Gatrill-Smith, Eleanor (2007) North Atlantic Climate, 1750-1800: Evidence from Ships' Logbooks. Doctoral thesis, University of Sunderland.

NORTH ATLANTIC CLIMATE, 1750-1800: EVIDENCE FROM SHIPS' LOGBOOKS

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A thesis submitted in partial fulfilment of the requirements of the University of Sunderland for the degree of Master of Philosophy

August 2007

ABSTRACT

Building on the achievements of the CLIWOC project and its use of ships' logbooks for climatic reconstructions, this thesis examines more closely the conditions over the North Atlantic during the latter half of the eighteenth century. Furthermore, and importantly, this thesis provides additional verification of this largely untapped data source for scientific purposes.

Such is the recent nature of this field that the logbook data required careful translation and manipulation before they could be used in climatological studies and a significant element of the thesis is devoted therefore to the important question of data verification and treatment.

Indices were derived from the logbook data that described the wind patterns in the areas north and south of the Azores anticyclone, taking the form of vectors combining wind force and direction. These indices were developed at monthly resolution (although the original logbook data are presented in daily form on CD1, which accompanies this thesis) and also aggregated up to annual resolution. The indices showed good agreement with accepted climatological theory and the general character of wind flows in the two constituent sub-regions noted above could be identified at this scale of resolution for the very first time.

Studies were developed using independently derived indices, including a grid-based North Atlantic Oscillation Index (NAOI), the Central England Temperature series (CET), the England and Wales Precipitation series (EWP) and sunspot number, which were selected for their coverage of the study period at monthly resolution. A number of significant correlations were found between the logbook indices and also between the latter and the 'independent' series. Some of

these, such as those between airflow and the Central England Temperature series were not unexpected, but welcome nonetheless by conforming to climatological theory. Others, however, especially those suggesting a solar signal in the climate record were new and more challenging. These require additional research, much of it beyond the scope of this thesis, and provide an inviting pointer for future studies using this demonstrably valuable data source.

ACKNOWLEDGEMENTS

Thanks are due to the University of Sunderland for the opportunity to be part of the CLIWOC Project (and the consequential funding of the data abstraction phase of this thesis), to the National Maritime Museum, Greenwich, for the hospitality of a base for the duration of the abstraction phase, use of images, and for the use of their archives of logbooks, and to the British Museum and National Archives for the use of their collections of ships' logbooks.

Gratitude is also owed to Dr Dennis Wheeler for his assiduous academic supervision over the course of the thesis and to Dr Clive Wilkinson for his valuable input into the background of the logbooks and the naval history. Acknowledgement of kind contribution also goes to A. R. T. Jonkers.

Significant appreciation is also given to my family, in particular to my parents, whose tireless support and financial assistance I will always be indebted to them for.

CONTENTS

INTRODUCTION, AIMS AND OBJECTIVES

This research thesis evolved directly from the EU-funded CLIWOC project (Climatological Database for World's Oceans: 1750 to 1850), which ran from 2001 to 2004 and of which I was a member in the capacity of a research assistant with responsibility for abstracting raw data from the logbooks and for transcribing them into the preliminary databases prior to their manipulation and inclusion in the final, publicly-available database. Whilst the CLIWOC project had a clear set of aims and objectives of its own (these can be found on the project website www.ucm.es/info/cliwoc) it was clear that many further, more modest, enterprises could be undertaken using the information, skills and raw material accumulated under its aegis. This is one such undertaking. Inevitably, and reflecting the greater limitations on time, funding and staffing, this current project had to be more narrowly focused than the CLIWOC project, and concentrates in just one oceanic basin, the North Atlantic, and a shorter period of the half century from 1750 to 1800. There are good reasons for the selection of the space and time frame. The North Atlantic is an area for which there is the largest and most consistent body of data, but it is also an area the climate of which has arguably been studied more closely than any other. The most recent activities, concerned with the North Atlantic Oscillation (NAO), are merely the latest of a long line of enquiries that date back to the seminal work of Halley (1686) and Hadley (1727). The time frame is of no lesser significance. The latter decades of the eighteenth century represent the final years during which anthropogenic influences on global climate can, with certainty, be assumed to have been absent (Houghton, 1997). It marks also the closing stages of the Little Ice Age, and it might be expected that some climatic differences might have existed in those times.

In addition to the purely scientific issues surrounding the climatic studies, this project seeks also to establish the validity of logbooks as a data source. It needs to be recognized that logbooks have been used only very occasionally in the past, the only clear reference before the CLIWOC project started being that of Oliver and Kington (1970) who drew attention to the potential inherent in this source, although even they failed to draw attention to truly enormous volume of material represented by the numbers of logbooks, running into tens of thousands, from the pre-instrumental, i.e. pre mid-nineteenth century, period. It is remarkable, given this early indication from Oliver and Kington and the volume of logbooks that can be found in UK archives, that CLIWOC was the first attempt at any comprehensive review of this source. It is also important to note at this early stage, one important characteristic of the logbooks, which is that they yield information rather than instrumental data as it is understood today. They contain non-instrumental observations, written in a narrative form that requires careful 'translation' into modern-day terms (in particular Beaufort Scale for wind force) and it is this task of 'translation' and 'homogenisation' that demanded much time during the project and lends a particular character to the thesis. A notable degree of attention was given to the question of the volume, quality and reliability of the data source, which, though applied to this project, would also have implications for logbook studies in a more general sense. Although the mechanical abstraction of the data was done as part of the CLIWOC project, it should be made clear that the matter of data processing and subsequent analysis was undertaken independently and solely under the remit of this thesis.

The aims and objectives itemized below were met by using raw data derived from the data abstracted for the CLIWOC database. These data needed, however, to be modified and re-arranged to meet the particular requirements of this project. With this background in mind, the aims (A) and objectives (O) can be itemised as follows:

O1. To assemble logbook data abstracted for the CLIWOC database into a new database designed to meet the needs of this project and confined to the period 1750 to 1800 and limited also top the North Atlantic region.

O2. To establish the validity of logbook data and information in climatic studies and to confirm them as a valuable ‘new’ source with application and potential well beyond the scope of this project.

O3. To develop methods of data preparation and processing by which archaic maritime information can be expressed in useful scientific terms.

O4. To use these logbook data to summarise some aspects of the climate of the North Atlantic for the period 1750 to 1800.

O5. To demonstrate how logbook data can be used to provide climatic information for periods of particular interest at the time scale of months or years.

A1. To collate raw logbook data from the CLIWOC database.

A2. To examine the evolution of nautical/meteorological terminology over the study period.

A3. To confirm the CLIWOC-derived nautical vocabulary of wind force terms, and to modify and amend it where necessary.

A4. To develop simple statistics and indices that summarise and express in numerical form the largely non-instrumental data found in logbooks from this period.

CHAPTER ONE

REVIEW OF LITERATURE CONCERNED WITH THE CLIMATE OF THE NORTH ATLANTIC

INTRODUCTION

In a century where significant advances were made in science and technology, the twentieth century also saw a move towards a better understanding of global climate. More detailed explanations were offered for the mechanics of meteorology, and the quest for accurate predictions of daily weather provided an added stimulus. With the advent of the computer came the possibility of modelling the climate, and of using past meteorological data, along with the knowledge of the processes involved, to suggest future climatic behaviour, both on a daily time-scale of resolution and longer.

Also over the last century, studies of change in climate over decades and centuries began to raise questions of the extent to which humans were affecting these changes. Climate is not a stationary phenomenon and has varied in the past, and so present and future climate change will be attributable to both natural climate variability and anthropogenic forcing (National Research Council (NRC), 1998). The ability to interpret recent significant climate trends and predict future change, and to confidently enforce environmental policies must therefore be linked to the ability to understand past climatic behaviour and its relationship with human induced change (Luterbacher *et al*, 2002, Jones *et al*, 2001, Hurrell *et al*, 2000).

Anthropogenic climate forcing is expected to be most obvious over the decade-to-century time scales (NRC, 1998) and therefore there has been a great focus in recent years upon the modes of climate variability over these time scales. It has been suggested that ocean-atmosphere interactions may play the largest part in influencing climate variability (Entekhabi, http://web.mit.edu/darae/WWW/entekhabi.html, 1999), due to the ocean's large heat capacity and circulations. Particular attention has been given to periodic coupled oscillations in oceanic regions as possible causes of significant variance (Da Costa and De Verdiere, 2002) and not least of these is the oscillation believed to be the dominant mode of variability in the North Atlantic (Hurrell *et al*, 2000, Trigo *et al*, 2002, Cullen *et al*, 2001, Jones *et al*, 2001), the so-called "North Atlantic Oscillation", or NAO. Because the NAO encapsulates and summarises so much of the climate of the North Atlantic (the area of study of the present thesis) it forms the basis of this review chapter. It is also an area of growing academic interest generating much debate and discussion in the contemporary literature.

THE NORTH ATLANTIC OSCILLATION

The NAO is based on the pressure field difference between the Icelandic Low pressure system (centre of action located around 65ºN), and the Subtropical High pressure system (centre of action located around 40ºN) (Barry & Chorley, 1998). Over the last few decades there has been a convention to describe the situation where the difference in pressure is greater than normal as a "positive phase" (Uppenbrink, 1999). Conversely, when the pressure difference between the two centres of action is less than normal, the NAO is in a "negative phase", though these phases are not representative of two absolutes, only a measure of the current conditions with respect to a normal. Variability in the NAO is more prominent, and thought of as more significant, in winter. It is then that the vigorous nature of the ocean-atmosphere coupling is evident (Deser and Blackmon, 1993), and the NAO reflects changes in the zonal trans-Atlantic airflow. This has important implications for the patterns of temperature and precipitation in Europe and North America (McCartney, 1996).

However, the North Atlantic is an area of complex interactions, conveniently summarised by Marshall *et al* (2001), who outline three main mechanisms and phenomena of climate variability, which affect marine meteorology in the North Atlantic (of which the NAO is one):

1) Tropical Atlantic Variability (TAV) – a covarying fluctuation in sea surface temperatures (SSTs) in the tropical Atlantic and the trade winds located around the Inter-Tropical Convergence Zone (ITCZ).
2) The Atlantic Meridional Overturning Circulation (MOC) – variations in the Atlantic’s thermohaline circulation (also known as the Conveyor Belt).
3) The North Atlantic Oscillation (NAO) – fluctuation in sea level pressure (SLP) difference between the Polar (Icelandic) low pressure system and the Subtropical (Azores) high-pressure system.

This current appreciation of the nature of the north Atlantic’s climate and oceanography is based on a long history of study going back over two hundred years, and it is important to review those developments.

HISTORY OF UNDERSTANDING OF THE NAO

Pre-1900

Unlike some other oscillations and circulation anomalies (e.g. Indian Ocean Dipole, North Pacific Oscillation), the effects and influence of the NAO (and TAV) upon the surrounding environment have been acknowledged for several hundred years. Mariners of the “Age of Sail” were well aware of the global wind fields and used them to their advantage for effective sailing. Eighteenth century sailors would have been able to detect a shift in the trade winds around the ITCZ (characterising the TAV) and the associated cross-equatorial flow, as they paid particular attention to this region to avoid the “Doldrums” – where winds were light or non-existent. Although the same awareness of the MOC would not have been present (as this mechanism is mainly associated with sub-surface processes), the integral role of the NAO in determining the strength and location of the mid-latitude westerly winds suggests that mariners leaving ports anywhere on the perimeter of the North Atlantic could not have failed to be aware of variability in the winds on an annual and seasonal basis, recognising both regularity in the latter but a less predictable level of variation at other times.

Although seasoned mariners of the eighteenth century probably recognised a fluctuation in North Atlantic conditions from year to year, there is no evidence that any attempts were made to explain them. It appears to have been known that the prevailing winds in the Atlantic varied seasonally (Brereton, 1771), but no acknowledgement was made of any oscillations of longer period. There were, however, a few attempts made in the eighteenth and early nineteenth centuries to investigate the wind fields and weather patterns, beginning with Halley's map of the winds in intertropical regions, first published in 1688 (Tucker & Barry, 1984). In a report contained in the *Sandwich Papers*, William Brereton wrote to the Admiralty in 1771, proposing the use of ships' logbooks to construct charts of wind patterns over the oceans, but it was not until fifty years later that this proposal was realised. Further developments took place after 1842 when Matthew Maury was appointed Superintendent of the Depot of Charts and Instruments for the U.S. Navy in Washington. Maury studied the large collection of naval reports available to him to construct global charts of ocean currents, surface winds and temperatures, and weather patterns. An ex-naval officer himself, Maury recognised the importance to sea-farers of knowledge of the ocean environment, and his charts soon became famous and in much demand. In 1855 he published his book entitled *The Physical Geography of the Seas*, the source of very detailed information on the subject and a substantial step towards our present understanding of oceanography. He recognised the nature of the atmosphere and ocean to be a coupled system, stating:

> *"Is it not as if the atmosphere and the ocean were united in marriage, and go hand in hand to stand by and to care for each other, so that they may fulfil all their duties together?"*
>
> Maury (1856), p270

At the time of these advances in general understanding of oceanography and meteorology, more specific phenomena were also under study, particularly in the North Atlantic. In the absence of abundant or continuous instrumental pressure observations in Europe until the early nineteenth century, no pressure field differences could be measured and it was through observation of temperature that the first acknowledgement of a mechanism with an oscillatory character over Europe and the surrounding seas was made. Van Loon and Rogers (1978) reported that the diary of a missionary named Hans Egede Saabye mentioned a seesaw effect in winter temperatures between Greenland and Denmark over the years 1770-78. He noted that when the winter was severe in Greenland, conditions were mild in Denmark, and *vice versa*. According to Van Loon and Rogers, the editor of the diary (1942) remarks that the phenomenon, still observed at the time of writing, must be a real one but that no satisfactory meteorological explanation had yet been given.

As more and longer series of data became available throughout the nineteenth century, investigations into temperature variation began to be made (Wanner *et al*, 2001). Dove (1839; 1841) studied 60 temperature series from the Northern Hemisphere and found them to vary more in a zonal (East-West) than meridionally (North-South) sense, and that seasonal or monthly anomalies in Europe were opposed to those in North America and Siberia (Wanner *et al*, 2001). Hann (1890) used a 42-year series that was more specific to Europe, analysing the monthly mean temperatures between Vienna and Jakobshavn, Greenland, and found that almost two thirds of the annual winter anomalies were opposed in the two locations (van Loon & Rogers, 1978). His table of results for these temperatures anomalies is shown in Table 1.1a (the scanned images are also included in Appendix I), where periods of several consecutive years of anomalously mild or cold winters in Jakobshavn correlate with opposed conditions in Vienna (e.g. 1866-69 and 1870-73). Hann comments on his results:

> *"If one goes through the table of the temperature deviations in Jakobshavn somewhat more attentively, then it is noticeable that numerous severe winters in Greenland corresponded with mild winters in middle Europe. In order to prove this signal more exactly, we visited the middle deviations of all winters (December the previous year combined with January and February of the following year, thus the true physical winters) and the appropriate deviations from Jakobshavn and Vienna placed among themselves. It results from the fact that in the table, 27 winters have opposed temperature deviations and only 15 where the deviations were not opposed.*
>
> *From 1844-46 three successive cold winters in Jakobshavn corresponded with two mild winters in Vienna, 1860-62 were three very warm winters in Greenland, and in Vienna all three were very cold. In Vienna four cold winters followed 1866-67 one behind the other, and all four in Greenland were substantially very warm. We find the straight reversal in the winters 1870-72, which were very cold in Greenland and abnormally warm in Vienna.*
>
> *Furthermore, similar trends are found in the winters 1875 and 1876 and 1882-84. Thus it seems to be present in the results a tendency for opposite deviations in west Greenland and middle Europe."*

Hann (1890) p112-113 (translated)

Table 1.1b shows that there is indeed a moderate negative correlation present in Hann's findings.

In addition to the temperature series analyses made in the late nineteenth century, more abundant pressure data enabled further investigation of macro-meteorology and climate variability, including links between large pressure systems and European winter temperature anomalies and an inverse pressure relationship between the Azores and Iceland (Wanner *et al*, 2001), to be made.

	1841	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	**50**	**51**
Jakobshavn	3.4	-2.4	0.6	-3.0	-1.7	-0.3	8.8	-1.9	-4.7	1.1	1.7
Vienna	-4.2	-1.9	3.3	0.8	-1.9	2.8	-1.3	-1.2	0.7	-0.7	0.3
	1858	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**
Jakobshavn	-0.8	-3.1	5.6	2.0	1.9	-9.4	-4.2	2.1	-2.7	-0.8	-2.3
Vienna	-2.6	1.6	-0.3	-0.4	-1.1	2.5	-2.0	-2.5	2.1	1.7	0.8
	1869	**70**	**71**	**72**	**73**	**74**	**75**	**76**	**77**	**78**	**79**
Jakobshavn	-1.7	2.3	4.2	6.7	3.0	-2.0	6.3	2.1	2.8	0.6	6.4
Vienna	2.8	-1.2	-2.5	-1.9	2.3	1.2	-1.3	-1.7	2.6	1.0	-0.2
	1880	**81**	**82**	**83**	**84**	**85**	**86**	**87**	**88**		
Jakobshavn	-3.5	3.7	-5.5	-0.1	-7.4	0.7	-2.3	-3.1	1.7		
Wien	-3.1	0.1	1.7	1.1	2.3	0.7	-1.1	-0.5	-1.4		

Table 1.1a: Table of results from Hann (1890), showing winter temperature deviations from the annual means (using the 43 years shown) in Jakobshavn and Vienna. The original can be seen in Appendix I.

	J	*V*
J	1	
V	-0.33955	1

Table 1.1b: Correlation table of Hann’s results

The Twentieth Century

The turn of the century saw a move towards a more statistical approach to climatology, including greater attention to the correlation method and a more concerted effort to explain phenomena, rather than to just describe them. The work of Sir Gilbert Walker (see figure 1.1), a British mathematician and meteorologist who became one of the most influential scientists in atmospheric science of the early twentieth century, focussed initially on prediction of the Indian Monsoon (Wanner *et al*, 2001), but later expanded this to include the entire globe (Walker, 1924). He noticed some patterns in rainfall and ocean temperatures in the Indian Ocean, and began to correlate large amounts of worldwide meteorological data. He developed the hypothesis of the Pacific circulation pattern which now bear his name, and was the first to mention the terms North Atlantic Oscillation and Southern Oscillation (SO) (Lamb and Peppler, 1987).

Further studies of the pressure anomalies associated with the NAO were published by Exner, and by Defant, both in 1924. Exner began his work in 1913 by examining monthly pressure anomalies at the North Pole and other northern hemispheric sites, his correlation patterns closely resembling what is known today as the Arctic Oscillation (AO) (Wallace, 2000). His work in 1924 investigated correlation patterns between pressure anomalies at Stykkisholmur in Iceland and approximately 70 sites for winter months (Sep-Mar), 1887-1916. The maps he produced identified an annular pattern exhibiting characteristics very similar to those of current understanding of the NAO (Wanner *et al*, 2001). Defant analysed monthly SLP anomalies over the North Atlantic, pointing to two pairs of opposed anomalies (one being the NAO, accounting for 83% of all months, the other a weaker pattern between 55ºN and 10-30ºN) and creating a time series of the anomalies he found (Wanner *et al*, 2001). The time series was constructed by attributing an anomaly type and strength to each month; this was a precursor to the work of Walker and Bliss who, in 1932, constructed the first NAO index using temperature series and SLP data (Wanner *et al*, 2001). This index was then related to European and North Atlantic climate (van Loon & Rogers, 1978).

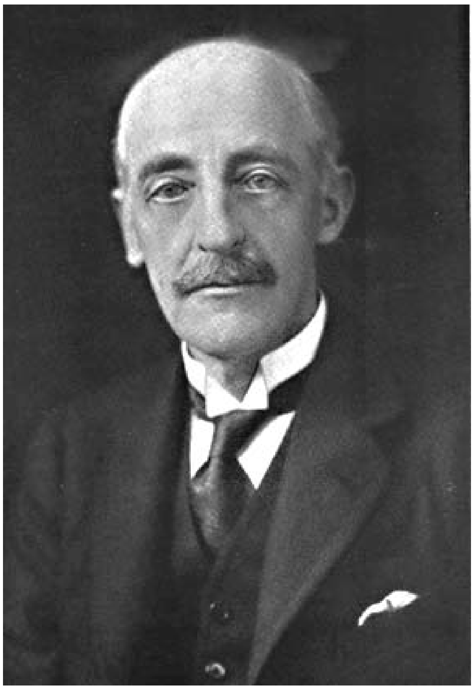


Figure 1.1: Portrait of Walker - Image courtesy of Eugene M. Rasmusson, University of Maryland and taken from the University of Washington's website (http://www.atmos.washington.edu/gcg/RTN/Figures/RTN8W.html)

As further advances were made in the understanding of the complex interactions in the atmosphere-ocean system, wave motion and zonal circulation were addressed and "zonal indices" were constructed. The most popular of these, presented by Rossby *et al.* (1939), used the mean SLP differences at 55ºN and 35ºN, averaged over the east-west plane. This was followed by a study of significant insight into the role of atmosphere-ocean circulations and interactions in North Atlantic climate variability by Bjerknes (1964). In addition to making the first link between El Nino and the Southern Oscillation (originally identified by Walker), Bjerknes constructed an index based upon the pressure differences between the Azores High and the Polar Low to illustrate the strength of zonal airflow over the North Atlantic. This index is not dissimilar to the NAO indices of more recent years (Wanner *et al*, 2001).

Van Loon and Rogers (1978) re-examined the seesaw effect of winter temperatures between northern Europe and Greenland and found relationships between the pressure anomaly patterns and SST's over a wide area of the northern hemisphere. Through this mathematical approach to describing the behaviour of the phenomenon, they also found associations between the NAO and the North Pacific Oscillation (NPO), and that either of the two opposed patterns of circulation would be dominant for several decades.

This observation of periodicity was timely, as the NAO had been in its "positive phase" for six out of the previous seven years, and was to remain dominantly positive for the next twenty five years, a situation which we are currently still experiencing.

Studies of the 1980s adopted a more statistical and mathematical approach, with several publications using developments of the Principle Component Analysis (PCA) methods (which find patterns in a set of data and create times series) for SLP and geopotential height fields (approximations of actual heights above mean sea-level of pressure surfaces). Examination of pressure fields as part of various studies found patterns and relationships in many areas of the world, including the mid-troposphere in areas such as the western Atlantic and north Pacific (Wanner *et al*, 2001) linking the NAO and SO at the 500 mb level (Rogers, 1984). In addition to the analysis of pressure anomaly patterns, attention was focussed upon the position of the pressure systems involved in the NAO phenomenon. Glowienka (1985) studied the annual cycles of the latitudinal position of the Azores High and Icelandic Low, and found that a northward shift in the centres of action was associated with the degree of intensification of both systems.

The relationship between the NAO and climate

As understanding of the NAO began to grow, so did the investigations into its effect upon Northern Hemispheric climate and climate variability. Barnston and Livezey (1987) demonstrated the importance of the NAO's role in European and North American climate, and showed that it is the only low frequency, large-scale circulation pattern which is found in every month of the year (Wanner *et al*, 2001). In a similar study, Lamb and Peppler (1987) related the NAO index to the Moroccan winter precipitation, finding that there was a strong inverse relationship between the two.

The NAO has also been shown to be linked with the behaviour of storm tracks in the North Atlantic (Rogers, 1997, Elsner *et al*, 2000, Elsner & Bossack, 2001, Dawson *et al*, 2002), temperature and precipitation anomalies in a variety of locations in Europe (Hurrell & van Loon, 1997, Ben-Gai, 2001, Wood, 2004) and synoptic scale variability (Gulev *et al*, 2000, Zveryaev, 1999). Further studies investigating the relationship between the NAO and blocking episodes in the North Atlantic (Schmutz *et al*, 2000) and the latitude of the Gulf Stream (Taylor & Stephens, 1998) show the link of the NAO to further aspects of meso-scale meteorology.

The use of oceanic data for study of the North Atlantic climate

There have been several studies that have used oceanic data for analysis of climatic variability. The source of these data is the International Comprehensive Ocean-Atmosphere Dataset (ICOADS), a digital database of ship logbook observations covering the period 1784-2002, which comprises surface marine reports, buoys, and pre-instrumental logbook data from the US Maury collection. This dataset has been used to analyse surface climate variability for SST, air temperature, wind and SLP (Deser & Blackmon, 1993), to identify fluctuations in the 100 year SST time series over the North Atlantic and associated circulation anomalies (Kushnir, 1994), to investigate the relationship between TAV and the

NAO (Bojariu, 1997), and to analyse the behaviour of the atmospheric centres of action of the Icelandic Low and Azores High (Machel *et al*, 1998).

ICOADS is not the only dataset used in studies on the NAO to include historical or non-instrumental observations. In 2002, Dawson *et al* used observations originally made by lighthouse keepers from historic weather records in Scotland to analyse the time series of storminess in the North Atlantic for the period 1876-1996. In this series, the frequency of "gale days" is used, where a gale day was that with the wind force being in excess of 34 knots over an accumulated time period of at least an hour. In the early part of this time series, gale days were found to be overestimated when the homogeneity of the data was checked against the Jenkinson Gale Index. It is suggested that this is probably due to the fact that winds classified as gales prior to the introduction of the Beaufort scale into Scottish Meteorological records in 1905 were not necessarily indicative of a storm, and were exaggerated with respect to strength. Such difficulties testify to the problem of integrating non-standard observations with present-day, conventionally gathered, marine data and to the care that must be taken in its use.

The evolution in approach of studies in the late twentieth century

Despite the emergence of PCA and correlation of data to analyse meteorological phenomena in the twentieth century, the focus of the majority of NAO studies in the twentieth century was still upon description and presentation of findings, as opposed to explanation or prediction. This changed in the 1980s, when attention began to shift towards measuring the NAO in an attempt to reconstruct its historical behaviour and suggest possibilities for the future. This developed until, in the late 1990s, when there was an exponential rise in the number of studies being undertaken of the NAO, the extent of which is shown in figure 1.2, including a number of summary papers giving an overview of the phenomenon of the NAO and the knowledge of its behaviour to date (Wanner *et al*, 2001, Marshall *et al*, 2001, Hurrell *et al*, 2001b, Visbeck *et al*, 2001).

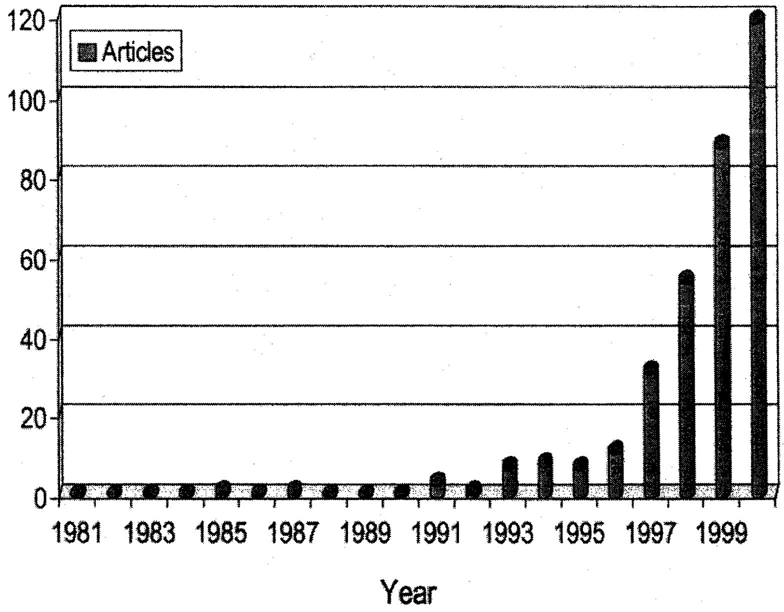


Figure 1.2: Bar-plot showing the increasing number of publications relating to the NAO over recent years, taken from Wanner *et al* (2001). Source is the Web of Science bibliographic database and figures represent items containing the term "North Atlantic Oscillation" in the title or abstract.

THE NAO INDEX

As has been shown thus far, much of the published work on the NAO was of a descriptive nature and tended to focus on the analysis of the behaviour of the

NAO. More recently however, an increasing number of studies have been concerned with measurement of the NAO.

The measurement of the behaviour of the NAO over time has become primarily represented by the NAO index, or NAOI. The most common definition of this is the difference between SLP anomalies from two stations close to the centres of action of the pressure systems (Jonsson & Miles, 2001, Jones *et al*, 2001, Hurrell, 1995). A simplified equation to represent this relationship may be drawn from the Climatic Research Unit’s website (www.cru.uea.ac.uk/cru/info/enso), who present an equation for the Southern Oscillation Index (SOI) (after Troup, 1965) which may be adapted:

$$\mathrm{NAOI} = 10.0 \times \frac{[\mathrm{SLPdiff} - \mathrm{avSLPdiff}]}{\mathrm{StdDev(SLPdiff)}}$$

- *Equation 1*

Where SLPdiff = (mean Azores SLP for the month) – mean Iceland SLP for the month)
avSLPdiff = long term mean of SLPdiff for the month in question, and
StdDev(SLPdiff) = standard deviation of SLPdiff for the month in question.

It is important in calculating the NAOI to use normalised monthly or seasonal averages, and this, as Jonsson and Miles (2001) explain, is because absolute variability in the Icelandic Low (IL) is much greater than the Azores High (AH). Normalisation of the data reduces the relative importance of the IL to the overall variability.

A number of NAO indices have been based upon this concept of pressure anomaly differences, but this is only possible where pressure data are available. Other indices have utilised different forms of data and consequently used an alternative method by which to create an NAOI. This differentiation in methodology leads to a convenient split in the types of indices presented over recent years. Most of these fall into two categories: indices based upon pressure data, and those based upon proxy data. These two types are examined in more detail below.

INSTRUMENTAL (PRESSURE) INDICES

Due to the quantitative and generally reliable nature of this type of data many NAO indices have been based upon pressure series from stations in Europe that fall within its broadly understood area of influence. As already mentioned, the first references to a wintertime atmospheric oscillation came in the mid nineteenth century with the investigation into temperature series, not pressure series, but indices in the conventional sense were not derived from them. Despite the discovery of a relationship between pressure circulation patterns and winter conditions in Europe by Teisserenc de Bort (1883) and Hildebrandsson (1897), it is generally accepted that the first instrumental NAO index was presented by Walker and Bliss in 1932 (Cullen *et al*, 2001). The index itself is derived by way of a rather complex procedure (not unlike principle component analysis (Wallace, 2000) involving seven time series of temperature and SLP data from Europe and North America and using the following equation:

$$P_{\mathrm{vienna}} + T_{\mathrm{Bodo}} + T_{\mathrm{Stornoway}} + 0.7P_{\mathrm{Bermuda}} - P_{\mathrm{Stykkisholmur}} - P_{\mathrm{Ivigtut}} - 0.7T_{\mathrm{Godthaab}}$$
$$+ 0.7(T_{\mathrm{Hatteras}} + T_{\mathrm{Washington}})/2$$

- Equation 2

Where P is the air pressure and T is the air temperature averaged over December-February. The SLP series from the Azores is excluded in this index due to being found unreliable, despite being a series which has enjoyed popularity in indices of recent years. It is also interesting to note that this method uses both pressure and temperature, unlike modern NAO indices.

A number of zonal indices were created in the mid-twentieth century, mostly using SLP. Rossby (1939) used SLP differences between 55N and 35N to investigate the strength of the polar vortex, whereas Bjerknes (1964) was the first to use SLP from Iceland and the Azores as a dipolar measure of westerly flow. Further studies which use SLP differences from Iceland and the Azores to create an NAOI include that by Rogers (1984). Having already published papers with Harry van Loon on the general anomaly patterns in the NA, Rogers created an index for the period 1895-1983 based on the mean normalised pressure difference between Ponta Delgadas, Azores and Akureyri, Iceland. He also presented the normalised winter mean SLP anomalies from the1900-1979 normal for the region 60-70ºN and 30-65ºW. Rogers then compared the NAO to the SO, finding only partial/weak interrelation and only at times.

Other point stations from which SLP data have been drawn are Stykkisholmur (Iceland) and Lisbon (Hurrell, 1995), and Gibraltar and Reykjavik (Jones *et al*, 1997c). Hurrell’s NAOI covers the period from 1864 to the present day (it is updated annually on his website (http://www.cgd.ucar.edu/~jhurrell/nao.stat.winter.html#winter), and his index is based on the difference of normalised pressures between the two points, shown in figure 1.3. Anomalies in SLP at each station were normalised by division of each seasonal pressure by the long-term mean (1864-1994) standard deviation (this procedure is not entirely dissimilar from equation 1). The index presented in Jones *et al* (1997c) extends back to 1823 and as far as 1996, and uses the simple method of subtracting the normalised pressure at the Icelandic site from the normalised pressure at the southern location, also an adaptation of the SOI methods.

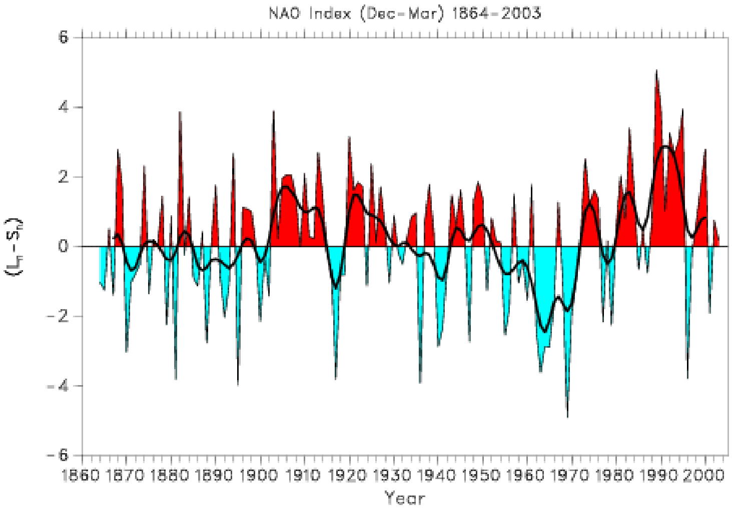


Figure 1.3 – Hurrell's NAO index for the period 1864-2003, based on December-March SLP anomalies (Hurrell *et al*, 2001a)

There are differing views and a certain amount of controversy surrounding the selection of point stations for the pressure series data, and NAOI values for any given month vary depending upon which set of points, and thus which index is used (Wanner *et al* 2001). Jones *et al* (1997c) suggest principle component analysis (PCA) of surface pressure, 500 or 700hPa fields as a means by which to determine the best locations, but studies by Wallace and Gutzler (1981) and Barnston and Liveszey (1987) show that these can vary with season. Perhaps in the light of this, attempts have been made to use gridded data instead. This approach, to some degree, takes into account the seasonal spatial shift in the centres of action of the AH and the IL, which could otherwise influence the climatic signal (Luterbacher *et al*, 1999). Ulbrich and Christoph (1999) derive an index that is defined as the difference between area averaged and normalised SLP anomalies, and use the areas northwest of Portugal (40-43°N, 11-14°W) and Iceland (65-68°N, 17-20°W). Luterbacher *et al* (1999) create and use an NAOI which is based on four adjacent grid points on a 5°x5° longitude-latitude grid, where the SLP is averaged over these four grid points in both the Iceland area and the Azores area. The former is then subtracted from the latter to give the NAOI value.

This same approach is used in by Jacobeit *et al* (2001). They take grid points over 20-30°W, 35-40°N (Azores) and 20-30°W, 60-65°N (Iceland) and calculate the differences between normalised SLP averages for these sections.

The majority of NAO indices only cover the winter period, as accuracy is questionable outside of these months due to the weaker signal of the NAO and the less organised nature of summer circulations in the northern hemisphere. However, there are several indices including Jones *et al* (1997c) which shows an index for all seasons, Jacobeit *et al* (2001) which shows summer and winter, and Luterbacher et al (1999) who analysed data on a monthly basis, but give an NAOI for autumn and winter for the purposes of showing the enhanced signal during these seasons.

Use of data from the Pre-Instrumental Period

Although most sources are in agreement that the instrumental period (when direct, instrumental measurements of atmospheric variables became widely available) begins around 1820, this is not to say that data are not available prior to this. Historical studies of the pressure circulation patterns in the pre-instrumental period have been undertaken, and some also developing NAO indices. Slonosky *et al* (2001) used daily pressure observations from Upminster, Essex, and from Paris, for the period 1657-1735 to reconstruct a time series of pressure differences between the two. They then correlated this with an existing NAOI, and found the agreement to be relatively poor (with a correlation coefficient of 0.2), and the relationship far from straightforward. They suggest that this may be due to the low correlation between European zonal circulation and the NAO in summer, or possibly due to problems with the reconstructed NAOI.

Long-term pressure time series in Europe have also been verified and used to reconstruct monthly pressure fields as far back as 1780 (Jones *et al*, 1999). These have subsequently been used to create an NAOI for the period 1780-1995 (Jacobeit *et al*, 2001) over the gridded area of 35º to 70ºN and 30ºW to 40ºE. The distribution of data over the study period for this index (only 10 continuous series were available over the grid in 1780, increasing to 20 by the 1820s and 51 by the mid nineteenth century) is demonstrative of the overall trend in instrumental data sources. However, further pressure station series have been found for Paris (1675-1713) and Basel (Switzerland, 1755 onwards) and used to produce an NAOI (Luterbacher *et al*, 1999), and then extended still further back to 1659

(Luterbacher *et al*, 2002) with monthly resolution using calibrated proxy data such as tree ring and other sources. In the most part, reconstructions of NAO indices prior to the eighteenth century have had to depend heavily upon non-instrumental (proxy) data.

PROXY INDICES

Reconstructing past climate in the absence of continuous series of instrumental data relies heavily upon data that are not direct measurements of the climate, but are reflections of the natural conditions of the environment from which they come. These data are called proxy data (Drake, 2000). Widely used proxy data include ice cores, deep-sea sediments, tree rings, oxygen-18 isotopes, fossil pollen and living organisms, and historical documentary evidence also falls into this category (www.ngdc.noaa.gov/paleo/proxies.html). It is the relationship between these proxy indicators and their surrounding climatic environment that allows reconstruction of past climatic conditions, but this relationship is not straightforward (Briggs & Smithson, 1985), and not without problems. The process assumes a constant relationship between the indicator and the climate over time, which may or may note be true (Drake, 2000), and accurate dating of the indicator is not always possible (Williams *et al*, 1993).

An early example of the use of proxy data for NAO reconstruction was Cook *et al* (1998), who draw on work by D’Arrigo *et al* (1993), which shows a relationship between tree ring data and winter-time climatic extremes induced by the NAO, to investigate the possibility of using these data to reconstruct an NAOI. Since the seasonal growth of the tree trunk thickness depends largely upon climatic variables such as temperature and precipitation, Cook *et al* found sufficient grounds to suggest this relationship would be sensitive enough to reflect the NAO signal. The index is based upon 66 tree-ring chronologies from eastern North America and 36 from Western Europe and covers the period 1700-1979. The data were carefully verified and calibrated against an existing NAOI (Rogers' index from 1984) and the resulting winter (DJF) index appears to reproduce the overall shape of the instrumental index to a high degree despite some limitations of the regression model used for the reconstruction.

Ice core data may also be used to investigate the temporal behaviour of the NAO, due to the ability of the snow accumulation to reflect the surrounding climatic environment as it turns to ice and traps air bubbles, particulates and various chemical signals in its layers. An index has been created using these data for a 350-year period (Appenzeller *et al*, 1998), which spans 1648-1990 and is annual (April-March).

Another natural formation that can lend itself to past climate reconstruction are speleothems. Precipitation of carbonate from flowing or dripping water in caves grow to form structures such as stalagmites and stalactites, and due to a mechanism similar to ice cores of incorporating environmental material into the formation, can be a reliable source of paleoclimatic data (Lowe & Walker, 1997). This potential has been realised with the reconstruction of the NAO from 907-1993 (Proctor *et al*, 2000) from stalagmite growth from NW Scotland, and the reconstruction is of annual resolution. This latter study relies heavily on the control exercised by the NAO on the geographical distribution of rainfall. In general, NW Scotland is wetter in positive NAO phase, but dry in its negative phase. In all such cases, therefore, calibration of the model is a vital part of the work.

Documentary evidence is the final type of proxy data which has been used in the context of North Atlantic climate reconstruction or historical analysis. Rodrigo *et al* (2001) used documentary records from southern Spain to reconstruct precipitation fields and relate it to the temporal behaviour of the NAO from 1501-1997. While Luterbacher, (2002) mention 11 reconstructed climatic indices (temperature, precipitation & sea ice conditions from the western Baltic) that exist prior to 1659. These are based upon documentary data (observations of cloud cover, snow and ice features as well as phonological and biological observations), and mostly of seasonal resolution. The data are calibrated over the 1901-1960 period and used alongside instrumental and other proxy predictors to reconstruct a seasonally based NAOI back to 1500.

Several papers have been published which present multi-proxy reconstructions of the NAO, allowing comparison of the performance of the proxy indicators. The most notable of these are Cullen *et al* (2001), who use indices from ice core data (from Appenzeller, 1998), tree-ring data (Cook *et al*, 1998 and D'Arrigo & Cook, 1997), and a multi-proxy reconstruction (using both Jones *et al*, 1997c and Mann, 2002); Luterbacher *et al* (1999 and 2002) who initially in 1999 amalgamated instrumental pressure, temperature and precipitation measurements with proxy data (ice, snow and tree-ring data), reworked their data in 2002 (as already mentioned) with new information to enable further extrapolation of the resulting index. Glueck & Stockton (2001), used tree ring data (from Morocco and Finland), delta O^{18} isotopes and snow accumulation data to create a wintertime NAOI for the period 1429-1983. Each of these studies suggests that the most favourable results (with respect to accuracy and performance of the index) are yielded with the amalgamation of several indicators to give composite reconstructions, rather than those based upon individual series (Cullen *et al*, 2001). However, individual series seem to have varying importance in the process of maximising the accuracy of multi-proxy indices. Glueck & Stockton (2001) outline ice core data to be the most “important” predictor, followed by the tree-ring data in order to produce an index with the highest correlation with an instrumental index. Luterbacher *et al* (1999) state that the instrumental pressure data used in their index were found to be the most important predictors. They explain that no significant correlations were found between their index and that of Appenzeller *et al* (1998), Cook *et al* (1998) or Stockton and Glueck (1999). Furthermore, they suggest that these studies are of poorer quality due to the small number of predictors and poor spatial coverage/temporal resolution.

It is clear that proxy data have limitations. Most cannot show the seasonality of the NAO and its strong annual cycle and display a much more limited range of timescales than instrumental data (which is much more versatile in this respect) (Luterbacher *et al*, 1999, Wanner *et al*, 2001). The problem of non-stationarity in the NAO teleconnection (both spatially and temporally) is not well resolved with proxy NAO reconstructions (Machel *et al*, 1998, Luterbacher *et al*, 2002) and there is a certain amount of uncertainty in the proxy reconstructions with regard to the extent to which variations are due to changes in the NAO, or to changes in the influence of the NAO on the climate (Luterbacher, 2002, Cullen *et al*, 2001).

Cullen *et al* (2001) draw attention to the fact that the tropics have an abundance of marine proxy data, such as coral isotopes, and suggest that extra-tropical regions like the NA are lacking in this type of data. They point to tree-rings and ice cores as the best source of proxy data for climate variability reconstruction in these regions. However, given that these are in the most part terrestrial indicators, and that temporal resolution with respect to NAO reconstruction is often less than satisfactory, there is a need for data which are more versatile in the timescales available on which to reconstruct NA climate.

The potential of logbook data for this purpose is good, as they are marine in nature and versatile in temporal resolution (daily, but can be aggregated to monthly, annual or decadal). They are the only data available for the pre-instrumental period that have daily resolution and are marine-based. Some logbook information as far back as 1784 can be found within the ICOADS (which has been shown to be suitable for use in NA climate reconstruction and link to the NAO, see Bojariu, 1997), but the abundance of logbooks at least a century prior to the 'instrumental period' is an opportunity to investigate the merit of these data for Atlantic studies and their implications for NAO reconstruction for the pre-instrumental period. This has been broached following the CLIWOC project through work by Jones and Salmon (2005), Gallego *et al* (2005), and Ward (2006), who have used the CLIWOC database to make some climatological studies and interpretations for the latter half of the eighteenth century. Indeed, Jones and Salmon go as far as to offer a preliminary reconstruction for the NAO and SOI, for the period 1750-1997. They used CLIWOC wind vector data (1750-1850) and ICOADS data (1851-1997) (linking wind fields and surface pressure patterns), and based upon aggregated 8° grid-squares, using orthogonal spatial regression techniques. However, the model did not fit the 1750-1850 period well and the authors suggest this could be due to the low number of observations available in some regions within the CLIWOC database (no grid-box series was complete for all of the CLIWOC period). Gallego *et al* (2005) utilised the same approach and successfully produced surface pressure reconstructions for the North Atlantic, using CLIWOC data and calibrated against ICOADS data, although they point out the importance in data coverage, and also the difference in the response of the regression model over the region of the North Atlantic. All three studies found the CLIWOC data to be reliable in terms of its conformation to accepted climatological theory.

Comparisons between the findings of these studies and the author's independently conducted investigations can be usefully made at a later stage, to ascertain the extent to which any findings may support each other.

CHAPTER TWO

THE HISTORY OF LOGBOOKS: their purpose and function

THE EARLY DEVELOPMENT OF THE LOGBOOK

Written accounts of the seafarer have been in existence for several centuries, if not millennia, and the earliest of these could realistically be placed with the emergence of narrative literature of a general kind (Taylor, 1956). However, even in these early cases it is only by chance that it is possible to extract any kind of factual information relating to climate since the author would only see fit to detail the events on board a ship should it be of significance or relevance. Nevertheless there are occasions when climatic events impinge upon a wider reality and, for example, Taylor (1956) refers to the Acts of the Apostles in which an eyewitness describes St Paul’s shipwreck. The same account mentions the apparent absence of the stars whilst navigating, thus indicating that stars were probably used in the navigational practices in force at the time:

> *“ We took such a violent battering from the storm that the next day they began to throw the cargo overboard. On the third day they threw the ship’s tackle overboard with their own hands. When neither sun nor stars appeared for many days and the storm continued raging, we finally gave up all hope of being saved.”*
>
> (Acts 27:18-20).

Whilst these kinds of accounts are interesting they are a long way from the dutifully kept logbooks of the seventeenth century and onwards in the information they yield and their regularity. The evolution of a regular journal kept on board a vessel probably came about with the advent of open water sailing i.e. out of sight of land, the timing of which can be placed around the late fifteenth century with such sailors as Columbus. Fuson (1987) states that "without doubt this [Columbus' logbook of his 1492 trans-Atlantic voyage] was the most accurate and complete ship's log ever produced up to its time." and it is evident that Columbus' logbook offers many similarities in content to those of the eighteenth century. The same meticulous precision for navigation (though Columbus used a process called dead reckoning, where distances and courses run were considered along with winds and currents to plot cumulative position, in necessary preference to the later celestial methods) is present, though errors are so rife – typical of early procedures of dead reckoning - that Fuson believed it might never be known exactly where the first landfall of this historic journey was made.

