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Climatic reconstructions for the northeast Atlantic region AD 1685–1700: a new source of evidence from naval logbooks

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Abstract: This paper draws on a newly developed source of data in the form of ships' logbooks to cast a detailed light on the weather and climate of a critical period in recent climatic history: the decades of the 1680s and 1690s, possibly the coldest of the last 1000 years. Logbooks of the period provide daily data for wind force, direction, precipitation and general weather conditions. These were abstracted and aggregated into monthly statistics. These data indicate the highly episodic character of air flow patterns at this time, with marked changes of phase between high and low zonality in the westerlies. The data also provide evidence of the stormy character of the period, particularly with respect to summer conditions. Comparisons are made with contemporary and independently derived instrumental and proxy series. The data source is confirmed as providing a valuable addition to climatic sources, and is additionally important because it is based on regular daily observations and made at sea – an area very poorly represented for this time period.

Key words: Ships' logbooks, 'Little Ice Age', Maunder Minimum, palaeoclimatology, climatic reconstructions, northeastern Atlantic.

Introduction

In 1809 Francis Beaufort wrote a letter to his brother-in-law, Richard Lovell Edgeworth, which included the following prescient observation:

> There are at present 1000 King's vessels employed. From each of them there are from 2 to 8 Logbooks deposited every year in the Navy Office; those log books give the wind and weather every hour ... spread across a great extent of ocean. What better data could a patient meteorological philosopher desire? Is not the subject, not more in a scientific than a nautical point of view, deserving of laborious investigation?

This quotation is of interest because the majority of the logbooks to which Beaufort drew attention have survived, yet it has taken two centuries to put to scientific use the climatic information that they contain. This paper focuses on the oldest of the English logbooks and uses them to examine the climate of the 1680s and 1690s and falling therefore within the period generally termed the 'Little Ice Age' (LIA – this paper adopts this short-hand description, whilst recognizing the term to be subject to redefinition (Jones and Mann, 2004)). The undertaking meets also the aim of drawing attention to this important source of evidence that will be shown to add to the already '... broad spectrum of high resolution multi-proxy and instrumental data ... ' for this period (Luterbacher *et al.*, 2001: 442) and, significantly, does so for a part of the planet's surface that is under-represented in observational information – the seas and oceans. The logbook-based findings can be compared profitably with those derived from other high-resolution data for this critical climatic period

An early paper by Oliver and Kington (1970) drawing attention to the utility of logbook data excited little immediate attention, and until the last few years the climatic application of logbook material has been restricted to small-scale studies of particular events, such as naval battles (Wheeler, 1999, 2001), or to specialized collections such as those of the logbooks of the Hudson's Bay Company (Catchpole, 1992). This reluctance to embrace the data source may stem from a misplaced lack of confidence in non-instrumental, qualitative observations or, ironically, from the very challenge presented by the huge number of logbooks that have survived from the pre-instrumental period before the mid-nineteenth century. In the UK alone, they number many tens of thousands, and their use demands Beaufort's 'laborious investigation' in the truest sense of the term. More recently, however, the activities of National Center for Atmospheric Research (NCAR) have seen the US collection of Matthew Maury's logbooks included with

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the ICOADS (International Comprehensive Ocean and Atmosphere Data Set) data base, while in Europe the EU-funded CLIWOC (Climatological Database for the World's Oceans 1750–1850 web site at http://www.ucm.es/info/cliwoc, last accessed 12 September 2005) project has made notable progress using eighteenth- and early nineteenth-century English, French, Dutch and Spanish logbooks. These sources have a near-global coverage but English logbooks for vessels in home waters (essentially the English Channel and the Western Approaches) can be called upon to provide a continuous daily record from the late seventeenth century. This paper examines these logbooks for the years from 1685 to 1700. This period, fortuitously, brings together the oldest logbooks in English archives, one of the coldest episodes of the LIA in Europe (Luterbacher *et al.*, 2004), and covers also part of the phase of solar quiescence known as the Late Maunder Minimum (Eddy, 1976). There are also sufficient land-based and reliable instrumental and proxy data to allow calibration and verification of the logbook results with records such as Manley's Central England Temperature series (Manley, 1974), the barometric records of William Dereham from Upminster, Essex and Louis Morin from Paris (Slonosky *et al.*, 2001), and Luterbacher *et al.*'s (1999, 2002) NAO and EU index reconstructions.

Logbooks: the data source

The National Maritime Museum (Greenwich, UK) houses the British national collection of logbooks prepared by the lieutenants of the Royal Navy. A few logbooks date from the 1670s, but they are abundant only from the 1680s onwards. The logbooks contain daily records kept whilst ships were operational, and were submitted to the Admiralty at the close of each voyage. They are thus of variable length, but usually cover periods of several months. The close of the seventeenth century saw much naval activity through the English Channel, with the English being variously engaged with the Dutch and the French navies and the large number of extant logbooks from that time provides the possibility of constructing a daily series of weather observations for the much frequented waters of the Channel and Western Approaches.

Logbooks served many purposes, but paid close attention to the weather that, in this age of sail, did much to circumscribe the activities of the ships. Weather observations were non-instrumental and based on the judgement of the officer in question. They included wind force, wind direction and notes on the general state of the weather. Such observations were made regularly at noon, this being the start of the nautical day although 12 hours ahead of the civil day. This hour was preferred as it allowed observations to be made of the midday sun and the vessel's latitude thereby to be estimated (Harries, 1928). Longitude, on the other hand, could only be calculated by the processes known as 'dead reckoning', and these required careful and reliable note of the weather conditions with which to estimate the 'leeway' of the ship; this being the effect that the wind had on the sailing direction of the ship in question. The solution to the famous longitude problem lay 100 years later than the period in question (Hewson, 1983). Most importantly, the logbooks were prepared using a broadly consistent vocabulary of weather terms and the records can be regarded as being prepared to a standard that, although unofficial, appears to have enjoyed wide currency (Wheeler, 2003). Finally, because the mariners were concerned with everyday weather, all of which is carefully recorded, there is no bias towards extreme conditions, indeed they seem to have adopted a phlegmatic attitude towards the harshest of conditions, noting them but not giving them undue emphasis. Unquestionably a few ships will have succumbed to extreme storms, but even that of 1703 (Wheeler, 2004) saw the vast majority survive to report the event.

