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Constraining the temperature history of the past millennium using early instrumental observations

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Abstract

The current assessment that twentieth-century global temperature change is unusual in the context of the last thousand years relies on estimates of temperature changes from natural proxies (tree-rings, ice-cores etc.) and climate model simulations. Confidence in such estimates is limited by difficulties in calibrating the proxies and systematic differences between proxy reconstructions and model simulations. As the difference between the estimates extends into the relatively recent period of the early nineteenth century it is possible to compare them with a reliable instrumental estimate of the temperature change over that period, provided that enough early thermometer observations, covering a wide enough expanse of the world, can be collected.

One organisation which systematically made observations and collected the results was the English East-India Company (EEIC), and their archives have been preserved in the British Library. Inspection of those archives revealed 900 log-books of EEIC ships containing daily instrumental measurements of temperature and pressure, and subjective estimates of wind speed and direction, from voyages across the Atlantic and Indian Oceans between 1789 and 1834. Those records have been extracted and digitised, providing 273 000 new weather records offering an unprecedentedly detailed view of the weather and climate of the late eighteenth and early nineteenth centuries.

The new thermometer observations demonstrate that the large-scale temperature response to the Tambora eruption and the 1809 eruption was modest (perhaps 0.5 °C). This provides a powerful out-of-sample validation for the proxy reconstructions – supporting their use for longer-term climate reconstructions. However, some of the climate model simulations in the CMIP5 ensemble show much larger volcanic effects than this – such simulations are unlikely to be accurate in this respect.

1 Introduction

The temperature history of the past millennium provides vital context for predictions of future change, and attributions of recent change to anthropogenic causes (Jones and Mann, 2004). Back to about 1850 large-scale temperature changes are fairly well known from thermometer measurements (Brohan et al., 2006), but longer-timescale reconstructions are based on a variety of natural proxies (tree-rings, ice cores, speleothems etc.) and have a large uncertainty (Fig. 1).

The proxy reconstructions not only disagree amongst themselves, but they share a reliance on calibration to recent instrumental (thermometer) records. Calibration is a statistical estimate of the scaling factor relating a change in the proxy value (ring width etc.) to a change in temperature, and it is necessary to assume that this scaling factor does not change with time or temperature. Recent years have seen a lot of research into improved calibration techniques, but despite these technical improvements the uncertainty in the reconstructions remains large (Frank et al., 2010; Jones et al., 2009).

An alternative estimate of temperature changes is given by General Circulation Model (GCM) simulations, and the WCRP Coupled Model Intercomparison Project — Phase 5 (CMIP5; Taylor et al., 2012) includes an ensemble of state-of-the-art GCM simulations covering the period 850–1850 (Fig. 1). Comparison of the GCM simulations with the proxy reconstructions shows systematic differences: the simulations usually have little inter-decdal variability (which would support those proxy reconstructions showing least variance) but often show large responses to volcanic eruptions (which are generally much less pronounced in the proxy reconstructions). This large difference has led to the suggestion that proxy reconstructions systematically under-represent the effects of large volcanic eruptions (Mann et al., 2012).

Although the reconstructions and the simulations do not agree, they do disagree consistently across the millennium, and this offers an opportunity: If the actual climate could be established with confidence at one point in time, the lessons from comparing the climate of this point with the reconstructions and simulations could be applied

across the whole period. So one good validation point could powerfully constrain our knowledge of the climate of the whole millennium. The cold period in the early nineteenth century is a strong candidate for such a validation point: As a cold period it would provide out-of-sample validation for the proxy reconstructions, and as it includes the Tambora eruption it would constrain the volcanic response. Accurate instrumental weather observations have been recovered for limited regions going back well before 1800 (Camuffo and Bertolin, 2011; Alcoforado et al., 2012), so it is merely a matter of recovering enough such observations, covering a large enough area of the Earth, to constrain the large-scale temperature.

2 New instrumental weather records for the early nineteenth century

Amongst the archives in the British Library (BL) in London are some 4000 logbooks from ships in the service of the English East India Company (EEIC); each recording the details and events of a voyage from England to the Indies (usually India, China or both) and back, typically taking the best part of two years. The EEIC received its charter from Elizabeth I in 1600, and many of its earliest voyages became famous because of their excellent records of new lands; for example that by Henry Middleton to the Moluccas in 1604–1606 (Foster, 2010). These early voyages were recorded in diaries; logbooks – formally prepared documents of a standard format – did not begin to appear until the 1650s. Their preparation was part of an officer's duties until the gradual expansion of the Company in the 1830s into a quasi-military and political body responsible for overseeing British interests in India and beyond. Those archived in the BL, therefore, extend from the 1600s through to the 1830s, and are well known to historians (Farrington, 1999). They document social conditions, discipline, medicine and health, the trade and transport of goods, people and passengers. They touch on first contact with new lands and peoples, convey colonial attitudes and cultures, and describe long lost coastal towns and villages. Many even contain detailed drawings of coastlines, ships, mammals, birds and sea creatures.

Ship's logbooks are also valuable sources of historical climate data (Chenoweth, 1996; Wheeler et al., 2006; Brohan et al., 2009, 2010), and the EEIC logbooks include daily records of the weather along the routes taken by the ships: They cover large parts of the Atlantic and Indian Oceans, and include the occasional foray into the Pacific. All the logbooks contain wind speed and direction records, as this was vital information for early navigators, but the later logs, starting in about 1790, are even more valuable, as some of them contain daily thermometer and barometer observations as well as the wind reports. The principal instigator of the addition of instrumental observations was Alexander Dalrymple – the Company's, and later the Royal Navy's, first hydrographer. Dalrymple was both an explorer and an enthusiastic scientist, and, as hydrographer, he was responsible for ensuring that the EEIC ships could transport goods to and from England as quickly as possible and at minimum risk of loss. With this in mind, he equipped the East Indiaman Grenville with a set of meteorological instruments for her voyage in 1775 under Captain Burnet Abercrombie (Dalrymple, 1778), and set a pattern to be later adopted by officers on all EEIC ships.

