the British Rainfall Organisation. As well as recording rainfall data, he compiled lists of phenological observations from his network of observers, and of aurorae. From 1860, he published these observations in annual booklets entitled *The Distribution of Rain over the British Isles*, continued after his death by the BRO and taken over by the Met. Office in 1919. These also appeared from 1866 onwards, in *Symons's Monthly Meteorological Magazine* (which became the *Meteorological Magazine* in 1920 and was published until 1993).

It now seems strange that these reports appear in weather bulletins; however, when Symons started, many people were convinced that the aurora was a harbinger of bad weather. The name "meteorology" comes from the Greek meaning "the study of things in the air" and the term "meteors" in the 18th century was used to refer to all luminous appearances in the sky, including aurora. After 1892, sightings from amateur observers were also published in the journals of the British Astronomical Association (BAA), compiled by G J Burns and after 1925 by W B Housman. These data are in the present catalogue.

The remarkable John Dalton also contributed greatly to our catalogue. Reading the two editions of Dalton's *Meteorological Observations and Essays* (published in 1793 and 1834), one is struck by the precise and methodical way that all his recordings (including of aurora) were classified and tabulated – with none of the flowery language and unnecessary detail that characterized contemporary science publications. With his ground-breaking research into atomic physics, gas laws, meteorology and colour blindness, Dalton was very much a forerunner of the modern professional scientist. Yet for most of his life he was an amateur, because he was a Quaker and so classed as a "dissenter". This truly brilliant man was barred from attending or holding a post in a university. From the age of 15 (in 1786) he and his brother ran a Quaker school in Kendal, Dalton having taught Latin from the age of 12. He made his first record of an aurora in the same year.

In 1893 he moved to Manchester to become a teacher of mathematics and natural philosophy at the New College, a dissenting academy. After seven years he resigned to try to ease the college's deepening financial woes, and made a living as a private tutor. The better and more generous academics of the day began to recognize Dalton's genius. In 1810 he refused Sir Humphry Davey's offer to propose him for fellowship of the Royal Society (probably because he could not afford the annual subscription); nevertheless, he was proposed and elected without his knowledge in 1822, and elected as a member of the French Académie des Sciences in 1816. He made his last meteorological recording the day before he died in 1844. Dalton's careful catalogue of observations clearly showed the decline in auroral activity and so ended any serious debate about the reality of the Maunder minimum and the notion that there was no secular change in solar activity. This debate still resurfaces today – see the rebuttal by Usoskin *et al.* (2015).

"Dalton's observations ended serious debate about the reality of the Maunder minimum"

The Maunder minimum

On the night of Tuesday 17 March 1716 (Gregorian or "new" date), auroral displays were seen across much of Europe, including in London. Very few people in the British Isles had seen aurora before (Fara 1996). The event was so rare that it provoked the commissioning of reviews by the Royal Society (carried out by Edmond Halley) and by l'Académie des Sciences of Paris (by Giacomo Filippo Maraldi, also known as Jacques Philippe Miraldi). It generated much interest in the Royal Prussian Academy of Sciences in Berlin, particularly from the husband-and-wife team of Gottfried and Maria Kirch, and later their daughter Christine. All these reviews found evidence of earlier aurora, but very few during what we now call the Maunder minimum.