Logbooks were set out over two pages, and a typical example of the period is given in Figure 1a and b. The left-hand page contained navigational data such as latitude, longitude (usually from some arbitrary zero meridian, the Greenwich system not yet being universal or, indeed, commonplace), the ship's course and wind direction. The date and year were also given, but these were in the Julian calendar, which was then ten days behind the Gregorian system that was adopted in England only in 1752. Moreover, the New Year, depending upon the view of the officer, could be either 1 January or 25 March (Lady Day). Calendrical corrections to the present-day system had, therefore, to be made. The right-hand facing page contains narrative accounts of the day including important descriptions of the wind force and general state of the weather.

The sample of logbooks

A total of 52 logbooks were examined to provide a daily series of wind force, wind direction and weather notes from January 1685 to December 1700. Logbook data also indicated the location of the vessel, and observations were included only if they fell within the general area that today would be defined by BBC Shipping forecast areas Thames (southern part only), Dover, Wight, Portland, Plymouth, Lundy, Fastnet and the easternmost one-third of Sole (Figure 2). Logbook data were included only for those times when the ship in question was at sea or at open anchorage such as the Downs or the Nore off the east and north Kent coastlines, respectively. This minimized boundary layer bias in the wind data and eliminated the problem of a general lack of attention to detail that characterizes the logbooks of vessels whilst in port. For only 24 of the 5844 days in the study period could no data be found.

Data standardization and verification

Few studies have been carried out to assess the quality of logbook data, but those that have (Wheeler, 1988, 2005) strongly suggest them to be reliable. Only one previous study (Wheeler, 2004) has examined logbooks of this antiquity. The data derived were treated under their three principal headings of wind force, wind direction and weather notes. Even overlooking the difficulties posed by an archaic form of English characterized by inconsistent, often idiosyncratic, spelling and punctuation, and the inevitable difficulties of late seventeenth-century calligraphy, problems of scientific comprehension remained. Those of the general descriptions of the weather were the easiest to solve, and most accounts use non-specialist language that, whilst occasionally antiquated, is readily understood; good examples are 'dark cloudy weather with raine' and 'constant snow and sleet all day'.

Wind direction was the most consistently recorded of all three elements, often being noted three times a day. The abstracted daily series was based on the noon-day observations only. Directions were recorded using a 32-point compass, ie, with a scale of resolution of 11.25°. The convention that they were described, as they are today, by reference to the direction from which they blew was well-established, and the contemporary handbook *The seamans secrets* (published in 1633) is unambiguous in this matter; '... for the winds receiveth his

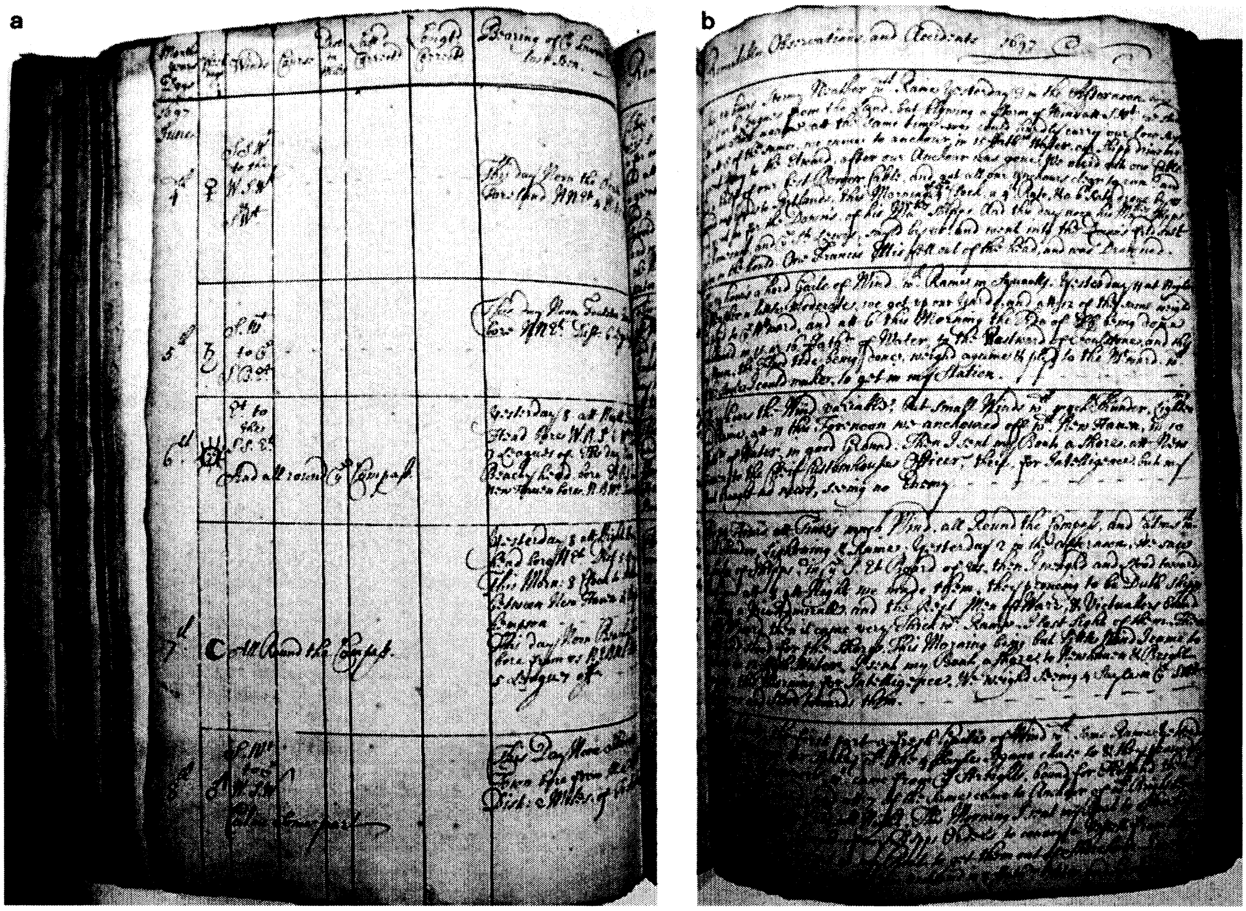

Figure 1 Facing pages from a logbook typical of the period. These written by an unknown officer on board HMS *Experiment* and date from June 1697. Courtesy of the National Maritime Museum

name by that part of the horizon from whence it bloweth.' The winds were recorded with respect to magnetic north, but the degree of local variation was relatively small at this time (Bloxham and Gubbins, 1985) and no correction had to be made to these data.

