1 The great frost fair of 1684, by an unknown artist. The painting is generally known as *Frost Fair on the Thames, with Old London Bridge in the Distance*, which is a title with hidden significance because London Bridge was important in generating the conditions that allowed the ice to become firm and thick enough to support the fair. (Yale Center for British Art, Paul Mellon Collection)

Frost fairs, sunspots and the Little Ice Age

Mike Lockwood, **Mat Owens**, **Ed Hawkins**, **Gareth S Jones** and **Ilya Usoskin** examine the links between the solar Maunder minimum, the Little Ice Age and the freezing of the River Thames.

Where spin doctors, politicians and newspaper editors understand well that a name alters how something is perceived, scientists know that a name does not change the reality one iota. By virtue of the name awarded to it, the "Little Ice Age" has been associated with full ice ages. The name Little Ice Age has also become almost synonymous with the Maunder minimum in solar activity in the minds of many people. Hence it has even become possible to build semantic arguments that imply there is some sort of link between solar activity and ice ages – and evidence for major control of climate by solar activity is often offered in the form of the occurrence of frost fairs on the Thames in London (figure 1). This paper discusses the true relationships, or lack of them, between these different events.

Ice ages

Before discussing the Little Ice Age we should be clear what a proper ice age is. Global temperatures can be inferred from polar ice cores, using the isotopic composition of the water molecules. In particular, the amounts of deuterium (^{2}H) and of the ^{18}O isotope present in the ice are lower if temperatures at lower latitudes at the time of their deposition were depressed. This is because it takes more energy to evaporate the water molecules containing these heavier isotopes from the surface of the ocean and, in addition, as the moist air containing the evaporated water is transported polewards and cools, the water molecules containing the heavier isotopes are more easily lost by precipitation. Both processes mean that less deuterium and ^{18}O reaches the polar regions if global temperatures are lower. This "fractionation" effect can be calibrated and so a record of temperatures back to the distant past can be generated from measurements of the abundance of ^{2}H and/or ^{18}O in deep cores into ancient polar ice sheets. Figure 2 shows temperatures deduced from ice cores taken at the Vostok station in Antarctica that are deep enough to allow us to see the variation over the past 420 000 years (from Petit *et al.* 1999). The temperature is shown as the difference relative to present day values (in other words as a temperature "anomaly", ΔT). The ice cores reveal that global temperature is characterized by rapid rises, followed by gradual declines. These cycles are known to be driven by the Milankovitch cycles in Earth's orbital characteristics, but are still not fully understood.

The feature to note here is the extremely large difference between the relatively short, warm "interglacials" (ΔT around or

exceeding zero, coloured red) and the cold "glaciations" (usually known as "ice ages" and here coloured blue), in which average temperatures are lower than during the present interglacial (the Holocene) by up to 8°C. The effects of such low global temperatures in the ice ages are profound, with polar ice sheets expanding to cover temperate latitudes and fundamental changes to the patterns of precipitation and temperature. During the last glacial maximum, ice sheets spread down to cover Scotland, Wales and northern England (Bowen *et al.* 2002); insect studies reveal temperatures in southern England averaged about –8°C, with minimum and maximum seasonal values of –30°C and +8°C (Atkinson *et al.* 1987). Under such conditions the UK, like most of northern Europe (to which the UK was joined by the Doggerland land bridge), was abandoned by humans and the archaeological record shows that it was permanently recolonized only after the ice age started to come to an end (Barton *et al.* 2003).

The Little Ice Age

Compared to the changes in the proper ice ages, the so-called Little Ice Age (LIA) is a very short-lived and puny climate and social perturbation. The term was introduced into scientific literature by François E Matthes in 1939 in relation to glacier advances in the Sierra Nevada, California. However, it is somewhat misleading and is open to misuse as it implies much greater similarities to a full ice age than really exist: some climate scientists argue the name should be abandoned (see discussion by Matthews & Briffa 2005).