It is the routine inclusion of regular instrumental weather observations that distinguishes the EEIC logbooks from all of their contemporaries such as the Royal Navy and the Hudson's Bay Company (which did not routinely make such records until many years later). The EEIC logbook records offer a potential source of detailed information on climate change and variability over a large area of tropical and sub-tropical ocean for the late eighteenth and early nineteenth century – a time and region where other observations are almost completely missing. About 10 % of these logbook observations have been examined in previous studies (Chenoweth, 1996; Farrington et al., 1998; Chenoweth, 2000), but most of them have never been digitised or examined, and none have made it into the standard climate datasets for widespread use.

3 Digitisation of the weather records

The BL's EEIC logbook collection has been catalogued (Farrington, 1999), but that catalogue, though extensive, does not distinguish those logbooks that contain instrumental data. So research was undertaken in the BL archives to produce a catalogue detailing exactly which logs contain instrumental observations; whether the observations are of pressure, air or sea surface temperature; the name of the ship; the year of its voyage; and the ship's route with dates. It also includes additional information such as how frequently the readings were taken, and whether any unusual weather events took place. Many of the logbooks dating from 1790 or later contained some instrumental observations, but not every log contained observations, and on occasion observational records were sporadic.

Using this catalogue, the 891 logbooks including consistent instrumental records were selected for digitisation: the earliest that of the Melville Castle, starting in February 1789; and the last that of the Sherborne, finishing in August 1834. Figure 2 shows a typical example, logbook records for one day from EIC ship Carmarthen. That logbook records a voyage from London to Bombay and back to the UK, through the Atlantic and Indian Oceans, and round the Cape of Good Hope. The voyage took 20 months (May 1810 to January 1812); records were only made on days when the ship was at sea, but even so the logbook includes 372 such daily records.

Digitising each day's observations from all 891 logbooks proved to be a major undertaking. To make it possible to work on the logbooks outside the BL, the books were photographed. This produced about 140 000 digital images, each showing one page. Most pages contained two day's records on a standard pre-printed form (Fig. 2 shows the top half of one page) though, in rare cases, variant form types were used that only containted one day's records; also hand-drawn forms were occasionally used – presumably to make up a shortfall in printed forms. These images were indexed and stored in the electronic media archive of the US Climate Database Modernisation Program (CDMP), managed from the National Oceanic and Atmospheric administration's (NOAA) National Climatic Data Center (NCDC).

CDMP also managed the transcription of the weather observations from the images. The data to be transcribed were selected – these are the highlighted sections in Fig. 2 – and staff were trained to read and key the specified elements. A detailed set of instructions was prepared for the keying operators to ensure that the data was transcribed into a uniform format. Budget constraints limited transcription to the noon observations of air temperature, barometric pressure, and location; the wind direction and force closest to noon; and all details of the state of the weather and sea. Each element was double keyed to a give a minimum transcription accuracy of 99 %.

For the most part the logbooks recorded elements to a basic standard that can easily be understood today. However, the age of the documents made the transcription unusually challenging: the handwriting is not easy to read and contains frequent and variable abbreviations, and the document format is not entirely regular, so judgement was often required in identifying the elements to be transcribed. Values were sometimes recorded in unconventional methods (e.g. complex fractions or the use of dashes (–) to represent the number zero), and sometimes positioned on the wrong part of the form. Every logbook was pre-screened to notify the keying operators of any strange and unusual recording methods or deviations from the most common recording practices, and the keying operators were vigilant in identifying irregularities. Unusual entries often required a full review of the logbook to determine how the observer was recording the questionable element and if they were consistent throughout with their recordings. Once the logbook was thoroughly inspected, an educated decision was made on how to transcribe the values to the common format outlined in the keying instructions. Once a logbook had been keyed in its entirety, it was then quality controlled by CDMP and distributed for further format conversions and analysis. In all 272 852 daily records were transcribed.

To be useful to the community of climate and other researchers who use historical marine observations, each record must be converted into the International Maritime

Meteorological Archive format (Woodruff, 2007). In most respects such conversion is straightforward – conversion of latitude from degrees-minutes seconds to decimal degrees, and of temperatures from Fahrenheit into Celsius. Conversion of pressure measurements is slightly more complicated, as not only must the measurements be converted from inches of mercury to hectopascals, but corrections may be applied for systematic biases in the method of measurement (Sect. 3.2.2). Conversion of wind direction from 32 or 64-point compass directions to degrees east is also straightforward, but the wind speed must be converted to $\mathrm{m\,s^{-1}}$ from verbal descriptions such as "light gale" or "moderate monsoon" (Sect. 3.2.3). Temperature, pressure, and wind records are further discussed below.

As well as the units conversion and adjustment, the opportunity was taken to apply some basic quality control to the ship positions. In many cases the hemisphere flags (E/W or N/S) attached to position observations were missing or obviously wrong, occasionally obvious errors would appear in latitudes and longitudes as well. All these problems can be seen plainly in a plot of the course of the ship and such erroneous values, when found, were corrected if the correction was obvious, and set to missing otherwise.

The IMMA format allows attachments, and the original version of each record is attached to each IMMA record, so that the un-converted and un-corrected data can be recovered if necessary. All the IMMA records are provided as Supplement.

3.1 Ship routes and observational coverage

A sailing ship travelling between England and the Indies, before the opening of the Suez canal in 1869, had to follow a route constrained by the global wind fields: the prevailing winds close to the Equator are the easterly trades, so sailing to the East from England meant travelling southwest through the Atlantic down to the latitudes of the Southern Hemisphere westerlies, and using those winds to make the necessary easting. Once in the Indian Ocean the ships could either sail up through the Mozambique Channel (between Madagascar and the continent of Africa) and use the Southwest monsoon to carry them over to India, or make all their Easting in the strong westerly winds around 35–40° S and then sail directly north to their destination. Both choices remained popular throughout the period: the Mozambique Channel could only be used if arriving in boreal summer (when the southwest monsoon blows in the Northern Indian Ocean) the alternative route was used throughout the year. Figure 3 shows examples of both routes. The route back was simpler – a direct route round the Cape using the easterly trades, north-west into the mid-Atlantic and then back to England with the Northern Hemisphere westerlies.