Re-expression of archaic wind force terms

Wind force observations presented a number of particular difficulties in comprehension. The vocabulary was specialist and adapted for use at sea, and terms had specific meanings not readily apparent to present-day readers. In common with the Beaufort Scale, expressions consisted of a basic descriptor with a single (occasionally two) adjectival qualifiers; for example 'strong gales', 'little wind' and 'pretty fresh gales'. A total of 70 different such descriptors were found. Importantly, the ten most commonly used terms (Table 1) accounted for 85% of all entries. Some of these, such as 'fresh gales' survived in common usage to be included in the Beaufort system, but many others are today unfamiliar; 'fine gales' and 'small gales' being good examples. Some 18 terms were used only three times or less. Officers were trained on board ship from a very early age, and the strong oral tradition that they acquired is reflected in these statistics. Thus, although the adoption of the

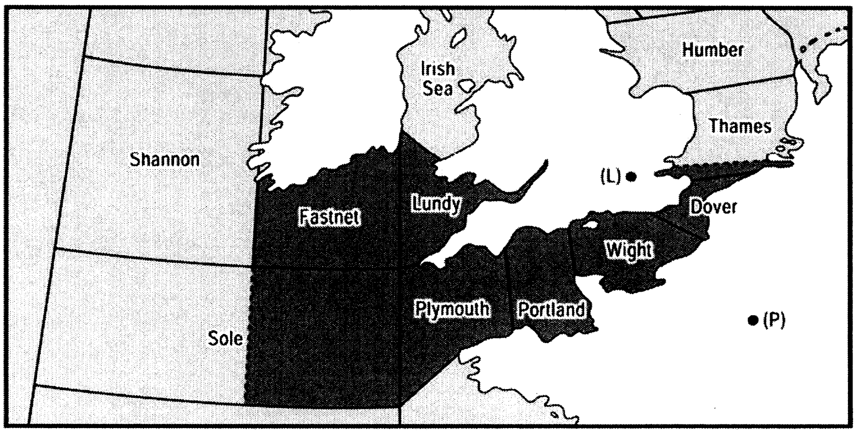

Figure 2 Study region indicated by reference to present day BBC Shipping forecast areas

Table 1 Frequency of usage of the ten most widely employed terms for wind force used in late seventeenth-century English logbooks

Rank of usage	Term	Frequency	Cum. frequency (%)
1	fresh gales	1211	29.4
2	little wind	621	44.5
3	moderate gales	457	55.6
4	blowing a hard gale	342	63.8
5	small gale	210	68.9
6	blows hard	207	74.0
7	variable	134	77.2
8	fine gales	129	80.4
9	calm	99	82.6
10	strong gales	93	84.9

Beaufort Scale by the Royal Navy had to wait until 1836, it is apparent that seventeenth-century officers were using a widely accepted, if unofficial, system of wind force descriptions.

Before the wind force terms could be used for analysis they had to be converted into modern-day Beaufort Scale equivalents. This process required care. For example, the word 'breeze' that today embraces forces 2 to 6 on Beaufort's Scale, was then new to the English language, having been derived from *brisa*, used by Spanish and Portuguese navigators to describe the trade winds. Yet it had already acquired a very specific meaning in English, made clear in Mainwaring's *Nomenclator Navalis* published in 1644 (see Manwaring and Perrin, 1922) in which is stated

> A breeze is a wind which blows out of the sea and doth daily in all seasonable fair weather keep his course, beginning likely about nine in the morning and lasting till it be within little of night. (1922: 110)

This is an unambiguous definition of what today is understood to be a sea breeze *sensu stricto*. The term was encountered only ten times in the current sample of over 5000 entries, and all for ships close to land. The term 'gale' had therefore to be more serviceable, and was used over the full range from what would today be Beaufort forces 2 to 10. The distinction between wind forces was made by the careful use of adjectival qualifiers, which, in addition to 'fresh' and 'strong', included such unfamiliar terms as 'fair', 'soft', 'easy', 'small' and many more. Some of these terms were popular at the time and the seventeenth-century definition of a gale betokened none of the foreboding that accompanies today's gale forecast warnings.

Understanding of the wind scale relied on grouping synonymous items, and placing those groups into an order determined by the meaning of the various adjectival qualifiers. Useful guidance was offered by contemporary nautical texts in which some of the terms are explained in more detail. John Smith's *A sea grammar*, written in 1627 (see Goell, 1970), *Boteler's dialogues*, first printed in the 1680s (see Perrin, 1929) and Mainwaring's *Nomenclator navalis* (Manwaring and Perrin, 1922) were of particular value. Logbooks also contained references to the sails carried in certain conditions, and this, too, helped to clarify the meaning of some terms. Lamb's (1991) use of Daniel Defoe's so-called 'Table of Degrees' (Defoe, 1704) to express archaic terms in Beaufort Scale equivalents was of limited assistance. Studies of the logbooks indicate that some of Defoe's terms were used only vary rarely whilst omitting others that were commonplace (Wheeler, 2003). After providing modern-day (Beaufort Scale) expressions of archaic terms, there remained from the original list of 70 descriptors only 20 that could not be classified with certainty, but these accounted for only 34 (0.01%) of all entries in the sample.