The black line in figure 3b shows the best estimate of the variation in the average air surface temperature in the northern hemisphere since AD850. This is a combination by Masson-Delmotte *et al.* (2013) of 18 separate reconstructions and was presented in the fifth assessment report (AR5) of the International Panel on Climate Change (IPCC). Each of these reconstructions employs multiple temperature proxies, including data from boreholes, corals and sclerosponges, ice cores, insect numbers, instrumental data, pollens, lake levels, loess (wind-blown silt), glacier extents, plant macrofossils, diatoms, molluscs, foraminifera, dinoflagellates, ostracods, heavy minerals, grain-size, trace elements speleothems, dendrochronology and historical records (recorded freeze/thaw dates, harvest yields and dates, etc) (see review of techniques by Jones & Mann 2004). The colours give the probability density function (pdf) in each year, which allows for both the computed uncertainties in each reconstruction and the differences between the reconstructions. The larger the peak pdf, the narrower is the
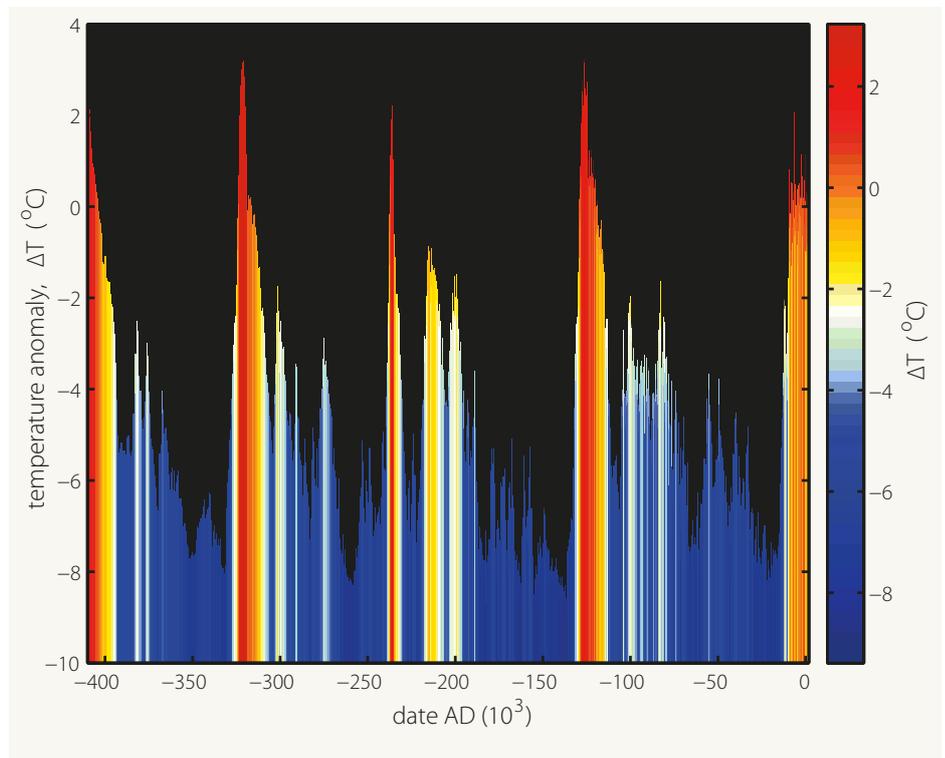
2 The variation of global temperatures over the past 420000 years deduced from ice cores taken at Vostok station, Antarctica. (From Petit *et al.* 1999)

distribution and so the closer the agreement between the various reconstructions. Temperatures in figure 3 are presented as the anomaly with respect to the average for 1961–1990, ΔT_{NH}. It should be recognized that figure 3b represents a truly outstanding scientific achievement; it is arrived at through a huge variety of paleoclimate techniques and a colossal number of measurements from all over the northern hemisphere.

The LIA can be seen in figure 3 as the dip in temperatures reaching minimum values around 1700. The first thing to note is that the best estimate of the amplitude of the dip is, at most, 0.5°C; this should be compared to the temperature decreases in ice ages of about 8°C shown in figure 2. Note also that the LIA persists for 500 years at most, compared to the 20000 years of the last ice age. Several causes of the LIA have been proposed, including lows in solar radiation, heightened volcanic activity, changes in the ocean circulation, the inherent internal variability in global climate and increased human populations at high latitudes through the deforestation they brought about.

The start and end dates of the LIA depend strongly on the temperature proxy used to derive them and on geographic region. Evidence from mountain glaciers suggests increased glaciation in a number of widely spread regions around the 12th century AD: these include Alaska, New Zealand, America and Patagonia. However, the timing of maximum glacial advances

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"The Samalas eruption has been postulated as the driver of glacial advances"

