Early Meteorological Data from London and Paris: Extending the North Atlantic Oscillation Series

by

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Abstract

It has been known for some time that the potential exists to create long daily series of pressure for the cities of London and Paris by piecing together the barometer readings from various observers and institutions. However, most of the readings prior to 1920 have not previously been digitized or converted to modern units. To rectify this, work began in 2006 to locate and digitize these observations and then to correct the data to form homogeneous series of pressure. Observations have been located to span the years 1670–2007 for Paris and 1692–2007 for London, although significant gaps exist for the periods 1726–47 (Paris) and 1717–22 (London) where no daily pressure observations appear to have survived. The barometer observations were subjected to a quality control procedure before being corrected to represent daily means of sea-level pressure at standard conditions. Statistically significant breakpoints were tested and corrected using the RH-test (version 2).

This thesis describes the sources of data used in the London and Paris daily pressure series, and how the data were corrected and homogenized. The new series are compared with previous *monthly* reconstructions of Mean Sea-Level Pressure (MSLP) for London and Paris. In addition to being of a higher resolution (daily) and stretching over a longer time period than the previous data, the new series resolve certain inhomogeneities apparent in the *monthly* reconstructions. The daily data are used to construct a westerly index for Europe, which extends instrumental North Atlantic Oscillation (NAO) indices back to the eighteenth century. The relationship of this westerly index to surface temperature across Europe is examined. The results support the findings of previous studies that have indicated non-stationary relationships over time between the atmospheric circulation and surface temperature in the region. The London and Paris series are also used to assess the variability of storminess in the English Channel area over the last 300 years.

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Abbreviations

ACRE Atmospheric Reconstructions over the Earth

ADVICE Annual to Decadal Variability in Climate in Europe [project]

AST Apparent Solar Time

BADC British Atmospheric Data Centre

CET Central England Temperature

EIP Early Instrumental Period

EMULATE European and North Atlantic daily to MULtidecadal climATE variability [project]

Geo-Wind Geostrophic Wind

GMT Greenwich Mean Time

LIA Little Ice Age

LMM Late Maunder Minimum

LWC London Weather Centre

LWD London Weather Diary

MSLP Mean Sea-Level Pressure

MST Mean Solar Time

NA-WE North Atlantic/Western European

NAM Northern Annular Mode

NAO North Atlantic Oscillation

NAOI North Atlantic Oscillation Index

NS New Style (Gregorian) calendar

OCR Optical Character Recognition

OS Old Style (Julian) calendar

PCA Principal Component Analysis

PMF Penalized Maximal F [test]

PMT Penalized Maximal t [test]

SNAO Summer North Atlantic Oscillation

SNHT Standard Normal Homogeneity Test

SSI Storm Severity Index

TPR3 Common-trend two-phase regression model based maximal F test

UTC coordinated universal time

WET Western European Time

Notes

Arithmetic mean

The term 'mean' used in this thesis refers to the arithmetic mean, defined as:

$$\bar{x} = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i,$$

where $\bar{x}$ is the arithmetic mean and n is the number of individual values x.

Calendar dates

Unless otherwise stated, all dates referred to in this thesis are in the New Style (Gregorian) calendar (NS) format.

Colour figures

The following figures are provided in colour in the original version of the thesis: figures 5.6, 5.7, 6.8, 6.9, 7.1, 7.2, 7.3, 7.4, 7.6, 8.2, 8.3, B.1, B.2, B.3, B.4 and B.5.

Observation times

Times are in coordinated universal time (UTC) format unless otherwise stated.

Previously published information

Certain information in this thesis has previously been published in the following papers: Cornes (2008) and Camuffo *et al.* (2010).

Units of measurement

Unless otherwise stated, pressure values are presented in the unit of hectopascal (hPa) and temperatures in degrees Celsius (°C).

Standard Equations

The following equations are used in this thesis for the correction of raw barometer observations to standard measures of atmospheric pressure, as recommended by the World Meteorological Organization (1983). The form of the equations below are taken from Moberg *et al.* (2002). The equations are referenced in the text using the prefix 'Standard Equation'.

Correction for thermal expansion

$$p_0 = p \cdot (1 - \gamma \cdot T), \tag{1}$$

where p_0 = barometric pressure reduced to 0°C, p = recorded height of mercury in hPa, $\gamma = 1.82 \cdot 10^{-4}$ or $\gamma = 1.63 \cdot 10^{-4}$ (thermal expansion coefficient of mercury dependent upon the construction of the barometer, see text for details) and T = barometer temperature in °C.

Conversion to standard gravity

$$p_g = \frac{g_{stn}}{g_n} \cdot p, \tag{2}$$

where p_g = pressure reduced to standard gravity, g_{stn} = gravity at station latitude, $g_n = 9.80665 m \cdot s^{-2}$ (standard gravity) and p = pressure (hPa). In using this equation, the reduction in gravity with altitude is disregarded given the relatively small values this would yield for stations in London and Paris. The change in the correction for different pressure values is also very small and has been disregarded.

Conversion of station level pressure to MSLP

$$P_{slp} = P_{stn} \exp^{\left(\frac{h \cdot g}{R_d \cdot T}\right)}, \tag{3}$$

where P_{slp} = pressure reduced to sea level, P_{stn} = pressure at station altitude, h = station altitude in metres, $g = 9.80665 m^{s-2}$ (gravitational constant), $R_d = 287.04 J \cdot K^{-1} \cdot kg^{-1}$ (gas constant for dry air) and T = temperature in K.

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The completion of the London and Paris datasets would not have been possible without the assistance of the staff at many archives and libraries in both the UK and France. I would like to thank Ian MacGregor and Kate Strachan at the National Meteorological Archive in Exeter for their help in locating many sources of data. Jean-Pierre Javelle, Pierre Paillot and Xavier Popineau at the Météo-France Bibliotheque provided great assistance with finding many of the Paris data. The assistance of the archive staff at the Royal Society and Wellcome Library is gratefully acknowledged. I would also like to extend my thanks to the archive staff at the *Observatoire de Paris*, *Académie des Sciences Archives* and the *Académie Nationale de Médecine* for help with finding sources of data for Paris. Thanks also to Mark Beswick at the Met Office's library for his assistance with locating several obscure publications.

I gratefully acknowledge the permission granted by a number of organizations to reproduce several images in this thesis. Figures 2.7 and 2.8 were kindly provided by Joanna Hopkins and remain copyright of the Royal Society. Thanks also to Science Photo Library Ltd for the provision of the images used in figures 2.3, 2.9 and 3.3. Thanks to the Bodleian Library for permission to reproduce the image from the Holborn weather diary in figure 2.5 and to the *Bibliothèque de l'Observatoire de Paris* for permission to reproduce figure 3.4.

The majority of the computing and plotting in this thesis was produced using `R`, which is a free language and environment for statistical computing (R Development Core Team, 2008).

On a personal note I would like to the thank my family and Kathleen for their support and encouragement throughout the last three years.

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Chapter 1

Introduction

In 1699 the *Académie des Sciences* in Paris reported that the French-Italian astronomer Giacomo Filippo Maraldi had compared the barometer observations recorded at the Paris Observatory with those recorded by Rev. William Derham at Upminster in Essex. Maraldi observed that

> "There is a great agreement between the variations of the height of the barometer observed at Paris and at Upminster. We generally find it to rise or fall at Paris, when it rises or falls at Upminster; tho' these variations are not always equal. In each month the days on which the quicksilver has been highest or lowest, have been the same both at Paris and Upminster; but commonly when it has been lowest, it has been 3 or 4 lines lower at Paris than at Upminster, the English measure being reduced to that at Paris." (Académie Royale des Sciences, 1699).[1]

Several studies published in the *Philosophical Transactions of the Royal Society* in the early eighteenth century continued this theme of comparing barometric pressure measurements recorded at different locations throughout Europe (Derham, 1709, 1731, 1733a,b,c,d; Hadley, 1737, 1742). These analyses were not restricted to pressure, however, and comparisons were made of many meteorological variables, such as temperature, wind direction and 'weather'. Nor were the comparisons restricted to Europe, and where possible observations from across the wider world were used. These early comparisons of instrumental observations typify the scientific enquiry that defined the scientific Enlightenment of the seventeenth century, and which were conducted under the Baconian system of inductive reasoning (Wolf, 1935; Kington, 1997a). In the context of modern-day climatology, Slonosky (1999) has more recently compared pressure observations from London and Paris and has suggested that this comparison can yield important information regarding the state of the atmospheric circulation across Europe in previous centuries. This thesis continues the theme of comparing barometric pressure observations recorded in London and Paris that was first established by Maraldi and has been re-established by Slonosky. The work in this thesis marks a development from previous investigations in that for the first time, daily homogeneous series of Mean Sea-Level Pressure (MSLP) have been prepared for the two locations that span a time period in excess of 300 years.

[1]Translated quotation taken from Académie Royale des Sciences (1742, p.12). See also the comments by Slonosky *et al.* (2001b).

1.1 A short history of barometric pressure observation in London and Paris

It is little wonder that some of the earliest comparisons of the spatial variability of barometric pressure by practitioners such as Maraldi and Derham should have employed observations recorded in London and Paris, given the importance of these two cities in the development of meteorological instrumentation during the Enlightenment. The barometer, as an instrument for measuring variations in atmospheric pressure, was invented during the 1640s in response to the experiments into atmospheric pressure by Evangelista Torricelli. These investigations followed earlier suggestions by the then late Galileo Galilei (Knowles Middleton, 1964). Over the 20 or so years following the Torricellian experiment an understanding of atmospheric pressure became an extremely active area of research, with several scientists conducting their own investigations using barometers. Most of the early work on instrument design was conducted by scientists working in France, England and Italy. In Paris, Blaise Pascal (1623–62) is of particular importance as he was the first scientist to establish that atmospheric pressure decreases with altitude. Further insight into this problem was provided by Robert Boyle (1627–91), working in Oxford and then London, who devised the fundamental laws relating to the compressibility of air (Frisinger, 1977). In Italy during the 1650s, the *Accademia de Cimento* is important in the history of barometric pressure observation as the scientists working under its control significantly improved the design of the barometer (Camuffo *et al.*, 2010). Given the interest in the barometer by scientists in the late seventeenth century, the newly founded learned societies of the *Académie des Sciences* in Paris and the Royal Society in London were also actively involved in barometer design (Wolf, 1935). In the 1660s Robert Hooke, working under the auspices of the Royal Society in London, devised further improvements to the instrument with his invention of the wheel barometer, which ensured his lasting reputation as a pioneer in the history of barometric pressure observation (Knowles Middleton, 1964).

In addition to the development of barometers and the fundamental laws of atmospheric physics, scientists working in the cities of London and Paris during the seventeenth and eighteenth centuries were also influential in stressing the need for consistent meteorological reportage. In Paris, the importance of recording consistent meteorological observations from various sites across Europe was recognised as early as the 1650s, when an experiment was conducted comparing observations recorded at Paris, Clermont-Ferrand and Stockholm (Kington, 1988). In London, Robert Hooke was one of the first proponents of the use of the barometer to study—and to potentially forecast—the weather, and he decided that consistent daily observations over a long period of time were required for the relationship between weather conditions and the fluctuations of the barometer to be adequately established (Taylor, 1967). Other London-based scientists also supported this effort of observation—most notably Isaac Newton, John Locke, William Derham and Robert Boyle[2]—under the auspices of the Royal Society (Manley, 1952; Golinski, 2007).

A recognition of the importance of consistent meteorological observation by an individual, however, does not necessarily follow through to them keeping a daily diary. Golinski (2007) has

[2]Indeed Knowles Middleton (1964) cites Robert Boyle as the first person to use the term 'barometer', with the term 'baroscope' mostly used before the 1660s.

analysed in some detail the motives behind the keeping of private weather diaries by individuals in seventeenth and eighteenth century Britain, and resorted to the quote by Manley (1952, p.300) that a "Prolonged maintenance of daily observations demands an odd and uncommon type of enthusiasm". Locke and Derham kept consistent diaries, although Hooke's diary, in contrast, contains many gaps. Luckily there were a sufficient number of individuals based around London in the late seventeenth and early eighteenth centuries with just this type of enthusiasm, and a sequence of meteorological data can be constructed from their observations (Manley, 1960). In Paris, it appears that the recognition of the importance of constant meteorological observation was not as forthcoming *by individuals* as it was in London. It was rather institutions, and specifically the newly founded Paris Observatory, that led the keeping of meteorological observations in the late seventeenth century. Under the directorship of Jean-Dominique Cassini, the Observatory started to keep daily instrumental observations during the 1660s (Maraldi, 1725). The maintenance of a daily weather diary by an institution, such as the Paris Observatory, rather than by enthusiastic individuals has the benefit of often being more complete, given the division of the work amongst several observers. This has been recognized for documentary sources (Pfister *et al.*, 2008), but the standardization of record-keeping afforded by institutions also benefits instrumental data sources. This need not always be the case, however, as the French physician Louis Morin maintained a nearly complete weather diary in Paris over the period 1670–1715, which included twice-daily barometer observations (Legrand & Le Goff, 1987, 1992). As described by Golinski (2007), in addition to enthusiasm, an effort such as this requires a regular daily routine, with no time spent away: Morin appears to have possessed both of these desirable features (Pfister & Bareiss, 1994).

The enthusiasm for keeping weather diaries waxed and waned throughout the course of the early eighteenth century. A brief flurry of activity followed James Jurin's request in 1723 for observations to be sent to the Royal Society. Indeed, Jurin himself kept a remarkably complete diary over the years 1728–50 at his domestic residences in London (Manley, 1952). During this period the Paris Observatory is known to have maintained its record-keeping, although most of these records have been lost or destroyed at some point in the late eighteenth century (Renou, 1881; Bigourdan, 1895). Fortunately, another astronomer—Joseph Delisle—kept a constant record of instrumental observations over the period 1748–60 at his small Observatory at the *Hôtel de Cluny*, near to the Sorbonne in the centre of Paris.

During the late eighteenth century, enthusiasm for constant record-keeping in Europe was once again revived; this time by the *Société Royale de Médecine*, as part of its enquiry into the connection between weather conditions and public health (Kington, 1970, 1988). A number of Physicians kept instrumental diaries around this time in France, with the *Journal de Médecine* publishing daily observations recorded in Paris from the late 1750s. In London, the Royal Society began to keep a daily instrumental record at its house from 1774, although this was independent of the efforts by the *Société Royale de Médecine* and it was motivated by demands by the Scientific community in London to have benchmark meteorological observations.

Over the course of the nineteenth century, meteorological observations of a consistent and standardized manner were increasingly kept by institutions. Early nineteenth-century record-keeping in London was dominated by the Greenwich and Kew Observatories (Kenworthy & Giles, 1994; Galvin, 2003). In Paris, the Paris Observatory remained the primary source for meteorological data (Davis, 1984). By the late nineteenth century, national meteorological services had been established and the responsibility for meteorological observation-keeping came under the command of the Met Office in Britain and the *Bureau Central Météorologique* in France (Kington, 1997a).

1.2 Previous attempts to create pressure series for London and Paris

The long history of meteorological observation and instrument development in London and Paris described above suggests that the creation of long-series of barometric pressure should be possible for these two sites. Indeed, there have been several attempts over the last 100 years to piece together the various instrumental series in order to produce long pressure series. The influential meteorologist Henry Storks Eaton compiled a monthly MSLP series for London by correcting observations contained in the registers of the Royal Society and Greenwich Observatory (Eaton, 1863, 1880). This series has since been further corrected by Jones *et al.* (1987) and during the ADVICE (1998) project. Work on earlier observations has also been completed. The climatologist Gordon Manley conducted a thorough review of the meteorological observations recorded in London, and embarked on a project—with the assistance of his research associate Elizabeth Shaw—to construct a daily register of weather for the capital city from 1723 through to 1805 (Manley, 1964, 1980). This *London Weather Diary (LWD)*, as the compilation was entitled, included a daily sequence of MSLP readings, which Manley had corrected, alongside temperature, wind direction/speed and 'weather' observations. Its seems that having constructed the *LWD*, the data were used at the Met Office for a short while (Manley, 1980) but were soon forgotten about. Sources of early pressure data from London, including the *LWD*, were investigated by the climatologist Hubert Lamb who used several data sources in his various studies (Lamb & Johnson, 1966). Kington (1988) used some of the pressure data from the *LWD* in his reconstruction of daily synoptic charts for the 1780s. Papers archived at the Climatic Research Unit's library at the University of East Anglia also indicate that the meteorological observations contained in Robert Hooke's diary were investigated in the early 1970s by James M. Craddock, although the data do not appear to have been put to any use. More recently the European and North Atlantic daily to MULtidecadal climATE variability (EMULATE) project has digitized and corrected a daily MSLP series for London, although only for the limited 1850–80 period (Ansell *et al.*, 2006).

A similar review of early meteorological series has previously been conducted for Paris. The influential eighteenth century meteorologist, Louis Cotte, provided a list of data sources in his two major works, *Traité de Météorologie* and *Mémoires sur la météorologie* (Cotte, 1774, 1788). During the late nineteenth century, researchers employed by the *Bureau Central Météorologique de France* compiled a list of early French meteorological series (Angot, 1897), with an earlier study providing a monthly MSLP series for Paris for the period 1757–1878 (Renou, 1881). These data were digitized and corrected by Jones *et al.* (1987), with the addition of later observations published by Angot (1910) to construct a monthly series of MSLP for the city that began in 1764. These data were later corrected further during the ADVICE (1998) project. A *daily* series of MSLP for Paris has been constructed as part of the EMULATE project, but only for the period 1851–80 (Ansell *et al.*, 2006).

Although there have been sporadic attempts over the last 100 years to prepare long series of pressure for London and Paris, there has not been a concerted effort to compile and correct long daily series for the two locations. To rectify this, work began in 2006 to locate, digitize and correct the various sequences of barometer readings from around London and Paris to construct long daily pressure series for the two locations. Considerable effort was also made to locate data to fill the gaps between and within previously known series. The conclusion from these searches is that a daily pressure series can be constructed for London that begins in 1692, with only a small number of missing years in the 1710s/20s (specifically 1717–22). By using the early observations of Louis Morin, the Paris series stretches back to 1670, although as the majority of meteorological records from the Paris Observatory for the early eighteenth century have been lost, a large gap exists in the series over the period 1726–47. It may be that observations for the missing periods may be contained in manuscripts held in private collections and it is hoped such records may come to light in the future to complete both the London and Paris series.

In assembling long series of pressure from early barometer measurements, the question arises as to how reliable early barometer measurements are in providing a measure of atmospheric pressure that is suitable for modern climatic research. The successful development of daily series of pressure for several sites in Europe stretching back to the eighteenth century has recently been demonstrated (Camuffo & Jones, 2002). Lamb & Johnson (1959, p.105), in comparing pressure series recorded by various observers across Europe from the late eighteenth century, concluded that "…the best barometers of the earliest decades considered [1790s] were quite capable of yielding consistent M.S.L. pressures when in the hands of a sound observer". The observers of historical instrumental observations were often pioneers in various branches of science (Lamb, 1995), and the observations used in the London and Paris pressure series are no exception. In the case of London and Paris, the barometers in use were some of the most advanced instruments at the time. Nonetheless, corrections needed to be applied to many of the data in order for the barometer readings to yield measures of atmospheric pressure at modern-day standard conditions. Given the 'patchwork' nature of the series, the homogeneity of the data also needed to be tested and corrections applied. It is shown in this thesis that the London and Paris MSLP series once corrected for these inhomogeneities are able to contribute to the body of research concerned with studying the past variability of the atmospheric circulation in the North Atlantic-Western European (NA-WE) region.

1.3 The contribution of this research to climatology

There have been several efforts in Europe over the last decade to recover barometer observations from historical sources and to develop these into long, daily series of atmospheric pressure. The 'Improved Understanding of Past Climatic Variability from Early Daily European Instrumental Sources' (IMPROVE) project in particular served as a catalyst for the generation of several long daily series of pressure (Camuffo & Jones, 2002). Under this project, pressure series were reconstructed for Uppsala (1722–1998) (Bergström & Moberg, 2002), Stockholm (1756–1998) (Moberg *et al.*, 2002) and Milan (1763–1998) (Maugeri *et al.*, 2002). Other daily series have been reconstructed for Padova (1725–1999) (Camuffo *et al.*, 2006) and for various sites in the

Po Valley region of Italy (Maugeri *et al.*, 2004). In addition, the EMULATE project recovered pressure series for several locations around Europe for the period 1850–80, including London and Paris (Ansell *et al.*, 2006). However, as described above no concerted attempts until now have been made to construct long daily series of pressure for the cities of London and Paris. The daily MSLP series that have been compiled for these two sites therefore contribute to research that is underway to complete homogeneous MSLP series in order to improve research on atmospheric circulation (Compo *et al.*, 2006). Specifically, the data contribute to the following three initiatives: the Twentieth Century Reanalysis Project (www.cdc.noaa.gov/data/20thC_Rean/), the Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative (www.met-acre.org/) and the Climate Data Modernization Program (www.ncdc.noaa.gov/oa/climate/cdmp/cdmp.html).

The London and Paris MSLP series used without the incorporation of data from other locations can provide a surprising amount of information about atmospheric circulation variability in the North Atlantic-Western European (NA-WE) region, particularly in relation to the North Atlantic Oscillation (NAO). In extra-tropical locations, an understanding of the variability in the atmospheric circulation is the key to understanding regional-scale climate variations on the interannual to decadal timescales (Trenberth *et al.*, 2007). In terms of surface temperature, variability at these timescales over the course of at least the last 50 years is superimposed on the long-term mean warming that is attributable to greenhouse gas forcing (Hegerl *et al.*, 2007). In the NA-WE region, the NAO explains a large proportion of the interannual to decadal temperature variation, particularly during the winter months of the year (Hurrell *et al.*, 2003). Therefore a thorough understanding of the variability of the NAO in the past and the relationship between the atmospheric circulation and temperature over that time period is required to fully appreciate future variability in the region. An important area of research is concerned with investigating the role that greenhouse gas forcing plays in the variability of the NAO (Gillett *et al.*, 2003a). Such investigations require long NAO series that extend into the pre-industrial era. In order to quantify the NAO, station-pair indices derived from MSLP data are most often used, but these only extend back to the 1820s at the earliest (Jones *et al.*, 2003). The state of the NAO further back in time remains uncertain. Proxy measures of the NAO extend over many centuries, but have generally only been reconstructed for the winter season of the year. The reconstruction by Luterbacher *et al.* (1999, 2002a) is an exception and is available at the monthly resolution back to 1675 and seasonally back to 1500. However, none of the proxy-based NAO indices can be used to examine the circulation–temperature relationship because the proxies themselves have been inferred directly or indirectly from temperature series, alongside precipitation-sensitive parameters. Further, several studies have shown that the predictor-predictand response may not be consistent over time (Jones *et al.*, 2003; Beck *et al.*, 2007). The reconstructed MSLP series produced by Küttel *et al.* (2009b) is independent from any temperature data and has been used to study the circulation–temperature connection in the NA-WE region back to 1750 (Küttel *et al.*, 2009a). However, this series is only available at the seasonal resolution and is only available back to 1750.

Research conducted over the last decade has shown that extension to the NAO time series can be provided by a westerly index constructed as the difference in MSLP at London and Paris (Paris *minus* London). Slonosky *et al.* (2000) used the monthly MSLP data for London and Paris developed from the ADVICE (1998) project, to construct this westerly index back to 1774. The authors showed that this index has a close relationship to the traditional 'station-pair' NAO indices and hence may be used to extend the series back in time. Slonosky *et al.* (2001b) demonstrated that a similar westerly index can be constructed for the period 1698–1708 using the barometer observations of Derham in Upminster and Morin in Paris. Jones *et al.* (2003), in searching for pressure-based indices to extend the NAO time series back in time, asserted that extension was most likely to be provided by this Paris–London westerly index given the lack of early pressure measurements from the 'centres-of-action' of the NAO. Such pressure-only indices have the benefit over proxy indices of allowing relationships between the atmospheric circulation and surface climate variables to be quantified. It was speculated by Jones *et al.* (2003) that this westerly index could be constructed back to the late seventeenth century if suitable pressure data could be found. This thesis therefore follows on from Jones *et al.* (2003) and shows that a westerly index (as a proxy for the NAO) can be constructed back to 1748 on a near continuous basis and back to 1692 on a more fragmentary basis using the newly reconstructed daily series for the two locations.

In addition to the construction of a westerly index, the daily London and Paris MSLP series can also be used to quantify changes in storminess in the NA-WE region over the last 300 years. The exceptional length of the London and Paris series allow the changes in storminess observed in the twentieth century (Alexandersson *et al.*, 1998; Trenberth *et al.*, 2007; Wang *et al.*, 2009) to be placed in the long-term context. Further, as the series stretch back across a large part of the Little Ice Age (LIA) [3], the often cited conclusion (e.g. Lamb, 1984a, 1991; Wheeler & Mayes, 1997) that storm activity in the NA-WE region was elevated at certain times during that period can be assessed in the context of the newly recovered data. This supplements previous long-term assessments of storminess (e.g. Bärring & von Storch, 2004; Bärring & Fortuniak, 2009) and the results gained from using early wind-speed data (Wheeler *et al.*, 2009).

1.4 Thesis structure

This thesis is divided into two parts: Part I describes the development of the daily MSLP series for London and Paris, and Part II provides an analysis of the variability of the atmospheric circulation in the NA-WE region over the last 300 years using the two series. Within Part I, Chapters 2 and 3 respectively provide information on the background to the sources of data used in the London and Paris MSLP series. These chapters also document the corrections that have been applied to the data. Chapter 4 follows with a description of the methods applied to the raw data to form homogeneous series of MSLP. A reliable homogenization test was required to test for statistically significant changepoints in the series. The RH-test (Wang & Feng, 2007) was chosen for this purpose and Chapter 4 provides background information about the test, its context in the field of climate data homogenization, and details the actual corrections applied to homogenize the data. The final chapter of Part I assesses the results from the homogenization of the London and Paris series by cross-comparing the two data series. This comparison is valid as the two series were kept separate at all stages of the data series development. It is concluded that the new data series have removed certain inhomogeneities that were evident in the previously

[3] The LIA is variously defined as covering the period 1450–1850 (Jones & Briffa, 2001).

available monthly resolution MSLP series for London and Paris that were corrected as part of the ADVICE (1998) project. However, Chapter 5 goes further than a simple comparison and performs analysis on the two data series, and this forms a bridge to part II of the thesis. The analysis is mainly concerned with examining the annual cycle of pressure at the two sites, and scrutinizes the data for evidence of singularities.

The opening chapter of Part II uses the difference in normalized pressure at Paris and London to develop a westerly index. This follows the example set by Slonosky (1999), Slonosky *et al.* (2000), Slonosky *et al.* (2001b) and Jones *et al.* (2003). The westerly index is compared against a variety of instrumental and proxy NAO indices. Brief consideration is given in that chapter to the extremes of westerly and easterly flow, which is permitted by the daily resolution of the data. In Chapter 7 the relationship between the westerly index derived from the Paris–London pressure difference and surface temperature is considered. The final analysis chapter of the thesis (Chapter 8) explores the use of the London and Paris data in examining changes in storm activity in the NA-WE region over the last 300 years. The thesis ends with a conclusions chapter, which summarizes the main findings of the thesis and provides suggestions for further research.

Part I

Data Series Development

Chapter 2

The London Daily Pressure Series

2.1 Introduction

The London daily pressure series spans the period from 1692 to present-day (31 Dec 2007) and has been constructed by joining several data sources; these are listed in Table 2.1 and Figure 2.1. The potential exists to extend the series further back than 1692 as earlier barometer observations were recorded in London. Examples of these very early measurements include those from Robert Hooke's weather diary, which cover the period 10 March 1672 to 27 April 1673 (Old Style (Julian) calendar (OS)), and those from Robert Boyle's diary, which are only complete for the year 1685 (OS). However, these data are fragmentary and cannot currently be assembled into a continuous series without the addition of other observations to fill the gaps. It is hoped that other barometer observations may eventually come to light to supplement these sources.

As can be seen from Table 2.1, the observations used for the London series for the seventeenth century and for much of the eighteenth century were recorded by individuals in private

Dates	**Source**
01/01/1692–31/12/1696*	John Locke's Weather Diary
01/01/1693–31/12/1693	Gresham College Weather Journal
01/01/1697–31/01/1709	William Derham's Weather Diary
01/02/1709–31/12/1716	Holborn Weather Diary
01/01/1723–31/07/1723	William Stukeley's Weather Diary†
01/08/1723–31/12/1727	Francis Hauksbee's Weather Diary†
01/01/1728–31/03/1750	James Jurin's Weather Diary†
01/04/1750–31/07/1765	John Hooker's Weather Diary†
01/08/1765–31/12/1773	Anon. Observations in the Gentleman's Magazine†
01/01/1774–31/08/1781	Royal Society Series: Crane Court
01/09/1781–30/06/1784	Thomas Hoy's Weather Diary
01/07/1784–31/12/1786	William Bent's Weather Diary†
01/01/1787–31/12/1842	Royal Society Series: Somerset House
01/01/1843–31/12/1849	Royal Observatory Series, Greenwich
01/01/1850–31/12/1881	EMULATE Series
01/01/1882–31/12/1949	Royal Observatory Series, Greenwich
01/01/1950–31/12/2007	Heathrow Airport Series

Table 2.1: Data sources used in the London Daily Pressure Series. A catalogue of the sources is provided in Appendix A of this Thesis. The only significant gap in the series occurs for the years 1717–22.
* Excluding the year 1693. †Values taken from Manley's *London Weather Diary (LWD)* (see §2.2.5).

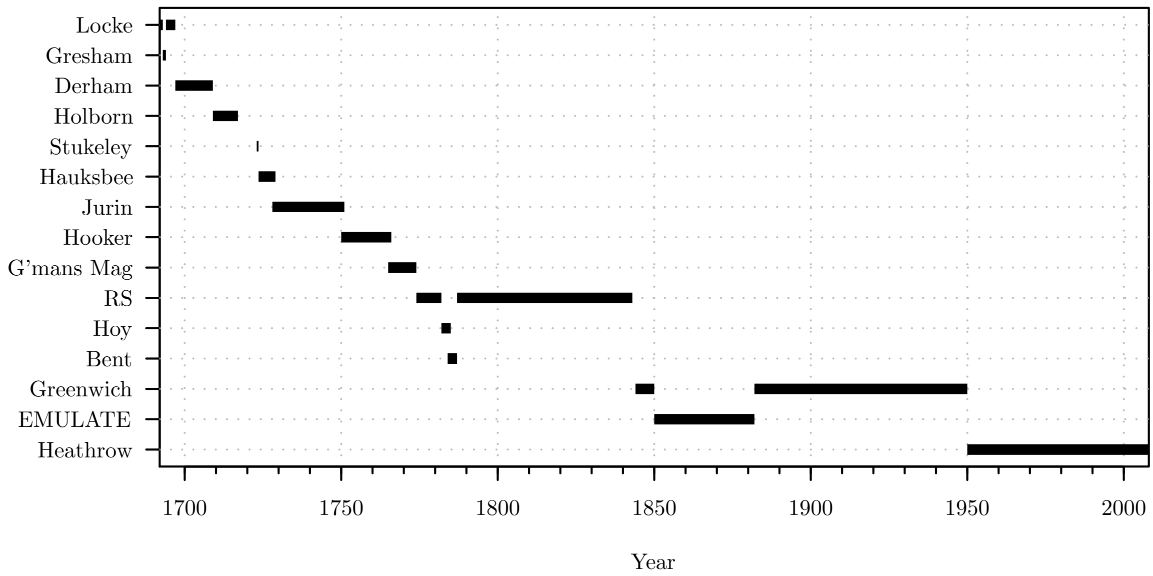

Figure 2.1: Gantt chart of the London sources. The bars indicate the span of each series and include no information about missing values within the series.

weather diaries. During this period a proliferation of instrument makers were resident in London and the barometer became a popular instrument in domestic life (Golinski, 2007). However, for the most part these instruments were not of a sufficient accuracy for the reconstruction of a reliable pressure series and regardless of this, very few of these individuals maintained a strict diary of instrumental observations. It is rather the observations from weather diaries kept by well-known philosophers that have been used in the London series. These observations were generally recorded using high-quality barometers for the time, such as those constructed by Francis Hauksbee, and were entered into a structured diary that appealed to the recommendations of the scientific community.

In contrast to the early part of the series, observations recorded at institutions were used to complete the London series from the late eighteenth century. These have the advantage that the recording of the data was not reliant upon a single observer and the records therefore tend to be more complete and consistent. It is mainly for this reason that the observations recorded at the Royal Society were used from 1774, despite the existence of other London records during this time. The consistency of the data in the period from the mid-nineteenth century has been further assured through the use of the observations recorded at the Royal Observatory, Greenwich.

At any one time in the London series, barometer observations have been used from only one source; Figure 2.2 shows the geographical location of the sources. The majority of the data were recorded within 20km of the centre of London (defined as the Strand). However, the Locke (1692–97) and Derham (1697–1708) observations were recorded to the east of London in Essex. During the period 1750–65 the observations by John Hooker recorded in Tonbridge, approximately 60km to the south-east of London, were preferred to observations recorded in the centre of London (see §2.2.5.4).

The quality and quantity of the information about the observations (meta-data) varies greatly

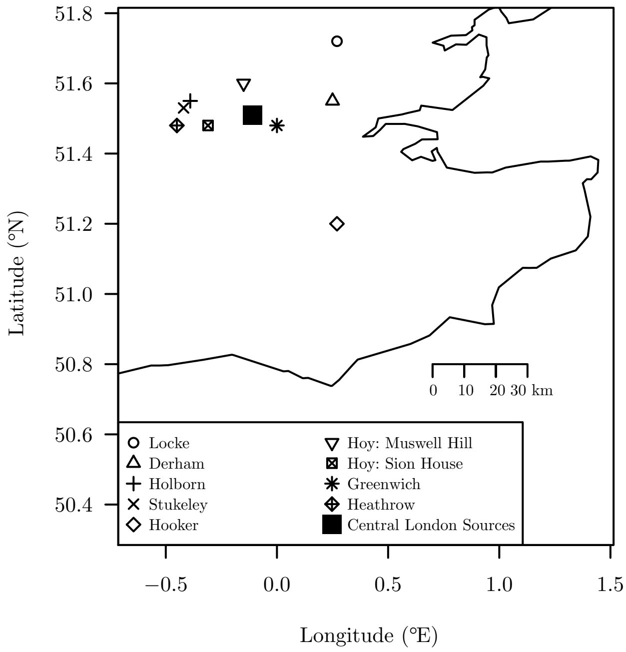

Figure 2.2: A map of south-east England showing the location of the London data sources listed in Table 2.1. The 'Central London Sources' category covers those sources located around the Strand, which are situated too close together to be rendered individually. This location groups the following sources: Gresham, Hauksbee, Jurin, Gentleman's Magazine, Royal Society and Bent.

between sources. As an example, the anonymous Holborn diary from the early eighteenth century contains no meta-data whereas full and complete meta-data are available for the Greenwich Observatory series. The first part of this chapter details these meta-data for each data source. Many of the daily observations from these sources have not previously been digitized and therefore several corrections needed to be applied to the data; these corrections are described in Section 2.3 of this chapter. These adjustments consisted of specific instrumental corrections and, in the case of the earliest readings, conversion to Gregorian calender dates. Further corrections were applied to reduce the data to standard gravity, 0°C and sea-level. In addition, the data were converted to the equivalent of a 24-hour mean, following the example of Ansell *et al.* (2006).

2.2 Description of the data sources

2.2.1 John Locke's weather diary, 1692–96

The English philosopher John Locke began to keep an intermittent diary of the weather in 1666 while living in Oxford (Manley, 1960, 1961b).[1] It would appear that Locke began to keep the diary after being persuaded by Robert Boyle, who suggested that a diary of regular and consistent observations may give an insight into the connection between weather and public health (Golinski, 2007). It is also likely that Locke was motivated by Robert Hooke's appeal

[1]Locke also recorded temperature and 'weather' observations in London during his short stays there during 1669–72 (Boyle, 1692, p.116-20).

for consistent meteorological registers to be kept throughout the country to provide the basis for weather forecasting (Kington, 1997a). Indeed Locke broadly followed Hooke's recommended format in his weather diary (see Manley, 1961b).

In 1692 Locke moved to Oates, the home of Sir Francis and Lady Masham in Essex (Cranston, 1959), and from this time his weather diary became more complete. The location of the observations from Oates permitted their inclusion in the London daily pressure series. According to Cranston (1959), Oates was a Tudor manor house situated to the north of Epping forest near Ongar in which Locke occupied two first-floor rooms. It would appear, from the information provided in the weather diary, that the instruments were periodically moved to different rooms in the house, although for the majority of the time until October 1696 the instruments were situated in Locke's chamber room. This room was southward facing and presumably had a fire lit at least during the winter months. On occasions the readings were taken from instruments in a closet room to the north of the house where it is stated that a fire was never lit. Finally from October 1696 until the end of the series the instruments were located in the large chamber of the house, which faced eastwards.

In his weather diary, Locke recorded observations of pressure, temperature, humidity[2], wind direction/strength and 'weather' at least once per day, following the format of his Oxford diary. During significant meteorological events—such as during a storm—Locke recorded more observations, sometimes at the frequency of hourly. Of particular importance is that the time of the observations (in 24-hour format) was also recorded (Locke, 1704), following Robert Hooke's scheme (see Wolf, 1935). The morning reading, taken around 9am, is the most consistent observation and was extracted from the diary for inclusion in the London pressure series. However, where this was missing the closest observation was taken.

The type of barometer that Locke used is not recorded. The instrument had a scale of 1/20ths English inch and this seems to be a different instrument to the one he used during his time in Oxford, which had a scale calibrated to 1/8ths inch (Boyle, 1692). It is likely that Locke used a barometer constructed by one of the high-quality London instrument makers.

Rather more is known about the thermometer that Locke used: it was constructed by Thomas Tompion and it was probably situated indoors, close to the barometer (Manley, 1961b). The temperature from this instrument was read as increasing degrees of heat and cold from a zero value marking 'temperate' (Locke, 1704). From later recording practices this zero value was probably at 45° according to the Royal Society standard (10°C) and it is assumed that the temperature unit likewise followed the Royal Society standard, giving 1° equal to 2.4°C (Patterson, 1951, 1953). The conversion of the morning readings by this method yielded monthly means of temperature comparable with the Manley (1961a) series, which during this period was derived from Locke's readings.

Although the number of gaps in the Oates diary are fewer than the Oxford diary many of the summer months are missing when Locke was away in London. A comparison of the dates when Locke was known to be in London (Cranston, 1959) with the gaps in the weather diary reveals that on certain occasions the readings must have been taken by another observer in his absence; this was most probably Locke's secretary.