Primary data analysis and general climatology

Wind directions were the most commonly recorded observations in the logbooks. In order to provide a clearer picture of airflow behaviour these 32-point data were aggregated into north (N), south (S), east (E) and west (W) categories, with the four cardinal points lying at the centre of each defined quadrant. Although some statistical detail was lost by this process, the data set was rendered more manageable and subject to simpler numerical manipulation. The daily data were aggregated into monthly statistics thereby giving a measure of 'westerliness', 'easterliness', etc. It has already been demonstrated by Jönsson and Holmquist (1995) that wind direction data can be used as a means of examining climatic change at the decadal scale, and they found important correlations to exist between wind direction (taken from Lund in southern Sweden) and temperatures, these varying according to season and month but demonstrating how zonality and westerliness contributed to the temperature regime. It was to be over a century before ship-board temperature observations would be made, but the Central England Temperature monthly series (CET) can be called upon to provide a reliable, contemporary thermal record. The correlations of wind direction with temperature in the traditional four three-month seasons of the year are shown in Table 2. The results are in close agreement with those found by Jönsson and Holmquist (1995) and exhibit a structure that accords with climatological behaviour as it is currently understood. Over the year as a whole N and E airflows yield negative CET anomalies, and S airflows correlate with positive anomalies. But the seasonal patterns are more illuminating. Warmth is associated with S airflow in three of the four seasons, but with W airflows in winter only. Coolness is associated with N airflows in autumn and winter, and with E airflows in winter. Not surprisingly, winter shows a higher degree of climatological coherence (all correlations are significant at the 0.05 level), and summer the least (no significant correlations). This reflects the generally higher degree of 'organization' of Northern Hemisphere winter climates. These correlations are also in close agreement with those offered by Jones and Hulme (1997) for the period 1861–1995 in respect of Lamb's N, E, S and W airflow types. The one exception is for westerly situations, for which the seventeenth-century data show lower degrees of correlation with temperature, being +0.49 for winter and +0.15 for the year. The

Table 2 The correlation between wind direction frequency and CET anomalies from the contemporary 30-year (1681–1710) mean

CET anomalies	N	E	S	W
Annual	–0.26*	–0.23*	0.38*	0.15
Spring (MAM)	–0.27	–0.25	0.44*	0.09
Summer (JJA)	0.02	0.19	0.08	–0.19
Autumn (SON)	–0.29*	–0.13	0.42*	0.04
Winter (DJF)	–0.40*	–0.48*	0.38*	0.49*

The data are presented as seasonal aggregates but based on monthly data, each season being three months long, for which the sample size is $n = 48$. For the annual series, $n = 192$.
Correlations indicated * are significant at the 0.05 level.

Table 3 Correlations between wind direction frequencies and the NAO index derived by Luterbacher *et al.* (2002)

NAO index	N	E	S	W
Annual	−0.219**	−0.402**	0.173*	0.363**
Spring (MAM)	−0.189	−0.326*	0.110	0.363*
Summer (JJA)	0.005	−0.085	−0.248	0.209
Autumn (SON)	0.016	0.358*	0.200	0.167
Winter (DJF)	−0.418**	−0.540**	0.414**	0.533**

The data are presented as seasonal aggregates but based on monthly data, each season being three months long.
Correlations indicated * (**) are significant at the 0.05 (0.01) level.

1861–1995 counterparts are +0.71 for winter and +0.24 for the year.

Although temperature records are not available from logbooks, mariners appear to have been careful observers of cold and frosty days (but not, oddly, hot days), and a series of frost days could be abstracted. The winter season monthly series correlates significantly at $\alpha = 0.01$ with the CET ($r = -0.594$) and with northerliness ($r = 0.497$).

Similar comparisons can be made with Luterbacher *et al.*'s (2002) NAO reconstructions derived from multivariate proxy sources (Table 3). In the key season of winter all correlations between wind direction and the NAO index are significant, with the expected negative associations with E, and positive with W: both in agreement with Jones *et al.* (1997). However, the degree of westerliness at other seasons provides a significant correlation with the NAO index only in spring. The strength of the annual correlations must therefore be attributed to the winter influence. These results clearly demonstrate that the logbook wind direction data are sensitive to the atmospheric state as summarized by derived indices such as the NAO.

Attention was also given to the contemporary air pressure data from Paris (Louis Morin's record) and from Upminster in Essex (William Derham's records – see also Slonosky *et al.*, 2001). Luterbacher *et al.* (2000) have already established the primary importance of the former in any attempt to reconstruct pressure fields from this time. The logbook data, being drawn from vessels in the English Channel, represent an area that falls conveniently midway between these two sites that lie almost exactly on a north–south axis that extends across the eastern half of the study area (Figure 2). The pressure gradient between them was expected to shed further light on the sensitivity of logbook data to airflow behaviour. In this case the pressure gradient is defined by Paris minus Upminster. Table 4 shows that W and E frequencies correlate significantly with the pressure gradient across the English Channel for all seasons expect autumn. The correlations, not unexpectedly, are positive for W airflow but negative for E. On the other hand, those for N and S airflows are significant in only one instance, that of S airflow in autumn. Nevertheless, winter N and S airflows do correlate significantly with the west–east orientated EU (Eurasian circulation – see Luterbacher *et al.*, 1999) index based on gridded data for Britain minus those for the northern Black Sea area with $r = +0.29$ and $r = -0.31$, respectively.

Table 4 Correlations between wind direction and pressure gradients across the English Channel between Paris and Upminster

Pressure gradient (English Channel)	N	E	S	W
Annual	−0.19	−0.49*	−0.04	0.51*
Spring (MAM)	−0.35	−0.68*	0.23	0.60*
Summer (JJA)	−0.19	−0.50*	−0.14	0.58*
Autumn (SON)	0.25	−0.47	0.51*	−0.02
Winter (DJF)	−0.32	−0.50*	−0.26	0.73*

The data are presented as seasonal aggregates but based on monthly data, each season being three months long.
Correlations indicated * are significant at the 0.05 level.

These results, based as they are on independently derived sources, suggest the logbook data to be a reliable source of climatic information, able to reflect contemporary conditions.

Climatic interpretations of the AD 1680s and 1690s using logbook data

Logbook data are the first to provide a daily, monthly and annual picture of airflow and weather across the British Isles maritime region and are additionally important in that the data are not based on any natural proxy, but drawn from direct observations. Furthermore, although the sample is regionally based, the area in question is an important one that responds to wider-scale subhemispherical, synoptic-scale processes and might be expected to reflect such wider influences, and Luterbacher *et al.* (2000) have already demonstrated that wind direction (in their case for Øresund – see also Frydendahl *et al.*, 1992) performed well as a predictor in multivariate modelling of large-scale pressure field reconstructions for this period.