Figure 4 shows the coverage of the observations from all 891 logs. The observations are strongly concentrated along the standard routes, but with enough variation to explore a large area of the Atlantic and Indian Oceans – occasional ships do take radically different routes – visiting the Red Sea and Persian Gulf, or looping through the South Pacific on the way to China. The records are fairly evenly distributed through time, with at least 30 ships contributing in every year between 1794 and 1833.

3.2 Temperature, pressure and wind

The logbooks contain instrumental observations of air pressure and temperature, and qualitative descriptions of wind speed. The details of how the measurements were made are not known, and we should expect some biases even in the instrumental observations, caused by limitations in the instruments used and the observational protocols. The model and make of instruments used on board the EEIC vessels is rarely recorded within the logbooks, and in most cases no record has been found indicating the manufacturer or type of instrument used. Dalrymple's 1775 voyages used barometers and thermometers of Nairne and Blunt manufacture (Dalrymple, 1778) but it is known from some of the more assiduously maintained logbooks that barometers of different manufacture were also used, such as Dolland, Barraud, Troughton, and Gilbert. On occasion more than one barometer was in use (e.g. Dolland, Barraud and Troughton on board the Thomas Coutts voyage of 1817–1819), and multiple thermometers are also occasionaly seen (e.g. Gilbert and Blunt manufactures on board the Neptune

voyage of 1814–1815). It is likely that a diverse range of instruments was used across the EEIC fleet.

The vast majority of the temperature and pressure observations were made at noon (a handfull of logbooks record morning and afternoon observations on the same day); the location of the instruments is not known for certain, but it is likely that the thermometer and barometer were kept together in the captain's quarters and adjacent gallery at the stern of the vessel – Dalrymple's report includes the following "this thermometer belonged to Mr. Russell, and hung in the open air in the balcony" (Dalrymple, 1778).

3.2.1 Temperature

The temperatures are recorded in degrees Fahrenheit: usually to a precision of 1° but sometimes to a quarter or a tenth of a degree. In some instances thermometer values were recorded in the format of degrees and seconds (e.g. 82°45′, representing 82.75 °F, as seen in Fig. 2), similar to the typical format for latitude or longitude. As the observations predate the development of the modern Stevenson-type screen, the major difficulty in comparing them to modern observations will be their exposure – the details of how the thermometer was screened from solar radiation. It is likely that the thermometers were less well screened than the modern standard, and also contaminated by ship heating (Chenoweth, 2000; Berry and Kent, 2005). They will therefore be biased warm, and the bias will be larger in regions where the surface solar radiation is large. Figure 5 shows the distribution of the temperature anomalies (difference from recent values). The temperatures are consistently warmer than their recent equivalents, but the difference is much more likely to be a result of exposure bias than an indication that surface temperatures were warmer in 1789–1834 than in 1961–1990. The mean temperature changes little over the period of the observations, with modest falls in 1809 and 1816 – almost certainly a consequences of the two large tropical volcanic eruptions in the period.

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3.2.2 Pressure

The pressures were recorded in inches of mercury, usually to a decimal precision of 1/100 of an inch, but occasionally as a fraction (e.g. $29\frac{7}{8}''$). The pressures have been corrected for gravity (using the observed ship latitude) and for temperature (using the associated air temperature where available – no barometer attached temperatures were recorded). Figure 6 shows the distribution of the pressure anomalies (difference from recent values). The pressures are systematically and consistently about 5 hPa (0.15 inches) below their recent equivalents. This bias has been observed before in pre-1855 marine observations (Ansell et al., 2006; Brohan et al., 2010) and the cause is still unknown. It is unlikely to be an effect of gravity or temperature correction because it doesn't vary with temperature or latitude, and it seems equally unlikely to be an artifact of the movement of the ship as it appears equally in stormy and calm regions.

In 1818, Alexander Adie patented the sympiesometer, a mercury-less marine barometer containing coloured almond oil and hydrogen gas (Middleton, 1964). Several of the later EEIC voyages carried a sympiesometer, either in tandem with the mercury barometer or as a standalone pressure gauge: 31 of the 893 digitized logbooks have records from sympiesometers. Of those 31 logs, 30 also contained records from a mercury barometer, and in some cases simultanious observations from both instruments were recorded.

There are large and systematic differences between the sympiesometer and barometer measurements. The sympiesometer was designed to be portable and to respond rapidly to pressure changes, rather than for accuracy and stability; and time-series of sympiesometer measurements (not shown) often show large drifts in pressure readings over a voyage. So the indications are that sympiesometer records will need close attention to calibration and correction in order to be useful for historical reconstructions.

The pressure observations included in the attached IMMA records are all believed to be from mercury barometers, but it is possible that in some of the later voyages the pressure observations are actually from a sympiesometer. That is, a sympiesometer

has been used in place of the usual mercury barometer but the substitution is not mentioned in the logbook.

3.2.3 Wind speed

The wind speed observations in the logbooks are, as is usual at sea, subjective assessments based on the sails carried and the state of the sea. The vocabulary of such assessments was not formally standardised until the 1830s, when Sir Francis Beaufort succeeded in introducing an official scale, but, even in this pre Beaufort-scale age, sailors were very consistent in their description of the winds, and it is possible to make quantitative estimates of the wind speed from the language in the logs (CLIWOC, 2003). Figure 7 shows the most frequent wind-force terms used and their Beaufort equivalents where available.

About 80 % of the terms encountered can be converted to Beaufort forces, and so to 10-m wind speeds in $\mathrm{m\,s^{-1}}$. Figure 8 shows the distribution of the inferred wind-speed anomalies (difference from recent values). The notable feature of Fig. 8 is the large anomalies in the trade-wind regions. It's possible that the trade winds were stronger around 1800, but as no equivalent anomaly appears in the pressure fields it's more likely that the CLIWOC dictionary is slightly mis-calibrated in those regions (stronger trades imply a stronger sub-tropical high or a deeper equatorial low).