[2]To measure humidity, Locke used the 'beard of a wild oat' in the manner described by Robert Hooke (see Wolf, 1935, pp 307–8).

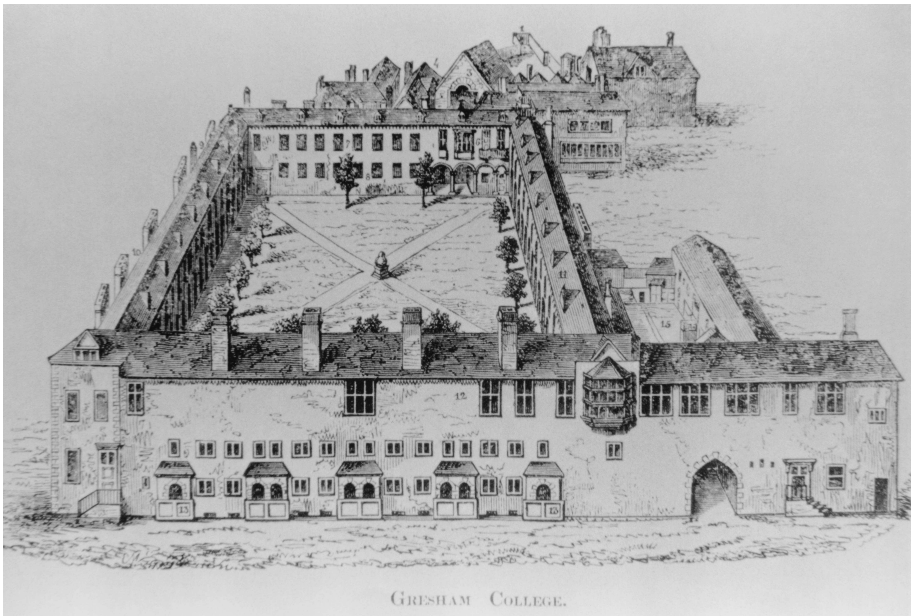

Figure 2.3: An engraving of Gresham College. This was the location of the meteorological observations taken by the Royal Society during 1693 (OS).

2.2.2 Gresham College, 1693

As has been stated above, Locke's diary contains many gaps, especially during the summer months. During this period there is only one other series of observations for London in existence to fill the gaps: this was recorded at the Royal Society's Gresham College premises during the year 1693 (OS) by the *Operator to the Society*, Henry Hunt.

The Royal Society was founded in 1660 and as an organisation devoted to the development of scientific understanding has been extremely influential in the science of meteorology since its inception. Indeed from these early days, the Royal Society—under the secretaryship of Henry Oldenburg—coordinated meteorological observations across the world (Golinski, 2007). Closer to home Robert Boyle had recommended in 1663 that mercury tubes be installed at Gresham College (Figure 2.3) for the observation of variations in the state of the atmosphere (Golinski, 2007). In 1679 meteorological instruments were installed in an astronomical turret at the College and scientists such as Robert Hooke carried out meteorological observations there (Weld, 1848). These observations do not appear to have been systematically recorded or have been lost in the intervening 300 years and the series for the year 1693 (OS) owes its survival to being published in the *Philosophical Transactions* as part of an investigation to ascertain the rate of evaporation from a body of water (Halley, 1694). In addition to the measurements of evaporation, Hunt also took measurements from a barometer and a thermometer: the readings being taken once daily at 8am.

The barometer readings at Gresham College were read to twelfths of an inch but nothing else is known about the instrument. The thermometer used a scale that was one-tenth that of Hooke's Royal Society standard (denoted °H), where 1°C = 0.24°H (Patterson, 1953). It would be reasonable to suggest that both instruments were constructed by Hunt himself given that he was a well respected instrument-maker in general, and a highly regarded barometer-maker in particular (Taylor, 1967).

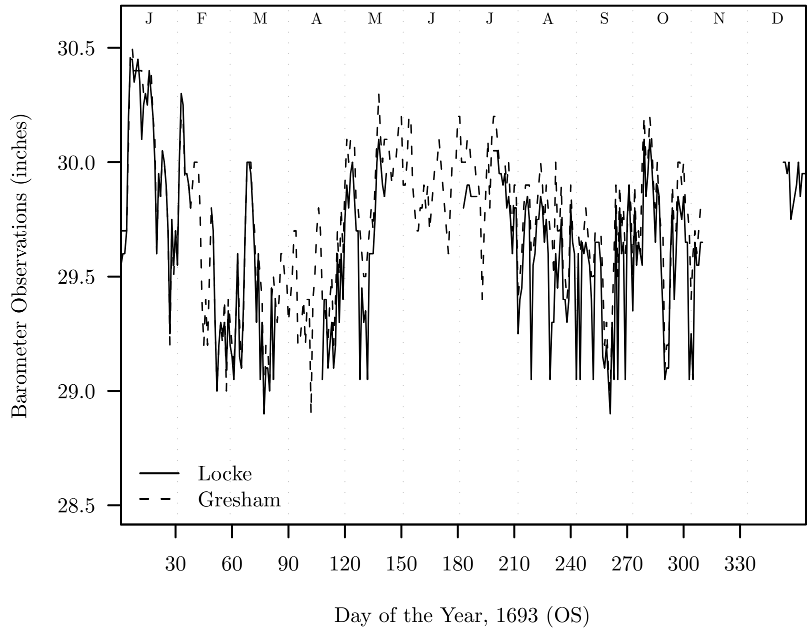

Figure 2.4: The barometer readings for each day of the year 1693 (OS) recorded by John Locke in Essex and by Henry Hunt at Gresham College. The readings have been converted to decimal inches but are otherwise as recorded in the original sources.

The pressure observations recorded at Gresham College, which are nearly continuous for the year 1693 (OS), provide a useful comparison with Locke's observations. Figure 2.4 shows a comparison of the Locke and Gresham barometer readings for the year 1693 (OS), from which it can be seen that the two series are in close agreement. This provides some evidence that the instruments used by both Locke and Hunt were responsive and of a high quality. Generally the Gresham barometer read 0.1 in. higher than Locke's, which is attributable to the differing altitudes of the two instruments: 25m for Gresham and 55m for Locke. Taking a station pressure of 1015hPa and a temperature of 10°C with these two altitudes in Standard Equation 3, a pressure difference of 3.7hPa between these two locations is achieved; this value is roughly equivalent to 0.1 inches of mercury. The close accordance of these two instruments may indicate that Locke's barometer was calibrated against the Royal Society instrument.

Given that the readings between the Locke and Gresham series are so similar, the entire year 1693 in the London series was completed by using the Gresham pressure data rather than Locke's data, for simplicity in identifying and correcting inhomogeneities in the final series.

2.2.3 William Derham's weather diary, 1697–1708

The meteorological diaries of Rev. William Derham have long been recognised as an important source of early instrumental data. In the diaries, he recorded thrice daily observations of barometric pressure, wind direction and strength, rainfall, and state of the sky from 1697 until 1708, with temperature recorded from 1699. Despite the length of the series, which was remarkable for the time, Derham considered 14 years of near-continuous observations insufficient for explaining the causes of the Great Frost of 1708 (Jankovic, 2001) and there is evidence that the observations were continued until the 1730s although these later observations appear to have been lost

(Slonosky, 1999; Slonosky *et al.*, 2001b); recent efforts to locate these diaries in various archives have also failed.

The meteorological observations were recorded three times daily: in the morning, between 6am and 8am depending on the season, at noon and in the evening at 9pm. Given the format of these diaries and the consistency of the series, Derham like Locke (§2.2.1) appears to be one of only a few natural philosophers who pursued Robert Hooke's recommendations for keeping regular instrumental observations of the weather.

This instrumental series is an important component of the London pressure series not least because it contains one of the few instrumental observations for the Great Storm of November 1703, as discussed in Derham (1704). The observations are considered to be of a high quality given Derham's great interest in the weather. Indeed, Derham regularly contributed to the *Philosophical Transactions of the Royal Society* on the subject and was keen on the comparison of observations recorded throughout Europe. This, along with Derham's work on natural history, prompted Taylor (1967, p410) to describe Derham as "an indefatigable observer and recorder of natural phenomena". As a natural philosopher Derham was also interested in explaining the observations, as demonstrated by his attempt to explain the Great Storm of 1703 (Derham, 1704) and the Frost of 1708 (Derham, 1708).

Derham's temperature measurements have long been highly valued as he is the first known observer to situate his thermometer out-of-doors in a shaded environment and these measurements were therefore an important component of the Central England Temperature (CET) series (Manley, 1953, 1974). In contrast, it was not until the late 1990s that Derham's barometer readings were considered in any detail. Slonosky (1999) digitized the values from the original manuscripts and applied several corrections to the raw data in order to produce a homogeneous daily series of surface pressure. Derham's morning observations for 1699–1706 as corrected by Slonosky (1999) were used in the London pressure series and these were supplemented by his noon observations for 1708, which have been newly digitized. Observations for 1707 were either not recorded or, as they had not been published in the *Philosophical Transactions*, have been lost.

2.2.4 Holborn diary, 1709–16

The cessation of Derham's weather diary in 1708 ends the good series of observations in the London pressure series until interest in the keeping of regular observations was revived in 1723 (see §2.2.5). A diary of observations does exist, however, to cover this gap until the year 1716. The diary was discovered at the Bodleian library in Oxford during the 1950s by Gordon Manley but neither the name of the observer nor the location of the observations are known. Manley (1961b) suspected, from notes contained in the diary, that the observations were taken in the Holborn area of Middlesex. In a later paper Manley (1974) thought that the diary was kept by Christopher Rawlinson, in whose collection the diary was discovered.

The observer began to keep the diary on 9 August 1698 (OS), with twice-daily observations (morning and night) of temperature and 'weather' alongside various astronomical observations. Observations of "The air's weight" (see Figure 2.5) were consistently recorded from January 1700 and Manley (1960, 1961b) thought these measurements could be translated into a measure of atmospheric pressure. Indeed there is evidence that both Manley and the climatologist Hubert

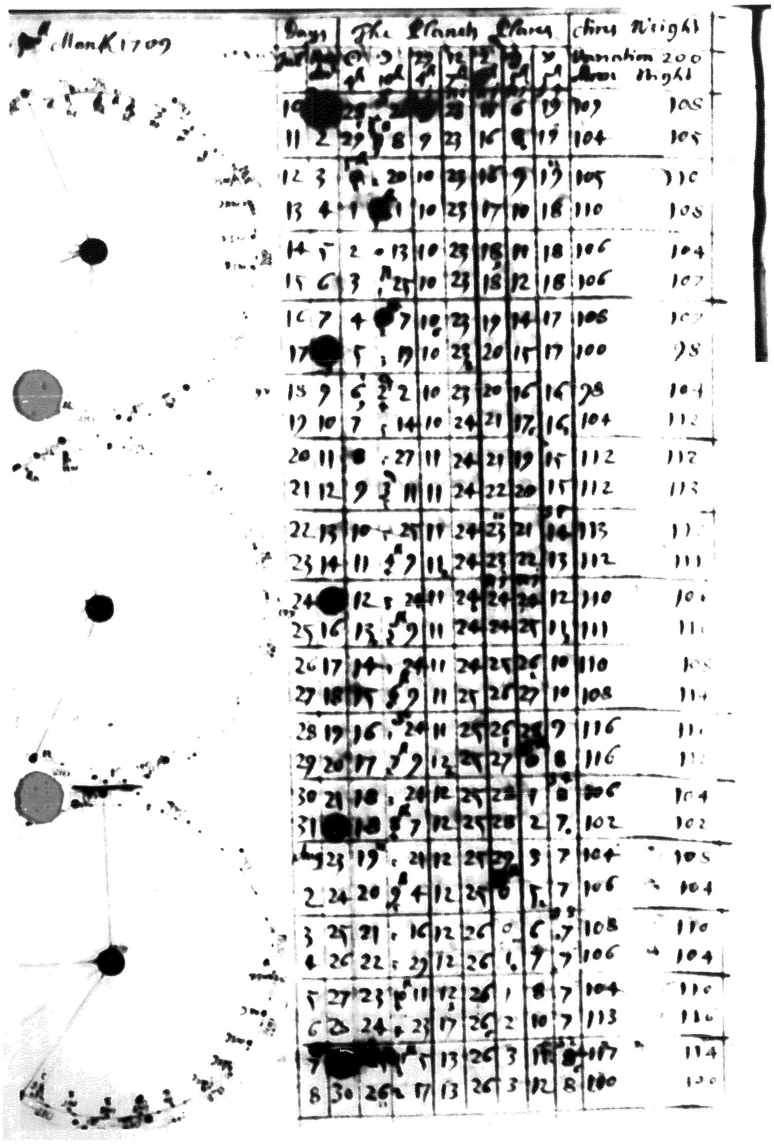

Figure 2.5: The Holborn weather diary for July/August 1709. The barometer readings are recorded in the right-most column under the title "Air's weight".

Lamb, then at the Met Office, looked into this possibility (Manley, 1980) although it appears that this reduction was never carried to a conclusion as their work appears to have been focused on the temperature and 'weather' observations, which Manley (1961b) regarded as consistent and well kept.

The derivation of a daily series of pressure by using the observations contained in the Holborn diary presented two immediate problems: the pressure scale was unknown and many of the pages of the diary are illegible due to water damage. Unknown scales for barometer measurements is a rare occurrence compared to early thermometers, which usually needed two fixed points to calibrate the scale: barometer measurements merely took the unit of measurement that was in general use, such as the Paris or English inch. To solve this problem the pressure scale was converted to a standard scale by comparing the readings with those recorded by William Derham during 1704–6. A linear regression model was developed from the overlapping measurements (Figure 2.6), taking the Holborn observations as the predictor and Derham's observations as the predictand. As demonstrated in Figure 2.6 there is a greater scatter in the afternoon

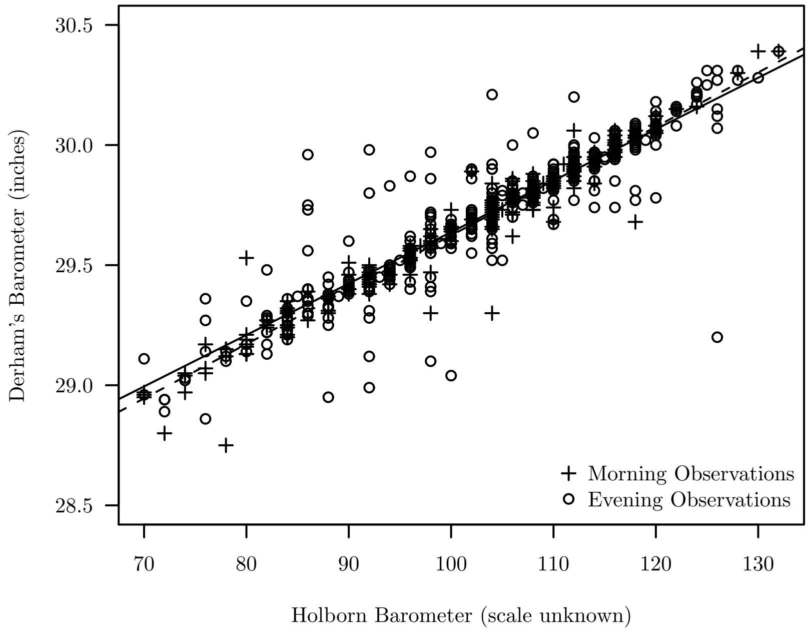

Figure 2.6: The relationship between the Holborn barometer and Derham's barometer, 1704–6 (OS). Crosses indicate the morning readings and circles represent the evening readings. The dashed and filled lines show the least squares fit for the morning and evening readings respectively.

observations (r^2 = 0.87) compared to those from the morning (r^2 = 0.95). This may have occurred for a variety of reasons, of which the most likely is that the observer used a different instrument for the morning and afternoon readings. It is also possible that the barometer may have been exposed to heat from a fire or to sunlight. A small proportion of the scatter may also be explained by different times of observation in the two diaries: the morning observation in the Holborn diary was probably close to Derham's observation time of 7–8am whereas the 'night' observation was probably midway between Derham's observation times of 12 and 9pm.

Different conversion models were used for the morning and evening readings and these were then used to convert the Holborn readings to the scale of English inches. The assumption had to be made therefore that this relationship existed throughout the series, that a change of instrument did not occur in the series and that there was no drift apparent in the readings. The morning reading from the Holborn diary was used to complete the London series due to the closer relationship to Derham's observations, although missing values were filled with the afternoon reading to ensure completeness of the series. These two readings could be interchanged as both readings had been reduced to the equivalent daily mean (see §2.3.6).

The problem of illegible observations in the Holborn diary could not so easily be solved. In many cases the water damage caused the ink to leach into the paper such that the integer could just be deduced. Due to the possible error from using these suspect values, they were flagged in the digital series. Other values that could not be estimated in this way were marked as missing. This flagging of values was considered a compromise to having as complete a series as possible for these important years in the instrumental period and having an accurate measure of atmospheric pressure. These flagged values should be carefully considered when using the London pressure series during this period.

2.2.5 Manley's London weather diary, 1723–73

During the late 1950s, the climatologist Gordon Manley, with the assistance of his research associate, Elizabeth Shaw, began to assemble London weather observations contained in various eighteenth century weather diaries into a single source. The *London Weather Diary (LWD)*, as it was known, consisted of daily values of temperature, pressure, wind direction and 'weather' from 1723 to 1805 that had been carefully compiled from a sequence of selected diaries (Manley, 1964). It seems that having reconstructed these data they were not put to a great deal of use, although Lamb & Johnson (1959) appear to have used the data from 1760–4 in their study of atmospheric circulation, and were aware that the series started in 1723. After several decades, Kington (1988) consulted the pressure readings in his construction of daily European synoptic charts for the years 1780–85.

The daily pressure data from the *LWD* were used to complete the London daily pressure series over the years 1723–73, and from July 1784 to the end of December 1786. Manley (1964) had applied corrections to the original pressure data to account for thermal expansion, gravity and altitude, but also to convert the series to Gregorian calendar dates where necessary (see §2.3.1). The correction for thermal expansion had been applied on the assumption that where indoor temperature values were included in the original sources then these were applicable to the temperature of the barometer. The corrections for altitude were based on estimated values for the height of the barometer. Given the uncertainties in the applied corrections, Manley only considered the pressure values to be accurate to the nearest whole hPa.

Manley also applied adjustments to the corrected series to account for inhomogeneities. These adjustments were done manually on the basis of meta-data and using Manley's meteorological knowledge. Manley also compared the pressure values on a monthly basis with those recorded at other locations in England and also on the near Continent, although there is no record of the exact comparisons. It seems that while the pressure data in the *LWD* were examined in some detail by Hubert Lamb (Manley, 1980), no further work was done to account for the remaining inhomogeneities in the data.

To complete the London pressure series the pressure data were digitized directly from the corrected values in the *LWD*. These values had been entered into the diary in both inches (entered to a precision of hundredths of an inch) and hPa (rounded to the nearest whole hPa) but to limit the chance of errors that may have arisen for the conversion to hPa, the values were extracted, where possible, in inches. However, over the period 1 August 1765 to 31 December 1770 the values were only entered into the diary as hPa and there is therefore a reduction in the precision of the London series during this period from 0.1hPa to 1hPa.

In many cases the exact time of the meteorological observation was not included in the original source. In general, the pressure observation represents a mid-morning value as observations between 8 and 10am were common in the various sources (Manley, 1980). The following subsections provide information on each of the component sources used in the *LWD* over the 1723–73 period.

2.2.5.1 William Stukeley, 1723

The first source of meteorological observations used in the London Weather Diary were recorded by William Stukeley. The exact location of the observations is not known although Manley

(1960) thought that they were recorded somewhere in West London. The observations from Stukeley's diary were used to complete the *LWD* from January–July 1723.

2.2.5.2 Francis Hauksbee, 1723–8

Francis Hauksbee, the younger, was a well respected instrument-maker in London and was the supplier of instruments to the Royal Society (Knowles Middleton, 1969). During the years from 1723 to 1729 Hauksbee kept a daily diary of pressure, temperature and 'weather' observations at Crane Court, near to the Royal Society's premises in the centre of London. The readings were taken twice daily, in the morning and evening (Manley, 1960), although only the morning readings were used in the *LWD*. It is probable that Hauksbee used his own instruments for these readings.

2.2.5.3 James Jurin, 1728–50

In 1723, on becoming the Secretary of the Royal Society, James Jurin published an appeal for meteorological observations from around the world to be sent to the Royal Society (Manley, 1952). In this request Jurin stipulated the exact methods by which daily observations should be made and how they should be recorded. Jurin was a physician and the motivation for establishing a network of meteorological observations was to determine the influence of weather on public health (Manley, 1952). To this end, Jurin kept a diary of daily meteorological observations at his private house in London from January 1728 until his death in March 1750.

Initially, Jurin recorded his observations at Garlick Hill but from May 1745 they were recorded a short distance away at Lincoln's Inn Fields; both of these locations are in the centre of London (Manley, 1952, 1960). There is no direct information regarding the instruments that Jurin used although it is known that he favoured instruments made by Francis Hauksbee the younger (Manley, 1952; Knowles Middleton, 1969). It is also known that the temperature was probably recorded from a thermometer attached to the barometer and that the instruments were located in a room where no fire was lit (Manley, 1952). The majority of the readings were taken between 8 and 9am.

Jurin's weather diary is remarkably complete with only 4% of the daily values missing, a large proportion of which occurred from December 1735 to June 1736. All missing values were completed by Manley using the observations recorded by John Hooker in Kent as a guide: Hooker's observations were also used to complete the *LWD* over the following 15 years.

2.2.5.4 John Hooker, 1750–65

A daily weather diary consisting of pressure, wind, rainfall and 'weather' was kept in Kent from 1728 until 1765 by John Hooker. His observations recorded at Tonbridge from 1750 until 1765 were used in the *LWD*. Little is known about Hooker although Manley (1960) considered the observations to be more reliable than the contemporary observations recorded in the *Gentleman's Magazine* from 1747 to 1751, which although recorded in the centre of London are of a poor quality. It is suspected that the observer who published in the *Gentleman's Magazine* had a barometer that was probably a poorly kept wheel instrument that was liable to stick (Manley, 1980). However, Hooker's observations are not without problems as, while on the whole the observations were regarded as consistent and well kept (Manley, 1960), the readings are of a lesser quality towards the end of the series; this has been attributed to Hooker's deteriorating eyesight with old-age (Manley, 1980).

Manley (1964) reduced the pressure data from Hooker's diary to measures of sea-level pressure at standard conditions, taking the altitude as 61m. The temperature corrections applied to the pressure readings by Manley (1964) were based on the monthly means of temperature derived from Jurin's diary from 1740 to 1742. Alongside these usual corrections, Manley adjusted the series to be comparable with Jurin's recordings.

2.2.5.5 Anon. observations in the Gentleman's Magazine, 1765–73

Due to the Hooker series ending in 1765, the observations recorded in the *Gentleman's Magazine* were used to complete the *LWD* from 1765–73. Various observers had contributed meteorological observations to the magazine from the 1740s (Sherbo, 1985) although it is not known who recorded the observations over the 1765–73 period. It is thought that the record was kept at a residence "7m west of Hyde Park Corner" (Manley, 1960, p.5). Furthermore there is no direct information regarding the instruments used, although from a review of the daily readings Manley (1960) concluded that the barometer was probably a wheel design that was liable to stick and therefore may have been poorly maintained. In addition to these errors there were several misprints in the original publication. To account for these errors Manley adjusted individual values that he considered to be erroneous. In addition, similar corrections as for the previous series were applied to account for thermal expansion, altitude (27m) and acceleration due to gravity. A further correction was applied to adjust the series to the standard of the Royal Society (1774–1805), although Manley did not specify how this correction was achieved.

2.2.6 The Royal Society series: Crane Court, 1774–81

As has been demonstrated above with the observations recorded at Gresham College in 1693 (§2.2.2) and Hauksbee's observations during the 1720s (§2.2.5.2), the Royal Society had been involved in meteorological observations throughout much of the late seventeenth and eighteenth centuries. However, it was not until January 1774 that routine observations were kept by the Society itself. The Society called upon the eminent Henry Cavendish to devise a scheme for maintaining the register (Jungnickel & McCormmach, 1996) using instruments at the Society's house in Crane Court (Figure 2.7). However, the Society moved premises in August 1781 from Crane Court to Somerset House (Martin, 1967) and it would appear that this coincided with a decision to end the register. This might explain the Society's decision to decline an invitation from the *Societas Meteorologica Palatinato* to join a European-wide network of meteorological observers (Fleming, 1998). This decision was later revoked and the measurements resumed on 1 January 1787; they were subsequently maintained until 1843. Due to this break in continuity, the Royal Society's observations are considered here as two separate series; the later series (1787–1842) is described in Section 2.2.9.

In accordance with Cavendish's recommendations, the clerk of the Society at Crane Court was instructed to record observations from internal/external thermometers and a barometer, alongside other meteorological parameters, twice daily: in the morning and afternoon. The morning observations from 1774 to 1822 were mostly read at 8am during the winter months

Figure 2.7: The Royal Society's premises at Crane Court, where meteorological observations were recorded over the period 1774–81. © The Royal Society.

and at 7am the rest of the year; the afternoon observations were recorded at 2pm. The observation times sometimes varied from these hours, although this variation was usually less than 30 minutes. Measurements from additional instruments were included over the course of the series, although the core variables of internal/external temperature, pressure, wind direction/speed, rainfall and 'weather' were recorded throughout. The meteorological register was published biannually in the *Philosophical Transactions of the Royal Society* as an Appendix and the monthly means and totals calculated from the daily observations were published at the end of the register.

The pressure readings at Crane Court were taken using a fixed-cistern barometer that had been installed by Cavendish. The exact location of the barometer at Crane Court is unknown, although from the description given by Cavendish (1776) it is known that the internal thermometer, which was placed close to the barometer, was in a northward facing room, in which a fire was sometimes lit. It seems that Cavendish gave a great deal of thought to the choice of barometer and rejected the siphon-type barometer in favour of the cistern-type, which he considered to be more accurate and easier to read, despite the fact that additional corrections had to be applied (Cavendish, 1776). The tube in Cavendish's barometer had an internal diameter of 0.25 in. with the cistern to tube ratio being 120:1. Using this instrument the pressure readings in the meteorological register were recorded in English decimal inches (1 inch = 25.4mm) to a precision of one-hundredth of an inch, with the value being read from the meniscus of the mercury.

The temperature readings were recorded using thermometers calibrated to the Fahrenheit scale and were measured to the nearest half-degree. The internal thermometer was placed close to the barometer for the correction of the pressure readings (Cavendish, 1776). The external thermometer was placed out of a northward facing, second-floor window and while this location was considered 'airy', the nearest building was only 25 feet away and this may have influenced the readings. During the summer months it was observed that the north side of the house was exposed to sunlight one hour before the morning observation, although the thermometer itself was never exposed to direct sunlight.

2.2.7 Thomas Hoy's weather diary, 1781–4

To cover some of the missing observations in the Royal Society series, the observations from Thomas Hoy's weather diary were used. Hoy began to keep regular meteorological observations in 1771 that consisted of once daily barometer, wind direction/strength and 'weather' readings at 8am; and twice daily temperature readings, at 8am and 3pm. The observations for the period used in the London pressure series were made firstly at Muswell Hill (until May 1782) and then at Syon House (from August 1782). Syon House is located close to the River Thames in west London and Hoy took employment there as steward to the Duke of Northumberland (Drummond, 1943).

Nothing is known about the instruments that Hoy used although it appears that they were not as accurate as those used at the Royal Society. Manley (1960) considered Hoy's temperature readings to be too warm by 4–5°F (≈ 2–3°C), although Drummond (1943) suspected that the thermometer was suspended outside a northward facing window. It is also apparent that the barometer readings are highly erroneous during the months of January to March 1785, with the values being more than 25hPa too low. It is for this reason that the barometer readings of William Bent were used from July 1784, despite Hoy's series extending to March 1822.

2.2.8 William Bent's weather diary, 1784–6

William Bent started to publish his daily weather observations in the *Universal Magazine* from July 1784 and continued until December 1807. A good deal of information exists regarding the nature of the observations, which is unusual for a private observer at the time. The sole source for this information is the *Universal Magazine* for February 1785, where it is stated that the observations were recorded at the King's Arms on Paternoster Row, which is located in the centre of London. The barometer was a closed cistern type with a perpendicular scale, the tube of which was 1/3 in. in diameter. It was located in a room on the ground floor of the premises. Temperature observations were taken both indoors and outdoors, with the indoor thermometer placed near the back door in the staircase passage and the outdoor thermometer placed in an open case that was sited in the northward facing back-yard (Manley, 1964).

Bent's observations had been corrected by Manley (1964) as described above (§2.2.5) and were digitized from the *LWD* for inclusion to the London pressure series.

2.2.9 The Royal Society series: Somerset House, 1787–1842

The Royal Society resumed its meteorological observations on 1 January 1787 at Somerset House (Figure 2.8). The observation times at Somerset House were initially the same as at Crane Court, with the morning observations until 1822 usually being read at 8am during the winter months and at 7am the rest of the year; the afternoon observations were recorded at 2pm. During the

Figure 2.8: The Royal Society's premises at Somerset House, where meteorological observations were recorded over the period 1787–1842. The drawing depicts the house from the south bank of the River Thames. © The Royal Society.

year 1811 the time of the observation varied by around half an hour although from 1823 the times became fixed at 9am and 3pm throughout the year. The instruments were moved from Crane Court and the Cavendish barometer, along with the internal thermometer, was sited in the Council Room (Baily, 1837). This was a westward facing room, in which a fire was constantly lit during the winter months (Royal Society, 1788).

The siting of the external thermometers proved more difficult than the barometer. A location where the thermometers were not subjected to direct sunlight could not be found and therefore two thermometers were used: both were sited out of a third storey window but one was placed facing ENE and the other WSW. The morning reading was taken from the westward facing thermometer and the afternoon reading taken from the eastward facing thermometer, to reduce the influence of direct solar radiation on the instruments (Royal Society, 1788). These thermometers, like the internal instrument, were read to the nearest half-degree Fahrenheit until June 1797, the nearest degree until April 1826 and tenths of a degree thereafter.

The Cavendish barometer appears to have remained unchanged at Somerset House until 1 January 1823 when it was replaced by a superior instrument constructed by John Frederic Daniell (Daniell, 1823). Daniell's barometer was sited in the closet adjoining the library, which was above the council Room where previously the Cavendish barometer had been situated (Baily, 1837). The tube of Daniell's barometer had an internal diameter of 0.53in. and a length of 33.75in. with the capacity/tube ratio being 100:1. The cistern of the barometer was constructed from well-seasoned mahogany and the mercury was boiled to remove any air that may have been present. It would appear that several tubes were broken through this boiling process, which was necessary in order for a better vacuum to be achieved (Knowles Middleton, 1964). To ensure further accuracy of the instrument, Daniell also applied a new method of extracting air from the tube by using a pump (Daniell, 1823). This new instrument allowed the pressure readings to be read to a precision of one-thousandth of an inch.

At the time of the installation Daniell compared the readings from his new barometer with those of the earlier Cavendish barometer. This comparison revealed that the newly installed barometer read an average of 0.07in. (1.78mm) higher than the earlier instrument. Furthermore, it was noted that the mercury in the Cavendish barometer was 'thickly studded with air bubbles' (Eaton, 1863, p. 275), which is an indication that the vacuum in the barometer's tube was imperfect. This inaccuracy is likely to have increased over the lifetime of the instrument and is almost certainly a result of the mercury not having been boiled in the instrument at the time of construction (Eaton, 1863).

It is clear that by 1823 Daniell's more accurate barometer was greatly needed. However, the accuracy of the readings was somewhat diminished by a poor keeping of the register. In the meteorological register for this period the observations are labelled as 'corrected' although the nature of this correction is not provided and indeed there appears to have been a great deal of confusion regarding the corrections that had been applied. The Royal Society was criticized for this failing by several leading scientists at the time; Baily (1837, p438) suggested that "this state of confusion and uncertainty ought not to exist in a meteorological journal emanating from this Society", and sought to clear up the confusion. He managed to ascertain that only corrections for cylinder capacity had been applied to the *daily* readings, although additional corrections for temperature had been applied to the *monthly* means, at the end of the register. However, even these corrections had been erroneously made during 1826, by using the external thermometer readings rather than the internal thermometer. Furthermore, even the temperature correction table used during this time was not applicable to the readings as it had been compiled for use with a scale that had been engraved onto the barometer's tube which was never used (Eaton, 1863). The readings had actually been measured using a short brass scale that was adjacent to the tube.

Daniell's barometer was itself replaced in 1837 with an instrument that consisted of two tubes: one made of crown-glass and one of flint-glass, leading from the same cistern of mercury (Baily, 1837). The installation of this barometer was presided over by the astronomer Francis Baily and the aim of the two tubes was to determine the chemical effect that the two different materials had on the mercury over time (Baily, 1837), although it seems that no paper was subsequently published on this subject. Eaton (1880) compared the readings from the two tubes and concluded that air must have been present in the crown-glass tube due to the fact that the readings were lower than in the flint-glass tube. As Eaton explains, the height of the mercury in the crown-glass tube should have been higher due to enhanced capillary action in the smaller diameter tube of the flint-glass tube, which was 0.594in. compared to 0.658in. for the crown-glass tube. Despite this error in the crown-glass tube the new instrument was an improvement over the earlier Daniell's barometer. A vernier was attached to each tube leading to a brass scale common to both and the height of the mercury was read via an eye-piece to improve accuracy (Baily, 1837). Using this vernier the readings were recorded to a precision of one-thousandth inch. The scale of the barometer was tipped with agate, which allowed the end of the scale to be brought into contact with the level of mercury in the cistern and thus resolved cistern-capacity errors.

In 1843, shortly after the installation of the new barometer, meteorological observations ceased to be recorded at the house of the Royal Society: this duty was transferred to the Royal Observatory, Greenwich (Moore & Sampson, 1995).

2.2.10 The Greenwich Observatory series, 1843–9; 1882–1949

Meteorological observations recorded at the Royal Observatory, Greenwich have long been valued as an important record of the climatology of south-east Britain (Jones, 1951). Continuing this tradition the Greenwich observations are a major component of the London daily pressure series and provide continuation to the Royal Society's observations. It should be noted that the joining together of the Royal Society series with the Greenwich series follows the example set by Eaton (1863, 1880) in his reconstruction of monthly means of pressure. With the European and North Atlantic daily to MULtidecadal climATE variability (EMULATE) series covering the years 1850 until 1881 (see §2.2.11) the Greenwich observations were used to complete the London daily pressure series from January 1843 until December 1849 and from January 1882 until December 1949.

Meteorological observations are known to have been recorded at the Greenwich Observatory from its earliest days in the late seventeenth century by the first Astronomer Royal, John Flamsteed; although these observations appear to have been lost over the intervening 300 years (Forbes *et al.*, 2002). However, the first attempt at recording consistent observations was initiated at the Observatory in 1836 by James Glaisher, Superintendent of meteorological observations, under the supervision of the seventh Astronomer Royal George Biddell Airy. These early observations were only recorded during the equinoxes and solstices and it was not until November 1840 that routine, daily observations were kept (Glaisher, 1848; Brazell, 1968).

As a reflection of Glaisher's recognition of the importance of consistent meteorological observation, both the observational routine and the instruments remained relatively unchanged at Greenwich over the 1841–1949 period. Indeed it has been recognised that Glaisher's observational scheme was adopted by the various observatories that were established in Britain throughout the nineteenth century and that the scheme also formed the basis for observations recorded at the Meteorological Office's stations from 1854 (Kenworthy & Giles, 1994). The pressure data may therefore be regarded as one of the longest homogeneous pressure series in Britain and are second only to those from the Kew Observatory, which were recorded routinely over an extended (1842–1980) period (Galvin, 2003). However, whilst generally consistent there were certain alterations to the location of the instruments and the nature of the observations at Greenwich that need to be taken into consideration. This information was obtained from various editions of the *Results of the magnetical and meteorological observations made at the Royal Observatory, Greenwich* publication.

The pressure observations were made throughout the series using a Newman standard barometer (No. 64) and until the 3 April 1917 this barometer was attached to the southern wall in the western arm of the Upper Magnet Room (see Figure 2.9). After this date the barometer was moved to the New Magnetograph House. This barometer had a brass scale that was divided into 0.05 in. and the readings were made using an attached vernier, which subdivided the scale into 0.002 in. This barometer had been installed on 18 December 1840 and the readings were observed to be consistent with those of the flint-glass barometer at the Royal Society over the years 1840–3 (Eaton, 1880). However, on 20 August 1866 the sliding rod was removed from the barometer for repair. Before the repair was carried-out the barometer was compared with three other barometers and one of these was used for the observations during the ten days it took to for the repair to be completed. When the sliding rod was reinstalled another comparison was

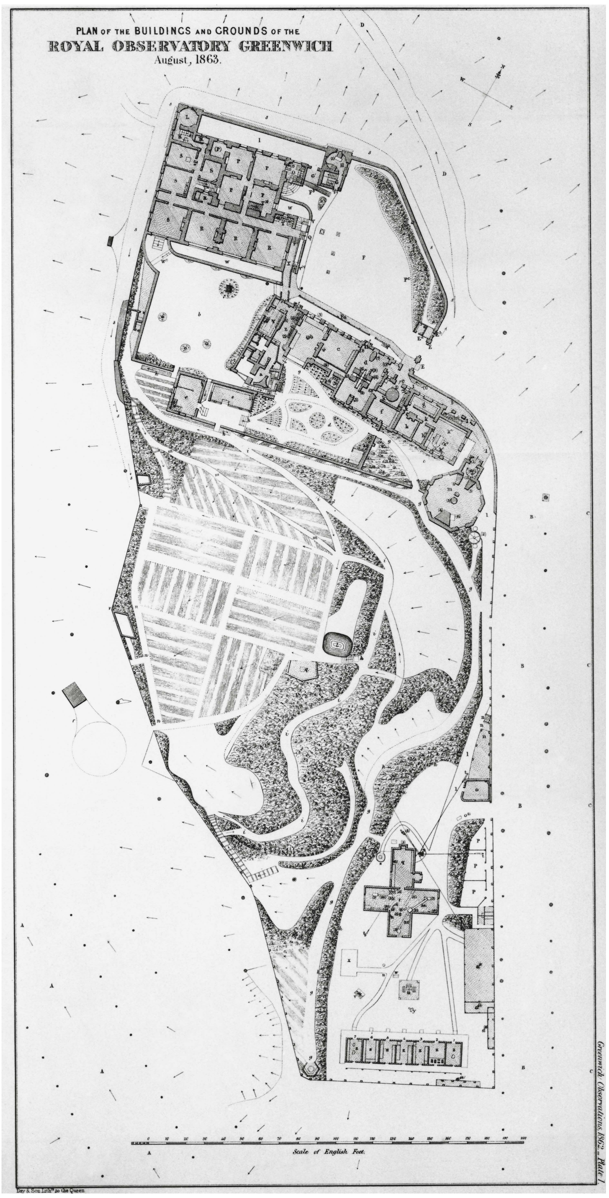

Figure 2.9: A map of the Royal Observatory, Greenwich in August 1863. The cross-shaped building (The Magnet House) in the bottom of the diagram housed the standard barometer until 1917. The building was constructed entirely of wood due to the magnetic observations also being observed there. In 1913–14 a new building was constructed adjacent to the Magnet House to which the standard barometer was transferred in 1917 (Dyson, 1932).

made with the three control barometers and from this it was ascertained that a correction of -0.006in. was required to ensure compatibility with the barometer in its previous state and hence the Royal Society's flint-glass barometer (Royal Greenwich Observatory, 1868). This correction was applied to all readings from this date. Further corrections were applied to the published values to reduce the measurements to 32°F, although no corrections were applied to the daily readings for capillarity, station altitude or for standard gravity.