Figure 3 emphasizes the overall dominance of westerlies, but indicates also its fluctuating character and those years (1688 and 1695) when their supremacy was challenged by easterlies. The monthly data provide a more detailed picture, and Figure 4 shows the variation in the proportion of westerly winds for each month together with a 12-month, and therefore non-seasonal, running mean. These values can be regarded as an index of westerliness (W-index), the mean of which is 0.40 and the standard deviation 0.18. Late 1687 and early 1688 are seen as the periods when westerlies were least abundant, followed by early 1695. The monthly picture, however, shows notable high-frequency variation, with some months (February 1688, March 1690, February 1692, December 1695 and April 1697) with a W-index of less than 0.01, but others (October 1693 and September 1696) with over 0.8. The mean monthly frequencies are shown in Table 5. Even at this aggregated level there are differences between the months. August and September, for example, are notably westerly in character, but March and May less so. Easterlies are the second most abundant direction but in some months, such as January, February and March, they assume greater significance.

It is important, however, to examine the differences between late seventeenth-century and twentieth-century patterns. Taking the current data and those for coastal sites on the English Channel for the mid-twentieth century (Meteorological Office, 1968), Table 6 was prepared. The differences between the two periods are not, importantly, distributed evenly through the year. Nine months reveal a more markedly easterly character in the 1680s and 1690s, but March and September differ in this respect and were clearly more 'westerly' at that time. February and April seem also to have undergone important changes, with northerlies being less abundant during the study period. In general it is the early part of the year that appears to have experienced the greatest changes in circulation patterns. Luterbacher *et al.*'s (2001) monthly sea-level pressure reconstructions have also identified these months, and spring in particular, as those in which changes were greatest, and it is

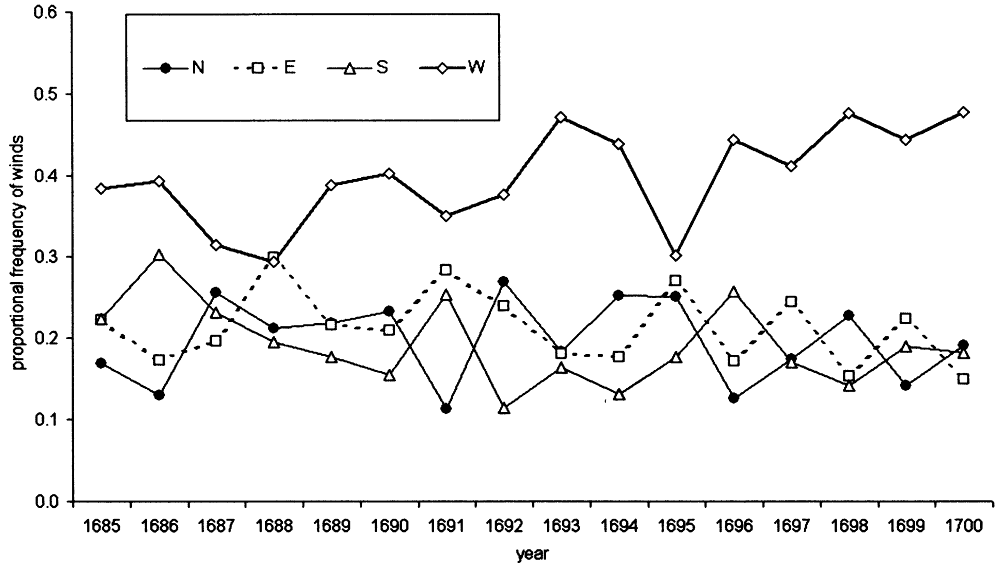

Figure 3 Annual frequencies (by proportion) of wind directions in the English Channel (1685 to 1700)

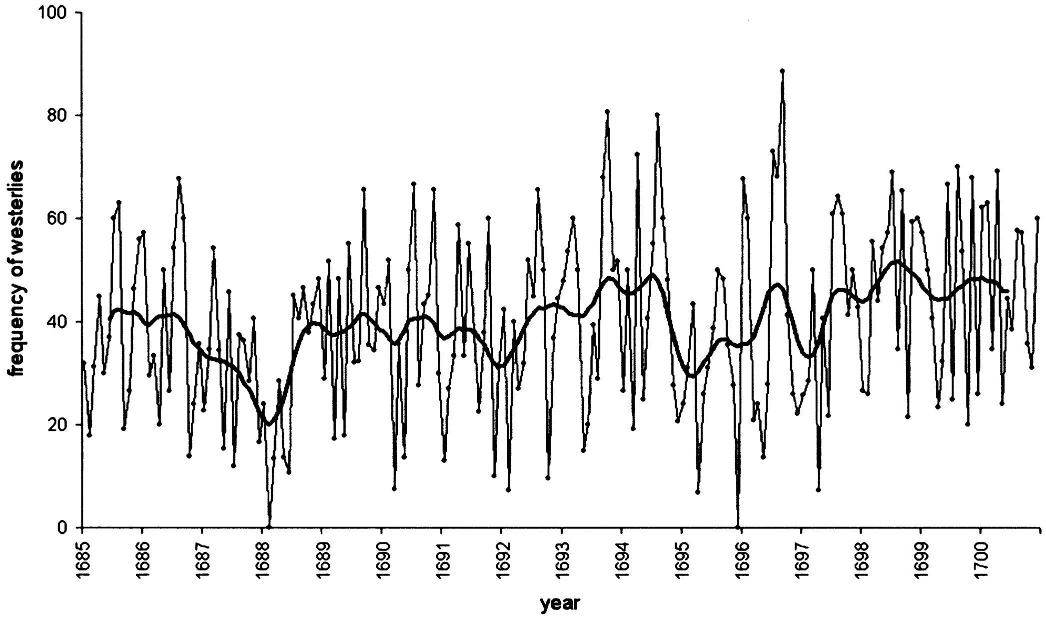

Figure 4 Monthly frequency (by proportion) of westerly winds in the English Channel (January 1685 to December 1700). The dark line is the 12-month running mean with Gaussian filter

encouraging to witness the ability of logbook data to identify the same patterns. The summer months show much less change with May and August being notable in this respect.