Halley himself had observed the 1716 event, and correctly noted that the auroral forms were aligned with the geomagnetic field. Halley was an avid watcher of the skies who had wanted to see aurora and actively searched for it: "… [of] all the several sorts of meteors [atmospheric phenomenon] I have hitherto heard or read of, this [aurora] was the only one I had not as yet seen, and of which I began to despair, since it is certain it hath not happen'd to any remarkable degree in this part of England since I was born [1656]; nor is the like recorded in the English Annales since the Year of our Lord 1574." In his paper to the Royal Society, Halley lists reports of the phenomenon, both from the UK and abroad, in the years 1560, 1564, 1575, 1580, 1581 (many reported by Brahe in Denmark), 1607 (Kepler in Prague) and 1621 (Galileo in Venice and Gassendi in Aix, France). Strikingly, thereafter Halley found no credible reports until 1707 (Rømer in Copenhagen and various in Berlin) and 1708 (Neve in Ireland). He states: "And since then [1621] for above 80 years we have no account of any such sight either from home or abroad." This analysis did omit some isolated sightings in 1661 from London (reported in newspapers and the Leipzig University theses by Starck and Früauff) and Derham's in Upminster. A similar reappearance of aurorae was reported between 1716 and 1720 in Italy and in New England (Siscoe 1980).

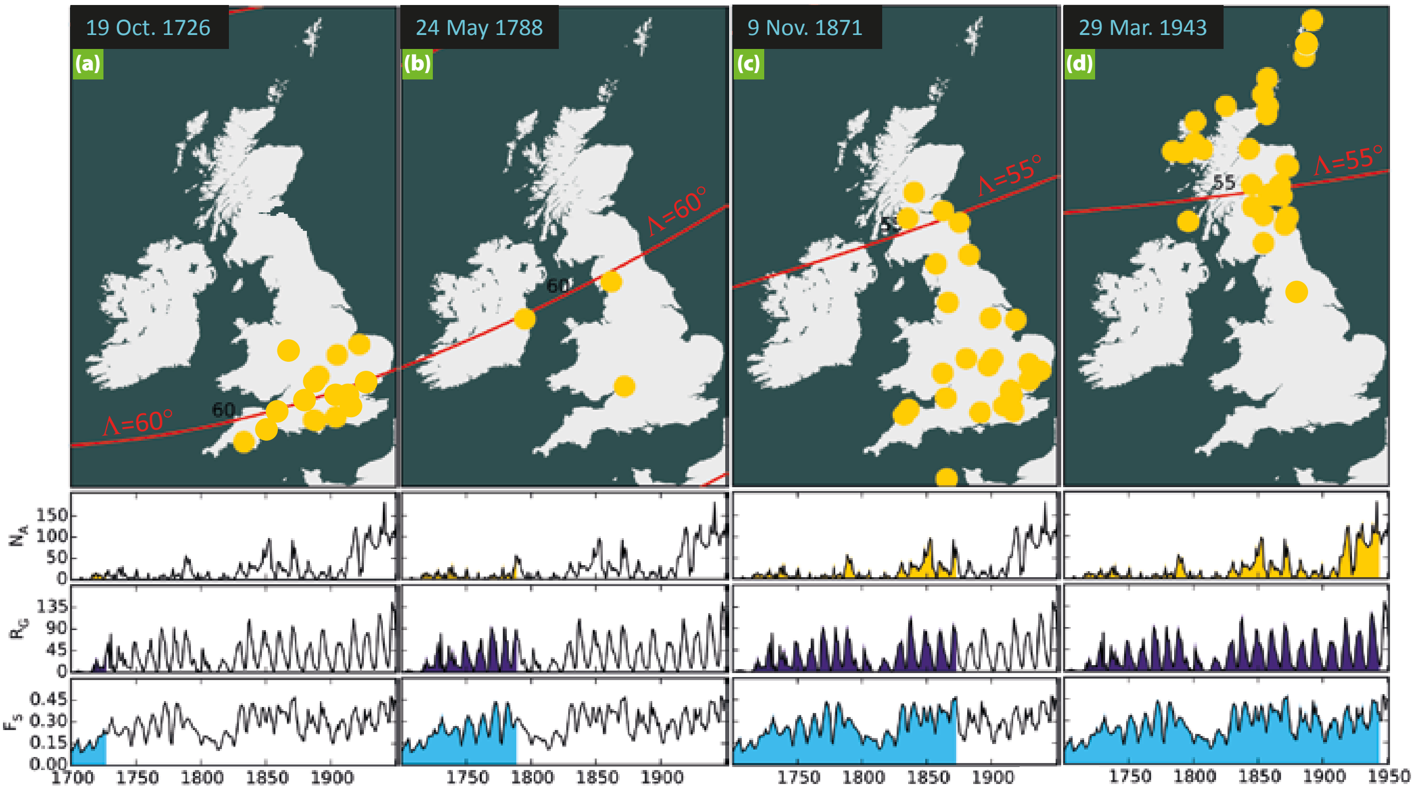
The almost complete absence of auroral reports from the British Isles during the Maunder minimum is remarkable. As figure 2 shows, all the major centres of population in southern England were ideal locations to see aurora under normal conditions. There were a few isolated auroral reports from mainland Europe during the Maunder minimum and sailors and fishermen who visited the far north were told of continued sightings during this time by locals. Thus it seems likely that aurora continued during the Maunder minimum, possibly with less intensity and a lower latitudinal span, and usually at very high latitudes. The few lower-latitude aurorae that were seen may well have been stable sub-auroral red (SAR) arcs generated from ring current particles or, as noted by Zhang (1985) for ancient Korean observations, possibly even intense airglow or zodiacal light. After 1716, reports of active auroral arcs, arches and streamers in the UK became much more common.