in these regions differs considerably, suggesting that they may represent largely independent regional climate changes, not a globally synchronous increased glaciation. Individual studies agree with the view of the LIA given in figure 3b; for example, based on about 150 samples of plant material collected from beneath ice caps on Baffin Island and in Iceland, Miller *et al.* (2012) find that cold summers and ice growth began abruptly between 1275 and 1300, followed by "a substantial intensification" from 1430 to 1455. Figure 3c shows the volcanic aerosol optical depth (AOD) inferred from sulphate abundances found in Greenland and Antarctic ice cores (Crowley & Unterman 2013). The largest spike is associated with the major volcanic eruption in 1257 of the Samalas volcano, next to Mount Rinjani on the island of Lombok, Indonesia. This was one of the largest eruptions during the Holocene and figure 3 shows it probably caused a temporary drop in ΔT_{NH}, but perhaps not as great as the sulphate yield suggests it should. (For example, the eruption of Tambora in 1815, seen in figure 3c as a smaller spike in AOD, is associated with a drop in ΔT_{NH} of similar magnitude). The Samalas eruption has been postulated as the driver of glacial advances and the growth in the Atlantic ice pack that mark the start of the LIA, as defined from the cryosphere. The intensification noted by Miller *et al.* (2012) after 1430 is associated with a steep drop in ΔT_{NH} that has been linked to a burst of
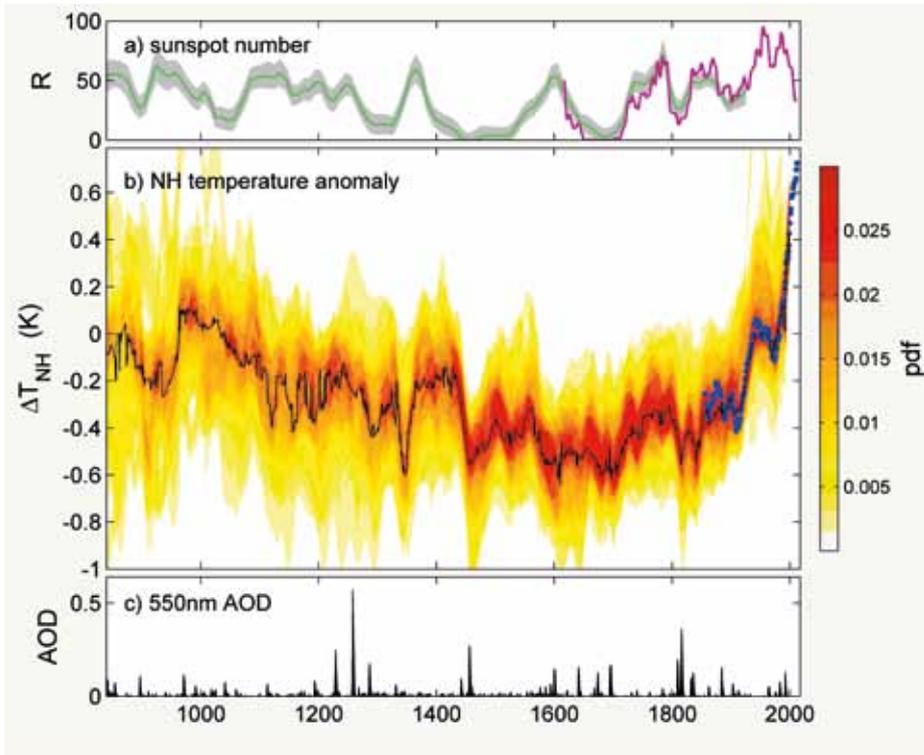
3 Variations around the Little Ice Age. (a) Sunspot number estimates: (mauve line) 11-year running means of the extended sunspot number sequence of Lockwood *et al.* (2014), $<R_C>$; (green line) smoothed sunspot numbers derived from dendrochronology data (^{14}C abundance measurements), R_{14C} (Usoskin *et al.* 2014). The grey area gives the computed uncertainty in R_{14C}. (b) A combination of 18 paleoclimate reconstructions of the northern hemisphere mean air surface temperature anomaly ΔT_{NH} by Masson-Delmotte (2013). The colour contours give the probability distribution function (pdf) obtained by combining the 18 different reconstructions and allowing for the uncertainty in each. The peaks (mode values) of the annual pdfs are joined by the black line. The blue dots show 10-year running means of ΔT_{NH} from the HadCRUT4 observational record (Morice *et al.* 2012). For both datasets, the anomaly is computed relative to a reference interval of 1961–90. (c) Volcanic aerosol optical depth (AOD) at 550 nm derived from sulphate abundances measured in Greenland and Antarctic ice sheet cores (from Crowley & Unterman 2013).

volcanic activity (reflected in the AOD). This can also be considered as the start date of the LIA, as defined from ΔT_{NH}. The lowest temperatures in the LIA, between about 1570 and 1730, are during a period of almost continuous, but smaller, volcanic activity.

The problem with the name Little Ice Age is that it implies a period of unremitting cold when even summer temperatures barely get above zero, as was seen at middle latitudes during the ice ages proper. This idea is frequently bolstered using paintings from the time, such as Pieter Bruegel the Elder's *Hunters in the Snow,* painted in 1565 (figure 4a). What is rarely mentioned in this context is that this painting is thought to be one of a series of 12 that Bruegel produced that year, one for each month (*Hunters in the Snow* being for January); none of the four others that survive show a landscape in the grip of deep cold. Indeed, both *Haymaking* (July) and *The Harvesters* (August, figure 4b) depict warm summer days with workers gathering a plentiful harvest. Even *The Return of the Herd* (thought to be the painting for November) and *The Gloomy Day* (known to be for February) show landscapes free of snow. The "Twelve Months" paintings depict a Europe that is very far

from the uninhabitable state of an ice age. *Hunters in the Snow* was clearly influenced by the scenery Bruegel saw when crossing the Alps on a trip to Italy in 1551/2, but he also painted other snow-bound scenes of the low countries in 1565 (and even the later wintry paintings by his son, Pieter Brueghel the Younger, were based on sketches that his father had made in 1565). We also know that it was in the December of that winter that the Thames in London froze sufficiently for Elizabeth I to walk on it, suggesting it may have been an unusually harsh winter throughout Europe.

Combining all the available chronicles, there are six reported severe winters in England in the 50 years prior to 1565 and six in the 50 years after. This is a much higher occurrence rate than we experience today, but it is not an ice age – little or otherwise. Many aspects of the paintings of Bruegel the Elder make them brilliant and innovative artworks rather than records of climate: they were revolutionary in depicting winter at all, it previously having been seen as a dull, dreary, even frightening season and avoided by artists. Hence it is possible that his winter scenes are primarily testament to his artistic inventiveness

and boldness and it is even possible that he painted them not because they were typical, but because they were unusual.

The Maunder minimum
The husband and wife astronomers Walter and Annie Maunder studied the occurrence of sunspots. In 1890, Walter presented a paper on the work of Gustav Spörer to the Royal Astronomical Society and in 1894 published a paper entitled "A prolonged sunspot minimum". The interval when the Sun was almost free of sunspots (c.1645–1715) had been noted by Spörer, and the Maunders' work to confirm its existence resulted in it being termed the "Maunder minimum". A prior period of minimal solar activity (c.1420–1550), identified from ^{14}C abundances in tree rings, is now named after Spörer. Figure 3a shows the sunspot number (decadal means of observations and inferred from ^{14}C) and demonstrates both the Spörer and Maunder minima.