Although all the pressure and temperature observations in the selected logbooks were digitised, budget constraints meant that not all of the much more numerous and various wind observations were. There are also wind observations in the more than 3000 logbooks in the BL archive that were not examined in this study (because they had no instrumental pressure or temperature observations). So much more information on wind fields is still potentially available in the BL EEIC logbook archive. If extracted in a future project, these records would provide information on sub-daily weather variability back into the 17th century.

4 Constraining proxy reconstructions and GCM simulations

The biases in the observed air temperatures mean that it's difficult to compare temperatures in the early nineteenth century with present day values, but the observational method and ship routes were constant over the period covered by the EEIC observations so they can be used directly to look at temperature variations over the period 1795–1833 (when there were enough ships contributing to give reliable results). Extracting a set of pseudo-observations from each GCM run, by sampling from the model output fields at the date and location of each observation allows a direct comparison between observations and simulations (Fig. 9: upper panel). It's clear that the observational coverage is sufficient to show the effect of the volcanoes in the simulations, and it's also clear that the observations support those simulations with a small temperature response to the Tambora and 1809 eruptions. That is, the large volcanic response simulated by some models did not occur.

Comparison with the proxies is more complicated, as they don't usually provide field reconstructions – just time-series for the entire Northern Hemisphere (NH). However comparing the GCM results subsampled to the coverage of the observations with their NH averages (Fig. 9: inset) indicate that the NH temperature anomalies are linearly related to the observational anomalies $\Delta T_{\mathrm{NH}} \approx \Delta T_{\mathrm{obs}} \times 1.2$, and Fig. 9 (lower panel) compares the proxy reconstructions to the observational series scaled by this factor.

With the exception of the glacier based reconstruction (O2005) which has (unsurprisingly) too little variance on these short timescales, the agreement between the proxy reconstructions and the observations is good. It's not easy to say which of the proxy series is the best, but as a group they match the observations well. As this comparison is for a period outside that used to calibrate the proxies (both in time and temperature) the observations form a powerful validation for the proxy reconstructions – demonstrating that the proxies can be used to extrapolate back into the past, and into different climates, with success.

5 Conclusions

The records of the English East India Company (EEIC), archived in the British Library, offer a remarkable new insight into the weather and climate of the late eighteenth and early nineteenth centuries. Their archives include 891 ships' logbooks containing daily temperature and pressure measurements, and wind-speed estimates, each covering a voyage from England to India or China and back. The 273 000 new weather observations extracted from those logs provide material for detailed reconstructions of the weather and climate between 1789 and 1834 and offer new insights into pre-industrial climate variability. For all three meteorological variables studied (temperature, pressure and wind) it's clear that the data can be used for investigating variability over the period of measurement, though comparison with measurements made decades or centuries later will require close attention to observational biases.

The observations demonstrate that the large-scale temperature change associated with the two big tropical volcanic eruptions in 1809 and 1816 was modest (perhaps 0.5 °C). Some of the GCM simulations in the CMIP5 ensemble show much larger volcanic effects than this – such simulations are unlikely to be accurate in this respect. Recent annualy-resolved proxy reconstructions of Northern Hemisphere temperature show a varied but similarly modest volcanic response (about 0.2–0.7 °C); the new observations therfore provide a powerful out-of-sample validation for the proxy reconstructions – supporting their use for longer-term climate reconstructions.

Supplementary material related to this article is available online at: http://www.clim-past-discuss.net/8/1653/2012/cpd-8-1653-2012-supplement.zip.

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Table 1. Proxy series (top) and modelling groups (bottom) providing data used in Figs. 1 and 9.

B2000	Briffa (2000); Briffa et al. (2004)
BOS..2001	Briffa et al. (2001)
DWJ2006	D'Arrigo et al. (2006)
HCA..2006	Hegerl et al. (2006)
ECS2002	Esper et al. (2002); Cook et al. (2004)
MJ2003	Mann and Jones (2003)
MSH2005	Moberg et al. (2005)
O2005	Oerlemans (2005)
RMO..2005	Rutherford et al. (2005)
MBH1999	Mann et al. (1999)
JBB.1998	Jones et al. (1998, 2001)
bcc-csm1-1	Beijing Climate Center, China Meteorological Administration
GISS-E2-R	NASA Goddard Institute for Space Studies
FGOALS-gl	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences
MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MPI-ESM-P	Max Planck Institute for Meteorology
CCSM4	National Center for Atmospheric Research

Table 2. Ships from which observations were taken (1 of 2 – starting dates 1789 to 1803).