Evidence of cross-sea voyages made before the age of exploration (initiated by Columbus and the contemporary Portuguese pilots) is tentatively approached by Taylor (1956). These crossings, made for the purposes of shipping building materials from one country to another such as Scotland to Denmark, or Greece to Crete, would have taken at least two days under favourable weather conditions and therefore inevitably required night-time navigation. The tendency to "hug" the coast was still evident however, and these voyages were clearly not of the same magnitude in terms of navigation as those of Columbus when longer journeys were made with weeks at sea, without the option to keep close to the coastline. It was under such circumstances that detailed logbooks were more commonly maintained as they formed an important part of the means by which navigation was conducted in those times.

THE PURPOSE OF LOGBOOKS

In the seventeenth and eighteenth centuries there was no absolute way to determine accurately where on the Earth's surface a ship that was out of sight of land might be positioned. This was particularly the case for longitude (degrees east or west), but less so for latitude. Often sailors were taken by surprise with their apparently premature landfall and this led to countless lives lost, increasing the urgency of finding a sure way of determining their longitude.

This increasing need for more accurate navigation and positioning led to the officers on board a vessel beginning to keep track of their course and positional observations day by day much more diligently. However, even though regularity was not a problem thenceforth, these logbooks were prepared by mariners without future students in mind and, as will be seen later, they can be difficult to understand and work with, being prepared for use by contemporaries familiar with the vocabulary and navigational methods of the age. Part of these methods required the reliable observation of wind force and direction. But, and it is worth emphasising again, such data were not collected with any scientific purpose in mind but for the more immediate and practical purposes of secure navigation. In this sense, there is a prima facie case for suggesting that the observations were reliable: the lives of the crew were partly dependent upon such a supposition.

NAVIGATION

In addition to navigational purposes, the recording of journeys was a requirement of Royal Navy Officers to receive their pay on decommissioning, and they were also used to secure promotion from junior to senior rank. Oliver and Kington (1970) cited a Naval Article that was published in the early eighteenth century where explicit instructions were laid out for the keeping of journals:

> *"He [the Captain or Commander] is, from the Time of his going on board, to keep a Journal, according to the Form set down, and to be careful to note therein all Occurrences, viz. Place where the Ship is at Noon; changes of wind and weather; salutes, with the reasons thereof; remarks on unknown places; and in general, every circumstance that concerns the Ship, her stores, and provisions. At the end of every six months he is to send a copy of his journal for the said time, to the Secretary of the Admiralty, and at the expiration of the voyage, to deliver a general copy of his journal, signed by himself, into the Admiralty and Navy Offices."*
>
> (Naval Instructions 1731)

This requirement placed logbooks very much in the category of formal documents – a role that they continue to enjoy today. It also ensured their survival upon completion of the voyage. Particular note should be made of the instructions to observe, and note, the wind and weather, indicating formal recognition of the importance of this part of daily sea life in the Royal Navy.

Understanding travel over the surface of the Earth

Before a reliable method of fixing the ship's position by longitude, sailors often employed a technique known as "sailing the parallel" or " running down the parallel" (Sobel, 1995), which was to keep to a certain line of known latitude and sail until landfall. This is possible as latitude is fixed with respect to an obvious and unchanging terrestrial reference (the equator) and could be estimated by reference to the altitude of the midday sun, whereas without a fixed zero meridian (as Greenwich is now), or a method by which to relate to one, longitude is unavoidably estimated on an approximate basis.

The difficulty in estimating longitude is illustrated by a brief review of the pertinent astronomical principles. The Earth takes twenty-four hours to complete one rotation and in that time a point on the surface has travelled three hundred and sixty degrees. Therefore one hour is equivalent to fifteen degrees and one degree is equal to four minutes. From a ship's point of view, each hour's difference between the present time at its starting point and the present local time (reset by observing the sun at its overhead point at noon) means a distance of fifteen degrees of longitude having been travelled. Unfortunately there were two problems with this concept for sailors in the middle of the last millennium. The first was that they had no means by which to accurately keep track of the time at their start point, since timepieces of the day were pendulum based, and developed significant errors when subject to external motion such as is experienced at sea, or differences in temperature. Secondly the distance actually travelled by the ship could not be directly translated into degrees of longitude since this relationship depends on latitude. One degree of longitude is equal to sixty-eight miles at the equator but closer to the poles is reduced to a relatively negligible amount, due to the curvature of the Earth.

Fixing the ship's position was vital for open water sailing, and the movement towards a more mathematical navigational system was taking place at least a century before the longitude problem was tackled (in the late eighteenth century). In the mid seventeenth century the determination of the length of a degree in navigational terms had to be resolved and Willebrod Snellius, a Dutch mathematician/astronomer (and English mathematician Edmund Gunter to a lesser extent), was instrumental in this achievement. The use of the Dutchman's log (the method of determining the ship's speed) into the eighteenth century raised the point (creating much contention amongst sailors, navigators and scientists) of the length of the nautical mile, which was tied into the greater problem of determining the length of an arc of terrestrial meridian. The problem was most successfully tackled by Richard Norwood in 1635 (Hewson, 1983), and these accounts ultimately led to the revision of the figure of 5000 ft to the mile, to a new figure of approximately 6000 ft to the mile. Thus the measure of the degree was also revised and eventually led to the confirmation that the Earth was not a sphere but in fact a spheroid. By 1756 the final figure, 6080 ft to the mile, was settled upon, and the length of one degree of arc was fixed.

Recording data during a voyage at sea

The key issue therefore for navigation revolved around estimating how far the ship had sailed, and in what direction. This was no easy matter. It was common practice to record the hourly data for any particular day on a type of blackboard called the *traverse* or *log board*, and written up into the paper journal at the end of each day. In fact, the presence at the British Library of two logbooks for some voyages suggests that there were two copies of the logbooks. The first was known as the *deck log*, which was the rough copy into which the information was transcribed at the end of the day, but not many of these have survived. The more widely available logbook was the final neat copy submitted to the Admiralty, which was probably copied from the deck log at sea but perhaps on occasion back on land.

The traverse board is thought to be originally intended for the sole purpose of noting the ship's speeds but became a popular location to record all other data in a type of intermediate stage between observation and logbook. By the middle of the nineteenth century the board was divided into six columns (Norie, 1864) in which were recorded hour, speed of the ship (knots, fathoms), course, wind direction and comments of note. When still in sight of land usually the distance and bearing to that land was used alongside latitude, whereas if the land were not conspicuous the bearing and distance would be an estimate based on the ship's movement since the last sighting. In this case the recording officer would use the full quota of positional data, that is, landmark bearing, latitude and longitude, all of which would be entered on the log-board and thus included in the logbook. The practice of noting the necessary information at noon every day, and then calculating the ships position was called a *Day's work*, which was in turn divided into *harbour-work* and *sea-work*, according to the whether the vessel was in port or at sea. The timing of the start of the day also differed along the same lines and the civil day was used in port but the nautical day whilst at sea. The civil day is that period of twenty-four hours beginning at midnight and running through to the following midnight, whereas the nautical day ran from the noon bisecting that civil day, until the following noon. Hence the information recorded for Friday in the logbook was taken from the twenty-four hours running from noon on Thursday, to noon on Friday. This distinction between the civil and nautical day was in place as early as 1672 (Harries, 1928) when the first reference to the use of nautical time was made in the log of the Bristoll kept by Commander Charles Wylde. The use of the nautical day was rendered obsolete in the early nineteenth century when, in 1805, the Royal Navy adopted the civil day for all voyages at sea.

CHRONOMETERS

Until the quest for the solution to the longitude problem was finally solved by John Harrison's invention of the chronometer in the late eighteenth century, mariners used a range of locational, environmental and meteorological data for navigational purposes (Hewson, 1983). However, even after the introduction of the chronometer, the recording of the environmental and meteorological data continued, due to a combination of duty and natural conservatism of methodology. Neither should it be forgotten that chronometers were notoriously expensive and available for many years to only the richest officers. Methods of longitude estimation by the lunar distances method (developed by the then Astronomer Royal), although coinciding with Harrison's inventions, were so complex and demanding as to be beyond many officers. Hence, for many years, old methods lingered and logbooks continued to hold useful weather observations.

During the age of exploration many logbooks invariably contained accounts of new lands that were discovered, and this was linked to the quest for longitude since risky expeditions required either exceptional navigation or accurate location estimates. Chronometers provided the latter but in order to ensure this reliability, they were sent on exploratory voyages in the care of commanders of known navigational merit, such as James Cook (Beaglehole, 1955-74). The logbooks in these cases not only served to steer them safely on their journeys (James Cook and his legendary search for the southern continent had to contend with large amounts of sea ice whilst attempting to cross the Antarctic circle), but also detailed their findings to whichever boards and committees (usually Royal or governmental) had commissioned the expedition. The need for accurate longitude was even more necessary here since any further trips to a newly discovered land were only possible if the next ship could arrive at the same location as pinpointed by the original latitude and longitude. Even in the eighteenth century there were discrepancies and wasted time at sea because of this problem.

The chronometer was by no means a fast or easily implemented solution. The great horologist John Harrison began his work on the chronometer back in 1736 but after trials, improvements and three prior versions, the Harrison’s fourth and final timepiece H4 (see figure 2.1) was submitted to the Board of Longitude in 1760. So stringent and suspicious were the Board (or perhaps politically corrupt, as Sobel (1995) suggests) that they put H4 through two sea-faring trials, demanded two duplicates and the surrender of the design plans before they would concede that the chronometer was a legitimate and viable way of determining longitude. The alternative method presented to the Board was the Lunar Distance

Method (LDM), the main perpetrator of which was Neville Maskelyne, Astronomer Royal in the late eighteenth century. His main aim was to make it the accepted method of calculating longitude to the highest degree of accuracy, over and above the up-and-coming chronometer.

In the meantime disasters were continuing to occur at sea, such as the misfortune of the *Centurion* commanded by George Anson and sailing from England to the South Pacific in 1740. Sobel (1995) details that by the time the ship rounded Cape Horn in March 1741 much of the crew were suffering from scurvy and there was inevitably some urgency with which Anson was heading for Juan Fernandez Island. Leo Heaps (1973) published an excellent transcription of Saumerez's logbook on board the *Centurion* and the *Tryall* and states that at this time, Cape Horn had not been accurately charted. This unknown quantity was difficult enough to overcome but a storm also blew up which raged for an unmerciful fifty-eight days. Having rounded the Cape, Anson sailed the parallel at approximately sixty degrees south, until he thought he had sailed two hundred miles west, beyond Tierra del Fuego, and then north towards Juan Fernandez when the weather had begun to abate. They reached the correct latitude by 24th May 1741 but were at a loss as to whether the island lay to their west or east and Anson chose to sail west. After four days he concluded that he had made the wrong choice and turned the ship around to sail east. Two days later they sighted land but yet again they were unpleasantly surprised to discover that it was in fact the western approaches of Chile. With scurvy raging below decks the ship sailed west again and by the time they reached Juan Fernandez island on 9th June more than half the original five hundred crew had been lost. This tale is well-known, but by no means exceptional for the age.

Figure 2.1 Harrison's fourth and final version of the chronometer, courtesy of the National Maritime Museum

Thanks to Larcum Kendall and Thomas Mudge, Harrison's chronometers were mass produced in the latter years of the eighteenth century, and, perfected by Thomas Earnshaw and John Roger Arnold, came into common use by the turn of the century. References to longitude by chronometer are evident in the logbooks from the 1770's, but not widely so, and longitude was often recorded twice; the chronometer reading alongside estimated or lunars. The English East India Company was the first to embrace officially the chronometer when, in 1791, captains of commercial vessels were issued with a new format of logbook with pre-printed pages including a column for chronometer readings. Due to the high level of accuracy the advance of the chronometer was inevitable and by the middle of the nineteenth century nearly all ships at sea carried at least one. The positioning and navigation of the ship on the open sea had reached its highest level of accuracy yet.

METHODS OF OBTAINING THE DATA RECORDED IN LOGBOOKS

As already stated, ships' logbooks were kept at the time for reasons of navigation and duty, but the information contained within can reveal much about the environment around the ship at the time of recording.

Finding the ships position in the late eighteenth century was done by knowing the distance travelled and in what direction (the method known as 'dead reckoning'). This required the use of a compass to track the ships course, knowledge of the wind and sea current directions, and means by which to measure the ship's speed.

Until the relatively recent development of continuously recording instruments, a vessel's speed was estimated every one or two hours and transcribed to the traverse board. Sometimes the speed would be noted in the logbook (more common with East India Company and later Royal Navy logbooks), but not always. The standard log line, as described in Norie (1864), was an essential item of equipment on all vessels engaged in deep sea navigation, and would have been found on Royal Navy ships as well as on merchant vessels, such as those in the employment of the English East India Company and the Hudson's Bay Company.

The standard log line was essentially a piece of wood (called the log ship or chip (Hewson, 1983)) attached to a line (usually by a small bridle) which was hove overboard, allowed to stand floating in the water for a certain length of time while the ship moved away from it (usually thirty seconds, determined by a half-minute glass, but in certain cases a quarter-minute glass would be used if the ship was sailing at a sufficiently high speed) and then hauled in. The speed of the vessel could be estimated by the length of line run out during that fixed interval of time. Interestingly, the origin of the knot (unit of speed) has its roots here, taken from the series of knots tied in the log line, and used as a measure of distance. After the length of the degree was fixed, navigation was significantly more accurate and the method of the log line was adjusted accordingly, reducing the errors that had previously been a point of concern. Cotton yarn was recommended for the line itself (Hewson, 1983) and the time-piece (almost always a sand-glass) tested regularly for accuracy.

As the technological age advanced, the inevitable introduction of mechanically recording logs was made (during the nineteenth century), marking the first appearance of the rotating log, a type of which is still used today but the ‘age of sail’ saw exclusive reliance on the older methods.

To fix the ship’s position the officer would have to pay attention to the landmark bearing and distance, latitude and longitude. The recording officer would use the distance travelled over the last twenty-four hours, and the ship’s compass, an example of which is shown in figure 2.2, to estimate a distance and bearing to the land.

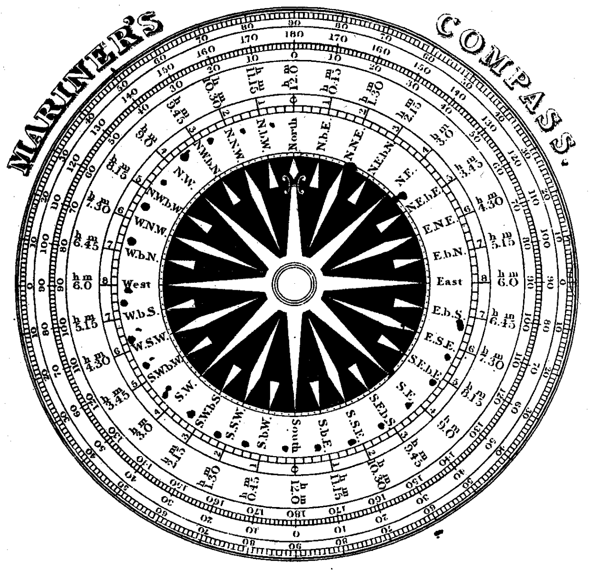


Figure 2.2: The Mariner's Compass, taken from Norie (1864).

In order to calculate their latitude, officers used a quadrant, octant or sextant to note the altitude of the midday sun at its meridian passage, or if it was nighttime they looked at the altitude of celestial bodies (usually Polaris, the North Star). The body's declination (number of degrees north or south of the celestial equator, the celestial equator being the circular line perpendicular to the axis of the Earth) was then added or subtracted from the zenith distance (90° - altitude) to give the latitude. Prepared tables detailing the expected altitude for time of year were available, although corrections must be made for the fact that Polaris does not lie exactly at the pole, and for refraction and dip.

Before the introduction of the chronometer, longitude could be obtained by means of dead reckoning. The Lunar Distance Method (LDM) became more popular during the heated quest for longitude, and was a complex way of calculating longitude which used tables of expected times that a particular star would cross the path of the moving moon, at a reference location. This was possible due to the steady and predictable rate at which the moon moves across the night (and day) sky - about it’s own width every hour (Sobel, 1995). The navigator would then compare the time he observed the meeting of the two celestial bodies with the predicted time in the tables and thus calculate his relative position.

As the chronometer grew in popularity the point of reference for ships that carried them was, of course, the place they started from and the place at which the chronometer was calibrated. In times of trial this was London. Up until this point sailors took their zero or prime meridian from the last land they sighted, or docked at, and this would then minimise cumulative errors in longitude. Prime meridians therefore could be anything, but the most common ones for leaving England were Start, Lizard, Eddystone and Cape Clear in Ireland. Once chronometers began to be used, the zero meridian for the entire journey would be London (or more specifically Greenwich, where the Royal Observatory was located).

The ship’s course was also required for navigation. Sea currents and, importantly, the wind governed this. Officers on board the ship would take great note of leeway and drift, (the responses of the ship to wind and currents, respectively) so that the ship’s course may be adjusted accordingly, and since the winds and currents could be so variable throughout a twenty-four hours period, sometimes the course had to be adjusted almost every hour. This was most obvious in the logbooks kept by the East India Company, who usually kept hourly records of all observations.

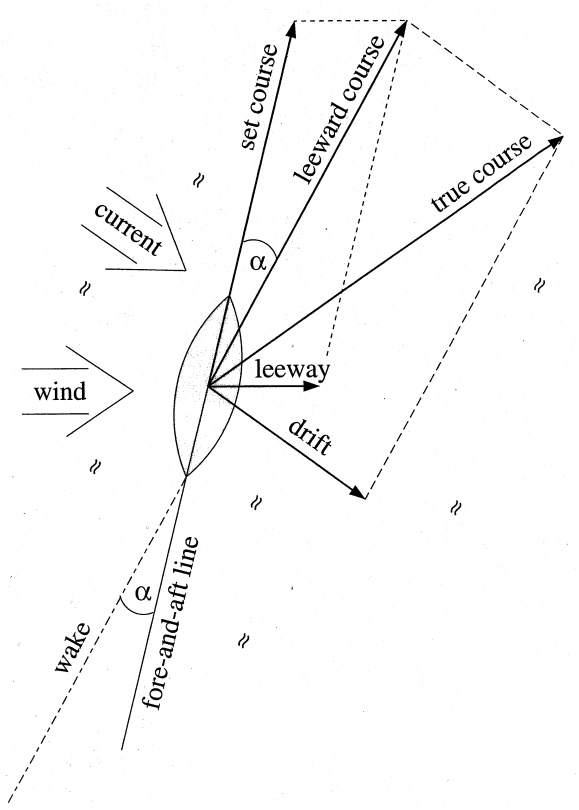


Figure 2.3: Diagram showing the effect of current and wind on a ship's movement (courtesy of A.R.T. Jonkers, Liverpool University)

Leeway was the key element to be controlled by the weather. The effect of the wind and current on the movement of a ship, including leeway and drift, is demonstrated in figure 2.3. For example, a ship following a compass course for due west, but experiencing a northerly wind, would not sail due west but along a course south of west by a degree that depended upon the wind force and speed of the vessel. The skill of the navigator lay in taking reliable wind force and direction observations to make such course corrections and thereby to estimate the ship’s location.

The course was changed when necessary according to the present weather conditions, and then at noon each day, when it was time to record the different fields of data in the logbook, latitude was estimated and other observations made. The many changes of course each day would each require a separate calculation, all of which would eventually be summarised by the ‘course made good’, as shown in figure 2.4. This course made good was the course, expressed as a straight line, between any two successive midday sets of data and locational estimates. This would then be plotted on the chart and a cumulative record thereby kept of progress across the ocean. The need for many and reliable wind and weather observations is, in this sense, self-evident.

The units used in these logbooks are reflective of the time, and are often quite different from those used today. Wind force has become standardised since the adoption of the Beaufort scale, the nautical mile has overtaken the league as the SI (standard index) unit of length or distance, and evidence can be seen of this in the lieutenant’s logs from the late 1790’s onwards. Bearings are now more often than not recorded in degrees rather than points of the compass (e.g. 135° instead of SE).

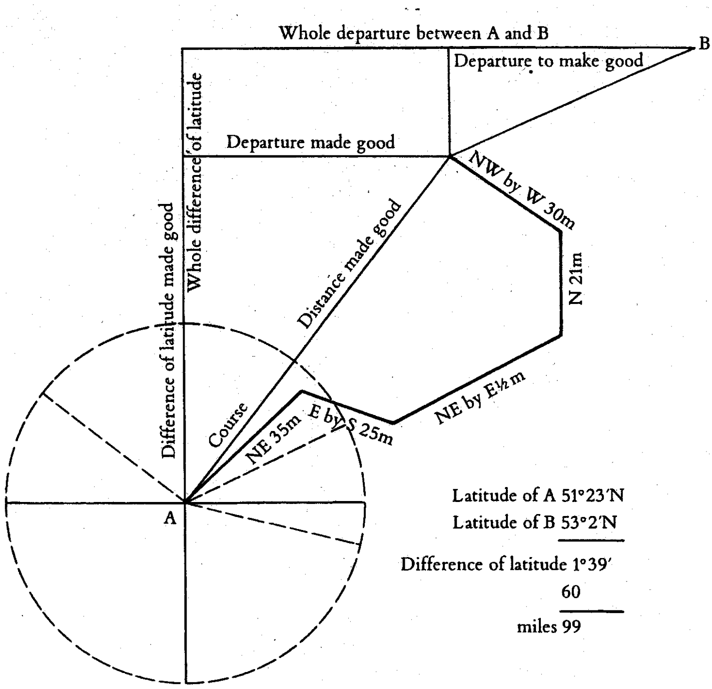


Figure 2.4: Traverse Sailing diagram taken from Whitelock *et al* (1978).

LOGBOOK LAYOUT

The developments of logbooks have run in parallel with developments in cartography, since the primary purpose of the logbooks is to locate the ship whilst aided by maps and charts of the area. Gradually, and largely during the seventeenth century, the practice of recording information in logbooks evolved into a much more regular form where the readings were laid out separately in categories and variables, and this was a much more efficient and methodical way of recording the data. The method did not really change significantly after that time but the level of detail increased in response to the need for more information for route planning and for scientific purposes: it has already been noted in the introduction that both Edmund Halley and George Hadley used logbooks in their studies of global wind circulations. .

East India Company officers used pre-printed pages from the late eighteenth and early nineteenth centuries, laid out as a kind of template for the officers to conserve time and effort, and to ensure optimum efficiency and accuracy. The Royal Navy logbooks on the other hand, seem to be left to the discretion of the recording officer until much later.

Figure 2.5 shows a typical Royal Navy logbook layout. On the left hand page are included landmark, the bearing to that landmark, latitude and longitude, wind direction, ship's course and distance travelled over the last twenty-four hours, while the right hand page includes more narrative information but always starts with the midday wind force and weather, complementing the wind direction data on the facing page.

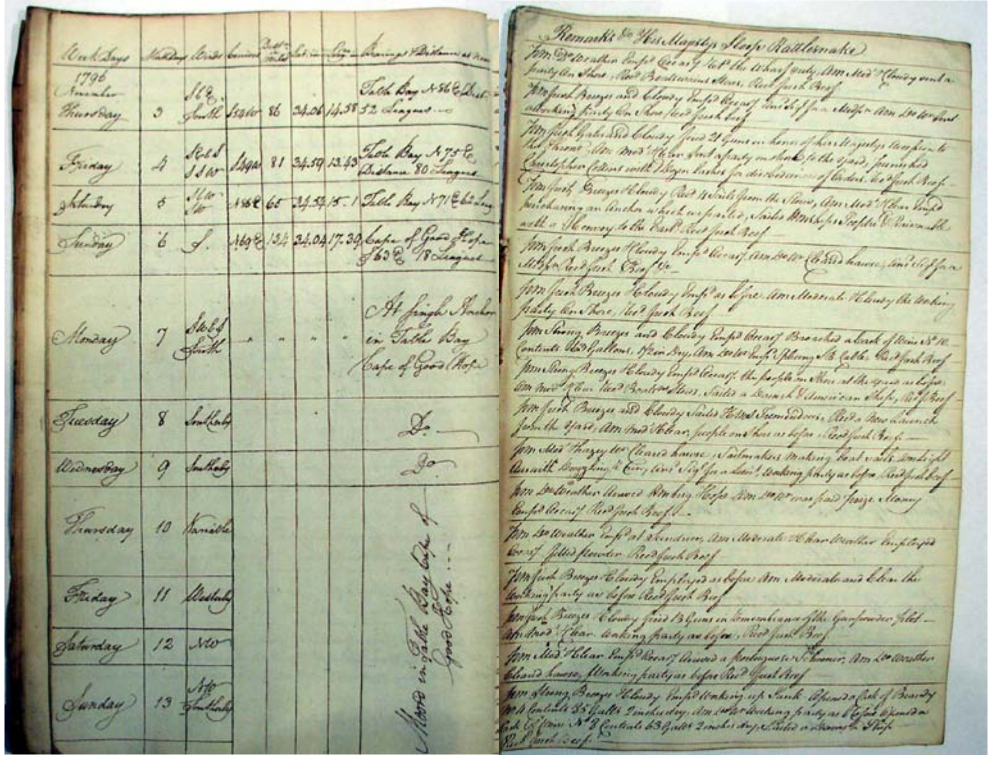


Figure 2.5 Example of a typical logbook page from a Royal Navy vessel (HMS Rattlesnake, November 1797)source: National Maritime Museum.

The right hand page was usually headed “remarkable observations”. In addition to wind force, the state of the sea and sky, precipitation and any fog would be noted. The residual text would be taken up with procedures being carried out on board the ship. Also sometimes recorded were azimuth and altitude, which related again to celestial bodies. Altitude was the angular distance of a body above the horizon and azimuth was the angle at the zenith between the observer’s meridian and the vertical circle through the observed body (Whitelock *et al*., 1978).

There are typically two types of layout of logbook; those that note their ‘remarkable observations’ in one paragraph, grouping together all remarks over twenty-four hours, and those that take several observations and lay them out in hourly tables (see figure 2.6). The latter type generally encompasses those recording officers that took in excess of three observations in any one twenty-four hour period, and most of the officers in the East India Company followed this regime. Those officers who did not record more than three observations tended to divide the day into first, middle and latter parts, detailing all comments noted at the end of each of the watches. The First part included the Afternoon Watch (1200 - 1600) and Dog Watch (1600 - 2000), the Middle Part contained the First Watch (2000 - 2400) and Middle Watch (0000 - 0400), and finally the Latter Part was the Morning Watch (0400 - 0800) and Forenoon Watch (0800 - 1200) (Oliver and Kington, 1970).

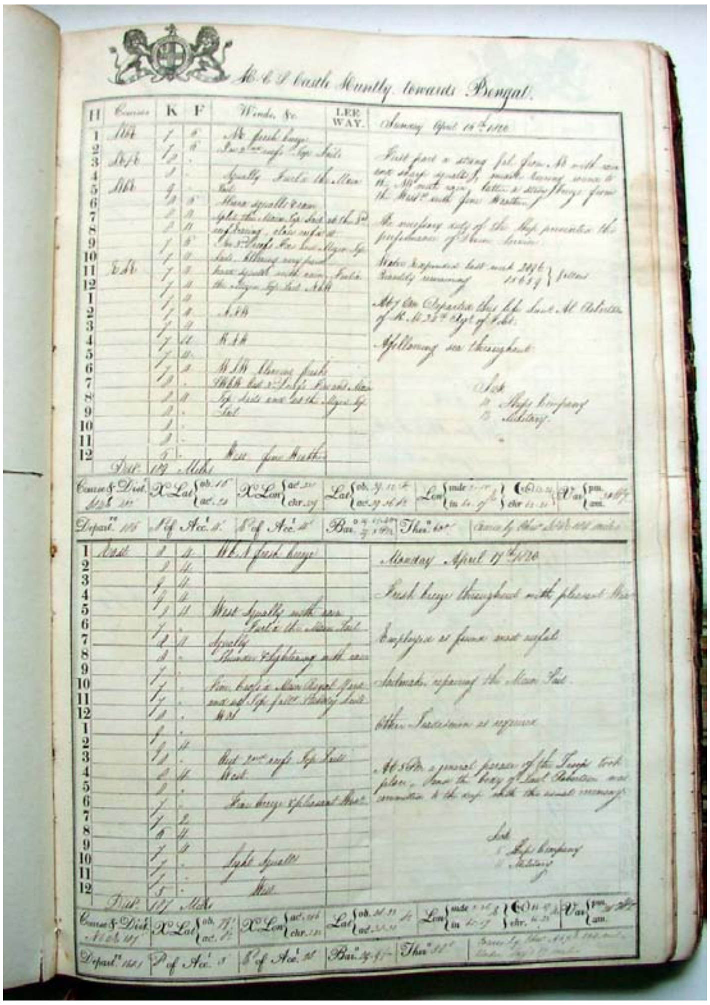


Fig 2.6: Example of East India logbooks, where the information is in the form of a table, split into hourly readings and comments (source: British Library)

RECORDING OFFICERS

Many officers were required to maintain logbooks. The most important ranks to do so were lieutenants, captains and masters. Lieutenant's logs, are held at the National Maritime Museum at Greenwich. Captains' and masters' logbooks are held in the National Archives at Kew. The layout of all three groups is broadly similar, and described above, the only slight difference being a general preference for masters to use an East India style layout. Where several logbooks exist for the same ship, it is evident that there was a good deal of transcription, possibly with the master's log being used as the original item. The master was a non-commissioned officer but had responsibility for the navigation of the vessel and, hence, tended to pay more attention to meteorological detail than the others. The main difference between the East India Company and the Royal Navy logbooks was that the latter tended to relate to a specific officers tour of duty, or six-month spell, while those of the former were based on individual voyages.

ARCHIVE SOURCES

The largest collections of original British logbooks are found in three places: The National Maritime Museum, Greenwich (NMM), The National Archives, Kew (NAR), and the British Library, North London (BL) (see Table 2.1). The number of logbooks available assumes that a lieutenant's log from the NMM contains an average of twelve logs per volume, and from the PRO, five logs per volume. The East India Company volumes are composed of journals containing the outward and return voyage to India or China. In this case each journal is identifiable and so the number of volumes is equal to the number of logbooks. The NMM holds some 62000 lieutenants' logbooks for the period 1670 to 1812 as this was the point at which officer's logbooks (specific to an individual officer) began to be phased out, to be replaced by ship's logbook, kept by a succession of duty officers. The NAR holds some 40,000 captains' and masters' logbooks, while the British Library is the best source for East India Company logbooks and over 4000 can be found embracing the period 1603 to 1838, when the companies sailing activities ceased. A full description of the logbooks available at each source can be found in Appendix II.

The NAR also holds microfil copies of about 34,000 logbooks of vessels in the service of the Hudson's Bay Company for the period 1750 to 1870.Good collections of logbooks can also be found in Holland, Spain, Argentina and France but these form no part of the present study.

Country	**Place of Source**	**Type of logbook (number of volumes)**	**Approximate number of logbooks available**	**Date Ranges**
England	National Maritime Museum, London	Royal Navy; Lieutenants (5205 volumes), Captains, Private collections (811)	63600	1678 to 1809 (lieutenants), mid 1600's to present (other)
England	British Library, London	East India Company	3820	mid 1600's to 1834
England	National Archives, London	Royal Navy; Captains (4563) Admirals (413) Masters (2103) Hudson Bay Company (129)	33850	1669-1852 (captains), 1702-1916 (admirals), 1672-1840 (masters), 1667-present (HBC)

Table 2.1: Table showing details of the logbook sources in the UK; what types of logbooks are found where and what date ranges they cover.

Logbooks are not a source of data that has enjoyed wide usage in climatological studies of the oceanic climate, indeed, and as noted above, they have rarely been used for anything other than narrowly-focussed case studies. Nevertheless, their abundance combined with the detailed and daily resolution of the observations represents a source with significant potential. Only a small proportion of the large volume available has thus far been abstracted, but preliminary studies thus far suggest that the data is reliable and meaningful, adding further to its scientific appeal. Thus far only a small proportion (but large number) of old logbooks have been studied but it is equally important to examine the methods by which the observations were made and how they were recorded. This question of ‘metadata’ is an important one in such studies where qualitative expressions cannot necessarily be taken at their face value.

CHAPTER THREE

TERMINOLOGY AND VOCABULARY: translating the logbook

INTRODUCTION

Logbooks were acknowledged by Francis Beaufort in the early nineteenth century, and later by Hubert Lamb (1995) as a valuable, yet untapped, source of climatological information. Such studies as have been carried out using this source have been small-scale undertaking, often concerned with specific events such as naval battles and based on short-period synoptic reconstruction (Wheeler, 2001). Nevertheless, the presence of large volumes of pre-instrumental logbook data lends itself to the possibility of studying oceanic meteorological phenomena on a larger, almost global, scale. This study, nevertheless, confines itself to one, albeit large, oceanic area; the North Atlantic. It is important to note that this is the first major research using logbooks for this region. However, since the primary logbook data are qualitative and not quantitative, they need to be rendered in a form that is suitable for objective scientific analysis. They need also to be consistently expressed and, therefore, homogenous. Thus not only do the meanings of terms need to be understood, we also need to know about the evolution and changes of terms and expressions over the study period.

Observing and recording the state of the weather at sea today employs (in addition to instrumental observations) a system of two digit codes, which denote different types of weather, to indicate past and present conditions on an hourly observational basis. The higher the numerical value of the code, the more 'significant' the state of the weather, for example, 00 means that there is no observable cloud present, and 01 denotes a reduction in amount of cloud. Code 16 indicates precipitation within sight, reaching the ground or the surface of the sea, near to, but not at the station, and code 17 denotes thunderstorm activity but no precipitation at the time of observation. The codes extend up to 99, which represents a thunderstorm with heavy hail at the time of observation. A full list of the codes is given in Appendix III.

These codes, set out by the World Meteorological Organisation to standardise observing methods, have only been in place since 1958. The system in place prior to this was Francis Beaufort's Notation. This used letters of the alphabet to denote the different types of weather (table 3.1) and according to the *Marine Observer's Handbook* (1995), it is still used today as a subsidiary means by which to note the weather between hourly observations.

Late eighteenth and early nineteenth century logbooks recorded weather information in a manner quite different to that used today. For the most part, mariners used words (not codes) to describe the conditions that they experienced. Instrumental records, although occasionally to be found in the form of temperature and barometer readings (and more commonplace after the 1830s), were very much the exception to this rule. Furthermore, there is evidence that the conventions and vocabulary for the descriptions gradually evolved over the century of the study period and later. Beaufort introduced his weather notation into his personal journal of 1806 (Garbett, 1926), but this was to undergo several modifications until it was adopted in 1838 (shown in table i, Appendix III). It is clear that nautical terminology, in common with all aspects of English language, evolved during the eighteenth and early nineteenth century. But, more importantly, within any one short time period (usually decadal), the use and application was consistent – as will be demonstrated later – and evolution was slow. Fortunately the resources of the CLIWOC project were sufficient to allow a very large sample to be drawn upon in order to assess such changes and usage.

Weather	**Beaufort letter**	**Weather**	**Beaufort letter**
Blue sky (0-2/8 clouded)	b	Overcast sky (unbroken cloud)	o
Sky partly clouded (3-5/8 clouded)	bc	Squally weather	q
Cloudy (6-8/8 clouded)	c	Rain	r
Drizzle	d	Sleet (rain and snow together)	rs
Wet Air (without precipitation)	e	Snow	s
Fog	f	Thunder	t
Gale	g	Thunderstorm with rain	tlr
Hail	h	Thunderstorm with snow	tls
Precipitation in sight of ship or station	jp	Ugly threatening sky	u
Line squall	kq	Unusual visibility	v
Storm of drifting snow	ks	Dew	w
Sandstorm or duststorm	kz	Hoar-frost	x
Lightning	l	Dry air	y
Mist	m	Dust haze	z

Table 3.1 Beaufort's weather notation, from *Marine Observer's Handbook* (HMSO, 1995)

LOGBOOKS AND THE CLIWOC PROJECT

Over seven thousand logbooks were examined as part of the CLIWOC project (numbers of logbooks examined and used are shown in table 3.2). Not all of those examined were used for abstraction; 16.5% were rejected. Some were too difficult to read, or were not clear in their presentation of the information, pages were damaged, water-stained or faded. Furthermore, and this was an action of judgement based on experience and familiarity, some officers were clearly less assiduous in their application to logbook writing than others. Fortunately, for every dubious or difficult logbook there were many others that would ‘fill the gap’. Not all of those logbooks rejected were done so due to problems with the data contained within them. Some were not used because they duplicated data already abstracted, for example when ships were travelling in company or convoy with each other.

The level of attention paid to the accurate recording of information depended on the individual officer. As noted in the previous chapter, there was a very practical requirement for reliability and the later use of the information for navigation, that requirement notwithstanding, some officers were evidently more assiduous than others. However, problems were encountered: sometimes there were a number of successive days (or even weeks) that either held no information on the state of the wind or weather, or conditions were denoted by the word 'ditto'. Logbooks with more than three or four consecutive entries of this word, several times throughout the voyage were discarded as unreliable, since it was questionable as to whether the officer had recorded the weather conditions accurately, or merely wished to complete the logbook for untroubled submission to the Admiralty.

Most officers would report both wind force and weather description together, e.g. 'fresh breezes and cloudy', 'moderate gales and fine', or 'heavy gales and hard rain'. These dual entries were sometimes recorded more than once a day, either being allocated to their respective parts of the day, that is, a.m./p.m. or first/middle/latter parts (Oliver & Kington, 1970), or occasionally in RN logbooks they were embedded at intervals within the text of the 'remarkable observations'. For the purposes of examining the range of terms from the logbooks and their definitions and frequency of use, weather terms, wind direction, and wind force will be assessed separately.

	individual logs examined	**individual logs used**
NMM	8544	6960
BL	150	138
NA	55	55
total	**8749**	**7153**

Table 3.2: Number of logbooks examined and used for the CLIWOC project. Full details of the number of logbooks used at each source can be found in Appendix II

SAMPLING WEATHER TERMS IN THE LOGBOOK DATA

The variables included in the data used for the thesis are largely coincident with those abstracted as part of CLIWOC, but the geographical area is not. The aim of this thesis is to concentrate on the North Atlantic area and to attempt to extend the climatological data available for study of North Atlantic ocean-atmosphere phenomena. In order to do so, attention in respect of the logbook data is confined to that oceanic basin. An estimate of the number of days of North Atlantic data abstracted and available for use in this thesis is approximately

25,000. Not all of this will be included in the final database as some days will be replicated by two or more ships, either in company or on separate voyages in different areas of the North Atlantic, and some data will lie outside the boundaries of areas considered to be of particular relevance in the context of the current aims and objectives. This large quantity of data facilitates verification exercises to be performed and exploits the large sample sizes available as a consequence of the abundance of logbooks, even for this distant period in time. Such large samples also minimise relative errors and allow detection of underlying signals.

The dataset as used here contains information from Royal Navy and East India Company logbooks and no attempt is made at this stage to discern any differences in vocabulary between the two. The aim is merely to secure a reliable overview of the frequency, character and, eventually, meaning, of the terms that were used. As mentioned earlier, it is likely that the terms evolved over the study period. This is neither remarkable nor problematic, and it should be recalled that even the Beaufort Scale itself has undergone changes in the terms that have been given this official recognition, and such considerations are true of wind force terms and of expressions used to describe the weather (Garbett, 1926). For example, on Beaufort's weather notation of 1806, the terms 'greasy sky' and 'watery skies' are both included but were subsequently omitted, as was his suggestion to use the expression 'hard gales with squalls'. It is for these reasons that this assessment of this evolution of terminology was given decadal resolution over the 80-year period of 1750 to 1830; all decades for which logbook data were gathered as part of the CLIWOC project.

Random sampling was conducted on the data from the North Atlantic area to try to provide a clear and representative picture of the range and variety of terms used over the study period. Approximately 3500 days were examined and the wind force and weather terms used on those days were counted, listed and included in sub-database. Terms appearing several times in one day's entry were only counted as one occurrence of that term. This procedure minimised any bias resulting from different forms of data entry in the logbooks themselves. Those occasions, of which there were many, when data were entered hourly, rather than three times a day, would see a single term repeated on many occasions were there to be, as there often was, periods of consistent wind and weather.

The sample yielded a total of 41 different weather terms, which mostly consisted of a single descriptor, such as ‘cloudy’, ‘unsettled’ or ‘snow’, but were sometimes composite, consisting of a ‘standard’ descriptor and an adjectival qualifier, for example ‘thick foggy weather’ or ‘dark cloudy weather’. In these cases the adjectives were acknowledged and a count was made for each, since it is the vocabulary that is under examination (not the climatology), and the occurrence of the term is more important than the context in which it is placed.

On the other hand, where a descriptor was preceded by the adjective ‘very’, the latter did not qualify for a separate category; for example, ‘thick fog’ and ‘very thick fog’ were treated as the same. The practical consequence of not recognising the distinction is minimal. For example, on a day where the state of weather is 'very cloudy', it is still cloudy and therefore can be counted as such. Furthermore, the frequency of these cases within the sample is small in comparison with the sample size.

The exception to this was in the case of ‘rain’. Making a distinction between small or drizzling rain, continuous rain, heavy rain and showers of rain shows the range of terms used to describe rainy conditions in the logbooks and could lead to further classification of precipitation as the type of rain – for example showers as opposed to drizzle – reflect different atmospheric states and offers the possibility of later, more detailed, interpretations of logbook information. This approach is supported by the recording system employed today (*Marine Observer's Handbook*, 1995) in which the distinction is made between rain, drizzle and showers.

Nevertheless some minor sub-grouping of adjectival qualifiers was needed in order to render the vocabulary more manageable, but without significant loss of ‘information’. Thus ‘continual’ and ‘constant’ have been amalgamated, as have ‘hard’ and ‘heavy’. ‘Small rain’ and ‘drizzling rain’ may potentially hold the same meaning and be interchangeable but at this stage have not been grouped together. Only two other groupings have taken place at this stage; thunder and lightning have been placed together, since it is impossible to have one occurring without the other, as have comparative adjectives such as cool and cooler, or warm and warmer. Appendix III lists the derived weather term vocabulary (table ii).

The term 'squally' required closer attention. It is generally accepted to relate to the behaviour of the wind, though from its entry into the logbooks it is unclear whether it was thought of by recording officers as pertaining to the wind or weather, for example 'fresh gales and squally'. Jenkins (2001) lists it as being 'a wind which strengthens quickly and lasts for a few minutes or so. Longer than a gust and some may become violent'. The *Oxford English Dictionary* (OED) defines a squall as 'a sudden violent gust or storm' and connects it with the meaning 'violent discordant scream or loud harsh cry'. Of obscure origin, it was first seen in 1570 as a term of abuse to a small or insignificant person and only recognised as a meteorological term in the early eighteenth century.

This evidence unquestionably links the term squally with the wind, however it is not strictly speaking a wind force, but an indication of tendency and variability in the strength of the wind. It is on this understanding that the term is included in the weather terms and not the wind force terms for the purposes of the sampling. It should also be noted that Beaufort did not include it as a wind force term.

SAMPLING RESULTS

From the 3500 days of data, 41 different terms were identified over the 80-year period, representing 6276 entries. In common with wind force terms almost 95 per cent of this total was accounted for by just twelve terms (table 3.3). Of these twelve terms several are included in the present day weather notation (table 3.1), originally set out by Beaufort and currently found in the *Marine Observer's Handbook*. These are cloudy, squally, rain, thunder, lightning, haze and fog. The very nature of these terms suggests a consistency in usage and definition over the past two or three centuries.

There were, however, a number of widely used terms that Beaufort, for reasons of ambiguity, did not include in his weather terms list. These require some modest discussion.

weather term	**50's**	**60's**	**70's**	**80's**	**90's**	**00's**	**10's**	**20's**	**Total**	**Cumulative total**	**Cumulative frequency (%)**
cloudy	216	222	180	136	167	253	164	170	**1508**	1508	24.03
squally	95	97	112	101	145	136	127	63	**876**	2384	37.99
rain	77	81	71	94	119	105	131	109	**787**	3171	50.53
fair	126	109	95	139	84	66	41	54	**714**	3885	61.90
hazy	105	116	80	81	45	72	67	61	**627**	4512	71.89
fine	0	0	2	39	45	86	140	204	**516**	5028	80.11
clear	29	39	46	43	89	140	59	4	**449**	5477	87.27
pleasant weather	2	0	9	68	25	28	31	14	**177**	5654	90.09
foggy	26	13	37	4	2	2	8	4	**96**	5750	91.62
thunder/lightning	14	17	10	9	0	2	11	9	**72**	5822	92.77
heavy/hard rain	2	6	4	8	16	12	13	10	**71**	5893	93.90
showers	7	5	7	1	8	13	10	5	**56**	5949	94.79

Table 3.3 – Table of 12 most frequently used weather terms in the random sample of logbook data over the 80-year period.

Fine

The *OED* states that the word ‘fine’ comes from the Old French word ‘fin’ meaning closure or end, or possibly the Roman word ‘fino’ meaning a finish (as in a gloss finish), but agrees that it has evolved to mean subtle perfection of the weather in which the sky is bright and comparatively free from cloud and rain. It is included in the Beaufort Weather notation from 1806 until 1820 denoted by the letter ‘f’, but was then replaced by ‘foggy’, perhaps reflecting the decline in general use of the term in formal meteorological observation vocabulary, or its ambiguity. The word fine also related to the wind direction with respect to the vessel, e.g. 'fine on the quarter', meaning half way between 'On the quarter' and 'astern', where the quarter is as its name suggests, a quarter of the way around the ship from the stern.

Fair

Defined in the *OED* as an old English word meaning ‘beautiful’, the word ‘fair’ can be used with reference to the wind or the weather. In relation to the wind it means to be favourable to a ship’s course, and to the weather it means to clear (away), that is, to experience an improvement. It may have become a term similar in meaning to ‘fine’, implying bright skies without precipitation, as suggested in the *OED* entry of ‘clear’, which assimilates the same to both ‘fine’ and ‘fair’.

Pleasant Weather

No such convenient definition is found in the *OED* for the term ‘pleasant weather’, indeed there is no reference to weather in the definition of ‘pleasant’. It should be re-iterated at this point that the recording officers were sailors and therefore their description of the weather would have indicated its influence on the progress of the ship. Thus ‘pleasant weather’ could mean that the environment was conducive to sailing, with no ‘significant’ weather (e.g. precipitation or hindering winds) to report.

Hazy

The term hazy, like fine, is included as a single entry in Beaufort’s earlier proposals of his notation codes but not in the version adopted into the British Navy in 1838. In the present day notation the letter ‘m’ is allocated to mist, haze being given its scientific definition of ‘dust haze’ and found under the letter ‘z’. It is clear that this term related to visibility, supported by its entry in Falconer’s *Dictionary of the Marine* (1815, reprinted 1970), which states that hazy “…appears much like a fog, yet differs from it, as in foggy weather the atmosphere is dense and moist; but in hazy weather the air is more dry." There is therefore a subtle difference between the precise definition applied today by the Met Office and it use in more general settings, that still reflects is older, more widely understood, definition.