There is no straightforward connection in figure 3 between the sunspot variations and the variations in ΔT_{NH}. One can identify times when the two appear to vary together but, for some of these, ΔT_{NH} follows sunspot number R, but for others it is the other way round. Of particular note are the most recent data, in which the opposite sense of trend in ΔT_{NH} and R – that Lockwood & Fröhlich (2007) noted as beginning in 1985 – has continued to the present day. It is, however, noticeable that the lowest ΔT_{NH} of the LIA did occur during the Maunder minimum (MM). For this reason, it has become increasingly common to associate the LIA with the MM; indeed, in some instances the two terms have even been used interchangeably.

Frost fairs
The frost fairs held on the frozen River Thames in London are often invoked as evidence for an effect of the MM on climate. Such evidence is anecdotal in nature and, as pointed out by Jones & Mann (2004) and Jones (2008), can be misleading for a host of different reasons. The date of the first such fair is often said to be 1608, and indeed this appears to be the first time that the name "frost fair" was used. However, there is also the definition of what constitutes a "frost fair" to consider. Eyewitness reports from as early as AD 250 talk of social gatherings on the river, which in that year was frozen solid for six weeks. Note that there is always the potential for confusion between "old" (Julian) and "new" (Gregorian) dates in these reports as the correction can be omitted, applied in error or even applied multiple times. The chronicler Thomas Tegg reports that that the Thames froze for over six weeks in 695 and that booths to sell goods were

4 Two works by Dutch painter Pieter Bruegel the Elder (c.1525–69), part of the series known as "the Twelve Months", commissioned by a wealthy patron in Antwerp, Niclaes Jonghelinck, and painted in 1565 during the Little Ice Age. (a) The January painting, *Hunters in the Snow* (also known as *The Return of the Hunters*), is often used to reinforce the idea of unremittingly cold conditions in the Little Ice Age. (b) Almost never shown in that context is the painting for August, *The Harvesters*, which depicts workers gathering crops on a warm summer's day. The other surviving pictures in the series are *The Gloomy Day* (February), *Haymaking* (July) and *The Return of the Herd* (probably November), none of which give any indication of unusually cold conditions. If Bruegel did paint all 12 months then, sadly, seven have been lost. (Courtesy of Kunsthistorisches Museum in Vienna and the Metropolitan Museum of Art, New York)

erected on it (Tegg 1835). Fires were lit and sports organized on the frozen river in 1309. It is probable that frost fairs became fashionable through the influence of Flemish immigrants from the Low Countries, where such events had been common for some time, and how much this contributed to their increased occurrence – as opposed to an increased occurrence in the required meteorological conditions – is not known.

Another problem with attaching significance to the frost fair dates is that it is certainly not true that a frost fair was held every winter in which the river was sufficiently frozen. In the winter of 923, the river carried loaded horse carts for 13 weeks and in both 1150 and 1410 the same was true for 14 weeks, but no frost fair is mentioned in the records. There are potential social, political, economic, health and, possibly, supply shortage reasons for this. Frost fairs were often bawdy and unruly events and were sometimes discouraged by puritanical authorities. It is noticeable that between the frost fairs of 1763 and 1789 there were five winters in which the Thames was reported as freezing yet there is no record of a frost fair being held. The winter of 1776 was particularly cold, with heavy snow and the river was known to be frozen. However, that winter London was also hit by an influenza epidemic, one that is estimated to have killed 40000 people in England.

The year 1740 may point to other problems. The Thames was frozen solid for about eight weeks, but before then ice floes, fog and damage to riverside wharfs disrupted shipping and there were great shortages of fuel, food and drink supplies in the city. Attempts to unload cargoes upstream and bring them by road were hampered by heavy snow. Andrews (1887) quotes a source as saying "the watermen and fishermen … and the carpenters, bricklayers … walked through the streets in large bodies, imploring relief for their own and families' necessities; and, to the honour of the British character, this was liberally bestowed. Subscriptions were also made in the different parishes, and great benefactions bestowed by the opulent, through which the calamities of the season were much mitigated". (This is true to an extent: for example, the philanthropist and, effectively, Britain's first prime minister Sir Robert Walpole donated £1000 – almost £100 000 at today's prices.) In 1740, a frost fair was held despite the crisis, but in other years such circumstances may have made it impossible.

Records indicate that harsh winters on their own did not generate food shortages in London, but harsh winters at times of economic depression did; how devastating they were for the population depended greatly on the readiness of welfare provision (Post 1985). Incidentally, in 1740 temperatures were exceptionally low on some days: the Reverend Derham in nearby Upminster, Essex (a regular and careful observer of meteorological and auroral phenomena and a Fellow of the Royal Society), recorded the frost of this winter as the most severe on record and that the temperature on 3 January fell to –24°C. This was after the end of the Maunder minimum – indeed Derham himself had noted the return of aurora over Upminster in 1707, 1726 and 1728 (Lockwood & Barnard 2015). The monthly mean Central England Temperatures (see next section) were –2.8°C in January and –1.6°C February that year.