Ship Name	Years of operation	Ship Name	Years of operation
Melville Castle	1789–1790, 1792–1793, 1796–1802	Earl Howe	1798–1810
Rose (2)	1789–1790, 1799–1800	Lord Duncan	1798–1806
Barwell (1)	1790–1791, 1795–1796	Ocean (3)	1798–1800
Belvedere	1790–1791	Tellicherry	1798–1799
Earl Of Abergavenny (2)	1790, 1797–1800	Earl Cornwallis	1798–1800
Marquis Of Lansdown	1790–1791, 1793–1800	Orpheus	1798–1800
Ocean (1)	1791–1797	Charlton	1799–1806
Bridgewater (3)	1791–1793, 1796–1797	Asia (4)	1799–1803
Lascelles	1792–1796	Hindostan (2)	1799–1800
Middlesex (2)	1792–1795	Duke Of Buccleugh (1)	1799–1800
Royal Admiral (1)	1792–1796	Preston	1799–1800
Swallow (3)	1792–1794	Herculean	1800–1801
Ganges (1)	1792–1795	Dorsetshire	1800–1801, 1803–1804, 1806,1811–1812,
General Goddard	1792–1793		1814–1815, 1817–1818, 1820–1823
Pigot (2)	1793–1794	Earl Spencer (2)	1800–1801, 1803–1810
Ceres (2)	1793–1794	Neptune (5)	1800–1801, 1804–1807, 1809–1810, 1812–1815
Warley (1)	1793–1794	Hugh Inglis	1800–1801, 1810–1812
Berrington	1793–1794	Lady Burges	1800–1805
General Coote	1793–1794	Walthamstow	1800–1801, 1804–1805, 1808–1813
Rodney (2)	1793–1796	Lord Nelson	1800–1801, 1806–1807
Princess Amelia (3)	1793–1796	Ceres (4)	1800–1805, 1808–1809
Francis (2)	1793–1796	City Of London	1800–1801, 1803–1808, 1812–1813
Exeter (2)	1793–1794, 1800–1801, 1803–1804, 1810–1811	Bengal	1800–1802, 1806–1807
Lord Thurlow	1793–1794, 1797–1802	Canton	1800–1805, 1808–1811
Lord Walsingham	1793–1794, 1797–1799	Georgiana (1)	1800–1803, 1805–1807
Minerva (1)	1793–1796, 1799–1800	Hawke (5)	1800–1801
Earl Of Chesterfield	1793–1794	Earl St	1800–1801, 1808–1813
Earl Of Wycombe	1794–1795, 1797–1799	Henry Dundas	1801–1802
Sir Edward Hughes	1794–1795, 1797–1803	Calcutta (4)	1801–1804
Woodford (1)	1794–1805, 1807–1808, 1810–1811	Alfred (2)	1801–1802, 1807–1808, 1810–1811
Thetis (1)	1794–1797	Caledonian (2)	1801–1803
Rockingham (1)	1794–1795, 1798–1802	Henry Addington (2)	1801–1802, 1805–1806, 1811–1812, 1814–1815
Walpole (4)	1794–1795	Walpole (5)	1801–1802
Phoenix (3)	1794–1795	Ocean (4)	1801–1803, 1805–1806, 1808–1809
Lord Hawkesbury	1794–1802, 1804–1806	Northampton (2)	1801–1805, 1807–1810, 1818–1819
Taunton Castle	1794–1795, 1799–1800, 1804–1805, 1809–1810	Princess Mary (2)	1801–1805
Europa (2)	1794–1795	Fort William (2)	1801–1802
Queen (4)	1794–1798	Monarch	1801–1802
Carnatic (2)	1794–1795, 1801–1802	Experiment (2)	1801
Princess Of Wales (3)	1795–1797	Manship (2)	1801–1803
Earl Of Oxford	1795–1796	Sarah Christiana	1801–1802
Cirencester	1795–1796, 1812–1813	Comet (2)	1801–1803
London (13)	1795–1796	Marquis Of Ely	1802–1805, 1811–1814, 1819–1820
Bellona	1795–1798	Marquis Wellesley	1802–1803, 1806–1808
Hillsborough (2)	1795–1798	Castle Eden	1802–1804
Kent (5)	1795–1797	Lady Jane Dundas	1802–1807
Woodcot	1795–1796	Thames (2)	1802–1805, 1809–1810, 1812–1813
Brunswick (1)	1795–1797	Sir William Bensley	1802–1811
Cuffnells	1796–1800, 1802–1805, 1809–1810	Tottenham	1802–1803, 1806–1810
Princess Charlotte (1)	1796–1797	Travers	1802–1806
Albion (2)	1796–1798	Alnwick Castle	1802–1813, 1815–1816
Royal Charlotte (5)	1796–1807, 1809–1815	Marchioness Of Exeter	1802–1803, 1811–1814, 1816–1817
Essex (4)	1796–1798	Devaynes	1802–1808, 1811–1812
True Briton (4)	1796–1798, 1801–1802	Ann (1)	1803–1809, 1814–1815
Airly Castle	1796–1797, 1804–1806	Experiment (4)	1803–1805
Walmer Castle	1796–1798, 1802–1805, 1815–1816	Cumberland	1803–1804, 1809–1810

Table 2. Continued.

Ship Name	Years of operation	Ship Name	Years of operation
Boddam	1796–1800	Warren Hastings (2)	1803–1804
Manship (1)	1796–1800	Harriet (3)	1803–1811
Good Hope (3)	1796–1799	Elphinstone	1803–1811
Henry Addington (1)	1796–1798	Tigris (2)	1803–1805, 1810–1815
Ganges (3)	1797–1802	Marquis Cornwallis (2)	1803
Prince William Henry	1797–1799	Windham (2)	1803–1806, 1816–1817
Britannia (4)	1797–1805	Europe (2)	1803–1807
Warley (2)	1797–1800, 1805–1809, 1811–1814	Euphrates	1803–1805
Hope (2)	1797–1808, 1811–1816	General Stuart	1803–1804, 1807,1811–1814
Arniston	1797–1798, 1804–1807, 1810–1811	Essex (5)	1803–1805, 1808–1809, 1819–1820
Eurydice	1797–1799	Carmarthen	1803–1818
Sulivan	1797–1798	Union (4)	1803–1804, 1808–1812, 1815–1818
Osterley (3)	1798–1800		

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Table 3. Ships from which observations were taken (2 of 2 – starting dates 1803 to 1833).