Bombing of London

On the night of 7–8 March 1918, aurora was observed throughout south and east England (see *Nature* editorial, 1918). There are Met. Office reports, newspaper articles and BAA reports and the associated magnetic disturbance was monitored at Kew observatory. This night became significant in the history of British auroral observations because of its role in early air warfare.

Aerial bombardments in the first world war began in 1915. Many of these early air raids hit small villages, largely because navigation was so crude. London and other cities were bombed in 23 airship raids in 1916. Both sides noted that the raids were more effective when moonlight overcame the navigation problem. This became part of the strategy for the British air defences and for the German aviators who increasingly used aircraft rather than Zeppelins.

On the night of 7–8 March 1918, seven planes approached London along the Thames estuary, navigating using the reflection of the bright aurora from the water; five turned back but two got through. There was much speculation in the press that the German air forces had predicted the aurora that had so greatly helped them – an idea that amuses present-day scientists who are still working hard to gain such a capability with advanced satellites such as the STEREO mission



3 The locations of auroral sightings on a given night (yellow spots). The red lines are contours of constant geomagnetic latitude (Λ). Note that the contour shown in full is for $\Lambda=60°$ in (a) and (b), whereas it is for $\Lambda=55°$ in (c) and (d). Beneath each map the panels show: the number of auroral nights in the British Isles and Ireland per year, N_A; the group sunspot number, R_G; and the open solar flux, F_S. The coloured sections show to where each parameter has evolved at that date. These data have been compiled into an animation that can be viewed on our website (http://www.met.reading.ac.uk/~spate).

(Davis *et al.* 2012) and projects such as Solar Stormwatch (Barnard *et al.* 2014; see also page 4.20 of this issue).

Before this air raid, aurora had been reported in a somewhat ad-hoc fashion in the yearbooks of observatories such as Kew, and in the remarks from observers in the BRO rainfall bulletins. In 1911 these were organized into *The British Meteorological and Magnetic Year Book* published by the Met. Office and the Air Ministry. Initially, aurora reports were somewhat hidden away, often only denoted by small symbols in tables of atmospheric data. The report published in 1919 (covering 1917) introduced a table of auroral data, probably in response to the air raid. This valuable table continued in exactly the same format in these yearbooks (renamed *The Observatories' Yearbook* in 1922) until 1954. For 1955–1967, data from the Lerwick observatory only were included, with summaries of the rest (compiled by the BSAL). This ceased in 1975 when the BSAL was closed. These yearbooks include the lighthouse observations; they have been digitized and placed online by the NERC's British Geological Survey.