> "The author claims the first page was printed by a press installed on the river ice"

Because of these multiple reasons why conditions favourable for frost fairs were not always exploited, we here look at the dates of both frost fairs and of reports that the Thames was frozen sufficiently for people to walk on it (and that the tidal variations did not break up the ice). However, this record is not homogeneous and the number of reports of such a freezing Thames increases with time over the years 1400–1600 as the number of surviving diaries and chronicles increases. It is notable that two of the three reports in 50 years of the mid-16th century exist because of royalty: in 1537, Henry VIII and his queen (then Jane Seymour) rode in a sleigh on the ice-bound river from Whitehall to Greenwich; and at Christmas 1564, Queen Elizabeth I is said to have walked and, in some accounts, practised archery on the frozen Thames. That it took royal involvement to generate an account may indicate an underreporting of the phenomenon in other years at this time; many of the chronicles describe some deep and prolonged frosts in England during winters for which we have no reports of the Thames freezing.

There are several books on the frost fairs, but perhaps the most interesting is that by Davis (1814). The title is entertainingly long and often shortened to *Frostiana*. An interesting aspect is that the author (and printer) claims that the first page was printed by a press installed on the river ice at the 1814 (and last) frost fair. In figure 5, the dates of known frost fairs are marked by vertical mauve lines, whereas the dates in which the Thames was known to be frozen solid, sufficient for people to walk on it (yet there is no known record of a frost fair), are shown
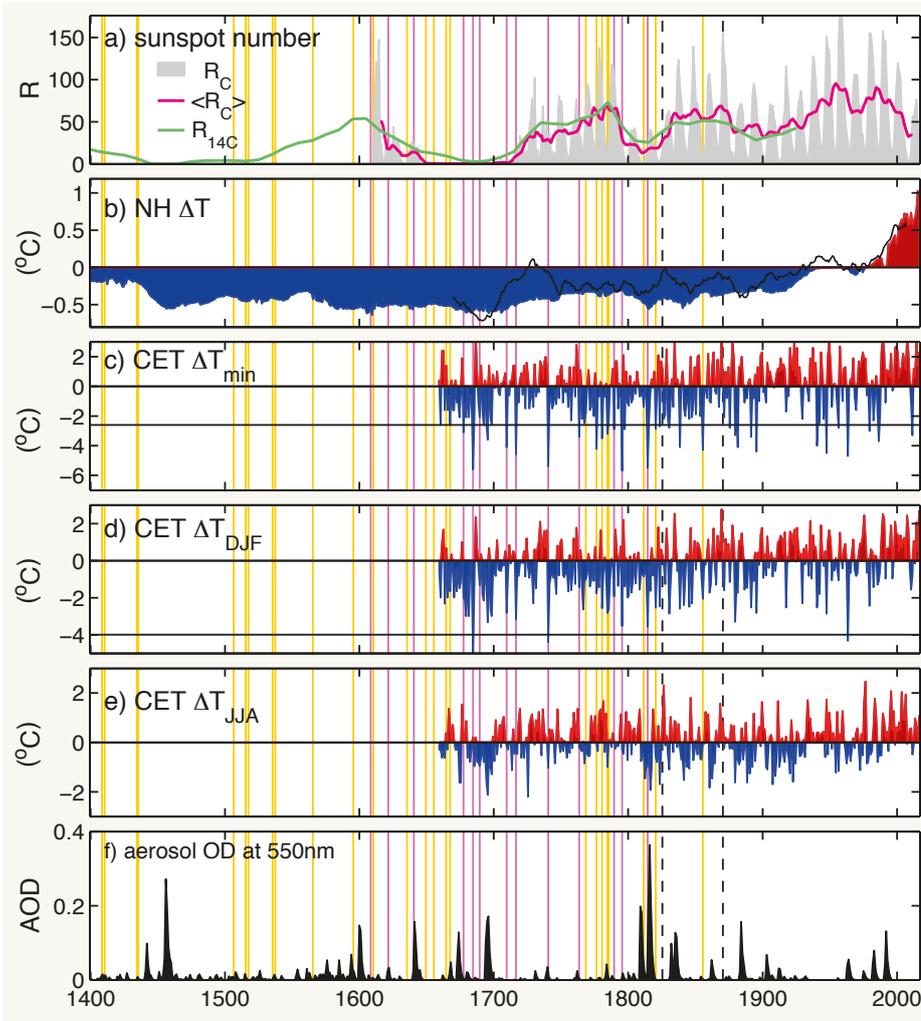
5 (a) Sunspot number estimates: (grey area) the extended sunspot number sequence of Lockwood *et al.* (2014), R_C; (magenta line) 11-year running means of R_C <R_C>; (green line) smoothed sunspot numbers derived from dendrochronology ^{14}C abundance measurements, R_{14C} (Usoskin *et al.* 2014). (b) The mode of the distribution of the reconstructions of the northern hemisphere mean air surface temperature anomaly by Masson-Delmotte (2013) extended to after 1997 using the HadCRUT4 observations record (Morice *et al.* 2012), ΔT_{NH}. The black line is 0.7<ΔT_{ann}> where T_{ann} is the annual mean of the Central England Temperature (CET) and the averaging is done over 10 years. (c) The anomaly in the lowest monthly mean CET in each winter, ΔT_{min}. The mean of T_{min} over the reference period (1961–90) is 2.6°C and so the horizontal line drawn at ΔT_{min}=−2.6°C corresponds to T_{min}=0°C. (d) The anomaly in December, January, February means in CET, ΔT_{DJF}. The mean of T_{DJF} over the reference period is 4.0°C and so the horizontal line drawn at ΔT_{DJF}=−4.0°C corresponds to T_{DJF}=0°C. (e) The anomaly in June, July, August means in CET, ΔT_{JJA}. The mean of T_{JJA} over the reference period is 15.3°C. (f) The volcanic aerosol optical depth (AOD) at 550 nm derived from sulphate abundances in ice sheet cores by Crowley & Unterman (2013). All anomalies are with respect to the mean for the reference interval 1961–90. Vertical mauve lines are the dates of frost fairs, and orange lines are reports of the Thames frozen solid. The vertical dashed lines are the demolition of the old London Bridge in 1825 and the completion of the embankments with the opening of the Victoria embankment in 1870.