Ship Name	Years of operation	Ship Name	Years of operation
Ocean (5)	1803–1805	Lowther Castle	1813–1828, 1831–1834
Lord Melville (1)	1803–1808, 1811–1816	Bombay	1814–1815, 1817–1822, 1825–1828, 1831–1834
Dover Castle	1804–1805, 1809–1810	Prince Regent	1814–1815, 1818–1829, 1833–1834
Indus	1804–1805, 1810–1815	Lady Melville	1814–1821, 1824–1827, 1829–1834
Alexander (3)	1804–1809, 1814	Minerva (7)	1815–1822, 1825–1832
Lord Eldon	1804–1814	Surrey (2)	1815
Waller	1804	General Kyd	1815–1816, 1823–1832
Winchelsea (3)	1804–1807, 1810–1815, 1817–1818, 1820–1823, 1831–1832	James Sibbald	1815–1816, 1826–1829
Ocean (6)	1804–1814	Sovereign (2)	1816–1817
Huddart	1804–1805, 1808–1809, 1815–1816	Northampton (3)	1816
United Kingdom	1804–1805, 1807–1808	Fort William (3)	1816–1817
Bombay Castle	1805–1806	Mangles	1816–1819
Surrey (1)	1805–1810	Buckinghamshire	1816–1824
Northumberland (5)	1805–1818	Providence (1)	1816–1817
Royal George (4)	1805–1811, 1814–1818	Larkins (1)	1816–1817
Sir William Pultney	1805–1807, 1815–1816	Earl Of Balcarras	1816–1833
Streatham (4)	1805–1814, 1817–1818	Vansittart (4)	1817–1824, 1827–1834
Glory	1805–1807	Lord Castlereagh (1)	1817–1820
William Pitt (2)	1805–1807, 1810–1820	Waterloo (1)	1817–1832
Phoenix (5)	1805–1809, 1816–1819	Bridgewater (5)	1817–1830
Wexford	1805–1817	Herefordshire	1817–1818, 1821–1826, 1829–1834
David Scott (2)	1806–1807, 1812–1813, 1815–1816	Barkworth	1817–1818
Glatton (4)	1806–1807, 1809–1810, 1812–1815	Castle Huntley	1818–1821, 1824–1825, 1828–1831, 1833–1834
Sir Stephen Lushington	1806–1811	General Hewett	1818–1825
Regent	1807, 1816–1819, 1822	London (14)	1818–1823, 1826–1833
Lady Castlereagh	1807–1817	Canning	1818–1832
Admiral Gardner	1807–1808	Duke Of York (2)	1818–1826, 1829–1830
Union (5)	1807–1808, 1813–1814	Dunira	1818–1819, 1822–1823, 1830–1833
Lord Keith	1808–1811, 1814–1819	Thomas Coutts	1818–1825, 1828–1833
Princess Amelia (4)	1809–1825	Henry Porcher	1818–1819
Thomas Grenville	1809–1832	Matilda	1819–1820
Warren Hastings (3)	1809–1810, 1814–1821, 1825–1828, 1831–1834	Kellie Castle	1819–1830, 1833–1834
Coutts	1809–1810, 1812–1815	Inglis	1819–1832
Lady Lushington	1809–1814, 1818–1819	Thames (5)	1819–1821, 1824–1827, 1829–1834
Farlie	1809–1814, 1818–1819	Cornwall	1819–1820, 1826
Charles Grant	1810–1816, 1819–1830, 1832–1833	Windsor (2)	1819–1820, 1825–1828, 1832–1833
Surat Castle (2)	1810–1815	Marchioness Of Ely	1820–1821, 1826–1829
Lady Carrington	1810, 1812–1817	Orwell	1820–1831
Midas	1810–1811	Kent (7)	1821–1824
Warren Hastings (5)	1811–1812, 1815–1816, 1819–1820, 1823–1826	Royal George (5)	1821–1824
Carnatic (3)	1811–1820	Farquharson	1821–1828, 1831–1834
John Palmer	1811	William Fairlie	1822–1833
Cambridge	1811–1812, 1825–1827	Berwickshire	1822–1833
Scaleby Castle	1811–1812, 1814–1828, 1831–1834	Sir David Scott	1822–1825, 1830–1833
William Pitt (3)	1811–1812	Duchess Of Athol	1822–1826, 1828–1833
Harleston	1811–1812	Repulse	1823–1830
Moffat	1811–1812, 1818–1819	Claudine	1824–1825
Rose (4)	1811–1822, 1824–1827, 1833–1834	Macqueen	1824–1825, 1830–1833
General Harris	1812–1831	Java	1825
Broxbornebury	1812–1813, 1825–1828	Clyde (2)	1825–1826
Asia (6)	1812–1826, 1832–1833	George The Fourth	1826–1833
Marquis Of Huntley	1812–1813, 1818–1823, 1831–1834	Edinburgh	1826–1831
Perseverance (2)	1812–1814, 1818–1819	Reliance	1828–1833
Marquis Camden	1812–1814, 1821–1829, 1832–1833	Abercrombie Robinson	1828–1833
Juliana	1812–1813	Maitland	1828–1829
Astell	1812–1813, 1818–1821, 1824–1825, 1830–1831	Asia (10)	1829–1830

Table 3. Continued.

Ship Name	Years of operation	Ship Name	Years of operation
Princess Charlotte Of Wales	1812–1822, 1825–1828	Susan (2)	1830–1831
Coldstream	1812–1813, 1816–1817, 1822–1823	Marquis Of Hastings	1830–1831
Cabalva	1812–1817	Lord Lowther	1830–1833
David Scott (1)	1813–1814	Duke Of Sussex	1831–1832
Marquis Of Wellington (1)	1813–1822, 1827,1829–1830	Duke Of Buccleugh (2)	1831–1832
Atlas (4)	1813–1830	Bencoolen	1832–1833
		Sherborne (2)	1833–1834

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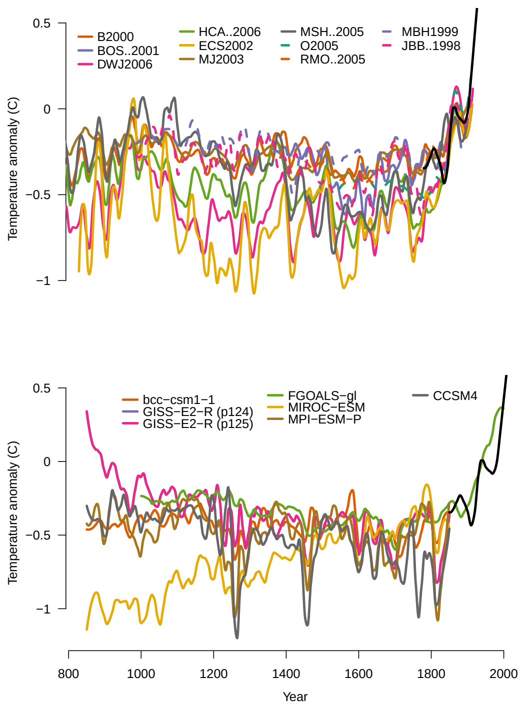

Fig. 1. Northern Hemisphere surface temperature estimates for the last millennium. Upper panel: recent proxy reconstructions (after Fig. 6.10 of Jansen et al., 2007). Lower panel: GCM simulations from CMIP5. In each case the black line shows instrumental observations (Brohan et al., 2006). Data used is listed in Table 1.