Guidelines also exist in the *Marine Observer's Handbook* for the assessment of visibility, mist/fog and haze. Mist or fog, comprised of water droplets may be distinguished from haze, which is due to solid particles in the atmosphere (e.g. dust). To differentiate between fog and mist the visibility must be judged and if found to be less than 1 km, the observer is experiencing fog, if not it is mist. The evidence offered by contemporary documents such as Falconer's *Universal Dictionary of the Marine* strongly suggest that such precision in the definition of these terms was unknown two centuries ago and are an artefact of more scientific approach to weather observing in recent years.

Close

The definition of the term 'close' in relation to the atmosphere derives from its original and more widely-used meaning; that of being 'shut' or 'closed'. The *OED* states that close weather is "...like that of a closed up room; confined, stifling, without free circulation; opposite of fresh". It does not appear in Beaufort's notation and is a relatively infrequently used term in the logbook sample, accounting for just 0.08 per cent of the total.

Thick

The term 'thick' is the thirteenth most frequently used term, yet still only accounts for 0.8 per cent of the total sample. Even so, an attempt to investigate its meaning may be made, particularly since it does not appear in the Beaufort notation . The *OED* likens it to ‘hazy’, citing a quotation from 1625, which contains both. This suggests that the term thick relates to visibility.

CONCLUSION

The evidence suggests that although a reasonable range of terms existed to describe weather conditions at sea, sailors tended towards the use of a small number of these. Investigation into their origin and definition suggests that the terminology employed in the eighteenth and nineteenth centuries, even prior to formal definition and categorisation, was not significantly different from that used today. The terms were those of everyday English. Some have acquired a more precise definition in response to the need for precision, but even these definitions would not be widely appreciated by the public of the twenty-first century and the old definitions continue to hold sway. This is helpful because it indicates that there is no need to ‘translate’ terms, as had to be done with wind force entries.

CHAPTER FOUR

WIND FORCE: Evolution and range of vocabulary

INTRODUCTION AND HISTORY OF WIND CLASSIFICATION

As explained in Chapter Three, wind force and state of the weather were recorded together in the logbooks (e.g. 'fresh breezes and cloudy') and their regularity reflects the general importance of weather to mariners. Of the two, wind force, the source power for propulsion of the ships, was the more significant.

Descriptions of the behaviour of the wind have a long history, beginning with Venerable Bede in the eighth century AD who recognised the control of the wind on the sea and also winds with particular character depending on their direction (Giles, 1843-4). The advent of meteorological instrumentation began with the inventions in the seventeenth century of the thermometer and barometer by Galileo and Torricelli respectively. Despite early versions of mechanical anemometers by Leon Alberti in 1450 and later by Robert Hooke, wind strength remained unmeasured to a reliable degree until 1846 when Thomas Robinson introduced the cup anemometer. By the end of the nineteenth century William Dines had invented the pressure tube anemograph (Wheeler & Wilkinson, 2003), which was an important step for terrestrial observations but could not be used at sea.

Although wind strength lacked quantitative measurement (both on land and at sea) until the latter part of the nineteenth century, conventions of classifying it were in place long before.

Of these systems of classification, Francis Beaufort's is the most notable and his scale of wind force (and weather) is still in use today, particularly in marine meteorology and shipping forecasts. Methods of satisfactorily measuring many meteorological variables, including wind speed, by instruments on land are unsuitable and inaccurate at sea (*Marine Observer’s Handbook*, 1995). This is due to a combination of the motion of the ship, exposure to spray, and the disturbance of the immediate atmosphere by the vessel. Though anemometers are sometimes carried on board ships that are able to place them at a suitable height of 23m so as to minimise the eddying effects, the usual way to measure and record wind strength at sea is by human observation of the state of the sea and, where applicable, by reference to the variety and area of sails carried by the ship.

Although Beaufort's scale is the most well known, it is by no means the first. Daniel Defoe presented a table of wind force terms in his account of the Great Storm of 1703 (Defoe, 1704). Work by Wheeler (2003) suggests that the terms included in the scale are not as representative of the vocabulary at the time as has been assumed. An independent study of almost 5000 wind force terms from ships logbooks, whilst broadly demonstrating a correspondence between the sample and Defoe’s scale, identified several terms used frequently that were not recognised by Defoe, and several of Defoe’s terms that could not be found in the sample. Wheeler created a separate scale, compared it with Defoe’s and presented Beaufort equivalents for each of them (see table 4.1)

The hydrographer to the East India Company, Alexander Dalrymple, used ships logbooks from Britain and France to identify the terms used and arranged them into an order according to his own judgement (Dalrymple, 1789), and then compared the resulting scale with a yet earlier one proposed by James Smeaton (see table 4.2). Smeaton's scale was based upon the effect of the wind on his wind-mill at Authorpe, near Louth in Lincolnshire. Despite this connection between land-based and oceanic scales, it seems that the vocabulary and conventions for describing wind strength developed independently between mariners and terrestrial observers (Wheeler & Wilkinson, 2003).

Sail architecture was also changing well into the study period, which prevents a direct translation process between earlier vocabulary and Beaufort's official scale. Even after Beaufort devised the scale, based on the sail able to be carried by the vessel, changes were taking place in the build and rig of ships, and in 1874 the wind scale was formally adapted to the full-rigged ship of that period (*Marine Observer's Handbook*, 1995). The advent of meteorological instruments and the demise of the age of sail gave rise to further adaptations of the scale, when more emphasis was placed on wind speed and effects on the land and sea, instead of the sail carried by the vessel.

Defoe's term	Beaufort term	**Beaufort number**	**Popular contemporary term (from Wheeler's sample)**	**Percentage frequency of use (Wheeler)**
Stark calm	Calm	0	Calm	2.5
Calm weather	Light air	1	Small wind	0.8
Little wind	Light breeze	2	Little wind	16.1
	Gentle breeze	3	Easy and gentle gale	2.2
Fine breeze	Moderate breeze	4	Fine gale	2.7
Small gale	Fresh breeze	5	Small gale	4.5
Fresh gale	Strong breeze	6	Moderate gale	14.5
Topsail gale	Moderate gale	7	Fresh, brisk and stiff gale	33.4
Blows fresh	Fresh gale	8	Blows/blowing fresh	2.4
Hard gale of wind	Strong gale	9	Hard and strong gale	12.9
Fret of wind	Whole gale	10	Blowing hard	4.7
Storm	Storm	11	Storm and stormy	1.1
Tempest	Hurricane	12	Tempest	<0.1

Table 4.1: Conversion table for Defoe's 'bald terms' and for early eighteenth century logbook wind forces into Beaufort equivalents (taken from Wheeler, 2003)

My Scale	Mr Smeaton's Scale	And his description	French Terms
0 Calm	0 Calm	The Motion of the Air not felt	0 Calme
1 Faint Air, i.e. not quite calm	Scarce a breeze	Do*….. scarcely felt	1 Petit fraicheur, ou feible
2 Light Air	Light breeze not working	The direction of the wind sensible, but insufficient to move the Mill, or under 6 turns a minute	2 Fraicheur
3 Light Breeze	Light working breeze	Just sufficient to move the Mill 6 turns	3 Petit frais, ou petit brise
4 Gentle Breeze	Breeze	Sufficient to move the branches of the trees, and Mill from 6 to 9 turns	4 Jolie brise?
5 Fresh Breeze	Fresh Breeze	Move the boughs with some noise, Mill 9 to 13 turns	5 Jolie frais?
6 Gentle Gale			6 Vent peu de frais
7 Moderate Gale			7 Vent moyenne frais
8 Brisk Gale	Fresh	Wind heard against solid objects and agitation of trees, Mill from 13 to 18	8 Vent frais
9 Fresh Gale	Very Fresh	Wind growing noisy, and considerable agitation of trees, Mill 18 to 3/4 cloth	9 Bon frais
10 Strong Gale	Hard	Wind troublesome, larger trees bend, 3/4 to 1/4 cloth	10 Grand frais
11 Hard Gale	Very hard	Wind very loud and troublesome, large trees much agitated, Mill 1/4 cloth to close struck	11 Vent fort
12 Storm	Storm	Wind exceeding loud, trees very much agitated and some broke, Mill 25 to 30 turns without cloth	12 Tempete

Table 4.2: Alexander Dalrymple's table of comparison of wind scales.

* ‘Do’ denotes ‘ditto’

SAMPLING THE RANGE OF WIND FORCE TERMS IN THE LOGBOOKS

To assess the vocabulary used for wind force in the logbooks for the present study, and to obtain Beaufort equivalents for those terms, a random sample was taken from the North Atlantic observations. To give as comprehensive a picture as possible all data that were available for sampling were used, encompassing the period 1750-1830, and regardless of ship type or company (RN or EIC). A total of 6316 entries were included and from this 54 separate wind force terms were identified, the full list of which can be seen in Appendix III (table iii). Qualifying adjectives such as 'very' were disregarded and a count was instead made for the term that it preceded.

It is clear that the range of vocabulary was greater before Beaufort’s classification was adopted, and included terms that indicate origin as well as strength (e.g. trade, monsoon etc). Despite this initially broad range of vocabulary, however, it was found that the 17 most commonly used terms accounted for 92.7 per cent of the sample. Beyond these, which are shown in table 4.3, the next term 'moderate gales' only occurs 51 times, which is less than 1 per cent of the total. The remainder of the terms were infrequently used, many occurring less than five times.

This indication of the narrow vocabulary suggests a consistency of use amongst mariners even in the absence of a formal scale of the type later proposed by Beaufort. This prompts the question of how such common usage arose. Though naval colleges existed in the eighteenth century, it was unusual to attend such an establishment in order to train for service at sea. More commonly, boys would join a crew as midshipmen, perhaps as young as ten years old, and ascend the ranks as they gained experience at sea. Upon joining, the newcomers would be trained on the ‘codes of practice’ through a strong oral tradition that was passed down through the generations (Wheeler & Wilkinson, 2003). It was in these formative years that they would acquire the vocabulary that they would take with them through their naval careers.

wind term	**50's**	**60's**	**70's**	**80's**	**90's**	**00's**	**10's**	**20's**	**Total**	**Cumulative total**	**Cumulative Percent**
moderate	212	219	182	110	87	234	68	32	**1144**	1144	**18.11**
fresh breezes	9	94	112	89	136	182	115	72	**809**	1953	**30.92**
fresh gales	221	189	138	57	22	20	10	8	**665**	2618	**41.45**
light breezes	17	34	38	52	90	135	80	98	**544**	3162	**50.06**
light airs	42	50	75	53	85	91	88	45	**529**	3691	**58.44**
moderate breezes	2	14	9	67	81	96	101	113	**483**	4174	**66.09**
calm	15	23	40	38	43	43	51	55	**308**	4482	**70.96**
variable	4	13	14	54	65	17	30	68	**265**	4747	**75.16**
light winds	3	4	6	54	10	15	36	70	**198**	4945	**78.29**
little wind	91	35	22	4	1	25	0	0	**178**	5123	**81.11**
strong gales	18	35	49	28	20	17	5	0	**172**	5295	**83.83**
fresh trade	4	0	0	22	22	6	30	30	**114**	5409	**85.64**
moderate trade	0	0	0	25	19	4	15	44	**107**	5516	**87.33**
pleasant breezes	7	2	0	28	27	1	33	8	**106**	5622	**89.01**
strong breezes	0	0	0	13	11	19	30	15	**88**	5710	**90.41**
pleasant trade	0	0	0	26	20	1	22	7	**76**	5786	**91.61**
hard gales	31	6	9	3	19	3	1	2	**74**	5860	**92.78**

Table 4.3: Table of seventeen most popular terms in the logbooks from the random sample.

The vocabulary was not, however, itself stable, and underwent slow evolution over the decades. Upon further examination of the most frequently used terms there is a noticeable decline in the use of all types of gales and an increase in breezes during the study period. This trend can be seen more clearly in figure 4.1 and is further illustrated in table 4.4, but it is important to realise that changes in the frequency of recorded wind forces is not an issue of climate change but of evolution of terminology.

The word 'gale' is a good example of a term that has evolved in its meaning over the last three centuries. To the seventeenth century mariner, almost all terms greater in strength than calm were described as a type of gale from ‘soft’ or ‘easy’ to ‘hard’ or ‘strong’ (Wheeler & Wilkinson, 2003), but in contrast the term 'gale' today implies a more severe state of the wind exemplified in the BBC's gale warning service. This suggests that nautical vocabulary of the late eighteenth century cannot easily be translated into present day terms, and further investigation is necessary.

Decade	**Occurrences of types of gale**	**Occurrences of types of breeze**
50's	298	41
60's	246	144
70's	199	162
80's	110	272
90's	65	360
00's	41	444
10's	16	379
20's	15	335
total	**990**	**2137**

Table 4.4: Frequency of use over 80-year period of terms using 'gale' and 'breeze'.

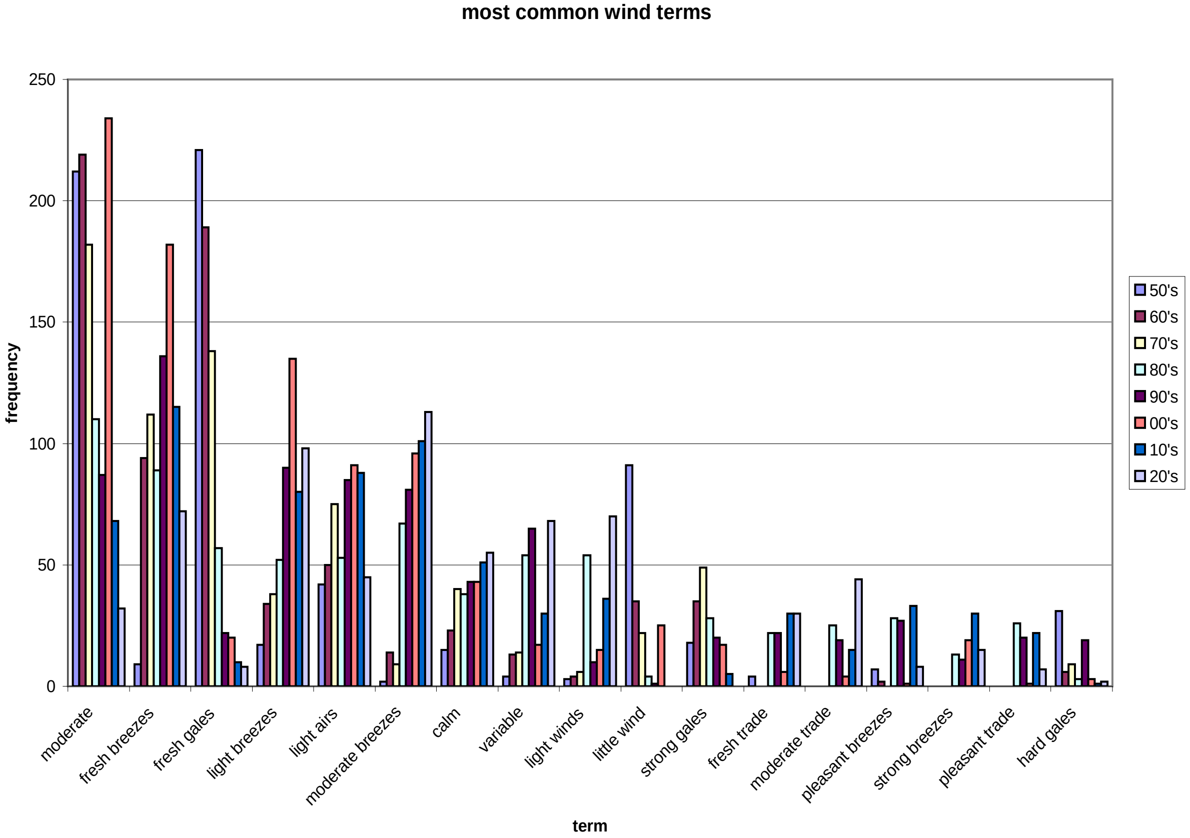


Figure 4.1: Graph of most frequently used terms for wind force in the logbooks

Gale

Despite its popularity in the seventeenth century, the *OED* states the origin of 'gale' as obscure. Suggestions have been made of a possible link to the Norwegian word 'galen', meaning 'mad, furious, bad', or to the Danish word 'gal', also meaning 'mad' or 'wacky'.

Seventeenth century texts seem to agree that a gale is a wind of reasonable strength that is conducive to good sailing. Captain Nathaniel Boteler and Sir Henry Mainwaring offer definitions of terms in the marine vocabulary in the seventeenth century (Perrin, 1929 and Mainwaring & Perrin, 1922, respectively) and both describe a gale as a wind that allows a ship to bear her topsails a-trip (hoisted to the highest point). John Smith's much earlier *Sea Grammar* (Goell (Ed), 1970) confirms this to have been the case in the seventeenth century.

All three aforementioned texts, and also Falconer's *Dictionary of the Marine* (Falconer, 1970, reprinted from 1815) go on to describe several classifications within the term. All mention 'fresh gales' but only Smith places it as the weakest type of gale, before fair/loom gales and stiff gales. Boteler and Mainwaring place loom gales before fresh gales and strong gales, whereas Falconer places fresh gales after hard gales and defines a gale as similar to a storm.

Breeze

Although not frequently used in the seventeenth and eighteenth centuries, there was a clear understanding of its very specific meaning at that time. Smith and Mainwaring agree that a breeze is a wind "…which blows out of the sea and doth daily in all seasonable fair weather keep his course, beginning about nine in the morning and lasting till it be within little of night" (Mainwaring & Perrin, 1922). This description is concurrent with today's understanding amongst meteorologists as a 'sea breeze'. Likewise, Falconer distinguishes between a land breeze and a sea breeze (present in fair weather at night and day, respectively), but also recognises the introduction of the word into common marine language by citing Dalrymple's scale of wind.

The sixteenth century Castilian word 'brisa', from which the word breeze is derived, has a direct connotation to a north-easterly wind on the South American coastline, and therefore to what was later recognised as the Trade Winds. The English adoption of the term has, therefore, a peculiar history, having little to do with its original meaning but being adopted to describe, in a very precise manner, local coastal circulations, but then being used more widely, and less discriminately, to describe light winds at the lower end of the ‘gale’ scale.

Calm

The term calm is probably the least questionable in definition of all the terms, and its meaning does not seem to have undergone the same evolution as other terms during the past three centuries. Both Mainwaring and the *OED* define calm in a straightforward manner as an atmosphere free from wind. Mainwaring goes on to mention the terms 'dead calm' or 'stark calm' as epithets of calm, perhaps reflecting the discernment of the mariner (also evident in the logbooks) between weather that is inclinable to calms but with some infrequent occurrence of wind, and weather that has no wind at all for a period of time.

Storm

Although mentioned in Falconer's *Dictionary of the Marine* under the entry of 'gale', as being synonymous with the same ("gale - a phrase used by sailors, to signify a storm or tempest"), Boteler is clear that they differ markedly. He states:

> *"...when it blows much wind it is called a swift or strong gale… but when it blows so much wind and so violently that a ship cannot bear any sail, and that withal there is some rain or hail mixed with the wind, then seamen say, it bloweth a tempest, and this they account a degree higher than a storm."*
>
> Perrin (1929), p161

Smith's *Sea Grammar* explains that "a storme is knowne to every one not to bee much lesse than a tempest", indicating a small difference between the two degrees.

Hurricane/Tempest

The word 'hurricane' was an adoption of the Carib word 'furacan' into the English language and, according to the *OED*, only became frequent after 1650 when voyages to the Caribbean were more common. Both Smith and Boteler were familiar with the term in the 1620s and 1630s respectively, and Smith recognised the restriction of the phenomenon to the West Indies. Due to its specific meaning and origin when the word was introduced, it has remained almost unchanged in definition since that time, and therefore can be directly translated from seventeenth century to present day language.

Despite the apparent continuity of certain wind force terms in meaning over the last two to three centuries, the evident evolution of other terms over the same time period means that further analysis into wind force is necessary in order to make the translation between the terminology used in 1750 and that of the present day.

CHAPTER FIVE

WIND FORCE AND DISTANCE

INTRODUCTION

A ship's officer calculating his position and setting his course for the next twenty-four hours had to pay attention to the nature (strength and direction) of the current and the wind, as both govern the calculations needed for effective navigation. Figures 2.3 and 2.4 in Chapter Two illustrate the principle of reaching a destination through allowing for departure due to natural forces of wind and current (known respectively as leeway and drift) from the magnetic course as steered by compass bearing.

Investigation into the relationship between these natural forces and the motion of the vessel requires further understanding of the mechanics of sailing. This process aids the understanding of the nature of the raw written information on which the project is based, and allows for further interpretation of the (wind force) terminology contained within the logbooks.

Before the advent of vessels specifically designed to undertake meteorological observations, a ship sailing on open waters was usually doing so with the objective of travelling from source to destination in the shortest time possible. This was particularly the case with East India Company ships, whose task was to be among the first to arrive back in Britain after a trip to India to collect a consignment of tea or spices (Sutton, 1981). The first such delivery to Britain would usually fetch the highest price. Commercial cruise ships were not in operation until the early nineteenth century, and although Royal Navy ships under military orders might be slowly patrolling, this would be primarily confined to shallow waters closer to home. Thus sailors travelling over deep sea would have sought conditions of a favourable nature to assist a speedy passage to their destination. The data set under study here is largely comprised of these latter types of voyage, since ships located close to land were rejected due to the high probability of their recorded meteorological data being influenced by boundary layer effects.

MARINERS’ AWARENESS OF THE WIND DURING THE 18th CENTURY

Sailors were aware of the nature of the global wind fields as far back as the mid- eighteenth century (and possibly further), as William Brereton demonstrated in 1771 in his paper submitted to the Admiralty Office. He writes:

> *"I have remarked that the winds follow the Sun in its approach to either of the Tropicks…This influence of the Sun, within the Tropicks where the general Easterly winds prevail, is clearly evident from my own observation. For there the Trade Winds are constantly diverted from their natural course by the presence of the Sun… For this reason, ships bound to the East Indies choose to sail in the winter, whilst the Northerly Winds blow in the Atlantick Ocean, even through the Torrid Zone. For those that sail in summer whilst the southerly winds prevail are often driven over to the coast of Brazil and lose much time there.*
>
> *It is well known that in the Atlantick Ocean to the northward of the Tropick, a westerly wind is a kind of Trade, as it prevails a great part of the year. But here, as in the Torrid Zone, in spring and summer, the southerly winds partake, and in autumn and winter the northern winds have a large share. Easterly winds seldom blow in this part of the Atlantick Ocean for any length of time, beyond the distance of two hundred leagues west of the land."*
>
> *(pp 5-6)*

The specific type of wind mentioned by Brereton, the Trade Winds, are winds that originate with the subtropical high-pressure cells and are generally found in the 20-30° latitude zone (Briggs & Smithson, 1985) on either side of the equator. They are seasonal in the Indian Ocean and perpetual in the Atlantic. Figure 5.1 shows where the two Trade Wind belts converge at the equator and cause an upward motion of the air. This is known as the Intertropical Convergence Zone (ITCZ) and is a region of very little wind, due to the small horizontal component of the air movement. This area was known to sailors as the Doldrums, and most would go to great lengths to avoid it, even if it meant sailing many more miles to find a route that spent as little time here as possible.

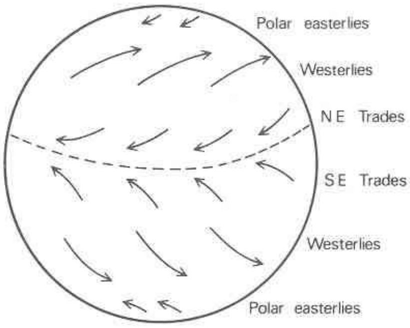


Figure 5.1 Diagram of main surface wind belts, from Briggs & Smithson (1985)

THE BEHAVIOUR OF THE SHIP DUE TO THE WIND

The response of the ship to the prevailing wind strength, in particular the vessel's speed, is a relationship governed by many factors, not least of which is the direction of the wind relative to that of the ship in question. Some wind directions were more favourable than others in this regard. Perhaps most obviously, the primary example of an unfavourable wind was a headwind (a wind in direct opposition to the direction of the ship). Other names for relative wind directions are shown in figure 5.2a.

The most favourable wind direction was a 'leading wind' (Harland, 1984), which was anything between the beam and the quarter (see figure 5.2b), though a ship could steer her course under a wind from the bow side of the beam (up to a point), called a 'scant wind', and also under a wind blowing astern, called a 'following wind'.

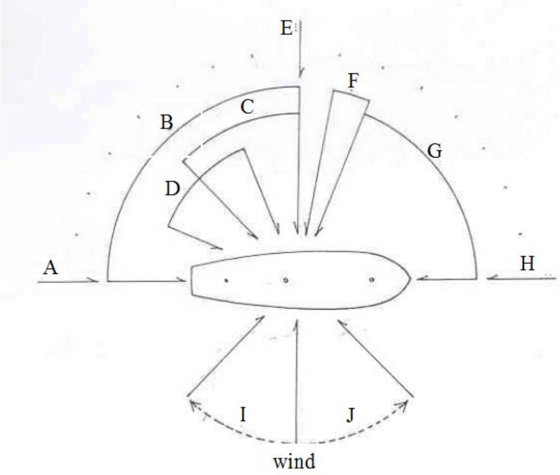


Figure 5.2a: Diagram of relative wind direction, from Harland (1984). A- following wind; B- fair wind; C- leading wind; D- large wind; E- soldier's wind; F- scant wind; G- foul wind; H- dead muzzler; I- wind veers aft; J- wind hauls forward.

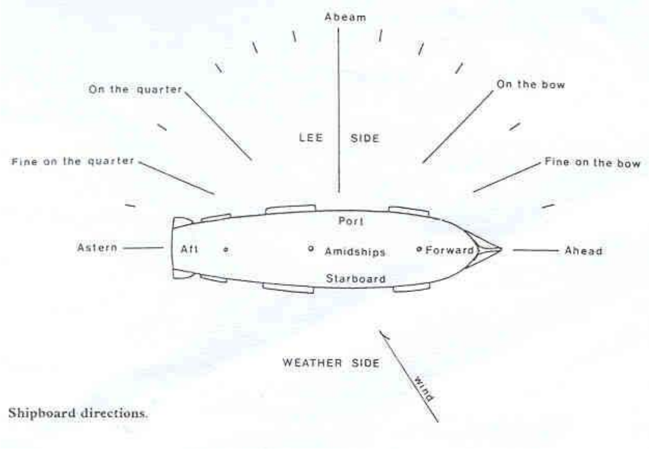


Figure 5.2b: Diagram showing shipboard directions, from Harland (1984)

The effects of these relative wind directions on the sails themselves are best explained through a simple example of a ship with a square sail, however, the ships on which the observations were made were usually three-masted men of war (an example of which is shown in figure 5.3) and the effect of the wind on two or more sets of sails is complex. The simplest case of two equally sized square sails, placed at equal distances from the centre of mass of the ship, is shown in figure 5.4, along with the movement of the ship in relation to the behaviour of the two sails. If the ship is on the starboard tack (turning towards the starboard side) and the wind is blowing from the starboard side, the ship will move ahead and also make some leeway. If the wind is blowing from the opposite direction (i.e. on the portside beam) then the ship will still make leeway from the component of the wind that is perpendicular to the direction of the vessel, but will begin to make sternway, that is, to be driven backwards.

Figure 5.3: "The Indiaman Thomas Coutts" by James Miller Huggins, courtesy of the National Maritime Museum

The relationship between the force acting upon the sails of a ship and the subsequent movement of the vessel cannot be expressed purely in terms of the number of sails carried. It is undeniable that the more sails that are carried, the greater the sum pressure incident upon the canvas shown by the ship. This will, in turn, propel the ship with greater force, but also places greater stress on the sails, rigging and ropes. Through experience, an officer could make a judgement of the maximum number of sails that his ship could carry under increasing wind strength, and thus attain greater speed. There would, however, come a point where he would have to begin shortening sail (removing some canvas), or risk ropes giving way to the extra pressure, and thus losing rigging, sails and masts.

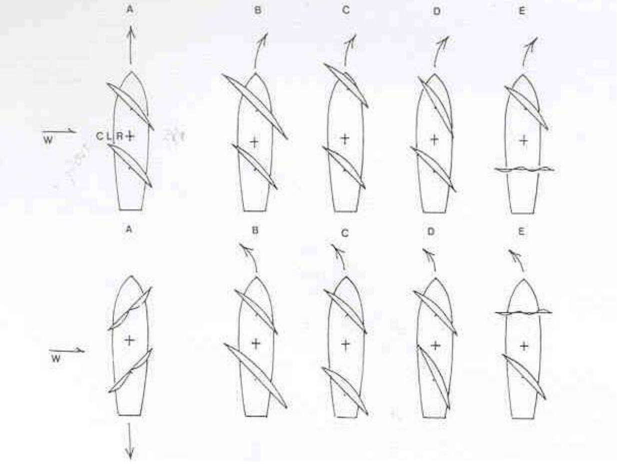


Figure 5.4 Effect of the wind on two square sails. The arrows on diagrams B to E (top and bottom) show the direction of the ship's movement

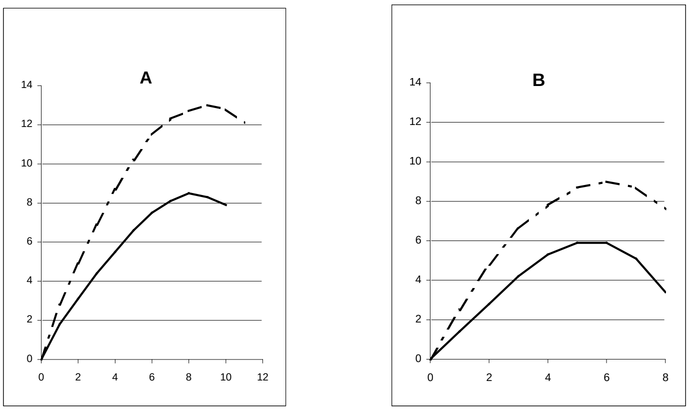
The sequence of removing canvas (and adding it) evolved slightly over the seventeenth and eighteenth centuries, and was the responsibility of the officer in command of the vessel (Harland, 1984). The highest sails (royal and topgallant sails) and the sails at the back of the ship (the mizzen masts and after sails) would come off first, to reduce heeling (the effect of the ship blowing over) and rotation of the ship.

Neither was it a rule that the more canvas added (up to the point where she could no longer bear it) the greater the rate of sailing. The sails would have a steadying effect on the ship, and give a greater propelling force, but this could be counteracted if the wind was directed into a relatively ineffectual sail (that is, having a particular sail present that was not in the most effective position to make use of the wind).

The response of the ship to the wind forces depended upon many factors, but did not differ greatly between ships in the study period. Thus in a large enough sample of ships it is reasonable to assume that either speed of the vessel, or distance covered by it, could be related consistently with wind force.

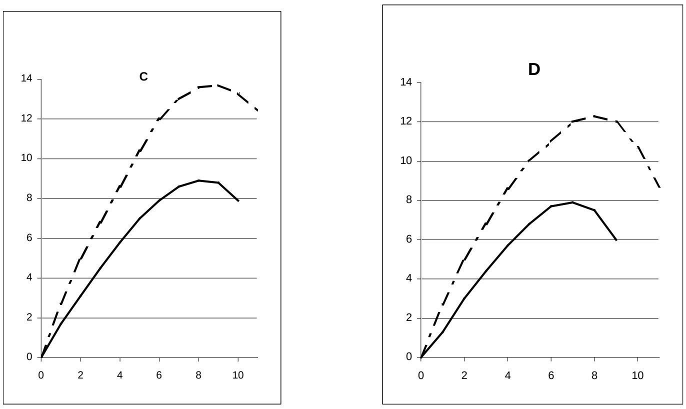
THE RELATIONSHIP BETWEEN WIND FORCE AND SHIP'S SPEED

Harland (1984), drawing heavily on the work of Prager (1905), prepared a number of diagrams that usefully summarise the complex relationship between the two variables of principle concern; wind force and ship's speed (which in turn is directly proportional to distance per day). Figure 5.5 depicts the non-linear relationship between wind force and ship speed. The solid line shows the performance of a small wooden barque, the broken line that of a five-masted steel ship. The vertical scale is the ship's speed in knots, the horizontal scale is the wind force using the Beaufort scale. The four graphs represent four different directions of the wind, relative to the vessel, with the blue arrows denoting the wind and the direction of the vessel is also shown. .



A – Before the wind

B – By the wind



C – In a quartering wind

D – In a beam wind

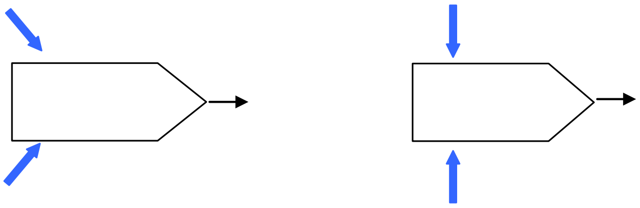


Figure 5.5: Relative speeds of ships on different points of sail, as given in Harland (1987), (after M Prager, 1905).

From these graphs it is evident that the maximum speeds attained between Beaufort force 6 and 9, depends on the relative direction of the wind.

THE RELATIONSHIP BETWEEN WIND FORCE AND DISTANCE TRAVELLED

Whilst the speed of the ship was carefully noted, often every hour, it was not always registered in the finished logbook. On the other hand, the distance covered each day was recorded by all officers on board. Since the speed of a ship is proportional to the distance travelled it can be postulated that the distance travelled under a particular wind force is a surrogate measure of the force of that wind.

The logbooks recorded the true distance denoted by the term ‘distance made good’ (see figure 2.4, Chapter Two). Thus the figure given was the mapped distance following a straight line from the position of the ship at noon over two consecutive days.

Sampling the logbook data for analysis on the relationship between wind force and distance travelled

It is recognised that a number of factors influence the relationship between wind force and distance covered, but a large enough sample should allow an underlying signal to emerge that demonstrates the association between wind force and distance travelled (ship’s speed).

Sampling has been confined to those daily entries for which only one wind force was recorded. Days with multiple wind force entries could not be used, as there is no means by which the distance could be split and allocated to the corresponding parts of the day. Entries with only one wind force are assumed to denote a day with consistent wind strength.

Such ‘single’ wind force days were not abundant, and to provide a large a sample as possible, data were not confined to entries from the North Atlantic region, but were drawn from the entire CLIWOC database, and for the period 1750 - 1830.

The ‘working’ hypothesis is that each wind force term should produce a mean distance different from other terms, reflecting the principles outlined above. Furthermore, examination of the distribution of mean distances for the range of wind force terms should allow correspondence with the Beaufort scale and the assignment of a Beaufort Force number (and thus a range of wind speeds) to each term.

In this particular analysis, the null hypothesis is as follows:

"There is no difference between the mean distance sailed by ships for each wind force term over the 1750-1830 period."

Attention is initially confined to the ten most frequently used terms, many of which were later adopted by Beaufort, although no attempt was made at this stage to break the data into decadal scale resolution and statistical tests are run on the whole eighty year period.

The mean distances for each wind force term can be seen in table iv in Appendix III, but a summary of the most widely used terms is shown in table 5.1.

wind force	**mean distance run (nm)**	**N**
fresh breezes	121.82	440
light breezes	71.78	414
moderate	96.98	395
light airs	50.92	394
moderate breezes	96.90	391
fresh gales	127.38	379
fresh trade	149.87	341
strong gales	105.24	339
pleasant breezes	118.21	317
moderate trade	123.70	310

Table 5.1: Table of results for mean distances for the ten most frequently used wind force terms.

A one-way analysis of variance test (ANOVA) was run on the data using the statistics software package SPSS. The significance level shows the probability that the results of differences between groups has arisen by chance, and thus how statistically significant the differences are. The conventional significance level chosen for this test is usually 0.05 or 0.01 (Shaw and Wheeler, 2000). The results of the ANOVA test are shown in table 5.2. The variance ratio (F) is significantly large at 64.04 and thus there are large differences between groups. The significance value (Sig) is 0.000, i.e. $p<0.01$ so the probability that these differences between groups has arisen by chance is extremely remote. Therefore the null hypothesis is rejected and it is concluded that there are inter-wind force differences in terms of distances sailed.

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	7472578.5	67	111531.0	64.04	0.000
Within Groups	11447191.0	6573	1741.6		
Total	18919769.6	6640			

Table 5.2: Results of ANOVA test for the difference between mean distances of wind force terms.

ORDERING THE SAMPLE OF WIND FORCE TERMS

The ANOVA test has shown a difference between wind force terms. It is now possible to impose some order on the list of terms, in rank order of the mean distance run, and to place them on an ordinal scale. Attention is preliminarily confined to those terms appearing more than thirty times in the data, and this provides a reliable framework within which the remaining terms can be progressively included.

The greatest speeds are associated with the wind force term "steady gale", which gives a mean distance of 170.96 nm. Taking into account Harland's observation that there is a peak in the mean speed attained (see figure 5.5), it is clear that although all wind force terms will produce a lower mean distance than the optimum state (‘steady gales’), some will fall to the left of steady gales, and some to the right. For example, ‘hard gales’ has a mean distance of 77.37 nm, which is less than steady gales, but is clearly of greater strength and therefore must fall on the right hand side of the graph. On the basis that fresh gales, strong gales and hard gales all produce lower mean distances than steady gales but are placed above steady gales on a scale of wind strength, the scale shown in table 5.3 can be suggested.

There are certain terms that did not occur in the sample more than thirty times, but which can be confidently placed on this scale in a category of their own. These include storm and hurricane, which due to their unambiguous meaning (Chapter Four) are of a higher strength than any of the terms included in table 5.3.

wind force	**mean distance run**
calm	19.72
light airs	50.92
little winds	63.00
light winds	69.50
light breezes	71.78
light gales	92.00
moderate breezes	96.90
moderate	96.98
moderate gales	99.87
light trade	100.81
pleasant breezes	118.21
pleasant winds	119.87
fresh breezes	121.82
moderate trade	123.70
fine breezes	129.47
pleasant trade	135.35
pleasant gales	136.53
strong breezes	139.66
steady breezes	140.17
fresh winds	140.95
steady trade	141.92
fresh trade	149.87
brisk trade	150.90
brisk gales	153.52
strong trade	163.16
steady gales	170.96
fresh gales	127.38
strong gales	105.24
hard gales	77.37

Table 5.3: A possible scale of wind strength for wind force terms occurring more than 30 times in the sample, with their respective mean distances.

BEAUFORT EQUIVALENTS FOR THE WIND TERMS

In order to attribute an equivalent Beaufort force to each wind strength term, and prior to the inclusion of those terms that occur less frequently, table 5.3 can be effectively 'split' into sections, and those sections corresponded with Beaufort numbers (table 5.4). A certain amount of subjective judgement is required for this, based upon knowledge of the Beaufort scale and definition of the different wind force terms.

For the purposes of this exercise, storm and hurricane are included to pinpoint forces 11 and 12, respectively. Force 0 may also be easily equated with the term 'calm', since this has held its definition over time and means the same today as it did in the mid-eighteenth century (Chapter Four). The fact that it has a mean distance of 19.72 nm (nautical miles) associated with it is probably due to the vessels' responses to ocean currents which would have an effect on the ship's movement in the absence of any wind.

On closer examination of figure 5.5 it is clear that for wooden ships the average Beaufort force that produces the optimum rate of sailing is just over force 7. For a first approximation this may be attributed to the wind force term that gives the highest mean distance, that is, steady gales. The three terms just below steady gales could be thought of as being broadly comparable, and gives a convenient cut-off point at a mean distance of 150 nm. Brisk gales seems to indicate a type of gale of a reasonable strength and not dissimilar to steady gales, whilst strong trade and brisk trade appear to fall at the top end of the type of wind known as 'trade'. Trade winds are generally accepted as being synonymous with breezes (which are placed below gales on the present Beaufort scale), so to place the strongest type of trade with gales of a moderately strong nature does not seem wholly unjustified.

The significant difference in mean distances for the three wind terms falling after steady gales lends itself to place them in separate categories, and indeed this conveniently allows Beaufort forces 8, 9 and 10 to be allocated to fresh gales, strong gales and hard gales respectively. Furthermore, this results in the last five categories in table 5.4 corresponding with Beaufort's initial scale (Kinsman, 1969). The only exception to this is force 10, which is represented by the term 'whole gale' in Beaufort's scale, but by 'hard gales' in table 5.4.

Since force 7 begins with brisk trades, it follows that force 6 must end with fresh trade. Below this there is a cluster of four terms that have similar mean distances, the least of these being strong breezes. It seems reasonable to group these with brisk trade in force 6, further compounded by the appearance of strong breezes in the early Beaufort scale at force 6.

Force 5 and force 4 may be approached in a similar manner, using fresh breezes (Beaufort force 5 in his early scale) and moderate breezes (Beaufort force 4) as the lower thresholds for each respective category.

Light breezes appear in the early Beaufort scale at force 2, so it follows that the same number be attributed to the term appearing in table 5.4. This results in only one term to place in the category of force 3 (light gales), but the gap in mean distances between the two may later be filled by some of those less frequently used terms not included at this stage.

Light airs can be confidently equated with Beaufort force 1, as they are the first term after calm. This leaves little winds and light winds to be classified. Light winds has been placed with light breezes at force 2, and little winds with light airs below in force 1, as the word 'little' suggests a strength less that that of 'light'.

wind force	**mean distance run**	**Beaufort equivalent**
calm	19.72	0
light airs	50.92	1
little winds	63.00	1
light winds	69.50	2
light breezes	71.78	2
light gales	92.00	3
moderate breezes	96.90	4
moderate	96.98	4
moderate gales	99.87	4
light trade	100.81	4
pleasant breezes	118.21	4
pleasant winds	119.87	4
fresh breezes	121.82	5
moderate trade	123.70	5
fine breezes	129.47	5
pleasant trade	135.35	5
pleasant gales	136.53	5
strong breezes	139.66	6
steady breezes	140.17	6
fresh winds	140.95	6
steady trade	141.92	6
fresh trade	149.87	6
brisk trade	150.90	7
brisk gales	153.52	7
strong trade	163.16	7
steady gales	170.96	7
fresh gales	127.38	8
strong gales	105.24	9
hard gales	77.37	10
storm	63.67	11
hurricane	n/a	12

Table 5.4: A provisional scale of the most frequently used terms, with their Beaufort force equivalents.

Once the most frequent terms have been amalgamated with the Beaufort scale, the other, less common terms can be inserted. This was done using the same approach of a combination of mean distance and judgement.

When placing the less frequently used terms (table iii, Appendix III) within this scale, some prove more difficult than others. Faint airs, small breezes and easy breezes are all clearly less in strength than the optimum state and thus are inserted at the lower end of the scale according to their respective mean distances. Likewise strong winds and violent gales are included at the higher end of the scale. Stiff breezes and stiff gales are inserted according to their definition in *Boteler’s Dialogues* (Perrin, 1929), which states that more sail is carried under fresh and strong gales than under stiff gales, the reduction of sail implying an increase in wind strength. Thus stiff gales have been placed above fresh and strong gales on the scale, and stiff breezes above strong breezes. 'Fair breezes' has a mean distance of 161nm, which would place it in category 7 (moderate gale), along with such terms as brisk gales and strong trade. This seems unlikely, and since it only appeared in the sample twice, the mean distance is assayed with caution. The term 'fair breezes' is therefore instead placed with a degree of subjective judgement in category 5, with fresh breezes and fine breezes.

The term ‘light trade’ produces a mean distance of 100.81, which would mean it was included above ‘moderate gales’. Since this seems improbable it has instead been inserted as the highest of those terms described by the adjective ‘light’, i.e. above ‘light gales’.

The work of Alexander Dalrymple (1789) explains that winds that are variable in nature (usually described by 'variable', 'squally' or 'unsteady') "…are so various in duration and violence, it seems impossible to reduce them to any standard…", and therefore are not included within the scale constructed here. This is further supported by the conclusion drawn in Chapter Three that the term “squally” should be included in the sampling process of weather terms, not wind terms, as it is not a wind strength term, but a description of the tendency of the weather.

From figure 5.6 it is clear that some points are significantly out of phase. One of these is 'fair breezes' (explained earlier), and the other two are 'blowing fresh' and 'fresh gales'. The term 'blowing fresh' has a mean distance of 54nm and if placed according to this it would feature either in force 1 (light airs) or 10 (hard gales), which seems very unlikely. Since there are only four incidences of this term in a sample of 6641, it is a relatively infrequent term and exercising judgement and placing it with 'fresh breezes' in force 5 does not seem inappropriate.

'Fresh gales', on the other hand, is clearly out of phase with a total count (N) of 379, and so cannot be treated in the same way. If placed according to its mean distance, it would fall between ‘blowing strong’ and ‘strong winds’, and seems out of place. However, relocating it to a position that appears more sensible, that is, immediately after ‘fresh monsoon’ means that the corresponding mean distance run is out of phase with its neighbouring points in figure 5.6. The relocation of the term can be supported by closer examination of the mean distances of fresh gales, in which most of the decades yield a value for N in excess of 50. The 1820s however, give a particularly low mean distance of 94nm in comparison to the other decades, and N is only equal to nine. It was found that of these nine counts of fresh gales, eight were recorded by the same officer, Joseph Dudman, on board the *Inglis*. On the basis that this reduces the reliability of the mean distance for this term over the decade, a value for the total was created without contribution from the 1820s. This resulted in a higher overall value of 134nm and better places the term at the top end of force 8, after “fresh monsoon”.

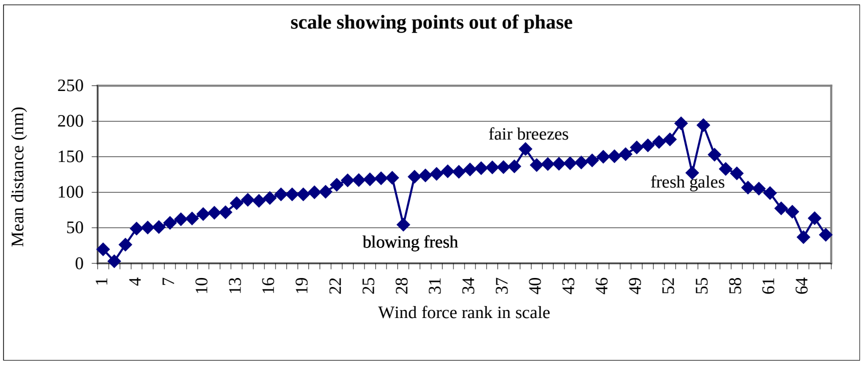


Figure 5.6 - Graph of scale of all terms. The equivalent terms to the rank numbers can be found in table 7 in Appendix 1.

This modification of the data meant that two other terms were slightly out of phase, these being 'heavy gales' and 'strong monsoon', whose mean distances would place them between fresh gales and blowing strong, and in the same category as fresh gales and also fresh monsoon. It seems contradictory to place the two types of gales and monsoon winds of differing strengths in the same category, so an adjustment to the location on the scale for them must be made. This is supported by the low count for these terms in the sample (heavy gales occurred twice and strong monsoon just once). Both are instead inserted into force 9.