by orange vertical lines. These have been identified by surveying original diaries and chronicles (e.g. Davis 1814, Tegg 1835, Lowe 1870, Andrews 1887) and the newspapers of the day; the list agrees well with that compiled by others (e.g. Lamb 1977).

Central England Temperature records

The Central England Temperature (CET) dataset is the world's longest instrumental record of temperature (Manley 1953, 1974, Parker *et al.* 1992). It starts in 1659, near the start of the Maunder minimum, and continues to the present day. The CET covers a spatial scale of order 300 km, which makes it a "small regional" climate indicator; to some extent it will reflect changes on both regional European (~3000 km) and hemispheric scales but, without the averaging over the larger areas, will show considerably greater inter-annual variability. The measurements were (and still are) made in a triangular region between London, Bristol and Lancaster and always in rural locations: this means the data sequence is not influenced by the "urban heat island" effect and the growth of cities. In winter, the North Atlantic Oscillation (NAO) and associated changes in thermal advection contribute a large fraction of the observed variability of CET. The CET does show a marked long-term warming trend (Karoly & Stott 2006). Monthly means of CET are available for January 1659 onwards, but the daily record begins on 1 January 1772 and continues to the present day. The uncertainty in monthly means from November 1722 onwards and for 1699–1706 inclusive (the latter period being largely based on Derham's observations made in Upminster) is estimated to be ±0.1°C. For the other years between 1659 and October 1722, the best error estimate for the monthly means is ±0.5°C.

Figures 5c–e show various sequences taken from the monthly CET data sequence. All are presented as a temperature anomaly ΔT with respect to their mean value for 1961–1990, with red shaded areas for positive anomalies and blue for negative. In figure 5c, the anomaly in the lowest monthly mean in each winter is shown, ΔT_{min}. There is an excellent agreement between the winters of large negative ΔT_{min} values and the dates of frost fairs and solid river freezing. This agreement exists from the start of the CET data until 1825. If there is uncertainty when the first Thames frost fair took place, there is none about when the last was, it being almost the last time that the Thames ice was thick and firm enough to support one. This frost fair, in 1814, lasted just five days (1–5 February), the river having frozen solid on the last day of January. An elephant was led across the river at Blackfriars and various booths and printing presses established on the ice. However, the fair ended badly with a sudden thaw: many booths were lost and at least two young men lost their lives (such tragedies were quite common at the end of frost fairs). This may explain why, six years later when the river froze solid for the last time in London, no frost fair was held.

After 1825, the ΔT_{min} values often fell to levels that had given frost fairs in previous years, but there are no reports of the river freezing to the same degree as before (a woodcut from February 1855 shows people walking on the ice in central London, but it also shows that the ice was not a complete covering). The mean of T_{min} over the reference period (1961–1990) is 2.6°C and so the horizontal line drawn at ΔT_{min}=−2.6°C in figure 5c corresponds to T_{min}=0°C, the freezing point of pure, static water. Although the freezing point of the brackish tidal water at London would be lower than 0°C, freezing conditions for a whole month would not be necessary to build up a great enough thickness of ice (of order 10 cm) sufficient to support groups of people. Hence ΔT_{min} below −2.6°C in monthly means would probably have been sufficient enough to freeze the Thames solid.

The reason why freezing increasingly failed to happen, even though monthly ΔT_{min} values repeatedly fell below –2.6°C, is almost certainly that in 1825 (marked by the first vertical black dashed line) the old London Bridge was demolished. This bridge had many small arches and elements of a weir, which slowed the flow and allowed ice to form and thicken. The river flow was further increased by the building of the embankments, a programme completed with the opening of the Victoria embankment in 1870 (the second vertical dashed line). Andrews (1887) notes of the very cold winter of 1881, "it was expected by many that a Frost Fair would once more be held on the Thames", but does not explain why there was none. In 1883 and 1896, ice floes formed on the river but it did not freeze solid. Hence the end of the frost fairs and Thames freezing was caused by the riverine developments rather than climate change. Jones (2008) notes that the low ΔT_{min} of 1963 did cause the Thames to freeze upstream of London at Windsor (figure 6), sufficient for football matches and other activities to be pursued on the ice: by this time the size, banks and flow rate of the river at Windsor were all similar to those prevailing in London 200 years earlier, although the river at Windsor is not tidal.