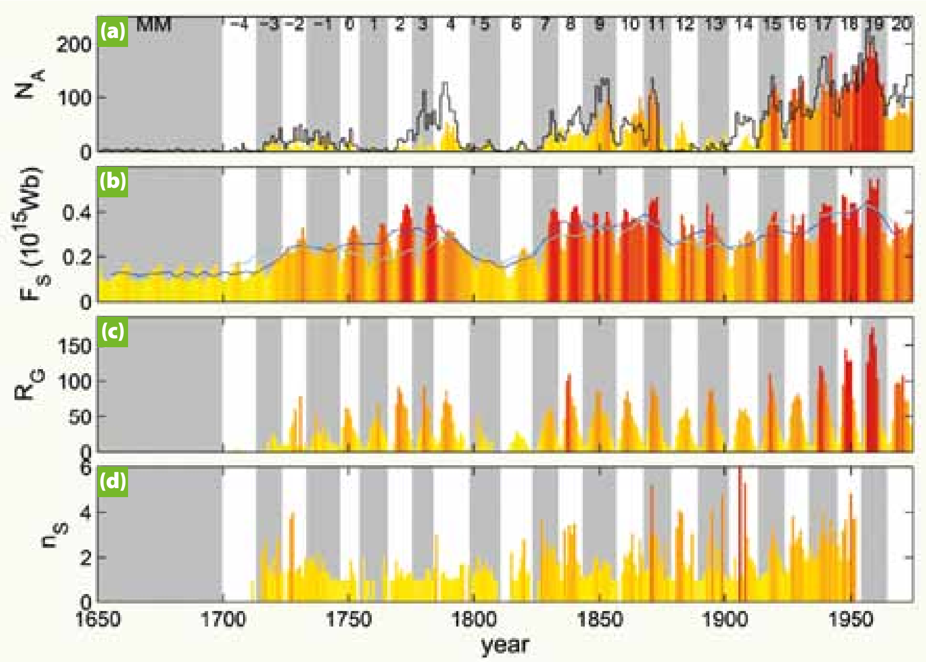
Maps of auroral sightings

Figure 3 shows four daily maps of auroral sightings. Map (a) is for 19 October 1726, early in the data sequence when the $\Lambda=60°$ contour lies across the south of England and aurora were visible from major centres of population. On this night aurora was recorded from Plymouth to King's Lynn. Map 3(b) is for 24 May 1788, when the $\Lambda=60°$ contour has moved to the north of England. Aurora was seen at just four locations on this night. This is typical of this period, when the data sequence relies heavily on a very few observers and, in particular, John Dalton and Thomas Hughes. The northward shift of the auroral oval may have contributed to the drop in regular observers; this is offset by the quality, commitment and rigour of the few active observers. But with fewer observers, no matter how committed and skilful, it becomes more likely that cloudy skies will cause auroral nights to go undetected. Map 3(c) is for 9 November 1871 when the $\Lambda=60°$ contour has moved even further north and the $\Lambda=55°$ contour lies across southern Scotland. This is a highly active day and aurora was seen at 34 locations between Guernsey in the Channel Islands and Perthshire in Scotland. These observations were mainly made by Symons' network of amateurs (by then extending to Orkney) and other people recorded in newspapers. Map 3(d) is for 29 March 1943 when aurora was seen from 29 sites between Leeds and Baltasound on the island of Unst in Shetland. These data were mainly supplied by observatory staff and lighthouse keepers and compiled into the joint Air Ministry/Met. Office reports.

Science implications

Having compiled the dataset, we are now beginning to study its implications. The most obvious problem with the data comes from long-term trends in the availability of observers at a given geomagnetic latitude and their ability, and willingness, to record what they saw. Cloud cover means that the data are more robust when the number of observers is high and increasing street lighting may have reduced the number of potential observers. It is remarkable that the variation in the number of auroral nights, N_A, in our survey (see figure 4) is very similar to that from corresponding surveys at other longitudes – from the USA, from Finland and from Sweden, covering the same range of Λ. The small differences are all consistent with the changes in Λ with time at the different longitudes and the variation with longitude of the length of the observing season (set by sunlight) at a given Λ. This gives us real hope that there is important geophysical information available from the series, especially in conjunction with other surveys.