The results of the merging process are shown in table 5.5. Confidence in this table can be drawn from the appearance of 11 of the 13 present day descriptions in their corresponding range of logbook terms. The only two exceptions to this are 'moderate gales' (which appears instead in category 4), and 'whole gale', which was not found in the logbook data sample at all.

This table can now be used to scale every wind force term that occurs in the logbooks, and allows climatological analysis to take place. These converted values allow more objective analysis of the derived data to be carried out in the confidence that the series have, effectively, been homogenised to present day standards.

Beaufort number	today's description	range of terms included from logbook data	Limits of velocity in knots	Average velocity in knots
0	Calm	calm	<1	0
1	Light air	light airs/baffling winds/faint airs/faint breezes/faint winds/small breezes/easy breezes/little winds	1 - 3	2
2	Light breeze	light breezes/light winds/faint gales	4 - 6	5
3	Gentle breeze	gentle breezes/gentle gales/light gales/faint trade	7 - 10	9
4	Moderate breeze	moderate breezes/moderate gale/moderate/easy gale/light trade/scant trade/gentle trade/easy trade/pleasant breezes/pleasant winds/light monsoon	11 - 16	13
5	Fresh breeze	fresh breezes/blowing fresh/moderate trade/agreeable gales/fine breeze/fine trade/moderate monsoon/pleasant gales/pleasant trade/fair breezes	17 - 21	19
6	Strong breeze	strong breezes/steady breezes/stiff breezes/fresh winds/steady trade/fresh trade/pleasant monsoon	22 - 27	24
7	Moderate gale*	brisk trade/brisk gales/brisk winds/strong trade/steady gales/steady monsoon	28 - 33	30
8	Fresh gale	fresh gales/fresh monsoon/blowing strong/strong winds	34 - 40	37
9	Strong gale	strong gales/strong monsoon/heavy gales/stiff gales	41 - 47	44
10	Whole gale	blowing hard/hard gales/great gales/much wind	48 - 55	52
11	Storm	storm/violent gales	56 - 65	60
12	Hurricane	hurricane	>65	-

Table 5.5: Table of Beaufort equivalents for all terms occurring in the sample. Range and average velocities are taken from *Marine Observer's Handbook* (HMSO, 1995)

* This is the only category where the present Beaufort description is present in the sample, but does not occur in the corresponding range of terms. The term moderate gale instead appears in category 4, with moderate breeze.

CHAPTER SIX

WIND DIRECTION IN LOGBOOK STUDIES

INTRODUCTION

Wind direction in eighteenth and nineteenth century logbooks was more straight-forward to interpret than wind force, as it was more quantitative and not based on judgement and description, but, nevertheless, it required verification. Furthermore, there are no grounds to suggest that methods of observing wind direction are significantly different today than they were two hundred years ago. Advances have led to the possibility of many meteorological observations being made instrumentally even at sea, yet wind direction procedures remains in a relatively unsophisticated state in this respect and observations on board ships rely almost exclusively on visual observations and use of the ship's compass, as set out in *The Marine Observer's Handbook* (1995):

> “*Wind direction is logged as the true direction and is given to the nearest ten degrees. The exposed position that a ship's standard compass usually occupies gives a clear all-round view and from it the observer takes a compass bearing, noting the tops of the waves, the ripples, the spray and the faint lines that generally show along the wind. It is usually best to look to windward in judging wind direction, but in some lights the direction is more evident when looking to leeward.”*
>
> (p 48)

A compass bearing based upon this observational method is then taken and recorded. On very dark nights where this method is not possible, the wind direction (and force) must be estimated by judging the 'feel' of the wind upon the face or moistened finger (*Marine Observer's Handbook*, 1995), but here allowances must be made for the ship's course and speed.

This emphasis on partially non-instrumental methods for estimating wind direction is remarkably similar to that of eighteenth century when the mariner's sole reliable instrument to ascertain direction was the compass.

THE COMPASS

This was arguably the most important instrument carried on board a ship; used to guide the vessel, and the only means by which to do so in the absence of a celestial body such as the sun or the pole star.

The Origins of the Compass

The exact origins of the compass are not known and it seems possible that the discovery of the link between magnetised minerals and direction was made in several different parts of the world at different times (Hewson, 1983). The type of rock responsible for such a discovery was the lodestone, whose properties were known about several centuries prior to the emergence of the compass. Many countries in which lodestone can be found have been accredited with the first use of a magnetised needle to point north, but opinion seems to rest with China, whose ships visiting Indian ports in the fourth century were guided by compasses (Hewson, 1983, after Von Humboldt, 1858). Certainly it seems probable that scientists and sailors of various nationalities were independently developing the primitive compass, and mentions were becoming more numerous throughout the thirteenth century. The initial method of floating a magnetised needle upon water was improved around this time by mounting it upon a pivot, and by the late fourteenth century, a circular card showing the directional points had also been employed by those who used this early compass.

The exposure of such a compass to the elements on board a ship quickly demanded protection in the form of a wooden box surrounding it, with a glass lid. This ensured the card and needle were not affected by the wind and damp. This was further developed by encasing the whole in a second box, and pivoted by two supports in the form of concentric circles made of laton (a type of metal not unlike brass), ensuring that the compass was kept steady when the ship laboured (Hewson, 1983).

A typical description of the kind of compass used by mariners during the study period is given in Norie's *Epitome of Navigation* (1864):

> *"This instrument is an artificial representation of the horizon of any place. It consists of a circular card, divided into 32 equal parts, by lines drawn from the centre to the circumference, called Rhumb Lines."*
>
> (p62)

An illustration taken from this text is shown in Chapter Two, figure 2.2.

It is clear that, despite a convention from the very earliest days of ocean sailing that the wind direction was determined by the compass point towards which it blew, by the time of the study period the definition of wind direction had altered 180 degrees and inferred the direction *from* which the wind is blowing

(Raper, 1852). In fact this convention was well-established by 1750 and was employed as early as the sixteenth century:

> *"The use of the 32-points of the Compass, is to direct the skilfull pilote by horizontal travers, how he may conclude the corse or paradorall [sic] motion of his ship, thereby with greater expedition to recover the place defined, because they guide the horizon in such limits as are most apt for navigation, they does also distinguish the winds by their proper names, for the winds receiveth his name by that part of the horizon* ***from whence it bloweth."***
>
> The Seaman's Secrets - Anon (1633) (p 2)

Although both Norie and the author of *Seaman's Secrets* describe the compass as having 32 points, mariners did not necessarily use them with equal discrimination in terms of the degree of detail in the compass point description. Closer examination of the logbook data with respect to wind direction shows that there was a bias present *away* from the use of all 32 points, as shown in table 6.1. The bias is clearly shown by an under-representation of the observed frequency of observations using those points of the compass, e.g. NbE, SWbS etc. that are specifically of a 32-point character. Those of a 16 point (SSE, NNW etc.), of an 8 point (SW, NE etc.) and a four point (N,S etc.) character occur with a greater frequency than might be expected if all 32 points were used with equal probability. This may be as a result of the recognised degree of uncertainty experienced by the officer who, taking the sensible option, would select a less precise measure if the degree of uncertainty warranted such an action.

	4-point	**8-point**	**16-point**	**32-point**	**Chi-square test statistic**
1750s	171.25	764.25	423.5	-1359	1278*
1760s	116.25	252.25	201.5	-570	482*
1770s	97.75	215.75	77.5	-391	403*
1780s	72.75	223.75	208.5	-505	433*
1790s	35.63	192.63	65.25	-293.5	266*
1800s	75.75	114.75	123.5	-314	240*
1810s	14.75	1.75	-7.5	-9	4.5
1820s	20.63	17.63	39.25	-77.5	50.7*

* SIGNIFICANT AT THE 0.01 LEVEL

Table 6.1: Table of differences based on observed - expected frequencies for the wind direction data from the logbooks (Royal Navy vessels only). The test statistic is based on a null hypothesis of all points of a 32-point compass being equally probable.

GEOMAGNETISM

Since the observations of wind direction were taken by compass, it is necessary to consider another important point - that of magnetic deviation.

The Earth's magnetic field may be thought of as being dipolar (Monroe & Wicander, 1995), with magnetic north and south poles, as depicted in figure 6.1.

The location of these magnetic poles is not necessarily coincident with the geographic (true) north and south poles, and also varies over time. This 'polar wander' is thought to be attributable to the fluid nature of the Earth's core, which produces the magnetic field by the generation of electrical currents, though full understanding of this process has not yet been achieved.

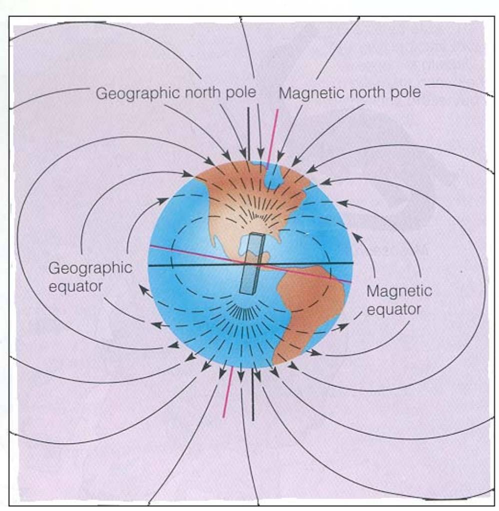


Figure 6.1 The Earth's magnetic field, from Monroe & Wicander (1995)

Compasses and geomagnetism – current understanding

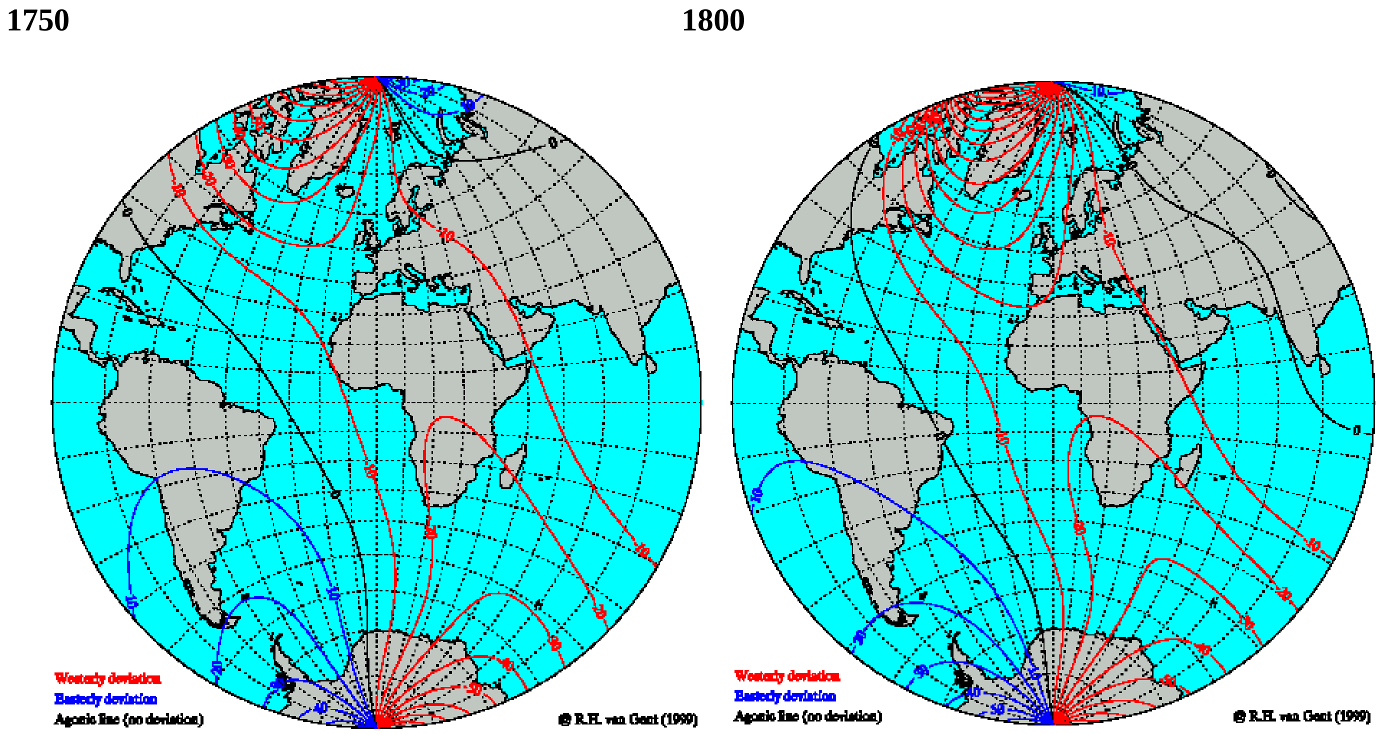
The needle of any compass points not to the geographic north pole (true north), but to the magnetic north pole. There is a difference between the two (currently about 6 degrees west in the UK), which varies in both space and time, termed 'magnetic variation' (some texts refer to this as magnetic declination). This is the horizontal component of the deviation, and there also exists a vertical component of this deviation, which is referred to by several different names: inclination, dip and sometimes declination. This vertical component arises from the increase in angle of the lines of magnetic force with progressing proximity to the magnetic north pole, evident in figure 6.1. Thus the compass needle will be completely horizontal at the magnetic equator, and at its most vertically inclined at either magnetic pole. To compensate for this, compasses in the Northern Hemisphere usually have a small weight placed on the south end of the needle (Monroe & Wicander, 1995).

Dr Robert van Gent from the University of Utrecht (http://www.phys.uu.nl/~vgent/magdec/magdec.htm) has reconstructed geomagnetic maps for historical epochs, and the two most relevant to the study period (1750 and 1800) are shown in figure 6.2.

Compasses and geomagnetism – historical understanding

Magnetic variation has been known about for several centuries. It was not until the sixteenth century that attempts were made to understand fully the reasons behind the behaviour of the compass (Hewson, 1983).

Columbus noted that the compass needle deviated from the north and south points of the horizon (Norie, 1864) and in 1581 Robert Norman, a compass maker, discovered that the needle also deviated in the vertical plane, effecting what is known today as the Dip of the needle (Hewson, 1983). Norman explored new theories of the behaviour of the needle, but concluded that there was no attracting force acting upon the needle and the properties were wholly attributable to the lodestone and not to any characteristic of the Earth. It was William Gilbert, a medical doctor, who discussed the possibility of the Earth itself possessing qualities of a large magnet in 1600 in his published work entitled *De Magnete, magneticisque corporibus*.



1750

1800

Figure 6.2: Geomagnetic maps for 1750 and 1800 (R.H. van Gent, 2001)

In 1634 Edward Gillibrand, Professor of Astronomy at Gresham College, realised the inconsistency of the magnetic field in any one place over time. Variation was even predicted as far back as the mid seventeenth century (Howarth, 2002), so it is not surprising, therefore, that mariners of the eighteenth and nineteenth centuries were well aware of the effect that this fluid magnetosphere had on their compasses. They also knew that all variables using a compass bearing must be corrected for this variation (Raper, 1852), if bearings and directions that could be related to maps and charts were required. Some compasses at this time were already corrected by rotating the compass card, setting it for the local variation (Hewson, 1983). This produced the effect of the compass pointing towards the geographic north pole when close to home, but demonstrating considerable errors when sailing further afield in regions of different variation. This practice was modified in the eighteenth century, when the card was regularly corrected upon the obtaining of the magnetic variation of the area in which they sailed.

It should also be noted that the other large factor in the departure of the compass from its correct reading, the deviation due to large amounts of iron present in close proximity, was first observed aboard Captain James Cook's second voyage (1772-1775) (Hewson, 1983). Differences of several degrees were obtained purely by orientating the ship differently, or by moving the compass around the ship, but a scientifically satisfactory explanation was not offered. Hewson suggests that this was perhaps slightly surprising, since two separate sources in the seventeenth century, John Smith (author of *The Seaman's Grammar*, 1657) and Captain Samuel Sturmy (writing in *The Mariners' Magazine* in 1684) had warned of the effects of iron within the ship itself upon the compass.

It was Captain Matthew Flinders who, whilst surveying off the coast of Australia in 1801-02, deduced that the significant deviations in the compass readings were due to the attractive power of the large amounts of iron on board his ship, most notably the store of shot. He observed that the south end of the needle was attracted in the Southern Hemisphere, and the northern end of the needle attracted in the Northern Hemisphere. His suggestion of specific placement of the compass within the ship to counteract such effects, and an optional vertical bar of soft iron in the stern to ensure this, promoted the level of importance placed upon this matter, and throughout the nineteenth century further developments resulted in a greater awareness of deviation.

COMPASS VARIATION IN THE LOGBOOKS

Logbooks recorded wind direction more often than any other weather element yet, ironically, no record has been found in any of the texts that have been studied in which any unambiguous indication is made of the system of recording. Most importantly, there is no direct statement to indicate whether the directions are in relation to true or to magnetic north. To what extent variation had a bearing upon wind direction data recorded in the logbooks was a matter that required further investigation.

Many logbooks that were examined contained daily entries of compass variation, either in points of the compass (e.g. “1 ½ points W”) or degrees and minutes (e.g. “15º 30’ E”). Such careful notation of magnetic variation has since been utilised by the scientific community for investigation into historical geophysics (Jackson *et al*, 2000) but it is clear that the recording officers had their own purpose for this inclusion. This lay in the correction of directional variables contained in the logbooks, but it was not indicated which of them had been corrected and which had not.

DIRECTIONS IN THE LOGBOOKS

One avenue of investigation used to indicate if logbook wind direction entries were ‘true’ or ‘magnetic’ is provided by the method of course estimation described in contemporary navigational texts. There is clear evidence that these were corrected for magnetic variation and this may help to answer the question of whether the wind directions were treated similarly. As mentioned in Chapter Two, the general practice on board a ship was to note their hourly information on the traverse board and then to transfer this information into the final paper logbook at a later stage, with the possibility of the transitional medium of a deck log.

In order to navigate the vessel, the officers must be aware of her current position at all times (as explained in Chapter Two), and therefore all factors affecting her previous progress (in direction and speed) must be taken into account when calculating this position (examples of the procedures in their entirety can be found in Norie, 1864, pp307-309). Important inclusions in such factors were wind, current, and compass variation.

Various texts set out procedures to correct the courses and bearings for compass variation and it is evident that they are corrected prior to their entry into the final logbook that was submitted to the Admiralty (May, 1973). Every course noted throughout the day was corrected for leeway (table 6.2). However, correction due to compass variation would either be applied to each course, or to the single “course made good” (see Norie’s *Epitome of Practical Navigation*

(1864), pp73-77) at the end of the calculation. The limited use of wind directions to correct only for leeway suggests that there would have been no need to correct them for compass variation in the same manner as the courses.

Given				**To Find**
Courses Steered	**Winds**	**Leeway**	**Variation**	**Courses corrected**
ENE	NW		1 ½ W	NE ½ E
WbS	NWbN	1		WSW
NWbN	NebN	1 ½	2 W	WNW ½ W
S	ESE	½	1 ¼ E	SbW ¾ W
NW	WSW	2	1 W	NWbN
SSW	SE	1 ¼	1 ¼ W	SSW
EbN	NbE	2 ½	0 ¾ E	SEbE ¾ E
W	NNW	¾	1 E	W ¼ N

Table 6.2: Table of variables considered when calculating ship’s position, from Norie (1864), p303. The wind direction is used to obtain the leeway correction, which, along with the (compass) variation, is applied to the course steered to obtain the corrected courses.

Despite the relative certainty from contemporary texts of which courses were true and which were magnetic, the same clarity was not evident for wind direction. Since the 1853 Brussels Conference, recorded wind directions of the subscribing nations have been true (as stated in the earlier quote from the *Marine Observer's Handbook*), but prior to this there seems to have been an underlying assumption that readers of navigational texts are already familiar with the practices in this context in which wind directions, as entered in the logbooks, were magnetic.

There is, however, further evidence to suggest that the wind directions given in the final logbook are probably magnetic. Horsburgh in his *Directions for Sailing* of 1809 states:

> *"In this directory, the direction of the wind is named from the point of the compass from which it blows. The course steered by a ship at any time, near land, or in the open sea, is by compass, or magnetic."*
>
> (p xiii)

This indicates that the accepted practice was that written wind directions were magnetic and not corrected for compass variation. Care must be taken however, in applying findings of one text to all sailing procedures, since there was no one definitive manual whose contents were irrefutable by the mariner, and verbal, practical traditions were still the preferred training method as opposed to formal colleges (see Chapter Four).

From this evidence it therefore seems almost certain, although not specified in the logbooks, that the wind directions given therein are magnetic. This is further supported by verification exercises undertaken as part of the CLIWOC project, where comparisons between the CLIWOC data and ICOADS (International Comprehensive Ocean-Atmosphere Data set) data were made in an area where magnetic variation was large.

The primary conclusion from these findings for the thesis is in the consideration of the errors in wind direction that may arise from magnetic variation. If, as discussed above, all wind directions contained in the logbooks are in fact magnetic, and do not represent the true wind direction, it is necessary to examine whether or not they should be homogenised with respect to true north prior to their use in any data analysis. Figure 6.2 shows the degree of variation at the beginning and end of the study period. In 1750 the variation in the geographical study area was between 0° in the south of the region, up to 20°W in the most northerly part, but by 1800 the polar wander in the Earth's magnetic field meant that a compass reading in the most northerly area (due west of the UK) could have been subject to a variation of up to 30°W. However, the proportion of data points this far north in the database is unlikely to contribute significantly to the total.

Furthermore, at this stage it is expected that wind directions will be categorised into the four points of the compass, in order to achieve a general picture of the wind fields (along with wind force), giving four 90° sectors. The degree of accuracy of the recording officer on board the ship also adds to this. For example, suppose a ship sailing from the UK to the west coast of North America in 1798 takes an observation of the wind direction when at 45°N and15°W, and records a wind direction of WNW by compass (292.5°). The variation at this point in time and space is approximately 26°W, therefore the wind is actually blowing from 318.5° (26° east of the observed direction – see figure 6.3). Under conditions where there was no variation, and the wind had indeed been blowing from 318.5°, the recording officer would have judged this to be a north-westerly wind, thereby reducing the error.

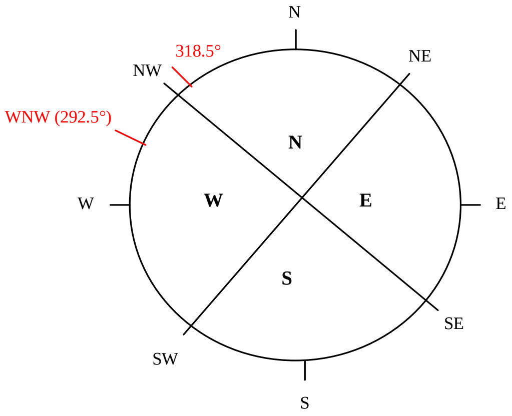


Figure 6.3: Example of effect of magnetic variation on observed wind direction

The degree of uncertainty in the data brought about by observational judgement, in addition to the expected small proportion of the data containing particularly high variation (ships sailing in the northern-most regions of the North Atlantic, in the latter part of the seventeenth century) and the intention to categorise the wind directions into 90° quadrants, form the basis for the decision not to correct the wind direction data for magnetic variation.

Following development of the understanding of the nature of the data, and the decisions made regarding treatment of them, it was possible to create a database of observations, and to then analyse that database.

CHAPTER SEVEN

CREATION OF THE DATABASE

INTRODUCTION

As outlined in the Introduction, abstraction of raw logbook data took place as part of the role of research assistant for the CLIWOC project. Due to the unavailability of the completed CLIWOC database (as was made available to the public in 2003) at the time of commencement of this North Atlantic-based project, it was necessary to create a unique database from the raw data. In order to do so, the data required modification and re-arrangement to create a database that was suitable for statistical analysis, and the extraction of climatological information. This modification process involved much time and resources, and therefore justifies further explanation in the context of the project as a whole.

MANIPULATION OF THE RAW DATA

The original Excel files into which the raw data were collated were unsuitable for immediate analysis as the information was of daily resolution and the variables required standardising and quantifying. Transitionary files were therefore created as a step towards a fully operational system.

The format of the data in the original files was such that the information first needed to be ‘transposed’ when cutting and pasting into the transitionary file, so that the different variables represented in the data (such as latitude, longitude, wind direction etc) constituted columns instead of rows. One workbook was used for each decade, thus creating five Excel files (1750-1800). A further, although supplementary, file was created for the 1820s, in order to provide the option of calibration of the data with data from the early Instrumental Period (generally agreed to begin around 1820). The first worksheet of each workbook was chosen to hold all the original information, and another worksheet created in which to perform manipulation of the data. The purpose of this was to ensure ease of reference to the original data in case of error or query at a later stage.

First of all it was necessary to ensure that all required information was present for all daily data (such as date, ship name, reference, zero meridian etc). Particular attention was given to the years 1750 to 52 as prior to the latter the anachronistic Julian calendar was still in force in Britain for which the New Year for some began on 25th March. Some recording officers would attempt to reduce confusion by stating both years during the January to March cross-over period, for example 12th February 1750 would be recorded as 12th February 1749/50. In September of the same year a decision was made to align the English (Julian) calendar with the European (Gregorian) calendar, which was ten days ahead and resulted in all English logbooks “losing” ten days. This meant a correction being applied to the date column for those data up to 19th September 1752.

Latitudes and longitudes, taken at noon each day, were originally entered in a format of DD:MMH where D= degrees, M = minutes and H = hemisphere (N/S or E/W), so for example 42 degrees, 51 minutes North would be 42:51N. However, in order to facilitate identification of potentially valuable data at a later stage, that is, data which fell into the desired geographical range, the degrees, minutes and hemisphere were required to be in separate cells. Therefore an Excel formula was written to extract the necessary component of the composite latitude or longitude and return the value to the correct column.

IDENTIFICATION OF GEOGRAPHICALLY RELEVANT DATA

One of the major issues of consideration was the identification from the CLIWOC files of those data that fell within the prescribed area of the North Atlantic. With regard to the desired geographical range it was felt most appropriate to split the North Atlantic region into grid squares sufficiently large to gather sufficient data, but not so large that climatic signals were lost or obscured. The area representing the centre of action of the Azores High was also avoided, as few vessels negotiated this area of uncertain and unreliable winds. Thus two ‘corridors’ of grid squares were created, one falling to the north of the Azores High, extending across the transatlantic region, and another to the south (figure 7.1). The exact latitudes and longitudes of the grid squares can be seen in table 7.1.

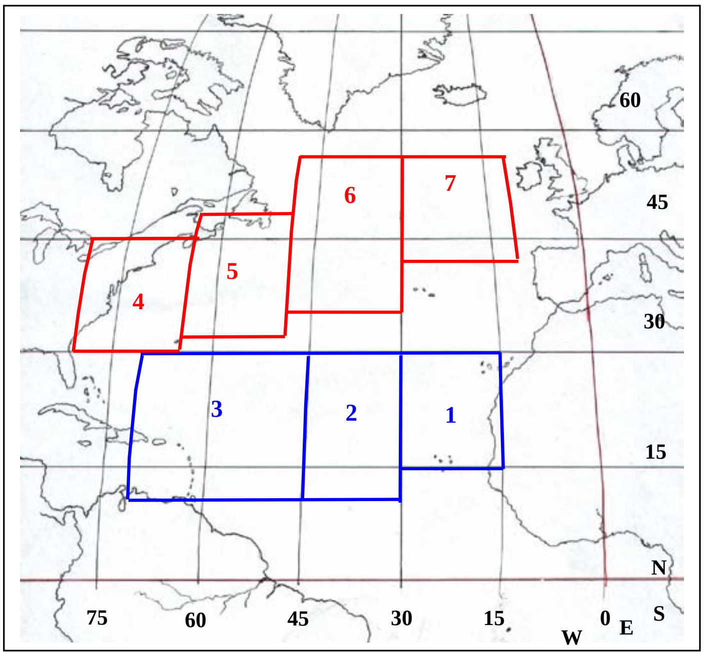


Figure 7.1: Map of geographical range of data.

	Sector	Latitude (North)		Longitude (West)	
		From	To	From	To
Southern Corridor	Sector 1	15	30	15	30
	Sector 2	10	30	30	45
	Sector 3	10	30	45	70
Northern Corridor	Sector 4	30	45	65	80
	Sector 5	32	50	50	65
	Sector 6	35	55	30	50
	Sector 7	40	55	10	30

Table 7.1: Latitudes and longitudes of grid squares for geographical range of data

Before the latitudes and longitudes of the individual data points could be interrogated with regard to whether they fell in range of any of the grid squares, one further amendment was required, and this was the correction for longitude. As

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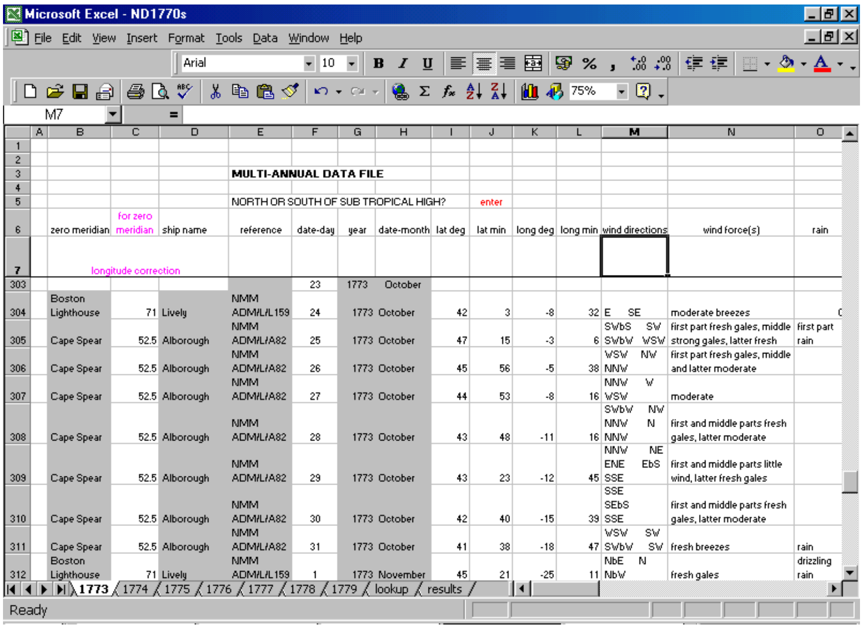
mentioned in Chapter Two, before the advent of the chronometer and in order to estimate reliably their longitude, mariners were inclined to fix their longitude with respect to a ‘zero meridian’ that was more often than not the last land that they had sighted. Therefore it was necessary to apply the correction corresponding to the zero meridian they had chosen (identified during the abstraction of the data) in order to obtain the equivalent to today’s values, relative to Greenwich. For the purposes of this project, a method contrary to that accepted today was employed for the longitude, that is, those values west of Greenwich were classified as positive, and those east of Greenwich were negative. The purpose of this was to avoid working with a large number of negative values for longitude, as the region of interest for this project spanned only those longitudes west of Greenwich, which would normally be negative values.

Following the estimation of the correct latitude and longitude, it was possible to identify those days of data which fell into range of the designated region of the North Atlantic. This was done through a simple formula, returning the phrase “in range” for the corresponding sector if the latitude and longitude fell within the borders of the square, or returning an “x” if not. For those days where the latitude and longitude were in range, the information was copied and pasted from the data in the first worksheet, to the second worksheet in which the manipulation and necessary transformations took place. An additional worksheet in the files was created in order to summarise the temporal coverage of data and depict the gaps in data over the decade. This information from each decade was later aggregated up into a calendar for the fifty-year period (see attached CD1).

It was also necessary to check the quality of the meteorological data of those days which met the requirements of geographical range, as some were found to have entries that would be unusable for the final database, such as those days with the sole wind direction or force recorded as “variable”. The final database yields vector indices which describe the wind fields in the North Atlantic and the absence of direction or magnitude for wind on these days therefore precluded them from inclusion in the final database. On the same basis, days where either wind direction or wind force were completely absent were also disregarded, as both were required for creation of a vector quantity. Furthermore, ambiguous or dubious recordings such as “NbS” (not a known or accepted wind direction) were unsuitable for use, though only if there were no other valid wind directions for the day would this render the entire day unusable for inclusion in the database.

CREATING THE FINAL DATABASE FILES

The Excel files derived from the transitionary files were collated to constitute the final database in the form of one file per decade, each containing ten annual worksheets (an example of which can be seen in figure 7.2) – separating the data into year-by-year format, but retaining daily resolution (these files are contained on the CD located at the back of this document). Information from the transitionary files was copied and pasted into these database files for days which held data meeting all the necessary criteria; geographic range, and no ambiguity with regard to data, or metadata.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1															
2															
3					MULTI-ANNUAL DATA FILE										
4															
5					NORTH OR SOUTH OF SUB TROPICAL HIGH?					enter					
6		zero meridian	for zero meridian	ship name	reference	date-day	year	date-month	lat deg	lat min	long deg	long min	wind directions	wind force(s)	rain
7			longitude correction												
303						23	1773	October							
304		Boston Lighthouse	71	Lively	NMM ADM/L/L159	24	1773	October	42	3	-8	32	E SE	moderate breezes	
305		Cape Spear	52.5	Alborough	NMM ADM/L/A82	25	1773	October	47	15	-3	6	SWbS SW SWbW WSW	first part fresh gales, middle strong gales, latter fresh	first part rain
306		Cape Spear	52.5	Alborough	NMM ADM/L/A82	26	1773	October	45	56	-5	38	WSW NW NNW	first part fresh gales, middle and latter moderate	
307		Cape Spear	52.5	Alborough	NMM ADM/L/A82	27	1773	October	44	53	-8	16	NNW W WSW	moderate	
308		Cape Spear	52.5	Alborough	NMM ADM/L/A82	28	1773	October	43	48	-11	16	SWbW NW NNW N NNW	first and middle parts fresh gales, latter moderate	
309		Cape Spear	52.5	Alborough	NMM ADM/L/A82	29	1773	October	43	23	-12	45	NNW NE ENE EbS SSE	first and middle parts little wind, latter fresh gales	
310		Cape Spear	52.5	Alborough	NMM ADM/L/A82	30	1773	October	42	40	-15	39	SSE SEbS SSE	first and middle parts fresh gales, latter moderate	
311		Cape Spear	52.5	Alborough	NMM ADM/L/A82	31	1773	October	41	38	-18	47	WSW SW SWbW SW	fresh breezes	rain
312		Boston Lighthouse	71	Lively	NMM ADM/L/L159	1	1773	November	45	21	-25	11	NbE N NbW	fresh gales	drizzling rain

Figure 7.2: Example of an Excel final database file.

Within the final database files, noon wind directions were then examined. Some marginal uncertainty surrounds the precise timing of these designated 'noon' observations. However, in the daily list of such entries the very last was taken on each occasion, it being reasonable to assume that to be the closest in time to midday. Differences, if any, were likely to have been of the order of a few hours or less.

In order to capture and best represent the weather experienced by the ships, the daily maximum wind force was used to represent the conditions of the day. These were extracted manually from the daily list of wind forces and entered into a separate column in the worksheet. Vertical Lookup tables and formulae were used to identify the corresponding Beaufort equivalent for these maximum wind forces already identified in Chapter Five (see table 5.5). Small sample sizes precluded any reliable use of mean or median values to summarise the daily state.

When the noon wind direction and maximum wind force for each day had been obtained, wind field indices could be created. These indices are of vector form, combining both direction and magnitude. Wind directions, originally on a 32-point compass, were reduced to a four-point cardinal system, as outlined in Chapter Six. Whilst there is an inevitable loss of statistical information in this process, a greater advantage is gained by rendering the data more suitable to statistical analysis (table 7.2). Thus each noon wind direction was allocated to a 90 degree quadrant (N, S, E, W) (see figure 6.3, Chapter Six), entering a “1” into the corresponding column for an occurrence of a wind direction falling into that quadrant (the other quadrants holding a value of “0”). Wind directions falling onto the boundary between two quadrants were shifted anticlockwise (based on an arbitrary decision), for example, NE was shifted into the N quadrant, SW became S etc. This process had to be undertaken manually, there being no easy means of computerising the process.

Wind forces were treated similarly to wind directions, the cell corresponding to the Beaufort equivalent of the daily maximum showing a value of “1”, the other cells remaining at zero.

Occurrences of rain, snow, fog and thunder were also recorded using the binary system, by way of a formula identifying non-zero values in the appropriate columns of meteorological data.

derived data block				wind direction				Beaufort Scale												wind vectors (frequency x force)			
conv. wind direction	trimmed wind direc	max. wind force	Beaufort equivalent	N	E	S	W	BF0	BF1	BF2	BF3	BF4	BF5	BF6	BF7	BF8	BF9	BF10	BF11	N	E	S	W
SW	SW	fresh gales	8	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	8	0
NbW	NbW	hard gales	10	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	10	0	0	0
SSE	SSE	moderate	4	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	4	0
SW	SW	fresh gales	8	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	8	0
SW	SW	fresh breezes	5	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	5	0

Table 7.2: Extract from final database, showing derived data and binary system to obtain wind vectors. Each row represents one day

Following the codification of wind direction and wind force, a wind type index was given for each day, comprising of the Beaufort number entered into the direction quadrant column. Therefore for example, if the noon wind direction was NWbW and the maximum wind force was fresh gales, the number 8 (the Beaufort equivalent for fresh gales) would be entered into the "W" quadrant. These numbers were totalled over each month to give a value for each quadrant for the month thereby providing a first estimate not only of the tendency of winds throughout the four quadrants but also of their vigour. However, since months with more days of data would have a heavier statistical weighting , it was necessary to weight equally all these monthly values so that a true representation of the wind vectors could be established. This was carried out by way of applying a correction factor to the indices, calculated by dividing the number of days in the month (e.g. Jan = 31, Nov = 30, Feb = 28/29 depending on whether the year was a leap year) by the number of days with data in that month. Each Directional Index was then multiplied by this factor for each month.

A worked example of this process is shown in table 7.3. Out of a possible 31 days of data, there were only 18 days of data, wind directions equally split between the southern and western quadrants (but of varying wind forces). This gave a correction factor of 1.72 (31/18) which could be applied to the vector values to simulate a full month's data. Table 7.3 shows that although there were 9 days with winds falling into the southern quadrant and 9 days in the western quadrant, the stronger winds fell into the latter, as demonstrated by the monthly vectors. Each vector for that month was then multiplied by the correction factor to give the weighted vectors (indices).

example: January 1763		
occurrences	N	0
	E	0
	S	9
	W	9
	days of data	18
	corr factor	1.72
occurrences	BF0	0
	BF1	0
	BF2	0
	BF3	0
	BF4	2
	BF5	1
	BF6	0
	BF7	0
	BF8	1
	BF9	10
	BF10	4
	BF11	0
vectors	N	0
	E	0
	S	68
	W	83
weighted vectors (indices)	N	0
	E	0
	S	117
	W	143

Table 7.3: example of weighting process to create indices

This exercise served a number of purposes; it created an operational and manageable database of the original information, but it also facilitated some important primary processing the data as a prelude to a more thorough analysis. By these means it is possible to meet Objectives 2-4 and Aim 4 of the project (see Introduction), having met Objective 1 and Aims 1-3, the results of which are presented in the following chapters.

CHAPTER EIGHT

RESULTS: data review and preliminary analysis

Following the completion of the database and the manipulation of the data into a consistent and comprehensible form, the important step can be made to undertake preliminary analysis of the data with a view to establishing the broad climatic characteristics of the North Atlantic over the second half of the eighteenth century. In this way, objectives 4 and 5 can be met and the value and versatility, as well as the limits, of the data can be demonstrated. The results can be expressed as statistical summaries that then lend themselves to climatic interpretation, completing thereby the step from raw, non-instrumental data into valuable scientific conclusions and numerical expressions.

COVERAGE OF THE DATA

These results are based on over 15,000 days of data extracted from the logbooks for the 50-year period. Substantial though this data set appears, there are gaps in the series that could not be filled under the time constraints of this project. This limitation notwithstanding, the overall conclusions are offered as reliable.

Spatial Distribution

The geographical coverage of the data shows a bias towards sector 7 (the grid square closest to the British Isles – see figure 8.1). This spatial bias is readily understandable since all vessels would have to pass through this area en route to or from the major ports of London, Portsmouth and Plymouth. Conversely, the fewest number of days data are found in sector 4 (adjacent to the east coast of North America) reflecting the fact that only a proportion of the vessels would be sailing to and from northern New England and a significant number of those leaving Britain would be heading towards the West Indies, or southwards to the Cape of Good Hope or the Mediterranean thereby avoiding this sector.

Table 8.1 shows the total number of days of data falling into each grid square decade by decade and in total. The full table of the coverage based on annual data availability is included in Appendix IV (table i). The inter-decadal variations are not random and, for example, the fall in numbers during the 1780s is the result of a period of peace, at which time governments even in those more belligerent days were less inclined to support large fleets at public expense. In this case the fall in available logbook numbers is marked and there are consequently almost 1000 days fewer than in the previous decade. It was not possible within the constraints of this exercise to redress the imbalances that resulted from such influences.

	S	S	S	N	N	N	N	
	sector 1	**sector 2**	**sector 3**	**sector 4**	**sector 5**	**sector 6**	**sector 7**	
Decade	**15-30Nx15-30W**	**10-30Nx30-45W**	**10-30Nx45-70W**	**30-45Nx65-80W**	**32-50Nx50-65W**	**35-55Nx30-50W**	**40-55Nx10-30W**	**total per decade**
1750s	275	327	394	206	465	598	1043	**3308**
1760s	372	410	296	276	306	540	953	**3153**
1770s	321	254	416	428	406	647	737	**3209**
1780s	302	288	294	130	212	448	611	**2285**
1790s	450	436	618	164	275	438	747	**3128**
Total	**1720**	**1715**	**2018**	**1204**	**1664**	**2671**	**4091**	**15083**

Table 8.1: Geographic data coverage; number of days of data falling into each grid square by decade.

The geographical coverage can also be represented in map form and this is depicted in figure 8.1, which shows the mean number of days per year in each sector, averaged over the whole 50-year period. Maps of the data coverage for each decade can be found in Appendix IV (maps i-v).

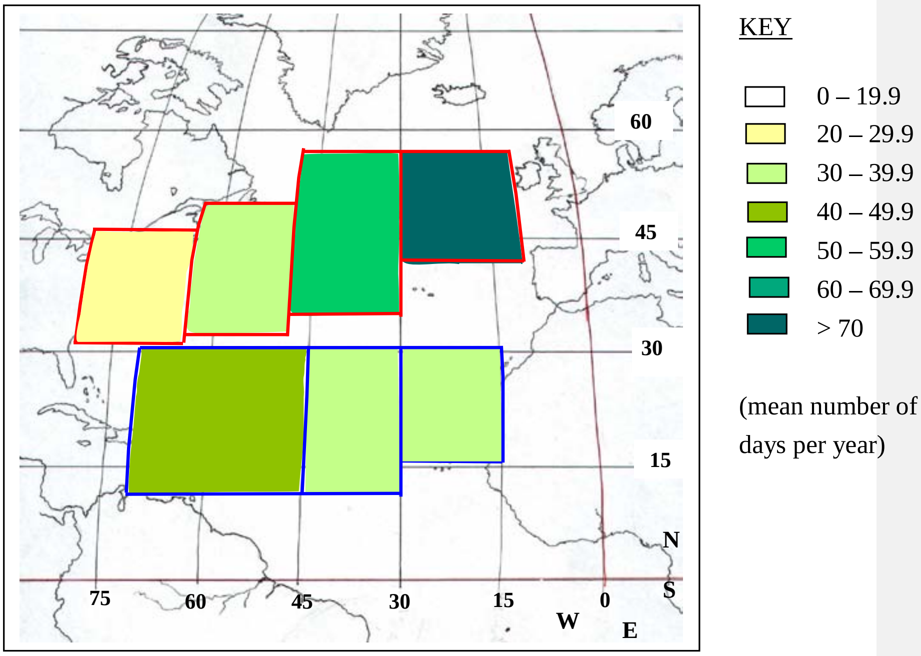


Figure 8.1: Map showing geographical data coverage in mean number of days of data per year, over the 50-year period

Sector (Hem)	Range	Mean number of days data per year
1 (S)	15 – 30N 15 – 30W	34.4
2 (S)	10 – 30N 30 – 45W	34.3
3 (S)	10 – 30N 45 – 70W	40.36
4 (N)	30 –45N 65 – 80W	24.08
5 (N)	32 – 50N 50 – 65W	33.28
6 (N)	35 – 55N 30 – 50W	53.42
7 (N)	40 – 55N 10 –30W	81.82

Table 8.2: Geographical data coverage – averaged over the 50-year period.

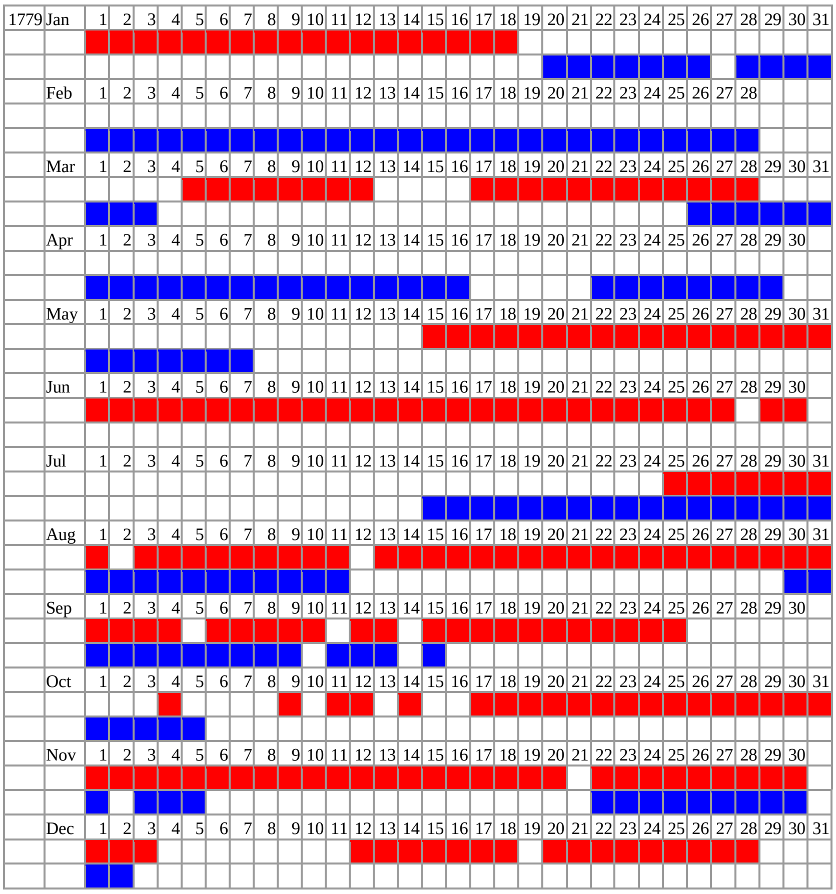
Temporal Coverage

Table 8.3 summarises the temporal distribution of the data but with the important distinction that the count is partitioned between those data from north of the Azores anticylone (and thus in sectors 4 to 7) and those for south of the anticyclone (sectors 1 to 3).