Over the period 1841–1847, observations of the standard barometer were made every two hours (on the even hours) on every day of the year except Sundays, Good Friday and Christmas day, when fewer observations were made. These observations were published in the *Magnetical and meteorological observations made at the Royal Observatory* volumes with the daily means compiled in a table at the end of each year's volume. The daily means for Sundays, Good

Friday and Christmas day were not included in this table due to fewer hourly observations being recorded on these days. From January 1848 the hourly observations were no longer published and instead the daily mean value was included in the main table alongside the other meteorological observations for that day. The daily mean was calculated using a method described by Glaisher (1848) from observations taken every three hours from 6am to 12 midnight UTC, although from fewer observations on Sundays and public holidays. This method used the diurnal pressure cycle derived from five years of observations to obtain a 'true' daily mean value from the limited number of hourly observations.

In the later period (from 1882) the direct observations from the standard barometer were no longer published as these were replaced by the readings from a photographic siphon barometer, which had been installed in 1877. This equipment enabled hourly barometer values to be recorded, which were calibrated from monthly mean readings made from the standard barometer at set hours throughout the day. These manual readings, which had been corrected as in previous years, were compared with the monthly mean photographic values at these hours and a correction was calculated. These small corrections were then applied directly to the photographic readings at these hours with the corrections to the intermediate hours deduced from interpolation. This practice was continued until 31st May 1950, when automatic readings were discontinued due to the transfer of personnel to the new observatory at Herstmonceux in Sussex. After this time, daily readings of the barometer and dry-bulb thermometer, alongside other variables, were only made at 9am.

During the spring of 1877, a comparison was made between the standard barometers of the Kew and Greenwich observatories (Whipple, 1878). This involved calibrating portable barometers with the barometers at Kew and then transporting these instruments to Greenwich, where they were compared with the standard barometer over the course of several days. The portable instruments were then transported back to Kew where further comparisons were made. This procedure was repeated three times during April and May, 1877. The conclusion from this study, after inclusion of all standard corrections, was a mean difference between the Kew and Greenwich standards of -0.0001in. and was therefore tantamount to no discernible difference. An important finding of this study was that the gas burners used to illuminate the Greenwich standard barometer could have an effect on the temperature of the rear of the barometer when turned to their highest setting—this value was not recorded by the attached thermometer. During normal use of the gas burners this discrepancy was only around 0.5°F but as there was a potential for larger errors, opal glass screens were subsequently fitted to ensure an even temperature around the instrument.

In addition to the barometer measurements, the dry-bulb thermometer observations were extracted from the Greenwich yearbooks in order to convert the barometer readings to sea-level (see §2.3.5). The thermometer used over the 1843–1849 period was constructed by Newman and was graduated to 0.5°F. In the later 1882–1949 period of observations a Negretti and Zambra (No. 45354) thermometer was used. The thermometers (from 1883) were calibrated annually with the standard thermometer at the Kew Observatory. In a similar manner to the barometer measurements, the daily mean temperature values were derived from observations every two hours until 1848 and after this date by daily means derived by applying a limited number of readings to the mean diurnal temperature cycle. In the later period from 1882, the daily means were derived from the readings from a photographic thermometer, which was calibrated on a monthly basis with the corresponding measurements of the standard thermometer read at the same set hours as the barometer. In 1938 observations were taken from a distance recording thermograph, which was similarly calibrated with readings from the standard thermometer. These readings were therefore representative of the value that would be obtained from the exposure of the dry-bulb thermometer.

The standard dry-bulb thermometer was mounted in a revolving frame or Glaisher stand until 1938 after which a Stevenson screen was employed. The stand was situated approximately 4m from the observatory buildings, although from 4 January 1899 the stand was relocated to a more open situation.

2.2.11 The EMULATE series, 1850–81

The station data for London recovered during the EMULATE project were used to complete the London daily pressure series over the 1850–81 period. These data had been corrected so that they were representative of sea-level pressure at standard conditions. As some of the observations in the original sources had been recorded only at a certain time during the morning, the values had also been adjusted to the equivalent of a 24-hour mean value (Ansell *et al.*, 2006). To ensure homogeneity in the series, the data were then adjusted so that the monthly means were comparable with the Annual to Decadal Variability in Climate in Europe (ADVICE) project's London series (Ansell, 2004).

2.2.12 The Heathrow Airport series, 1950–2007

To bring the London pressure series up to the present-day the observations from Heathrow airport were used. The first consistent meteorological observations began at the airport on 31 May 1946 (Webster, 1984), although its seems that only the data from 1949 have been digitized; these were retrieved from the British Atmospheric Data Centre (BADC) repository (UK Meteorological Office, 2008). Hourly data were retrieved and the daily (24-hour) mean was calculated.

According to Webster (1984), the observing station at Heathrow was moved three times prior to 1984 although these relocations were not thought to bias the climatological record appreciably. Until 31 December 1964, the instruments were situated in a grass-covered enclosure close to the south of the forecasting office, which in turn was located to the north of the airport's central terminal area. From 1 January 1965 the instrument enclosure was relocated 11m to allow for expansion of the airport's perimeter road. The instruments remained in this location until 17 February 1972 when there were moved 90m south-south-east to allow for further work to the road.

Until 1971 the pressure observations were recorded from Kew-pattern mercury barometers, after which they were replaced by precision aneroid barometers (Webster, 1984).

2.3 Corrections to the data

The barometer readings were digitized, where necessary, from the sources described above. All of these data, with the exception of those taken at Heathrow airport from 1971, were recorded

	Calendar Dates	Cylinder Capacity	Capillarity	Temperature	Gravity	MSLP	Daily Mean
John Locke's Weather Diary	•			•	•	•	•
Gresham College Weather Diary	•			•	•	•	•
William Derham's Weather Diary: 1697–1706							•
William Derham's Weather Diary: 1708	•			•	•	•	•
Holborn Weather Diary	•			•	•	•	•
LWD (incl. William Bent's readings, 1784–6)							•
Royal Society: Cavendish barometer		•	•	•	•	•	•
Royal Society: Daniell/Flint-glass barometers			•	•	•	•	•
Thomas Hoy's Weather Diary				•	•	•	•
Royal Observatory, Greenwich			•		•	•	
EMULATE Series							
Heathrow Airport							

Table 2.2: The corrections that were necessary for each of the component London series.

using mercury barometers and in most cases these readings were purely measurements of the height of the mercury in the tube of the barometer. In addition to atmospheric pressure this measurement is affected by a variety of factors, which need to be corrected for.

After being subjected to a quality control procedure (see Chapter 4) the data were corrected, where necessary, to New Style (Gregorian) calendar (NS) dates and for cistern-capacity errors, capillarity, thermal expansion, acceleration due to gravity and altitude. A further correction was applied to those readings only taken at a limited number of hours per day to bring the observations to the equivalent of a 24-hour daily mean. The corrections necessary for each series are listed in Table 2.2.

2.3.1 Conversion to the Gregorian style calendar

The Gregorian calendar was introduced in Britain in 1752, which is late compared to many other countries in Europe; until this time the Julian calendar was used. The conversion took place in September 1752 when 2 September (OS) was followed by 14 September (NS) (Cheney & Jones, 2000). As a result of this change all of the observations in the London series prior to 2 September 1752, excluding the data taken from the *LWD* (1723–73) and those of Derham for 1697–1706 which had already been corrected, needed to be converted from the recorded Julian date to the equivalent Gregorian date. This correction consisted of shifting the dates forward by ten days for observations taken in the seventeenth century and forward by eleven days for the eighteenth century observations after 18 February 1700 (OS).[3]

[3]This one-day difference in the correction is due to the year 1700 being a leap-year in the Julian calendar but not in the Gregorian calendar (see Cheney & Jones, 2000).

2.3.2 Corrections for cistern capacity and capillarity

In fixed-cistern mercury barometers an adjustment needs to be applied to account for the changes in the relative height of the mercury in the tube and cistern. This error occurs because as the mercury moves from the cistern to the tube, and *vice versa*, the relative height changes (Knowles Middleton, 1964). A correction for this had been applied to all barometer measurements made after the Greenwich series (from 1843); the Daniell and Flint-glass barometers used at the Royal Society from 1823 had also been corrected (see §2.2.9). All of the other series using fixed-cistern barometers would need to be corrected. However, in order to apply this correction the neutral point—i.e. the point at which no correction needs to be applied—and the relative capacities of the barometer cistern and tube need to be known. These values are only recorded for the Cavendish barometer used at the Royal Society (1774–81), to which the following correction was applied:

$$h_{corr} = \frac{h - f}{r} + h, \tag{2.1}$$

where h_{corr} = the height of the mercury corrected for capacity error (in.), h = the measured height of the mercury (in.), f = the neutral point (29.75in.) and r = the capacity of the cistern relative to the tube (120).

A further instrument-specific correction that needs to be applied to the readings from mercury barometers is for capillarity. This error arises primarily as a result of the surface tension of the mercury, which leads to the mercury level being depressed by a value that is inversely proportional to the diameter of the barometer tube. The correction for capillary depression tends to be small and is negligible for tubes greater than 25.4mm (Meteorological Office, 1969), but should be taken into account. However, the application of this correction once again depends on knowledge of the diameter of the barometer tube. This was only known for the Royal Society barometers and the Greenwich standard barometer.

The Royal Society readings were adjusted for capillarity by adding 0.04in., 0.006in. and 0.004in. to the readings taken from the Cavendish (1774–1822), Daniell (1823–36) and Flint-glass (1837–42) barometers respectively. At the Greenwich observatory all readings had been calibrated by the Standard Barometer and as the correction for capillarity (+0.002 in.) had not been incorporated into this adjustment it needed to be applied to these readings. It would be expected that by this time the correction for capillarity had been incorporated into the index-correction, which is a correction for calibrating a particular barometer against a standard instrument. Indeed the Standard Barometer at the Greenwich observatory had been compared against the Royal Society's flint-glass barometer although it seems that this correction did not take into account the correction for capillarity.

2.3.3 Temperature corrections

The density of mercury in a barometer varies in accordance with temperature, as does the scale. To compare data from different locations or at different times barometer readings need to be reduced to a standard temperature. By modern standards the value of 0°C is used (World Meteorological Organization, 1983). In the London pressure series, all observations recorded from 1843 had been corrected to this standard in the original publications. In addition, the data extracted from the *LWD* (1723–73) had also been corrected to the standard temperature by Manley (1964), as had Derham's observations (1697–1706) by Slonosky (1999). All the other data, however, needed to be corrected.

To correct the Locke series (1692–6) the concurrent internal temperature observations from Locke's weather diary were used. However, the data first needed to be converted to °C from the scale used on the Tompion thermometer, using the conversion described in Section 2.2.1. These data were then entered into Standard Equation 1 as the T term, and taking a thermal expansion coefficient of $\gamma = 1.82 \cdot 10^{-4}$, which only takes into consideration the thermal expansion of mercury given that it is unlikely that this barometer had a brass scale.

In the case of the majority of the observations recorded at the Royal Society (1774–1842) the barometer temperature was recorded concurrently with the height of mercury and could be directly entered into Standard Equation 1 as the T term, after being converted to °C. However, these temperature readings were missing between 1 January 1823 and 6 April 1826 and therefore had to be estimated. To derive this estimation the method used by Moberg *et al.* (2002) and van der Schrier & Jones (2008b) was repeated. This involved estimating internal temperatures as a smoothed function of the outdoor temperatures, using the assumption that the internal temperatures have a lagged and less variable relationship to external temperatures. To quantify this relationship, internal temperatures for the years 1827–31 were estimated by fitting a one-way Gaussian weighted low-pass filter to the external temperature data. These temperature data had been arranged sequentially in the format am, pm, am etc and the few missing values had been linearly interpolated. The optimum standard deviation value for the low-pass filter was obtained by regressing the smoothed external temperatures against the measured internal temperatures over this period; this model also calibrated the *estimated* internal temperatures. The highest r^2 value was achieved using a filter with a standard deviation of 11 and this relationship was validated over the years 1832–6 by once again regressing the *estimated* outdoor temperatures against the *recorded* internal temperatures. This produced an r^2 value of 0.97 at $p < 0.01$.

The completed Royal Society internal temperature series were then used to correct the pressure data using Standard Equation 1. Given that the scale on the Cavendish barometer was wooden, a thermal expansion coefficient of $\gamma = 1.82 \cdot 10^{-4}$ was used over the period 1774–1822, which only takes into account the expansion/contraction of the mercury. The brass scale used on the Daniell (1823–36) and Flint-glass (1837–42) barometers resulted in $\gamma = 1.63 \cdot 10^{-4}$ being used, which takes into account the expansion/contraction of both the mercury and the scale.[4]

Corrections for thermal expansion also needed to be applied to several other series (see Table 2.2) but a lack of any indoor temperature readings necessitated the use of estimated barometer temperatures. In these cases the method used by Bergström & Moberg (2002) was repeated, which involved developing a seasonal model of internal temperatures by taking the average temperature for each day of the year and then smoothing this series by using a cubic smoothing spline with ten degrees of freedom. In the case for the Hoy series (1781–4), the 9am barometer temperatures recorded at the Royal Society from 1827–36 were used to develop this model (Figure 2.10a). These particular years were selected as there are no known instrument

[4]As the brass scale used on the Daniell barometer was short (4–5in. long) this coefficient may not strictly be applicable, but the error is small.

changes during this period and the observations were taken at regular hours of the day. For the Derham observations recorded at noon during the year 1708, the noon outdoor temperatures over the years 1699–1706 were modelled (Figure 2.10b) in order for the corrections to be consistent with Slonosky (1999); Slonosky *et al.* (2001b) who similarly used Derham's outdoor temperatures to correct the pressure data. Further models (Figures 2.10c and d) were derived for the am and pm temperatures recorded by Derham to correct the am and pm pressure observations from the Holborn series (1709–16). These data were preferred to developing models from modern-day temperature readings as they were considered to be better indications of the seasonal cycle of temperatures, despite the potential for errors arising from the poor exposure and inaccuracy of the instruments.

Using these modelled temperatures, the correction was applied using Standard Equation 1 and a thermal expansion coefficient of $\gamma = 1.82 \cdot 10^{-4}$, to take into account only the expansion/contraction of the mercury given the uncertainties surrounding the exact construction of the barometers.

2.3.4 Reduction to standard gravity

A further correction needed to be applied to certain barometer readings (see Table 2.2) to reduce the values to the standard gravity of $9.80665ms^{-2}$ (World Meteorological Organization, 1983). This was achieved by using Standard Equation 2 and taking the local value of gravity as $g_{stn} = 9.81189ms^{-2}$. This value (g_{stn}) was calculated for the latitude 51°29'N and the small variations in the value at the various observation sites around London was disregarded.

2.3.5 Reduction to sea-level

A correction was needed for many of the series to reduce the station level pressure to Mean Sea-Level Pressure (MSLP) (see Table 2.2). In general, this correction was small due to the low altitude of London, which is generally less than 50m and a good proportion of which is near to sea-level (see Table 2.3). Indeed there existed for a long-time in meteorology the so called 50 feet rule, which stated that due to the relatively small correction needed for stations of less than 50 feet in altitude (15m) no correction was applied. However, Wang *et al.* (2007) have recently highlighted the quite large inhomogeneities ($\approx$ 0.3hPa) that may arise in pressure series due to the application of this rule and prove the need for accurate reductions of station pressure series to sea-level.

In the case of the Greenwich Observatory (1843–49; 1882–1949), Royal Society (1774–81, 1787–1842), Hoy (1781–4) and Locke (1692–96) series, the daily thermometer measurements as recorded in the original sources were used as the T term in Standard Equation 3 to reduce the pressure readings to sea-level using the values listed in table 2.3 as the term h. These temperature data had not been corrected from the original sources but had been converted from the respective unit of measurement to K. There is therefore the question of the accuracy of these data. Manley (1964) suspected that the external thermometer measurements of the Royal Society from 1794 to 1799 may have been misread. Parker *et al.* (1992) have also found errors in the early part of the Royal Society temperature series, but these errors are of the order of 1.5°C and are therefore only likely to cause minor errors in the MSLP correction especially given the low altitude of the barometer.

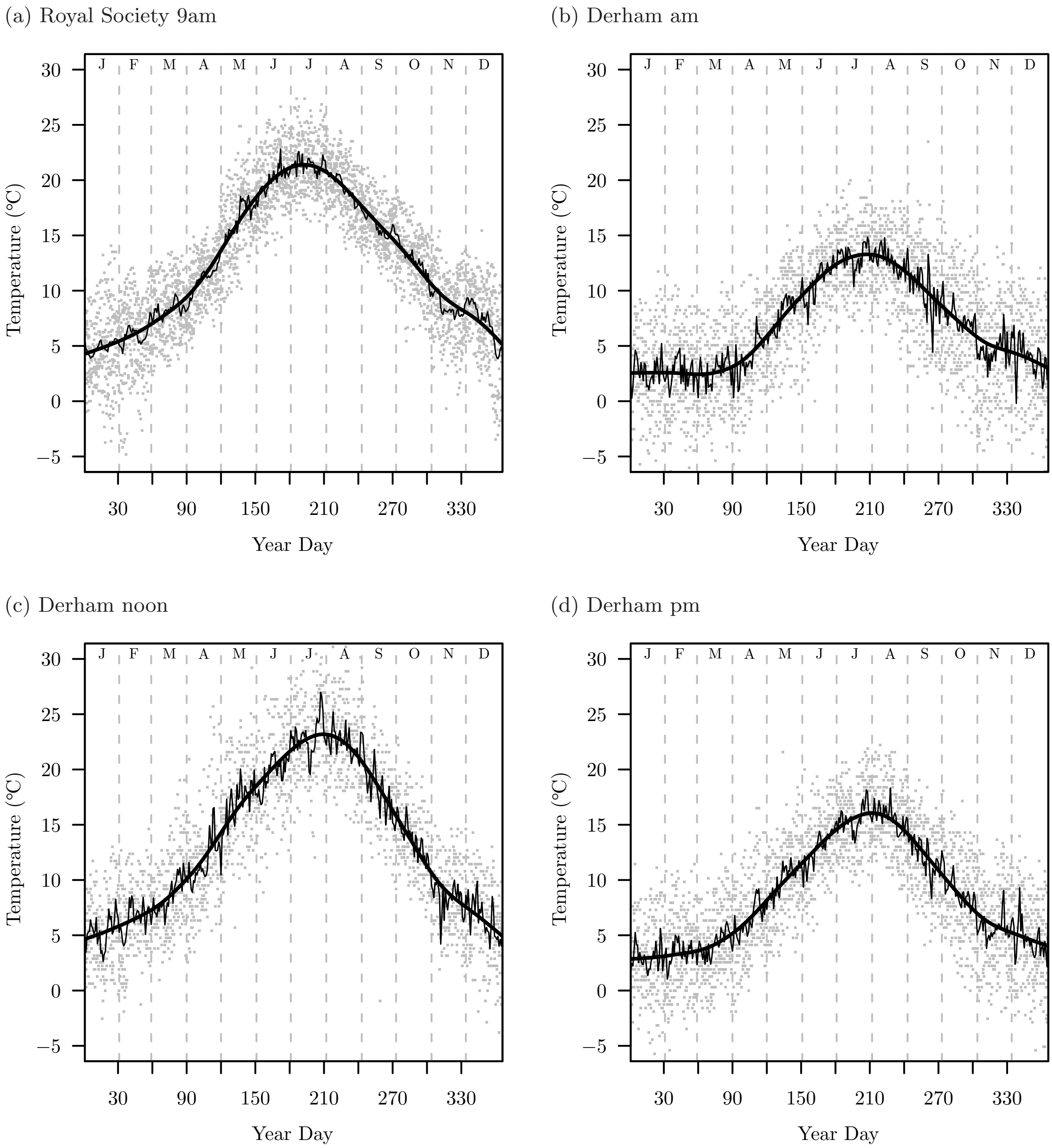

Figure 2.10: Temperature models used to correct certain pressure readings. The grey dots represent the individual temperature readings, the thin black line shows the mean for each day of the year and the thick black line shows the mean values smoothed with a cubic smoothing spline (df=10).

As described in Section 2.2.8, Manley (1960) considered Hoy's temperature readings to be too warm by approximately 4–5°F (≈ 2–3°C) but like the Royal Society temperatures, this would *not* have caused large errors in the sea-level correction.

The use of the Glaisher screen at the Royal Observatory, Greenwich during 1843–1938 is likely to have rendered the dry-bulb thermometers susceptible to radiation influences (see Parker, 1994; Moberg *et al.*, 2003). The daytime readings would therefore be elevated during spring and summer but the night-time temperatures would typically be reduced throughout the year. Based on a comparison at Greenwich during 1887–89 between the thermometers in the Glaisher stand with those in a Stevenson screen, the monthly mean minimum temperatures were in error by

Source / Location	**Years**	**Height (m)**
John Locke / Oates, Essex	1692–6 (excl. 1693)	55.0
Henry Hunt / Gresham College	1693	25.0
William Derham / Upminster, Essex	1708	25.0
Holborn Diary / Middlesex	1709–16	25.0
Royal Society / Crane Court; Somerset House	1774–81; 1787–1836	23.8
Royal Society / Somerset House	1837–42	29.6
Thomas Hoy / Muswell Hill	1781–2	90.0
Thomas Hoy / Syon House	1782–4	14.0
Greenwich Observatory / Upper magnet room	1842–1917	48.5
Greenwich Observatory / New manetograph house	1917–50	46.3

Table 2.3: The altitude values used to reduce the London sources to MSLP.
N.B. The area where the Holborn series is thought to have been recorded is generally at 55m altitude. However, as the Holborn series was calibrated to the Derham series the same altitude as for Derham was used.

approximately -0.2°C throughout the year with the maximum temperatures reaching the highest monthly mean error of +1.2°C in July (Parker, 1994). Based on these values, the error from using the dry-bulb temperature measurements from Greenwich for the reduction of the pressure values to sea-level is therefore small especially given that the daily mean value is taken, which reduces diurnal radiation influences.

In the case of the Derham (1708) and Holborn (1709–16) series, no concurrent temperature observations were available and the modelled temperatures, as developed for the thermal corrections (see §2.3.3), were used. Once again these temperatures were used as T in Standard Equation 3 with the values of h listed in table 2.3.

2.3.6 Correction to 'true' daily means

A further correction was applied to the data to correct for errors arising from the differing times of the observations. The observations after 1843 were the mean of 24-hourly values (or equivalent) but prior to this time the observations were taken at varying hours of the day depending on the series (see §2.4). It was therefore decided to adjust all series prior to 1843 to the equivalent daily mean.

Atmospheric pressure is known to exhibit cycles on both the diurnal and semi-diurnal timescales, which are related to diurnal temperature cycles and gravity waves. These cycles are often referred to as 'Tides' and in extra-tropical regions the value of these tides is small and is frequently masked by synoptic scale disturbances (Chapman & Lindzen, 1970). Thus the errors arising from pressure observations recorded at a limited number of hours a day are likewise small, but still need to be accounted for (Ansell *et al.*, 2006).

The corrections were obtained for the London series by analysis of the hourly data recorded at Heathrow Airport (1981–2007, see Figure 2.11). These data display the twice daily peaks at 9–11am and 9–11pm and the troughs at 3–5am and 3–5pm that would be expected (Chapman & Lindzen, 1970). Figure 2.11 also shows the values calculated by Glaisher (1848) at the Royal Observatory, Greenwich who used observations over the years 1841–5. These values were used at the Observatory to adjust the pressure data over the years 1843–9 (see §2.2.10) and it is clear from Figure 2.11 that the use of only five years of data to derive the corrections led to inaccurate adjustments being applied to the pressure data, as suspected by Eaton (1863). These errors for individual hours are of the order of ±0.3 hPa but averaged over the course of the day are small

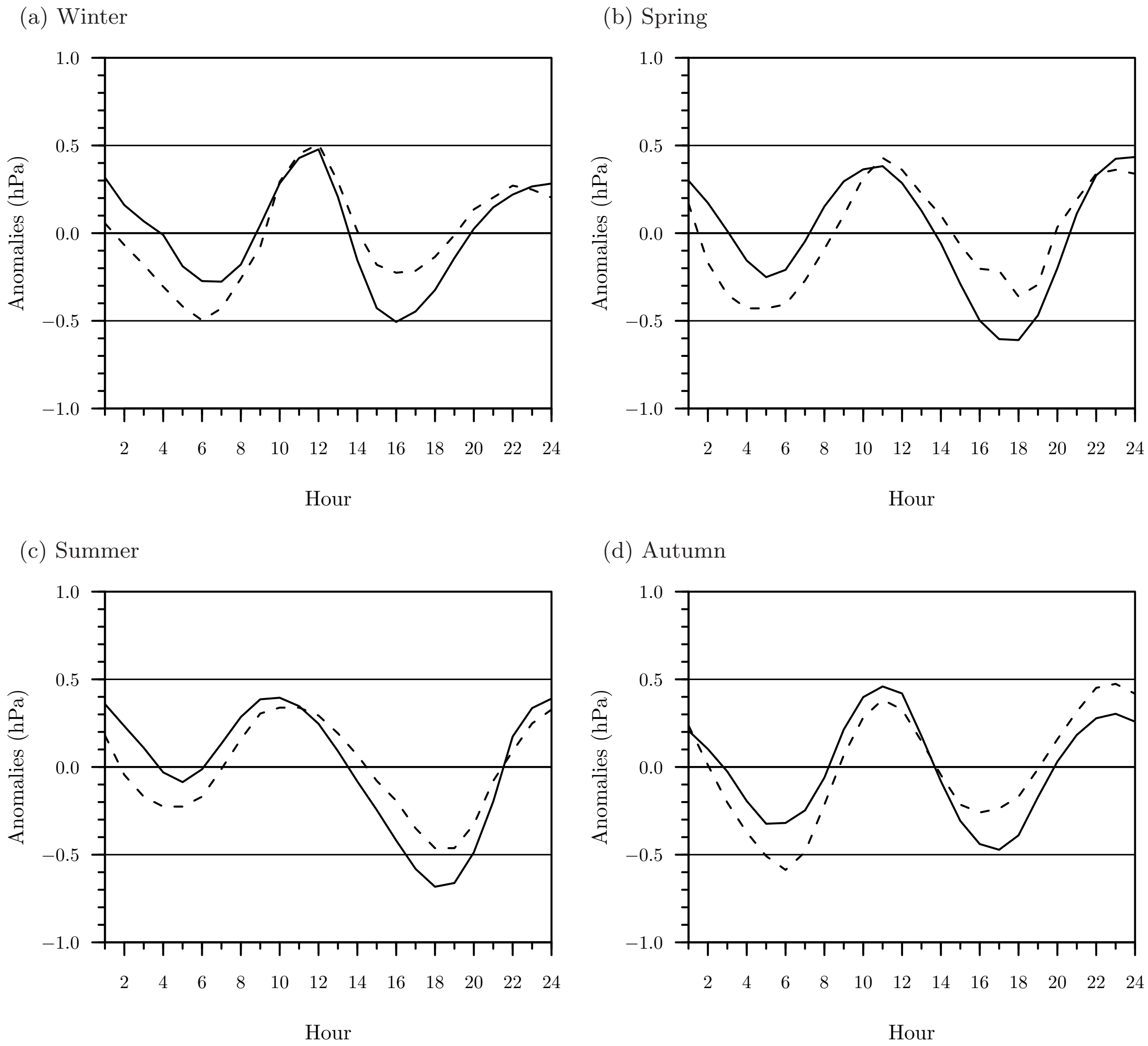

Figure 2.11: Hourly mean pressure defined by season using hourly pressure data from Heathrow airport, 1981-2007. Winter is the mean of the days in December, January and February; spring of March, April and May; etc. The dashed line represents the values obtained by Glaisher (1848) during 1841–5 at the Royal Observatory, Greenwich.

and the Greenwich pressure data (1843–9) have not been corrected for this error.

The data corrections for the other series were obtained by repeating the method of Maugeri *et al.* (2002) and using the Heathrow data. This consisted of calculating the difference between the true daily mean pressure and the value at the observation times for each day of the year. Due to the limited number of observations (27 years giving each day as the mean of 27 observations) these errors were then smoothed with a Gaussian Filter with a window of 90 days to eliminate the day-to-day noise from the low frequency variance at the seasonal time scale. In general these corrections (Figure 2.12) were less than ± 0.4hPa, although the 6pm correction for the evening Holborn reading reached 0.7hPa in the late-summer period. In the case of the Royal Society series both the am and pm observations were used to derive the daily mean and in this case each observation was reduced to the daily mean for each time and the mean of these corrected values was taken.

In applying the diurnal correction, the times of the observations needed to be recorded using

Source	Years	Observation Times
John Locke	1692–6 (excl. 1693)	9am
Gresham College	1693	8am
William Derham	1697–1706	7am*
William Derham	1708	12pm
Holborn Diary	1709–16	8am*, 6pm*
London Weather Diary	1723–73	9am*
Royal Society	1774–81; 1787–1842	7/8/9am, 2/3pm†
Thomas Hoy	1781–4	8am
EMULATE	1850–81	24-hour mean
Greenwich Observatory	1842–9; 1882–1949	24-hour mean
Heathrow Airport	1950–2007	24-hour mean

Table 2.4: The observation times of the component London series.
* These times are approximate. In the case of Derham (1697–1706) the observations varied between 6–8am depending on season but a lack of times in the datafile led to 7am being used throughout the series.
†The Royal Society's observation times varied seasonally and over the course of the series (see §§2.2.6 and 2.2.9).

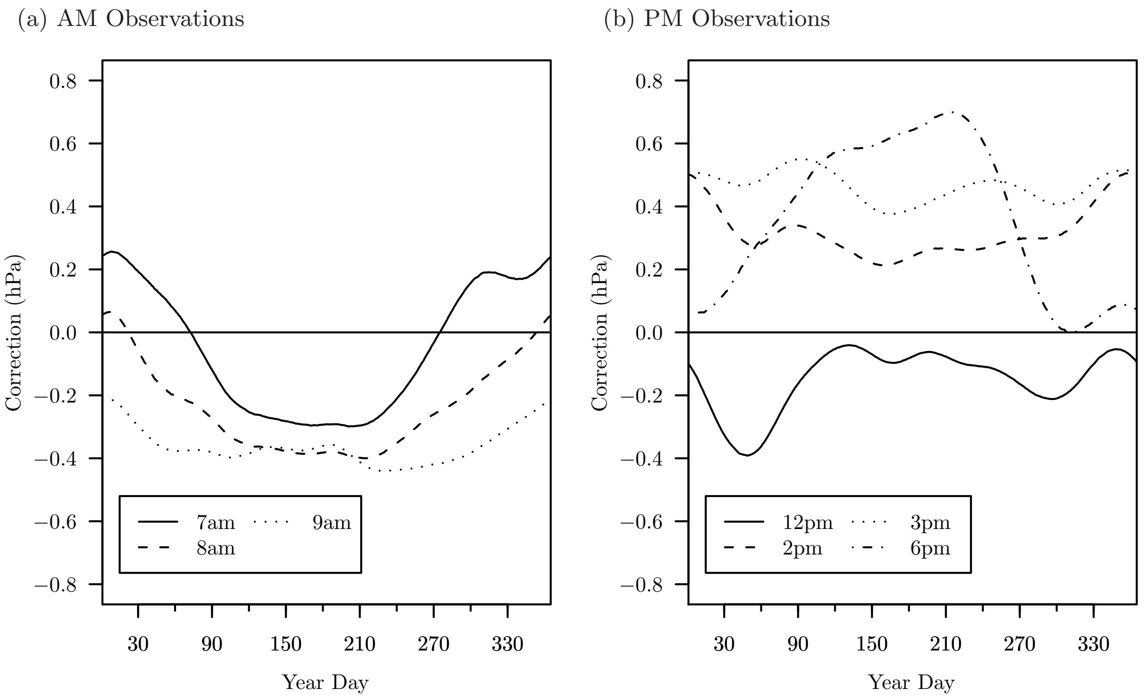

Figure 2.12: Corrections applied to adjust for differing observation times. The times relate to those for each series listed in Table 2.4. These corrections were derived by smoothing the daily mean differences with a Gaussian weighted filter (90-day window).

the same scheme as Heathrow, i.e. at coordinated universal time (UTC). This time-keeping measurement is a relatively new concept (adopted in 1958) and until the late seventeenth century Apparent Solar Time (AST) was used, at least in civilian life, where noon was defined as the time at which the sun crossed the local meridian. AST varies throughout the year by as much as 16 minutes due to the axial tilt of the earth, as dictated by the Equation of Time. By the late seventeenth century, clocks were available that had an accuracy sufficient for useful time keeping. These used Mean Solar Time (MST) at a particular location, where noon is defined as the mean time throughout the year at which the sun crosses the local meridian, so as to divide every day of the year into equal portions. MST was officially adopted into civilian life in

England in 1792 (Howse, 1980). MST varied across the country but with the development of railways in the early nineteenth century, standardized time was gradually adopted country-wide and this was defined as MST at the Greenwich Meridian. Greenwich Mean Time (GMT), as this standardized time was more succinctly termed, was formally adopted as standard legal time in 1880 (Ward, 1958).

Given that UTC is essentially the same as GMT (Howse, 1980), the observation times as entered in the London weather diaries (§2.2) could be taken as equivalent to UTC. It is likely that most of the observers used clocks calibrated to MST and given that the observers were located close to the Greenwich meridian (Figure 2.2), the observation times are very close to GMT and thus UTC. However, even if the observers recorded time using AST the difference from UTC reaches a maximum of only 16 minutes and is therefore negligible for the diurnal pressure correction. The accuracy of the clocks may also be called into question although this cannot be quantified and is also a negligible factor in this correction.

2.4 Chapter summary

The London daily pressure series spans the period 1692–2007, and has been constructed by joining together various series of barometer observations. Most of the observations during the seventeenth and eighteenth centuries were kept by individuals in private weather diaries. Manley (1964) collated these sources into the *LWD*, and these data have been extracted to complete the London daily pressure series over the period 1723–73. The year 1774, when the Royal Society began to record observations at its premises in central London, marks a changing point in the series; from then on, barring certain observations during the 1780s, the observations were taken from the records of institutions. The barometer observations have been corrected, where required, to represent measures of MSLP at modern-day standard conditions.

Chapter 3

The Paris Daily Pressure Series

3.1 Introduction

In a similar manner to the London series described in Chapter 2, the Paris daily pressure series is a composite of data from various non-overlapping sources (see Table 3.1). There is a long history of scientific research in Paris and during the mid-seventeenth and early-eighteenth centuries, scientists in Paris—like their contemporaries in London—were extremely active in meteorological research and instrument design/improvement. Blaise Pascal was particularly influential through his work with hydraulics and it is known that Pascal recorded barometer measurements during the 1640s by extending the Torricellian experiment (Renou, 1881), although it is not known if he kept a continuous daily diary of pressure observations. In general, the enthusiasm for barometer measurements was more apparent in Paris than London during the mid-seventeenth century (Knowles Middleton, 1964) and it is probably as a consequence of this that we have the remarkably early series of observations from Louis Morin's weather diary, which are nearly complete for the years 1670–1712. The astronomical observatories also recorded meteorological observations from an early date, with the influential Paris Observatory recording barometer observations from 1669 (Cotte, 1774; Legrand & Le Goff, 1987). Later, during the mid-eighteenth century, consistent meteorological observations were recorded in Paris as part of the interest in understanding the connection between public health and weather, and it is the barometer observations published in the *Journal de Médecine* periodical that have been used to complete the Paris pressure series over the period 1760–82. In the later period of the Paris pressure series, from the late nineteenth century, observations have been used that were recorded at

Dates	**Source**
01/01/1670–31/12/1712	Louis Morin's Weather Diary
01/01/1713–31/12/1725	Paris Observatory Journal
01/01/1748–31/12/1759	Joseph Delisle's Weather Diary
01/01/1760–31/07/1776	Augustin Roux's Weather Diary
01/08/1776–31/12/1782	Pére Louis Cotte's Weather Diary
01/01/1783–31/12/1850	Paris Observatory Journal
01/01/1851–31/12/1880	EMULATE series
01/01/1881–31/12/1922	Parc Saint Maur Series
01/01/1923–31/12/2007	Le Bourget Airport Series

Table 3.1: Data sources used in the Paris Daily Pressure Series. A catalogue of the sources is provided in Appendix A of this Thesis. The only significant gap in the series occurs over the years 1726–47.

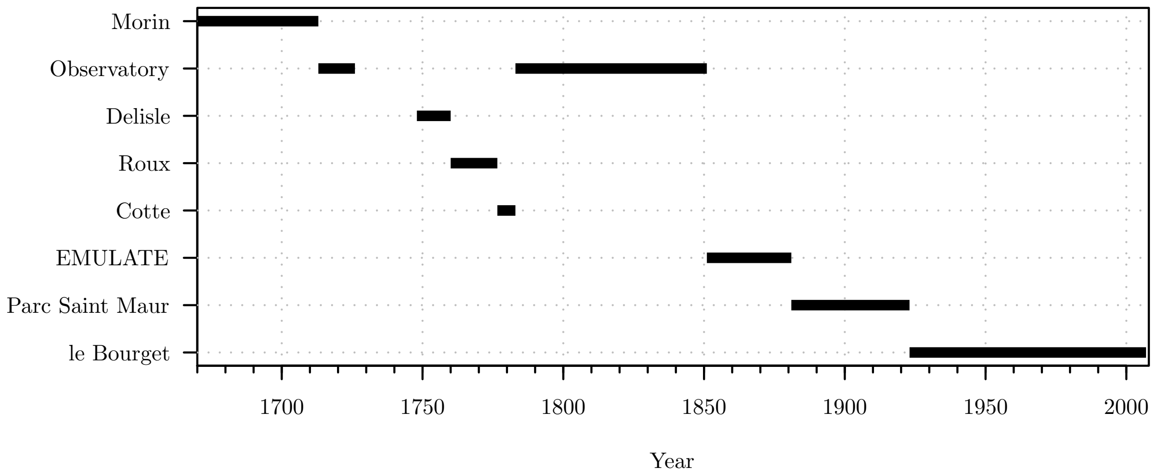

Figure 3.1: Gantt chart of the Paris sources. The bars indicate the span of each series and include no information about missing values within the series.

meteorological stations established by the *Bureau Central Météorologique de France*.