The colour histogram in figure 4(a) shows the number of auroral nights per year in the British Isles and Ireland, N_A. The black line shows the results of the global survey by Krivský & Pejml (1988) who combined several catalogues. This covers the interval up to 1900 and is extended here using the global annual values of Legrand & Simon



4 Time series plots of: (a) the number of reported auroral nights in the British Isles and Ireland, N_A; (b) the open solar flux, F_S; (c) the group sunspot number, R_G; (d) the average number of distinct locations from which aurora is observed on each auroral night, n_S. The annual histogram elements are coloured according to the magnitude of the parameter plotted. The grey and white areas highlight odd- and even-numbered sunspot cycles, respectively, which are numbered along the top of panel (a). The black line in (a) shows the results for N_A for the global combination of catalogues compiled by Krivský & Pejml (1988) which has been extended to after 1900 using the annual global values by Legrand & Simon (1987). In (b) the blue line shows 11-year running means of the annual values and the cyan line is derived from N_A using a polynomial fit derived from a fit to the reconstructed OSF values after 1845, see figure 5(b).

(1987). The UK catalogue has very similar long-term variation. Figure 4(b) shows the open solar flux (OSF), F_S, and 4(c) the group sunspot number, R_G. The OSF is as derived from geomagnetic activity data for 1835 onwards by Lockwood *et al.* (2014) using the procedures discussed by Lockwood (2013). This is here extended to before 1835 using the model of Owens & Lockwood (2012), as applied by Lockwood & Owens (2014), and using R_G as model input. There is an anomalously high value of observed N_A in the UK in 1941, not seen in the other surveys; this may be caused by the glow from fires generated by second world war air raids (which peaked in 1941) being mistaken for red aurora. If so, it is somewhat ironic because our survey has shown that the inverse story, of citizens or firemen rushing to a fire that turned out to be aurora, is as old as newspapers themselves.