Yr	**N**	**S**	**Yr**	**N**	**S**	**Yr**	**N**	**S**	**Yr**	**N**	**S**	**Yr**	**N**	**S**
1750	234	127	1760	251	87	1770	237	135	1780	295	101	1790	97	63
1751	181	64	1761	170	129	1771	220	97	1781	207	118	1791	75	74
1752	175	97	1762	185	145	1772	162	136	1782	239	123	1792	106	97
1753	219	66	1763	192	158	1773	170	71	1783	190	125	1793	138	128
1754	193	76	1764	151	104	1774	175	68	1784	149	84	1794	132	233
1755	271	127	1765	194	90	1775	179	104	1785	51	52	1795	199	178
1756	277	67	1766	258	57	1776	317	49	1786	75	62	1796	209	195
1757	272	140	1767	210	115	1777	306	112	1787	73	79	1797	230	197
1758	278	110	1768	220	100	1778	240	71	1788	56	55	1798	259	160
1759	212	122	1769	244	93	1779	212	148	1789	66	85	1799	179	179

Table 8.3: Temporal coverage of data with annual resolution over the Northern and Southern Corridors

If the study area is coarsely resolved into two corridors, the north and the south, the maximum possible number of days of data for each year is 730 (365 for each corridor). It helpful to express the coverage in percentage as well as absolute terms and these figures are shown in table 8.4. The daily data coverage inventory from which table 8.3 has been compiled is too large to present in paper form but can be viewed as an Excel file on CD1, named "temporal coverage", as part of Appendix IV. A part of this spreadsheet is given in figure 8.2 to illustrate its layout.



1779	Jan	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
		🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥													
																					🟦	🟦	🟦	🟦	🟦	🟦	🟦		🟦	🟦	🟦	🟦
	Feb	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28			
		🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦			
	Mar	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
						🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥					🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥			
		🟦	🟦	🟦																							🟦	🟦	🟦	🟦	🟦	🟦
	Apr	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
		🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦						🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦		
	May	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
																🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
		🟦	🟦	🟦	🟦	🟦	🟦	🟦																								
	Jun	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
		🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥		🟥	🟥	
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	Aug	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
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	Dec	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
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		🟦	🟦																													

Figure 8.2: Example of calendar of temporal data coverage. The year shown is 1779. The red represents the Northern Corridor and the blue the Southern Corridor

It is against this backdrop of data coverage that the following discussions should be viewed. In general the data are plentiful and provide for a comprehensive coverage, but it is recognised that it is by no means complete and, even given the huge number of logbooks available in the archives, might not be for some considerable length of time, the effort involved in its abstraction being highly demanding.

INDICES DEVELOPED FROM THE DATA

As explained in Chapter Seven, directional wind indices were created from the data to give a vector quantity for each wind quadrant (N, S, E, W) for each month of the 50-year period in the ‘northern’ sectors. These values are the representation of the total frequency and force of the winds lying in that quadrant for that month, weighted to take account of the proportion of days of data for that month out of the total possible. In this form they provide a valuable’ first-hand’ estimation of the wind flow conditions across the study areas.

Due to the nature of the North Atlantic climate and the two dominant meteorological features of the Azores ‘high’ and Icelandic ‘low’, it is informative to examine those indices and derived statistics that most closely represent the dominant climatologies of the northern and southern corridors as defined in figure 8.3. For the northern corridor particular attention is given to the index of westerliness (WI), and for the southern corridor, an easterly index. For the purposes of this study, the latter may, more appropriately, be referred to as the trades index (TI), the north-easterly trade winds being the dominant airflow in this region and extending towards the Inter-Tropical Convergence Zone.

Yr	total	% of poss cov	% of total days	Yr	total	% of poss cov	% of total days	Yr	total	% of poss cov	% of total days	Yr	total	% of poss cov	% of total days	Yr	total	% of poss cov	% of total days
1750	361	49.5	2.4	1760	338	46	2.2	1770	372	51	2.5	1780	396	54	2.6	1790	160	22	1.1
1751	245	33.6	1.6	1761	299	41	2.0	1771	317	43.4	2.1	1781	325	45	2.2	1791	149	20	1.0
1752	272	37.2	1.8	1762	330	45	2.2	1772	298	40.7	2.0	1782	362	50	2.4	1792	203	28	1.3
1753	285	39	1.9	1763	350	48	2.3	1773	241	33	1.6	1783	315	43	2.1	1793	266	36	1.8
1754	269	36.8	1.8	1764	255	35	1.7	1774	243	33.3	1.6	1784	233	32	1..5	1794	365	50	2.4
1755	398	54.5	2.6	1765	284	39	1.9	1775	283	38.8	1.9	1785	103	14	0.7	1795	377	52	2.5
1756	344	47	2.3	1766	315	43	2.1	1776	366	50	2.4	1786	137	19	0.9	1796	404	55	2.7
1757	412	56.4	2.7	1767	325	45	2.2	1777	418	57.3	2.8	1787	152	21	1.0	1797	427	58	2.8
1758	388	53.2	2.6	1768	320	44	2.1	1778	311	42.6	2.1	1788	111	15	0.7	1798	419	57	2.8
1759	334	45.8	2.2	1769	337	46	2.2	1779	360	49.3	2.4	1789	151	21	1.0	1799	358	49	2.4

Table 8.4: Annual number of days of data in absolute and percentage counts. The first percentage column relates to the proportion of the possible coverage for that year, and the second column to the percentage of the total number of days for the 50 year period (15,083)

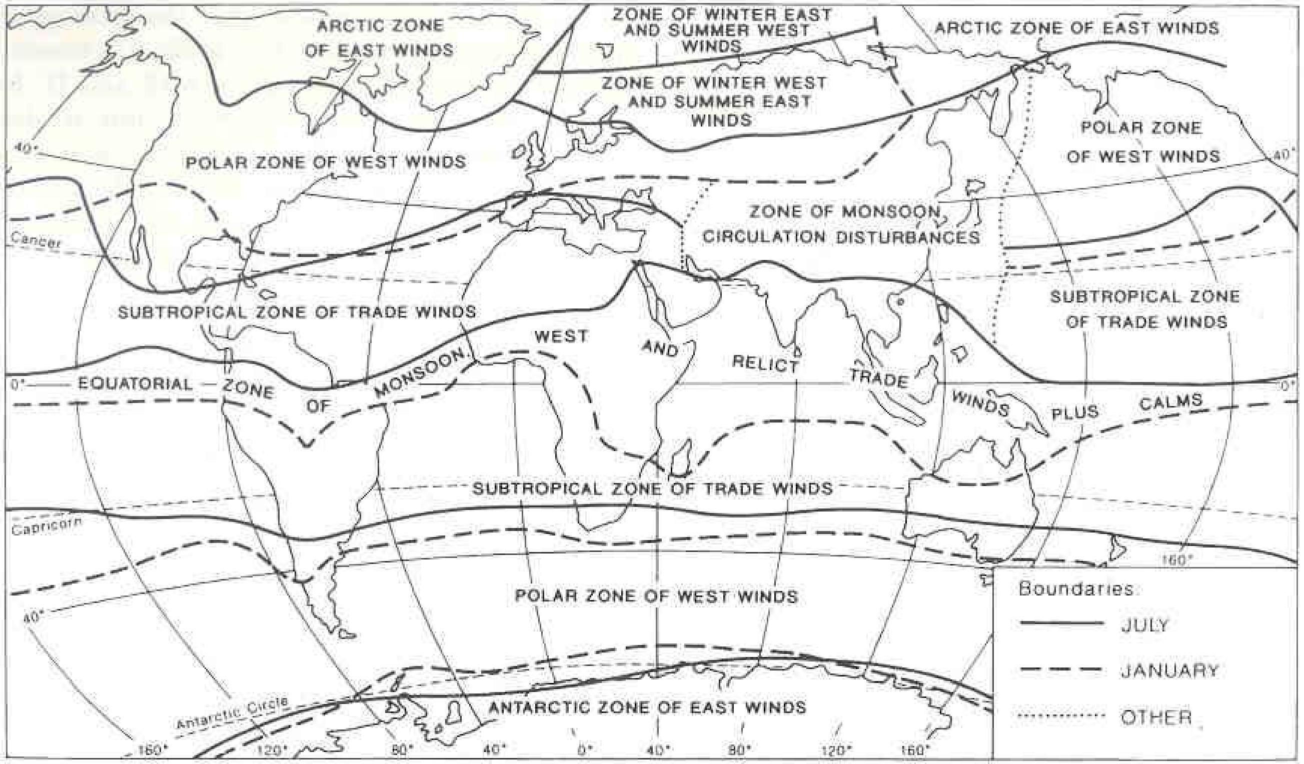


Figure 8.3: Global Wind Zones. Taken from Barry & Chorley (1998), after Okolowicz and Martyn (Martyn, 1992)

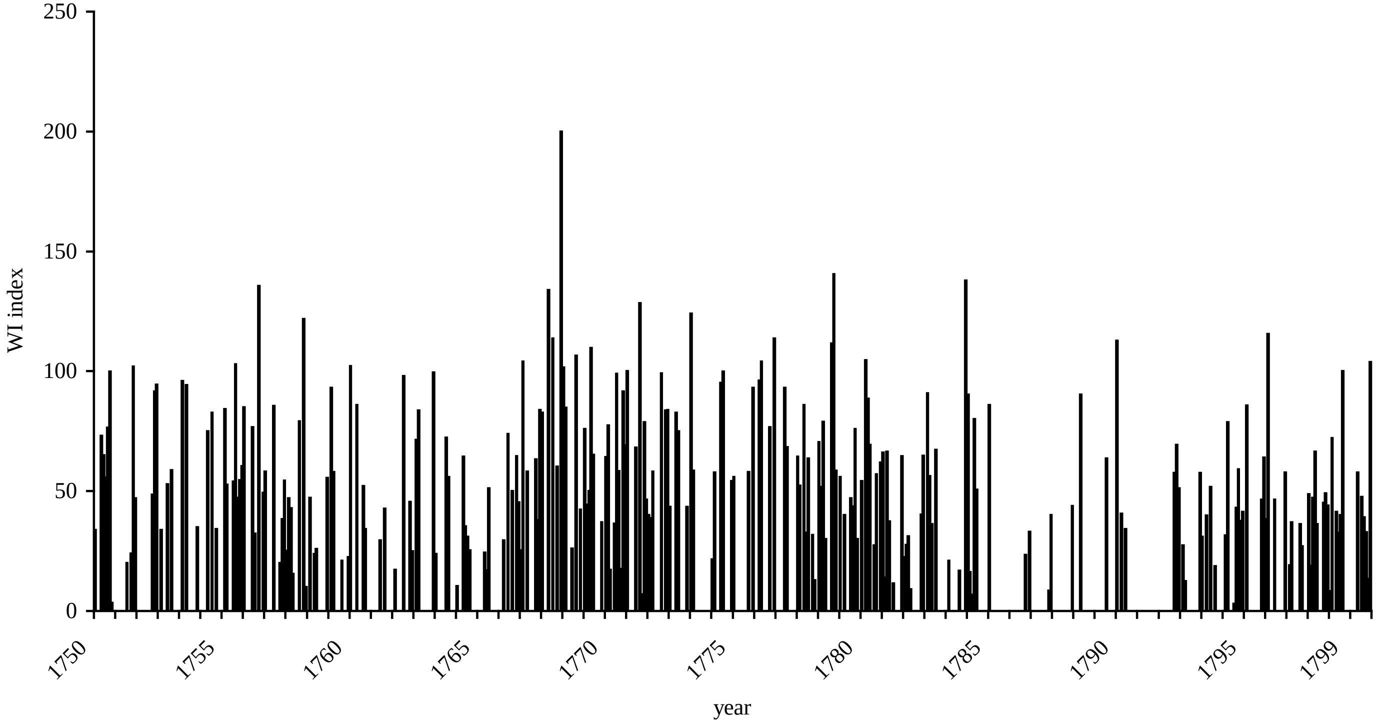


Figure 8.4a: Time series of the Westerliness Index (WI) the 50-year period 1750 to 1799

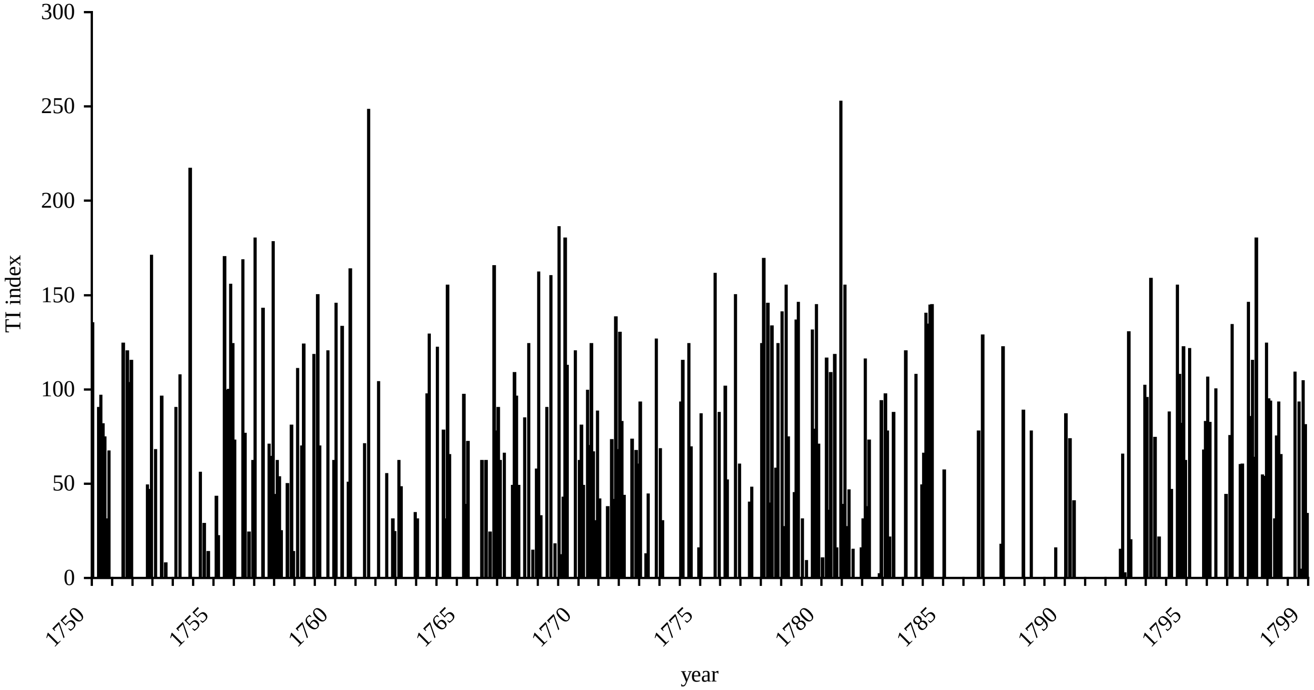


Figure 8.4b: Time series of the Trade Index (TI) the 50-year period 1750 to 1799.

The westerly and trade indices (1750-1799)

A graphical time series summary of these two indices are given in figures 8.4a and b in which the monthly figures are summarised (figures for every month of the period can be found in table i of Appendix V). The lack of continuity noted above in the data is evident in these two presentations but a picture of month-by-month variability is evident, although no clear trend is discernible. There is, however, a suggestion of increased westerliness during the period 1768 to 1775 but the picture is partially obscured by the gaps in the data series. There is a similar, but equally uncertain, impression of a decrease in westerliness accompanying the climatic disruptions that followed the huge volcanic eruptions of 1783 in Iceland. Such a finding would, however, accord with some of the reconstructions and models of the consequences of such events (Robock, 2000).

The trade index reveals no variations that correspond with those of the WI and the series has the appearance of being more random in character.

The time series charts shown in figures 8.4a and b also usefully depict the general characteristics of the two indices. The month-by-month variability is notable in both cases and is quantified by the standard deviations shown in table 8.5, in which other basic descriptive statistics are also summarised.

Whilst the degrees of variation (as expressed by the standard deviation) are similar for both WI and TI, it should be noted that the mean of the latter is much the greater of the two, reflecting the greater persistence and consistence in direction of the trade winds circulation when compared with the more variable circulations in the zones to the north of the Azores ‘high’. This numerical distinction is more broadly significant and reflects at the same time the effectiveness of this vector-based index of wind force and direction.

	N	Minimum	Maximum	Standard Deviation	Mean	Median
WI	483	2.64	255	41.05	65.96	57.93
TI	406	1.94	252.43	44.88	83.58	80.69

Table 8.5: Descriptive statistics of WI and TI for 50 year period

Of similar interest is the annual pattern of the two indices expressed as their monthly means over the study period. Figure 8.5 shows that the TI is best developed during the summer months and at a time when the Azores ‘high’ might itself be expected to be close to its maximum development. The WI shows that the degree of westerliness to the north of the Azores ‘high’ has a less marked seasonal rhythm although there is a suggestion of a tendency to higher values in winter – as might be anticipated given the greater degree of ‘organisation’ of the weather systems at that time of year. This point is made more convincingly however in table 8.6, in which the seasonal summaries are presented and in which the winter peak for WI and the summer peak for TI are more obvious. Such results are of interest in themselves as a means of expressing and summarising the logbook data, but they serve also to suggest, through their correspondence with climatological theory, that the data and the means by which they are processed yield a faithful record of the conditions at the time.

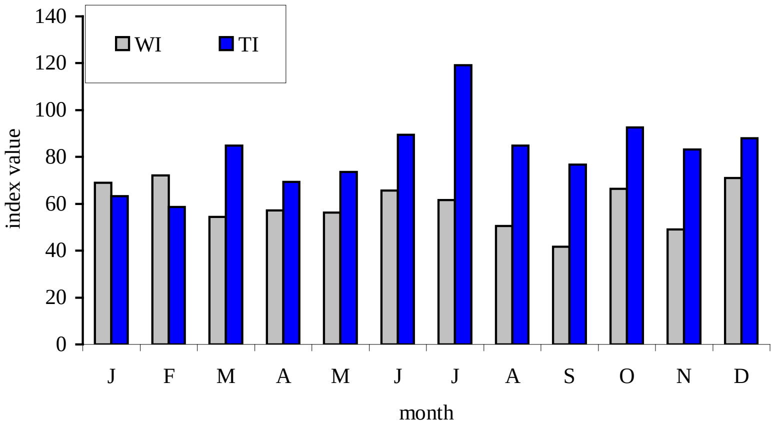


Figure 8.5. Monthly mean TI and WI indices

	winter	**Spring**	**Summer**	**autumn**
WI	72.91	**56.33**	**58.19**	**52.78**
TI	**72.95**	**75.56**	97.78	**84.45**

Table 8.6. Seasonal summary of TI and WI indices

Derived indices for the northern ‘corridor’

Whilst the W index most faithfully summarises conditions in the ‘westerlies’ latitudes north of the Azores, other directions are far from absent and variability in direction is a feature of the circulations in these regions. Figure 8.6 reveals, as might be anticipated, that westerlies dominate for much of the time although a weakening of this circulation is noted for September (perhaps linked to a maximum in frequency of blocking high pressure systems in the extreme North Atlantic (Tucker & Barry, 1984)). Easterlies are the least frequent direction at all times of the year but demonstrates the most marked seasonal rhythm with maxima in winter declining to summer minima. Southerlies and northerlies occupy, with the exception of September, a more median position in terms of vector strength.

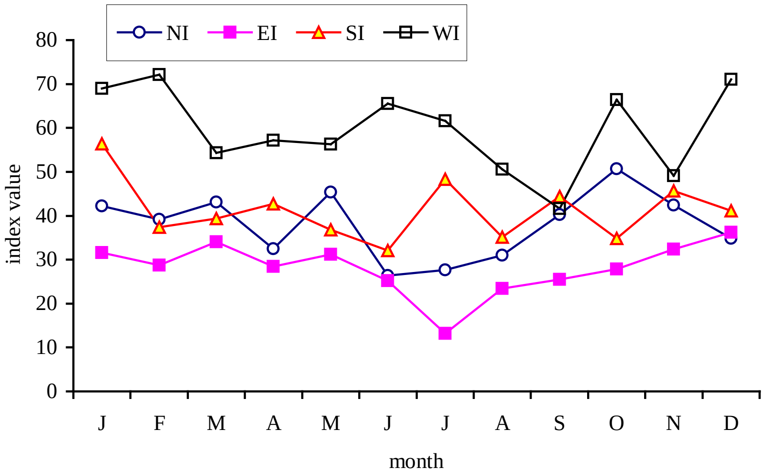


Figure 8.6. Monthly mean indices for westerliness (WI), easterliness (EI), southerliness (SI) and northerliness (NI).

Gale days and frequencies.

Not only could directional data be abstracted from the logbooks but it was also possible to provide a series for 'gale days'. Indeed, it is probable that only logbooks could provide such data for oceanic areas and it is therefore important to review the properties of this data series. Days were identified where the maximum wind force recorded was of Beaufort equivalent 8 or above. This is a rather conservative estimate but, given the issues raised earlier focussing on the uncertainty that surrounds the precise definition of the archaic term 'fresh gale', and also the overestimation of gale days within the work of Dawson *et al* (2002) (reviewed in Chapter One), it was considered prudent to err on the side of caution when estimating gale frequencies. By this means the number of gale days could be counted for each month. However, data were not always available for every day and the final monthly estimates are expressed as proportions of gale days over the number of days for which data are available. This weighting procedure eliminates any bias in taking merely the total count of gale days for incomplete months. These data were based only on observations from ships to the north of the Azores 'high' and within the realm of the mid-latitude frontal cyclones.

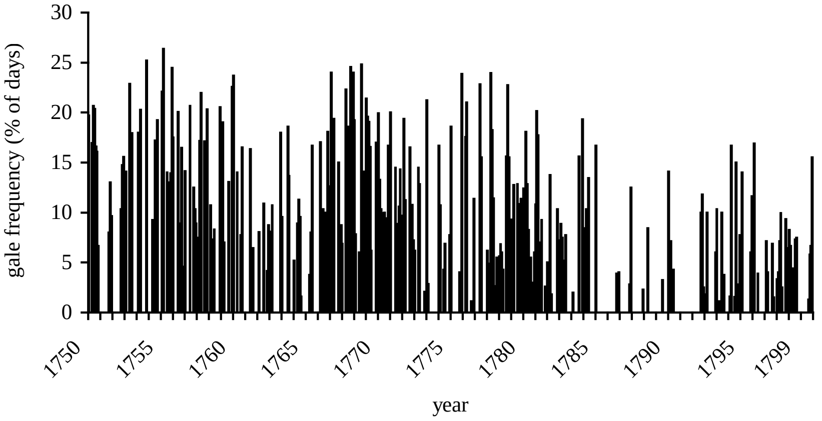


Figure 8.7: time series of monthly gale frequencies.

Figure 8.7 shows the time series for these data. Although the gaps noted above are evident, there is a suggestion of decreasing gale frequency during the period of study. This finding would support the work of Ward (2006) who used logbook data to study the far North Atlantic climate (1760-1799), and who found that despite an overall dominance of gales (force 8 and above) during the period, a decline from around the 1780s was evident.

The periods centred on 1755 and 1770 appear to have been particularly stormy. Although it might not, within the context of this thesis, be appropriate to provide a comprehensive explanation for such relatively low-frequency fluctuations it is again important to note how logbook data provide a new and largely unambiguous climatic signal providing the substance for further research. Further attention may also be profitably be directed towards a comparison with modern-day wind frequencies from the ICOADS dataset, however it was not practical to secure the necessary data in the required format and resolution to do so within the remit of this thesis.

Table 8.7 summarises the statistics of this series, and the average proportion of gale days per month is 11.15 but, and in common with the wind direction vector indices, there is significant inter-monthly variation and a standard deviation of 6.46.

Mean	11.15
Standard deviation	6.46
Maximum	26.35
Minimum	0.0

Table 8.7. Statistics for the gale series of logbook data

Also of interest is the distribution of gales through the year as witnessed by the monthly means (figure 8.8). Again, it should be noted that logbook data are sensitive to the anticipated climatic signal, which in this case is one of summer minima but winter maxima; very much in accordance with climatological theory in which the steeper tropics – pole energy/temperature gradient of the winter season generates more active and more abundant cyclone formation.

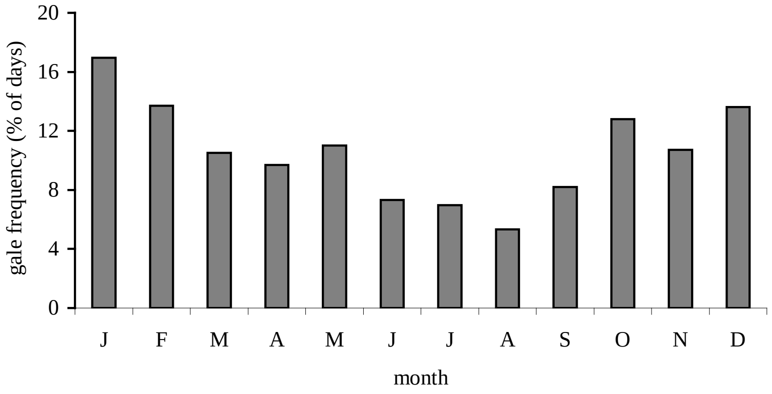


Figure 8.8. monthly distribution of gale days.

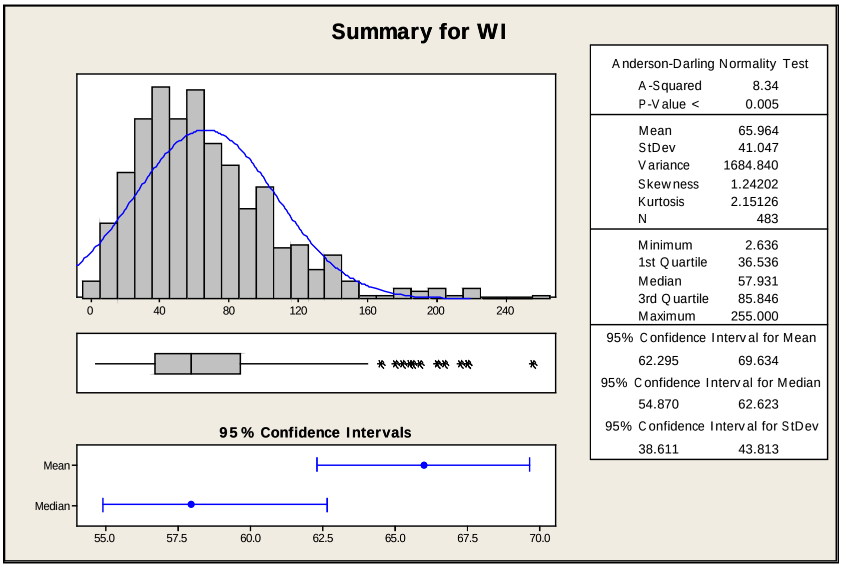
Data distributional properties

Closer inspection of the above indices revealed, however, a significant degree of positive skewness in their distributions. Anderson Darling normality tests of both the WI and the TI confirmed this suggestion of significant non-normality (table 8.8) at the 0.05 level. The WI is more severely skewed with a value of 1.24, and an Anderson-Darling (AD) statistic of 8.34, but the TI better fits the normal distribution with both a lower degree of skewness. In order to normalise the data and render them in a form more suitable for subsequent statistical analysis, the usual procedure of transforming the data by expressing them in their logarithmic (logs to the base 10 in this case) form was adopted. However in neither case was an acceptable result achieved, indeed the positive skewness was replaced by a similar degree of negative skewness (table 8.8, further summary of this process is also given in figures i-vi, Appendix V).

A further attempt to normalise the data was made using Johnson Transformations. This method was more successful, creating transformed indices that were acceptably normal, with p-values of 0.982 (WI) and 0.632 (TI) – see table 8.8. A full description of the Johnson Transformation procedures can be found in Appendix V (figures vii and viii) while figures 8.9a and b graphically summarise the distributional qualities of the two indices.

	Unaltered		Log_{10} transformation		Johnson transformation	
	p-value	AD statistic	p-value	AD statistic	p-value	AD statistic
WI	<0.005	8.343	<0.005	4.466	0.982	0.132
TI	<0.005	1.477	<0.005	8.617	0.632	0.283

Table 8.8: Normality testing for unaltered data and transformed data



Anderson-Darling Normality Test

A-Squared	8.34
P-Value <	0.005
Mean	65.964
StDev	41.047
Variance	1684.840
Skewness	1.24202
Kurtosis	2.15126
N	483
Minimum	2.636
1st Quartile	36.536
Median	57.931
3rd Quartile	85.846
Maximum	255.000

95% Confidence Interval for Mean

62.295 69.634

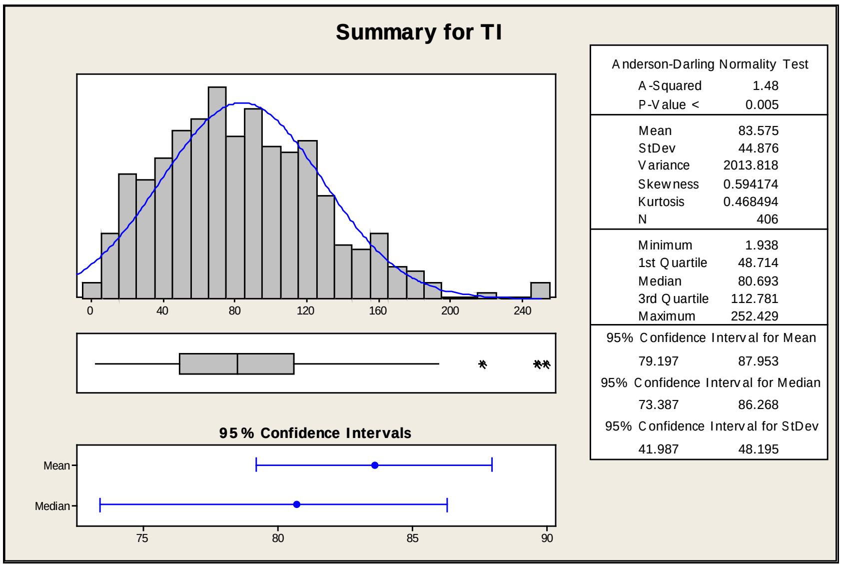
95% Confidence Interval for Median

54.870 62.623

95% Confidence Interval for StDev

38.611 43.813

Figure 8.9a: Statistical summary for WI for 50 year period



Anderson-Darling Normality Test

A-Squared	1.48
P-Value <	0.005
Mean	83.575
StDev	44.876
Variance	2013.818
Skewness	0.594174
Kurtosis	0.468494
N	406
Minimum	1.938
1st Quartile	48.714
Median	80.693
3rd Quartile	112.781
Maximum	252.429

95% Confidence Interval for Mean

79.197 87.953

95% Confidence Interval for Median

73.387 86.268

95% Confidence Interval for StDev

41.987 48.195

Figure 8.9b: Statistical summary for TI for 50 year period

The series of monthly gale frequencies also revealed a significant degree of skewness and the results of the Anderson-Darling test are summarised in table 8.9. This too could be corrected by Johnson transformations.

	AD statistic	p-value	Mean	SD	skewness
Gale Days	1.985	<0.005	11.15	6.46	0.301

Table 8.9: Summary of statistical characteristics for gale day series

CONCLUSION

The preliminary statistical analysis and summary of the derived data for wind vectors and for the series of gale days are interesting in two respects. Firstly, the general agreement of the distributions and the nature of the statistical properties with climatological theory provides strong support to the suggestion that logbook data are reliable and provide a clear climatic signal when appropriately treated. Secondly, the data also show that it is possible to identify the climatic characteristics and variability during the study period. The gale series, for example, indicates that research could be profitably directed towards explaining why the frequency of gales falls so sharply towards the end of the eighteenth century and why there are two peaks of activity, those around 1755 and 1770.

In a similar fashion the wind vector data identify annual patterns and also help to provide a series showing how the circulations varied from month-to-month. In this instance the two series (WI and TI) appear to have a more random nature, but even this might be of importance in defining the climate of the period. Clearly, however, it is important to relate these findings to other, independently derived climatic parameters to examine the degree of possible association between them. This is the task of the next chapter.

CHAPTER NINE

CLIMATOLOGICAL ASPECTS OF THE LOGBOOK DATASET: interpretations and conjectures

The first stage of data analysis and general interpretation having been completed, the second stage may now be undertaken, building on the findings of the first stage offered in Chapter Eight. It has been demonstrated that despite a number of gaps in the monthly data, the evidence from the preliminary analysis suggests that not only are the derived indices sensitive to climatological influences but that the logbook data generally can also be regarded as reliable and valuable in climatological studies. It is on the basis of this confidence in the dataset that the following interpretations are offered. Care has been taken thus far to maintain the integrity of the data abstracted from the logbooks by retaining its independence to any other data, and also by conducting the processing, manipulation and preliminary analysis in isolation. Opportunity can now be taken to introduce independently derived and authoritative datasets. The introduction of these additional datasets serves two purposes:

1: they allow for further testing of the logbook data with which certain consistencies of behaviour might be expected on *a priori* climatological grounds.

2: they enhance the utility of the logbook data in providing indications of possible linkages in the climatological system.

These independently-derived series were carefully selected with respect to covering the period of study and, equally importantly, to offer data at the same –

monthly – scale of temporal resolution. One of these measures, the North Atlantic Oscillation Index (Luterbacher *et al*, 1999), has already been reviewed in Chapter One and need not be discussed further here other than to note the use of the grid-based index for the purposes of similar spatial approach to the logbook data, and also to recognise the importance of its measure of general airflow across the North Atlantic. The other sources are introduced below:

Central England Temperature (CET) series:

The CET is obtained from the British Atmospheric Data Centre (BADC), run by the National Environmental Research Council (NERC). The series was developed by Professor Gordon Manley (Manley, 1974), and extends back to 1659 at monthly resolution, although the data prior to 1721 are considered to be less reliable than those of a later date (Jones & Hulme, 1997c). Data are also available on a daily basis back to 1772 and in the case of both series, represent the average of the daily maximum and minimum temperatures over a number of stations in England. The original definition of these stations was three locations; one in the north (Lancashire), one at the western extremity of the south Midlands, and one at the east. Recent developments in these locations have seen the use of Rothamsted, Malvern, and an average of Ringway (Manchester) and Squires Gate (Blackpool). Further changes to the process of recording the series lie with the necessary correction to measured temperatures since 1980 to allow for urban warming, however, discrepancy may still exist in earlier temperatures in the series.

England and Wales Precipitation (EWP) series:

Also obtained from the BADC, unfortunately the EWP was only available from 1766 onwards and therefore does not cover the entirety of the study period. The series was developed by the Climatic Research Unit, Norwich (CRU) and uses seven stations in each of five regions of England (north-east, north-west, central, south-west and south-east), which were defined from a principle component analysis of over sixty long homogenous precipitation series covering the British Isles between 1861 and 1970 (Jones, Conway & Briffa, 1997b). The predecessor of this series was one developed in 1931, and extended back to 1727. Despite being generally accepted as an 'official' UK Met Office precipitation series, the series was based on data which lacked homogenous coverage as there were no rain gauges in Wales until the late eighteenth century and few in western and northern England until about 1840. This was reviewed in the 1980s and eventually replaced by the series developed by the CRU.

Sunspot numbers:

The sunspot record was obtained from the Royal Observatory of Belgium (SIDC (Solar Influences Data Analysis Center), RWC Belgium, World Data Center for the Sunspot Index; Royal Observatory of Belgium). The work of SIDC continues that begun by firstly the Swiss astronomer Johann Rudolph Wolf, and then the Zurich Observatory, in the calculation of the sunspot number, the oldest solar index measuring the solar activity. The calculation of the sunspot number is based upon a formula involving the number of observed sunspots, the number of observed sunspot groups, and a quality factor to take into account the variability between different observers and their interpretation, the location of the observer, the telescope used and the stability of the Earth’s atmosphere in the vicinity of the observing site. This quality factor uses a weighted average of measurements across several observatories.

The monthly sunspot data used for the purposes of this thesis is that of the Provisional International Sunspot Number. The data include sunspot number and monthly smoothed sunspot numbers from 1750 and they are subject to various stages of calculation, the details of which can be viewed at http://sidc.oma.be/aboutSIDC/paper.php.

STATISTICAL ANALYSIS

Correlation analysis was completed based on the period 1766-1799, this being the period when all indices were present. In order to achieve meaningful correlation, both the Central England Temperature series (CET) and the England and Wales Precipitation series (EWP) were re-calculated based on the departure from a 30-year mean for each month, in order to give an anomaly rather than absolute values. The selection of the 30 year period for the mean was on a purely arbitrary basis, however, in the case of the EWP it was 1767-1798, this being the first 30 years of the series. For the CET the period 1761-1790 was chosen. The use of an anomaly has the important consequence of de-seasonalising the signal, particularly for the CET series. In a similar fashion, the Sunspot data used a running mean number as well as absolute values.

It should also be recalled from the preceding chapter that many of the logbook variables required transformation to resolve problems of data skewness. In the following correlation analyses attention will be drawn to both sets of logbook variables. These are summarised in table 9.1. Correlation analysis was used to investigate the statistical associations between the variables, thereby providing a basis on which a climatological interpretation of the results could be gauged. Because of the markedly seasonal character of the mid-latitude climates that characterise the study region, the preliminary and annual correlation analysis was followed by a season-based partitioning of the data set using traditional seasons of spring (M, A, M), summer (J, J, A), autumn (S, O, N) and winter (D, J, F).

In all cases three categories of correlation need to be recognised:

1) spurious correlations between complementary variables, these being the four cardinal wind directions. It must be the case that as one increases, the other decreases, thereby creating inevitable degrees of association.

2) established correlations – those that exist between CET, NAOI and EWP are well known and whilst some attention will be drawn to them, they do not fall into the category of ‘original’ findings

‘new’ correlations – those between pairs of logbook data variables and between logbook data and the various independent series.

Of the above three, only the latter requires close attention in the pages that follow.

Derived indices	**Johnson transformed derived indices**	**Independent indices**
N_N	**J N_N**	**NAOI**
N_E	**J N_E**	**CET**
N_S	**J N_S**	**CET anomaly**
N_W	**J N_W**	**EWP**
TI	**J TI**	**EWP anomaly**
GD	**J GD**	**Sunspot number**
		Sunspot (running mean)

Table 9.1: List of variables for correlation

ANNUAL CORRELATIONS

Table 9.2 shows the correlation matrix for the annual analysis. The first point to note is that the use of the transformed indices rather than the original derived data made little difference to the value of the correlation coefficients; for example the correlation coefficient between N_N and CET was 0.197, and between J N_N and CET 0.190. Such differences were commonplace in the correlation matrix and it was therefore decided that for the ease of interpretation the original indices would be used in the following statistical analyses.

	N_N	N_E	N_S	N_W	TI	NAOI	CET	CET anom	EWP	EWP anom	SSpot	SSpot _r_m	gale days	J N_N	J N_E	J N_S	J N_W	J TI
N_N	1.000																	
N_E	-0.015	1.000																
N_S	-0.252	-0.063	1.000															
N_W	-0.226	-0.270	-0.219	1.000														
TI	-0.148	-0.093	0.160	0.014	1.000													
NAOI	-0.038	-0.052	-0.040	-0.075	0.003	1.000												
CET	**-0.197**	**-0.226**	-0.061	-0.125	0.156	**0.419**	1.000											
CET anom	-0.085	0.001	0.106	-0.048	0.025	**0.418**	0.274	1.000										
EWP	0.043	-0.083	-0.127	0.145	0.025	0.137	**0.192**	-0.096	1.000									
EWP anom	0.044	-0.025	-0.144	**0.190**	-0.028	0.079	0.039	-0.118	0.927	1.000								
SSpot	0.051	0.008	-0.033	0.050	-0.005	0.125	0.060	**0.192**	-0.077	-0.070	1.000							
SSpot_r_m	0.046	-0.011	0.000	0.040	0.005	0.041	0.052	0.175	-0.121	-0.107	0.933	1.000						
gale days	**0.205**	**0.194**	**0.269**	**0.509**	-0.046	-0.183	**-0.431**	-0.037	0.046	0.110	0.106	0.124	1.000					
J N_N	0.967	0.010	-0.242	-0.208	-0.118	-0.020	**-0.190**	-0.096	0.043	0.028	0.058	0.048	**0.218**	1.000				
J N_E	0.041	0.946	-0.088	-0.270	-0.086	-0.060	**-0.257**	-0.005	-0.145	-0.068	-0.015	-0.034	0.171	0.058	1.000			
J N_S	-0.255	-0.074	0.981	-0.209	0.162	-0.061	-0.047	0.092	-0.156	-0.165	-0.034	0.002	**0.250**	-0.247	-0.090	1.000		
J N_W	-0.230	-0.268	-0.237	0.970	0.011	-0.060	-0.109	-0.056	0.140	0.173	0.054	0.044	**0.463**	-0.207	-0.264	-0.221	1.000	
J TI	-0.150	-0.099	0.153	0.026	0.994	-0.002	0.143	0.028	0.016	-0.037	-0.023	-0.012	-0.040	-0.122	-0.091	0.156	0.021	1

Table 9.2: Annual correlations; R crit (0.01) = 0.190

Green entries refer to ‘complementary’ correlations (see above), while those in bold red are significant at the 0.01 level.

Annual correlations include associations between a variety of variables. Most interesting are those between the logbook data and the so-called independent data sets. The CET data reveals an important correlation with the index of northerliness (N) of r = -0.197. This partly reflects the cooling effect of northerlies in the CET and is the first of a number of such climatologically consistent correlations that tend to support the reliability of logbook data. The CET data also correlate with index of easterliness (E) with r = -0.226. The same argument concerning wind flow with temperature might apply here. However, it should be noted that the CETanom series does not, in either case (N or E), offer a similar degree of correlation and the association may be partly spurious perhaps being a consequence of ‘phasing’ of the seasonal patterns of easterlies and northerlies. For example, a higher frequency of northerlies in winter would provide a negative correlation because winters are inherently cooler than other seasons.

The EWPanom data correlate with westerly index, r = 0.190. This is not unexpected, and it might be anticipated that precipitation would be higher in westerly conditions with moisture imported from the Atlantic in the prevailing air maritime masses. It is nevertheless an important correlation because it demonstrates that the logbook data are sensitive to other climatological factors; in this case those that promote higher rainfall over the British Isles. Gale days correlate with all directional wind vectors, again this is not unexpected as the latter include an element for wind force. Nevertheless the much higher degree of association with the westerly index (W) suggests that gales are particularly more abundant when westerlies are well established. The negative correlation (r = -0.431) between gale days and CET is, however, likely to be a function of lower gales frequencies in summer (when it is warmer) and higher frequencies in winter (when it is cooler), and there is no corresponding correlation between gale days and CET anomaly at annual resolution. This annual rhythm to the distribution of gales has been demonstrated in figure 8.8.

There is also a correlation between the CET and sun spot activity, r = 0.192. This association, although not derived from logbook data, is an interesting finding that suggests higher temperatures when sun spot activity is greater. Such a signal may not be altogether without some explanation in this age before anthropogenic greenhouse gases came firmly into play as a forcing factor and solar forcing may have been relatively more important. Although sunspots are areas of cooler temperature on the sun's surface, they are surrounded by areas of bright activity, known as faculae (Barry & Chorley, 1998), and the net result is an increase in solar output with an increase in number of sunspots. The suggested relationship between sunspot number and CET would support the study made by Mende and Stellmacher (2000), who noted a parallelism between the solar activity and hemispheric temperatures and suggested that the Sun was a possible candidate for a low-frequency variability source in temperatures. The relationship between solar variability and climate is still not fully understood but the presence of a signal in data that pre-exists the accepted period of anthropogenic influence invites further study in this area.

SEASONAL CORRELATIONS

The complete correlation matrices are not included here but can be seen in Appendix V (tables ii-v), however, significant correlations are given in tables 9.4-

9.7. The seasons will be reviewed under separate headings but some preliminary and more general conclusions can be offered at this stage.

A number of the significant correlations based on annually aggregated data are partly explicable by seasonal variations in the data sets. By disaggregating the data into the four seasons this bias is eliminated and provides also the possibility of establishing how relationships varied through the course of the year. One of the most well-known studies adopting a similar approach are those by Jones and Hulme (1997c) in which they correlate seasonal CET data against the frequency of Lamb's weather types (Lamb, 1950). This study is helpful because there is a broad correspondence between four of Lamb's types (E, W, S and N) and the four wind vector categories used in the current study. Table 9.3 summarises both sets of findings and provides a useful starting point for the consideration of the seasonal correlations. Important differences need however to be noted: the Jones and Hulme results are based on twentieth century data whereas the current data are drawn from the second half of the eighteenth. At the same time the latter's geographic focus is the North Atlantic open water areas, while Jones and Hulme were concerned with airflow over the British Isles.

	A	**C**	**N**	**E**	**S**	**W**	**NW**	**NAO**
Winter	-0.26	-0.06	-0.57 (-0.25)	-0.63 (0.25)	0.28 (-0.1)	0.71 (0.00)	0.06	0.67
Spring	0.22	-0.35	-0.43 (-0.04)	-0.18 (-0.14)	0.34 (0.13)	0.31 (-0.03)	0.01	0.45
Summer	0.62	-0.44	-0.35 (0.14)	0.19 (0.06)	0.19 (0.12)	-0.30 (-0.29)	-0.10	0.14
Autumn	-0.05	-0.03	-0.64 (0.01)	-0.12 (-0.16)	0.46 (-0.03)	0.16 (-0.04)	-0.08	0.38
Annual	0.16	-0.22	-0.44 (-0.19)	-0.25 (-0.23)	0.25 (-0.06)	0.24 (-0.13)	-0.07	0.46 (0.42)

Table 9.3: Seasonal correlations between the Central England Temperature and totals of the seven basic Lamb weather types & NAO (Jones & Hulme, 1997c). Included (in brackets) are the corresponding correlations from logbook data.

Table 9.3 reveals, despite the caveats stated above, a degree of agreement between the correlations found by Jones and Hulme and those of the current author. Most notable is the tendency, well understood in climatological terms, for westerlies to promote coolness in summer although, interestingly, the counterpart of winter warming is absent in the logbook data. This signal is, of course, obscured in the annual record where the two factors cancel each other out. The absence of a winter warming effect may, although one can only speculate, reflect a generally cooler North Atlantic with perhaps more frequent southward extension of Arctic waters, thereby minimising this influence that is so much more prominent today. It should, however, also be noted the easterly winter cooling is another factor less in evidence from the logbook data but, again, easterlies in the open Atlantic sector may not be simultaneously evident across the British Isles.

It is also interesting to note from the seasonal correlation tables that winter reveals relatively few significant associations. Yet this is the season in which the northern hemisphere’s climate is widely held to be more ‘organised’ in response to the greater energy gradient between the tropical and polar latitudes. Spring and summer, popularly regarded as being less structured as the driving force of the cross-latitudinal energy gradient decreases, in this case indicate more frequent correlations.

How far this temporal pattern of associations is a feature of the study period alone could not be determined. Regrettably, it was not possible to explore the full range of contrasts between late eighteenth and twentieth century climatic behaviour as comparable data sets for the two periods could not be easily derived within the scope of this project. But such studies might offer a future topic of investigation.