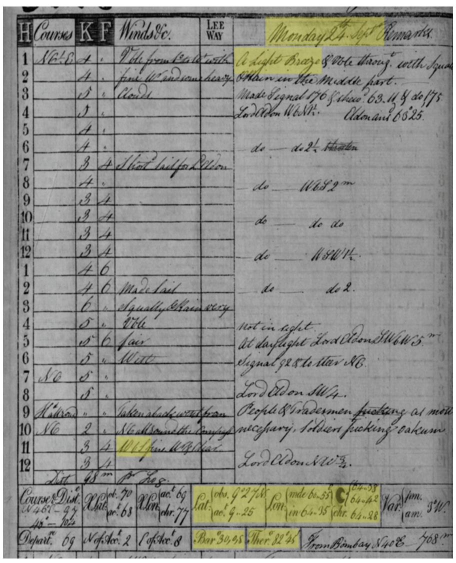

Fig. 2. Logbook of EIC ship Carmarthen for 24 September 1810. Ship's days run from noon to noon 12 h ahead of the civil day, so this covers the afternoon of the 23 and the morning of the 24. For each hour there is space to enter the ship's course, its speed (in Knots and Fathoms), and the wind direction. To the right of this table is a section for general remarks (which almost always includes reference to the wind speed); and at the bottom is a table of summary data for the day. The elements digitised are highlighted in yellow. from top to bottom they are: the date (24 September); the wind force (a light breeze – Beaufort force 2), the wind direction (West by South – 258.75° magnetic), the noon position (9°27′′ N, 64°28′′ E), the barometric pressure (30.05 inches of mercury) and the air temperature (82°45′′– 82.75° Fahrenheit).

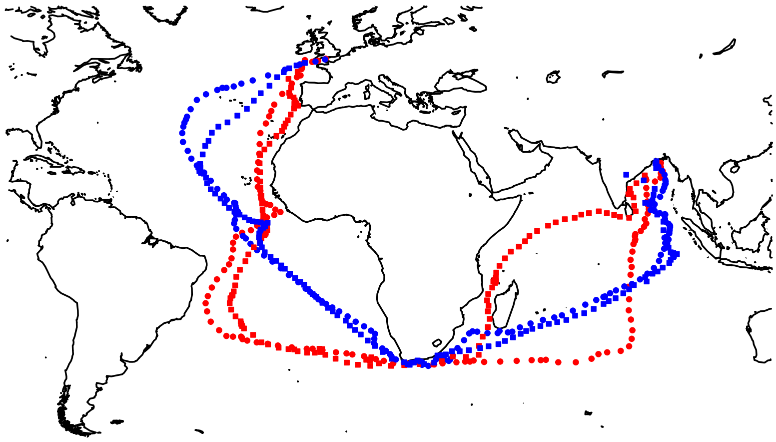

Fig. 3. Daily positions on the outward (red) and return (blue) voyages of the Astel in 1812–1813 (squares) and Thomas Grenville in 1827–1828 (circles).

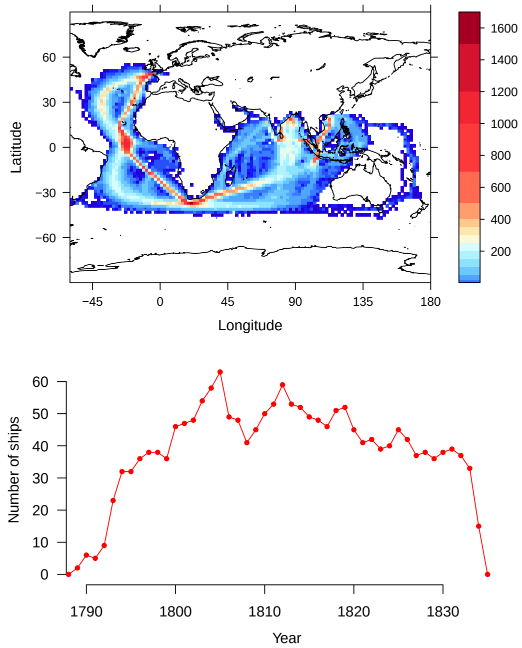

Fig. 4. Geographical coverage of the observations. Upper panel: total number of observations in each $2 \times 2^{\circ}$ square. Lower panel: number of ships providing observations in each year.

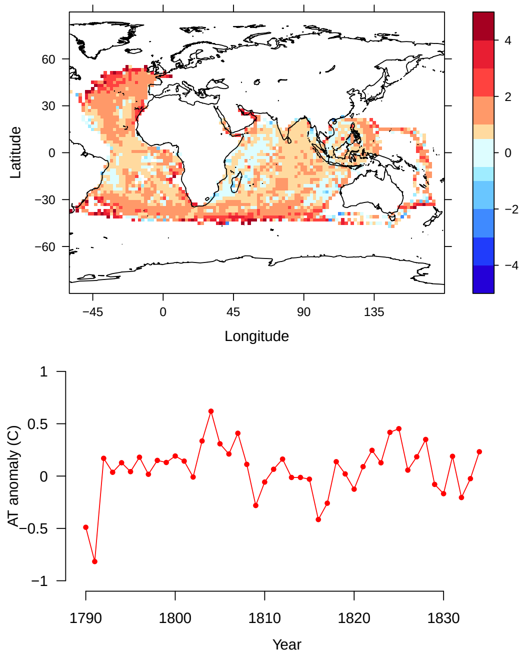

Fig. 5. Air temperature (AT) anomalies: observations minus an air-temperature climatology for 1961–1990 (Rayner et al., 2003). Upper panel: truncated mean AT anomaly in each 2 × 2° square. Lower panel: truncated mean AT anomaly in each year.