As can be appreciated from Table 3.1 there are fewer component sources in the Paris series compared to the London series, which is attributable in part to the eighteenth century scientists recording observations over longer time spans than their London counterparts; a visualisation of the time spans of the component series is provided in Figure 3.1. However, there is also a longer period of missing observations in the Paris series compared to the London series during the mid-eighteenth century (1726–1747). While it is known that the Paris Observatory recorded daily observations during this period, the meteorological registers for most of the eighteenth century were lost/destroyed during the late eighteenth century (Renou, 1881; Bigourdan, 1895); this unfortunate situation is described in Section 3.2.2 of this chapter.

Figure 3.2 shows the location of the data sources used in the Paris daily pressure series. The majority of the sources prior to the twentieth century were recorded near to the *Île de la cité* in the centre of Paris. The exception is the Cotte series (1776–82), which was recorded in Montmorency; this is a town approximately 15km to the north of the city in the Val-d'Oise département. The twentieth century sources are dominated by the Bourget Airport series (1923–2007), which is approximately 11km to the north-east of Paris.

Many of the eighteenth century sources used in the Paris daily pressure series were described and reviewed in detail by Renou (1881, 1889) in his study of the climate of Paris and it is from these references that a great deal of information regarding the sources (metadata) can be obtained. These metadata have been combined with information from a wide variety of sources to build the station histories provided in Section 3.2 of this chapter. Section 3.3 follows with a description of the corrections that have been applied to the raw data. These corrections have converted the barometer readings to daily mean measurements of atmospheric pressure at standard conditions in the unit of hPa.

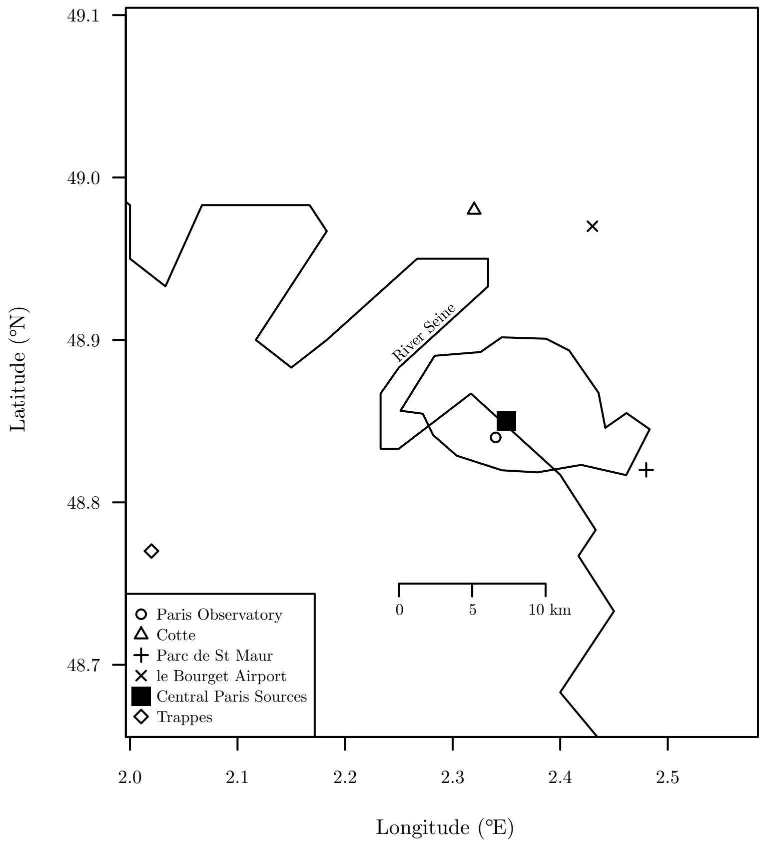

Figure 3.2: The locations of the stations used in the Paris Daily Pressure Series. See Table 3.1 for the years covered by each station. The 'Central Paris Sources' category includes the Morin, Roux and Delisle sources, which are located too close together to be rendered individually. The location of Trappes is indicated, and while not forming a major component of the Paris series the data from this station were used to complete missing observations in the Bourget Airport series (1923–2007). The region indicated is the modern-day Paris region.

3.2 Description of the data sources

3.2.1 Louis Morin's weather diary, 1670–1712

The meteorological journals of the French physician Louis Morin are probably the most remarkable resource available in instrumental meteorology. The 48 years of near-continuous measurements beginning in 1665 constitute the earliest known source of instrumental data that cover a usable length of time. Indeed, the barometer measurements—which Morin began on 2 February 1670—were initiated a mere three decades after the Torricellian Experiment in the 1640s (Knowles Middleton, 1964). It is further remarkable that while the eighteenth century meteorologist Pére Louis Cotte was aware of these valuable registers (Cotte, 1774), they were forgotten until their rediscovery in 1985 by Joseph Konvitz from Michigan State University (Pfister & Bareiss, 1994). Since this time a good deal of use has been made of the data contained in the journals (Legrand & Le Goff, 1987, 1992; Pfister & Bareiss, 1994; Slonosky, 1999; Slonosky *et al.*, 2001b).

Morin recorded observations from various meteorological instruments, along with detailed notes about the 'weather', three or four times a day. The observation times are not included in the journal although given Morin's strict daily routine it is assumed that the observations were taken consistently in the morning at 6am, in the early afternoon between 11am and 2pm and finally in the evening at between 6 and 7pm (Legrand & Le Goff, 1987, 1992; Pfister & Bareiss, 1994).

Certain potential inhomogeneities can be identified in the series associated with Morin's change of residence. Until October 1685 the observations were recorded at the Hôtel Dieu, after which they were taken from Hôtel Rohan-Soubisse. The final relocation occurred in June 1688 when Morin relocated to the Abbaye de Saint Victor (Pfister & Bareiss, 1994). All of these residences are situated close to the *Île de la cité* in the centre of Paris. A further inhomogeneity has been identified in the pressure series on 12 May 1678 before which the readings appear too low. This is probably due to a change of instruments although no corrections have previously been applied to correct the earliest observations (Legrand & Le Goff, 1992).

Little is known about the instruments that Morin used for his measurements. It is suspected that the thermometer was a Florentine instrument (Cotte, 1774; Legrand & Le Goff, 1987). The pressure measurements were recorded in Paris inches and lines (1 Paris inch=27.08mm and 1 line=1/12 Paris inch) and given the dates of the register, the barometer was probably little more than a simple 'U' shaped siphon instrument: a barometer with a diagonal scale or a wheel barometer cannot be ruled out.

The barometer measurements over the period March 1670–December 1712, as used in the Paris daily pressure series, have previously been transformed into the unit of mm and reduced to standard temperature, gravity and sea-level by Legrand & Le Goff (1992). As a first attempt at homogenization, Legrand & Le Goff (1992) also applied a correction of +6.8mm to bring the values in-line with contemporary observations recorded at the Paris Observatory by the astronomer Philippe de la Hire. To ensure that the data were comparable with the contemporary observations of William Derham recorded at Upminster in England, Slonosky (1999) converted the data into the unit of hPa and added 0.3hPa to all values in the series in order for the series mean to equal that of the mean of the monthly pressure series for Paris (1764–1995). In the preparation of the Morin series for inclusion in the Paris daily pressure series in this thesis, none of the homogenization corrections used by Legrand & Le Goff (1992) or Slonosky (1999) were applied and the data were only corrected for temperature, acceleration due to gravity and altitude (see §3.3).

3.2.2 The Paris Observatory journal, 1713–1726

The Paris Observatory (Figure 3.3) was formally established by Royal charter in 1667 (Débarbat *et al.*, 1984) and daily meteorological observations were recorded by a succession of astronomers beginning with Phillipe de la Hire in 1669 (Cotte, 1774; Legrand & Le Goff, 1987). His son, Gabriel-Philippe de la Hire, was also involved with the observations during the late seventeenth/early eighteenth century. The observations were continued through the early eighteenth century by Giacomo Filippo Maraldi (Maraldi I, 1719–28) and his son Giovanni Domenico Maraldi (Maraldi II, 1729–43) (Slonosky, 2002). While these astronomers were primarily responsible for the meteorological observations, the recording of the observations appears to have been more of a collaborative effort with the observations during the early eighteenth century also being recorded by the Observatory's director, Giovanni Domenico Cassini (Maraldi, 1720).

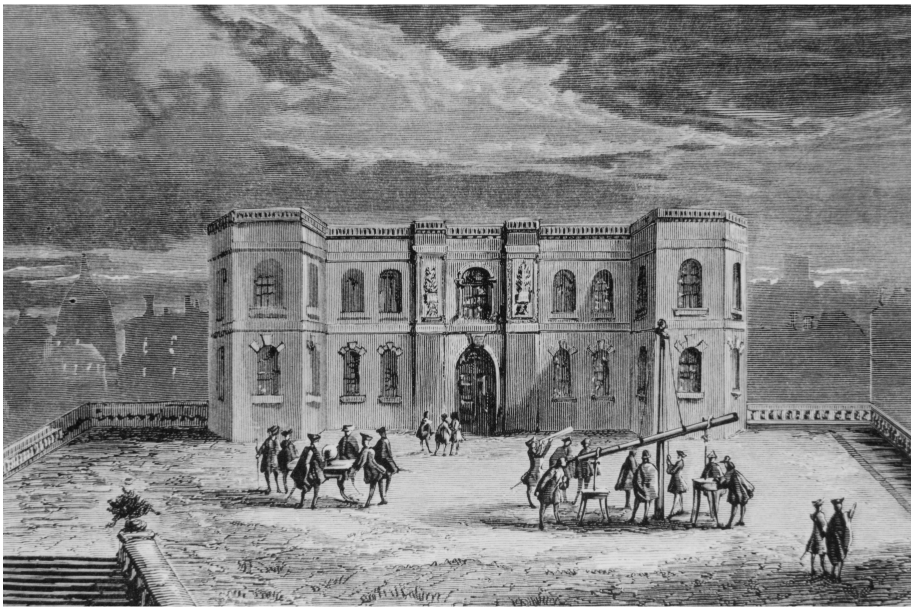

Figure 3.3: An engraving of the Paris Observatory during the late seventeenth century.

Annual summaries of the meteorological observations were published in the *Memoires de l'Academie Royale des Sciences* and *Connoissance des Temps* periodicals. The entries in these publications indicate, at least for the early eighteenth century, that the meteorological observations at the Paris Observatory were taken with care and that the astronomers had a great interest in the weather. It would appear that this went beyond simply providing a basis for reducing the error in their astronomical calculations. This is also the opinion of Slonosky (2002) who extracted the precipitation measurements made at the Observatory during the eighteenth century.

The long history of meteorological observation at the Paris Observatory led Linacre (1992) to assert that the Paris Observatory meteorological series is the longest available in climatology. However, this is somewhat inaccurate as while daily observations were indeed recorded, most of the daily meteorological registers for the early eighteenth century are no longer available. The annual maxima and minima of the measurements were the only data published in the *Memoires de l'Academie Royale des Sciences* and *Connoissance des Temps* periodicals and thinking this sufficient most of the original registers containing the daily observations were destroyed in the late eighteenth century (Renou, 1881; Bigourdan, 1895). Fortunately, Maraldi's daily registers over the years 1718–25 have survived and these contain daily observations of temperature, pressure, wind direction and 'weather'. However, certain portions of the registers are illegible and the barometer measurements can only be used for the period 1 November 1720–20 January 1725.

The observations extracted from Maraldi's meteorological register have been supplemented over the years 1713–26 by other barometer observations that have been discovered in the Observatory's general astronomical journal (*Journal de l'Observatoire de Paris*). The *Journal* consists mainly of astronomical notes although temperature, pressure and wind direction observations were often added at the end of each day's notes. Figure 3.4 shows an example of a page from the journal that is unusually dominated by meteorological observations. The time of the meteorological observation in the *Journal* is noted sporadically and tended to be at noon or sometimes

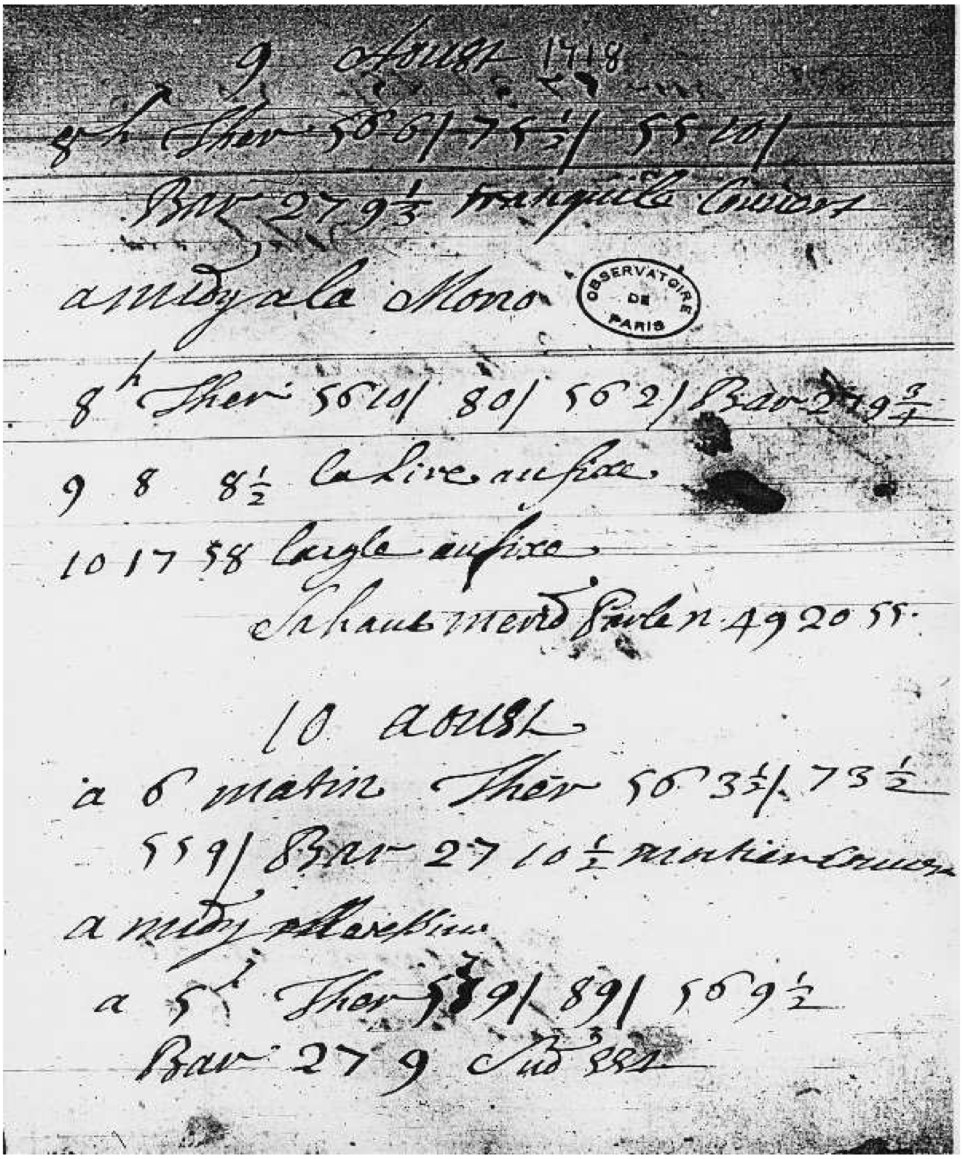

Figure 3.4: A page from the *Journal de l'Observatoire de Paris* for 9–10 August 1718. The barometric and thermometric observations are clearly indicated with the prefixes *Bar* and *Ther*. Reproduced by permission of the *Bibliothèque de l'Observatoire de Paris*.

at 8am.[1] According to Bigourdan (1895), the observations in this journal were recorded by Maraldi I over the years 1719–20 and before this time it is assumed that the data were recorded by Phillipe de la Hire. However, the overlapping observations in Maraldi's register and the *Journal* during November–December 1720 do not match, with the observations in the *Journal* being 2–3 lines lower than in Maraldi's register. It is known that there were two barometers in use at the Observatory during this time, both of which were situated in the Great Hall. One of the barometers had been in use at the observatory since the 1670s and had been used by Jean Picard[2]; a different instrument was used by la Hire (Renou, 1881). The barometer used by la

[1] See Section 3.3.5 for a discussion of the potential misinterpretation of these times.

[2] Picard is cited by Knowles Middleton (1964) as being the first person to record the phenomenon of luminescence, which he observed in a barometer at the Paris Observatory. It is not known whether it was the barometer situated in the Great Hall from which this was observed but this discovery gave rise to great debate in the scientific community and it became widely believed, for a few years at least, that luminescence was an indication of a high quality barometer with a good vacuum.

Hire consistently measured three lines lower than the Picard barometer (de la Hire, 1715) and it would therefore appear that the observations in the *Journal* were recorded from the la Hire barometer with the observations in Maraldi's register being taken from the Picard barometer. Renou (1881) considered the measurements from the Picard barometer to be more accurate and more in-keeping with modern-day measurements than the la Hire barometer, which were too low. This is despite the la Hire barometer being luminescent and evaluated as having a good vacuum. Indeed it is suspected that a barometer owned by la Hire and from which observations were taken to ascertain the effect of temperature on a barometer had an imperfect vacuum on account of the negligible effect that temperature had on the level of mercury (Knowles Middleton, 1964). It is not known if the readings in the *Journal* where recorded using this instrument but is an indication that even at the Paris Observatory such inferior instruments could go undetected at this time.

Meteorological observations continued to be recorded in the *Journal de l'Observatoire de Paris* until 1754 although with the establishment of the specialist meteorological registers in 1718 increasingly fewer meteorological observations were recorded. A gap therefore exists in the Paris daily pressure series from 1726 until 1748 when the barometer observations recorded by Joseph Delisle at the *Hôtel de Cluny* in Paris can be used.

3.2.3 Joseph Delisle's weather diary, 1748–1759

A meticulous journal of meteorological observations was kept in Paris from December 1747 to November 1760 by the astronomer Joseph Nicholas Delisle[3]. The journal was discovered amongst Delisle's papers by the meteorologist Pére Louis Cotte during the late eighteenth century when they were in the possession of the library of the *Académie Royale des Sciences* (Cotte, 1774); the journal has since been archived at the Paris Observatory.

Delisle was educated by Giovanni Domenico Cassini at the *Académie Royale des Sciences* and went on to establish an astronomical observatory at the *Palais de Luxembourg* during the 1710s (Jones, 1991). During the early 1720s Delisle developed, with his brother, a temperature-scale for spirit thermometers which ranged from 0° to 100°, taking these fixed points as the boiling point of water and the temperature of the cellars at the Paris Observatory respectively (Knowles Middleton, 1966). In 1725 Delisle moved to St Petersburg under the invitation of Tzar Peter to establish a school of astronomy (Jones, 1991). Continuing his interest in instrument development, Delisle devised a further temperature-scale while in St Petersburg but used mercury for the thermometers. This scale became widely used in Russia (Knowles Middleton, 1966) and across Europe as a result of Delisle sending calibrated thermometers to various scholars (Camuffo, 2002). In 1747 Delisle returned to Paris and began recording astronomical and meteorological observations from an observatory that he set-up in the Hôtel de Cluny[4], which is situated in the centre of Paris close the River Seine. It is Delisle's barometer measurements from this observatory that were used to complete the Paris pressure series from January 1748 to December 1759.

In the meteorological journal, Delisle recorded observations—possibly with the help of his observational assistant Charles Messier—from barometers and thermometers, alongside the state

[3] His surname is sometimes spelt *de L'Isle*.

[4] This observatory was also termed *l'Observatoire de la Marine* (The Observatory of the Navy) (Renou, 1881).

	Dates of use	Description
A	20/12/1747–21/10/1750	Old Barometer
B	13/11/1749–06/02/1757	Large Barometer with screws
C	16/11/1750–14/11/1760	Luminous Barometer
D	21/02/1754–14/11/1760	New Barometer

Table 3.2: The Barometers used by Delisle. The descriptions are translated from those entered in the journal. Barometer 'D' was removed on 13 July 1759 with a note in the journal reading *dérangé*. It seems to have been repaired and was reinstalled on 20 August 1759.

of the sky, three to four times per day. The exact time of the observations is recorded in the journal and following the convention of the time the instruments were read at around 6–7am, noon and 8–9pm, although the time of the am and pm readings could vary by as much as three hours.[5] To complete the Paris daily pressure series only the observations taken around noon were digitized from the journal but in the few cases where these observations were missing the closest observations taken between 10.30am and 1.30pm were extracted to ensure as complete a series as possible.

Delisle recorded concurrent observations from two or three barometers using the unit of decimal Paris inches to two decimal places. He used different instruments throughout the series; these are listed in Table 3.2 and the descriptions give an indication of the type of instruments that he used. Barometer 'C' is particularly noteworthy given that Delisle identified it as a luminous barometer. As described above (§3.2.2), luminous barometers were considered by some scientists during this time to be the most accurate instruments. Given the active interest of barometer luminescence in the scientific community in Paris, Delisle may have considered the inclusion of such a barometer in his array as an experiment into this effect, and it is likely that he considered this to be his most accurate instrument given that it was used for the longest period of time.

Delisle's exchange of barometers throughout the series is probably an indication that he was aware of the inaccuracies of these instruments and he even went as far as to apply corrections in an attempt to calibrate the barometers with each other. To complete the Paris daily pressure series, the values recorded from barometer 'A' were used from 1 January 1748 to 31 December 1749, barometer 'B' were used for the year 1750 and those from barometer 'C' were from 1 January 1751 to 31 December 1759. The readings were extracted from the register as raw values without any of Delisle's corrections added.

The temperature readings were also digitized from Delisle's journal in order to correct the barometer measurements (see §3.3.1). Following the common practices of the time, the thermometer was probably situated indoors close to the barometer. This is indicated by the fact that during July 1757 Delisle included observations from an 'oil of tartar' thermometer that is stated explicitly as being outdoors and it is suspected that the other instruments were more usually situated indoors.

Delisle employed three thermometers in the journal: a spirit thermometer for the first three months of the journal and two mercury thermometers thereafter. The temperature-scales used on these instruments are not recorded although it can be deduced from the diurnal variation that they were reverse scales. As described above, Delisle's temperature-scale is well known (Beckman, 1997; Camuffo, 2002) and it is assumed that this scale was used for the two mercury

[5] See Section 3.3.5 for a discussion of the potential misinterpretation of these times.

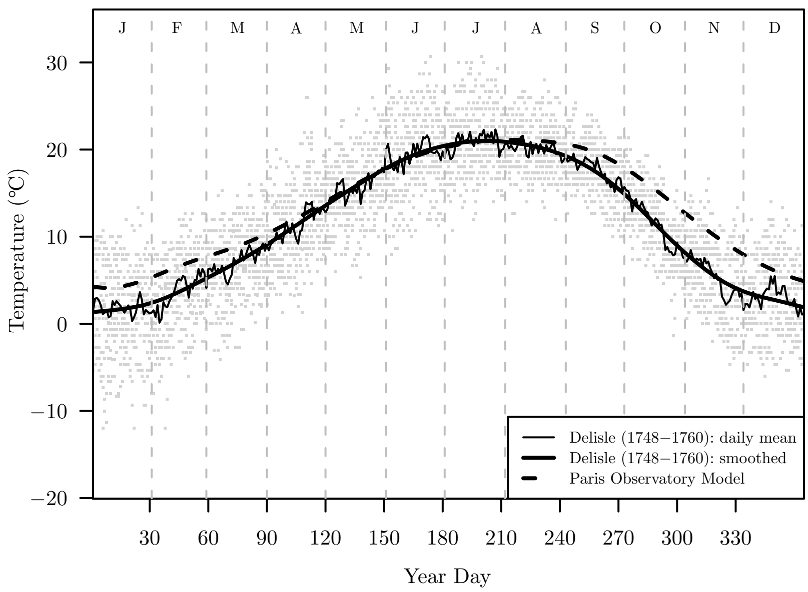

Figure 3.5: The annual cycle in the noon Delisle temperature series. The data have been converted to °C and the grey dots represent the individual daily values, the thin line represents the mean for each day of the year and the thick black shows the daily mean values smoothed with a cubic smoothing spline(df=10). The indoor temperature model derived from the Paris Observatory series (1809–18) is shown as a dashed line (see §3.3.1).

thermometers. Converting the temperatures to °C from this scale yields reasonable annual temperature variation (Figure 3.5). The early spirit thermometer was probably one of Delisle's instruments developed in the 1720s and as such for a correction to be effected we need to know the temperature of the cellars at the Paris Observatory, which was the 100° mark. Given that this can not be known for sure, and that we are not even certain that it was calibrated in this manner, the overlap with the mercury thermometer during April–June 1748 (n=72) was used to devise the following correction through the regression of the two series:

$$T_m = \frac{11}{7} \cdot T_s - 23, \tag{3.1}$$

where T_m and T_s are the temperatures measured on Delisle's mercury and spirit thermometers respectively. By taking this conversion, the 100° fixed mark must have been 10.6°C. If this was indeed one of Delisle's original spirit thermometers with the 100° point calibrated to the pseudo-constant temperature in the cellars of the Paris Observatory then this value is reasonable. According to Knowles Middleton (1966) the cellar temperature was estimated to be 10.25°R (degrees Réaumur), which equates to 12.8°C. The difference with the calculated value of 10.6°C here may be accounted for by the relatively small number of calibration observations ($n = 72$) and/or differences in the exposure of the thermometers.

The meteorological register ends abruptly in November 1760, which would suggest that the later parts have been lost. It is known that Delisle continued to keep a journal of observations after his retirement from the *Hôtel de Cluny* at his home from 1766–68 (Renou, 1881) and it is reasonable to suggest that he maintained the register at the Hôtel de Cluny until this time. Delisle's assistant, and later successor, Charles Messier is known to have kept a register of observations at his lodgings from 1763 until 1771 and thereafter until 1817 at the *Hôtel de Cluny* (Cotte, 1773, 1788; Renou, 1881). Indeed Felix Vicq d'Azyr in his establishment of the network of meteorological observers in the 1770s advised the correspondents to calibrate their barometers against Messier's standard instrument at the *Hôtel de Cluny* (Desaive *et al.*, 1972). However, it seems that Messier's meteorological journal has been lost (Renou, 1881) and further recent efforts to locate the manuscript have failed.

3.2.4 Augustin Roux's weather diary, 1760–1776

During the 1770s, the *Société Royale de Médecine* was established in France. One of the main activities of this organisation was to investigate the relationship between weather and public health. To enable this, a network of weather stations was established across the French kingdom (Kington, 1997a). However, interest in this subject was apparent over a decade before as exemplified in the *Journal de Médecine, de Chirurgie et de Pharmacie* periodical. Beginning in the late 1750s, this monthly publication printed tables of thrice-daily observations of temperature, pressure, wind direction and 'weather' recorded in Paris and linked these to the month's observed maladies in the city. In the period from June 1762 until June 1776 the instrumental observations were recorded by the *Docteur Regent* and editor of the journal, Augustin Roux. Before this time Roux's observations were published in the *Journal Œconomique* and while the name of the observer is not explicitly stated in the *Journal de Médecine* until the July 1776 edition, Renou (1881) ascertained that the observations from June 1762 were taken by Roux by comparing the overlapping observations from the two sources. The pressure readings in the *Journal Œconomique* were recorded concurrently with the temperature observations although from 1762 when the observations were published in the *Journal de Médecine* the temperature readings were taken at 7am, 2pm and 11pm, although barometric pressure was still recorded in the morning, at noon and in the afternoon/evening.

Roux took his observations from instruments located on the third floor of a domestic residence on the *rue de Seine* in Paris (Renou, 1881), which is in the centre of the city approximately 500m from the *Hôtel de Cluny* (see §3.2.3). Further information regarding the instruments used or the nature of the observations is lacking although it can be stated that the pressure observations were recorded in Paris inches/lines. It would appear that the mercury in the barometer had not been boiled as it was discovered that the readings gradually declined with time, in a similar manner to those recorded from the Cavendish barometer at the Royal Society in London (see §2.2.9), but at the much more alarming rate of 0.02hPa month^{-1}. However, the boiling of mercury was not necessarily a guarantee against this problem, as is demonstrated by the Megnié barometer in use at the Paris Observatory, which suffered from the same problem but in which the mercury had been boiled (see §3.2.6).

The temperature readings appear to have been recorded in degrees Réaumur. The temperature-scale that Roux used is not explicitly recorded in the publications although it is reasonable to assume that the Réaumur scale was used for these observations as it was the *de facto* temperature scale in France at this time; the metric Celsius scale was not widely used until after the Revolution (Knowles Middleton, 1966). The thermometer was placed in a window on the same level and presumably in the same room as the barometer (Renou, 1889). To provide extension to the Delisle series (1748–59), the noon pressure and 12pm/2pm temperature readings were digitized from January 1760 until they ended in July 1776.

3.2.5 Pére Louis Cotte's weather diary, 1776–1782

A series was required to bridge the gap from the end of the Roux series to the start of the second phase of the Paris Observatory series (§3.2.6), which is usable from 1783. One of the best series recorded in the Paris area during this period was kept by Pére Louis Cotte and was published in the *Journal de Médecine*, upholding its tradition of publishing meteorological observations from Paris.

Cotte is well known for his meteorological work and Feldman (1990, p.165) went as far as to describe Cotte as "France's foremost meteorologist" during the eighteenth century. In his two major works on meteorology, *Traité de Météorologie* and *Mémoires sur la Météorologie*, Cotte gathered together and analysed meteorological observations from across the world. Cotte is also well known for his efforts with the *Société Royale de Médecine* in establishing a network of observers across the French kingdom who recorded measurements to agreed standards (Kington, 1997a; Fleming, 1998). The director of this program, Felix Vicq d'Azyr, took recommendations from Cotte on the best observation methods. Cotte then collated the observations for publication in the *Histoire de la Société de Médecine* (Kington, 1970).

In addition to this work, Cotte kept his own register of thrice-daily meteorological observations from 1765 until September 1782 at his residence in Montmorency, which is a town approximately 15km to the north of the centre of Paris. The observations from 1776 until 1782 were used in the Paris daily pressure series. The altitude of Cotte's barometer has been estimated to be 106.5m above sea-level (Renou, 1881). Despite this height and the greater distance from the centre of Paris, Cotte's observations were considered the most reliable for this period compared to contemporary series. In establishing the network of observers under the *Sociètè Royale de Mèdecine*, Cotte was conscious of the need for accurate and consistent meteorological measurements (Feldman, 1990). Adhering to this standard there is a good deal of information recorded about the location and types of instruments that Cotte used.

The first barometer that Cotte used in the series published in the *Journal de Médecine* was constructed by Cappi in 1773 and had an internal tube diameter of 9mm and a cistern diameter of 54mm. In addition, the mercury in the barometer had been boiled to exhaust any air that may have been present. All of these features meant that it was one of the best instruments available at the time (Renou, 1881). Continuing the format of earlier meteorological measurements in the *Journal de Médecine*, the readings from this barometer were published in Paris inches and lines. However, from July 1778 Cotte began to use a much more precise scale, which recorded the height of the mercury in twelfths of a line and it is most likely that this signals the use of a Megnié barometer. It is known that Cotte was one of the few people to be given one of eight barometers that had been constructed by the highly regarded instrument-maker Pierre Bernard Megnié (Knowles Middleton, 1964). These instruments had been constructed in 1778 under the instruction of Antoine Lavoisier and they consisted of two tubes dipping into the same cistern of mercury. The pressure measurement was read from a scale that was initially moved to adjust the zero mark (Knowles Middleton, 1964). This alleviated the need to apply corrections for changes in the relative level of mercury in the cistern and tube. The two-tube design of this instrument aimed to guard against an imperfect vacuum in either one of the tubes, which would be indicated by a reduced level of mercury in the defective tube (Knowles Middleton, 1964) and in an attempt to prevent this problem occurring in the first place the mercury in the tubes had first been boiled to exhaust any air that may have been present (Truchot, 1879). The two-tube design was not necessarily a guarantee of a perfect vacuum, however, as if both tubes contained air then the defect can not be identified Knowles Middleton (1964). It appears that while Cotte's instrument did have a good vacuum, the Megnié barometer in use at the Paris Observatory suffered from an alarming rate of drift (see §3.2.6).

Cotte's noon barometer measurements were digitized from the *Journal de Medécine* to complete the period August 1776–December 1782 in the Paris daily pressure series. His 2pm temperature observations were also digitized in order to correct the pressure data (see §3.3). These temperature measurements were recorded using a mercury thermometer that was calibrated to the Réaumur scale. It is known that Cotte favoured the positioning of his thermometer outdoors, facing north, in an open air position (Kington, 1970) and that he constructed a shade to further reduce the influence of insolation on the readings (Cotte, 1788). It would seem likely that the temperature readings published in the *Journal de Médecine* are these outdoor temperature readings (Renou, 1889).

Cotte ceased to record meteorological observations at Montmorency in September 1782. The last four months of the pressure data used in the Paris pressure series were recorded by Cotte's successor, Pére Jaucour.

3.2.6 The Paris Observatory journal, 1783–1850

In the late eighteenth century the keeping of meteorological observations once again became an important activity at the Paris Observatory. Daily data were continuously recorded from January 1783 although the greatest improvements in the observations occurred in 1785 under the reorganisation of the observatory by Jean Dominique Cassini (Cassini IV) (Wolf, 1902). The observations after this time were recorded in journals separate from the astronomical observations and the developments in meteorology over the 100 years since the earlier Paris Observatory series (§3.2.2) meant that instruments with a greater accuracy could be employed. As a reflection of this, the observations were published in a succession of high quality journals beginning with the *Journal de Physique* from 1798 (Fleming, 1998). It would seem therefore that these observations were considered as a standard for the scientific community.

The type of barometer used at the Observatory from the start of the series in 1783 is not known. However from 1st July 1785 in accordance with the restructuring of the observatory by Cassini IV the observatory installed one of the eight Megnié barometers that had been constructed in 1778 under the supervision of Lavoisier (Cassini, 1787; Wolf, 1902, see §3.2.5). In the meteorological registers of the observatory, readings from both tubes of the Megnié barometer were recorded and to ensure that the most reliable reading was digitized, the highest value was systematically extracted from the hand-written registers (M. Barriendos, pers. comm). It was discovered after the correction of these data that the readings gradually decreased with time, despite the design of the barometer that was supposed to guard against this (see §3.2.5). This drift was at a rate of 0.02hPa month^{-1} and by August 1800, when the readings were 4.5hPa too low, it would appear that a new barometer was installed or the Megnié barometer was repaired;

in either case the readings after this time did not drift.

In 1864 the Paris Observatory became the hub for early experiments in sending weather information via telegraph with a view to issuing forecasts (Fleming, 1998). In accordance with this new role, a constant recording siphon barometer was installed at the Observatory during a restructuring of operations in 1855 (le Verrier, 1855) in order to provide continuous measurements of atmospheric pressure. To calibrate the readings from this instrument a standard mercury barometer was used, but the design of this instrument is not recorded; it is known, however, that from January 1881 a Fortin barometer was installed as the standard instrument (Wolf, 1902). Unfortunately there is no further information available regarding the nature of the meteorological observations made at the Observatory during this time. However, a cross-check with the observations published in the *Annales de Chimie et Physique* reveals that the values extracted from the observatory's registers had not been corrected for temperature or altitude.

3.2.7 The EMULATE data series, 1851–1880

The Paris station series as developed under the European and North Atlantic daily to MULtidecadal climATE variability (EMULATE) project (Ansell *et al.*, 2006) was used to complete the 1851–80 period in the Paris daily pressure series. The base data used for this series were the barometer readings from the Paris Observatory (M. Barriendos, Pers. Comm). Like the London station series developed under the EMULATE project (see §2.2.11), the data for Paris had been corrected to represent Mean Sea-Level Pressure (MSLP) at standard conditions and the daily data had been adjusted to represent the equivalent of a 24-hour mean.

3.2.8 The Parc Saint Maur series, 1881–1922

During the late nineteenth century, several meteorological stations were operating in Paris. The Paris Observatory continued to record daily meteorological observations, although with an increasing number of missing values, until 1907. In 1870 observations also began to be recorded at the new Montsouris Observatory, situated in the centre of Paris. Montsouris was modelled on the observatory at Kew in London and was planned to be purely a magnetic/meteorological observatory (Davis, 1984). This may explain why enthusiasm for maintaining the journal of meteorological observations at the Paris Observatory waned during this time: the responsibility being transferred to the stations operated by the *Bureau Central Météorologique de France*. The monthly pressure readings from Montsouris have previously been reconstructed but the daily observations, from which these means were obtained, were fragmented during the First World War and were therefore difficult to reconstruct. Pressure observations were also recorded for several years at both the Eiffel Tower (1889–1905) and the offices of the *Bureau Central Météorologique* in Paris (Angot, 1910). However, a more complete series of observations exist for an observatory on the outskirts of Paris at Parc Saint-Maur. It is the daily pressure data from this observatory that were used to complete the Paris series from 1881 to 1922. The noon dry-bulb temperature readings were also digitized in order to correct the pressure data to sea-level (see §3.3.3).

The Observatory at Parc Saint Maur was formally established in 1873 by Emilien Renou (Moureaux, 1904) and was situated approximately 11km to the south-east of the Paris Observatory (see Figure 3.2). Despite the greater distance from the centre of Paris compared to other stations such as Montsouris, the data from this station were used in the Paris pressure series for three reasons: the series is complete throughout the period; the observations are easily obtainable from the *Annales du Bureau Central Météorologique de France* publication; and the hourly observations are available. This last point is important as the majority of observations used in the Paris daily pressure series from 1748 to 1880 were recorded at noon and to be comparable with these data the noon readings (local time) were extracted from the Parc Saint-Maur record. Furthermore, the observations from Parc Saint-Maur are considered to be of a high quality given that they were used extensively in studies by the *Bureau Central Météorologique* as the representative station for Paris; for example, in the study of diurnal atmospheric tides (Angot, 1889). Dettwiller (1970) also considered the observations at Parc Saint-Maur to be consistently well-kept and used the temperature measurements as the basis for his study of the urban temperature of Paris. The following description of the observatory and the instruments used were obtained from Moureaux (1904).