Winter

The only significant correlation beyond those cited above in table 9.3 is that between the degree of westerliness and the frequency of gales (r = 0.519, see table 9.4). Evidently, more zonal flows in the North Atlantic region are associated with greater cyclonicity and consequent storm activity. That this should be so marked in winter is not surprising given the dynamics of the atmosphere at that time of year (noted above). Other correlations for the season that are significant are listed in table 9.4 and reflect well-known associations between the independently-derived data sets, especially those of the NAO, CET and EWP. The linkages between the NAO and temperatures and rainfall are particularly strong, but the absence of any association between the former and the westerly index suggests that the two may be measuring slightly different aspects of the North Atlantic system. The westerly index is a direct measure of the character of the air flow across a region that is more latitudinally defined than that of the NAO, which is concerned with the pressure gradient between the Azores and Iceland and is therefore more longitudinally constrained. Interestingly, Ward (2006) also noted the absence of any correlation between the NAO and wind vector data from the ship logbooks of the Hudson Bay Company for the region 50-65°N, 0-70°W. Ward suggests that this absence of correlation may be due to the geographical study area was located on the northern-most fringes of the accepted NAO-influenced area, but also makes reference to the possibility that the linearity of trend of the pressure gradient differences which characterise the NAO may not hold true over shorter distances, and that it may be inappropriate to use the NAO to represent the degree to which the circulation is zonal in character over more restricted spatial domains. However, further investigation into this is required, particularly in light of work by Jones and Salmon (2005), who used wind field data from both the CLIWOC database and ICOADS to produce an NAOI, and who also found that the CLIWOC series did not correlate significantly with existing NAOIs.

	NAOI	**CET**	**CETanom**	**N_W**
CET	**0.567**			
CET anom	**0.544**			
EWP	**0.466**	**0.531**	**0.521**	
EWP anom	**0.482**	**0.480**	**0.473**	
gale days				**0.519**

Table 9.4: Significant correlations for winter (significant at the 0.01 level)

Spring

Recalling that negative correlations were found between CET and the E and N indices but not the S and W or CET anomaly at annual resolution, it is interesting to note that in spring there is a positive correlation between the S index and the CET anomaly (r = 0.383; other significant correlations are shown in table 9.5). This suggests a seasonal impact from airflow over the North Atlantic and the UK. This signal, already identified by Jones and Hulme (1997c) indicates warmer conditions with more southerly patterns. This is probably a direct result of equinoctial warming of the tropical regions and the movement of air northwards as part of the more general circulation.

A further correlation, but one for which a ready explanation is not forthcoming and might therefore need to be categorised as a 'teleconnection', is the negative correlation between the trade wind index (TI) and the EWP (r = -0.295). It would appear, on the basis of this correlation, that more organised and persistent trade winds south of the Azores anticyclone lead to drier conditions in the British Isles.

The correlation established above for winter between westerliness and gale days persists into spring time when r = 0.583 and is one of the few signals to prevail for a significant part of the year.

	N_S	**N_W**	**TI**	**NAOI**	**CET anom**
CET anom	**0.383**				
EWP			-0.295		
EWP anom			-0.296		**-0.382**
SSpot				**0.469**	
SSpot_r_m				**0.304**	
gale days		**0.583**			

Table 9.5: Significant correlations in Spring. Those in bold denote significance at the 0.01 level, and those in standard type significance at the 0.05 level

Further to the point noted within the annual correlations, another correlation was found involving the sunspot indices and the NAOI. Although not involving the logbook derived data, this is particularly noteworthy, especially as previous studies have declared otherwise:

> *"The patterns of natural variability like the NAO are not affected by variations in solar forcing… The insensitiveness of the NAO patterns is in agreement with the results of Palmer (1999) and Corti et al (1999)."*
>
> Haarsma *et al* (2000), p293

The finding that the NAO may be more well-developed during periods of greater solar activity is one of great significance but is perhaps another area of expansion for future study and cannot be fully explored within the remit of this thesis.

Summer

In summer the subtropical high pressure cell (Azores anticyclone) shifts polewards in response to the contraction of the circumpolar vortices (Barry & Chorley, 1998) and therefore, as mentioned in Chapter Eight, weather systems in the North Atlantic are less organised (demonstrated by the decrease in the prevailing westerlies – see Chapter Eight). Therefore one might expect a lack of correlations in summer between the derived indices and the independent variables, however this is not the case (see table 9.6).

There is a negative correlation between the N index and the EWP (r = -0.295), suggesting that the more frequent and persistent northerlies are in summer over the North Atlantic, the drier conditions are over the UK. This might be a consequence of ‘blocking’ situations leading to meridional airflow in the mid-latitudes leading to drier conditions as the ‘blocking highs’ inhibit the normal eastwards movement of rain-bearing fronts and air masses.

Both gale days and the W index display significant negative correlations with CET and CET anomalies (r = -0.294 for CET/gale days and -0.292 for CET/W). At this time of year the waters of the North Atlantic have a well-known tempering influence on the temperature regime of the British Isles and it is interesting to see this expressed so clearly through these correlations. The associations, based on late eighteenth century data, also suggest a consistency of cause-and-effect over long periods of time and that climatic change signals may need to be sought in more subtle adjustments of the system to changing forcing factors.

	N_N	**N_S**	**N_W**	**NAOI**	**CET**	**CET anom**
TI		**0.374**				
CET			-0.292	**0.387**		
CET anom			-0.284	**0.438**		
EWP	-0.295		**0.328**		**-0.381**	**-0.518**
EWP anom	-0.298		**0.331**	-0.282	**-0.484**	**-0.546**
gale days				-0.325	-0.283	-0.294

Table 9.6: Significant correlations in Summer. Those in bold denote significance at the 0.01 level, and those in standard type significance at the 0.05 level

The W index correlates positively with the EWP (r = 0.328), suggesting that more well-developed westerly circulations give rise not only to cooler but also to wetter conditions in summer. Again, this conforms to expected behaviour as it is polar maritime and tropical maritime air masses of Atlantic origin that provide much of the moisture for precipitation.

Gale days correlate negatively with the NAOI (r = -0.325). This is an unexpected result as stronger airflow might be thought to be associated with a more pronounced pressure gradient difference between the tropical high and Icelandic low (leading to a more positive NAOI). This finding is, however, supported by the work by Dawson *et al* (2002), which also showed that historic periods of increased storminess (by virtue of land-based gale day data from northern Scotland and western Ireland for the period 1884-1996) did not coincide with times when the NAOI was positive. Although they also noted that this was in contrast to more recent times (approximately the last 20 years) when increased storminess has indeed coincided with a strong and predominant positive phase of the NAO.

Finally, there appears also to be a connection between the southerly airflow in the North Atlantic and the trade wind circulation south of the anticyclone and the correlation between S and TI is 0.374. This is not readily explicable and would require further investigation to interpret and is a useful pointer for future research.

Autumn

As with winter, there are markedly fewer significant correlations than in spring or summer. However, three sets of correlations are evident (table 9.7). Firstly, there is a positive association between gale days and the S and W indices (r = 0.457 and 0.594 respectively). The latter is a signal that emerges in most seasons and is readily explicable (see above), although the former would appear to be more seasonal in nature.

Of greater interest is the positive correlation between CET anomaly and the sunspot index (r = 0.284). This indicates that greater solar activity leads to higher temperatures and echoes the association found at the annual scale of resolution, perhaps indicating that the signal found in the annual correlations is contributed to most significantly by the autumn season. It is unclear, however, why this season should be one in which this signal is so manifest and reflects the inherent uncertainty of understanding on this seemingly complex and inconsistent forcing element.

Finally, and equally interestingly, there is a significant correlation between gale days and both the sunspot number and the sunspot running mean (r = 0.378 and 0.394 respectively), suggesting that a higher solar output would give rise to stronger winds over the North Atlantic. This finding helpfully supports those of both Ward (2006) and Van Loon & Labitzke (2000). The latter found a downward connection between the stratospheric and tropospheric circulations in terms of the geopotential heights in early winter in periods of westerly phase of the Quasi-Biennial Oscillation (QBO) (a 26-month wind regime within the stratosphere). More significantly, they asserted this connection to be phased with the solar cycle with greater solar activity being associated with stronger westerlies north of 45°N. More recently such connections between stratosphere and troposphere and the control exercised by the solar cycle on those connections, has been examined by Baldwin and Dunkerton (2004). They too assert the nature of such connections but also recognise that the nature of the interaction depends upon the phase of the solar cycle with zonality of stratospheric circulations being intensified during solar maxima. Ward (2006) also found a significant positive correlation between sunspot number and gale days in July and October for the far North Atlantic, but also found an apparent tendency for southerly winds to be more common across the region during periods of solar maxima. Whilst there may be a degree of explanation for the correlation between gale days and sunspot number in the hypothesis that increased energy input into the atmosphere would lead to an increase in atmospheric energy and cyclonicity, Ward asserts that the degrees of variation of solar input within the solar cycle are less than 1% of the solar energy budget (Frohlich, 2000), and therefore some amplification would be necessary to yield the apparently evident signal.

It could also be speculated upon here that perhaps increased zonality in the stratosphere could lead to greater zonality in surface winds, however it is beyond the scope of this thesis to explore this suggestion further. Whilst this area remains a rich one for further research, it is interesting to find a similar signal in the logbook record from the late eighteenth century.

The suggestion of a consistency of cause and effect is also worthy of note, suggesting, not for the first time in this investigation, that climate change may be well-recorded through the medium of temperatures but is a less distinct phenomenon where other climatic variables are concerned.

	N_S	**N_W**	**CET anom**	**SSpot**	**SSpot_r_m**
SSpot			0.284		
SSpot_r_m					
gale days	**0.457**	**0.594**		**0.378**	**0.394**

Table 9.7: Significant correlations in Autumn. Those in bold denote significance at the 0.01 level, and those in standard type significance at the 0.05 level

Finally, it should again be noted that no significant correlation could be found between the degree of westerliness from the logbook record and the NAO index (see above).

CONCLUSION

Correlation analysis has proved to be a useful, if simple, investigatory tool. It has highlighted a number of important associations. Some of these conform to known climatological principles, but others are new and demonstrate important lines for future research, especially where the constraints on the present thesis prevented a full elaboration of the possible causal mechanisms.

CONCLUSION

The work undertaken as part of the preparation of this thesis has demonstrated the validity and reliability of logbooks as a source of climatological data. The statistical results have given an indication of connections between different variables, some of which can be readily explained within the constraints of time of the research programme, but others of which provide an indication of possible future areas of research. A review the thesis can be summarised by returning to the initial aims and objectives Table 10.1 evaluates the outcomes against the aims and objectives and reflects the success enjoyed by the project.

O1. To assemble logbook data from the CLIWOC database into a new database designed to meet the needs of this project.	This was done through manipulation in Microsoft Excel, and the database files are presented on CD1 included in this thesis.
O2. To use these logbook data to summarise some aspects of the climate of the North Atlantic for the period 1750 to 1800.	The character and variability in the derived wind vector indices is summarised in Chapter 8.
O3. To establish the validity of this data source (logbook data) in climatic studies and confirm it as a valuable ‘new’ source with application and potential well beyond the scope of this project.	Verification was undertaken through a better understanding of the source and context of the data (Chapters 2 – 6), and expressed in a form that could be used in statistical analysis (Chapters 5 – 7). Preliminary statistical correlation analyses demonstrate that the data conform to known climatological principles (Chapter 9).

O4. To demonstrate how logbook data can be used to provide climatic information for periods of particular interest at the time scale of months or years.	Periods of particular behaviour of the derived indices (e.g. gale days and westerliness) are discussed in the context of documented climatological events and periods of interest (e.g. 1783 volcanic eruption) in Chapter 8.
A1. To collate raw logbook data from the CLIWOC database.	This was accomplished in the form of Excel spreadsheets.
A2. To examine the evolution of nautical/meteorological terminology over the study period.	A study of the evolution of the nautical terminology was undertaken as part of the verification and data manipulation process (e.g. wind forces were homogenized into Beaufort numbers), see Chapters 3 – 6.
A3. To confirm the CLIWOC-derived nautical vocabulary of wind force terms, and to modify and amend it where necessary.	Wind force terms for the data set were sampled and summarised (Chapter 4), and modified in the context of the Beaufort scale (Chapters 5 and 6) through the use of relationship with distance sailed.
A4. To develop simple statistics and indices that summarise and express in numerical form the largely non-instrumental data found in logbooks from this period.	Vector indices derived from the wind data were developed and described over a variety of time scales (e.g. annual, monthly) through basic descriptive statistics (Chapter 8), and also correlated with independent climatological indices to further verify the data and obtain preliminary suggestions of relationships to confirm existing findings or present new ones (Chapter 9).

Table 10.1: Evaluation of the aims and objectives of this thesis, and examples of where and how they have been met

Turning to the main scientific findings, these fall under two, though not mutually exclusive, headings; those to do with the verification of the data set and those concerned with the climatological conditions during the latter half of the eighteenth century.

Data verification

It is important to appreciate that whilst logbook data exist in prodigious quantities, they require careful ‘translation’ into present day and standardized terms before they can be of scientific value. It is also important to test the data for reliability and consistency. Inevitably, there are limitations when dealing with such historical source material describing events that cannot otherwise be re-captured. Nevertheless by exploring the internal consistency of the data and by careful processing of the data into present day forms of expression it can be confidently suggested that the data set are reliable. This is of importance to this thesis but has the wider and greater significance of suggesting that the same reliability can be expected in other logbook data from at least this period.

In this connection, the general agreement of the behaviour of the derived indices and preliminary statistical analysis with accepted climatological theory provides strong support to the proposal that logbook information is reliable and valid for climatological studies.

The majority of the derived indices showed however a significant degree of skewness and Johnson transformation was performed on them to enable statistical testing, In this instance the transformation made little difference to the scientific findings, but future researchers should take due note of the high degrees of non-normality that were encountered.

Scientific findings

The derived data were used to gauge successfully the persistence and nature of circulations to the north and south of the Azores sub-tropical high-pressure system. In this respect it is important to note that logbooks probably provide the only source of such information at this daily and monthly scale of resolution for the pre-instrumental period.

An important series of ‘gale’ frequencies was produced that allowed periods of greater and lesser cyclonic activity to be identified. The seasonal and monthly patterns of gale frequencies accorded with those experienced today, i.e. more frequent in winter but less so in summer.

When correlated with independent data series, including NAOI, CET, EWP and sunspot number, many significant correlations were found, some supporting existing theory and some suggesting new findings. The statistical links between sunspot activity and logbook data were of particular importance, although ready explanations for such associations were not forthcoming and went beyond the scope of this thesis. But these, and the many other correlations, demonstrated the value of logbook data in searching for climatic signals from oceanic areas in the historic past. It is also important to note how the use of monthly aggregated data allowed seasonal variations in the nature of the climatic signal to be identified, some being present at some times of year, but not at others. On the other hand, some anticipated correlations failed to materialize.

Most significant amongst these was that which might have been anticipated between the NAO and westerly indices. But, as noted in Chapter Nine, this may be a result of the different spatial arrangements on which these two measures are based and need not undermine the integrity of either.

In order to highlight the originality of the thesis, attention is drawn to the new findings of the work undertaken herein:

- The correlation between CET and sunspot activity at the annual level and also within the autumnal record suggests a hitherto overlooked link between solar output and temperature
- The absence of the winter warming effect (common today) on the UK of the westerly airflow over the North Atlantic, though this may be an artifact of the geographical distance between the study area and the UK
- Few correlations between the dominant airflow over the North Atlantic and the independently-derived datasets in winter, when the climate is generally accepted to be more ‘organised’ and more associations therefore expected
- A negative correlation between the Trade Wind index and the EWP in spring, suggesting that perhaps more persistent trade winds south of the Azores anticyclone may lead to drier conditions in the UK.
- Positive correlation between the sunspot index and the NAOI in spring, suggesting that perhaps, contrary to the indications of other studies, the NAO may be more pronounced during periods of greater solar activity
- A negative correlation in summer between the Gale Day index and the NAOI. Although climatologically unexpected, this finding is supported

by work by Dawson *et al* (2002), who found that periods of increased storminess on the Atlantic side of the UK did not coincide with periods of positive phase of the NAO, as might be expected.

- A connection between the southerly airflow over the North Atlantic and the trade wind circulation south of the Azores anticyclone in summer
- A negative correlation between the northerly airflow index and the EWP in summer, possibly demonstrating a ‘blocking’ effect in the eastwards movement of air masses.
- Significant positive correlation between gale days and solar activity in autumn, which, although suggested by other studies, is not borne out in the same statistical manner.

Finally, and looking to the future, areas of further research based on these findings but which could not be pursued within the remit of this thesis include:

1) Explanations for periods of increased storminess (with respect to gale days)

2) Comparison of eighteenth century and present day airflow conditions using similarly-derived indices with a view to detecting any signal for climatic change

3) A springtime association of sunspot number with NAOI and autumn-time correlation with CET. Indeed, the whole question of solar connections with climate seems to assume particular, if poorly understood, significance at this time

4) The suggested relationship between summer-time southerly airflow in the region north of the Azores anticyclone with the trade wind circulation.

It is clear from the investigations and findings herein that logbook data are to be viewed as a reliable data source, when treated correctly. This makes a helpful addition to available datasets that enable further study of historical climatology, and could assist future understanding of atmosphere-ocean interactions.

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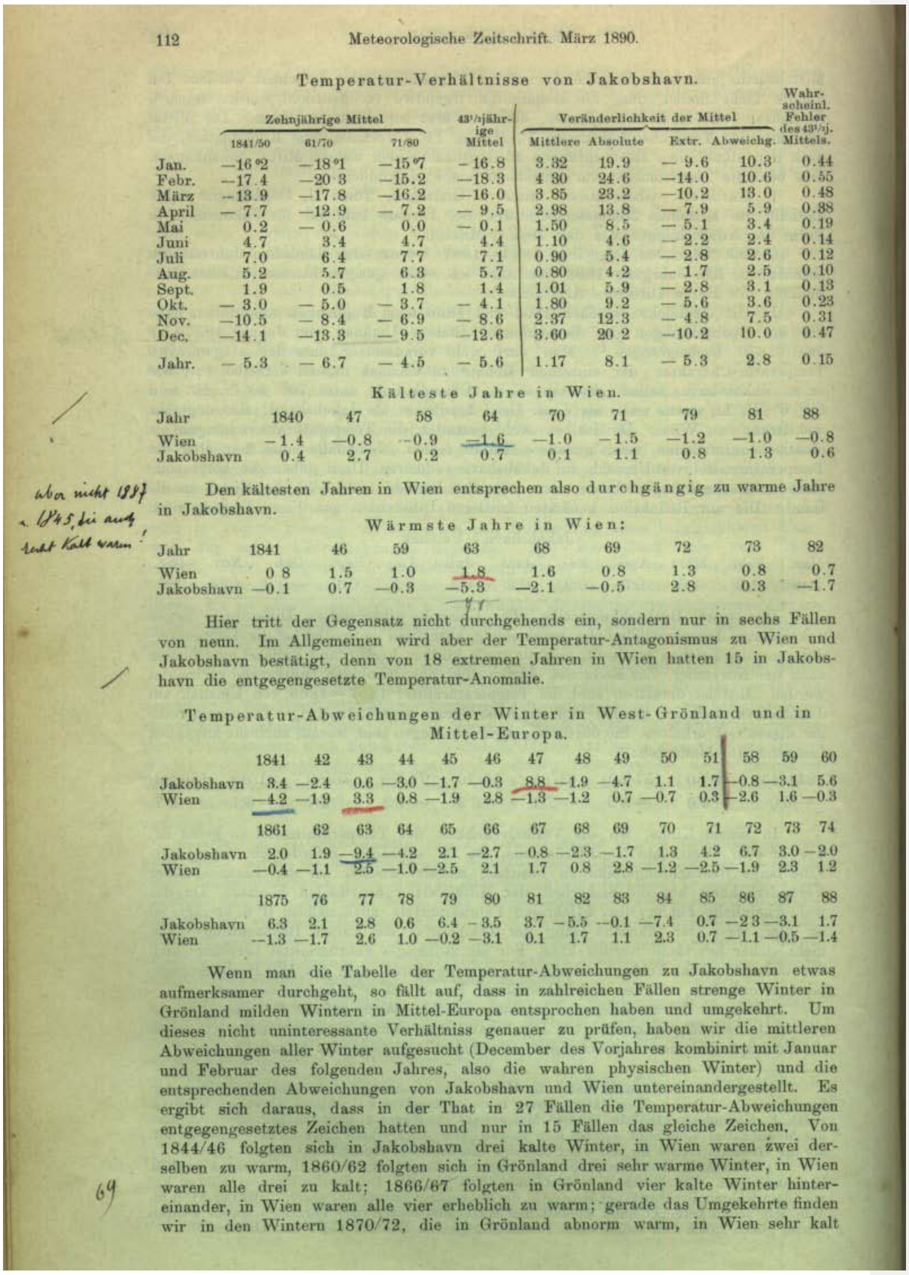
LIST OF ABBREVIATIONS

AH	Azores High
ANOVA	Analysis of Variance
AO	Arctic Oscillation
BADC	British Atmospheric Data Centre
BL	British Library
CET	Central England Temperature series
CLIWOC	Climate of the World's Oceans (Project)
CRU	Climate Research Unit (Norwich)
EIC	East India Company
EWP	England & Wales Precipitation series
ICOADS	International Comprehensive Ocean-Atmosphere Dataset
IL	Icelandic Low
ITCZ	Intertropical Convergence Zone
LDM	Lunar Distance Method
MOC	Meridional Overturning Circulation
NA	North Atlantic
NAO	North Atlantic Oscillation
NAOI	North Atlantic Oscillation Index
NAR	National Archives
NMM	National Maritime Museum
NPO	North Pacific Oscillation
OED	Oxford English Dictionary
PCA	Principle Component Analysis
QBO	Quasi- Biennial Oscillation
RN	Royal Navy
SI	Standard Index
SIDC	Solar Influence Data Analysis Centre
SLP	Sea Level Pressure
SO	Southern Oscillation
SOI	Southern Oscillation Index

SST	Sea Surface Temperature
TAV	Topical Atlantic Variability
TI	Trade Index
WI	Westerliness Index

APPENDIX I - LITERATURE

Scanned results pages from Hann, 1890



112 Meteorologische Zeitschrift. März 1890.

Temperatur-Verhältnisse von Jakobshavn.

	Zehnjährige Mittel			43½jährige Mittel	Veränderlichkeit der Mittel				Wahrscheinl. Fehler des 43½j. Mittels.
	1841/50	61/70	71/80		Mittlere	Absolute	Extr.	Abweichg.	
Jan.	—16°2	—18°1	—15°7	—16.8	3.32	19.9	— 9.6	10.3	0.44
Febr.	—17.4	—20.3	—15.2	—18.3	4.30	24.6	—14.0	10.6	0.55
März	—13.9	—17.8	—16.2	—16.0	3.85	23.2	—10.2	13.0	0.48
April	— 7.7	—12.9	— 7.2	— 9.5	2.98	13.8	— 7.9	5.9	0.38
Mai	0.2	— 0.6	0.0	— 0.1	1.50	8.5	— 5.1	3.4	0.19
Juni	4.7	3.4	4.7	4.4	1.10	4.6	— 2.2	2.4	0.14
Juli	7.0	6.4	7.7	7.1	0.90	5.4	— 2.8	2.6	0.12
Aug.	5.2	5.7	6.3	5.7	0.80	4.2	— 1.7	2.5	0.10
Sept.	1.9	0.5	1.8	1.4	1.01	5.9	— 2.8	3.1	0.13
Okt.	— 3.0	— 5.0	— 3.7	— 4.1	1.80	9.2	— 5.6	3.6	0.23
Nov.	—10.5	— 8.4	— 6.9	— 8.6	2.37	12.3	— 4.8	7.5	0.31
Dec.	—14.1	—13.3	— 9.5	—12.6	3.60	20.2	—10.2	10.0	0.47
Jahr.	— 5.3	— 6.7	— 4.5	— 5.6	1.17	8.1	— 5.3	2.8	0.15

Kälteste Jahre in Wien.

Jahr	1840	47	58	64	70	71	79	81	88
Wien	—1.4	—0.8	—0.9	—1.6	—1.0	—1.5	—1.2	—1.0	—0.8
Jakobshavn	0.4	2.7	0.2	0.7	0.1	1.1	0.8	1.3	0.6

aber nicht 1887 u. 1845, die auch recht kalt waren!

Den kältesten Jahren in Wien entsprechen also durchgängig zu warme Jahre in Jakobshavn.

Wärmste Jahre in Wien:

Jahr	1841	46	59	63	68	69	72	73	82
Wien	0.8	1.5	1.0	1.8	1.6	0.8	1.3	0.8	0.7
Jakobshavn	—0.1	0.7	—0.3	—5.3 4.1	—2.1	—0.5	2.8	0.3	—1.7

Hier tritt der Gegensatz nicht durchgehends ein, sondern nur in sechs Fällen von neun. Im Allgemeinen wird aber der Temperatur-Antagonismus zu Wien und Jakobshavn bestätigt, denn von 18 extremen Jahren in Wien hatten 15 in Jakobshavn die entgegengesetzte Temperatur-Anomalie.

Temperatur-Abweichungen der Winter in West-Grönland und in Mittel-Europa.

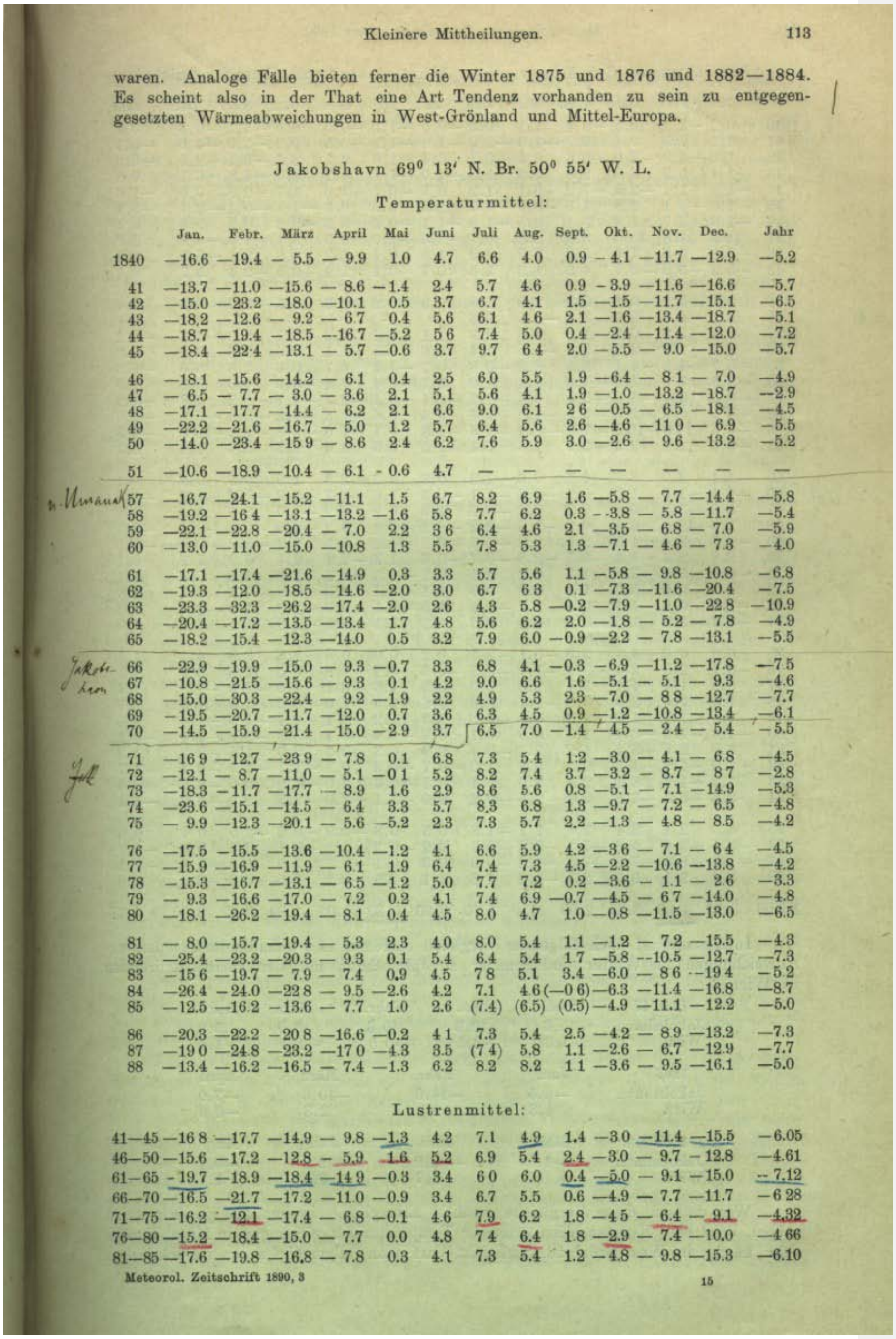
	1841	42	43	44	45	46	47	48	49	50	51	58	59	60
Jakobshavn	3.4	—2.4	0.6	—3.0	—1.7	—0.3	8.8	—1.9	—4.7	1.1	1.7	—0.8	—3.1	5.6
Wien	—4.2	—1.9	3.3	0.8	—1.9	2.8	—1.3	—1.2	0.7	—0.7	0.3	—2.6	1.6	—0.3

	1861	62	63	64	65	66	67	68	69	70	71	72	73	74
Jakobshavn	2.0	1.9	—9.4	—4.2	2.1	—2.7	—0.8	—2.3	—1.7	1.3	4.2	6.7	3.0	—2.0
Wien	—0.4	—1.1	2.5	—1.0	—2.5	2.1	1.7	0.8	2.8	—1.2	—2.5	—1.9	2.3	1.2

	1875	76	77	78	79	80	81	82	83	84	85	86	87	88
Jakobshavn	6.3	2.1	2.8	0.6	6.4	—3.5	3.7	—5.5	—0.1	—7.4	0.7	—2.3	—3.1	1.7
Wien	—1.3	—1.7	2.6	1.0	—0.2	—3.1	0.1	1.7	1.1	2.3	0.7	—1.1	—0.5	—1.4

Wenn man die Tabelle der Temperatur-Abweichungen zu Jakobshavn etwas aufmerksamer durchgeht, so fällt auf, dass in zahlreichen Fällen strenge Winter in Grönland milden Wintern in Mittel-Europa entsprochen haben und umgekehrt. Um dieses nicht uninteressante Verhältniss genauer zu prüfen, haben wir die mittleren Abweichungen aller Winter aufgesucht (December des Vorjahres kombinirt mit Januar und Februar des folgenden Jahres, also die wahren physischen Winter) und die entsprechenden Abweichungen von Jakobshavn und Wien untereinandergestellt. Es ergibt sich daraus, dass in der That in 27 Fällen die Temperatur-Abweichungen entgegengesetztes Zeichen hatten und nur in 15 Fällen das gleiche Zeichen. Von 1844/46 folgten sich in Jakobshavn drei kalte Winter, in Wien waren zwei derselben zu warm, 1860/62 folgten sich in Grönland drei sehr warme Winter, in Wien waren alle drei zu kalt; 1866/67 folgten in Grönland vier kalte Winter hintereinander, in Wien waren alle vier erheblich zu warm; gerade das Umgekehrte finden wir in den Wintern 1870/72, die in Grönland abnorm warm, in Wien sehr kalt

69



waren. Analoge Fälle bieten ferner die Winter 1875 und 1876 und 1882—1884. Es scheint also in der That eine Art Tendenz vorhanden zu sein zu entgegengesetzten Wärmeabweichungen in West-Grönland und Mittel-Europa.

Jakobshavn 69° 13′ N. Br. 50° 55′ W. L.

Temperaturmittel:

		Jan.	Febr.	März	April	Mai	Juni	Juli	Aug.	Sept.	Okt.	Nov.	Dec.	Jahr
	1840	−16.6	−19.4	−5.5	−9.9	1.0	4.7	6.6	4.0	0.9	−4.1	−11.7	−12.9	−5.2
	41	−13.7	−11.0	−15.6	−8.6	−1.4	2.4	5.7	4.6	0.9	−3.9	−11.6	−16.6	−5.7
	42	−15.0	−23.2	−18.0	−10.1	0.5	3.7	6.7	4.1	1.5	−1.5	−11.7	−15.1	−6.5
	43	−18.2	−12.6	−9.2	−6.7	0.4	5.6	6.1	4.6	2.1	−1.6	−13.4	−18.7	−5.1
	44	−18.7	−19.4	−18.5	−16.7	−5.2	5.6	7.4	5.0	0.4	−2.4	−11.4	−12.0	−7.2
	45	−18.4	−22.4	−13.1	−5.7	−0.6	3.7	9.7	6.4	2.0	−5.5	−9.0	−15.0	−5.7
	46	−18.1	−15.6	−14.2	−6.1	0.4	2.5	6.0	5.5	1.9	−6.4	−8.1	−7.0	−4.9
	47	−6.5	−7.7	−3.0	−3.6	2.1	5.1	5.6	4.1	1.9	−1.0	−13.2	−18.7	−2.9
	48	−17.1	−17.7	−14.4	−6.2	2.1	6.6	9.0	6.1	2.6	−0.5	−6.5	−18.1	−4.5
	49	−22.2	−21.6	−16.7	−5.0	1.2	5.7	6.4	5.6	2.6	−4.6	−11.0	−6.9	−5.5
	50	−14.0	−23.4	−15.9	−8.6	2.4	6.2	7.6	5.9	3.0	−2.6	−9.6	−13.2	−5.2
	51	−10.6	−18.9	−10.4	−6.1	−0.6	4.7	—	—	—	—	—	—	—
n. Umanak	57	−16.7	−24.1	−15.2	−11.1	1.5	6.7	8.2	6.9	1.6	−5.8	−7.7	−14.4	−5.8
	58	−19.2	−16.4	−13.1	−13.2	−1.6	5.8	7.7	6.2	0.3	−3.8	−5.8	−11.7	−5.4
	59	−22.1	−22.8	−20.4	−7.0	2.2	3.6	6.4	4.6	2.1	−3.5	−6.8	−7.0	−5.9
	60	−13.0	−11.0	−15.0	−10.8	1.3	5.5	7.8	5.3	1.3	−7.1	−4.6	−7.3	−4.0
	61	−17.1	−17.4	−21.6	−14.9	0.3	3.3	5.7	5.6	1.1	−5.8	−9.8	−10.8	−6.8
	62	−19.3	−12.0	−18.5	−14.6	−2.0	3.0	6.7	6.3	0.1	−7.3	−11.6	−20.4	−7.5
	63	−23.3	−32.3	−26.2	−17.4	−2.0	2.6	4.3	5.8	−0.2	−7.9	−11.0	−22.8	−10.9
	64	−20.4	−17.2	−13.5	−13.4	1.7	4.8	5.6	6.2	2.0	−1.8	−5.2	−7.8	−4.9
	65	−18.2	−15.4	−12.3	−14.0	0.5	3.2	7.9	6.0	−0.9	−2.2	−7.8	−13.1	−5.5
Jakobshavn	66	−22.9	−19.9	−15.0	−9.3	−0.7	3.3	6.8	4.1	−0.3	−6.9	−11.2	−17.8	−7.5
	67	−10.8	−21.5	−15.6	−9.3	0.1	4.2	9.0	6.6	1.6	−5.1	−5.1	−9.3	−4.6
	68	−15.0	−30.3	−22.4	−9.2	−1.9	2.2	4.9	5.3	2.3	−7.0	−8.8	−12.7	−7.7
	69	−19.5	−20.7	−11.7	−12.0	0.7	3.6	6.3	4.5	0.9	−1.2	−10.8	−13.4	−6.1
	70	−14.5	−15.9	−21.4	−15.0	−2.9	3.7	6.5	7.0	−1.4	−4.5	−2.4	−5.4	−5.5
Jak	71	−16.9	−12.7	−23.9	−7.8	0.1	6.8	7.3	5.4	1.2	−3.0	−4.1	−6.8	−4.5
	72	−12.1	−8.7	−11.0	−5.1	−0.1	5.2	8.2	7.4	3.7	−3.2	−8.7	−8.7	−2.8
	73	−18.3	−11.7	−17.7	−8.9	1.6	2.9	8.6	5.6	0.8	−5.1	−7.1	−14.9	−5.8
	74	−23.6	−15.1	−14.5	−6.4	3.3	5.7	8.3	6.8	1.3	−9.7	−7.2	−6.5	−4.8
	75	−9.9	−12.3	−20.1	−5.6	−5.2	2.3	7.3	5.7	2.2	−1.3	−4.8	−8.5	−4.2
	76	−17.5	−15.5	−13.6	−10.4	−1.2	4.1	6.6	5.9	4.2	−3.6	−7.1	−6.4	−4.5
	77	−15.9	−16.9	−11.9	−6.1	1.9	6.4	7.4	7.3	4.5	−2.2	−10.6	−13.8	−4.2
	78	−15.3	−16.7	−13.1	−6.5	−1.2	5.0	7.7	7.2	0.2	−3.6	−1.1	−2.6	−3.3
	79	−9.3	−16.6	−17.0	−7.2	0.2	4.1	7.4	6.9	−0.7	−4.5	−6.7	−14.0	−4.8
	80	−18.1	−26.2	−19.4	−8.1	0.4	4.5	8.0	4.7	1.0	−0.8	−11.5	−13.0	−6.5
	81	−8.0	−15.7	−19.4	−5.3	2.3	4.0	8.0	5.4	1.1	−1.2	−7.2	−15.5	−4.3
	82	−25.4	−23.2	−20.3	−9.3	0.1	5.4	6.4	5.4	1.7	−5.8	−10.5	−12.7	−7.3
	83	−15.6	−19.7	−7.9	−7.4	0.9	4.5	7.8	5.1	3.4	−6.0	−8.6	−19.4	−5.2
	84	−26.4	−24.0	−22.8	−9.5	−2.6	4.2	7.1	4.6	(−0.6)	−6.3	−11.4	−16.8	−8.7
	85	−12.5	−16.2	−13.6	−7.7	1.0	2.6	(7.4)	(6.5)	(0.5)	−4.9	−11.1	−12.2	−5.0
	86	−20.3	−22.2	−20.8	−16.6	−0.2	4.1	7.3	5.4	2.5	−4.2	−8.9	−13.2	−7.3
	87	−19.0	−24.8	−23.2	−17.0	−4.3	3.5	(7.4)	5.8	1.1	−2.6	−6.7	−12.9	−7.7
	88	−13.4	−16.2	−16.5	−7.4	−1.3	6.2	8.2	8.2	1.1	−3.6	−9.5	−16.1	−5.0

Lustrenmittel:

	Jan.	Febr.	März	April	Mai	Juni	Juli	Aug.	Sept.	Okt.	Nov.	Dec.	Jahr
41—45	−16.8	−17.7	−14.9	−9.8	−1.3	4.2	7.1	4.9	1.4	−3.0	−11.4	−15.5	−6.05
46—50	−15.6	−17.2	−12.8	−5.9	1.6	5.2	6.9	5.4	2.4	−3.0	−9.7	−12.8	−4.61
61—65	−19.7	−18.9	−18.4	−14.9	−0.3	3.4	6.0	6.0	0.4	−5.0	−9.1	−15.0	−7.12
66—70	−16.5	−21.7	−17.2	−11.0	−0.9	3.4	6.7	5.5	0.6	−4.9	−7.7	−11.7	−6.28
71—75	−16.2	−12.1	−17.4	−6.8	−0.1	4.6	7.9	6.2	1.8	−4.5	−6.4	−9.1	−4.32
76—80	−15.2	−18.4	−15.0	−7.7	0.0	4.8	7.4	6.4	1.8	−2.9	−7.4	−10.0	−4.66
81—85	−17.6	−19.8	−16.8	−7.8	0.3	4.1	7.3	5.4	1.2	−4.8	−9.8	−15.3	−6.10

Source: Andreas Hense (November 2000)
http://www.meteo.uni-bonn.de/english/kihz/nao/naokihz.html

APPENDIX II – LOGBOOK INFORMATION

Logbooks available and used for the CLIWOC project at the three primary holding sites in London

National Maritime Museum – Greenwich					
Lieutenants' logs	**Pre 1700**	**1700-1749**	**1750-1809**		**Total**
Volumes	316	1921	2968		5205
Approximate no. of individual logs*	3500	24000	35000		62500
Volumes examined	0	0	c.650		c.650
Volumes Used	0	0	518		518
Other collections	**Pre 1700**	**1700-1749**	**1750-1799**	**1800-1849**	**Total**
Volumes	5	56	243	507	811
Approx. no. of individual logs	10	70	350	700	1130
Volumes Used	0	0	5	57	62
*Assuming an average of 12 logs per volume					

Table i

British Library					
	Pre 1700	**1700-1749**	**1750-1799**	**1800-1850**	**Total**
Add. MS	2	10	29	20	61
Volumes used	0	0	0	0	0
East India Company Journals	**Pre 1700**	**1700-1834**			
	< 200	3625			3822
Volumes examined	0	150			150
Volumes used	0	138			138
Each journal records both the outward and return voyage to India or China					

Table ii

National Archives				
	Admirals' Journals	**Captains' logs**	**Masters' logs**	**Hudson Bay Company (microfilm)**
Reference	ADM 50	ADM 51	ADM 52	BH 1
Range	1702-1916	1669-1852	1672-1840	From 1667
Volumes	413	4563	2103	129
Aproximate no. of individual logs*		22800	10500	
Volumes used	0	7	0	11
*Assuming an average of 5 logs per volume				

Table iii

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APPENDIX III – WEATHER TERMS AND CLASSIFICATION

Weather coding for present day categorisation

Past weather:

Past weather is defined as weather occurring in the past 6 hours at 00, 06, 12, 18 UTC, and the past 3 hours at 03, 09, 15, 21 UTC.

WMO code 4561: Past weather

0 - cloud covering half or less of the sky throughout the period

1 - cloud covering more than half the sky during part of the period & half or less for the rest

2 - cloud covering more than half the sky throughout the period

3 - sandstorm, duststorm or blowing snow

4 - fog or ice fog or thick haze

5 - drizzle

6 - rain1

7 - snow, or rain and snow mixed

8 - shower(s)

9 - thunderstorm(s) with or without precipitation

Present weather:

WMO code 4677: Present weather reported from a manned station.

00 - Cloud development not observed or not observable

01 - Cloud generally dissolving or becoming less developed

02 - State of sky on the whole unchanged

03 - Clouds generally forming or developing

04 - Visibility reduced by smoke, e.g. veldt or forest fires, industrial smoke or volcanic ashes

05 - Haze

06 - Widespread dust in suspension in the air, not raised by wind at or near the station at the time of observation

07 - Dust or sand raised by wind at or near the station at the time of observation, but not well-developed dust whirl(s) or sand whirl(s), and no duststorm or sandstorm seen; or, in the case of ships, blowing spray at the station

08 - Well-developed dust or sand whirl(s) seen at or near the station during the preceding hour or at the time of observation, but no dust storm or sandstorm

09 - Duststorm or sandstorm within sight at the time of observation, or at the station during the preceding hour

10 - Mist

11 - Patches of shallow fog or ice fog at the station, whether on land or sea not deeper than about 2 metres on land or 10 metres at sea

12 - More or less continuous shallow fog or ice fog at the station, whether on land or sea, not deeper than about 2m/land or 10m/sea

13 - Lightning visible, or thunder heard

14 - Precipitation within sight, not reaching the ground or the surface of the sea

15 - Precipitation within sight, reaching the ground or the surface of the sea, but distant, i.e. > 5 km from the station

16 - Precipitation within sight, reaching the ground or the surface of the sea, near to, but not at the station

17 - Thunderstorm, but no precipitation at the time of observation

18 - Squalls at or within sight of the station during the preceding hour or at the time of observation

19 - Funnel clouds at or within sight of the station during the preceding hour or at the time of observation

20 - Drizzle (not freezing) or snow grains, not falling as showers, during the preceding hour but not at the time of observation

21 - Rain (not freezing), not falling as showers, during the preceding hour but not at the time of observation

22 - Snow, not falling as showers, during the preceding hour but not at the time of observation

23 - Rain and snow or ice pellets, not falling as showers; during the preceding hour but not at the time of observation

24 - Freezing drizzle or freezing rain; during the preceding hour but not at the time of observation

25 - Shower(s) of rain during the preceding hour but not at the time of observation

26 - Shower(s) of snow, or of rain and snow during the preceding hour but not at the time of observation

27 - Shower(s) of hail, or of rain and hail during the preceding hour but not at the time of observation

28 - Fog or ice fog during the preceding hour but not at the time of observation

29 - Thunderstorm (with or without precipitation) during the preceding hour but

not at the time of observation

30 - Slight or moderate duststorm or sandstorm - has decreased during the preceding hour

31 - Slight or moderate duststorm or sandstorm - no appreciable change during the preceding hour

32 - Slight or moderate duststorm or sandstorm - has begun or has increased during the preceding hour

33 - Severe duststorm or sandstorm - has decreased during the preceding hour

34 - Severe duststorm or sandstorm - no appreciable change during the preceding hour

35 - Severe duststorm or sandstorm - has begun or has increased during the preceding hour

36 - Slight/moderate drifting snow - generally low (below eye level)

37 - Heavy drifting snow - generally low (below eye level)

38 - Slight/moderate blowing snow - generally high (above eye level)

39 - Heavy blowing snow - generally high (above eye level)

40 - Fog or ice fog at a distance at the time of observation, but not at station during the preceding hour, the fog or ice fog extending to a level above that of the observer

41 - Fog or ice fog in patches

42 - Fog/ice fog, sky visible, has become thinner during the preceding hour

43 - Fog/ice fog, sky invisible, has become thinner during the preceding hour

44 - Fog or ice fog, sky visible, no appreciable change during the past hour

45 - Fog or ice fog, sky invisible, no appreciable change during the preceding hour

46 - Fog or ice fog, sky visible, has begun or has become thicker during preceding hour

47 - Fog or ice fog, sky invisible, has begun or has become thicker during the preceding hour

48 - Fog, depositing rime, sky visible

49 - Fog, depositing rime, sky invisible

50 - Drizzle, not freezing, intermittent, slight at time of ob.

51 - Drizzle, not freezing, continuous, slight at time of ob.

52 - Drizzle, not freezing, intermittent, moderate at time of ob.

53 - Drizzle, not freezing, continuous, moderate at time of ob.

54 - Drizzle, not freezing, intermittent, heavy at time of ob.

55 - Drizzle, not freezing, continuous, heavy at time of ob.

56 - Drizzle, freezing, slight

57 - Drizzle, freezing, moderate or heavy (dense)

58 - Rain and drizzle, slight

59 - Rain and drizzle, moderate or heavy

60 - Rain, not freezing, intermittent, slight at time of ob.

61 - Rain, not freezing, continuous, slight at time of ob.

62 - Rain, not freezing, intermittent, moderate at time of ob.

63 - Rain, not freezing, continuous, moderate at time of ob.

64 - Rain, not freezing, intermittent, heavy at time of ob.

65 - Rain, not freezing, continuous, heavy at time of ob.

66 - Rain, freezing, slight

67 - Rain, freezing, moderate or heavy

68 - Rain or drizzle and snow, slight

69 - Rain or drizzle and snow, moderate or heavy

70 - Intermittent fall of snowflakes, slight at time of ob.