Figure 5d shows the winter (December, January and February) mean CET anomalies, ΔT_{DJF}. Agreement with the occurrence of Thames freeze dates is good, but not as consistent as for ΔT_{min}. This is not surprising because the cold snap required to freeze the river would depress the temperature in one month and so reduce ΔT_{min}, but the three-month average need not be so greatly depressed if temperatures before and after the cold snap were not as low. Note the great inter-annual variability in the CET winter temperatures: the coldest winter (lowest ΔT_{DJF}) in the series is 1684 (the year of the most famous frost fair, shown in figure 1) yet the fifth warmest winter in the whole series to date is just two years later. Hence even at the peak of the LIA there were exceptionally mild winters in England.

Figure 5e looks at the summer CET anomalies (means for June, July and August) and shows that the agreement of cold summers and Thames freeze dates is even poorer. Indeed, several of the frost-fair years had relatively hot summers (bear in mind the anomalies are with respect to the CET JJA mean for 1961–90, which is $T_{JJA} = +15.3°C$). Thus the CET data, like Bruegel's paintings, dispel the impression that the LIA was a period of unremitting cold: the cold winters were often interspersed with very mild winters and/or with hot summers.

Figure 5b shows the anomaly (again with respect to 1961–90) in the mode of the pdf of the northern temperature, ΔT_{NH},

6 A cyclist, David Joel, rides on the frozen River Thames at Windsor in 1963.

from the paleoclimate reconstructions used in figure 3b. Note the smaller range of the scale for this panel. Averaging over a whole hemisphere has smoothed out the inter-annual variability in the seasonal CET data. The black line shows the annual mean CET anomaly that has been passed through a 20-year running mean filter to smooth out this inter-annual variability. It has also been divided by 1.4 for comparison. It can be seen that the CET shows a similar long-term trend to the reconstructed northern hemisphere temperature since 1900 (but one that is larger by a factor of 1.4). Before 1900, we do see considerably more variability in the CET trend, but this is not unexpected because CET is a small-regional climate measure and not a hemispheric or global one.

Potential causes of Thames freezing events

Figures 5a and 5f give indicators of the solar and volcanic aerosol variations. Figure 5f shows the volcanic aerosol optical depth, AOD at 550 nm. Many of the dates of reported Thames freezing events are soon after volcanic eruptions, even if in some cases the associated rise in AOD is relatively minor. This not always true: for example, the major rise in AOD thought to be caused by eruption of Kuwae (or potentially Tofua) in 1452/3 is not followed by a known report of the Thames freezing; the same is true for the peak AOD associated with a number of erupting volcanoes in 1441/2, and that associated with the eruption of Huaynaputina in 1600.

The putative Kuwae/Tofua eruption is one of those that has been linked with the second pulse of the LIA. Thames freeze winters that could be associated with significant AOD rises (to within the estimated 1-year uncertainty in the ice sheet core dating) are 1595, 1640, 1677, 1695, 1811 and 1814. The largest peak in the AOD in the period covered by figure 5 is the major eruption

of Tambora in July 1815. The effect of this can be seen in ΔT_{NH} and in all the CET anomalies, including for summer (ΔT_{JJA}), the negative values of which in 1816 mark the so-called "year without summer". Eyewitness accounts tell us that the Tambora eruption took place after the 1814 frost fair; that year's fair might be related to the major unknown eruption inferred from the ice core data to have taken place two or three years earlier at tropical latitudes and followed soon after by four known eruptions. Hence it is probable that volcanic eruptions contributed to generating conditions that led to the Thames freezing over, but the lack of a clear one-to-one relationship indicates that they are not the only factor involved.

The grey area in figure 5a gives the annual mean sunspot number composite of Lockwood et al. (2014), R_C. It should be noted that there is discussion about the most accurate sunspot number reconstruction (e.g. Lockwood et al. 2016), but greater problems have been identified with the only other reconstructions that reach back to before the Maunder minimum. The differences between the reconstructions are not important here: we simply require a sequence that identifies both the Maunder and Dalton minima (c.1650–1710 and 1790–1825, respectively). The magenta line shows 11-year running means of R_C. The green line is the sunspot number derived from ^{14}C abundances measured in tree rings, which are used to extend the sunspot data to before the first observations. In the period of overlap with the sunspot observations there is good agreement between R_{14C} and $<R_C>$ (the magenta line), where the averaging of R_C is done over the sunspot cycle length of 11 years. The ^{14}C data define the Spörer minimum (c.1420–1550).

Lockwood et al. (2010) noted that the coldest years in the CET winter temperatures (lowest ΔT_{DJF}) were at low solar activity, but that low solar activity did not always lead to such cold winters. The most likely explanation of this potential solar influence on the occurrence frequency of cold European winters is being confirmed by numerical modelling that extends up into the stratosphere and allows for upper-end estimates of the long-term variability of the UV solar flux with solar activity, via its action on the stratospheric temperature gradient in the winter hemisphere (Ineson et al. 2015, Maycock et al. 2015). Hence low solar activity may well also have played a role in generating cold winters in the UK.