Few studies have hitherto explored such seasonal and monthly behaviour. Those by Wanner *et al.* (1994) and Kington (1995, 1997 and 1999) are noteworthy, although relying on land-based sources. The studies by Wanner *et al.* yielded a series of monthly summary synoptic charts; drawing upon these, Kington paid attention to the exceptionally cold winters of 1694/95, 1696/97 and 1697/98, which he defined as running from December to May. The modal wind direction for each of the months is summarized in Table 7. Of the 18 months, seven could be described as having an easterly character and a further three to be northerly. The remaining eight were, in contrast, westerly in character. There is therefore some independent corroboration for suggestions that meridionality was a feature of these months (Luterbacher *et al.*, 2001). However, the conditions were not those of an unremittingly easterly character. Thus, it might be concluded that whilst the coldest winter weather was indeed a result of

Table 5 Mean monthly wind directions (in proportions of each month) for 1685–1700

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
N	0.24	0.16	0.22	0.18	0.25	0.17	0.22	0.17	0.18	0.19	0.19	0.20	0.20
E	0.25	0.26	0.25	0.23	0.28	0.20	0.20	0.14	0.13	0.23	0.21	0.19	0.21
S	0.13	0.21	0.20	0.22	0.20	0.23	0.12	0.19	0.15	0.22	0.20	0.24	0.19
W	0.37	0.37	0.34	0.37	0.27	0.40	0.47	0.51	0.54	0.36	0.40	0.37	0.40

Table 6 Differences in proportions of wind direction frequencies between (modern) logbook (seventeenth century) data

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
N	0.01	0.10	– 0.09	0.12	0.02	0.08	0.02	0.02	– 0.04	0.01	0.06	– 0.06
E	– 0.09	– 0.05	0.13	0.03	– 0.04	– 0.04	– 0.09	– 0.02	0.09	– 0.04	– 0.03	– 0.05
S	0.11	0.02	0.06	– 0.06	0.00	– 0.04	0.02	0.00	0.08	0.02	0.08	0.04
W	– 0.02	– 0.07	– 0.11	– 0.09	0.02	0.01	0.05	0.00	– 0.13	0.01	– 0.10	0.08
Sum[a]	0.23	0.24	0.39	0.30	0.06	0.17	0.18	0.04	0.34	0.08	0.27	0.23

Differences (modern minus logbook) greater than 0.1 are indicated in bold.
[a]Sums of the absolute differences.

Table 7 Modal wind directions (and relative frequencies) for three cold winters in the Late Maunder Minimum

	1694/95	1696/97	1697/98
December	E (0.31)	E (0.30)	W (0.43)
January	E (0.34)	E (0.39)	N (0.30)
February	W (0.32)	N (0.33)	E (0.50)
March	W (0.42)	W (0.48)	W (0.54)
April	E (0.48)	E (0.46)	W (0.44)
May	N (0.37)	W (0.41)	W (0.54)

'blocking', such patterns tended not to be persistent and were episodic, and the climatic in these critical years seems to have varied greatly between periods of marked zonality and meridionality in the westerlies.

Storm activity in the 'Little Ice Age'

It has been suggested (Douglas *et al.*, 1978; Lamb, 1991; Kington, 1998) that the LIA was a time of notable storminess. Lamb observed that '... there are indications from the logs of ships of the nations around the North Sea, and from harbour records, that the 1690s – the climax decade of the cold climate in Britain, Iceland, Scandinavia and central Europe – may have been particularly stormy ... ' (1991: 123). Although he was unable to pursue this line of enquiry, the current data set helps to illuminate this area of debate. Using the wind force conversion table, a series of 'gale days' was prepared and aggregated into monthly totals. Figure 5 contrasts twentieth-century monthly gale frequencies for exposed sites on the southwest coast of England and for the sea area between 50° and 52°N and 5° and 10°W (abstracted from Couper *et al.*, 1974 and Meteorological Office, 1968) with those for the close of the seventeenth century. The latter are a conservative estimate based on those logbook terms that equate to force 9 or higher. This threshold of force 9 removes any possible bias in gale frequency overestimation should force 8 have been used. The number of such gales days annually was, even so, much higher, at 44, than was the situation in the mid-twentieth century, when the annual gale day frequency was 32 over a 30-year period. Of greater interest than this general indication of storminess is the distribution of gales through the year that demonstrates that the summer months account for most of the additional storm activity. The higher frequencies at this season may reflect cooler northern latitude conditions, and the consequent steepening of the temperature gradients over the mid-latitudes. The CET series confirms the period 1685 to 1700 to have experienced the coldest summers of the 346-year series while Jones *et al.* (1998) go further and suggest this period's summers to have been the coldest of the past millennium. Luterbacher *et al.* (2004) suggest this summer coolness to have embraced much of Europe at this time with temperatures being 0.2°C lower than the average for the twentieth century. This would imply greater cyclonic activity, perhaps of the type described in Douglas *et al.*'s (1978) account of the exceptional summer of 1588. Luterbacher *et al.* (2001) have also proposed that summer storm tracks were displaced southwards in the 1680s and 1690s. This would place them more certainly over the British Isles than is currently the case, and the logbook evidence supports this hypothesis.

In contrast, mid-winter storms were less frequent. Such a finding is not inconsistent with what has gone before. Most

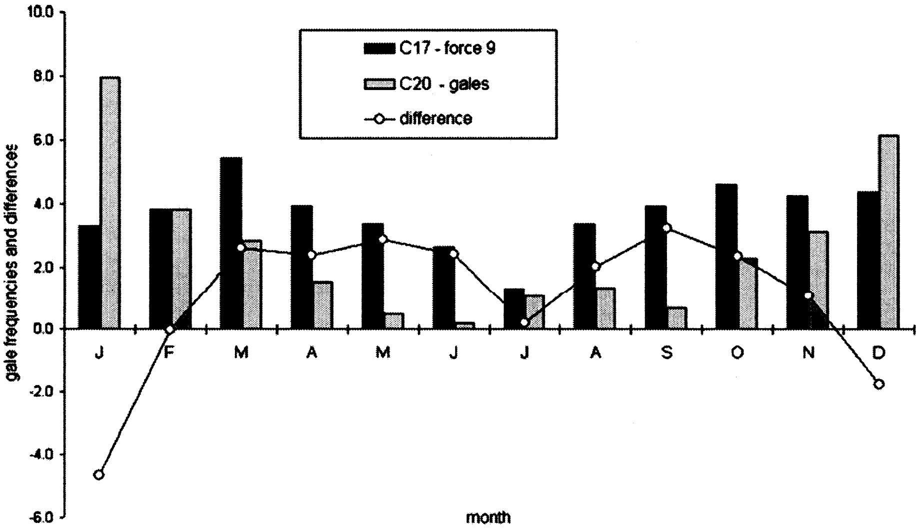

Figure 5 Bar chart of twentieth-century and late seventeenth-century gale frequencies in the English Channel. The difference is given by C17 minus C20 gale frequencies