The barometer was situated in the main observatory building from the 1 July 1880 until 1 January 1891. After this date it was transported to a newly constructed building at the observatory. To preserve the consistency of the pressure observations the barometer was placed at the same height (49.3m) as its previous situation. The actual movement of the barometer is unlikely to have affected subsequent readings given that the barometer used at this time, in accordance with the *Bureau Central Météorologique de France*, was made by Tonnelot. This barometer had a unique design which allowed the cistern to be full of mercury during transport although in operation it functioned as a fixed-cistern barometer (Knowles Middleton, 1964). In January 1903 the hourly readings ceased to be recorded from the Tonnelot barometer: these were reduced to three-hourly readings between 6am and 9pm, with the intermediate hours estimated from the readings of an aneroid barograph constructed by the French instrument-maker Jules Richard.

3.2.9 Le Bourget Airport series, 1923–2007

Daily pressure observations recorded at Le Bourget airport were used to complete the Paris Pressure series from 1923 until present-day (31 December 2007). All data, excluding those during the Second World War, were obtained in digital form from Météo France. Until 1940 the pressure observations used were recorded once daily at 1800 coordinated universal time (UTC) and at 0600, 1200 and 1800 UTC from 1945 until 1949; from 1949 hourly values are available. The daily values from 1949 to 2007 were simply calculated as the mean of these 24-hourly data.

The period during the Second World War presented a particular challenge to this project. During the occupation of France, the meteorological observations taken at Le Bourget, amongst other stations in France, were recorded in the German publication *Täglicher Wetterbericht* but suffer from some gaps most probably as a result of war-time operations. The pressure data were extracted from this source to cover the period 10 July 1940–23 August 1944. All of these data had been corrected in the original publication to represent MSLP at standard conditions. Most of the observations were recorded at 1900 Central European Time but where the observation at that time was missing, observations at 0800 and 1400 were used.

One change in the location of the instruments at Le Bourget is recorded. This occurred on 1 February 1993 when the instruments were moved a few hundred metres to a new location; this

	Temperature	Gravity	MSLP	Daily Mean
Louis Morin's Weather Diary	•	•	•	•
Paris Observatory Journal (1713–25)	•	•	•	•
Joseph Delisle's Weather Diary	•	•	•	•
Augustin Roux's Weather Diary	•	•	•	•
Louis Cotte's Weather Diary	•	•	•	•
Paris Observatory Journal (1783–1850)	•	•	•	•
EMULATE Series				
Parc Saint Maur Series		•	•	•
Le Bourget Airport Series (1923–40)			•	•
Le Bourget Airport Series (1940–44)				•
Le Bourget Airport Series (1945–48)			•	•
Le Bourget Airport Series (1949–2007)				

Table 3.3: The corrections that were necessary for each of the component Paris series.

new location was 7m lower than the original position.

3.3 Corrections to the data

The majority of the barometer readings digitized from the sources described above needed to be corrected in order for them to provide a measure of atmospheric pressure at standard conditions. The corrections necessary for each series are listed in Table 3.3 and consisted of reductions to 0°C, standard gravity and sea-level. As the pressure data prior to 1949 were recorded at set hours of the day, a further correction was applied to transform these data to the equivalent of a 24-hour daily mean, to ensure the series was comparable with the London pressure series. Prior to the application of these corrections the pressure observations (excluding those of Morin, 1670–1712) had been converted to the unit of hPa, from the units of Paris inches/lines, where necessary. In the case of the Morin series the corrections were applied to the units of mm following Legrand & Le Goff (1992) and the data were then converted to hPa.

Corrections for cylinder capacity and capillarity (see §2.3) could not be applied due to a lack of information regarding the diameter of the tubes or cylinders in the barometers. While this information is available for the barometers used by Cotte and the Megnié barometer in use at the Paris Observatory, the corrections could not be applied due to uncertainty regarding the exact dates of use of the barometers. In any case the correction for capacity in the Megnié and Cappi barometers used by Cotte and at the Paris Observatory would be small due to the large tube:cistern ratio of these instruments.

3.3.1 Temperature corrections

All of the observations prior to 1851 needed to be corrected for changes in the density of the mercury due to temperature variations (see Table 3.3). The earliest readings from Louis Morin (1670–1712) were simply corrected using the values recommended by Legrand & Le Goff (1992); these corrections are shown in Table 3.4.

Months	Legrand	Model
October–April	-1.0mm	-1.3mm
May–June	-1.5mm	-2.5mm
July–September	-2.0mm	-2.8mm

Table 3.4: Comparison of the corrections for temperature used by Legrand & Le Goff (1992) and those derived from the modelled internal temperature at a pressure of 1016hPa. The months are as defined by Legrand & Le Goff (1992).

To correct the Delisle observations (1748–60), the thermometer readings concurrent to the pressure readings were used. The readings were converted to °C following the methods described in Section 3.2.3. The readings from the spirit thermometer were used for the first four months of 1748, whereas the readings from the mercury thermometers could be used thereafter.

In the case of Roux's observations (1760–76) the temperature readings from his Journal recorded at 2.30pm were used; these had been converted from °R to °C. Although not concurrent, these readings give an indication of the room temperature, as the thermometer was placed in the window of the room where the barometer was kept (Renou, 1889). It is evident from these readings that during the summer months the thermometer was probably affected by exposure to direct insolation, with temperatures as high as 35°C apparent on certain days during the months of July and August. The influence of outdoor conditions is also apparent during the winter months with temperatures as low as -10°C recorded. Nevertheless the temperature readings were considered to be a more accurate indication of barometer temperature than a modelled temperature.

In the case of the pressure readings from the Paris Observatory (1713–25 and 1783–1850), the barometer temperature readings had not been digitized from the meteorological register due to time constraints of the project. To correct these pressure data for temperature, a model was developed by using the mean monthly indoor temperature values recorded at the Paris Observatory (1809–18) published in Renou (1881). The daily values were interpolated by taking the monthly values as the centroid for each month and fitting a cubic smoothing spline (df=10) to the data (see Figure 3.6). These estimated temperatures were also used to reduce Cotte's (1776–82) barometer readings to °C.

The correction for pressure that the temperature model would give at 1016hPa was calculated and compared against the corrections used by Legrand & Le Goff (1992) for the Morin series. The results from this analysis (Table 3.4) reveal that the corrections to the Morin series are too low in all of the three periods, but especially so during May and June. However, this was not corrected for and the corrections recommended by Legrand & Le Goff (1992) were retained.

The temperature data reconstructed for the respective series were entered as the T term in Standard Equation 1. A thermal expansion coefficient of $\gamma = 1.82 \cdot 10^{-4}$ was used for the early readings from the Paris Observatory (1713–25) as well as for the Delisle (1748–59) and the Roux (1759–76) series, given that the exact construction of the barometers used is unknown and may or may not have had a brass scale. Certainly the barometers used at the Paris Observatory and by Delisle would probably have been constructed with a wooden scale. For the Cotte (1776–82) and the late observations from the Paris Observatory (1783–50) a coefficient of $\gamma = 1.63 \cdot 10^{-4}$ was used as it is known that the Megnié barometer was constructed with a brass scale and it is likely that the later barometers were constructed likewise.

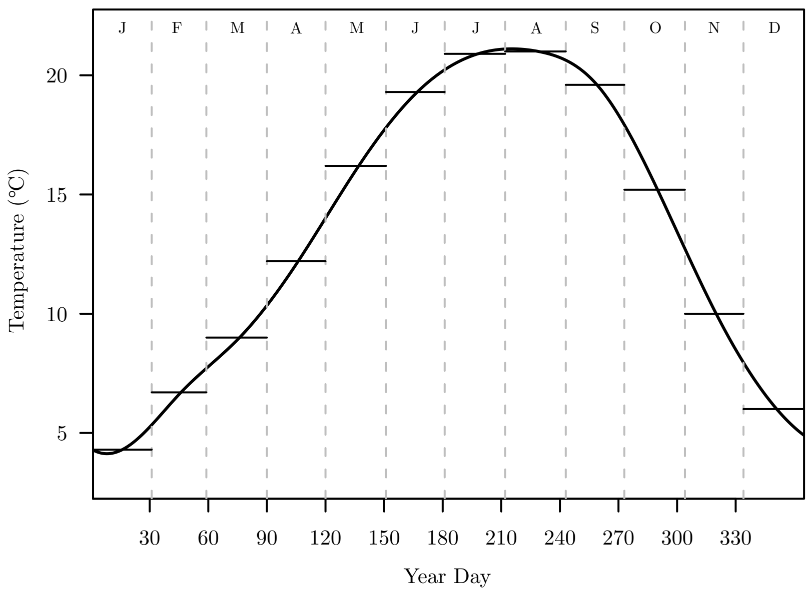

Figure 3.6: Paris Observatory Internal Temperature Model. The horizontal lines indicate the monthly mean values of internal temperature from Renou (1881) calculated from data recorded in the period 1809–18.

Observer/ Location	Years	Height (m)
Various / Paris Observatory	1713–1725; 1783–1850	67.0
Joseph Delisle / Hôtel Cluny	1748–1759	57.0
Augustin Roux / Rue de Seine	1760–1776	57.0
Louis Cotte / Montmorency	1777–1782	106.5*
Various / Parc Saint Maur	1881–1902	49.3
Various / Parc Saint Maur	1903–1922	50.3
Various / Le Bourget	1923–1940; 1945–1948	59.0

Table 3.5: The altitude values used to reduce the Paris sources to MSLP.
* The height of the church in Montmorency was ascertained by Renou (1881).

3.3.2 Reduction to standard gravity

The next stage in the correction procedure adjusted the barometer readings to standard gravity. This correction was applicable to all series prior to 1923. The correction was achieved by using Standard Equation 2 and taking the local value of gravity as $g_{stn} = 9.80967ms^{-2}$. This value was calculated for the latitude 48°48'N and following the example of the London series (see §2.3.4) the small variations in the value of local gravity at the various observation sites in Paris were disregarded.

3.3.3 Reduction to sea-level

The correction of the data to MSLP needed to be applied to all data prior to 1949, apart from the observations taken during the Second World War, which already had the correction applied in the original publication. In the case of the Morin series (1670–1712), the correction of +4mm recommended by Legrand & Le Goff (1992) was simply used. The other series were corrected using Standard Equation 3. The altitude values for each series—the h terms—are listed in

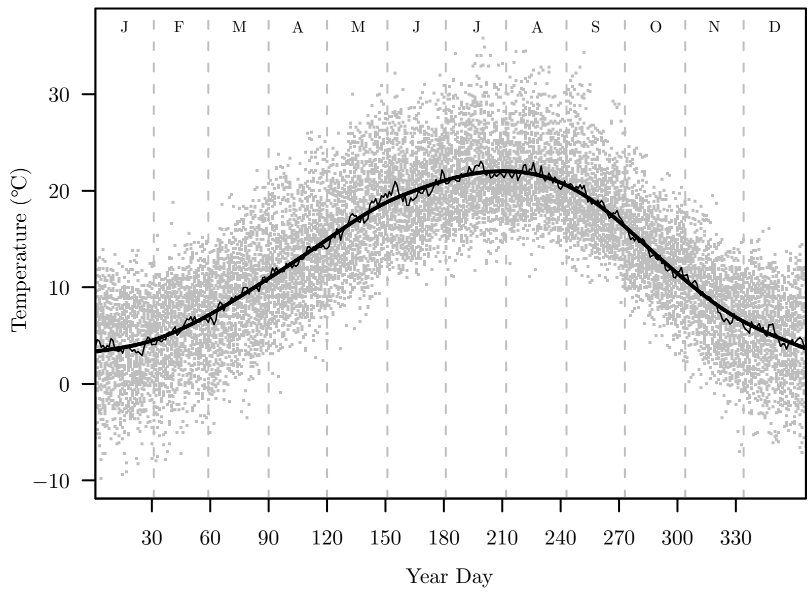

Figure 3.7: Parc Saint Maur Dry-bulb Temperature Model. The grey dots represent the individual temperature readings (1881–1922), the thin black line shows the mean for each day of the year and the thick black line shows the mean values smoothed with a cubic smoothing spline (df=10).

Table 3.5 but the temperature data—the T terms—could not be so easily estimated. In the case of the Parc Saint-Maur series (1881–1923), the dry-bulb temperature concurrent to the pressure observations had been digitized and could simply be entered into Standard Equation 3 for each day. Concurrent temperature readings were not available or have not been digitized for the other series and several methods were used to derive an estimate of this temperature for the various series.

To correct the Bourget Airport series (1923–48) the daily temperature values were estimated from the mean of the daily minimum and maximum temperature readings recorded at the airport. This estimation is commonly used for calculating the monthly mean of temperature, given that temperature is typically normally distributed (Wilks, 1995). In mid-latitude regions such an estimation at the daily resolution would generally give a deviation of less than 0.3°C from the true mean (Linacre, 1992), which given the low altitude of the stations in Paris would only yield a very small error in the calculated sea-level pressure value.

In the case of the Cotte series (1776–82) the temperature values as extracted from the *Journal de Médecine* publication for 2pm were used to reduce the barometer readings to MSLP as the temperature readings are likely to have been recorded from a shaded outdoor position and are therefore indicative of a dry-bulb temperature reading (see §3.2.5). In the case of the remaining series prior to 1850, modelled temperature data were used. As all of the barometer readings were recorded at noon during this period the noon observations of the dry-bulb temperatures from Parc Saint-Maur were used. The daily mean for each year day was calculated and this was subsequently smoothed with a cubic spline (df=10, see Figure 3.7).

Source	Years	Observation Times
Louis Morin	1670–1712	6am, 3pm and 7pm*
Paris Observatory	1713–1725; 1783–1850	12pm†
Joseph Delisle	1748–1759	12pm
Augustin Roux	1760–1776	12pm
Louis Cotte	1777–1782	12pm
EMULATE	1851–80	24-hour mean
Parc Saint Maur	1881–1922	12pm
Le Bourget	1923–1940	6pm
Le Bourget	1940–1944	7am, 1pm or 6pm‡
Le Bourget	1945–1948	6am, 12pm and 6pm
Le Bourget	1949–2007	24-hour mean

Table 3.6: The observation times of the component Paris series.
*These times are estimated.
‡The majority of the times were recorded around 12pm (but also see §3.3.5) although certain observations were taken at 8am. No consideration has been given to these differences and all observations were taken as 12pm for simplicity.
‡The most consistent observation was at 6pm but where this was missing observations at either 6am or 12pm were used where this was missing. The observations at Le Bourget are recorded in UTC, whereas the other series are at local time.

3.3.4 Correction to 'true' daily means

The same method employed in the London data series was used to correct the observations from Paris into daily mean values (see §2.3.6). Hourly values from Le Bourget from 1993–2007 were used to derive models of diurnal pressure (see Figure 3.8). The corrections are shown in Figure 3.9a.

As these models were calculated from data recorded in UTC the data to be corrected needed to be likewise. The standard time used in France until 11th March 1911 was derived from the Paris Prime Meridian, as either Apparent Solar Time (AST) or Mean Solar Time (MST) (see §2.3.6), and was therefore in advance of UTC by 9 minutes 21 seconds (Reingold & Dershowitz, 2001). This small difference was disregarded in the corrections and hence the local observation times were taken as UTC. After 11 March 1911, Western European Time (WET) was adopted and was also equal to UTC as it was calculated from the Prime (Greenwich) Meridian. However, the Parc Saint Observatory (1881-1922) continued to record time according to the Paris meridian. The observations obtained for Le Bourget from the *Täglicher Wetterbericht* source (see §3.2.9) were recorded in Central European Time (UTC +1) and were simply corrected to UTC by subtracting one hour.

3.3.5 Uncertainties in the observation times

Table 3.6 shows the times of the observations used to complete the Paris pressure series, and which were used in the corrections described above. However, there is some uncertainty in the times of the observations recorded at the astronomical observatories in the eighteenth century.

It was common practice at astronomical observatories until 1925 to record the time by astronomical reckoning. This eliminated the problem of date changes occurring during astronomical observations as midnight in civil time became noon in astronomical reckoning and *vice versa* (Howse, 1980). It may be, therefore, that while the observations from the Paris Observatory (1713–25) were recorded in the astronomical notebooks as midday (midy) this might actually

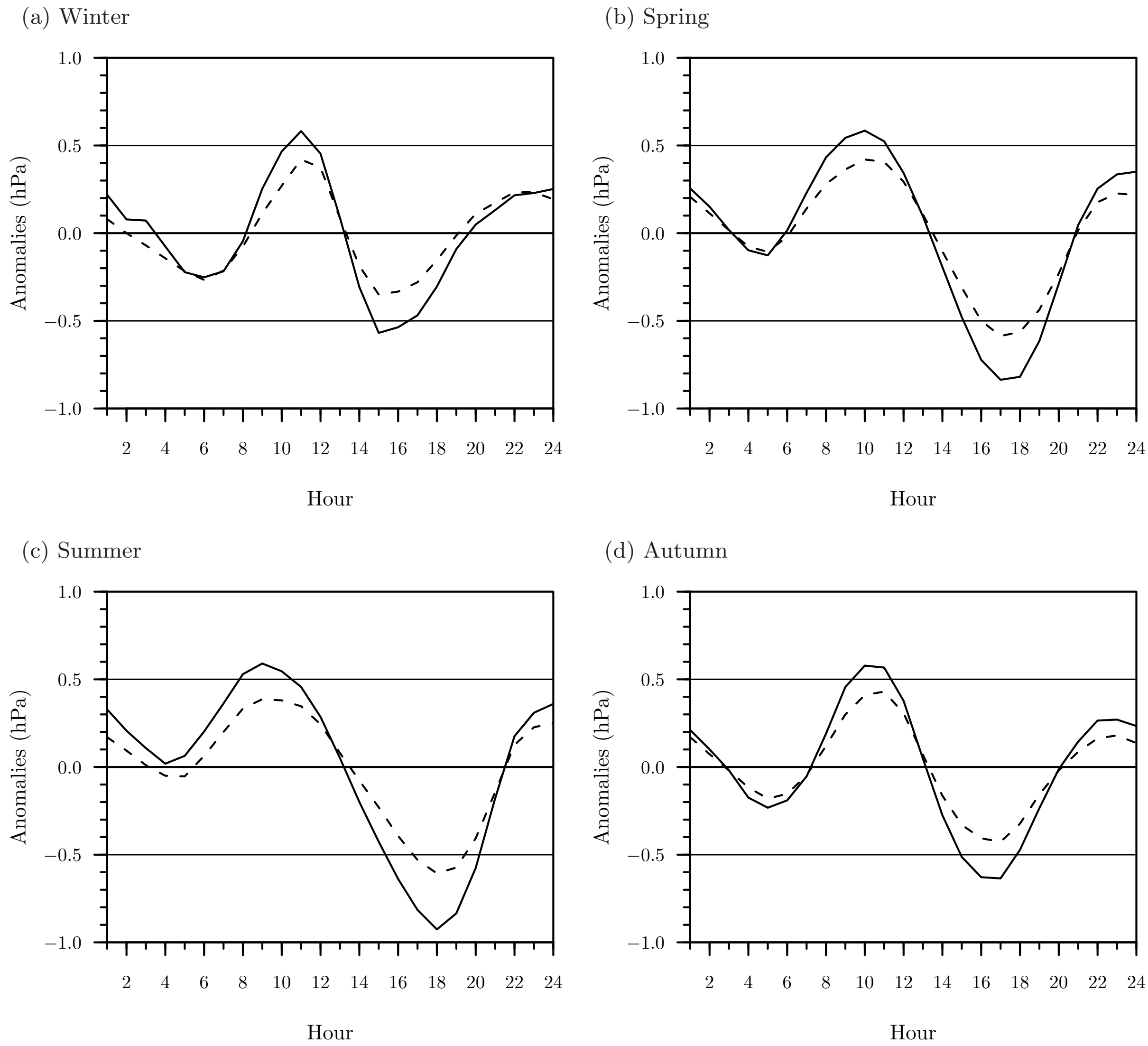

Figure 3.8: The diurnal pressure cycles for Paris on a seasonal basis. The continuous lines shows the modern results derived from data recorded at Le Bourget (1993–2007). The dashed lines indicate the values obtained by Angot (1880), who used hourly data recorded at Parc Saint-Maur (1873–9).

be a midnight reading according to civil time. Indeed, Lamb (1991) was certain that this was the case. However, this may not be the case as the temperature generally shows the expected increase at 'midy' given that the temperature was probably recorded on a reverse scale; further work on these data would be required to ascertain this.[6]

It seems unlikely that the time was recorded in astronomical reckoning at the *Hôtel de Cluny* (1748–59) given that the temperature values extracted from the diary and converted from °D to °C matches the noon value from the Paris Observatory so well (see Figure 3.5). Further, it seems unlikely that Delisle would have recorded the observations either-side the '12 hr' value as 'morning' (matin) and 'afternoon' (soir) if astronomical reckonings were used; the possibility cannot be ruled-out however.

The possible misinterpretation of the times in the early Paris Observatory (1713–25) and

[6]Lamb (1991) states that Paris Observatory used the Fahrenheit scale during this period. This seems unlikely, however, as the Fahrenheit scale was slow to be adopted in France, and was not even in use by the late eighteenth century (Knowles Middleton, 1966).

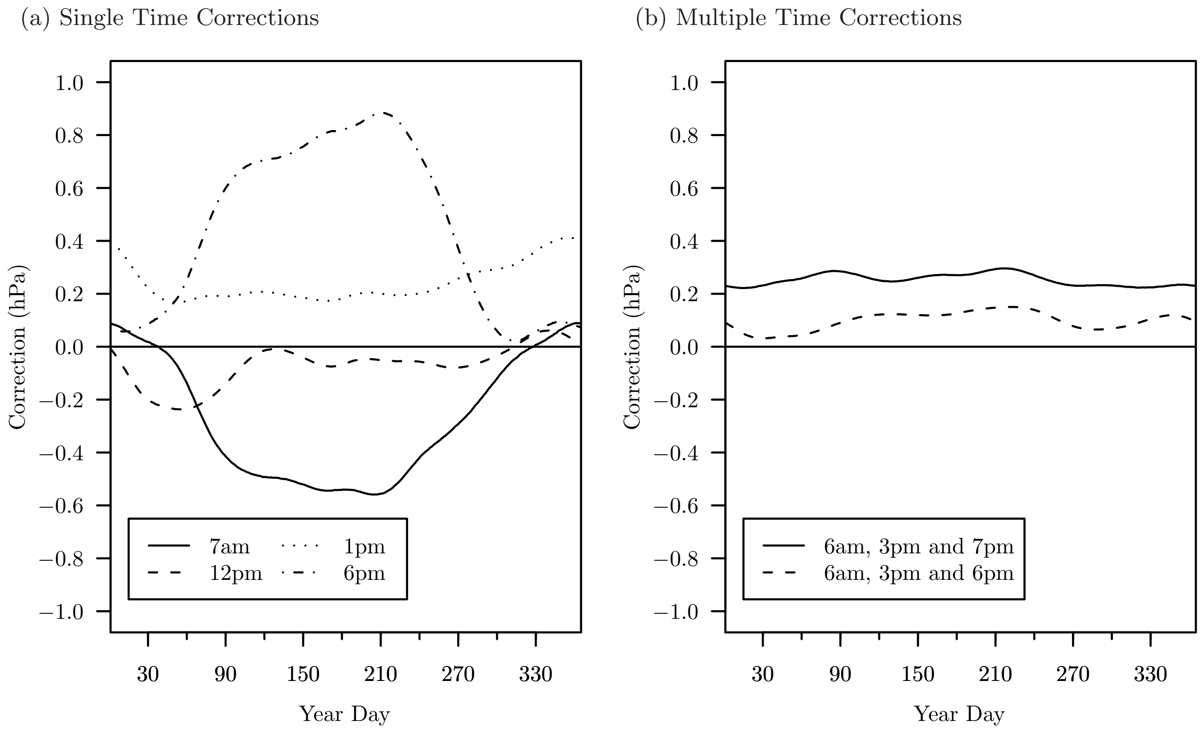

Figure 3.9: Corrections applied to adjust for differing observation times. The times relate to those for each series listed in Table 3.6. These corrections were derived by smoothing the daily mean differences with a Gaussian weighted filter (90-day window).

Hôtel de Cluny (1748–59) series would not cause a large error in the correction to 'true' daily means, as due to the diurnal cycle of pressure (Figure 3.8) the corrections at noon and midnight are almost identical. A potential error would occur in the temperature correction and to a lesser extent the MSLP correction. However, given the early nature of the instruments and the scale used (Paris Inches/lines) this error is likely to be small. A later comparison of the values between Paris and London (Chapter 5) has not revealed any large errors.

3.4 Chapter summary

The Paris daily pressure series has been constructed to cover the period 1670–2007 by joining barometric pressure observations recorded from various sources. Many of these readings have not previously been digitized from the original sources. These data have been corrected to provide a daily-mean measure of atmospheric pressure in the unit of hPa at standard conditions, i.e. standard gravity, 0°C and at sea-level; the observations have also been corrected to the equivalent of a 24-hourly mean to reduce the error associated with a limited number of observations per day. A reasonably detailed station history has been compiled by incorporating metadata contained in various written sources. This has been possible as the majority of the observations were recorded by some of the leading scientists of the seventeenth and eighteenth centuries, who regularly published their research findings. These station histories have facilitated the homogenization of the data series, which is documented in the following chapter.

Chapter 4

Homogenization

4.1 Introduction

The homogenization of data series is one of the most active and important areas of climate research as inferences about climate change or variability derived from climate data can only be trusted if the data are free from artificial breakpoints or discontinuities. A definition that has often been cited in the climate homogenization literature, but which is nonetheless still valid, is provided by Conrad & Pollack (1962, p. 223):

> "A numerical series representing the variations of a climatological element is called 'homogeneous' if the variations are caused only by variations of weather and climate".

Typical non-climatic influences (inhomogeneities, breakpoints or changepoints) can be grouped into the following categories: changes in the situation of the instruments or the location of the station, alterations to the recording practice, changes in the method of calculating means, and sudden or gradual changes in the station environment (Jones *et al.*, 1986; Aguilar *et al.*, 2003). Complications are added when using observations from the Early Instrumental Period (EIP) by the potential for poorly maintained or calibrated instruments, unknown measurement units or poorly situated instruments. Temperature series are greatly influenced by the type of screen used to house the thermometers (Jones *et al.*, 2009). However, the assumption that earlier observations may be less accurate may not always be a valid assumption (Camuffo *et al.*, 2010). An inherent problem with the formation of long climate series, such as the London and Paris daily pressure series, from a patchwork of data series is that the incorporation of inhomogeneities is inevitable.

Regardless of the exact cause of the inhomogeneities in a climate data series, they can lead to variations that are as large or larger than the climate signal and it is therefore the job of the data analyst to bring the climate signal to the fore, beyond this background of noise, through the application of necessary data corrections (Slonosky, 1999; Caussinus & Mestre, 2004). The testing of the homogeneity of a candidate series is often most easily achieved through the comparison of the series against neighbouring series (Slonosky, 1999), and a simple way of detecting likely inhomogeneities is to visually compare the candidate series with other series from the same climatic region, as demonstrated by Jones *et al.* (1986). The incorporation of station history information (metadata) can also be useful to indicate the cause of a detected inhomogeneity (Karl & Williams Jr, 1987) but cannot be totally relied upon, as the metadata may not be complete or accurate (Aguilar *et al.*, 2003).

Relative homogeneity testing in this manner forms the basis of most homogenization procedures, although the application of statistical tests is preferred to visually comparing time series in order to lend objectivity to the process (Ducré-Robitaille *et al.*, 2003). Most of these tests have been applied to the detection and correction of inhomogeneities in temperature or even precipitation series, with less attention being directed towards the homogenization of pressure datasets. This may be attributable in part to fewer pressure series having been reconstructed, although there are notable exceptions (e.g. Slonosky *et al.*, 1999), and Jones (1987) provides a good example of the grossly erroneous conclusions that may be reached from using poor quality, inhomogeneous pressure data. The principles for the homogenization of pressure data series are, however, the same as for temperature and in general the homogenization of pressure data is aided by the low spatial variation of atmospheric pressure and by the low variability of the annual mean of pressure at a given location, which does not typically vary over decades by more than 3–4hPa (Mitchell *et al.*, 1966) and for most locations by much less than even this value. These features mean that the homogeneity of a candidate series can be tested against a reliable reference series from the same climatological region, up to several hundreds of kilometres away. In addition, pressure data are affected less by site changes than temperature or precipitation data, and most inhomogeneities can be rectified by applying suitable corrections for altitude (Jones, 2001a).

In this context, this chapter describes the homogenization scheme used to detect and correct inhomogeneities in the London and Paris daily pressure series. These data were homogenized after the application of the corrections detailed in chapters 2 and 3. It should be noted that the two series were kept separate during the homogenization process to eliminate questions regarding circularity that may have arisen in future comparisons of the data in Part II of this thesis. The data from the two locations were occasionally compared but corrections were never solely based on the comparison. Given that relative homogeneity testing is more powerful than absolute testing when highly correlated homogeneous reference series are available (Wijngaard *et al.*, 2003), the London/Paris data were tested for homogeneity against several European pressure series back to 1780 using the Penalized Maximal t (PMT) test. Before this time, in the absence of reliable reference series, the homogeneity of the series was tested using the Penalized Maximal F (PMF) test. Both tests were applied through the RH-test (version 2) software package (Wang & Feng, 2007), which has several improvements over other software, including: an improved detection rate of changepoints at the ends of the time series, more accurate breakpoint detection by accounting for autocorrelation, the ability to incorporate metadata into the analysis and the detection of multiple breakpoints through the incorporation of a stepwise testing algorithm.[1] As this appears, to the best of the author's knowledge, to be one of the first applications of this software to long pressure series, the algorithms are described in some detail in Section 4.3.

[1]It has recently been discovered (June 2009) that an error exists in the RH-test version 2 software that causes the false-alarm rate of the PMF test to be too low. Version 2 of the software may therefore miss certain inhomogeneities (X. Wang, pers. comm.). This error has been rectified in Version 2_090619 of the software. The homogenized London and Paris series were tested with the latest version of the software at both the monthly and annual resolution. The results indicated that there are no significant breakpoints in the series. This indicates that the breakpoints in the raw series were so large that even the software with the lower false-alarm rate was able to detect the shifts.

This is followed (§4.4) by a description of the reference series used in the analysis. Sections 4.5 and 4.6 follow with a description of the results from these tests when applied to the London and Paris pressure series respectively. Those sections also detail the corrections applied to achieve homogeneous series. Prior to the application of the homogenization procedures and indeed before any corrections were applied to the data, quality control checks were applied to ensure that no grossly erroneous values remained in the data: quality control is the subject of the first section of this chapter (§4.2)

4.2 Quality Control

The scheme shown in Figure 4.1 was used for digitizing the London/Paris data and for identifying random errors. The quality control checks broadly follow those used by Brunet *et al.* (2006), who implemented the recommendations of Aguilar *et al.* (2003). These checks were carried-out before the instrument-specific adjustments, detailed in chapters 2 and 3, were made to the data. This facilitated the cross-checking of flagged values against the original sources as the data were in the same measurement units as the original sources.

The quality control procedure flagged errors that may have been introduced by the digitization process but also errors that were apparent in the original documents. Digitization errors were easily resolved through comparing the flagged errors with the values in the original sources. Other errors demanded more consideration. Where figures had obviously been recorded incorrectly, e.g. where 29in. was recorded instead of 30in., the values were easily corrected; this was also the case where figures had been transposed. Such errors occurred most frequently where the preceding whole inch value was omitted for simplicity in the original registers. Other errors were corrected by scrutinizing adjacent values or as a last resort by examining other meteorological parameters contained in the registers, such as wind speed or weather. In the case of errors between 1780 and 1785, the progression of daily values surrounding the flagged error were compared with the daily synoptic charts published in Kington (1988).[2]

Where a reasonable correction could not be made using these various methods then the value was marked as missing. In general, a conservative approach was taken to correcting the flagged values, i.e. the least changes necessary were made to the data, following the example of Moberg *et al.* (2002). It is for this reason that the very large value of ±25hPa was used in the check of day-to-day pressure changes.

4.3 The background to the Penalized Maximal t and F tests

4.3.1 The Penalized Maximal t test

A variety of statistical tests have been developed over the last 50 years for detecting inhomogeneities in climate datasets (see Aguilar *et al.*, 2003, for a list of these tests) but there remains no universally agreed best homogenization test. This results in the fact that two researchers independently homogenizing the same data series would achieve slightly different results (Maugeri

[2]While it has been suggested by Jones *et al.* (1999b) that there may be systematic biases in the monthly means of these data, the daily evolution of pressure presented in the published charts were useful for identifying relative pressure change anomalies.

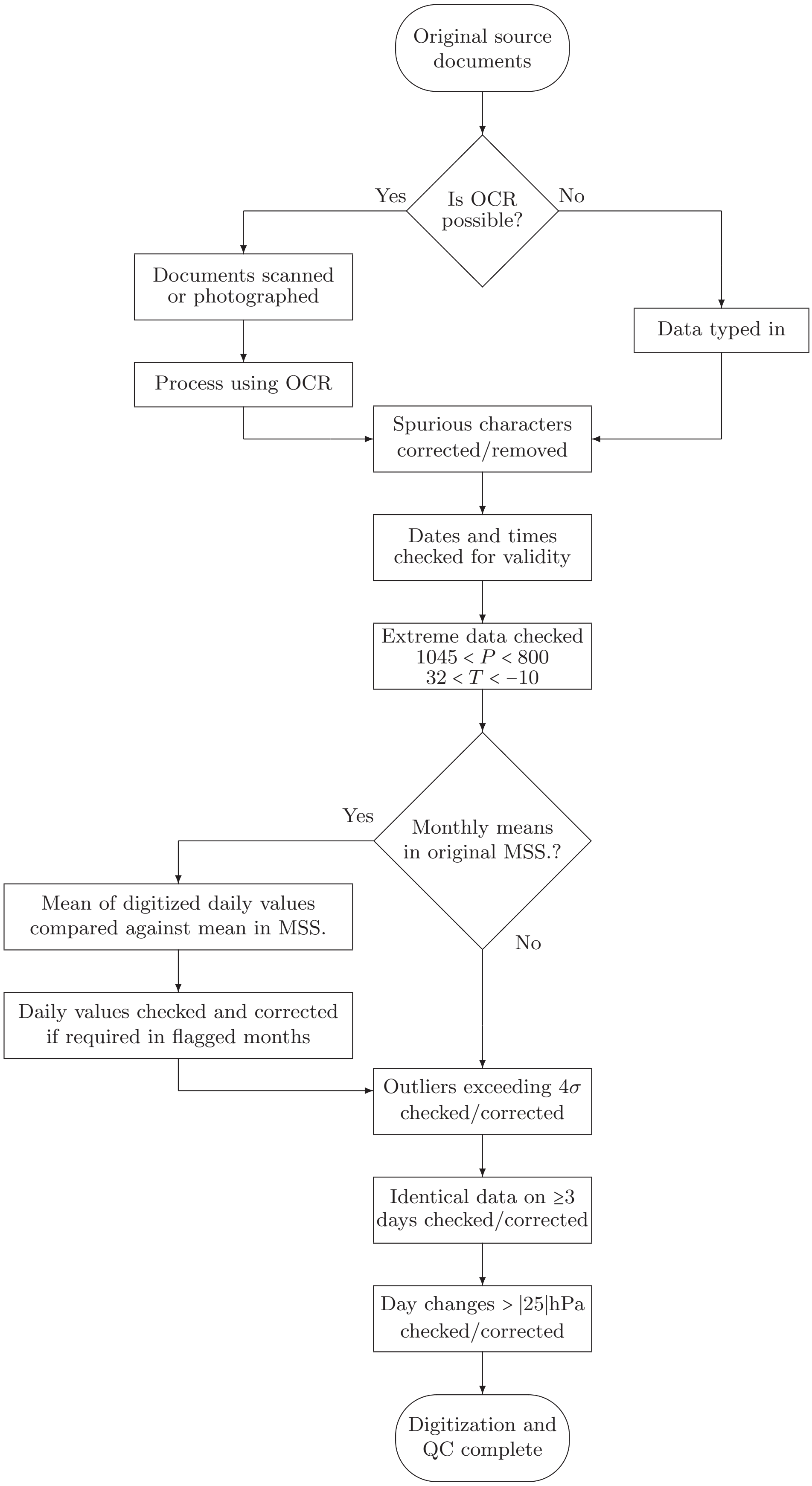

Figure 4.1: The Digitization and Quality Control (QC) Process. OCR stands for Optical Character Recognition.

et al., 2004). However, there are certain recommendations that can be made in selecting homogenization tests by taking a variety of theoretical and practical features of the tests into account. Building on earlier studies (Easterling & Peterson, 1995; Peterson *et al.*, 1998; DeGaetano, 2006; Ducré-Robitaille *et al.*, 2003), Reeves *et al.* (2007) have recently reviewed eight commonly used tests and concluded that none of the eight procedures were optimal in all situations, i.e. the tests performed differently when assessed by different criteria. When taking into account test complexity alongside general performance, Reeves *et al.* concluded that a Common-trend two-phase regression model based maximal F test (TPR3) (Wang, 2003) was best for dealing with most climate time series, whereas the Standard Normal Homogeneity Test (SNHT) (Alexandersson, 1986, or its nonparametric version) was optimal when the use of a homogeneous reference series reduces the adverse influence of trends or periodicities in the test.

The conclusions reached by Reeves *et al.* regarding the SNHT are important given that this is perhaps the most widely used test for detecting inhomogeneities in climate data series. It has been used to detect inhomogeneities in temperature (e.g. Alexandersson & Moberg, 1997; Moberg & Alexandersson, 1997; Moberg *et al.*, 2002; Bergström & Moberg, 2002; Brunet *et al.*, 2006), precipitation (e.g. Alexandersson, 1986; Hanssen-Bauer & Førland, 1994; Tomozeiu *et al.*, 2000, 2005) and pressure (e.g. Bärring *et al.*, 1999; Slonosky, 1999; Moberg *et al.*, 2002; Bergström & Moberg, 2002) data series. This is by no means an inclusive list and there are many more examples in the scientific literature.