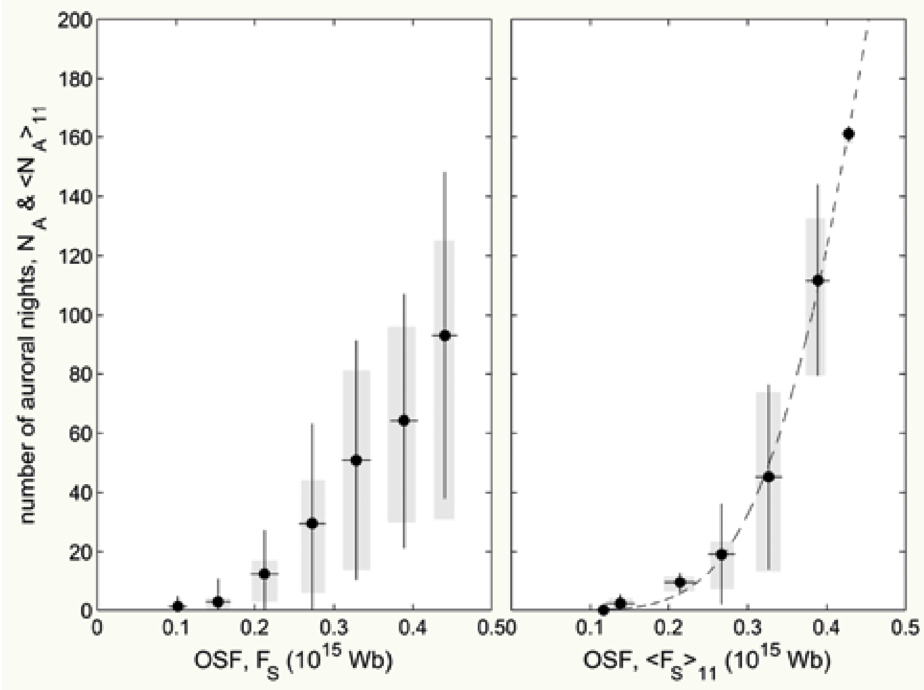
We have studied the annual means of n_S, the number of distinct locations from which aurora were observed on an auroral night, to investigate if the N_A series is strongly influenced by a long-term variation in the number of available observers at the optimum latitudes. The average over the entire period is $<n_S> = 2.33$ and the variation is shown in figure 4(d). Interestingly, n_S shows a solar cycle variation and a long-term variation rather similar to N_A, indicating that aurora tend to be more extensive and visible in years when it is more common. The regression slope of n_S against N_A over 20th-century solar cycles is very similar to that for the long-term variation over the whole period, which suggests that the long-term variation of both is real and not strongly influenced by the availability of observers. Note that there are years early in the series when the average number of sites from which an aurora night is observed approaches four, which is in the upper decile of values for recent decades. This indicates that larger events were detected and recorded soon after the Maunder minimum as effectively as they were in the 20th century. However, this alone does not mean that we can treat the sequence shown in figure 4(a) as homogeneous. For example, it may be that for early years only active, dynamic auroral displays ("streamers") were recorded, whereas later on more static, less structured glows were recorded as well. John Dalton was systematically searching for, and documenting, both these types of aurora between 1786 and 1844; even this may not be a homogeneous subset because he moved from Kendal to Manchester and may have failed to see more auroral nights in Manchester as a result of greater cloud cover. The value of our new catalogue is that we can compare it others from other locations to try to deconvolve changes associated with observer and cloud effects from changes caused by variations in solar activity. Hence, we are employing statistical methods to use the different datasets to quantify any effects of variability in the efficiency of auroral detection.

Figure 4 demonstrates the well-known relationship between auroral occurrence and sunspot number, but also reveals that this relationship is not as simple as is often assumed. First, the relationship to sunspot numbers is highly nonlinear, with N_A falling to very low values during the Dalton minimum (around solar cycle 6) and even during the less-pronounced Gleissberg minimum (around cycle 14). Secondly, the variation in the amplitudes of the cycle peaks in N_A and R_G shows some similarities but also considerable differences. Thirdly, some solar cycles are very different in waveform with very large peaks in N_A during the declining phase. In particular, cycle 18 shows a maximum almost at the end of that cycle, a feature also seen in cycle 10. Figure 4(b) shows that the OSF usually peaks after the sunspot number but this is not enough to explain the extremely delayed peaks in the number of aurorae.

Figure 5 shows why we are confident that we can overcome the limitations of the auroral sighting data and derive meaningful geophysical insights. The left plot shows the mean N_A value as a function of the mean F_S for averaging over F_S bins that are 0.06×10^5 Wb wide. Here we have only used data after 1845, for which the OSF was reconstructed using a number of pairings of geomagnetic data series (Lockwood *et al.* 2014). It can be seen that, on average, N_A increases monotonically with F_S but the spread in the data (given by the standard deviation and quartile ranges shown) is very large at larger F_S. The right-hand plot shows the result of the same procedure applied to 11-year running means of the data. The nonlinearity of the relationship is now clear and the scatter in the data is greatly reduced, especially away from the change in slope in the middle of the plot. The dashed line shows a 6th-order polynomial fit to these smoothed data, constrained to pass through the origin.

Using the fit shown in figure 5(b), the 11-year smoothed N_A data, $<N_A>_{11}$, can be used to predict the 11-year means of OSF over the whole period. The results are shown by the cyan line in figure 4(b) which can be compared with the 11-year means from the OSF reconstruction (blue line). The OSF values before 1845 are modelled and hence the comparison provides a test of that modelling. There is quite good agreement although the cyan line tends to be low at times. However, this mainly occurs when figure 4(a) shows that the UK N_A values are lower than the global values from the Krivský & Pejml catalogue (black line). We are confident that agreement will be even closer when the UK auroral data are combined with the data from elsewhere.