71 - Continuous fall of snowflakes, slight at time of ob.

72 - Intermittent fall of snowflakes, moderate at time of ob.

73 - Continuous fall of snowflakes, moderate at time of ob.

74 - Intermittent fall of snowflakes, heavy at time of ob.

75 - Continuous fall of snowflakes, heavy at time of ob.

76 - Diamond dust (with or without fog)

77 - Snow grains (with or without fog)

78 - Isolated star-like snow crystals (with or without fog)

79 - Ice pellets

80 - Rain shower(s), slight

81 - Rain shower(s), moderate or heavy

82 - Rain shower(s), violent

83 - Shower(s) of rain and snow, slight

84 - Shower(s) of rain and snow, moderate or heavy

85 - Snow shower(s), slight

86 - Snow shower(s), moderate or heavy

87 - Shower(s) of snow pellets or small hail, with or without rain or rain and snow mixed - slight

88 - Shower(s) of snow pellets or small hail, with or without rain or rain and snow mixed - moderate or heavy

89 - Shower(s) of hail, with or without rain or rain and snow mixed, not associated with thunder - slight

90 - Shower(s) of hail, with or without rain or rain and snow mixed, not

associated with thunder - moderate or heavy

91 - Slight rain at time of observation - Thunderstorm during the preceding hour but not at time of observation

92 - Moderate or heavy rain at time of observation - Thunderstorm during the preceding hour but not at time of observation

93 - Slight snow, or rain and snow mixed or hail at time of observation - Thunderstorm during the preceding hour but not at time of observation

94 - Moderate or heavy snow, or rain and snow mixed or hail at time of observation - Thunderstorm during the preceding hour but not at time of observation

95 - Thunderstorm, slight or moderate, without hail, but with rain and/or snow at time of observation

96 - Thunderstorm, slight or moderate, with hail at time of ob.

97 - Thunderstorm, heavy, without hail, but with rain and/or snow at time of observation

98 - Thunderstorm combined with dust/sandstorm at time of observation

99 - Thunderstorm, heavy with hail at time of observation

Weather Notation Code	**1806-1807**	**1807-1810**	**1810-1812**	**1820-1825**	**1826-1832**
b.	Blue sky	Blue sky	Blue sky	Blue sky	Blue sky, clear or turbid atmosphere
c.	Clear i.e., definite, sharp horizon	Definite sharp horizon, distant objects clearly visible	Bright objects visible from afar	Clear, transparent atmosphere	Individual passing clouds
ci.				Cirrus clouds	
cl.	Cloudy	Cloudy	Cloudy	Cloudy	
cu.				Cumulus clouds	
d.	Dry, warm air			Mist (damp air)	Drizzle, fine rain
da.		Damp air	Damp air		
dk.	Dark, close air	Dark, gloomy weather	Dark weather	Dark weather but atmosphere clear	
dp.	Damp air				
dr.	Drizzle	Drizzle	Drizzle		
f.	Fine weather	Fine weather	Fine weather	Foggy	Fog
f:					Dense Fog
fg.	Foggy	Fog	Fog		
g.	Dark, gloomy weather		Dark, gloomy weather	Gloomy weather	Dark, gloomy weather
ge.		Gloomy weather			
gr.	Greasy sky	Greasy sky	Greasy sky		
h.	Haze	Hazy weather	Haze	Haze	Hail
hr.	Heavy rain	Heavy rain	Heavy rain		
hsh.	Heavy showers	Heavy showers	Heavy showers		
hsq.	Heavy squalls	Heavy squalls	Heavy squalls		
l.	Lightning	Lightning	Lightning		Lightning
m.		Mist		Mist in valley	Mist or hazy atmosphere

o.					Overcast. Entire sky covered by thick clouds.
p.	Passing cloud	Passing cloud	Passing cloud	Passing cloud	Passing shower
q.					Squally winds
r.	Rain	Rain	Rain	Rain	Rain, continuous
s.	Sultry			Strong squalls	Snow
sd.	Settled weather				
sh.	Showers	Weather with Showers	Weather with Showers	Showers	
sy.	Steady breeze				
sr.	Light rain	Light rain	Light rain	Light rain	Light rain
sq.	Squally wind	Squally wind	Squally wind		
st.				Stratus clouds	
t.	Thunder	Thunder	Thunder		Thunder
thr.	Threatening skies	Threatening skies	Threatening skies		
vr.					Violent rain
w.	Watery skies	Watery skies	Watery skies		Wet, dew

Table i: Sir Francis Beaufort's personal weather notation and it's modifications between 1806 and 1832.

From http://www.islandnet.com/~see/weather/history/beawxnto.htm, *The Weather Legacy of Admiral Sir Francis Beaufort* ©1998, Spectrum Educational Enterprises. All Rights Reserved. Correspondence may be sent to P.O. Box 8302, Victoria, BC, Canada V8W 3R9.

weather term	**50's**	**60's**	**70's**	**80's**	**90's**	**00's**	**10's**	**20's**	**Total**	**Cu total**	**Cu percent**
cloudy	216	222	180	136	167	253	164	170	**1508**	1508	24.03
squally	95	97	112	101	145	136	127	63	**876**	2384	37.99
rain	77	81	71	94	119	105	131	109	**787**	3171	50.53
fair	126	109	95	139	84	66	41	54	**714**	3885	61.90
hazy	105	116	80	81	45	72	67	61	**627**	4512	71.89
fine	0	0	2	39	45	86	140	204	**516**	5028	80.11
clear	29	39	46	43	89	140	59	4	**449**	5477	87.27
pleasant weather	2	0	9	68	25	28	31	14	**177**	5654	90.09
foggy	26	13	37	4	2	2	8	4	**96**	5750	91.62
thunder/lightning	14	17	10	9	0	2	11	9	**72**	5822	92.77
heavy/hard rain	2	6	4	8	16	12	13	10	**71**	5893	93.90
showers	7	5	7	1	8	13	10	5	**56**	5949	94.79
thick	11	9	14	2	6	2	3	3	**50**	5999	95.59
variable weather	6	6	8	1	15	3	6	0	**45**	6044	96.30
unsettled	0	2	1	15	6	2	6	4	**36**	6080	96.88
small rain	7	4	2	2	4	7	7	0	**33**	6113	97.40
drizzling rain	3	4	4	5	0	0	7	3	**26**	6139	97.82
dark	0	3	0	4	4	6	2	0	**19**	6158	98.12
snow	0	2	14	0	0	0	0	0	**16**	6174	98.37
sultry	0	0	0	0	1	1	1	11	**14**	6188	98.60
constant/continual rain	1	1	0	0	6	1	1	3	**13**	6201	98.80
hail	0	0	4	2	1	3	2	0	**12**	6213	99.00
sleet	0	0	10	1	0	0	0	0	**11**	6224	99.17
hot	3	0	0	1	0	0	0	5	**9**	6233	99.31
sea ice	0	0	9	0	0	0	0	0	**9**	6242	99.46
serene	0	0	0	6	0	0	0	0	**6**	6248	99.55
close	1	0	0	2	0	2	0	0	**5**	6253	99.63
warm/warmer	0	0	1	0	0	1	0	2	**4**	6257	99.70
frost	0	0	3	0	0	0	0	0	**3**	6260	99.75
uncertain	3	0	0	0	0	0	0	0	**3**	6263	99.79
moderate weather	2	0	0	0	0	0	0	0	**2**	6265	99.82
temperate	0	0	0	2	0	0	0	0	**2**	6267	99.86
clearing up	0	0	0	0	1	0	0	0	**1**	6268	99.87
cold	0	0	0	1	0	0	0	0	**1**	6269	99.89
cool/cooler	0	0	0	0	0	1	0	0	**1**	6270	99.90
damp air	0	0	0	0	0	1	0	0	**1**	6271	99.92
gloomy	0	0	0	1	0	0	0	0	**1**	6272	99.94
good weather	0	0	0	1	0	0	0	0	**1**	6273	99.95
misty	0	0	0	0	0	0	1	0	**1**	6274	99.97
settled	0	0	0	0	1	0	0	0	**1**	6275	99.98
sunshine	0	0	1	0	0	0	0	0	**1**	6276	100.00

Table ii: The full range of weather terms used in the logbook sample. ‘Cu’ denotes ‘cumulative’

wind term	**50's**	**60's**	**70's**	**80's**	**90's**	**00's**	**10's**	**20's**	**Total**	**Cu total**	**Cu Percent**
moderate	212	219	182	110	87	234	68	32	1144	1144	18.11
fresh breezes	9	94	112	89	136	182	115	72	809	1953	30.92
fresh gales	221	189	138	57	22	20	10	8	665	2618	41.45
light breezes	17	34	38	52	90	135	80	98	544	3162	50.06
light airs	42	50	75	53	85	91	88	45	529	3691	58.44
moderate breezes	2	14	9	67	81	96	101	113	483	4174	66.09
calm	15	23	40	38	43	43	51	55	308	4482	70.96
variable	4	13	14	54	65	17	30	68	265	4747	75.16
light winds	3	4	6	54	10	15	36	70	198	4945	78.29
little wind	91	35	22	4	1	25	0	0	178	5123	81.11
strong gales	18	35	49	28	20	17	5	0	172	5295	83.83
fresh trade	4	0	0	22	22	6	30	30	114	5409	85.64
moderate trade	0	0	0	25	19	4	15	44	107	5516	87.33
pleasant breezes	7	2	0	28	27	1	33	8	106	5622	89.01
strong breezes	0	0	0	13	11	19	30	15	88	5710	90.41
pleasant trade	0	0	0	26	20	1	22	7	76	5786	91.61
hard gales	31	6	9	3	19	3	1	2	74	5860	92.78
moderate gales	25	16	3	2	0	0	0	5	51	5911	93.59
light trade	0	0	0	11	8	0	16	12	47	5958	94.33
steady trade	0	0	0	1	2	0	8	34	45	6003	95.04
steady/constant breezes	0	0	0	5	3	1	12	22	43	6046	95.73
fresh winds/airs	3	1	13	11	6	6	0	0	40	6086	96.36
inclinable to calms	5	4	2	4	8	7	8	1	39	6125	96.98
increasing/ decreasing breezes	0	0	0	8	10	8	7	6	39	6164	97.59
unsettled	0	0	1	12	0	0	6	4	23	6187	97.96
Strong trade	0	0	0	0	5	0	2	9	16	6203	98.21
blows hard/strong	1	0	0	6	1	0	2	6	16	6219	98.46
fine breezes	0	0	2	8	1	1	1	0	13	6232	98.67
pleasant gales	2	0	0	7	1	0	0	0	10	6242	98.83
brisk trade	0	0	0	7	2	0	0	0	9	6251	98.97
strong winds	0	0	0	0	1	1	5	2	9	6260	99.11
small breezes	5	0	1	0	0	0	0	0	6	6266	99.21
steady gales	0	0	0	5	1	0	0	0	6	6272	99.30
brisk gales	0	0	0	5	1	0	0	0	6	6278	99.40
steady monsoon	0	0	0	0	0	0	2	2	4	6282	99.46
strong gusts	0	0	0	2	0	0	0	2	4	6286	99.53
moderate monsoon	0	0	0	0	0	0	3	0	3	6289	99.57
pleasant winds	0	0	0	2	1	0	0	0	3	6292	99.62
increasing gales	0	0	0	3	0	0	0	0	3	6295	99.67
hurricane	0	0	0	1	0	1	0	1	3	6298	99.72
small airs	2	0	0	0	0	0	0	0	2	6300	99.75
fresh steady	0	0	0	1	0	0	0	1	2	6302	99.78

breezes											
variable breezes	0	0	0	1	1	0	0	0	2	6304	99.81
increasing/ decreasing trade	0	0	0	1	0	1	0	0	2	6306	99.84
gentle winds	0	0	0	0	0	1	0	0	1	6307	99.86
little breezes	1	0	0	0	0	0	0	0	1	6308	99.87
gentle breezes	0	0	0	0	0	1	0	0	1	6309	99.89
light monsoon	0	0	0	0	0	0	1	0	1	6310	99.91
fresh monsoon	0	0	0	0	0	0	1	0	1	6311	99.92
great gales	1	0	0	0	0	0	0	0	1	6312	99.94
tremendous gales	0	0	0	0	0	1	0	0	1	6313	99.95
violent gales	0	0	0	0	1	0	0	0	1	6314	99.97
violent storm	0	1	0	0	0	0	0	0	1	6315	99.98
sea breeze	0	0	0	0	1	0	0	0	1	6316	100.00
total	721	740	716	826	812	938	789	774	6316		

Table iii: The full range of wind force terms used in the logbook sample. ‘Cu’ denotes ‘cumulative’

wind force	**mean distance run**	**N**	**wind force**	**mean distance run**	**N**
baffling winds	3.00	1	pleasant winds	119.87	75
calm	19.72	207	light monsoon	120.50	4
faint airs	26.33	3	fresh breezes	121.82	440
great gales	37.00	1	moderate trade	123.70	310
violent gales	40.00	1	agreeable gales	126.00	1
faint breezes	48.88	8	strong winds	126.67	6
faint winds	50.29	7	fresh gales	127.38	379
light airs	50.92	394	steady winds	128.82	11
blowing fresh	54.25	4	fine breezes	129.47	43
small breezes	57.06	16	fine trade	132.25	16
easy breezes	62.00	4	blowing strong	133.00	1
little winds	63.00	215	moderate monsoon	133.86	7
storm	63.67	3	fine gales	134.91	11
light winds	69.50	284	pleasant trade	135.35	279
faint gales	71.00	1	pleasant gales	136.53	173
light breezes	71.78	414	stiff breezes	138.50	2
much wind	72.67	3	strong breezes	139.66	219
hard gales	77.37	179	steady breezes	140.17	155
faint trade	84.67	6	fresh winds	140.95	42
gentle gales	88.00	12	Unsteady breezes	141.00	1
gentle breezes	89.56	16	steady trade	141.92	167
light gales	92.00	36	pleasant monsoon	145.00	6
moderate breezes	96.90	391	fresh trade	149.87	341
moderate	96.98	395	brisk trade	150.90	61
easy gales	97.20	5	strong monsoon	153.00	1
Blowing hard	99.00	2	brisk gales	153.52	69
moderate gales	99.87	150	fair breezes	161.00	2
light trade	100.81	245	strong trade	163.16	69
strong gales	105.24	339	Unsteady trade	165.00	1
stiff gales	106.50	4	Brisk winds	166.00	3
unsteady winds	108.00	1	steady gales	170.96	50
scant trade	110.57	7	steady monsoon	174.43	7
gentle trade	116.67	3	Heavy gales	194.50	2
easy trade	117.30	10	fresh monsoon	197.00	3
pleasant breezes	118.21	317			

Table iv: Sampling of mean distance run for each wind force, for analysis of the relationship between wind force and distance and the translation of 18th Century wind terminology into present day equivalent.

APPENDIX IV – DATA CHARACTERISTICS

Spatial distribution of data for the period 1750-1850

	S	**S**	**S**	**N**	**N**	**N**	**N**
	sector 1	**sector 2**	**sector 3**	**sector 4**	**sector 5**	**sector 6**	**sector 7**
	15-30Nx15-30W	**10-30Nx30-45W**	**10-30Nx45-70W**	**30-45Nx65-80W**	**32-50Nx50-65W**	**35-55Nx30-50W**	**40-55Nx10-30W**
1750	56	38	33	45	30	59	100
1751	15	40	9	12	31	46	92
1752	43	28	26	5	39	67	64
1753	13	11	42	32	64	65	58
1754	18	22	36	25	23	68	77
1755	24	25	78	25	72	74	100
1756	23	20	24	6	63	51	157
1757	22	66	52	16	27	57	172
1758	28	33	49	24	61	60	133
1759	33	44	45	16	55	51	90
1760	25	39	23	18	44	80	109
1761	43	30	56	34	32	30	74
1762	30	72	43	31	16	37	101
1763	60	53	45	27	40	32	93
1764	36	37	31	18	14	35	84
1765	41	45	4	40	20	41	93
1766	23	16	18	21	44	90	103
1767	20	53	42	13	38	74	85
1768	53	32	15	35	20	74	91
1769	41	33	19	39	38	47	120
1770	43	39	53	62	32	72	71
1771	13	30	54	37	42	55	86
1772	34	54	48	41	29	18	74
1773	30	13	28	34	27	54	55
1774	45	8	15	14	27	66	68
1775	39	41	24	28	36	52	63
1776	2	9	38	97	70	74	76
1777	45	19	48	41	67	118	80
1778	17	16	38	51	32	77	80
1779	53	25	70	23	44	61	84
1780	49	20	32	28	41	116	110
1781	29	25	64	37	32	53	85

1782	29	32	62	17	39	73	110
1783	18	27	80	36	72	39	43
1784	20	37	27	6	12	60	71
1785	44	0	8	0	3	15	33
1786	19	39	4	6	13	26	30
1787	34	40	5	0	0	15	58
1788	12	43	0	0	0	25	31
1789	48	25	12	0	0	26	40
1790	22	36	5	5	13	23	56
1791	30	27	17	8	12	23	32
1792	40	23	34	10	19	30	47
1793	39	34	55	0	10	33	95
1794	47	60	126	31	26	26	49
1795	38	42	98	20	28	56	95
1796	60	50	85	4	47	54	104
1797	57	54	86	21	48	83	78
1798	55	66	39	37	29	66	127
1799	62	44	73	28	43	44	64
total mean	**34.4**	**34.3**	**40.36**	**24.08**	**33.28**	**53.42**	**81.82**

Table i: Spatial distribution of the data over the seven grid squares for each year, showing number of days of data per year.

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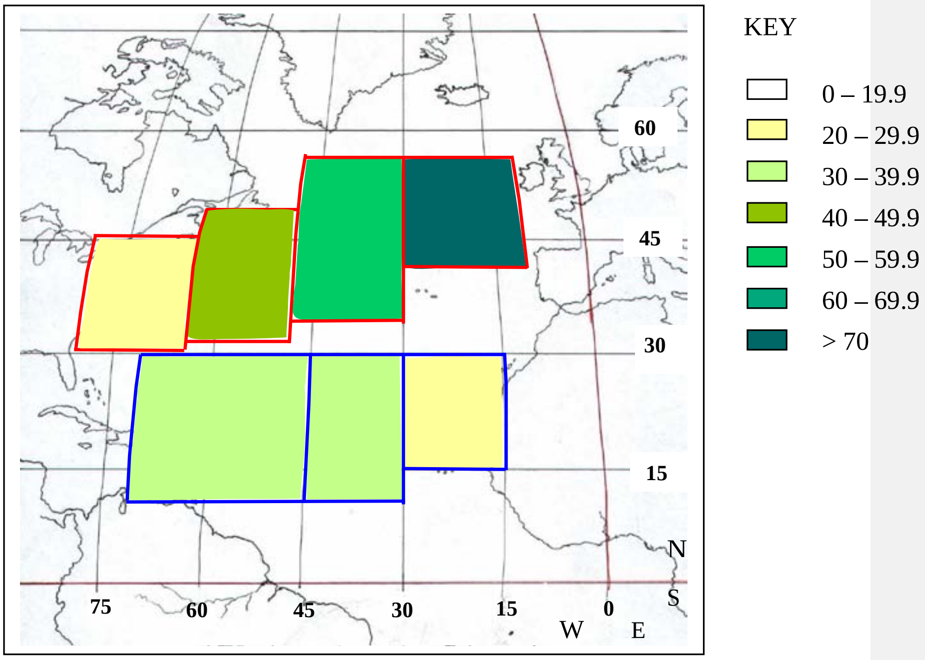
Maps of spatial distribution for each decade



Map i: Map of spatial distribution of 1750s

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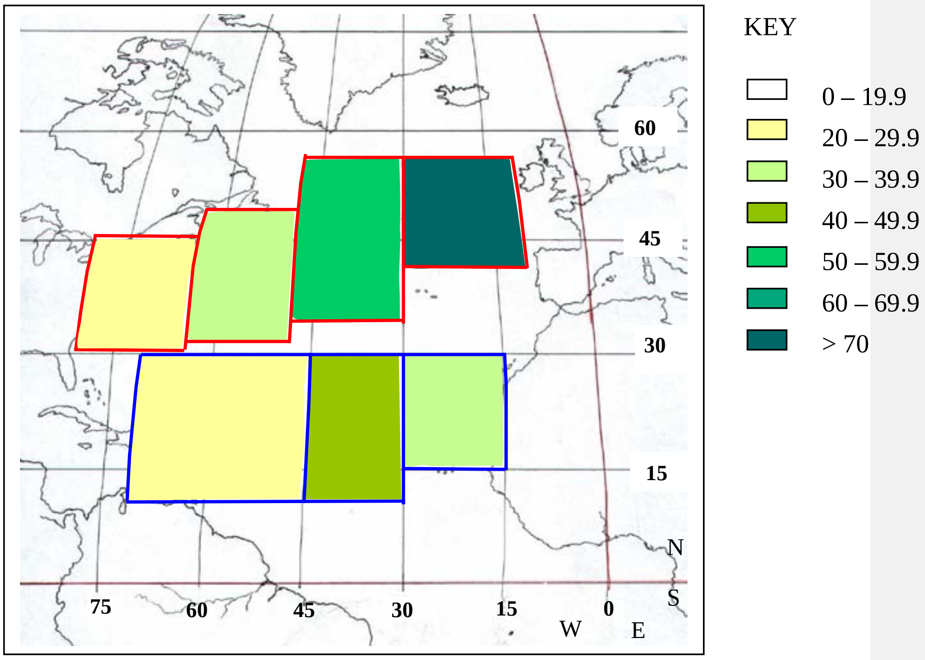
Sector (Hem)	Range	Mean number of days data over the decade
1 (S)	15 – 30N 15 – 30W	27.5
2 (S)	10 – 30N 30 – 45W	32.7
3 (S)	10 – 30N 45 – 70W	39.4
4 (N)	30 –45N 65 – 80W	20.6
5 (N)	32 – 50N 50 – 65W	46.5
6 (N)	35 – 55N 30 – 50W	59.8
7 (N)	40 – 55N 10 –30W	104.3

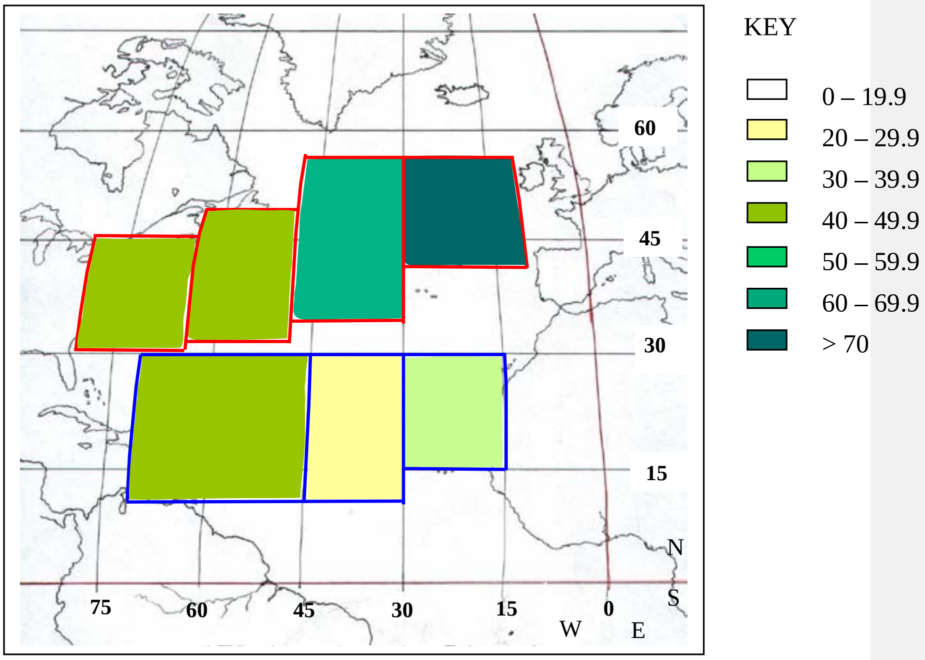
Table ii: spatial distribution of data coverage for 1750s



Map ii: Map of spatial distribution of 1760s

Sector (Hem)	Range	Mean number of days data over the decade
1 (S)	15 – 30N 15 – 30W	37.2
2 (S)	10 – 30N 30 – 45W	41.0
3 (S)	10 – 30N 45 – 70W	29.6
4 (N)	30 –45N 65 – 80W	27.6
5 (N)	32 – 50N 50 – 65W	30.6
6 (N)	35 – 55N 30 – 50W	54.0
7 (N)	40 – 55N 10 –30W	95.3

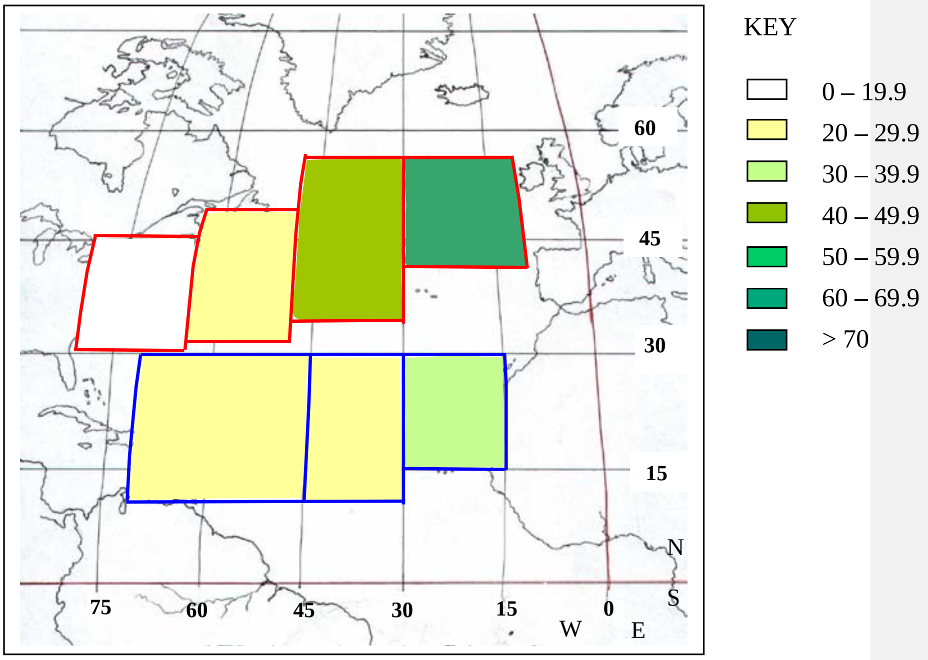
Table iii: spatial distribution of data coverage for 1760s



Map iii: Map of spatial distribution of 1770s

Sector (Hem)	Range	Mean number of days data over the decade
1 (S)	15 – 30N 15 – 30W	32.1
2 (S)	10 – 30N 30 – 45W	25.4
3 (S)	10 – 30N 45 – 70W	41.6
4 (N)	30 –45N 65 – 80W	42.8
5 (N)	32 – 50N 50 – 65W	40.6
6 (N)	35 – 55N 30 – 50W	64.7
7 (N)	40 – 55N 10 –30W	73.7

Table iv: spatial distribution of data coverage for 1770s



Map iv: Map of spatial distribution of 1780s

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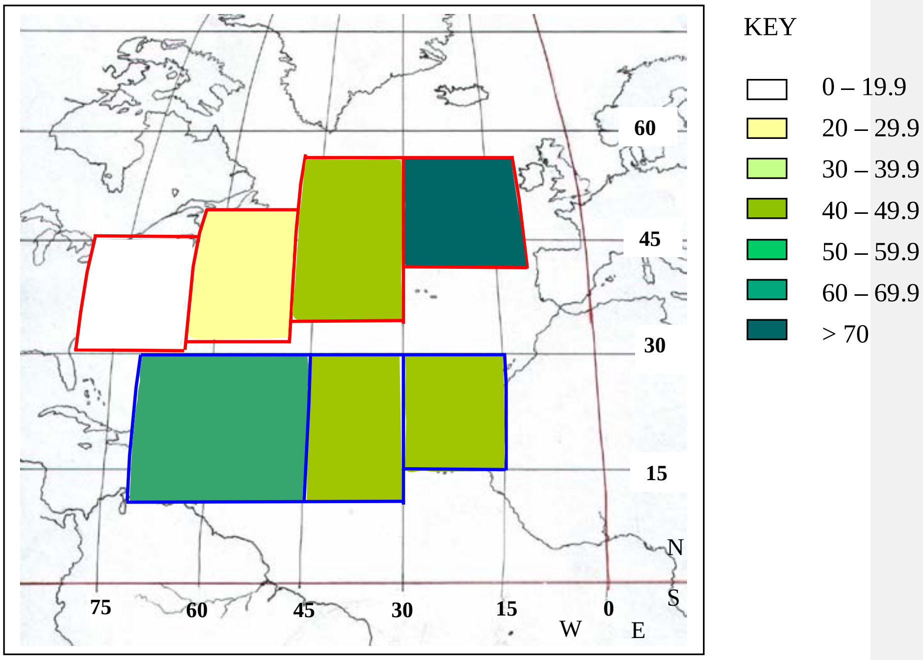
Sector (Hem)	Range	Mean number of days data over the decade
1 (S)	15 – 30N 15 – 30W	30.2
2 (S)	10 – 30N 30 – 45W	28.8
3 (S)	10 – 30N 45 – 70W	29.4
4 (N)	30 –45N 65 – 80W	13.0
5 (N)	32 – 50N 50 – 65W	21.2
6 (N)	35 – 55N 30 – 50W	44.8
7 (N)	40 – 55N 10 –30W	61.1

Table v: spatial distribution of data coverage for 1780s



Map v: Map of spatial distribution of 1790s

Sector (Hem)	Range	Mean number of days data over the decade
1 (S)	15 – 30N 15 – 30W	45
2 (S)	10 – 30N 30 – 45W	43.6
3 (S)	10 – 30N 45 – 70W	61.8
4 (N)	30 –45N 65 – 80W	16.4
5 (N)	32 – 50N 50 – 65W	27.5
6 (N)	35 – 55N 30 – 50W	43.8
7 (N)	40 – 55N 10 –30W	74.7

Table vi: spatial distribution of data coverage for 1790s

Temporal coverage of data for each corridor

		days of data																						
		N	**S**	**total**			**N**	**S**	**total**			**N**	**S**	**total**			**N**	**S**	**total**			**N**	**S**	**total**
1750	Jan	11	17	28	1760	Jan	17	16	33	1770	Jan	14	24	38	1780	Jan	20	12	32	1790	Jan	11	5	16
1750	Feb	9	20	29	1760	Feb	14	2	16	1770	Feb	24	14	38	1780	Feb	17	0	17	1790	Feb	0	1	1
1750	Mar	3	8	11	1760	Mar	27	0	27	1770	Mar	9	7	16	1780	Mar	24	4	28	1790	Mar	13	19	32
1750	Apr	23	6	29	1760	Apr	30	23	53	1770	Apr	4	5	9	1780	Apr	21	16	37	1790	Apr	6	24	30
1750	May	21	18	39	1760	May	29	0	29	1770	May	28	5	33	1780	May	30	10	40	1790	May	29	13	42
1750	Jun	28	7	35	1760	Jun	28	0	28	1770	Jun	30	6	36	1780	Jun	21	0	21	1790	Jun	4	0	4
1750	Jul	28	5	33	1760	Jul	28	8	36	1770	Jul	26	3	29	1780	Jul	17	16	33	1790	Jul	0	0	0
1750	Aug	27	5	32	1760	Aug	30	11	41	1770	Aug	23	7	30	1780	Aug	31	2	33	1790	Aug	0	0	0
1750	Sep	18	13	31	1760	Sep	13	0	13	1770	Sep	18	22	40	1780	Sep	29	0	29	1790	Sep	0	0	0
1750	Oct	31	6	37	1760	Oct	0	0	0	1770	Oct	22	19	41	1780	Oct	31	14	45	1790	Oct	2	0	2
1750	Nov	16	2	18	1760	Nov	24	0	24	1770	Nov	24	13	37	1780	Nov	25	7	32	1790	Nov	29	0	29
1750	Dec	12	6	18	1760	Dec	6	21	27	1770	Dec	11	7	18	1780	Dec	20	1	21	1790	Dec	0	0	0
1751	Jan	21	1	22	1761	Jan	2	0	2	1771	Jan	12	6	18	1781	Jan	14	31	45	1791	Jan	2	8	10
1751	Feb	0	3	3	1761	Feb	0	24	24	1771	Feb	14	4	18	1781	Feb	12	5	17	1791	Feb	0	0	0
1751	Mar	16	19	35	1761	Mar	19	7	26	1771	Mar	15	19	34	1781	Mar	11	0	11	1791	Mar	11	2	13
1751	Apr	6	7	13	1761	Apr	4	24	28	1771	Apr	18	0	18	1781	Apr	13	18	31	1791	Apr	9	0	9
1751	May	0	10	10	1761	May	24	2	26	1771	May	14	14	28	1781	May	5	7	12	1791	May	1	6	7
1751	Jun	15	7	22	1761	Jun	6	9	15	1771	Jun	17	8	25	1781	Jun	19	0	19	1791	Jun	8	0	8
1751	Jul	31	6	37	1761	Jul	17	0	17	1771	Jul	26	11	37	1781	Jul	24	4	28	1791	Jul	0	7	7
1751	Aug	29	7	36	1761	Aug	4	12	16	1771	Aug	16	11	27	1781	Aug	18	12	30	1791	Aug	14	0	14
1751	Sep	23	0	23	1761	Sep	29	0	29	1771	Sep	30	6	36	1781	Sep	24	7	31	1791	Sep	10	7	17
1751	Oct	12	0	12	1761	Oct	27	29	56	1771	Oct	24	3	27	1781	Oct	21	0	21	1791	Oct	16	21	37

1751	Nov	12	0	12	1761	Nov	29	0	29	1771	Nov	16	20	36	1781	Nov	24	8	32	1791	Nov	0	2	2
1751	Dec	1	3	4	1761	Dec	6	20	26	1771	Dec	14	0	14	1781	Dec	17	23	40	1791	Dec	2	19	21
1752	Jan	0	3	3	1762	Jan	4	23	27	1772	Jan	3	25	28	1782	Jan	25	0	25	1792	Jan	0	8	8
1752	Feb	0	9	9	1762	Feb	18	26	44	1772	Feb	0	0	0	1782	Feb	6	8	14	1792	Feb	0	0	0
1752	Mar	8	0	8	1762	Mar	26	28	54	1772	Mar	15	11	26	1782	Mar	14	0	14	1792	Mar	5	17	22
1752	Apr	29	11	40	1762	Apr	12	12	24	1772	Apr	21	0	21	1782	Apr	1	0	1	1792	Apr	12	14	26
1752	May	21	14	35	1762	May	15	8	23	1772	May	23	12	35	1782	May	30	16	46	1792	May	21	9	30
1752	Jun	27	13	40	1762	Jun	24	21	45	1772	Jun	29	4	33	1782	Jun	25	16	41	1792	Jun	24	13	37
1752	Jul	18	5	23	1762	Jul	7	12	19	1772	Jul	20	20	40	1782	Jul	31	0	31	1792	Jul	0	0	0
1752	Aug	11	11	22	1762	Aug	23	2	25	1772	Aug	4	13	17	1782	Aug	14	22	36	1792	Aug	17	5	22
1752	Sep	2	0	2	1762	Sep	28	5	33	1772	Sep	7	3	10	1782	Sep	24	12	36	1792	Sep	12	9	21
1752	Oct	22	0	22	1762	Oct	0	0	0	1772	Oct	15	10	25	1782	Oct	18	16	34	1792	Oct	3	0	3
1752	Nov	21	10	31	1762	Nov	12	0	12	1772	Nov	14	19	33	1782	Nov	29	0	29	1792	Nov	10	1	11
1752	Dec	9	11	20	1762	Dec	12	6	18	1772	Dec	4	15	19	1782	Dec	12	22	34	1792	Dec	0	18	18
1753	Jan	19	4	23	1763	Jan	18	9	27	1773	Jan	3	15	18	1783	Jan	5	28	33	1793	Jan	5	5	10
1753	Feb	0	5	5	1763	Feb	12	0	12	1773	Feb	11	11	22	1783	Feb	27	0	27	1793	Feb	0	0	0
1753	Mar	0	2	2	1763	Mar	9	16	25	1773	Mar	15	13	28	1783	Mar	12	22	34	1793	Mar	0	0	0
1753	Apr	11	0	11	1763	Apr	25	7	32	1773	Apr	12	9	21	1783	Apr	0	7	7	1793	Apr	25	23	48
1753	May	26	9	35	1763	May	26	12	38	1773	May	19	10	29	1783	May	11	0	11	1793	May	24	13	37
1753	Jun	15	16	31	1763	Jun	11	27	38	1773	Jun	21	4	25	1783	Jun	30	8	38	1793	Jun	4	16	20
1753	Jul	25	9	34	1763	Jul	11	21	32	1773	Jul	12	0	12	1783	Jul	22	0	22	1793	Jul	28	18	46
1753	Aug	26	13	39	1763	Aug	5	7	12	1773	Aug	23	0	23	1783	Aug	26	14	40	1793	Aug	21	13	34
1753	Sep	30	1	31	1763	Sep	22	0	22	1773	Sep	18	0	18	1783	Sep	22	0	22	1793	Sep	18	19	37
1753	Oct	8	0	8	1763	Oct	15	29	44	1773	Oct	16	0	16	1783	Oct	6	0	6	1793	Oct	0	0	0
1753	Nov	25	0	25	1763	Nov	22	10	32	1773	Nov	16	0	16	1783	Nov	25	17	42	1793	Nov	8	7	15
1753	Dec	15	0	15	1763	Dec	8	12	20	1773	Dec	2	9	11	1783	Dec	1	26	27	1793	Dec	1	12	13

1754	Jan	16	4	20	1764	Jan	0	17	17	1774	Jan	0	0	0	1784	Jan	0	14	14	1794	Jan	1	28	29
1754	Feb	0	0	0	1764	Feb	13	0	13	1774	Feb	9	0	9	1784	Feb	12	16	28	1794	Feb	0	27	27
1754	Mar	5	11	16	1764	Mar	12	16	28	1774	Mar	13	17	30	1784	Mar	22	8	30	1794	Mar	11	14	25
1754	Apr	0	12	12	1764	Apr	7	8	15	1774	Apr	14	12	26	1784	Apr	26	6	32	1794	Apr	19	27	46
1754	May	8	0	8	1764	May	4	0	4	1774	May	30	0	30	1784	May	9	15	24	1794	May	13	14	27
1754	Jun	26	7	33	1764	Jun	27	20	47	1774	Jun	6	0	6	1784	Jun	18	16	34	1794	Jun	2	20	22
1754	Jul	31	0	31	1764	Jul	22	5	27	1774	Jul	29	14	43	1784	Jul	30	6	36	1794	Jul	0	19	19
1754	Aug	18	26	44	1764	Aug	26	8	34	1774	Aug	18	17	35	1784	Aug	13	0	13	1794	Aug	20	1	21
1754	Sep	13	0	13	1764	Sep	19	6	25	1774	Sep	9	0	9	1784	Sep	0	0	0	1794	Sep	30	17	47
1754	Oct	29	9	38	1764	Oct	5	18	23	1774	Oct	6	0	6	1784	Oct	10	0	10	1794	Oct	11	22	33
1754	Nov	23	0	23	1764	Nov	5	5	10	1774	Nov	21	0	21	1784	Nov	0	0	0	1794	Nov	8	27	35
1754	Dec	14	0	14	1764	Dec	5	0	5	1774	Dec	16	6	22	1784	Dec	3	0	3	1794	Dec	12	5	17
1755	Jan	7	21	28	1765	Jan	17	0	17	1775	Jan	5	5	10	1785	Jan	13	6	19	1795	Jan	0	0	0
1755	Feb	21	26	47	1765	Feb	6	8	14	1775	Feb	8	11	19	1785	Feb	0	10	10	1795	Feb	16	3	19
1755	Mar	20	7	27	1765	Mar	0	16	16	1775	Mar	2	12	14	1785	Mar	5	8	13	1795	Mar	9	29	38
1755	Apr	7	0	7	1765	Apr	16	13	29	1775	Apr	9	15	24	1785	Apr	4	20	24	1795	Apr	2	11	13
1755	May	29	0	29	1765	May	31	4	35	1775	May	15	5	20	1785	May	0	0	0	1795	May	7	14	21
1755	Jun	30	12	42	1765	Jun	27	5	32	1775	Jun	5	7	12	1785	Jun	0	0	0	1795	Jun	30	23	53
1755	Jul	31	5	36	1765	Jul	22	0	22	1775	Jul	10	22	32	1785	Jul	0	0	0	1795	Jul	30	26	56
1755	Aug	21	14	35	1765	Aug	23	0	23	1775	Aug	31	10	41	1785	Aug	0	0	0	1795	Aug	23	0	23
1755	Sep	28	22	50	1765	Sep	0	23	23	1775	Sep	30	0	30	1785	Sep	0	7	7	1795	Sep	20	12	32
1755	Oct	19	8	27	1765	Oct	30	0	30	1775	Oct	13	11	24	1785	Oct	17	1	18	1795	Oct	16	9	25
1755	Nov	24	7	31	1765	Nov	20	0	20	1775	Nov	16	2	18	1785	Nov	0	0	0	1795	Nov	29	28	57
1755	Dec	17	0	17	1765	Dec	0	18	18	1775	Dec	31	3	34	1785	Dec	11	0	11	1795	Dec	11	20	31
1756	Jan	0	0	0	1766	Jan	20	4	24	1776	Jan	30	11	41	1786	Jan	0	8	8	1796	Jan	9	29	38
1756	Feb	21	0	21	1766	Feb	0	0	0	1776	Feb	29	9	38	1786	Feb	4	0	4	1796	Feb	4	14	18

1756	Mar	17	23	40	1766	Mar	21	2	23	1776	Mar	18	0	18	1786	Mar	6	5	11	1796	Mar	24	31	55
1756	Apr	27	11	38	1766	Apr	30	0	30	1776	Apr	8	6	14	1786	Apr	0	13	13	1796	Apr	19	14	33
1756	May	31	0	31	1766	May	31	9	40	1776	May	27	0	27	1786	May	4	11	15	1796	May	4	27	31
1756	Jun	31	5	36	1766	Jun	19	0	19	1776	Jun	27	6	33	1786	Jun	23	17	40	1796	Jun	7	24	31
1756	Jul	15	11	26	1766	Jul	24	9	33	1776	Jul	30	0	30	1786	Jul	3	0	3	1796	Jul	30	10	40
1756	Aug	27	2	29	1766	Aug	28	2	30	1776	Aug	30	15	45	1786	Aug	31	7	38	1796	Aug	29	12	41
1756	Sep	17	10	27	1766	Sep	19	14	33	1776	Sep	30	0	30	1786	Sep	2	0	2	1796	Sep	12	0	12
1756	Oct	26	0	26	1766	Oct	31	8	39	1776	Oct	28	0	28	1786	Oct	0	0	0	1796	Oct	13	7	20
1756	Nov	23	0	23	1766	Nov	11	0	11	1776	Nov	29	0	29	1786	Nov	0	0	0	1796	Nov	30	15	45
1756	Dec	24	0	24	1766	Dec	16	8	24	1776	Dec	22	2	24	1786	Dec	0	0	0	1796	Dec	16	7	23
1757	Jan	21	15	36	1767	Jan	7	24	31	1777	Jan	19	14	33	1787	Jan	11	0	11	1797	Jan	10	19	29
1757	Feb	15	0	15	1767	Feb	0	0	0	1777	Feb	28	20	48	1787	Feb	4	6	10	1797	Feb	7	17	24
1757	Mar	10	7	17	1767	Mar	5	3	8	1777	Mar	18	0	18	1787	Mar	5	8	13	1797	Mar	18	28	46
1757	Apr	12	17	29	1767	Apr	28	16	44	1777	Apr	29	1	30	1787	Apr	4	9	13	1797	Apr	20	8	28
1757	May	21	29	50	1767	May	22	20	42	1777	May	30	0	30	1787	May	11	16	27	1797	May	4	10	14
1757	Jun	27	15	42	1767	Jun	24	15	39	1777	Jun	24	0	24	1787	Jun	24	13	37	1797	Jun	27	17	44
1757	Jul	21	12	33	1767	Jul	18	7	25	1777	Jul	25	9	34	1787	Jul	0	0	0	1797	Jul	28	20	48
1757	Aug	29	13	42	1767	Aug	24	0	24	1777	Aug	19	11	30	1787	Aug	0	0	0	1797	Aug	23	12	35
1757	Sep	28	18	46	1767	Sep	28	0	28	1777	Sep	29	0	29	1787	Sep	5	12	17	1797	Sep	21	18	39
1757	Oct	24	5	29	1767	Oct	25	26	51	1777	Oct	22	16	38	1787	Oct	9	11	20	1797	Oct	28	20	48
1757	Nov	29	0	29	1767	Nov	12	1	13	1777	Nov	23	29	52	1787	Nov	0	0	0	1797	Nov	24	1	25
1757	Dec	23	0	23	1767	Dec	15	2	17	1777	Dec	19	10	29	1787	Dec	0	0	0	1797	Dec	3	18	21
1758	Jan	29	5	34	1768	Jan	9	11	20	1778	Jan	24	0	24	1788	Jan	0	0	0	1798	Jan	7	15	22
1758	Feb	3	22	25	1768	Feb	13	10	23	1778	Feb	11	10	21	1788	Feb	0	0	0	1798	Feb	18	17	35
1758	Mar	29	5	34	1768	Mar	0	9	9	1778	Mar	17	1	18	1788	Mar	0	0	0	1798	Mar	29	11	40
1758	Apr	3	24	27	1768	Apr	15	12	27	1778	Apr	8	12	20	1788	Apr	13	21	34	1798	Apr	28	7	35