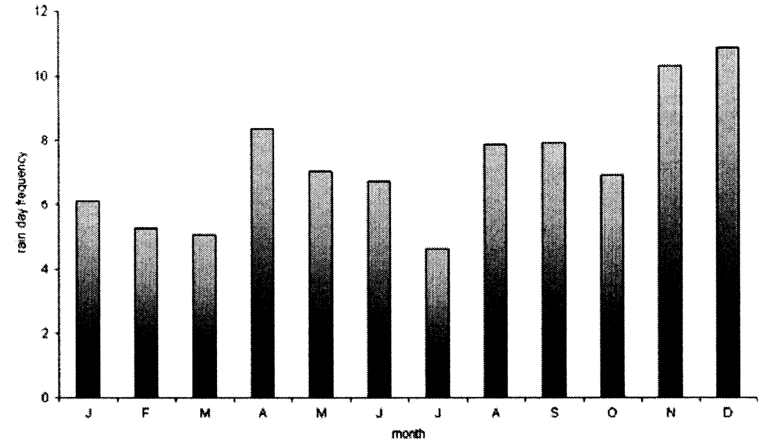

Figure 6 Bar chart of mean monthly rain days 1685 to 1700

importantly, episodes of 'blocking', which at this time of year are likely to be the consequence of westwards extensions of the Siberia anticyclone or persistent appearances of Scandinavian systems, would exclude cyclonic activity from the British Isles leaving systems to decline *in situ* to the west, or adopt anomalously northerly or southerly routes in order to pass eastwards. This finding again supports the suggestions of Luterbacher *et al.* (2001) who proposed the winter Icelandic low to have been less developed at this time with consequently weaker westerlies over the eastern North Atlantic.

Logbook precipitation records

No records were kept of rainfall depths, but precipitation in its various forms was noted. The terms used to describe rainfall varied, and sometimes indicated differences between light, heavy or showery types. In this study all such distinctions have been overlooked to provide a monthly series of rain days. The monthly rain day means are shown in Figure 6 in which the relative dryness of the first half of the year contrasts with the wetter conditions in the autumn and early winter. It will be noted from Table 5 that the first half of the year had a more pronounced tendency to easterly conditions, and possibly blocking situation initiated by late winter continental 'highs', giving rise thereby to situations in which rainfall is suppressed. Furthermore, the logbook data show a significant correlation (at $\alpha = 0.01$) of precipitation days with degrees of easterliness ($r = -0.306$) and of westerliness ($r = 0.187$). This suggests that the annual pattern may partly reflect this dominant circulation rhythm. Slonosky (2002) has prepared a precipitation series for Paris that embraces the late seventeenth century. She found no significant correlation with the NAO series – a result confirmed with the current data set – but also suggested nevertheless that synoptic-scale circulation patterns over western Europe were important in controlling rainfall. This suggestion is supported by the above results. In this same sense, the notable dryness of July may reflect a short period of dominance by the Azores anticyclonic system. Figure 4 shows that July recorded far fewer gales than any other month. Taken together these two items – lack of gales and dry conditions – point to a consistent, but limited duration, period of activity on the part of this system at this time.

It is probable that rainfall was an under-recorded phenomenon, and whilst this does not influence the monthly patterns discussed above, the sequence of dry and wet months are more clearly depicted if expressed as standardized deviations from the mean rain days per month over the whole series (Figure 7). There are no clear patterns evident in the results, but the tendency to wetter conditions towards after the summer of 1697 should be noted, this period marking a break in the series hitherto dominated by generally drier conditions. The four driest months were May 1687, February 1688, February 1693 and July 1699, during none of which was any form of

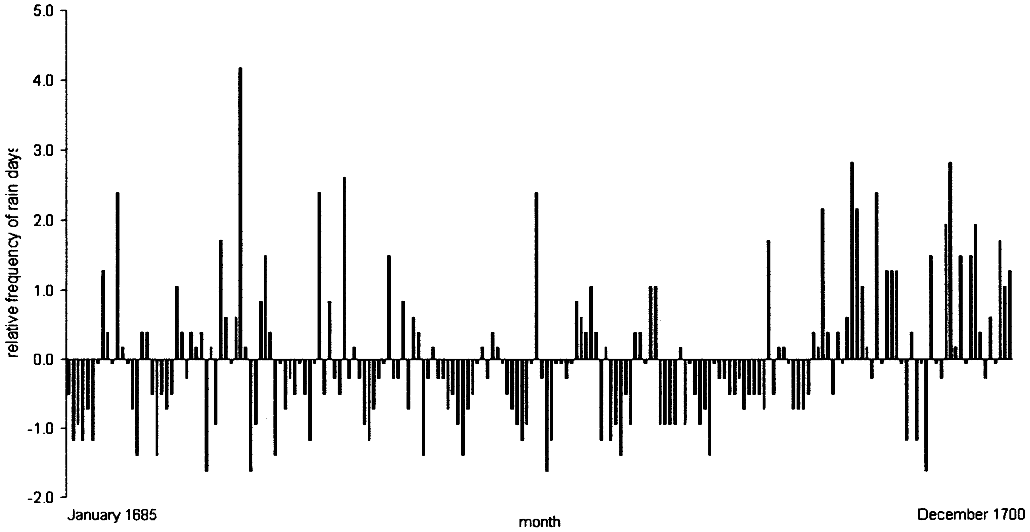

Figure 7 Monthly rain day series 1685 to 1700 expressed as standard deviations about the overall mean

precipitation recorded. The lack of precipitation of the former two months may have been widespread and Pfister (1999) and Glaser (2001) have identified them as very dry also in central Europe. At the other extreme, December 1687 recorded 26 rain days, and April 1698 and December 1699 20 each.