At this point it is worth asking the question "what causes low-latitude aurora?". Combined analysis of global ultraviolet auroral images from the Swedish Viking satellite and the Tsyganenko model of the magnetospheric magnetic field have indicated that the main, lower-latitude auroral oval maps to the earthward edge of the cross-tail current in the plasmasheet of the geomagnetic tail (Elphinstone *et al.* 1993, 1995). This current sheet thins and moves earthward under the additional magnetic pressure exerted by the magnetic fields in the tail lobe when the open magnetospheric flux is increased by enhanced magnetopause reconnection. Thus the main auroral oval migrates equatorward during the growth phase of substorms (Milan *et al.* 2012). The expanding–contracting polar cap paradigm predicts that this growth-phase increase in open flux is later balanced by an increase in the rate at which open flux is lost by reconnection in the cross-tail current sheet (Lockwood *et al.* 2009). The lag time, τ, in the tail response means that the long-term average of the magnetospheric open flux is enhanced when the dayside reconnection rate is enhanced and this is reflected in average positions of the auroral oval that are further equatorward (Milan *et al.* 2009). On annual timescales, the magnetopause reconnection rate depends on the magnitude of the interplanetary magnetic field (IMF) and hence on the OSF; the north–south IMF orientation factor averages to a near-constant value on these timescales, see Lockwood (2013). From this we would expect N_A to vary in a very similar way to OSF. Figure 4 shows that this is only partly true. In particular, we note that there seems to be an "accumulative" effect whereby N_A grows after several cycles of large OSF. Two possibilities that we will investigate are if this is related to long-term variations in the time constant τ and/or if there is any effect of potential cycle-to-cycle variations in the energetic particle population in the near-Earth plasma sheet.



5 Mean values for 1845–1975 of the number of auroral nights, N_A, as a function of mean values of the open solar flux, F_S, for bins of F_S that are 0.06×10^5 Wb wide and centred on $[0.03{:}0.06{:}0.51] \times 10^5$ Wb, left) for annual values and (right) 11-year running means of annual values. Error bars are ± one standard deviation in both dimensions and grey areas show the quartile ranges for each bin in both dimensions. The dashed line is a 6th-order polynomial fit to the smoothed data, constrained to pass through the origin.

Future work

The catalogue of locations of auroral sighting presented here covers the years from 1700 to 1951. The series of data on auroral nights has been extended up to 1975 using the summaries published in the *Observatory* magazine by the BSAL, work that was carried out mainly by James Paton and his successor, Douglas H MacIntosh. These data, giving the locations of all sightings, are now held on paper at Aberdeen University. Work has continued since then under the auspices of the BAA and these data are held, again as paper records, at the RAS's Burlington House in London. We hope in the near future to add these data to extend the series, with locations, up to the present day. This will enable us to study in more detail how the data depend on near-Earth interplanetary and magnetospheric conditions, as measured by spacecraft.

One reason why this work is important is that we have very few observations that allow us to study centennial variations in the Sun and near-Earth space. The recent decline in solar activity raises the real possibility of a return to Maunder minimum conditions within about 50 years (Barnard *et al.* 2011), with implications for the operation and design of all systems that are influenced by space weather. In addition, recent modelling (Macock *et al.* 2015) shows implications for the stratosphere and even tropospheric climate in some regions but little effect globally; see review by Lockwood (2012). ●

AUTHORS
Mike Lockwood and **Luke Barnard**, Department of Meteorology, University of Reading, UK.

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CATALOGUE/WEBSITE
A listing of the full catalogue and the animation of the auroral sightings will be posted shortly at http://www.met.reading.ac.uk/~spate

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