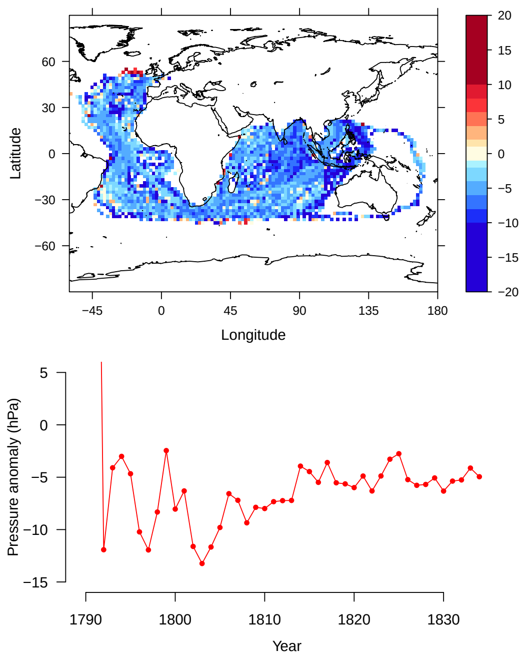

Fig. 6. Air Pressure (AP) anomalies from mercury barometers: observations minus a sea-level pressure climatology for 1961–1990 (Allan and Ansell, 2006). Upper panel: mean AP anomaly in each 2 × 2° square. Lower panel: mean AP anomaly in each year.

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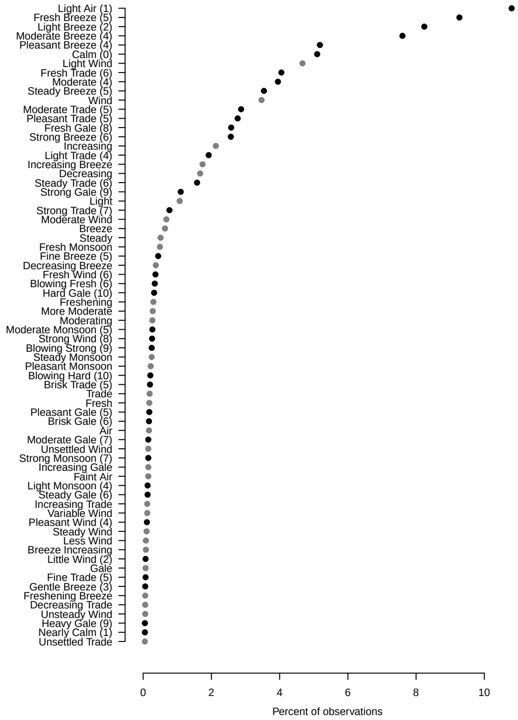

Fig. 7. The most common wind-force descriptors in the logs. Black points mark descriptors that can be converted to a Beaufort force using the CLIWOC dictionary (the Beaufort category is given in brackets after the descriptor in these cases). Grey points are terms which can't be converted.

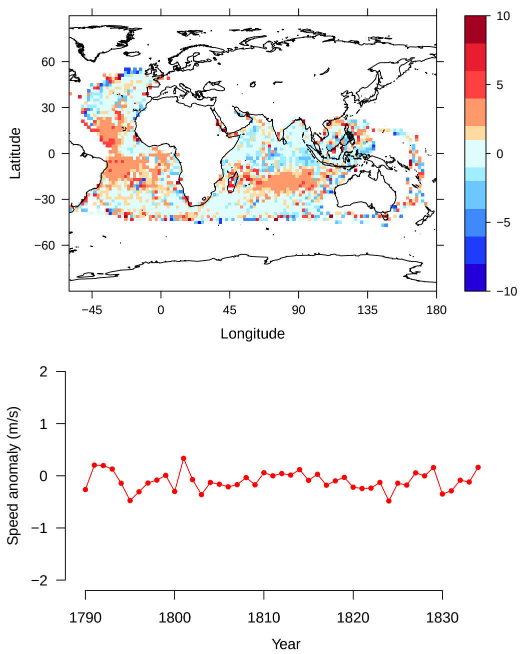

Fig. 8. Wind Speed (WS) anomalies: observations minus a wind-speed climatology for 1961–1990 from the ERA-40 reanalysis (Uppala et al., 2005). Upper panel: truncated mean WS anomaly in each 2 × 2° square. Lower panel: truncated mean WS anomaly in each year.

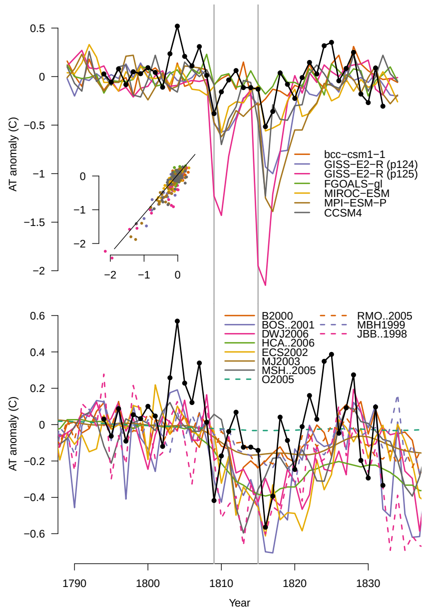

Fig. 9. Comparison of observed, simulated, and proxy-derived large-scale near-surface temperature variability over the early nineteenth century. Upper panel: tropical (observations coverage) marine temperatures from observations (black) and the CMIP5 simulations. Lower panel: Northern Hemisphere temperatures from observations (black) and proxy reconstructions. Inset: relationship between observations coverage (*x*) and Northern Hemisphere (*y*) temperature in the simulations, with best fit line (slope 1.2). All series normalised to have mean zero over 1795–1805. The grey vertical lines mark the dates of two large volcanic eruptions (1809 and 1816). Data used is listed in Table 1.

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