Figure 7 compares the occurrence of Thames freezing events with solar activity and the northern hemispheric air surface temperature reconstructions. Figure 7b shows f_{FT}, the occurrence frequency of

> **"Low solar activity may also have played a role in generating cold winters in the UK"**
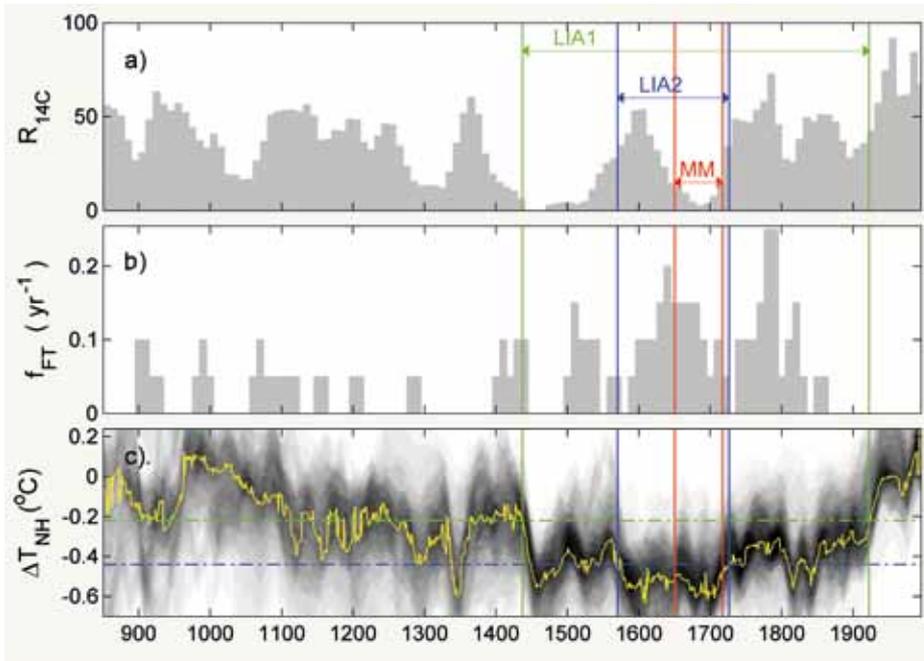
7 (a) 10-year means of sunspot numbers derived from ^{14}C abundances, R_{14C}. (b) The occurrence frequency f_{FT} of winters in which the Thames is reported to have frozen solid (computed for intervals 20 years long and 10 year apart). (c) The pdf (grey scale) of combined reconstructions of the northern hemisphere temperature anomaly, ΔT_{NH}, and the optimum (mode) value of the distribution (yellow line). The horizontal green and blue dashed lines are at –0.22°C and –0.44°C (ΔT_{NH} anomalies with respect to the means for 1961–90). In all three panels the vertical green lines mark the Little Ice Age defined by the mode anomaly ΔT_{NH} below the –0.22°C threshold (termed LIA1, which covers 1437–1922); the vertical blue lines mark the Little Ice Age defined by the mode ΔT_{NH} below the –0.44°C threshold (termed LIA2, which covers 1570–1726); the vertical red lines mark the Maunder minimum set by the decadal means of R_{14C} below 15 (labelled MM and covering 1650–1717).

winters in which the Thames was reported to freeze solid (computed in 20-year intervals with start times that are 10 years apart, so intervals overlap by 50%). Figure 7a shows the decadal means of the sunspot number calculated from ^{14}C abundance in tree rings, R_{14C}. It can be seen that f_{FT} and R_{14C} show no clear relationship. The horizontal green and blue dashed lines in figure 7c mark ΔT_{NH} anomaly levels (with respect to the mean for 1961–1990) of –0.22°C and –0.44°C. The mode value of the reconstructed ΔT_{NH} falls below these thresholds during the years 1437–1922 (here

termed LIA1 and delineated in figure 7 by the vertical green lines) and 1570–1726 (here termed LIA2 and shown between the two vertical blue lines). The vertical red lines mark the Maunder minimum, when the decadal means of R_{14C} are below 15 (labelled MM and covering 1650–1717).

It can be seen that there was a rise in f_{FT} that coincides with the Little Ice Age defined by the lower threshold of ΔT_{NH} (LIA2). However, there is a bigger peak in f_{FT} at 1780–1800 that is after the end of LIA2 (but still within LIA1) when average northern hemisphere temperatures have

risen again. This peak is also after the MM ended and when mean sunspot numbers R_{14C} and $\langle R_C \rangle$ exceed 50.

We conclude that winters in which the Thames froze are not at all good indicators of the hemispheric or global mean temperatures, although well-correlated with the lowest temperatures in the local observational record, the CET. The often-quoted result that they were enhanced during the solar Maunder minimum is false. Thames freeze years are slightly more frequent before the Maunder minimum began and also considerably more common 65 years after it ended. The association of the solar Maunder minimum and the Little Ice Age is also not supported by proper inspection and ignores the role of other factors such as volcanoes. Together these mean that, although the LIA covers both the Spörer and Maunder solar minima, it also persisted and deepened during the active solar period between these two minima. The latest science indicates that low solar activity could indeed increase the frequency of cold winters in Europe, but that it is a phenomenon that is restricted to winter and is just one of a complex mix of factors.

It is vital to avoid semantic arguments based on the name the Little Ice Age: ice ages proper are a lot more than a period in which the frequency of somewhat colder winters is somewhat elevated. Lastly, if we must use the name Little Ice Age, we should know it for what it really was and our best insight into that comes not from anecdotal reports influenced by a great many factors, nor from speculation about the inspiration for a few artists 450 years ago, but from the truly colossal number of objective datapoints, derived by many scientists using a huge variety of sources and techniques, that have gone into the construction of figure 3b. ●

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