The SNHT is equivalent (when used to detect shifts) to a maximal t test (Wang *et al.*, 2007) and is most commonly applied by taking a reference series, which is known (or tested) to be homogeneous. In the case of temperature or pressure series a new series (Q_t) of length ($t = 1, \ldots, N$) is computed as the difference between the reference and the candidate series; for precipitation data the ratio series is calculated (Moberg & Alexandersson, 1997). If both the reference and candidate series are from the same climatic region, both series should display similar trends and therefore the $\{Q_t\}$ series should have zero trend, and would consist of a sequence of random numbers (white-noise) (Menne & Williams, 2009). Assuming that the $\{Q_t\}$ series is normally distributed (IID Gaussian) the presence of changepoints can then be tested by taking the null hypothesis

$$H_0 : \{Q_t\} \sim \mathrm{IID}\mathcal{N}(\mu, \sigma^2) \tag{4.1}$$

and the alternative hypothesis as

$$H_1 : \begin{cases} \{Q_t\} \sim \mathrm{IID}\mathcal{N}(\mu_1, \sigma^2), & t = 1, \ldots, k \\ \{Q_t\} \sim \mathrm{IID}\mathcal{N}(\mu_2, \sigma^2), & t = k+1, \ldots, N \end{cases} \tag{4.2}$$

where, following the example of Wang *et al.* (2007), "$\{Q_t\} \sim IID\mathcal{N}(\mu_1, \sigma^2)$" is a term that indicates that $\{Q_t\}$ is normally distributed with a mean of μ and variance of σ^2. To test the validity of H_0, a t statistic is calculated for each point k by taking two samples: one over the range $t \leq k$ and the second over the range $t > k$. To detect a changepoint in the series the most probable value of k needs to be found and the statistical significance of the difference in the means from the two samples at that point must be tested. The test used to establish this is the likelihood ratio test and the most probable breakpoint value is the maximal value (T_{max}) of the log likelihood ratio (see Wang *et al.*, 2007, for a detailed description of this test). If T_{max} exceeds a critical level at the predefined level of significance, H_1 must be accepted. In this case $\mu_1 \neq \mu_2$ and the stepsize induced by the inhomogeneity at time k has a value of $|\mu_1 - \mu_2|$.

The model described in Equation 4.2 therefore follows the generally accepted view that an inhomogeneity in a monthly or annual resolution series occurs as a step in the mean value, with the higher moments of the distribution remaining unchanged (Rust *et al.*, 2008). In the case of daily or sub-daily resolution data, this assumption may not be valid and techniques have been presented that consider alterations to the higher moments of the distribution (Trewin & Trevitt, 1996; Brandsma & Können, 2006; Della-Marta & Wanner, 2006). These techniques are still at an early stage of development, however, and while probably easily transferable to several climate variables have only been used to adjust temperature series. There is a need for greater research to be conducted on the homogeneity of the higher moments of the distribution in pressure series, especially when assessing the homogeneity of data recorded during the EIP, when poorly maintained barometers could easily lead to a suppression of variance in the data.

A limitation of the maximal t test is that different points in a series have different probabilities of being identified as breakpoints due to the increasingly unequal sample sizes moving away from the mid-point ($N/2$) in the $\{Q_t\}$ series. Consequently the chance of mistakenly identifying a changepoint towards the end of the series (false-alarm rate) is higher than at the middle point of the series. This feature of the SNHT has previously been noted by Wijngaard *et al.* (2003), although Wang *et al.* (2007) went further and showed specifically, through Monte Carlo simulations, that the false-alarm rate is 'U' shaped. In order to remove this undesirable feature from the test, Wang *et al.* (2007) proposed a penalization factor for the test algorithm, which effectively smoothes the false-alarm rate throughout the series. By applying this empirically derived penalization factor to the maximal t test the chance of identifying breakpoints is similar throughout the series and this amended version of the maximal t test was termed the Penalized Maximal t (PMT) test.

The PMT test was chosen for the homogenization of the London and Paris series given the improvements over the maximal t test (and the equivalent SNHT). However, this test is only of use when a candidate series can be compared against a suitable reference series. In the case of the London and Paris series (as discussed in greater detail in §4.4) reliable reference series were only available back to 1780. Before this time a test was required that did not require a reference series: the Penalized Maximal F (PMF) test was chosen for this purpose.

4.3.2 The Penalized Maximal F test

As described above (§4.3.1), Reeves *et al.* (2007) identified the TPR3 as optimal for detecting changepoints in most climate data series when reference series are not available. Tests such as TPR3 are more complicated than tests such as the maximal t test as they need to incorporate a trend component. Indeed if a test designed to detect shifts without a trend is used for series containing a trend then the position of the changepoint will be indicated as occurring midway through the homogeneous trend section (Moberg & Alexandersson, 1997; Wang, 2003).

According to Wang (2003, 2008) the null hypothesis of a series $\{X_t\}$ is tested using TPR3 by evaluating a regression model, thus

$$H_0 : X_t = \mu + \beta t + \varepsilon_t, \quad t = 1, \ldots, N \tag{4.3}$$

with the alternative hypothesis taking the form of a two-phase regression model,

$$H_a : \begin{cases} X_t = \mu_1 + \beta t + \varepsilon_t, & t \leq k \\ X_t = \mu_2 + \beta t + \varepsilon_t, & k - 1 \leq t \leq N, \end{cases} \tag{4.4}$$

where ε_t is a zero-mean random error with constant but unknown variance σ^2 and β is a linear trend component, following the notation of Wang (2003, 2008). The statistical significance for a changepoint at time $k \in \{2, ..., n-1\}$ is assessed by taking the F statistic as

$$F_c = \frac{(SSE_{Red} - SSE_{Full})}{SSE_{Full}/(n-3)}, \tag{4.5}$$

where

$$SSE_{Red} = \sum_{t=1}^{N} (X_t - \bar{\mu}_0 - \bar{\beta}_0 t)^2, \tag{4.6}$$

and

$$SSE_{Full} = \sum_{t=1}^{k} (X_t - \bar{\mu}_1 - \bar{\beta} t)^2 + \sum_{t=k+1}^{N} (X_t - \bar{\mu}_2 - \bar{\beta} t)^2. \tag{4.7}$$

The most likely changepoint is identified at the maximum value (F_{max}) of F_c, at time k. In the situation where F_{max} exceeds a critical value at the predetermined significance level (usually α=0.05), $\mu_1 \neq \mu_2$ and the alternative hypothesis is accepted, with the stepsize taking the value $|\mu_1 - \mu_2|$.

The situation described in Equation 4.4 effectively splits the data series into two samples: one of size N_1 (with $t = 1, \ldots, k$) and the second of size N_2 (with $t = k + 1, \ldots, N$) (Wang, 2008). Due to increasingly different sample sizes moving away from the midpoint of the series ($N/2$), and in a similar manner to the maximal t test described above, the false-alarm rate of the TPR3 test is different at different points in the series (Wang, 2008). Again using Monte Carlo simulations Wang (2008) has shown that this false-alarm is 'W' shaped with a higher chance of detecting a given mean shift at the ends of the series than between the middle and the end. Wang (2008) proposed a penalization factor, derived empirically, that smoothes the false-alarm rate throughout the series. This modified version of the maximal F test is termed the Penalized Maximal F (PMF) test.

4.4 The development of reference series

As discussed above, the PMT test identifies probable breakpoints in a series by forming a new series as the difference between the candidate series and a homogeneous reference series. However, the assumption of homogeneity in a single reference series may not be valid. To remove this unrealistic requirement, a method of comparing the candidate series with several reference series in turn has been proposed (Slonosky *et al.*, 1999; Caussinus & Mestre, 2004). In selecting suitable reference series, it has been recommended that series from different countries are used to prevent problems of masking, which may arise when a switch to new recording practices occurred simultaneously within a single country (Slonosky *et al.*, 1999; Alexandersson, 2001). The main criticism of this pairwise approach has been that at some stage in the analysis a subjective evaluation needs to be made as to whether the breakpoint is attributable to the candidate or reference series. To remove this subjective aspect of the test, Menne & Williams (2009) have recently proposed an automated procedure. While still in development, this objective pairwise approach shows promising results and may become a widely used system in the homogenization of climate series.

A different approach to the inhomogeneity of reference series has been proposed, which forms a composite series from the mean of several reference series. Moberg & Alexandersson (1997) cite five as the minimum number of stations to be used in a composite. In forming a composite reference series it is common to weight the individual series by some parameter to ensure that the reference series is representative of the candidate station's climatological signal. These weights are typically computed from the squared correlation coefficients between the candidate series and each reference series, assuming that the correlation coefficients are positive (Moberg & Alexandersson, 1997). However, a limitation of this method is that if inhomogeneities remain in the component reference series, then the highest correlations will be achieved for those series with inhomogeneities common to the candidate series. This effectively masks the inhomogeneity in the candidate series (Alexandersson, 2001). In an attempt to eliminate this undesirable situation Peterson & Easterling (1994) recommended computing the correlation coefficient from the first-difference series (dT/dt), using

$$(dT/dt)_i = T_{i+1} - T_i, \tag{4.8}$$

where $\{T\}$ is a time series with time units $i \in \{1, 2, \ldots, N-1\}$. In this way a breakpoint in the reference series would only affect the time unit when it occurred, leaving the remainder of the series unaffected.

The method of obtaining reference series weights from first-difference series has been used in the homogeneity assessments of various climate series (Moberg & Alexandersson, 1997). Recent research has shown, however, that the derivation of correlation coefficients in this manner may lead to further complications. Using simulated climate series Menne & Williams (2005) have shown that inhomogeneities in component reference series are more easily transferred to the composite series when the correlation-based weights are calculated from the first-difference series. Furthermore, step-like changes and random walks may be introduced when the reference series contain missing values or where in general terms the composition of the series changes with time. This could lead to a higher false-alarm rate in the analysis and occurs when the first-difference series is transformed back into the units of the original series. However, if raw series are used then the original problem remains, in that the weighting may be biased by those component reference series that contain similar breakpoints to the candidate series and not necessarily those series that are most highly correlated with the candidate series. On balance Menne & Williams (2005) conclude that the use of first-difference composite reference series is best avoided.

In this context, three monthly reference series were created with which to compare the Lon-

Period	**Constituents**	**Correlation (r) with London**[a]	**Correlation (r) with Paris**[b]
1850–2007	HadSLP$_{lon/par}$		
	0°W × 50°N grid	0.96	0.91
1850–1995	ADVICE-7$_{lon/par}$		
	Basel	0.81	0.95
	Copenhagen	0.66	0.55
	Debilt	0.96	0.91
	Dublin	0.93	0.75
	Edinburgh	0.86	0.61
	Geneva	0.74	0.91
	Liverpool	0.95	0.78
1780–1995	ADVICE-4$_{lon/par}$		
	Basel	0.81	0.96
	Edinburgh	0.85	0.62
	Geneva	0.73	0.92
	Lund	0.66	0.54

Table 4.1: Reference series used to homogenize the London and Paris series. The correlations were derived from the monthly means, and once squared formed the weights in the respective composite series. [a] the correlations for ADVICE-7 were obtained over the period 1882–1995, ADVICE-4 over the period 1850–1995 and HadSLP over the period 1882–2007. [b] the correlations for ADVICE-4 and ADVICE-7 were obtained for the period 1850–1995, and HadSLP over the period 1850–2007. The correlation coefficients for ADVICE-4 were derived in both cases from the corrected candidate series. The subscripts *lon/par* on the reference series names are used to denote London or Paris reference series.

don and Paris series: the 0°W × 50°N grid square from the HadSLPr gridded pressure series was used from 1850–2007 (HadSLP$_{lon/par}$, Allan & Ansell, 2006); a composite of seven stations, mostly from the ADVICE (1998) project, was derived for 1850–1995 (ADVICE-7$_{lon/par}$); and a composite of four stations for 1780–1995 was also obtained from the ADVICE database (ADVICE-4$_{lon/par}$) (see Table 4.1). In the ADVICE-7$_{lon/par}$ composites, the non-ADVICE series of Liverpool was included as it is highly correlated with the London series, and to a lesser degree with the Paris series, and is considered to be homogeneous (Woodworth, 2006). The other stations were selected from the ADVICE database primarily based on the geographical distance from London/Paris, i.e. the closest stations were selected. In the case of the ADVICE-4$_{lon/par}$ composites, the correlations with London/Paris are lower than for ADVICE-7$_{lon/par}$ given that the stations are more geographically dispersed but the series selected were considered a compromise between their length and geographical distance. Indeed there exist series that are earlier than 1780 in the ADVICE dataset but there are too few to create a robust composite series. It should also be noted that the London and Paris series from the ADVICE database were deliberately avoided to reduce the potential for masking of homogeneities. Following the recommendations of Menne & Williams (2005) the composite series (ADVICE-7$_{lon/par}$ and ADVICE-4$_{lon/par}$) were generated from the weighted means of the station data with the weights being derived from the squared correlations coefficients between the London series and each reference series, and not from first-differences. Periods that appeared not to contain any large inhomogeneities in the candidate series were selected to compute the correlation coefficients; these are detailed in Table 4.1.

4.5 Homogenization of the London daily pressure series

To identify the timing and magnitude of changepoints in the London daily pressure series, the data were firstly reduced to monthly and annual means.[3] In the calculation of these means, the period (month or year) was marked as missing where the number of missing days exceeded 20%. As a first step in homogenization a simple review of the unhomogenized time series can be instructive (Mitchell *et al.*, 1966). This showed for the London series (Figure 4.2a) that there were not too many problems back through the series until the late nineteenth century. Thereafter several potential breakpoints can be identified.

A three-stage homogenization scheme was adopted for the London pressure series:

1. The 1850–2007 period was assessed and corrected using the HadSLP$_{lon}$ reference series in the PMT test. The results were cross-compared with those from the ADVICE-7$_{lon}$ reference series

2. The 1780–1849 period was tested and corrected using the ADVICE-4$_{lon}$ reference series again using the PMT test

3. The 1692–1779 period was tested and corrected using the PMF test.

In the case of stages 2 and 3 of the homogenization scheme, the actual periods tested were 1780–1995 and 1692–2007 respectively. The period covered by the previous test was considered homogeneous and the corrections adjusted the test segment to the mean of that period.

If the pressure data over the period 1692–1779 contained no trend, then the PMT could have been used instead of the PMF test (Wang & Feng, 2007). While it would be expected that the London pressure data contained no long-term trend (Slonosky, 1999; Slonosky *et al.*, 1999), it was considered better to apply the homogenization tests without any *a priori* assumptions. The PMF test was therefore used, which would be unaffected by any trend element that may have been present in the data (see §4.3.2).

The homogenization tests were applied to the monthly or annual means arranged sequentially. The assumption was therefore made that the annual cycle is unaffected by a particular inhomogeneity. This follows the example of Bergström & Moberg (2002) and Moberg *et al.* (2002) in their reconstruction of pressure series for the cities of Uppsala and Stockholm, although the latter study applied the test to annual mean data. This assumption relies primarily on the accuracy of the temperature corrections in reflecting the actual temperature of the mercury when reducing the data to 0°C. Given the locations of London and Paris the annual cycle of temperature is relatively small and the low altitude of the stations means that large (temperature dependant) height corrections were not required. As is shown in the following chapter (Chapter 5) through assessments of the annual cycle of the London and Paris pressure series, this assumption appears to be valid. In general, the viewpoint of Menne & Williams (2009) is taken in that the benefits arising from a larger sample size when arranging the data sequentially outweigh any benefits from testing monthly data separately. Further, the testing of sequential data eliminates the need to smooth the corrections to prevent the incorporation of artificial jumps between months.

[3] While the RH-test permits the assessment using daily values the large amount of noise in the series renders the identification of changepoints difficult (Wang & Feng, 2007).

Dates	Correction (hPa)	Description
01/01/1882 – 31/12/2007	0.0	–
01/01/1850 – 31/12/1881	-1.2	EMULATE series
18/03/1836 – 31/12/1849	0.0	–
12/10/1835 – 17/03/1836	+6.0	Adjusted according to Kew and Eaton (1863, 1880)
01/01/1823 – 11/10/1835	0.0	–
01/01/1787 – 31/12/1822	$y = 0.003x$	Drift in the Royal Society Cavendish barometer (x refers to the number of months from January 1774)
01/07/1784 – 31/12/1786	+6.2	Bent's observations from Manley's *London Weather Diary (LWD)*
20/04/1783 – 30/06/1784	+11.0	Unknown breakpoint in Hoy's observations
01/08/1782 – 19/04/1783	+0.4	Hoy's observations taken at Sion House
01/04/1782 – 31/07/1782	–	Break in Hoy's observations
01/09/1781 – 20/04/1782	+2.3	Hoy's observations taken at Muswell Hill
01/01/1774 – 31/08/1781	$y = 0.003x$	Drift in the Royal Society Cavendish barometer. x refers to the number of months from January 1774)
01/01/1771 – 31/12/1773	+4.3	Gentleman's Magazine Observations
01/08/1765 – 31/12/1770	+4.0	Gentleman's Magazine observations recorded in the *LWD* to nearest hPa
01/01/1755 – 31/07/1765	+4.3	Hooker at Tonbridge in Kent
12/05/1745 – 31/12/1754	-1.0	Jurin's observations at Lincoln's Inn Fields
01/01/1723 – 11/05/1745	+3.7	Stukeley, Hauksbee and Jurin's (Garlick Hill) observations from Manley's *LWD*
01/01/1708 – 31/12/1716	+9.7	Derham's 1708 observations / Holborn diary
01/01/1697 – 31/12/1706	-1.1	Derham's observations reconstructed by Slonosky (1999)
01/01/1692 – 31/12/1696	+8.3	Locke's observations

Table 4.2: Corrections applied to homogenize the London daily pressure series. The values of the corrections were obtained from the results of the various tests carried-out at the monthly resolution.

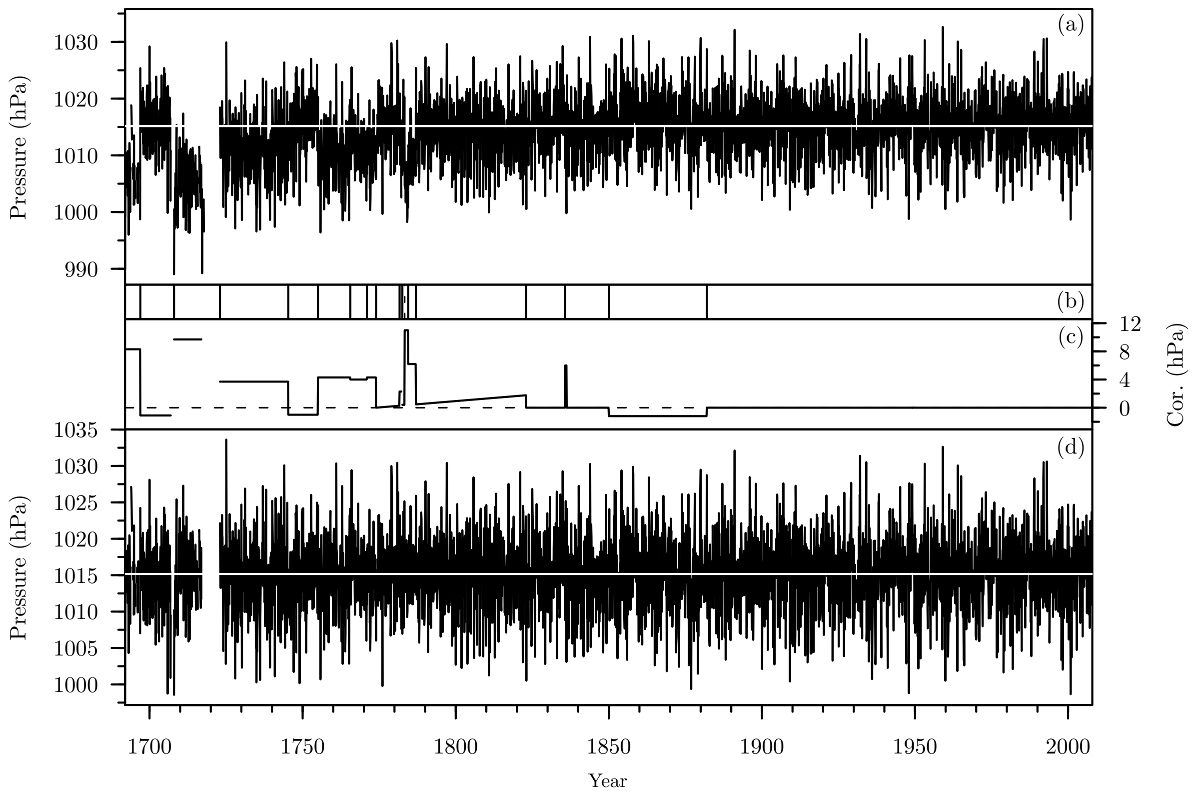

Figure 4.2: The Homogenization Scheme for London. a) Shows the monthly mean values of the data prior to the application of the homogenization corrections. b) identifies the timing of the breakpoints identified, with the solid lines showing Type-0 errors and the dashed lines showing the Type-1 errors. c) shows the corrections applied to the series in a), with the dashed horizontal line marking the zero level. The homogenized series is shown in d). The white horizontal line marks the overall mean of the homogenized series and is shown in a) for reference purposes.

4.5.1 The homogenization of the 1850–2007 period

As described above (§4.3), the PMT test assumes that the time series being assessed has zero trend. Having fulfilled this requirement, the recommendations of Wang & Feng (2007) were followed and the monthly and annual means were initially screened for Type-1 errors. These are errors that are so large as to be significant even without metadata support (Wang & Feng, 2007). The timing of identified errors near to known disruptions (Chapter 2) were amended where necessary but even errors with no supporting information were retained. Following this, the presence of Type-0 errors was tested. These are errors that are only deemed to be significant when supported by metadata. The timing of the Type-0 breakpoints were amended where possible according to the metadata and those errors with no supporting metadata were removed from the analysis. The sizes of the retained breakpoints were then re-estimated using the software's 'stepsize' function and the statistical significance of the breakpoints was re-evaluated. Where the test statistic resided in the 95% uncertainty range, the breakpoint had to be subjectively evaluated to be significant due to uncertainty in the lag-1 autocorrelation (Wang & Feng, 2007). This decision was aided by the consultation of metadata and by the cross-comparison with the results from the annual resolution tests and the different reference series. Where a breakpoint was deemed to be insignificant it was removed from the analysis and the 'stepsize' function was re-run. This procedure was repeated until all breakpoints were significant at α=0.05.

The results for using the two reference series (HadSLP$_{lon}$ and ADVICE-7$_{lon}$) were broadly similar, although there was one major difference. The results from the ADVICE-7$_{lon}$ test indicated a significant Type-1 breakpoint around January 1971, but in the results from the HadSLP$_{lon}$ test this was only indicated as a Type-0 breakpoint, the value of which resided in the 95% uncertainty range; the breakpoint was not apparent in the annual HadSLP$_{lon}$ test. It is known that the mercury barometers at Heathrow airport series were replaced with precision aneroid instruments sometime during 1971 (see §2.2.12) although it would seem unlikely that this would lead to the shift of +0.5hPa as indicated in the ADVICE-7$_{lon}$ test results. To provide further information on this breakpoint the test was repeated by using each of the constituent series used in the ADVICE-7$_{lon}$ composite separately in a pairwise approach similar to that of Slonosky *et al.* (1999), Caussinus & Mestre (2004) and Menne & Williams (2009). This revealed the breakpoint to be evident in the Edinburgh and Basel series but not the other five series. As the composite reference series was heavily weighted to these two series (Table 4.1) it would appear that the breakpoint was carried through to the composite series and was compounded. It was decided not to retain this breakpoint given this information and particularly as the size of the change in comparison with the HadSLP$_{lon}$ monthly difference series was less than 0.1hPa. It is suspected that inhomogeneities reside in the Edinburgh and Basel series and further tests should be conducted to establish this. It is indicative of the common problem of inhomogeneities in reference complicating the homogenization of a candidate series, despite the use of composite reference series to eliminate the problem (Menne & Williams, 2009).

Having rejected the breakpoint in 1971, only one statistically significant breakpoint ($\alpha = 0.05$) was retained in the 1850–2007 period (see Figure 4.2b). This breakpoint occurred at the change from the EMULATE series to the Greenwich Observatory series in 1882. The magnitude of the correction for the EMULATE data was obtained from the results from the monthly HadSLP$_{lon}$ test (see Table 4.2). To correct the daily series the corrections were simply added to all of the days in the respective period, following the example of Moberg *et al.* (2002)

The reduction of the EMULATE data series (1850–81) indicates that the overall mean of the new daily data series is approximately 1hPa lower than that of the London series created as part of the ADVICE (1998) project. This is because the EMULATE data had simply been adjusted so that the monthly means were identical to those of the ADVICE series (Ansell, 2004). The overall mean of the new daily pressure series (1015.2hPa) is in accordance with the value expected for London from previous analyses of the general circulation of the atmosphere (Hsu & Wallace, 1976). In addition this solves a problem identified by Woodworth (2006) when comparing the London, Edinburgh and Liverpool series. It was theorized that the mean of the Liverpool series should be the average of the London and Edinburgh means given that Liverpool is approximately midway between the other two cities, i.e. Liverpool should be 50% of the London–Edinburgh difference. This was found *not* to be the case and the Liverpool data were found to be 80% lower than London. The mean of the new London daily series is more in-line with what would be expected when comparing the data from these three stations.

4.5.2 The homogenization of the 1780–1849 period

The ADVICE-4$_{lon}$ composite reference series was used to test for breakpoints in the period from 1780. The same system described above (§4.5.1) of identifying and amending Type-1 and

Type-0 errors was used.

An obvious drift in the barometer readings from the Royal Society's Cavendish barometer was apparent over the years 1774 to 1822. This gradual reduction has previously been noted by Eaton (1863, 1880) and is most likely a result of the mercury having not been boiled in the barometer (see §2.2.9). This drift is a good example of an inhomogeneity causing a change in the trend of a candidate data series and is therefore contrary to the thesis of Wang (2003, see §4.3.2), which is based on the situation where an inhomogeneity occurs only as a mean shift with the trend remaining constant. As this situation is not addressed in the PMT test it can lead to erroneous conclusions, and therefore the data were corrected for this drift before being subjected to the PMT test. The rate of drift, and hence the correction required, was estimated by fitting a linear regression model to the monthly measurements and interpolating through the missing months, during which measurements were not recorded but the mercury level continued to decline. It was deduced from this model that the mercury level declined by 0.003 hPa month^{-1} over the life-span of the barometer and therefore by December 1822—the last month of use—the readings were reduced by 1.8hPa. This correction is similar to that applied by Eaton (1880) in his reconstruction of monthly pressure for this period.

Further interesting results can be seen from Table 4.2 and Figure 4.2c in that no significant breakpoints were identified in the Royal Society's readings from the Daniell barometer (Jan 1823–Dec 1836), the Flint-Glass barometer (Jan 1837–Dec 1842), or even the Greenwich observations (Jan 1843–Dec 1849; Jan 1882–Dec 1949). This is in accordance with the assertions made by Glaisher that the observations from the Greenwich standard barometer and those from the Royal Society's flint-glass observations are in accordance (see §2.2.10). In addition, having corrected the Cavendish barometer readings (1774–1882) for drift, no other corrections needed to be applied. This is a further indication that the instruments and method of recording the observations used at the Royal Society were generally of a very high quality despite certain concerns about the reliability of the register in the 1820s (see §2.2.9).

The gap in the Royal Society's readings from September 1782 until December 1786 presented a major challenge in the homogenization of the London Pressure Series. Thomas Hoy's barometer measurements recorded at Syon House from September 1782 were reasonable. However, a large breakpoint is evident in the readings during April 1783 for which there is no reason evident in the original manuscript. Indeed the barometer readings continued to be erratic throughout the following years with corrections of more than 25hPa required. This feature of Hoy's barometer readings has previously been noted by Wheeler (2001), who examined the data during October 1805, but found that the readings were too low by approximately 5hPa. William Bent's readings were found to be more consistent throughout this period and were substituted (see §2.2.8 for details about the Bent series).

The corrections applied to the data (Table 4.2) adjusted the mean of the 1780–1849 period to the mean of the 1850–2007 period, which had been corrected in stage 1. In order to substantiate the corrections suggested from the results of the PMT test during 1780–85 and to pinpoint breakpoints, the data were compared with values for London estimated from the synoptic charts published by Kington (1988). Although data from the *LWD* were used in the construction of these charts, many other station series were also included which means that this is not strictly a circular comparison. The charts provide a general indication of synoptic conditions on the days in question and were therefore useful to decide if the corrected pressure values were reasonable.

Post-homogenization testing/correcting revealed a further problem in the London data during the winter of 1835/6. A comparison with the Gibraltar/Reykjavik North Atlantic Oscillation Index (NAOI) (Jones *et al.*, 1997) revealed that the pressure difference between London and Paris was a large outlier. The problem was traced to the London data, which were too low during this period leading to a large positive pressure gradient. A comparison with the Royal Society's registers during this time with those from the Kew Observatory at Richmond revealed that the break occurred on 12 October 1835 and lasted until 17 March 1836. The difference in the readings between the Kew and Royal Society registers was normally 0.1in. but during this period was approximately -0.1in., i.e. the Royal Society's pressure readings appear to have dropped by 0.2in. This was also observed through a comparison with the monthly Mean Sea-Level Pressure (MSLP) series corrected by Eaton (1863, 1880). The conversion of Eaton's values to hPa revealed that the corrected London pressure data were too low by approximately 6hPa; this was also confirmed by comparing with the corrected Paris data. The correction of +6hPa was therefore added to all readings from 12 October 1835 to 17 March 1836.

4.5.3 The homogenization of the 1692–1779 period

The PMF test was applied to the monthly/annual means of the London pressure data over the 1692–1779 period following the recommendations of Wang & Feng (2007). In a similar manner to the PMT test, Type-1 tests were initially identified. Where these errors were supported by metadata the date of the breakpoint was altered and then the series was screened for Type-0 errors. Type-0 errors not supported by metadata were removed. The retained errors were then assessed one-by-one until all breakpoints were statistically significant.

The breakpoints identified using the PMF test (Figure 4.2b) could all be linked to metadata. William Derham's observations (1697–1706) reconstructed by Slonosky (1999) were reduced by a value of -1.1hPa. This is in accordance with the correction applied to the EMULATE data (1850–81) described above, which is attributable to the ADVICE data series for London being approximately 1hPa too high. Derham's observations for 1708, which are newly digitized, proved difficult to correct as applying the same correction for the 1697–1706 period yielded values that were too low in comparison with the homogenized Paris series. The input of a breakpoint was not possible given that the series only lasted for one year. As a compromise the same corrections as for the Holborn series (1709–1716) values were applied; this gave more sensible results.

As with the previous two stages of the homogenization procedure the corrections adjusted the data to the mean of the latest homogenized segment (1780–2007 in this case). The corrections applied to the data are shown in Table 4.2 and Figure 4.2c.

4.6 Homogenization of the Paris daily pressure series

A visual inspection of the unhomogenized Paris series (Figure 4.3a) reveals certain potential inhomogeneities throughout the twentieth century. Further back in time distinct breakpoints are evident during the 1750s and during the late seventeenth/early eighteenth centuries.

The same process as used for London (§4.5) was used to homogenize the Paris series. The first stage of the homogenization test considered the period 1850–2007 using the HadSLP$_{par}$

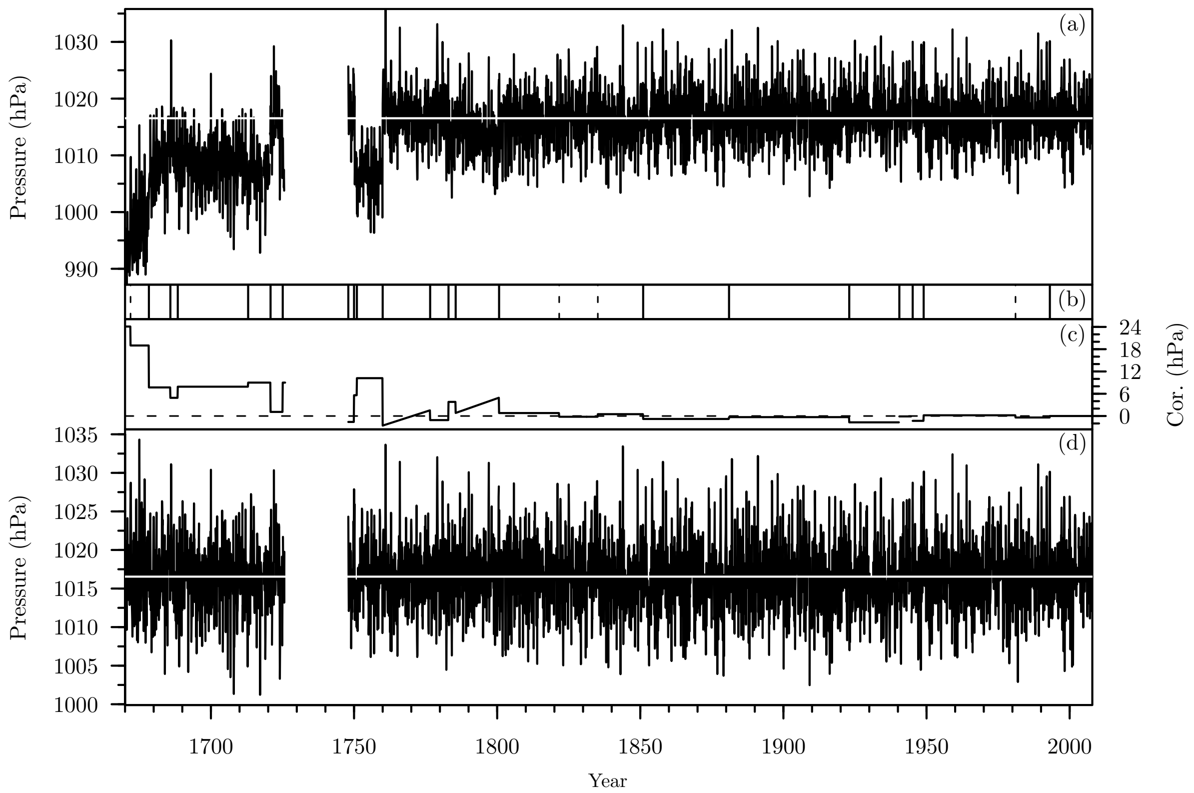

Figure 4.3: The Homogenization Scheme for Paris. a) Shows the monthly mean values of the data prior to the application of the homogenization corrections. b) identifies the timing of the breakpoints identified, with the solid lines showing Type-0 errors and the dashed lines showing the Type-1 errors. c) shows the corrections applied to the series in a), with the dashed horizontal line marking the zero level. The homogenized series is shown in d). The white horizontal line marks the overall mean of the homogenized series and is shown in a) for reference purposes.

reference series and the PMT test. The results from that test were compared over the period 1850–1995 with the results from the ADVICE-7_{par} test. The ADVICE-4_{par} test was used with the PMT test to analyse the 1780–1849 period. Finally the data for the 1670–1779 period were assessed using the PMF test. As with the London series the data were corrected in stages, working back from the 1850–2007 period, with the series being adjusted to the most recent segment.

4.6.1 The homogenization of the 1850–2007 period

The majority of the breakpoints (Table 4.3, Figure 4.3b) could be linked to known disruptions by referring to the metadata detailed in Chapter 3. However, it is not known what caused the breakpoint in January 1981. This breakpoint was a statistically significant Type-1 breakpoint and appeared in the results from both the HadSLP$_{par}$ and ADVICE-7_{par} reference series at the monthly and yearly resolutions. For these reasons this breakpoint was retained and corrected.

The EMULATE series (1850–80) was reduced by 0.8hPa. As with the London series, this indicates that the overall mean of the new Paris series (1016.5hPa) is lower than the series homogenized during the ADVICE (1998) project. This highlights the fact that while a series may be internally homogeneous the absolute mean of the series may be inaccurate.

Dates	Correction (hPa)	Description
01/02/1993 – 31/12/2007	0.0	–
01/02/1981 – 31/01/1993	-0.4	Station relocation on 1 February 1993
01/01/1949 – 31/01/1981	+0.2	Unknown breakpoint in January 1981
01/03/1945 – 31/12/1948	-1.3	Bourget airport observations (three-times daily). Changepoint possibly related to a relocation of instruments after WW2.
24/08/1944 – 28/02/1945	–	Gap
10/07/1940 – 23/08/1944	-0.1	Bourget airport observations taken from *Täglicher Wetterbericht* publication
01/06/1940 – 09/07/1940	–	Gap
01/01/1923 – 31/05/1940	-1.7	Observations from Bourget airport taken once daily at 6pm.
01/01/1881 – 31/12/1922	-0.3	Observations from Parc Saint-Maur Observatory.
01/01/1851 – 31/12/1880	-0.8	EMULATE series
01/03/1835 – 31/12/1850	+0.5	Unknown breakpoint in March 1835
01/09/1821 – 28/02/1835	-0.2	Unknown breakpoint in September 1821
01/09/1800 – 31/08/1821	+0.8	Paris Observatory series. Megnié barometer possibly replaced
01/07/1785 – 31/08/1800	$y = 0.02263x + 0.8$	Drift in the Megnié barometer. x refers to the number of months from July 1785
01/01/1783 – 30/06/1785	+3.8	Paris Observatory series
01/08/1776 – 31/12/1782	-1.1	Cotte series at Montmorency
01/01/1760 – 31/07/1776	$y = 0.02073x - 2.6$	Drift in the Roux series. x refers to the number of months from January 1760
01/01/1751 – 31/12/1759	+10.2	Delisle series at the Hôtel Cluny, barometer ‘C’
01/01/1750 – 31/12/1750	+5.6	Delisle series at the Hôtel Cluny, barometer ‘B’
01/01/1748 – 31/12/1749	-1.6	Delisle series at the Hôtel Cluny, barometer ‘A’
01/01/1726 – 31/12/1747	–	Gap
21/01/1725 – 31/12/1725	+9.0	Paris Observatory series, observer unknown
01/11/1720 – 20/01/1725	+1.1	Paris Observatory series, recorded by Maraldi
01/01/1713 – 31/10/1720	+9.0	Paris Observatory series, observer unknown
12/06/1688 – 31/12/1712	+7.9	Morin’s observations recorded at Abbaye de Saint Victor
19/10/1685 – 11/06/1688	+4.9	Morin’s observations recorded at Hôtel Rohan-Soubisse
13/05/1678 – 18/10/1685	+7.7	Suspected barometer change on 12 May 1678
23/11/1671 – 12/05/1678	+19.0	Unknown breakpoint in November 1671
01/01/1670 – 22/11/1671	+24.1	Morin’s observations recorded at Hôtel Dieu

Table 4.3: Corrections applied to homogenize the Paris daily pressure series. The suffixes ‘A–C’ for the Delisle barometers relate to the description of Delisle’s barometers in Table 3.2.