1758	May	15	0	15	1768	May	29	18	47	1778	May	11	13	24	1788	May	6	0	6	1798	May	30	18	48
1758	Jun	14	13	27	1768	Jun	23	23	46	1778	Jun	22	10	32	1788	Jun	0	0	0	1798	Jun	27	17	44
1758	Jul	31	0	31	1768	Jul	30	0	30	1778	Jul	31	4	35	1788	Jul	0	9	9	1798	Jul	30	13	43
1758	Aug	17	24	41	1768	Aug	15	0	15	1778	Aug	29	10	39	1788	Aug	11	2	13	1798	Aug	21	10	31
1758	Sep	29	8	37	1768	Sep	15	9	24	1778	Sep	12	0	12	1788	Sep	1	11	12	1798	Sep	22	14	36
1758	Oct	29	0	29	1768	Oct	14	0	14	1778	Oct	31	0	31	1788	Oct	16	0	16	1798	Oct	17	14	31
1758	Nov	28	0	28	1768	Nov	29	6	35	1778	Nov	25	6	31	1788	Nov	7	0	7	1798	Nov	12	6	18
1758	Dec	24	0	24	1768	Dec	24	0	24	1778	Dec	15	5	20	1788	Dec	0	9	9	1798	Dec	9	11	20
1759	Jan	10	21	31	1769	Jan	11	7	18	1779	Jan	18	10	28	1789	Jan	0	12	12	1799	Jan	12	13	25
1759	Feb	24	9	33	1769	Feb	3	11	14	1779	Feb	0	29	29	1789	Feb	0	0	0	1799	Feb	7	8	15
1759	Mar	4	2	6	1769	Mar	29	6	35	1779	Mar	20	9	29	1789	Mar	2	4	6	1799	Mar	6	28	34
1759	Apr	30	8	38	1769	Apr	23	5	28	1779	Apr	0	24	24	1789	Apr	10	16	26	1799	Apr	9	0	9
1759	May	31	4	35	1769	May	13	16	29	1779	May	17	7	24	1789	May	11	10	21	1799	May	11	23	34
1759	Jun	13	7	20	1769	Jun	29	6	35	1779	Jun	29	0	29	1789	Jun	10	0	10	1799	Jun	14	24	38
1759	Jul	20	4	24	1769	Jul	30	8	38	1779	Jul	7	17	24	1789	Jul	10	16	26	1799	Jul	16	0	16
1759	Aug	19	24	43	1769	Aug	18	16	34	1779	Aug	29	13	42	1789	Aug	19	2	21	1799	Aug	28	9	37
1759	Sep	23	2	25	1769	Sep	30	0	30	1779	Sep	22	13	35	1789	Sep	1	0	1	1799	Sep	23	14	37
1759	Oct	0	25	25	1769	Oct	20	7	27	1779	Oct	20	3	23	1789	Oct	2	14	16	1799	Oct	16	25	41
1759	Nov	25	1	26	1769	Nov	30	7	37	1779	Nov	29	14	43	1789	Nov	0	7	7	1799	Nov	9	10	19
1759	Dec	11	6	17	1769	Dec	6	3	9	1779	Dec	19	2	21	1789	Dec	0	1	1	1799	Dec	20	21	41

Table vii: Temporal coverage of data (number of days of data for the month for the Northern and Southern Corridors. Calendar representation of this coverage can be found on CD1

APPENDIX V – RESULTS

WI and TI Indices (where NC = northern corridor and SC= southern corridor)

		NC	SC			NC	SC			NC	SC			NC	SC			NC	SC
year	**mon**	**WI**	**EI (TI)**	**year**	**mon**	**WI**	**EI (TI)**	**year**	**mon**	**WI**	**EI (TI)**	**year**	**mon**	**WI**	**EI (TI)**	**year**	**mon**	**WI**	**EI (TI)**
1750	Jan	33.82	134.94	1760	Jan	102.12	145.31	1770	Jan	64.21	62.00	1780	Jan	54.25	10.33	1790	Jan	112.73	86.80
1750	Feb	77.33	114.80	1760	Feb	82.86	0.00	1770	Feb	77.33	80.79	1780	Feb	35.82	0.00	1790	Feb	0.00	0.00
1750	Mar	0.00	15.50	1760	Mar	95.30	0.00	1770	Mar	17.22	48.71	1780	Mar	104.63	116.25	1790	Mar	40.54	73.42
1750	Apr	73.04	90.00	1760	Apr	86.00	133.04	1770	Apr	37.50	48.00	1780	Apr	88.57	35.63	1790	Apr	0.00	73.75
1750	May	64.95	96.44	1760	May	60.93	0.00	1770	May	36.54	99.20	1780	May	69.23	108.50	1790	May	34.21	40.54
1750	Jun	55.71	81.43	1760	Jun	30.00	0.00	1770	Jun	99.00	70.00	1780	Jun	107.14	0.00	1790	Jun	0.00	0.00
1750	Jul	76.39	74.40	1760	Jul	52.04	50.38	1770	Jul	58.42	124.00	1780	Jul	27.35	118.19	1790	Jul	0.00	0.00
1750	Aug	99.89	31.00	1760	Aug	34.10	163.45	1770	Aug	17.52	66.43	1780	Aug	57.00	15.50	1790	Aug	0.00	0.00
1750	Sep	3.33	66.92	1760	Sep	11.54	0.00	1770	Sep	91.67	30.00	1780	Sep	72.41	0.00	1790	Sep	0.00	0.00
1750	Oct	20.00	0.00	1760	Oct	0.00	0.00	1770	Oct	69.05	88.11	1780	Oct	62.00	252.43	1790	Oct	0.00	0.00
1750	Nov	39.38	0.00	1760	Nov	53.75	0.00	1770	Nov	100.00	41.54	1780	Nov	66.00	38.57	1790	Nov	57.93	0.00
1750	Dec	0.00	41.33	1760	Dec	67.17	115.14	1770	Dec	50.73	110.71	1780	Dec	13.95	155.00	1790	Dec	0.00	0.00
1751	Jan	159.43	0.00	1761	Jan	139.50	0.00	1771	Jan	23.25	103.33	1781	Jan	66.43	27.00	1791	Jan	217.00	23.25
1751	Feb	0.00	112.00	1761	Feb	0.00	98.00	1771	Feb	124.29	0.00	1781	Feb	37.33	46.40	1791	Feb	0.00	0.00
1751	Mar	184.06	34.26	1761	Mar	29.37	70.86	1771	Mar	68.20	37.53	1781	Mar	5.64	0.00	1791	Mar	56.36	77.50
1751	Apr	20.00	124.29	1761	Apr	0.00	63.75	1771	Apr	36.67	0.00	1781	Apr	11.54	15.00	1791	Apr	33.33	0.00
1751	May	0.00	80.60	1761	May	42.63	248.00	1771	May	128.43	73.07	1781	May	0.00	44.29	1791	May	0.00	20.67
1751	Jun	24.00	120.00	1761	Jun	100.00	176.67	1771	Jun	7.06	41.25	1781	Jun	80.53	0.00	1791	Jun	0.00	0.00
1751	Jul	102.00	103.33	1761	Jul	71.12	0.00	1771	Jul	78.69	138.09	1781	Jul	64.58	15.50	1791	Jul	0.00	88.57
1751	Aug	47.03	115.14	1761	Aug	0.00	64.58	1771	Aug	46.50	67.64	1781	Aug	22.39	31.00	1791	Aug	68.64	0.00
1751	Sep	31.30	0.00	1761	Sep	102.41	0.00	1771	Sep	40.00	130.00	1781	Sep	27.50	115.71	1791	Sep	0.00	98.57

1751	Oct	116.25	0.00	1761	Oct	17.22	103.69	1771	Oct	38.75	82.67	1781	Oct	2.95	0.00	1791	Oct	124.00	51.67
1751	Nov	0.00	0.00	1761	Nov	75.52	0.00	1771	Nov	58.13	43.50	1781	Nov	31.25	37.50	1791	Nov	0.00	75.00
1751	Dec	0.00	134.33	1761	Dec	41.33	106.95	1771	Dec	203.71	0.00	1781	Dec	9.12	72.78	1791	Dec	0.00	94.63
1752	Jan	0.00	0.00	1762	Jan	131.75	48.52	1772	Jan	0.00	17.36	1782	Jan	65.72	0.00	1792	Jan	0.00	81.38
1752	Feb	0.00	51.56	1762	Feb	98.00	54.92	1772	Feb	0.00	0.00	1782	Feb	42.00	90.63	1792	Feb	0.00	0.00
1752	Mar	34.88	0.00	1762	Mar	149.04	73.07	1772	Mar	99.20	73.27	1782	Mar	37.64	0.00	1792	Mar	99.20	56.53
1752	Apr	48.62	49.09	1762	Apr	45.00	42.50	1772	Apr	52.86	0.00	1782	Apr	0.00	0.00	1792	Apr	57.50	15.00
1752	May	91.52	46.50	1762	May	45.47	31.00	1772	May	83.57	67.17	1782	May	40.30	1.94	1792	May	69.38	65.44
1752	Jun	94.44	170.77	1762	Jun	25.00	24.29	1772	Jun	83.79	60.00	1782	Jun	64.80	93.75	1792	Jun	51.25	2.31
1752	Jul	55.11	0.00	1762	Jul	39.86	64.58	1772	Jul	43.40	93.00	1782	Jul	30.00	0.00	1792	Jul	0.00	0.00
1752	Aug	33.82	67.64	1762	Aug	71.43	62.00	1772	Aug	186.00	62.00	1782	Aug	90.79	97.23	1792	Aug	27.35	130.20
1752	Sep	255.00	0.00	1762	Sep	83.57	48.00	1772	Sep	64.29	80.00	1782	Sep	56.25	77.50	1792	Sep	12.50	20.00
1752	Oct	78.91	0.00	1762	Oct	0.00	0.00	1772	Oct	82.67	12.40	1782	Oct	36.17	21.31	1792	Oct	0.00	0.00
1752	Nov	52.86	96.00	1762	Nov	135.00	0.00	1772	Nov	75.00	44.21	1782	Nov	66.21	0.00	1792	Nov	57.00	0.00
1752	Dec	127.44	81.73	1762	Dec	15.50	36.17	1772	Dec	0.00	126.07	1782	Dec	67.17	87.36	1792	Dec	0.00	99.89
1753	Jan	58.74	7.75	1763	Jan	142.94	48.22	1773	Jan	175.67	90.93	1783	Jan	0.00	106.29	1793	Jan	179.80	0.00
1753	Feb	0.00	67.20	1763	Feb	123.67	0.00	1773	Feb	2.64	94.91	1783	Feb	62.22	0.00	1793	Feb	0.00	0.00
1753	Mar	0.00	248.00	1763	Mar	0.00	135.63	1773	Mar	43.40	126.38	1783	Mar	56.83	35.23	1793	Mar	0.00	0.00
1753	Apr	24.55	0.00	1763	Apr	99.60	34.29	1773	Apr	22.50	146.67	1783	Apr	0.00	90.00	1793	Apr	57.60	101.74
1753	May	73.92	192.89	1763	May	23.85	31.00	1773	May	124.00	68.20	1783	May	14.09	0.00	1793	May	31.00	95.38
1753	Jun	96.00	90.00	1763	Jun	32.73	113.33	1773	Jun	58.57	30.00	1783	Jun	21.00	120.00	1793	Jun	150.00	101.25
1753	Jul	71.92	82.67	1763	Jul	14.09	48.71	1773	Jul	33.58	0.00	1783	Jul	59.18	0.00	1793	Jul	39.86	158.44
1753	Aug	94.19	107.31	1763	Aug	0.00	128.43	1773	Aug	35.04	0.00	1783	Aug	85.85	73.07	1793	Aug	54.62	83.46
1753	Sep	16.00	0.00	1763	Sep	42.27	0.00	1773	Sep	10.00	0.00	1783	Sep	12.27	0.00	1793	Sep	51.67	74.21
1753	Oct	46.50	0.00	1763	Oct	72.33	97.28	1773	Oct	40.69	0.00	1783	Oct	87.83	0.00	1793	Oct	0.00	0.00
1753	Nov	88.80	0.00	1763	Nov	55.91	129.00	1773	Nov	73.13	0.00	1783	Nov	16.80	107.65	1793	Nov	18.75	21.43
1753	Dec	82.67	0.00	1763	Dec	213.13	111.08	1773	Dec	0.00	0.00	1783	Dec	124.00	33.38	1793	Dec	0.00	105.92
1754	Jan	34.88	217.00	1764	Jan	0.00	87.53	1774	Jan	0.00	0.00	1784	Jan	0.00	57.57	1794	Jan	0.00	105.18

1754	Feb	0.00	0.00	1764	Feb	20.08	0.00	1774	Feb	0.00	0.00	1784	Feb	137.75	48.94	1794	Feb	0.00	118.22
1754	Mar	0.00	67.64	1764	Mar	10.33	122.06	1774	Mar	21.46	93.00	1784	Mar	90.18	65.88	1794	Mar	53.55	104.07
1754	Apr	0.00	57.50	1764	Apr	167.14	131.25	1774	Apr	57.86	115.00	1784	Apr	16.15	140.00	1794	Apr	31.58	87.78
1754	May	34.88	0.00	1764	May	0.00	0.00	1774	May	36.17	0.00	1784	May	6.89	134.33	1794	May	78.69	46.50
1754	Jun	75.00	55.71	1764	Jun	64.44	78.00	1774	Jun	50.00	0.00	1784	Jun	80.00	144.38	1794	Jun	0.00	91.50
1754	Jul	101.00	0.00	1764	Jul	35.23	31.00	1774	Jul	95.14	124.00	1784	Jul	50.63	144.67	1794	Jul	0.00	106.05
1754	Aug	82.67	28.62	1764	Aug	31.00	155.00	1774	Aug	99.89	69.29	1784	Aug	16.69	0.00	1794	Aug	3.10	155.00
1754	Sep	57.69	0.00	1764	Sep	25.26	65.00	1774	Sep	110.00	0.00	1784	Sep	0.00	0.00	1794	Sep	43.00	107.65
1754	Oct	34.21	13.78	1764	Oct	0.00	161.89	1774	Oct	129.17	0.00	1784	Oct	27.90	0.00	1794	Oct	59.18	81.73
1754	Nov	57.39	0.00	1764	Nov	0.00	48.00	1774	Nov	60.00	0.00	1784	Nov	0.00	0.00	1794	Nov	37.50	122.22
1754	Dec	19.93	0.00	1764	Dec	124.00	0.00	1774	Dec	54.25	15.50	1784	Dec	0.00	0.00	1794	Dec	41.33	62.00
1755	Jan	124.00	97.43	1765	Jan	71.12	0.00	1775	Jan	55.80	86.80	1785	Jan	85.85	56.83	1795	Jan	0.00	0.00
1755	Feb	84.24	43.08	1765	Feb	37.33	59.50	1775	Feb	83.38	108.09	1785	Feb	0.00	63.80	1795	Feb	85.75	121.33
1755	Mar	52.70	22.14	1765	Mar	0.00	54.25	1775	Mar	0.00	36.17	1785	Mar	6.20	85.25	1795	Mar	65.44	106.90
1755	Apr	115.71	0.00	1765	Apr	24.38	96.92	1775	Apr	110.00	86.00	1785	Apr	0.00	51.00	1795	Apr	0.00	100.91
1755	May	39.55	0.00	1765	May	17.00	38.75	1775	May	35.13	0.00	1785	May	0.00	0.00	1795	May	39.86	90.79
1755	Jun	54.00	170.00	1765	Jun	51.11	72.00	1775	Jun	30.00	60.00	1785	Jun	0.00	0.00	1795	Jun	43.00	82.17
1755	Jul	103.00	99.20	1765	Jul	53.55	0.00	1775	Jul	99.20	67.64	1785	Jul	0.00	0.00	1795	Jul	130.20	91.81
1755	Aug	47.24	99.64	1765	Aug	51.22	0.00	1775	Aug	58.00	161.20	1785	Aug	0.00	0.00	1795	Aug	31.00	0.00
1755	Sep	54.64	155.45	1765	Sep	0.00	45.65	1775	Sep	63.00	0.00	1785	Sep	0.00	51.43	1795	Sep	46.50	67.50
1755	Oct	60.37	124.00	1765	Oct	28.93	0.00	1775	Oct	93.00	87.36	1785	Oct	72.94	0.00	1795	Oct	63.94	82.67
1755	Nov	85.00	72.86	1765	Nov	30.00	0.00	1775	Nov	82.50	0.00	1785	Nov	0.00	0.00	1795	Nov	38.28	106.07
1755	Dec	153.18	0.00	1765	Dec	0.00	13.78	1775	Dec	120.00	0.00	1785	Dec	50.73	0.00	1795	Dec	115.55	82.15
1756	Jan	0.00	0.00	1766	Jan	29.45	62.00	1776	Jan	96.10	101.45	1786	Jan	0.00	31.00	1796	Jan	189.44	169.97
1756	Feb	33.14	0.00	1766	Feb	0.00	0.00	1776	Feb	104.00	51.56	1786	Feb	0.00	0.00	1796	Feb	0.00	93.21
1756	Mar	76.59	168.48	1766	Mar	73.81	62.00	1776	Mar	55.11	0.00	1786	Mar	139.50	43.40	1796	Mar	46.50	100.00
1756	Apr	32.22	76.36	1766	Apr	85.00	0.00	1776	Apr	78.75	0.00	1786	Apr	0.00	83.08	1796	Apr	30.00	102.86
1756	May	33.00	0.00	1766	May	50.00	24.11	1776	May	74.63	0.00	1786	May	38.75	70.45	1796	May	0.00	96.44

1756	Jun	135.48	24.00	1766	Jun	108.95	0.00	1776	Jun	76.67	150.00	1786	Jun	23.48	77.65	1796	Jun	55.71	92.50
1756	Jul	70.27	112.73	1766	Jul	64.58	165.33	1776	Jul	47.53	0.00	1786	Jul	93.00	0.00	1796	Jul	52.70	83.70
1756	Aug	49.37	62.00	1766	Aug	45.39	77.50	1776	Aug	113.67	59.93	1786	Aug	33.00	128.43	1796	Aug	57.72	43.92
1756	Sep	58.24	180.00	1766	Sep	25.26	90.00	1776	Sep	76.00	0.00	1786	Sep	120.00	0.00	1796	Sep	147.50	0.00
1756	Oct	98.96	0.00	1766	Oct	104.00	62.00	1776	Oct	44.29	0.00	1786	Oct	0.00	0.00	1796	Oct	19.08	75.29
1756	Nov	16.96	0.00	1766	Nov	68.18	0.00	1776	Nov	31.03	0.00	1786	Nov	0.00	0.00	1796	Nov	37.00	134.00
1756	Dec	41.33	0.00	1766	Dec	58.13	65.88	1776	Dec	39.45	0.00	1786	Dec	0.00	0.00	1796	Dec	63.94	0.00
1757	Jan	85.62	142.60	1767	Jan	141.71	100.75	1777	Jan	93.00	39.86	1787	Jan	50.73	0.00	1797	Jan	139.50	32.63
1757	Feb	61.87	0.00	1767	Feb	0.00	0.00	1777	Feb	68.36	47.85	1787	Feb	105.00	48.33	1797	Feb	48.00	24.71
1757	Mar	71.30	186.00	1767	Mar	0.00	10.33	1777	Mar	70.61	0.00	1787	Mar	217.00	58.13	1797	Mar	36.17	59.79
1757	Apr	20.00	70.59	1767	Apr	63.21	48.75	1777	Apr	62.07	0.00	1787	Apr	0.00	0.00	1797	Apr	27.00	60.00
1757	May	38.38	64.14	1767	May	38.05	108.50	1777	May	44.43	0.00	1787	May	8.45	17.44	1797	May	77.50	40.30
1757	Jun	54.44	178.00	1767	Jun	83.75	96.00	1777	Jun	51.25	0.00	1787	Jun	40.00	122.31	1797	Jun	72.22	112.94
1757	Jul	25.10	43.92	1767	Jul	82.67	48.71	1777	Jul	64.48	124.00	1787	Jul	0.00	0.00	1797	Jul	48.71	145.70
1757	Aug	47.03	62.00	1767	Aug	86.54	0.00	1777	Aug	52.21	169.09	1787	Aug	0.00	0.00	1797	Aug	18.87	85.25
1757	Sep	42.86	53.33	1767	Sep	66.43	0.00	1777	Sep	36.21	0.00	1787	Sep	12.00	70.00	1797	Sep	47.14	115.00
1757	Oct	15.50	24.80	1767	Oct	133.92	84.65	1777	Oct	85.95	145.31	1787	Oct	199.78	152.18	1797	Oct	66.43	63.55
1757	Nov	137.59	0.00	1767	Nov	142.50	0.00	1777	Nov	32.61	39.31	1787	Nov	0.00	0.00	1797	Nov	36.25	180.00
1757	Dec	113.22	0.00	1767	Dec	113.67	124.00	1777	Dec	63.63	133.30	1787	Dec	0.00	0.00	1797	Dec	103.33	117.11
1758	Jan	79.10	49.60	1768	Jan	144.67	25.36	1778	Jan	98.17	0.00	1788	Jan	0.00	0.00	1798	Jan	70.86	134.33
1758	Feb	77.33	98.00	1768	Feb	60.23	14.50	1778	Feb	31.64	58.00	1788	Feb	0.00	0.00	1798	Feb	45.11	54.35
1758	Mar	121.86	80.60	1768	Mar	0.00	31.00	1778	Mar	12.76	124.00	1788	Mar	0.00	0.00	1798	Mar	49.17	53.55
1758	Apr	10.00	13.75	1768	Apr	200.00	57.50	1778	Apr	33.75	10.00	1788	Apr	43.85	88.57	1798	Apr	43.93	124.29
1758	May	14.47	0.00	1768	May	101.55	161.89	1778	May	70.45	140.69	1788	May	0.00	0.00	1798	May	8.27	94.72
1758	Jun	47.14	110.77	1768	Jun	84.78	32.61	1778	Jun	51.82	27.00	1788	Jun	0.00	0.00	1798	Jun	72.22	93.53
1758	Jul	68.00	0.00	1768	Jul	69.23	0.00	1778	Jul	79.00	155.00	1788	Jul	0.00	86.11	1798	Jul	41.33	114.46
1758	Aug	23.71	69.75	1768	Aug	26.87	0.00	1778	Aug	29.93	74.40	1788	Aug	90.18	77.50	1798	Aug	41.33	31.00
1758	Sep	25.86	123.75	1768	Sep	26.00	90.00	1778	Sep	22.50	0.00	1788	Sep	0.00	147.27	1798	Sep	32.73	75.00

1758	Oct	24.59	0.00	1768	Oct	126.21	0.00	1778	Oct	44.00	0.00	1788	Oct	60.06	0.00	1798	Oct	40.12	93.00
1758	Nov	107.14	0.00	1768	Nov	106.55	160.00	1778	Nov	111.60	45.00	1788	Nov	90.00	0.00	1798	Nov	100.00	65.00
1758	Dec	130.46	0.00	1768	Dec	77.50	0.00	1778	Dec	140.53	136.40	1788	Dec	0.00	48.22	1798	Dec	106.78	22.55
1759	Jan	65.10	84.14	1769	Jan	42.27	17.71	1779	Jan	58.56	145.70	1789	Jan	0.00	10.33	1799	Jan	90.42	138.31
1759	Feb	55.58	118.22	1769	Feb	0.00	73.82	1779	Feb	0.00	129.00	1789	Feb	0.00	0.00	1799	Feb	104.00	70.00
1759	Mar	217.00	62.00	1769	Mar	75.90	186.00	1779	Mar	55.80	31.00	1789	Mar	0.00	116.25	1799	Mar	20.67	56.46
1759	Apr	93.00	150.00	1769	Apr	44.35	12.00	1779	Apr	0.00	72.50	1789	Apr	3.00	35.63	1799	Apr	46.67	0.00
1759	May	58.00	69.75	1769	May	50.08	42.63	1779	May	40.12	8.86	1789	May	28.18	108.50	1799	May	67.64	94.35
1759	Jun	103.85	0.00	1769	Jun	109.66	180.00	1779	Jun	80.69	0.00	1789	Jun	0.00	0.00	1799	Jun	57.86	108.75
1759	Jul	57.35	0.00	1769	Jul	65.10	112.38	1779	Jul	124.00	111.24	1789	Jul	71.30	118.19	1799	Jul	104.63	0.00
1759	Aug	63.63	127.88	1769	Aug	0.00	106.56	1779	Aug	47.03	131.15	1789	Aug	63.63	15.50	1799	Aug	47.61	93.00
1759	Sep	20.87	120.00	1769	Sep	80.00	0.00	1779	Sep	43.64	78.46	1789	Sep	150.00	0.00	1799	Sep	39.13	4.29
1759	Oct	0.00	126.48	1769	Oct	66.65	57.57	1779	Oct	75.95	144.67	1789	Oct	62.00	33.21	1799	Oct	32.94	104.16
1759	Nov	66.00	0.00	1769	Nov	37.00	120.00	1779	Nov	30.00	70.71	1789	Nov	0.00	38.57	1799	Nov	13.33	81.00
1759	Dec	22.55	62.00	1769	Dec	124.00	20.67	1779	Dec	42.42	0.00	1789	Dec	0.00	155.00	1799	Dec	103.85	33.95

Table i: Westerliness Index for the Northern Corridor (WI) and Easterly, or Trades, Index for the Southern Corridor (TI)

Statistical representation of results for 50-year period (1750-1799)

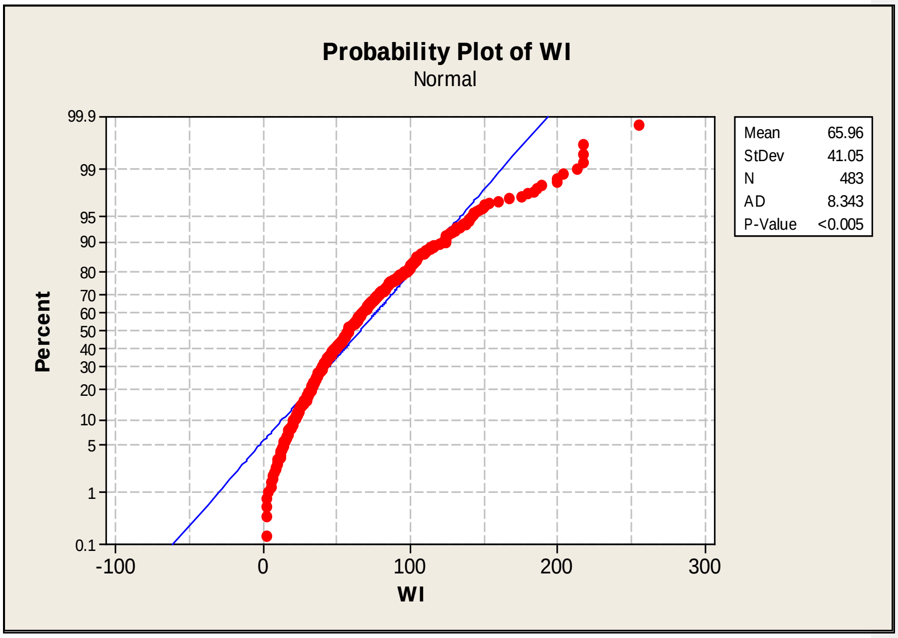


Figure i: Anderson-Darling Normality test for WI

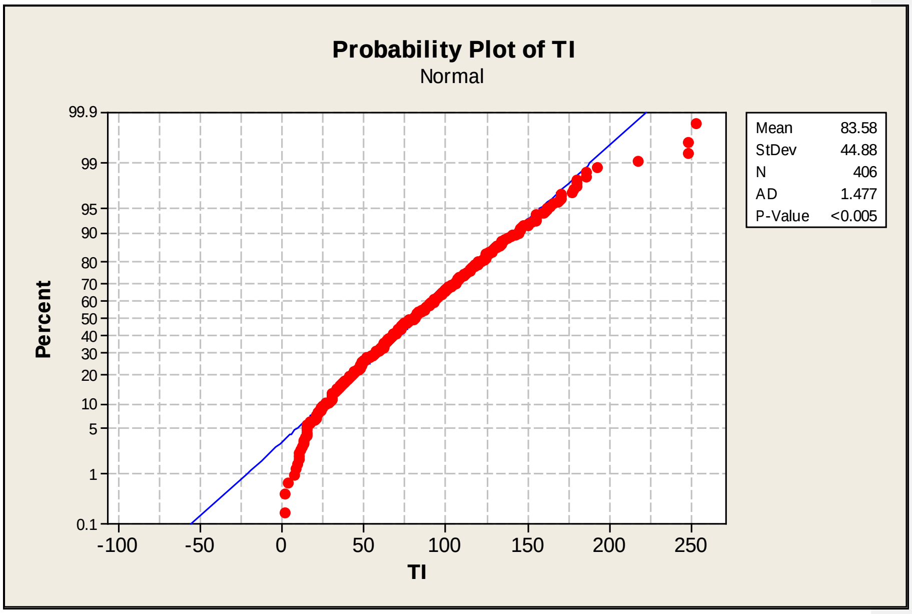
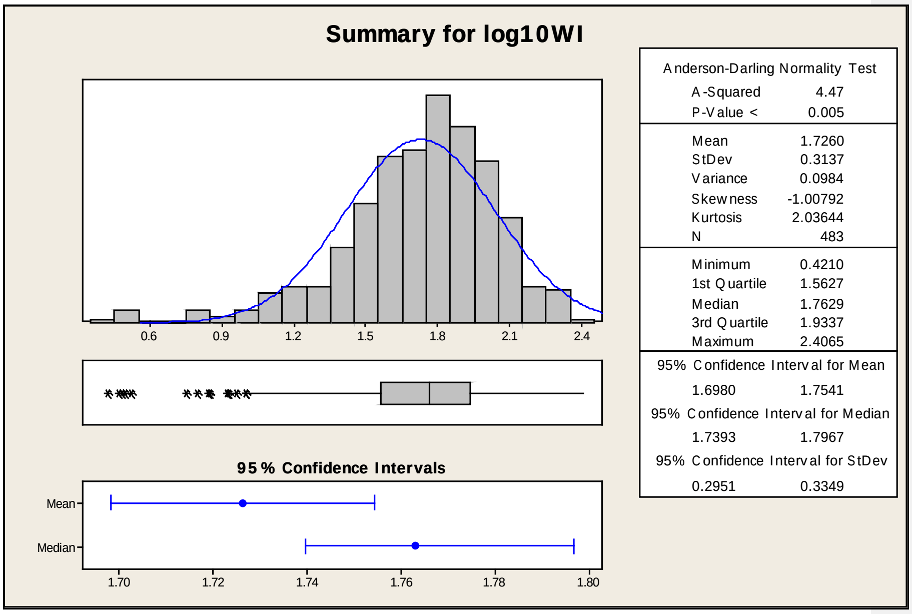
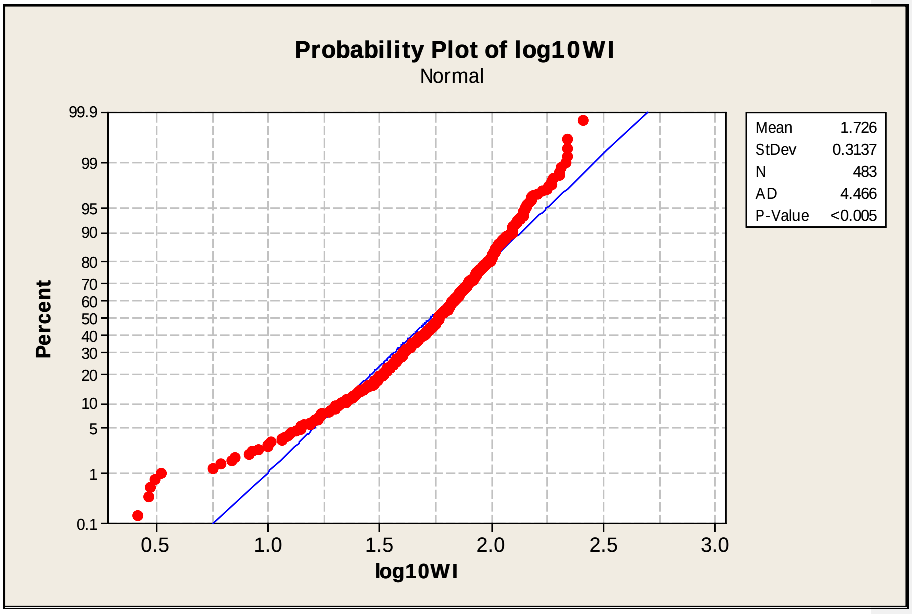


Figure ii: Anderson-Darling Normality test for TI



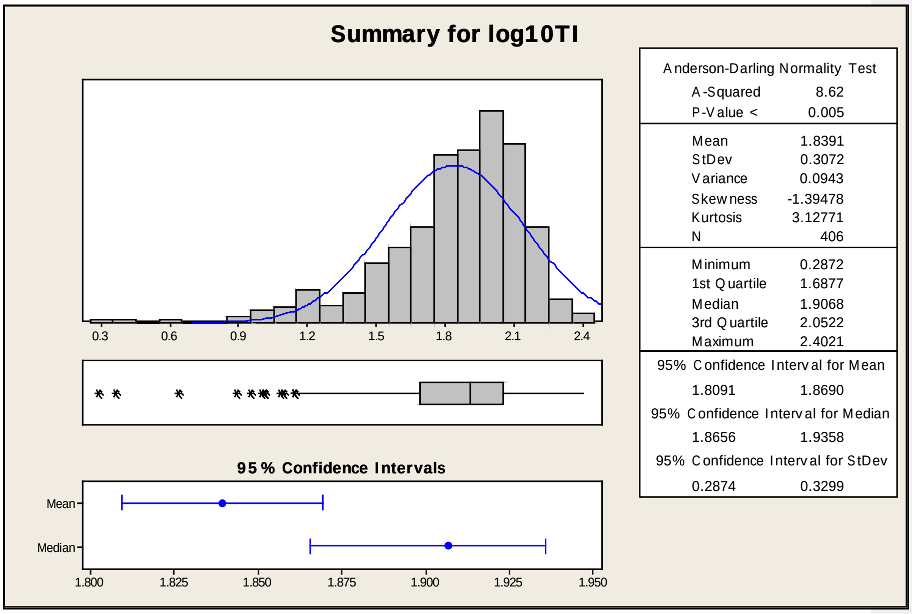
```
Anderson-Darling Normality Test
   A-Squared           4.47
   P-Value <          0.005

   Mean              1.7260
   StDev             0.3137
   Variance          0.0984
   Skewness        -1.00792
   Kurtosis         2.03644
   N                    483

   Minimum           0.4210
   1st Quartile      1.5627
   Median            1.7629
   3rd Quartile      1.9337
   Maximum           2.4065

 95% Confidence Interval for Mean
   1.6980            1.7541
95% Confidence Interval for Median
   1.7393            1.7967
 95% Confidence Interval for StDev
   0.2951            0.3349
```

Figure iii: Statistical summary for $\log_{10}$WI



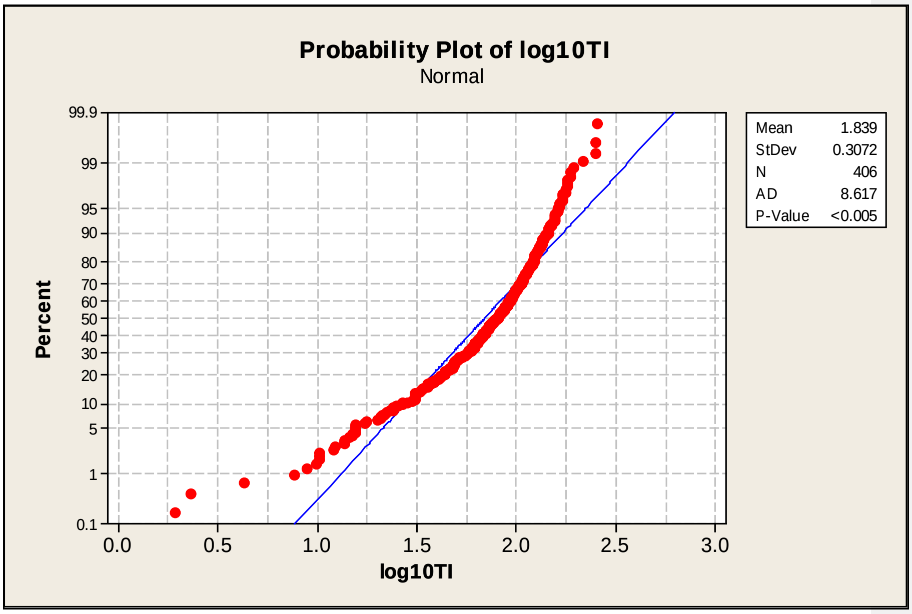
```
Mean       1.726
StDev     0.3137
N            483
AD         4.466
P-Value   <0.005
```

Figure iv: Anderson-Darling probability test for $\log_{10}$WI



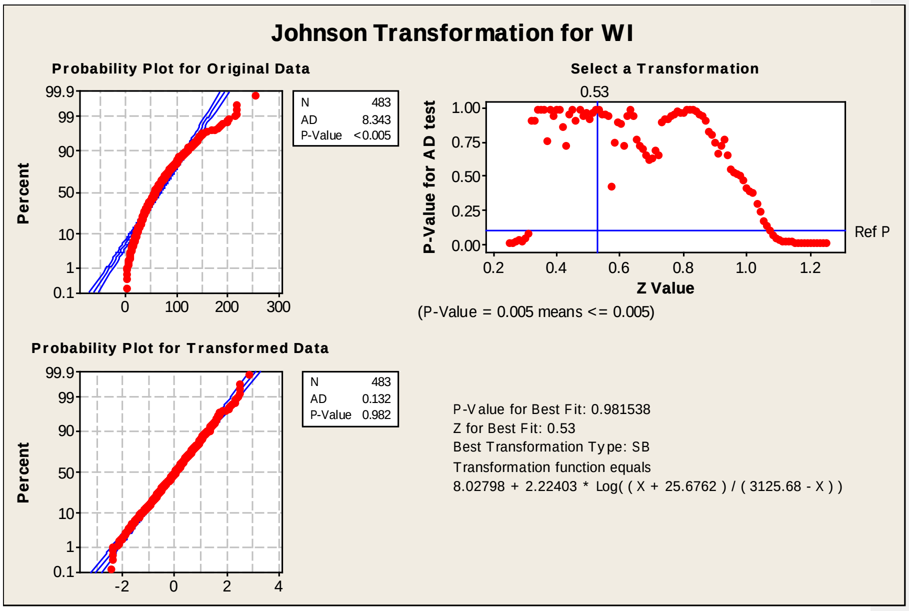
Anderson-Darling Normality Test	
A-Squared	8.62
P-Value <	0.005
Mean	1.8391
StDev	0.3072
Variance	0.0943
Skewness	-1.39478
Kurtosis	3.12771
N	406
Minimum	0.2872
1st Quartile	1.6877
Median	1.9068
3rd Quartile	2.0522
Maximum	2.4021
95% Confidence Interval for Mean	
1.8091	1.8690
95% Confidence Interval for Median	
1.8656	1.9358
95% Confidence Interval for StDev	
0.2874	0.3299

Figure v: Statistical summary for $\log_{10}$TI



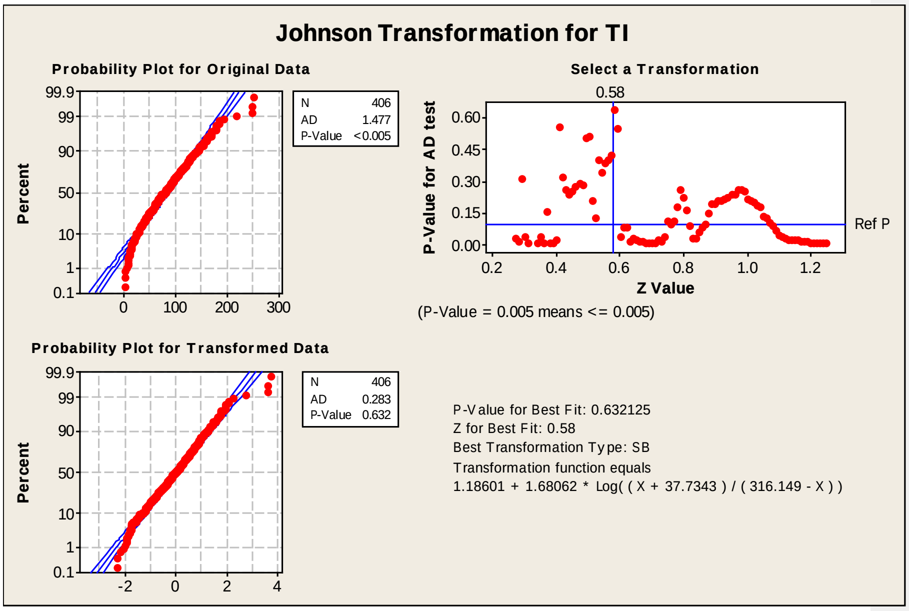
Mean	1.839
StDev	0.3072
N	406
AD	8.617
P-Value	<0.005

Figure vi: Anderson-Darling probability test for $\log_{10}$TI



```
P-Value for Best Fit: 0.981538
Z for Best Fit: 0.53
Best Transformation Type: SB
Transformation function equals
8.02798 + 2.22403 * Log( ( X + 25.6762 ) / ( 3125.68 - X ) )
```

Figure vii: Johnson Transformation of WI



```
P-Value for Best Fit: 0.632125
Z for Best Fit: 0.58
Best Transformation Type: SB
Transformation function equals
1.18601 + 1.68062 * Log( ( X + 37.7343 ) / ( 316.149 - X ) )
```

Figure viii: Johnson Transformation of TI

	N_N	N_E	N_S	N_W	TI	NAOI	CET	CET anom	EWP	EWP anom	SSpot	SSpot_r_m	gale days
N_N	1.000												
N_E	-0.087	1.000											
N_S	-0.345	0.311	1.000										
N_W	-0.209	-0.339	-0.295	1.000									
TI	-0.264	0.071	0.087	0.139	1.000								
NAOI	-0.136	0.199	0.024	-0.056	-0.062	1.000							
CET	-0.252	0.246	-0.093	0.001	0.137	**0.567**	1.000						
CET anom	-0.261	0.223	0.027	0.020	0.100	**0.544**	0.936	1.000					
EWP	-0.101	0.096	-0.080	0.232	-0.209	**0.466**	**0.531**	**0.521**	1.000				
EWP anom	-0.083	0.075	-0.053	0.243	-0.235	**0.482**	**0.480**	**0.473**	0.988	1.000			
SSpot	-0.095	-0.034	-0.053	-0.073	0.290	0.120	0.155	0.218	-0.014	-0.033	1.000		
SSpot_r_m	-0.115	-0.008	-0.048	-0.110	0.301	0.044	0.161	0.235	-0.073	-0.104	0.938	1.000	
gale days	0.154	0.238	0.270	**0.519**	0.108	-0.013	-0.066	0.021	0.184	0.221	-0.093	-0.113	1.000

Table ii: Winter correlations.

Those in bold denote significance at the 0.01 level (R>0.46), and those in standard type significance at the 0.05 level (R>0.361)

	N_N	N_E	N_S	N_W	TI	NAOI	CET	CET anom	EWP	EWP anom	SSpot	SSpot_r_m	gale days
N_N	1.000												
N_E	0.005	1.000											
N_S	-0.362	-0.218	1.000										
N_W	-0.240	-0.304	-0.266	1.000									
TI	-0.081	-0.125	0.171	0.024	1.000								
NAOI	-0.087	-0.098	0.109	-0.046	0.073	1.000							
CET	-0.044	-0.135	0.127	-0.025	0.004	0.450	1.000						
CET anom	-0.230	-0.183	**0.383**	-0.061	0.174	0.531	0.353	1.000					
EWP	0.127	0.221	-0.242	0.192	-0.295	-0.103	0.168	-0.400	1.000				
EWP anom	0.108	0.243	-0.237	0.204	-0.296	-0.160	-0.051	**-0.382**	0.968	1.000			
SSpot	0.100	-0.035	-0.244	0.094	-0.056	**0.469**	0.247	0.136	-0.065	-0.126	1.000		
SSpot_r_m	0.140	-0.020	-0.200	0.046	-0.087	**0.304**	0.101	0.112	-0.115	-0.142	0.879	1.000	
gale days	0.242	0.018	-0.011	**0.583**	-0.041	-0.142	0.009	-0.073	0.275	0.277	-0.017	0.065	1.000

Table iii: Spring Correlations

Those in bold denote significance at the 0.01 level (R>0.36), and those in standard type significance at the 0.05 level (R>0.28)

	N_N	N_E	N_S	N_W	TI	NAOI	CET	CET anom	EWP	EWP anom	SSpot	SSpot_r_m	gale days
N_N	1												
N_E	0.278	1.000											
N_S	-0.005	-0.263	1.000										
N_W	-0.449	-0.444	-0.274	1.000									
TI	0.073	-0.144	**0.374**	0.017	1.000								
NAOI	0.116	0.077	-0.007	-0.219	0.084	1.000							
CET	0.137	0.056	0.119	-0.292	-0.021	**0.387**	1.000						
CET anom	0.128	0.204	-0.005	-0.284	-0.114	**0.438**	0.889	1.000					
EWP	-0.295	-0.225	-0.006	**0.328**	0.155	-0.269	**-0.381**	**-0.518**	1.000				
EWP anom	-0.298	-0.167	-0.059	**0.331**	0.116	-0.282	**-0.484**	**-0.546**	0.983	1.000			
SSpot	0.188	0.023	0.023	-0.112	-0.118	-0.113	0.127	0.153	-0.220	-0.216	1.000		
SSpot_r_m	0.152	-0.064	0.083	-0.029	-0.093	-0.108	0.104	0.117	-0.197	-0.196	0.964	1.000	
gale days	0.249	0.026	0.251	0.357	0.213	-0.325	-0.283	-0.294	0.129	0.134	0.135	0.187	1.000

Table iv: Summer Correlations

Those in bold denote significance at the 0.01 level (R>0.36), and those in standard type significance at the 0.05 level (R>0.28)

	N_N	N_E	N_S	N_W	TI	NAOI	CET	CET anom	EWP	EWP anom	SSpot	SSpot_r_m	gale days
N_N	1												
N_E	-0.303	1.000											
N_S	-0.300	-0.123	1.000										
N_W	-0.157	-0.138	-0.122	1.000									
TI	-0.232	-0.013	0.087	0.025	1.000								
NAOI	0.087	-0.050	-0.145	0.155	-0.301	1.000							
CET	0.014	-0.164	-0.031	-0.036	-0.078	0.261	1.000						
CET anom	0.137	-0.109	-0.021	0.169	-0.087	0.160	0.244	1.000					
EWP	0.200	-0.098	-0.175	0.196	0.010	0.235	0.071	-0.051	1.000				
EWP anom	0.206	-0.090	-0.178	0.210	0.016	0.224	0.009	-0.044	0.998	1.000			
SSpot	0.009	0.099	0.165	0.180	0.031	-0.002	-0.101	0.284	0.062	0.074	1.000		
SSpot_r_m	0.047	0.089	0.203	0.150	0.057	-0.081	-0.002	0.252	0.011	0.016	0.960	1.000	
gale days	-0.053	0.169	**0.457**	**0.594**	-0.046	0.117	-0.074	0.204	0.085	0.100	**0.378**	**0.394**	1.000

Table v: Autumn Correlations

Those in bold denote significance at the 0.01 level (R>0.36), and those in standard type significance at the 0.05 level (R>0.28)

CD – DATABASE FILES

CD1 contains the Excel files of the database of information from the ships' logbooks, after modification and re-arrangement of the original data extracted as part of the CLIWOC project. The CD also contains other supplementary information and files, as referred to earlier in the document.

Contents:

1) Database files for the northern corridor of the North Atlantic:

ND1750s

ND1760s

ND1770s

ND1780s

ND1790s (where ND = <u>n</u>orthern corridor <u>d</u>atabase file)

2) Database files for the southern corridor of the North Atlantic:

SD1750s

SD1760s

SD1770s

SD1780s

SD1790s (where SD = <u>s</u>outhern corridor <u>d</u>atabase file)

3) Explanatory notes for the database files

4) Supplementary files for the 1820s:

ND1820s

SD1820s

5) Calendar of data coverage:

Temporal coverage