Structural analysis of the data set

The correlation matrices have demonstrated a high degree of coherence between the logbook information and the independently derived instrumental and proxy data. The structure of this data base can also be explored further using Factor Analysis. Attention is focused on data for the winter season, at which time the hemispherical weather systems are more clearly organized. The variables included are, from logbooks, the proportion of north, east, south and westerly winds (N, E, S and W) and the number of days with gales of force 9 or more, and days per month with rain, snow and frost. Other variables included were the monthly CET anomalies, the Paris air pressure and the NAO and EU indices.

Factor analysis with varimax rotation indicated that four components only were needed to account for 73% of the variance in the data set (Table 8). The loadings of variables on those factors are given in Table 9, the patterns of which offer the following interpretations:

Factor 1: this is a 'thermal/meridionality' factor in which the most important of the variables are the degree of northerliness and southerliness, frost days and the CET.
Factor 2: this is a 'zonality' factor in which E and W are the dominant variables. Interestingly the NAO index does not load heavily on this factor.
Factor 3: the factor reflects continental air pressure patterns through the Paris air pressure and Eurasian Circulation index.
Factor 4: this is a 'cyclonicity' factor on which only the gales and precipitation variables load strongly.

It is interesting to speculate on the dominance of the 'thermal/meridional' element. This may reflect the nature of the global energy budget at the time, and some have laid great stress on the significance of the Maunder Minimum in this respect. Lean and Rind (1998) have already demonstrated a very close positive correlation ($r = +0.86$) between northern hemisphere temperatures and reconstructed solar irradiance in the pre-industrial period (1610–1800). If the driving force was indeed the reduced atmospheric energy budget, the changed synoptic conditions and the tendency to meridionality should be seen as a consequence and not a direct cause of the prevailing coolness of the period. Although, for the southern British Isles and English Channel area, a greater frequency of winter blocking would amplify this cooling signal by encouraging yet lower temperatures in easterly outbreaks. Shindell *et al.* (2001) have shown also that weakening of the westerly circulations and greater meridionality are a modelled response to reduced solar inputs, giving rise to significantly cooler winters in Europe as a result of reduced warm oceanic air advection.

Table 8 Eigenvalues and explained variance for the extracted factors of the logbook/instrumental/proxy data set

Component	Initial eigenvalues		Sum of squares loading after rotation	
	Total	% of variance	Total	% of variance
1	4.04	33.7	2.90	24.2
2	1.96	16.3	2.53	21.0
3	1.56	13.0	1.70	14.2
4	1.12	9.3	1.56	13.0

Table 9 Rotated factor loadings of the logbook/instrumental/proxy data set

	Component 1	Component 2	Component 3	Component 4
N	**−0.814**	−0.097	−0.066	−0.010
E	−0.060	**0.915**	−0.031	−0.202
S	**0.614**	0.110	−0.307	0.137
W	0.149	**0.838**	0.130	0.100
Gales force 9+	0.119	0.099	0.081	**0.823**
Rain days	0.009	0.161	−0.266	**0.720**
Snow days	−0.615	−0.109	−0.295	0.289
Frost days	**−0.713**	−0.093	−0.072	−0.393
CET anomaly	**0.634**	0.598	0.115	0.116
Paris air pressure	0.410	0.178	**0.783**	−0.199
NAO index	0.501	**0.716**	−0.171	−0.036
EU index	−0.337	−0.074	**0.870**	0.019

Factors interpreted to characterize the factors are in bold.

Shindell *et al.* (2003) have drawn attention to the importance of volcanic events on climate of the preindustrial period. They argue that although this factor's influence is of a transient nature and more clearly registered in seasonal temperature anomalies, there is a suggestion that it can, in contrast to solar forcing, accentuate the zonality of mid-latitude circulations. There were four major volcanic events in the study period, one in 1693 (Serun, in the Moluccas) and three in 1694 (Amboina and Gunung Api, again both in the Mollucas, and Celebes). These had, respectively, global dust veil indices of 500, 200, 400 and 250 (Lamb, 1970). Although the steady decrease in westerliness apparent in 1694 was reversed by mid-1695 (Figure 4), there is no unambiguous indication of any sustained increase in late 1694 to 1696. Quite the opposite, and the period is marked by a notable degree of variation in the westerlies from the absolute minimum of zero in December 1695 to high values the following summer, reaching a series absolute maximum of 0.88 in September 1696. This instability might reflect a delicate but unstable and temporary balance of these two forcing elements (volcanic and solar forcing) at this time.

Conclusions

Logbook data have been shown to provide a new and valuable source of information for studying climatic change. They offer also the important advantage of being taken from oceanic settings where not only are boundary layer effects minimized – no small matter when wind directions and wind force are to be considered – but data are otherwise impossible to come by for this period. They also allow climatologists to examine changes at a fine scale of temporal resolution; monthly aggregated data were employed here, but the daily record can also be called upon. The raw data require careful treatment, but have been shown to be based on a systematic method of recording that helps greatly in this task. Furthermore, given that these data were recorded principally for the purposes of safe navigation, there was a compelling reason for them to be estimated with the greatest possible accuracy. On the other hand, they are of a non-instrumental nature, and based on the judgement of the observing officer. Confidence does, however, have to be derived from the manner in which the logbook data correlate and amplify independently derived instrumental and other series.

The nature of synoptic-scale airflows over the region at this distant time have been clearly identified, highlighting the episodic, rather than the persistent nature of meridionality. New emphasis is also given to the hypothesis that the late seventeenth century at least was a period of notable storminess in the mid-latitudes. The evidence suggests that this greater storminess was a notable feature of the summer months and resulted from the southerly displacement of the polar front and jet streams.

Finally, this exercise has called upon only a very small number of the logbooks available and the results indicate that significant benefit would be gained from undertaking a more exhaustive analysis of those that remain to be digitized. As Beckman and Mahoney (1998) observed in relation to studies of the Maunder Minimum, and has been so clearly demonstrated here: 'We can never be sure of what future generations may pick up from an archive or a well maintained historical library'.

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