4.6.2 The homogenization of the 1780–1849 period

The second stage of the analysis considered the period after 1780 by using the ADVICE-4_{par} reference series. Two undocumented breakpoints were identified in the results from this test in the Paris Observatory series (1783–1850). These occurred in September 1821 and March 1835 but it is not known what caused the breakpoints given the lack of metadata for this series. An analysis of the daily series failed to pinpoint the exact date of the breakpoints and so the corrections were added from the start of the respective months.

As has been described in Section 3.2.6, the Megnié barometer in use at the Paris Observatory from 1 July 1785 suffered from a drift in the measurements despite the design of the instrument to guard against this possibility. The drift was at a much higher rate than that observed in the Cavendish barometer in use at the Royal Society (1774–1822, see §4.5.2). By fitting a linear regression line to the data the drift-rate was calculated to be 0.02hPa month^{-1}. This drift ended in August 1800, when it would appear that a new barometer was installed or the Megnié barometer was repaired. This drift was corrected before the homogeneity of the series was tested. Having applied the test it would appear that the change to the barometer in August 1800 did not introduce any further inhomogeneities into the series.

4.6.3 The homogenization of the 1670–1779 period

In homogenizing the 1670-1779 period of the Paris series, using the PMF test, large corrections were required in all of the component series, but especially for the Louis Morin data (see Table 4.3 and Figure 4.3c). As has been described in Section 3.2.1, the earliest pressure data recorded by Morin prior to 12 May 1678 have previously been identified as being too low (Legrand & Le Goff, 1992) but no corrections have previously been applied to correct for this apparent error. In the homogenization of the data in this study, several combinations of corrections were trialled but none gave entirely satisfactory results. The corrections that were finally decided upon, shown in Table 4.3 and Figure 4.3, gave the best results and are linked to Morin's known changes of residence (Pfister & Bareiss, 1994) along with the suspected instrument change on 12 May 1678 (Legrand & Le Goff, 1992) and the incorporation of a breakpoint on 22 November 1671. This latter changepoint is evident from scrutinizing the daily sequence of values, but has an unrecorded cause. Slightly different corrections were applied to the remaining Morin data, compared to those applied by Slonosky (1999), who took the 6.8mm (9.04hPa) correction recommended by (Legrand & Le Goff, 1992) and added 0.3hPa to bring the data in-line with the monthly mean value of the 1764–1995 Paris pressure series. The corrections decided upon in this study incorporated Morin's unknown changes of residence (Pfister & Bareiss, 1994). Further improvements could probably be made to the Morin data, which once corrected appear a little too high, but this would most successfully be achieved through the comparison with data from neighbouring locations. Given the dates of the observations, this is unlikely to ever be achieved.

In the case of the early barometer measurements recorded at the Paris Observatory (1713–26), contemporary literature recorded that Maraldi's readings consistently registered approximately three lines (≈9hPa) higher than la Hire's readings (see §3.2.2). This is comparable, to the different corrections applied to the data from the two barometers in this study, where the difference in corrections is 7.9hPa. The relatively small correction of 1.1hPa applied to Maraldi's readings is also in accordance with the assertion of Renou (1881, see Section 3.2.2), that Maraldi's readings are more consistent with modern-day measurements.

Drift was evident in Augustin Roux's barometer observations over the period 1760–1776 and the data were corrected in the same way as the Paris Observatory's Megnié and Royal Society's Cavendish barometer readings (see §§4.5.2 and 4.6.2). The results indicated that the barometer level drifted at a rate of 0.02hPa month^{-1}, which is comparable to the rate of drift in the Megnié barometer in use at the Paris Observatory during the 1780s.

In keeping with Louis Cotte being described as "France's foremost meteorologist" during the eighteenth century (Feldman, 1990, p.165), his barometer readings appear to have been well calibrated and required the least correction of all of the data during this period. The change from the Cappi barometer to the Megnié barometer in July 1778 (see §3.2.5) appears to have not introduced a statistically significant breakpoint in the series at $\alpha = 0.05$. Interestingly, while the Megnié barometer in use at the Paris Observatory suffered from a high rate of drift (see §4.6.2), Cotte's Megnié barometer did not show any sign of such a defect.

4.7 The completion of missing values

The presence of missing values are inevitable when constructing data series for point locations (Jones, 2001a). This is equally true for the London and Paris pressure series, despite the selection of series that were the most complete. A combination of regressing values from nearby stations and linear interpolation was used to complete the missing values in these series.

The question arises as to whether the missing values should be infilled prior to homogenization or afterwards. If data are infilled prior to homogenization then the timing and magnitude of inhomogeneities could potentially be masked. An additional problem is that the relationship obtained by linear regression could also be inaccurate as a result of inhomogeneities in either series (Štěpánek, 2004). However, if data are infilled after the homogenization procedure then any inhomogeneities in the infilling series will not be detected. The demonstration of both methods exist in the literature. Bärring *et al.* (1997), Bärring *et al.* (1999) and Slonosky (1999) infilled values prior to homogenization, whereas Bergström & Moberg (2002) and Moberg *et al.* (2002) favoured infilling afterwards. The choice is linked to the number of data that need to be infilled: large blocks of data need to be checked for homogeneity, whereas small numbers can be adequately adjusted by regressing against the main series. Given the relatively small number of data used for infilling the London and Paris series, missing values were completed after homogenization.

In the case of London over the period 1981–2007, missing values were completed by regressing the daily observations of pressure recorded at the Met Office's London Weather Centre (LWC) station. These data were extracted from the British Atmospheric Data Centre (BADC) repository (UK Meteorological Office, 2008). The regression model had $r^2 = 0.999$ at $\alpha < 0.001$ and was used to complete 54 values over this time period. Missing observations over the years 1782–3 were completed by using the observations recorded in the *Gentleman's Magazine*. These values had been corrected in the same way as the Hoy series (see section 2.3) and were regressed against the homogenized series over these years. This model had $r^2 = 0.78$ at $\alpha < 0.001$, which is a reflection of the greater range of observations recorded on early and unstandardized instruments. They were considered sufficiently accurate to complete the 105 missing values during

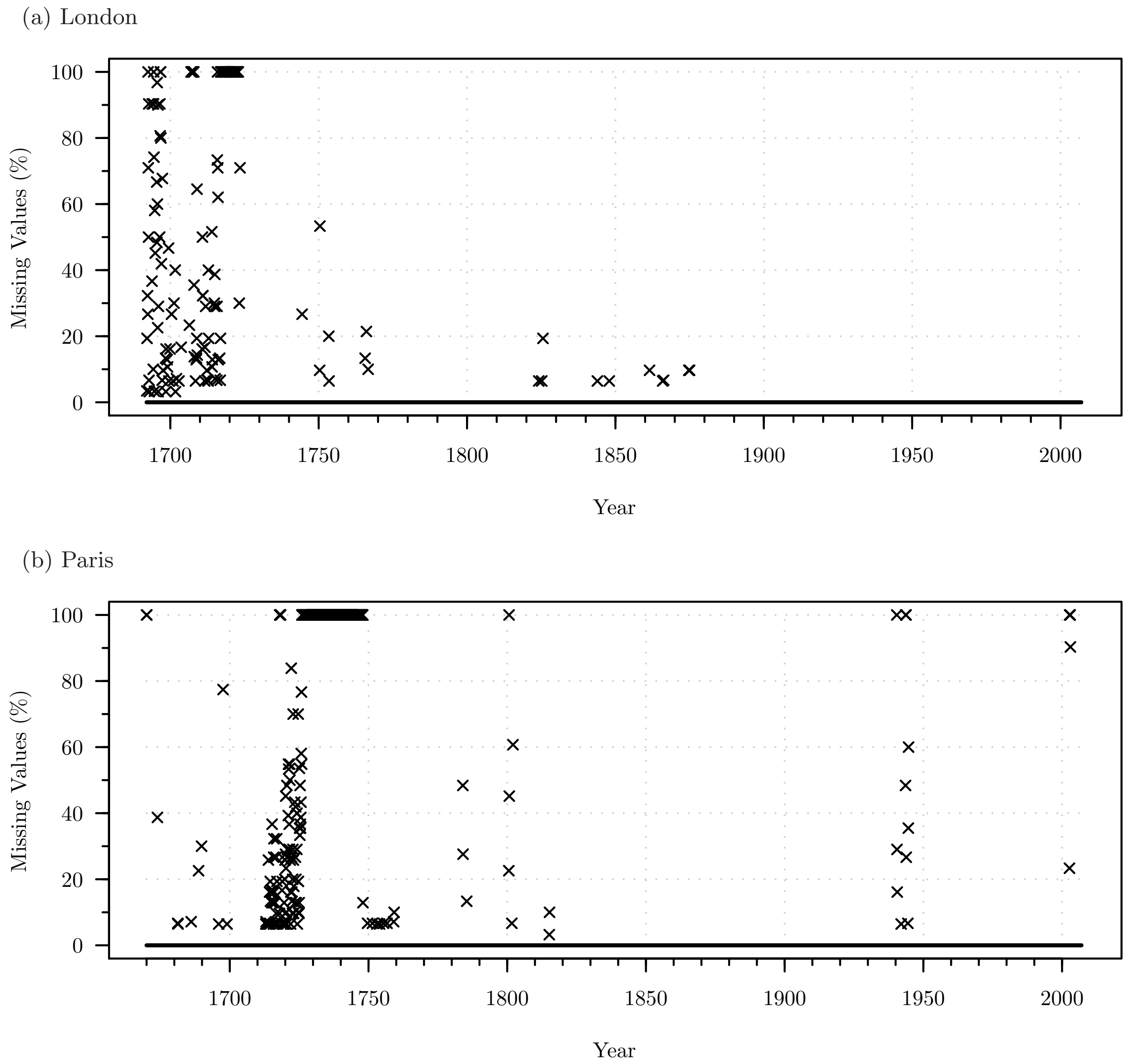

Figure 4.4: The number of missing values per month (N_{miss}) in the completed London and Paris daily pressure series, expressed as percentages. Each cross marks one month and only months where $N_{miss} > 0$ are shown.

these two years. Missing values during the year 1826 were completed from the meteorological register of the instrument-maker William Cary, who recorded his observations in premises on the Strand and published them in the *Gentleman's magazine*.[4] These observations appear to have been much more accurate than Hoy's and were in close agreement to the Royal Society's observations, with $r^2 = 0.96$ at $\alpha < 0.001$. Remaining missing values of not greater than one-day's duration were completed by the linear interpolation of adjacent values; in this way 841 (0.7%) days were filled.

To complete missing values in the Paris series over the period 1958–2007, daily mean values recorded at the Montsouris station were regressed against the homogenized Paris series. The regression model had $r^2 = 0.9978$ at $\alpha < 0.001$ and was used to complete 42 values over this time period. Remaining missing values (13) were completed using data from the Trappes station over the 1953–2007 period ($r^2 = 0.995$ at $\alpha < 0.001$). The period from 18 September 1944 to

[4]These data were corrected for temperature and altitude using the concurrent temperature readings from the *Gentleman's Magazine*, and were adjusted to standard gravity, and to an equivalent 24-hour mean following the methods described in Section 2.3.

28 February 1945 was also completed using the Trappes data, which had been reduced to the equivalent daily mean value. Remaining missing days of not more than one day's length were filled using linear interpolation; 474 (0.4%) values were completed in this way.

The number of missing values remaining in the completed London and Paris series are shown in Figure 4.4. An apparent disparity exists between the missing values in the daily series and the complete monthly London and Paris series developed during the (ADVICE, 1998) project. It would be expected that if the monthly series exist then the daily data must have been recorded. Every effort was made to locate the daily series in public archives and libraries, but none were located. It seems likely that the monthly series were either infilled from neighbouring stations across Europe or the daily data have been lost.

4.8 Chapter summary

A variety of statistical techniques exist for the assessment of inhomogeneities in climate data series. The PMT and PMF tests were chosen to identify statistically significant breakpoints in the London and Paris daily pressure series as they have been shown both theoretically and in practice to have several advantages over other tests. These tests were applied to the monthly and annual means of the daily London and Paris data by using the RH-test version 2 software (Wang & Feng, 2007). The data were corrected to the most modern segment, given that these are likely to be the most accurate; this also facilitates the update of the series to present-day.

Most of the breakpoints identified in the London series could be linked to the known disruptions documented in Chapter 2. The common problem of attributing detected changepoints to either the candidate series or the reference series was evident in the homogenization of the London series. It was discovered that inhomogeneities may exist in the Basel and Edinburgh series constructed by the ADVICE (1998) project. Further work is required to assess the magnitude of these potential inhomogeneities. Pairwise comparisons, such as the technique demonstrated by Menne & Williams (2009), would be useful in this respect.

In the case of the Paris series, rather more unknown (Type-1) breakpoints have been identified and corrected. This is partly a reflection of a lack of metadata compared to London. Drift was corrected in two of the component pressure series, and this needed to be done before the application of the PMT/PMF tests to eliminate the incorporation of spurious breakpoints.

The overall means of both the London and Paris pressure series are approximately 1hPa lower than the series developed by the ADVICE (1998) project. These new values appear to be more in-keeping with generally held conditions at these two locations (Hsu & Wallace, 1976). In the case of the London series this resolves a problem that has been identified by Woodworth (2006). Further testing is carried-out in the following chapter on the homogenized pressure series.

Chapter 5

Daily Barometric Pressure Statistics

5.1 Introduction

The main aim of this chapter is to assess the success of the homogenization of the London and Paris daily pressure series. This is achieved by subjecting the data to several simple statistical tests and cross-comparing the results from the two series. This comparison of results is valid given that the two series were kept separate during the homogenization of the data.

The first section in this chapter (§5.2) provides an overview of the London and Paris pressure series by examining various measures of central tendency and variance of the data. The overview also includes a list of the ten highest and lowest readings in the two series. This list provides information about the storm climatology of the North Atlantic-Western European (NA-WE) region over the last 300 years, and the newly recovered data for the late seventeenth/early eighteenth centuries begins to fill certain gaps in the storm record for the region. The chapter continues (§5.3) with a comparison between the monthly means of the daily London/Paris series with the London/Paris monthly pressure series that were developed as part of the ADVICE (1998) project. Section 5.4 analyses the correlation between the London and Paris pressure data, and running correlations provide information about the change in this relationship over time. Time series of the annual and seasonal means/standard deviations of pressure at the two sites are analysed in Section 5.5, and a lack of long-term trends in the series is discussed with reference to the homogenization techniques used to correct the data. The final section of the chapter (§5.6) examines the seasonal cycle of barometric pressure at London and Paris. As part of that analysis, the data are screened for the presence of meteorological singularities.

As may be ascertained from this chapter overview, the results presented in this chapter go beyond simply providing an assessment of the success of the homogenization scheme and provide some interesting information in their own right. This chapter therefore forms a bridge between parts I (Data Series Development) and II (Data Series Analysis) of this thesis. Over recent years, several studies have presented long daily pressure series for various sites throughout Europe. The research project entitled 'Improved Understanding of past climatic variability from early daily European instrumental sources (IMPROVE)' in particular provided many of these series, which have allowed more information to be gathered about atmospheric circulation variability over the last 300 years (Camuffo & Jones, 2002). The daily barometric pressure statistics presented in this chapter are similar to the statistics presented by the reports from the IMPROVE project, but provide information for two sites where long daily pressure series have hitherto been lacking.

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	S	Skew	n
Overall series									
London	953.7	1008.8	1016	1015.2	1022.4	1048.6	10.5	-0.5	111758
Paris	962.1	1011.1	1017	1016.5	1022.6	1050.4	9.2	-0.4	114007
Winter (DJF)									
London	953.7	1006.2	1016.3	1015.2	1025.1	1048.6	13.3	-0.4	27586
Paris	962.1	1009.7	1018.7	1017.5	1026.3	1050.4	11.8	-0.4	28117
Spring (MAM)									
London	966.2	1008.4	1015.7	1015.0	1022.3	1047.5	10.1	-0.4	28320
Paris	965.7	1009.9	1015.8	1015.4	1021.6	1044.0	8.8	-0.3	28765
Summer (JJA)									
London	983.4	1011.3	1016.4	1015.8	1020.8	1038.5	7.0	-0.4	28070
Paris	990.2	1013.1	1017.1	1016.8	1021.0	1039.9	5.7	-0.3	28819
Autumn (SON)									
London	963.5	1007.9	1015.8	1014.7	1022.6	1044.0	10.8	-0.5	27782
Paris	966.2	1010.9	1017.3	1016.4	1023.0	1044.0	9.2	-0.5	28306

Table 5.1: Seven measures of central tendency and dispersion from the London and Paris daily pressure series. 1st Qu. and 3rd Qu. refer to the upper and lower quartiles, S to the standard deviation and Skew to the skewness. The data for London are from the period 1692–2007 and Paris 1670–2007.

5.2 Data overview

5.2.1 Measures of central tendency and variance

Table 5.1 lists measures of central tendency and dispersion of the London and Paris daily pressure series. The overall mean of the London series is 1.3hPa lower compared to Paris, although the difference varies seasonally with the largest differences apparent during the winter and the smallest during the summer. The range of pressures as quantified by the standard deviation is higher in London than Paris, but as with the mean the difference in standard deviations between the two sites is greater in the winter compared to the summer.[1] In terms of extremes of pressure, the lowest pressure readings occur in London with the highest in Paris. For both London and Paris both the lowest and highest pressures occurred during the winter. The histograms shown in Figure 5.1 present a visual perspective of these statistics, and highlight in particular the slightly positive skew of the data; this is confirmed by the QQ-plots.

5.2.2 Extremes of pressure

In Table 5.2, the ten highest and lowest daily values in the London and Paris pressure series are listed. Assuming that erroneous values have been excluded from the data, and the barometer measurements are a true reflection of atmospheric pressure, then the ten lowest pressures in the table should indicate the storms with the deepest central pressure that have passed over southern England/northern France during the last 300 years.[2]

The lowest daily pressure reading in both the London and Paris series occurred on 19 December 1724. There is no mention of this event in the storm chronologies for northwest Europe

[1] According to Knowles Middleton (1964) this was noted as early as the 1760s by scientists and instrument-makers in western Europe, and had implications for the design of barometers with expanded scales.

[2] The very low pressure values for which there is no correlative in the alternate series have been checked for accuracy. This revealed that in all cases low pressure was also recorded at the other location, but the value was not low enough to be entered into the list. This was also the case for the ten highest pressures.

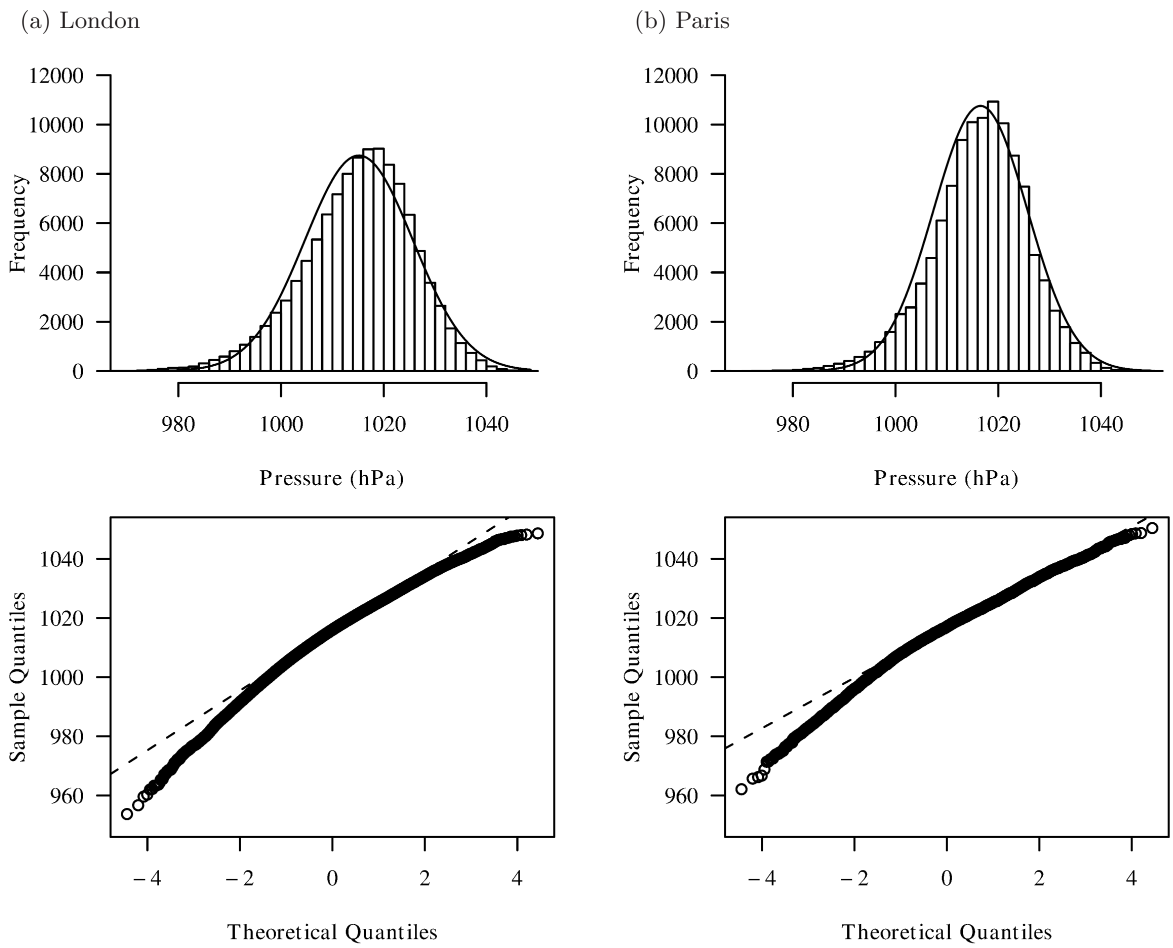

Figure 5.1: Histograms and QQ-plots of the London and Paris daily pressure data. The reference lines in the histograms show the normal curve. The data for London are from the period 1692–2007 and Paris 1670–2007.

London			Paris		
1	18-01-1882	1048.6	1	06-02-1821	1050.4
2	09-01-1825	1048.2	2	17-01-1882	1048.7
3	17-01-1882	1048.0	3	29-01-1905	1048.6
4	26-01-1932	1047.9	4	18-01-1882	1048.4
5	29-01-1905	1047.6	5	07-02-1821	1048.0
6=	06-03-1852	1047.5	6	27-01-1905	1047.7
6=	10-01-1825	1047.5	7=	28-01-1905	1047.1
8	28-01-1905	1047.2	7=	30-01-1896	1047.1
9	26-12-1778	1047.1	7=	16-01-1882	1047.1
10	06-02-1821	1047.0	10	15-02-1686*	1046.7
10	26-02-1989	963.7	10	25-12-1821	972.5
9	05-11-1706	963.5	9	22-11-1768	972.4
8=	04-12-1876	963.3	8	14-03-1681	972.2
8=	25-12-1821	963.3	7	20-01-1791	971.5
6	26-12-1734	962.2	6	02-02-1823	971.4
5	20-01-1791	962.0	5	26-02-1989	966.7
4	15-02-1702	960.3	4	25-02-1989	966.7
3	25-02-1989	959.6	3	18-11-1916	966.2
2	30-01-1724	956.7	2	30-03-1762	965.7
1	19-12-1724	953.7	1	19-12-1724	962.1

Table 5.2: The ten highest and lowest pressures in the London and Paris daily pressure series. The data for London are from the period 1692–2007 and Paris 1670–2007. * This value was also recorded on 13 and 14 February 1686.

published in Short (1767), Brazell (1968) or Lamb (1991). However, contemporary evidence for this event is provided in the *British Journal* published during December 1724 by an observer from Portsmouth who commented on the exceptionally low barometer readings that were recorded in southern England during the period:

> "On Tuesday morning last [19 December 1724 NS] the quicksilver was lower in all the barometers here than had ever been observed by our most ancient Vertuosi[sic], even almost five tenths lower than in the great November storm in 1703; and yet during the whole time of its sinking, which was from Monday afternoon, between three or four of the clock, to six the next morning, (in which space it fell an inch and five tenths) we had no wind so considerable, as to do any remarkable damage. Its greatest violence was from six to seven of the clock on Monday night, when there fell a great quantity of rain, and the wind (as far as i could perceive) was south east".[3]

Maraldi (1725), in his annual summary of meteorological observations recorded at the Paris Observatory, also commented on the low pressure during 19 December 1724, and noted that it was the lowest pressure value that had been recorded in the Paris Observatory's registers since their commencement in 1696. Maraldi records that this low reading was preceded on the 18 December by a strong southerly wind, and that the conditions lasted for two days, during which high rainfall was experienced. The London daily Mean Sea-Level Pressure (MSLP) data indicate that the pressure started to drop on 13 December and remained low until 23 December. A similar sequence is apparent in the Paris series.

The low-pressure event of 18–19 December 1724 occurred during a year that experienced several very deep low pressure systems. The second lowest recorded pressure in the London series occurred in January of that year; unfortunately, the pressure reading for that day in Paris is missing. Lamb (1991) suspected that there was a severe storm that occurred in 1725, although he was uncertain about the exact date and the data were too few to permit a synoptic reconstruction. It seems unlikely that either of the two events described so far in 1724 are Lamb's 'missing storm' due to the apparent limited destruction caused. However, Maraldi (1725) mentions a storm that created great damage in Cadiz on 19 *November* 1724 NS. The *British Journal* in the days and weeks following the event reported the huge damage caused to ships in the area, and the loss of many sailors. It seems likely therefore that Lamb's 'missing storm' of 1725 was in fact the Cadiz storm of 19 November 1724.

Information on another storm documented by Lamb (1991) can be provided by the London and Paris daily pressure series. Lamb suspected that a severe storm (classified as fifth severest in his Storm Severity Index) swept through the British Isles in late October/early November 1694. In the London series the pressure on 30 October 1694 dropped to 997.8hPa but recovered quickly to 1027.2hPa the following day. In the Paris series, values of 987.0hPa and 989.7hPa are evident for the 30/31 October. Locke, in his London weather diary, recorded that a great quantity of rain fell on 30 October New Style (Gregorian) calendar (NS), which turned to snow on the 31st; he also recorded the wind as force 3, which was the highest value on his scale. This storm was responsible for the Culbin sands disaster in northeast Scotland and both the London

[3]British Journal, Saturday December 19, 1724 (OS); issue CXVIII, p3. The publication date is 29 December in the New Style (Gregorian) calendar (NS).

and Paris data pinpoint the date to the 30 October (see also the comments in Camuffo *et al.*, 2010). It should also be noted that storms appear to have plagued the latter half of the month of November, with values below 1000hPa recorded in both the London and Paris series for most days between 14 and 26 November 1694.

The information quoted from the *British Journal* above raises an important feature of the London and Paris MSLP in connection with the Great Storm of 1703. The observer from Portsmouth records that the low pressure reading of 19 December 1724 NS was "almost five tenths [of an inch] lower than in the great November storm in 1703". The 1703 storm has become a benchmark for the assessment of storm severity in the British Isles (Wheeler, 2003; Golinski, 2007; Pfister *et al.*, 2010), although interestingly the event does not appear in the lowest ten pressures in either the London and Paris series. In London the value for 8 December 1703 is 982.6hPa, and for Paris 1013.7hPa, and therefore the readings fail to enter the list of ten lowest pressures in Table 5.2. Part of this may be explained by the timing of the observations, which for London were recorded during mid-morning: the lowest pressures for the 1703 storm occurred during the night of the 7th December NS, and reached a maximum shortly after 12am on the 8th (Lamb, 1991), whereas the 1724 event appears to have occurred early in the morning. Probably of greater importance is the trajectory of the storm, which for the 1703 event was approximately 200km to the north of London (Lamb, 1991; Pfister *et al.*, 2010): the 1724 storm is likely to have passed over the English Channel and therefore influenced the barometers in southern England to a greater degree. This also highlights the important differentiation between low pressure values and wind storms. While these are inextricably linked, the pressure gradient is a better measure of a wind storm than the absolute pressure value.

In contrast to the prevalence of extremely low pressure values in the early eighteenth century, most of the highest ten pressures in both the London and Paris series occurred after the mid-nineteenth century. The high-pressure events of 16–18 January 1882 relate to an anticyclone that was centred over central Europe on 14 January but which subsequently moved westwards, and became situated over southern England on the morning of 18 January (Burt, 2007). The only pressure value to enter the table for the seventeenth century was recorded on 13–15 February 1686. Indeed the pressure for most of the period January to March of that year remained above 1020hPa. These results must be viewed with caution, however, as the mean of the Paris pressure series in the winter during this early period appear too high (see §5.5) which would give exaggerated results. Nonetheless the apparent anticyclonic conditions indicated in the data relate well to the note by Short (1767, p. 86) that a 'severe winter, [and] droughty spring' occurred across Europe.

Despite the apparently consistent results presented in Table 5.2, the examination of extremes in the London and Paris MSLP series is complicated by the changing observations times of the barometer readings used to complete the series. As described in chapters 2 and 3, both pressure series before the mid-nineteenth century were completed using one or two barometer readings per day; after that time an increasing number of observations were used, up to 24 hourly observations per day. Corrections were applied to the data to reduce the observations to the equivalent of a 24-hourly mean value and while this correction reduced the error in weekly or monthly means of pressure, the individual daily data are inconsistent in detecting the passage of storms. Therefore while it would appear that most of the deepest cyclones to pass over southern England/northern

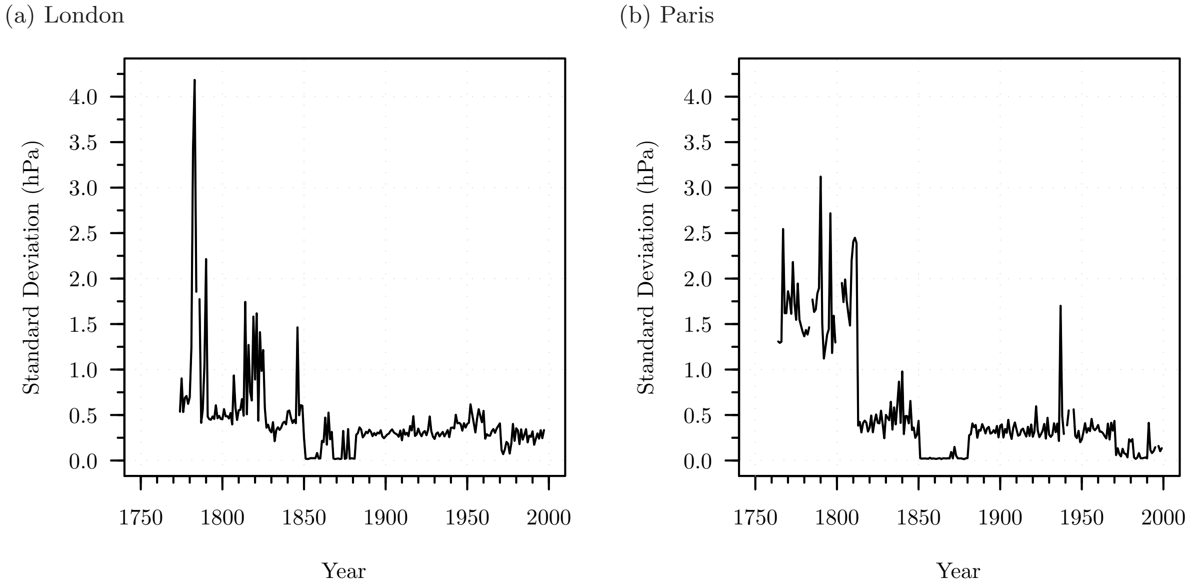

Figure 5.2: Annual standard deviations of the differences between the ADVICE series for London (1774–2000) and Paris (1764–2000) and the new series for these cities.

France over the last 300 years did so during the seventeenth and eighteenth centuries, and the highest pressures occurred after the nineteenth century, definite conclusions cannot be reached. This feature of the data is examined further in Chapter 8 (§8.3.1).

5.3 A comparison with the ADVICE pressure series

As part of the ADVICE (1998) project, monthly pressure series were corrected and homogenized for many sites across Europe, including London and Paris. The series for these two sites were essentially the same data that had been digitized by Jones *et al.* (1987), although the data were subjected to more rigorous homogenization testing. As has been recognized in the previous chapter (§§4.5.1 and 4.6.1), the major difference between the ADVICE London/Paris series and the new series is that the overall mean of the latter are approximately 1hPa lower than the former. This section of the chapter investigates the differences between the series in more detail.

The standard deviations of the differences between the monthly series for each year are plotted in Figure 5.2. For both London and Paris the largest differences occur during the eighteenth century. In the case of London, the standard deviation peaks in 1782 and 1790, which is attributable to a lack of data from London in the ADVICE series. To complete these missing years, the average of the Paris and Edinburgh series were used, and while on multidecadal timescales the mean pressure difference between these two sites would approximate that of London, on monthly timescales large errors appear to have been introduced. Given this information, the London daily series during the 1780s is an improvement over the ADVICE series. An increase in the range of differences is also apparent for the London series during the 1810–20s, but during the 1850–80 period the values drop to zero for several years. This latter difference is due to the monthly means of the EMULATE series (which was used to complete the London daily series over the period) being adjusted to the mean of the ADVICE series (Ansell, 2004). Throughout most of the twentieth century the standard deviation of the differences does not exceed 0.5hPa.

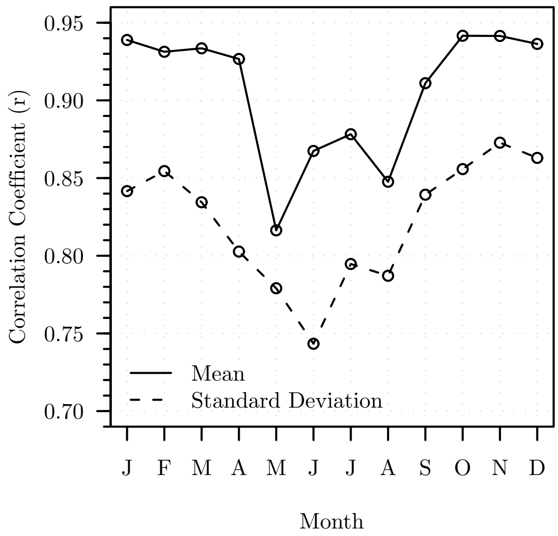

Figure 5.3: Monthly correlations between the monthly means and standard deviations of the London and Paris pressure series for the period 1692–2007.

In the case of the Paris series (Figure 5.2b) an interesting result is evident during the early 1800s. The standard deviations are high until 1810, after which the values suddenly drop. This would appear to correspond to corrections applied to the ADVICE Paris series. As with the comparison for the London series above, the range of differences during the EMULATE period (1850–80) is very small (and is mostly zero) given the adjustments made to the data to have the same mean as the ADVICE series. During 1938 a spike of values is evident, which has an unknown cause but is probably related to a short-term inhomogeneity in either series during World War II. A step is apparent in the difference series in 1970, which probably relates to the problem with the Basel and Edinburgh ADVICE series identified in Section 4.5.1.

5.4 Correlation between the London and Paris series

The proximity of London and Paris, combined with the low spatial variability of barometric pressure (Mitchell *et al.*, 1966), would lead to the expectation that the London and Paris daily pressure series are highly correlated.[4] This is indeed the case with $r = 0.90$ (significant at the 99% level) for the daily series over the common 1692–2007 period. However, the correlation between pressure at the two locations varies seasonally, as demonstrated in Figure 5.3. High positive correlations are achieved between the monthly means of pressure for the months of October to April, during which values greater than 0.92 are found. In May the value drops to 0.81 but remains at a value of between 0.85 and 0.88 during the summer months. A similar seasonal cycle of correlations is evident for the monthly standard deviation values, although the correlation coefficients are consistently lower than for the monthly mean values.

The change in correlation over time between the London and Paris series is assessed in Figures 5.4 and 5.5 using 31-year centred running correlations. A clear contrast is evident between the results in the months from October to April compared to those in the months from

[4]This was noted as early as 1699 by Maraldi (Académie Royale des Sciences, 1699) in his comparison of pressure observations from London and Paris (see the opening quote to Chapter 1).

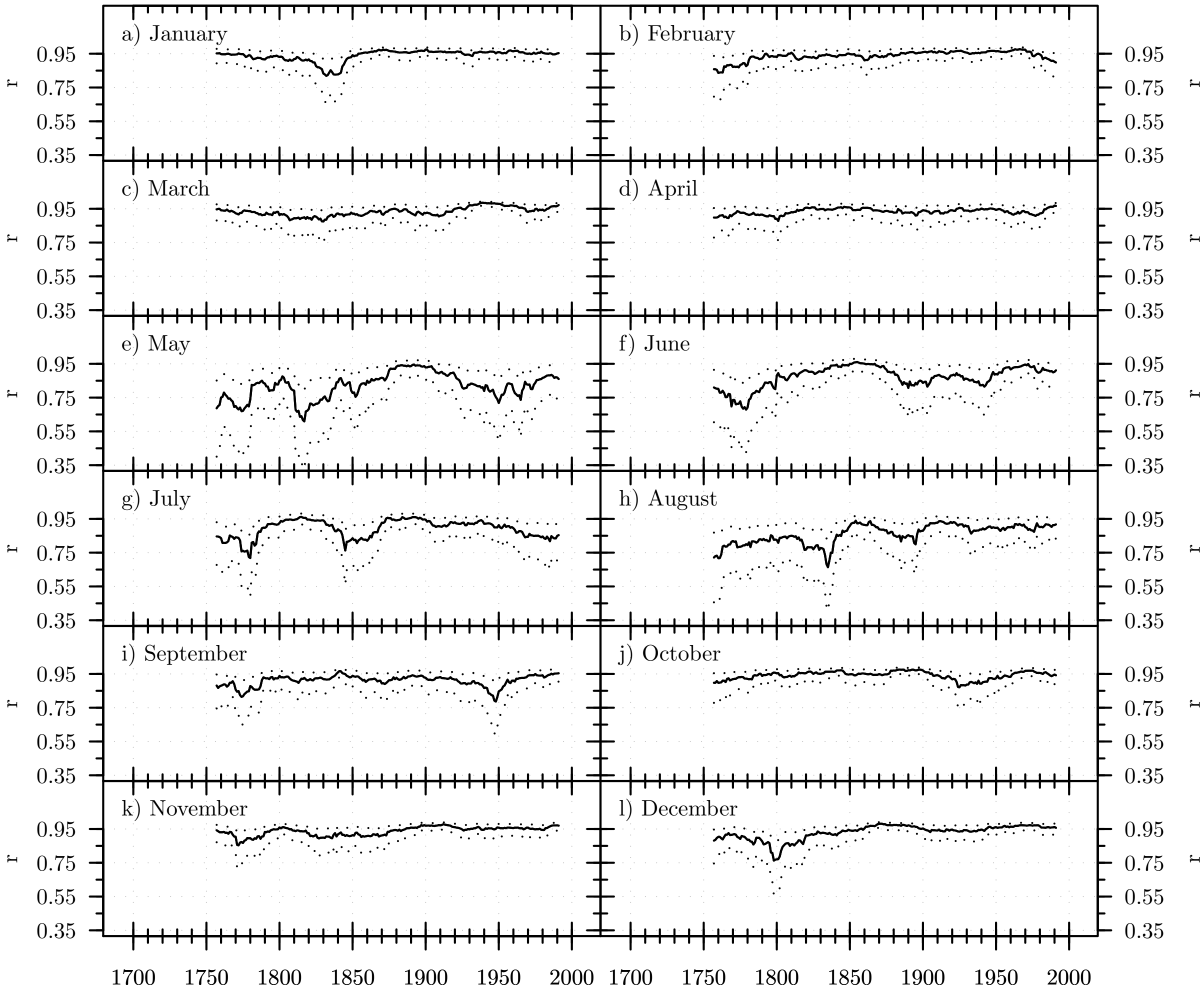

Figure 5.4: Running correlations between the monthly means of the London and Paris daily pressure series. The correlations are calculated from 31-year centred segments. A lack of data before 1748 precludes the calculation of means for that period. The dotted lines represent the 95% confidence levels of the correlations.

May to September. In the months from October to April the correlations between the monthly mean values at the two sites are quite consistent over time, with correlation coefficients usually greater than 0.85, and for a large part of the 250-year period greater than 0.90. During the months of May to September there is greater variability over time in the correlations, although the values remain higher than 0.65. Similar results are also evident in the running correlations of the monthly standard deviation, although the values of the correlation tend to be lower. There is little consensus in the variability of the running correlations during the summer months, and therefore the apparent time varying correlations probably do not indicate any changing relationship between pressure at the two sites. As is explained at length in Section 6.5.2, variability in running correlations is an inherent feature of running correlation analyses on account of the use of several small sample sizes. However, as the variability occurs most clearly during all of the months from May to September, this would appear to be a real feature of the data. Further, the temporal variations occur in the most recent data as well as those further back in time, which would indicate that the variations are not caused by lower quality early observations.

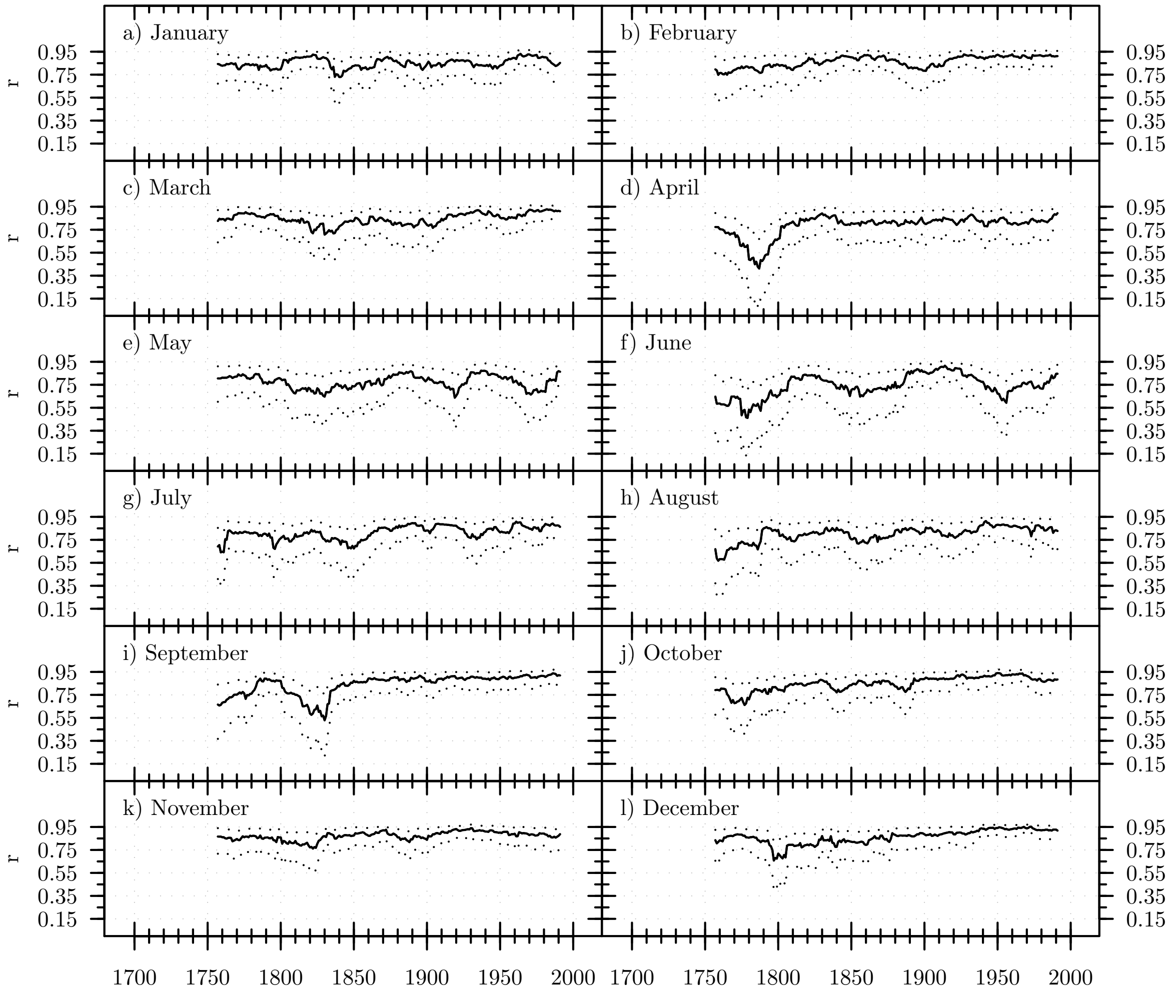

Figure 5.5: As for Figure 5.4 but for standard deviations. Note the different scale used on the y-axis compared to Figure 5.4.

5.5 Time series analysis

Time series plots of the annual and seasonal means derived from the London and Paris daily pressure series are shown in Figure 5.6. Given the high positive correlations between the two series at the monthly resolution (§5.4) it is not surprising that the inter-annual variability of the annual and seasonal means is very similar at the two sites. In addition, the decadal-scale variations appear very similar.

A feature that is clearly defined in these time series plots is the high values in the Paris series during winter in the period 1670–90 and the low values during summer in the same period. Wheeler *et al.* (2009) have indicated that western European winters in the period 1685–92 experienced a prevalence of anticyclonic conditions with frequent incursions of polar continental air. However, the fact that the changes only occur during the winter and summer seasons and that the series shows step-like breakpoints may indicate that the temperature corrections applied to the pressure data may be at fault. Fixed temperature corrections were applied to the Morin data over this period depending on the month (see §3.3.1). During the spring and autumn seasons the corrections seem adequate, but during winter and summer improvements may be needed. As demonstrated by Camuffo *et al.* (2010), improvements can be made to the data through the

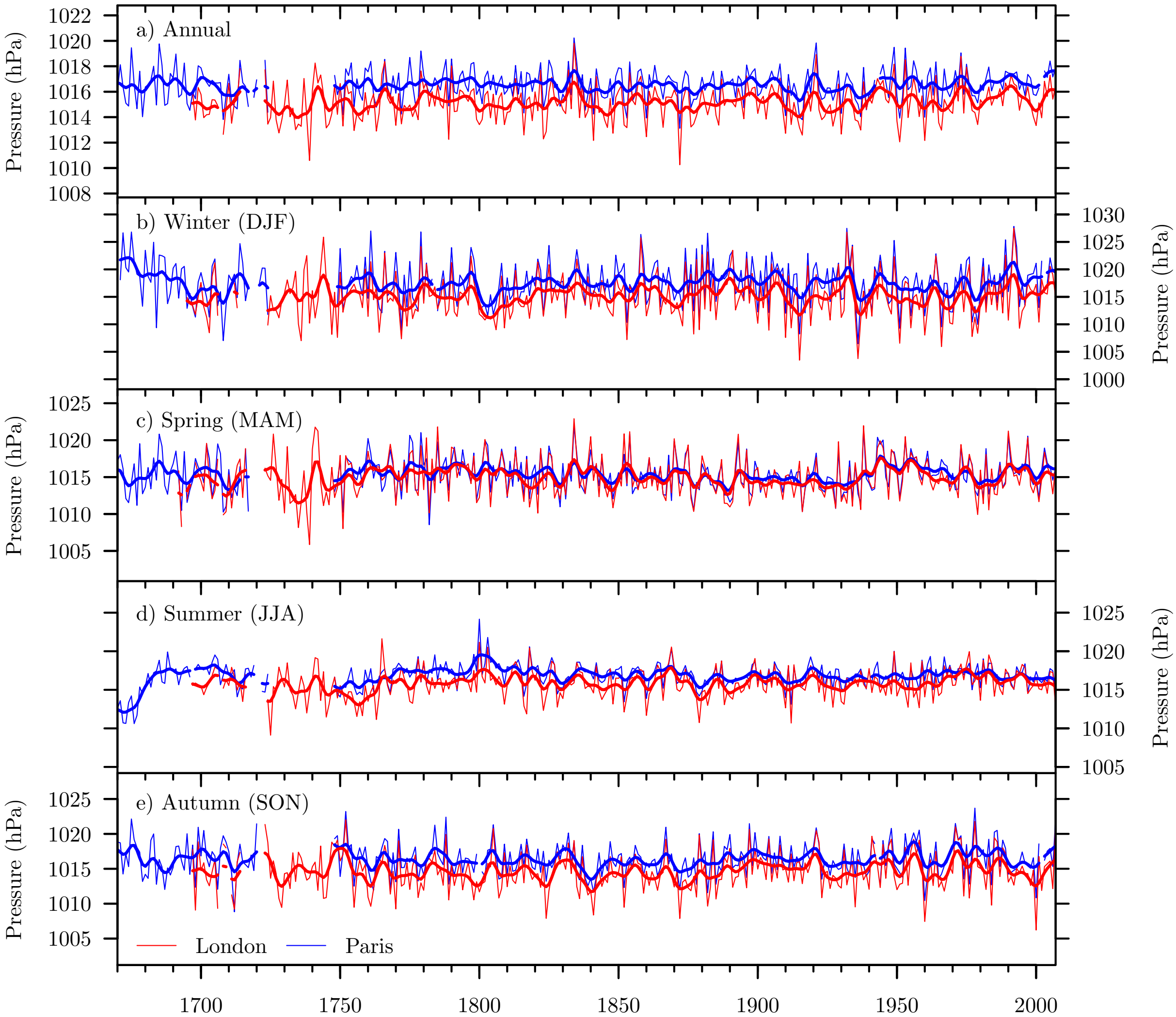

Figure 5.6: Annual and seasonal mean time series calculated from the London and Paris daily pressure series. The period was marked as missing when the number of missing values in a year or season exceeded 20%. The thick lines represent 10-year Gaussian filtered values. Note that different scales used on the five plots.

use of Morin's contemporary temperature readings. If this feature of the Paris data is due to inadequate temperature corrections, then the homogenization test would not have been able to detect the breakpoints because the monthly means of the data were arranged sequentially (see §4.5). When used for pressure data that have reliable temperature corrections applied, the arrangement of the data sequentially is preferred and the accuracy of the test is improved by the resulting increased sample size. However, when used for data that require seasonally varying homogenization corrections, the data are best tested on a seasonal basis, although this requires smoothing of the corrections to prevent the introduction of additional breakpoints. The earliest Paris data would therefore benefit from further homogenization testing and corrections. It would seem likely that certain seasonally dependent inhomogeneities reside in the data, but that these data are also indicating a real climatic effect. A comparison with Wheeler *et al.*'s 2009 independent data would provide useful information in this respect.

Certain short-term variations are evident in Figure 5.6 that are worthy of further comment. A dip in MSLP during the winter can be observed during the 1930s. In addition, in approximately

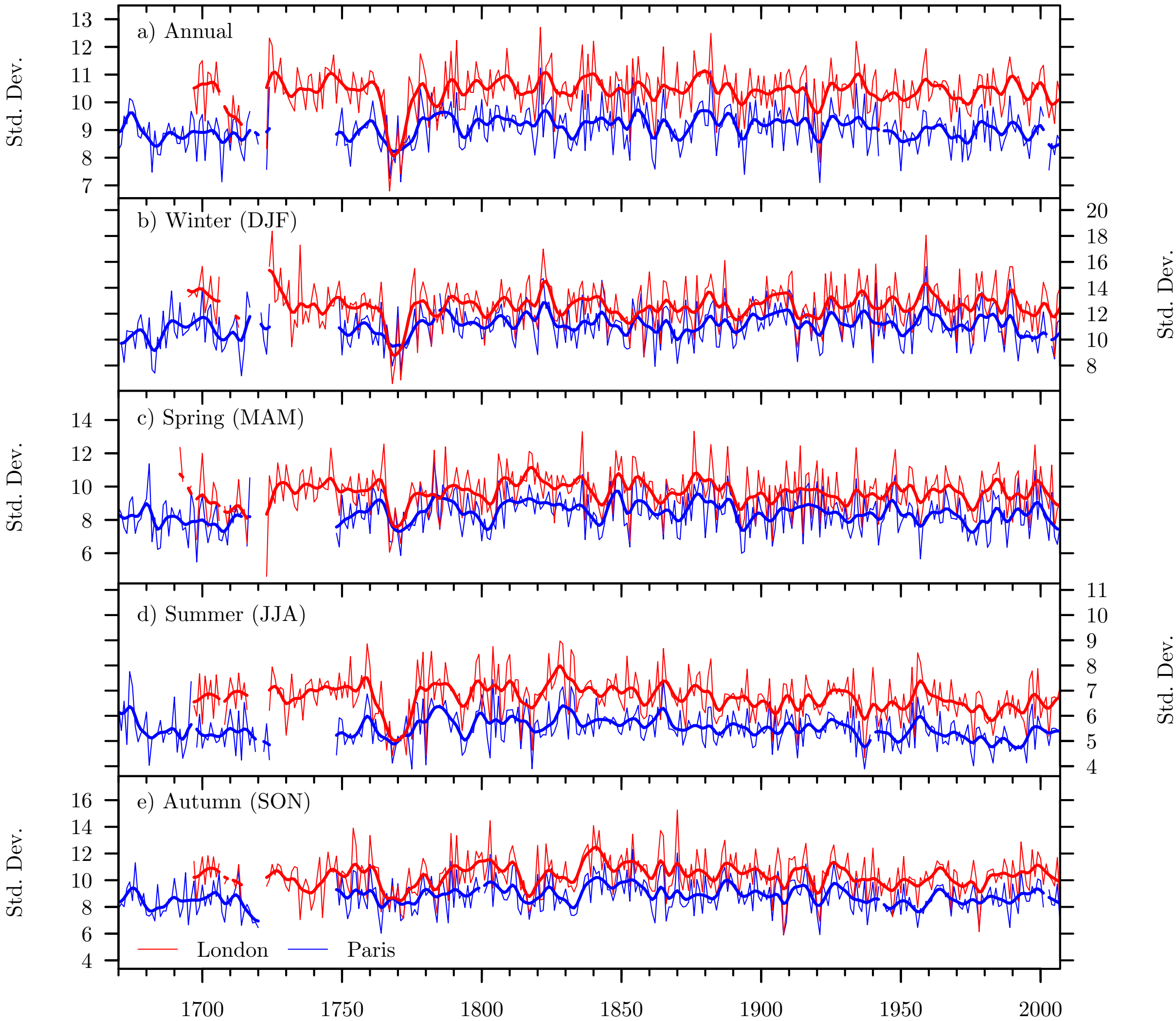

Figure 5.7: As Figure 5.6 but for the annual/seasonal standard deviations.

1945 during the spring season a sudden increase in MSLP at both London and Paris can be observed, which gradually declines to 1970; thereafter the values are comparable to the long-term mean. This would appear to be a real feature of the atmospheric circulation and not a data inhomogeneity given that it does not appear in any of the other seasons. This feature also appears in the pressure series for Milan constructed by Maugeri *et al.* (2002).

Excluding the earliest data from Paris, no long-term trends are apparent in either the London or Paris series. As has been described in the previous chapter (§4.3), the Penalized Maximal t (PMT) test—which was used to homogenize the data for the period 1780–2007—requires there to be zero trend in the data. The reference series were chosen to be from the same climatological region so as to satisfy this requirement. Given that no trend is evident in the London or Paris data over the 1780–2007 period, indicates that MSLP in northwest Europe does not display any long-term trend. This was also the conclusion reached by Slonosky *et al.* (1999). Further proof for this assertion comes from the Paris/London data for the 1692–1779 period, which were homogenized using the Penalized Maximal F (PMF) test. This test allows a trend to be present in the data, and the corrections take this feature, if any, into account. However, even over the

1692–1779 period no long-term trend is evident in the times series.

Time series of the annual and seasonal values of the standard deviation of MSLP at London and Paris are shown in Figure 5.7. As with the seasonal/annual mean values there appears to be no long-term trend in the standard deviation. In addition, the early Morin data for Paris appear to be comparable with the long-term mean, which suggests that the seasonally dependent inhomogeneities that reside in the data only affect the mean level.

A striking feature of the time series plots of standard deviations for London is the exceptionally low values for all seasons in the period 1765–70. The barometer observations for that period were recorded by an anonymous observer who published in the Gentleman's magazine (see §2). The values, which were extracted from Manley's *London Weather Diary (LWD)*, were only available rounded to the nearest whole hPa. However, this rounding would be unlikely to cause the large reduction in standard deviations indicated. As proof, the difference in standard deviation between the London data for the period 1961–90 rounded to whole units and the more usual 0.1hPa is a negligible 1×10^{-3}. This indicates that the reduced variance is probably due to the poor condition of the barometer. Manley (1960) suspected that the barometer was a poorly kept wheel instrument, which was liable to stick; the results shown here support his assertion.

Additional seasonal/annual time series plots for several statistical parameters are provided in appendix B, and serve to support the comments already made in this section.

5.6 The annual cycle of pressure and singularities

5.6.1 The annual cycle

Atmospheric pressure is known to exhibit an annual cycle (Hsu & Wallace, 1976). The cause of this cycle is primarily the change of solar insolation throughout the year, although atmospheric pressure is subjected to a range of complex mechanisms that divorce the cycle from this control (Rezníčková *et al.*, 2007). The annual cycle of MSLP at London has previously been studied by Chandler (1965) and at Paris by Angot (1910). The results from those two studies indicated that the magnitude of the annual cycle at both sites is small, although the variance was shown to be much higher during the winter months compared to the summer. However, the results from both studies were limited by the consideration of only monthly statistics, short records (less than 50 years) and rudimentary assessments of data homogeneity.

Research that was carried out during the 1970s attempted to identify spatial patterns in the annual cycle of MSLP across the globe by extracting the annual and semi-annual cycles from the data using harmonic analysis (Hsu & Wallace, 1976). The results presented by Hsu & Wallace supported the findings of much earlier work by Hann & Süring (1939), which indicated that the annual cycle of MSLP can be classified into three groups according to geographical location: a continental type for regions where MSLP reaches a maximum in the winter and a minimum in summer; a maritime type where MSLP is at a maximum in summer and minimum in late autumn; and an Arctic/sub-Arctic type, which is typified by a maximum in April or May, a secondary maximum in November, and a minimum in January and February. The results from Hsu & Wallace (1976) show that the annual cycle of MSLP in the vicinity of London and Paris is less than 0.5hPa, and no information about the phase of the cycle was provided in the study due to this small value. The amplitude of the semi-annual cycle at London and Paris was also

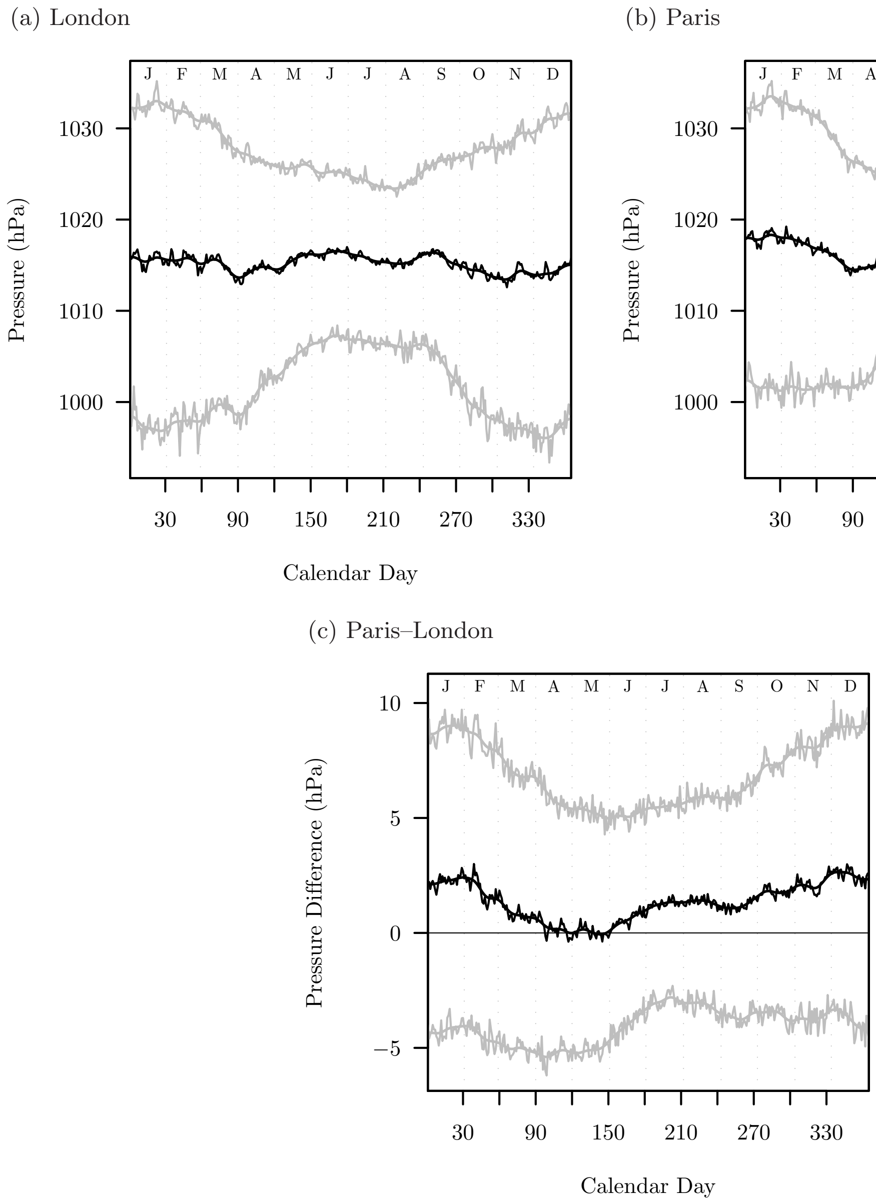

Figure 5.8: Means of pressure for each day of the calendar year for the London (1692–2007), Paris (1670–2007) and Paris–London (1692–2007) series. The upper and lower grey lines show the 90th and 10th percentiles respectively. The smoothed lines show the data smoothed using a 30-day Gaussian filter.

small (0.2hPa), but showed maxima in approximately May and November. However, this study also failed to capture intra-month variability of MSLP throughout the year due to the use of monthly mean data.

Information about the intra-month variability of MSLP at mid-latitude stations in the northern hemisphere has been provided by several recently compiled long daily MSLP series. In the 250-year Uppsala series, a maximum of MSLP is evident in May and a minimum in July (Bergström & Moberg, 2002), which corresponds well to the results of Hsu & Wallace (1976). In addition, increased variability was evident in the data during the winter months, which is attributable to increased storm activity during that period of the year. Information for more northerly latitudes has been provided by Jónsson & Miles (2001), who showed that daily MSLP at Reykjavik displays an annual cycle that obeys the Arctic/sub-Arctic classification of Hann & Süring (1939), with a minimum in winter, a maximum in late spring and a second maximum in late autumn.

A different perspective on the annual cycle of MSLP in Europe has been provided by Yan *et al.* (2001) through the development of two westerly indices at the daily resolution by using several long MSLP series from mainland Europe. They noted that in comparison to temperature, the annual cycle of the westerly indices shows greater intra-month variability on account of the incorporation of atmospheric disturbances at synoptic timescales. Taking the smoothed cycle of the westerly indices, a maximum of westerly conditions was apparent during the winter months, dropping to a minimum during late spring.

The seasonal values of MSLP at London and Paris shown earlier in Table 5.1 provide a broad indication of the annual cycle in pressure at the two sites. The mean of MSLP at both sites is high in the winter and summer and low during the autumn and spring; the variability is highest in the winter and lowest in the summer. The means for each day of the year (Figures 5.8a and 5.8b) provide additional information about the annual cycle of MSLP through the capture of sub-monthly variations. These figures show that MSLP in London shows a significant drop to a minimum value at the beginning of April and a recovery to a peak in June/July. Following a drop in later summer, a second peak occurs in early September and values decline slightly thereafter. The magnitude of the annual cycle at London (approximately 2hPa) is not large however and broadly confirms the results of Hsu & Wallace (1976). At Paris the annual cycle generally follows the pattern evident in London, but is more distinct with a magnitude of approximately 5hPa.

In correspondence to the results presented earlier in Table 5.1, the variance of MSLP at both London and Paris is highest in the winter due to increased cyclonic activity. The 10th percentiles of daily pressure at the two sites shown in Figures 5.8a and 5.8b indicate a sharp decline in the variance from the beginning of April to June, after which it plateaus. A similar quick drop-off is also apparent between the beginning of September to November. This provides an indication of the storm climatology of northwest Europe, which is at a maximum between the months of November and March.

Information about the annual cycle in westerliness is shown in Figure 5.8c by an index that has been calculated as the difference between the London and Paris data (Paris *minus* London). The principles of this index are discussed at length in the following chapter (§6.3), and it is sufficient here to state that the Paris–London index provides a measure of the intensity of westerly flow across western Europe. Positive values of the index indicate westerly flow and negative values indicate reduced-westerly or easterly flow. The annual cycle of the Paris–London westerly index shows a very similar pattern to that shown in the westerly indices constructed by Yan *et al.* (2001). A maximum in the westerlies is evident at the end of January, with a secondary maximum in early December. A marked decline in the westerlies is evident throughout the spring, reaching a minimum in late April.

Of equal interest to the general annual cycle of MSLP is the change in the annual cycle over time. Yan *et al.* (2001) employed wavelet analysis to analyse this subject in some detail. In a more simplistic manner, the change in annual cycle of MSLP at London and Paris is assessed here by comparing 31-year samples of the data. The main reason for this analysis is to assess the validity of the seasonally dependent corrections that were applied to the data. It can be observed from the results (Figures 5.9 and 5.10) that none of the 31-year sampled periods are substantially different from the values for the 1970–2000 period. To substantiate this conclusion,

Dates	Singularity	Circulation	% years	Period
19–25/1	January continental anticyclones	AC,S,E	50	IV
27/1–4/2	Renewed storminess, gales and rain or snow	C,E,NW	—	—
7–12/2	February anticylones	AC,S,E	50	IV
1–9/3	Early March cold period, sometimes stormy	N,NW,E	50	IV
17–19/3	Mid-March Anticyclones	E	20	I,II,III
31/3–3/4	Spring return of the Atlantic depressions	W	40	IV
12/4–20/5	The Spring northerlies	AC,N,E	70	IV
21/5–10/6	Early Summer Anticyclones	AC	40	I,II,III
1–30/6	Return of the Westerlies	W,NW	—	—
31/7–4/8	Thundery cyclonic weather	C	35	II
17/8–2/9	End of summer turning point	W,NW	70	IV
6–19/9	September anticyclones	AC	30–40	I,II,III
21–30/9	Late September Storminess	C	25–30	IV
5–7/10	Early October Anticyclones	AC	40	IV
24/10–13/11	Late Autumn rains	C	—	—
17–20/11	Mid-November Anticyclones	AC	30	I,II,III
3–11/12	Early winter storms and rain	W,NW	70	I,II,III
17–21/12	December continental anticyclones	AC	25	I,II,III
26/12–12/1	Storms of mid winter	W	60	IV

Table 5.3: A calendar of singularities for the British Isles, summarized from Lamb (1964). The circulation types relate to Lamb's weather type catalogue for the British Isles. The percentage of years column indicates the frequency of the particular weather types in the period indicated in the final column. Period I is 1873–97, II 1898–1937, III 1938–61 and IV 1890–1950 ±10 years approximately.

a t-test was performed for each day between the two samples and significant differences at the 95% level are indicated on the plots. While there are certain days in all series where there are significant differences, for any given sample there do not appear to be any systematic errors and the significant differences appear to be attributable to sampling errors.

5.6.2 Meteorological singularities: an overview

A concept that is closely related to the annual cycle of barometric pressure is that of meteorological singularities. Singularities describes the propensity of certain weather types to occur on certain days of the year and has a long history in the form of weather lore. As an example, Chaucer in his prologue to *The Canterbury Tales* opens with a reference to the drought of March giving way to the showers of April, in a manner that indicates that this feature of the annual cycle of weather was well known in Medieval farming lore (Daley, 1970). Scientific interest in the subject became abundant during the late nineteenth century, with many data series being scrutinized for evidence of singularities (Barry & Carleton, 2001). This interest was probably sparked by the increasing availability of systematic and accurate weather observations. One of the most enduring studies from this period was conducted by Buchan (1868) who identified nine cold/warm periods in data from Edinburgh; Mossman (1896) sought further evidence in his extended Edinburgh data series. It should be noted however that the term 'singularities' was not used until the 1930s, when Schmauss (1938) adopted the term from mathematics, to describe significant departures of weather events from the smooth annual cycle.

During the 1940–50s a good deal of research time was devoted to the subject of singularities, particularly by German meteorologists looking for a way of improving weather forecasts (Lamb, 1977; Neumann & Flohn, 1988). Other notable examples of research during that period are by

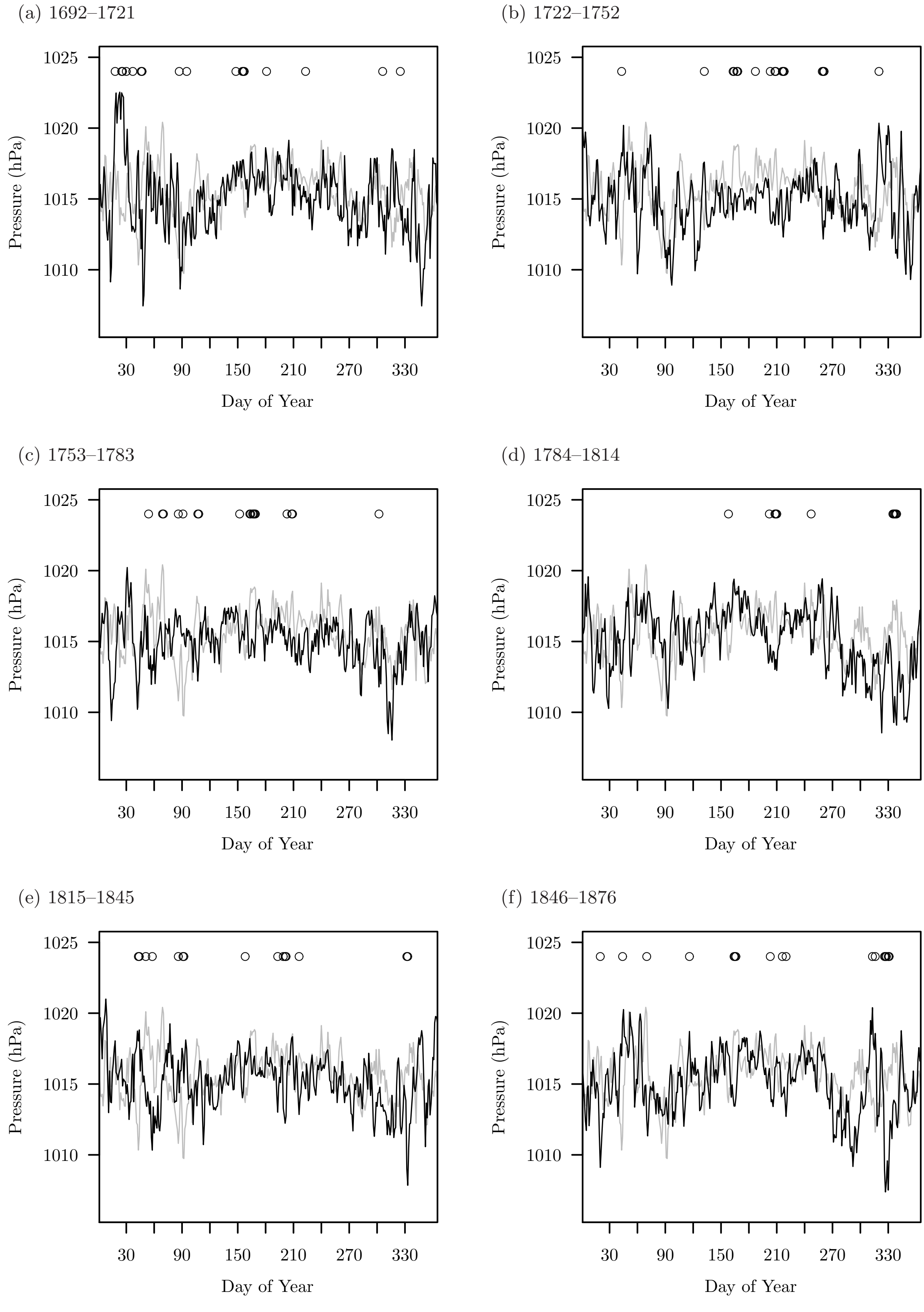

Figure 5.9: Comparisons of 31-year samples of MSLP (black) with the 1970–2000 mean (grey) for each day of year for the London series. The black dots mark days where the differences between the two samples are statistically significantly different at the 95% level.

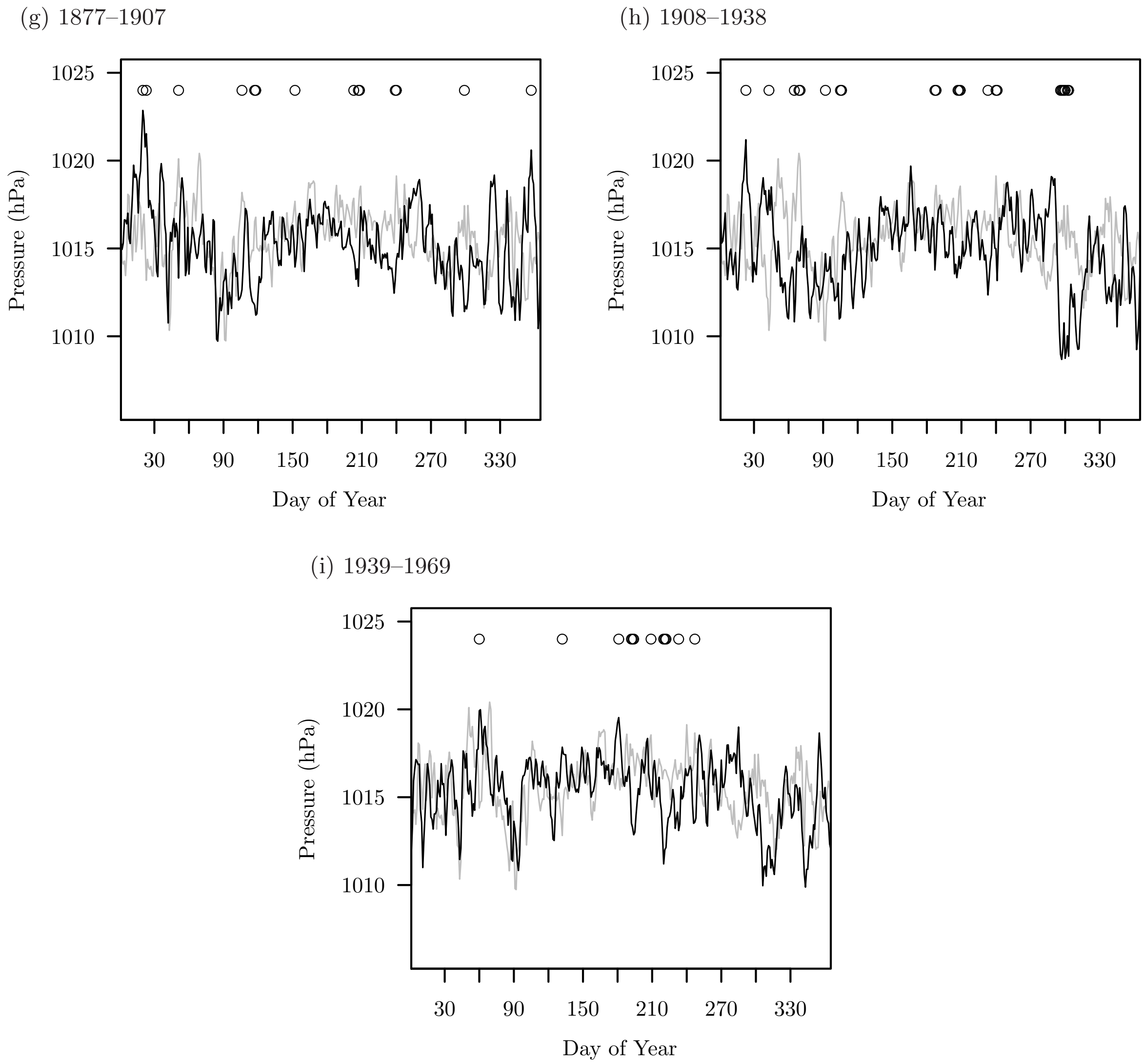

Figure 5.9: Continued.

Brooks (1946) and Craddock (1956). The climatologist Hubert Lamb also became interested in the subject of singularities during his employment at the Forecasting Research Division of the UK Met Office. Lamb (1950) conducted a thorough investigation into singularities in the British Isles climate, which provided most of the material for his later rewrite of Brooks' *The English Climate* (Lamb, 1964). Lamb used the classification of each day's weather from 1898 to 1947 (the Lamb Weather Types) in combination with precipitation, temperature and sunshine hours data to devise a 'calendar of singularities' for the British Isles (Table 5.3). The table contains three types of events, which taken in total contribute to Lamb's definition of meteorological singularities:

1. Seasonal trends of weather types that are imprecisely dated;

2. Periodic tendencies for weather types throughout the year;

3. Short duration peaks in the frequencies of certain weather types.

His definition therefore encompasses a wider range of events compared with Schmauss' (1938)

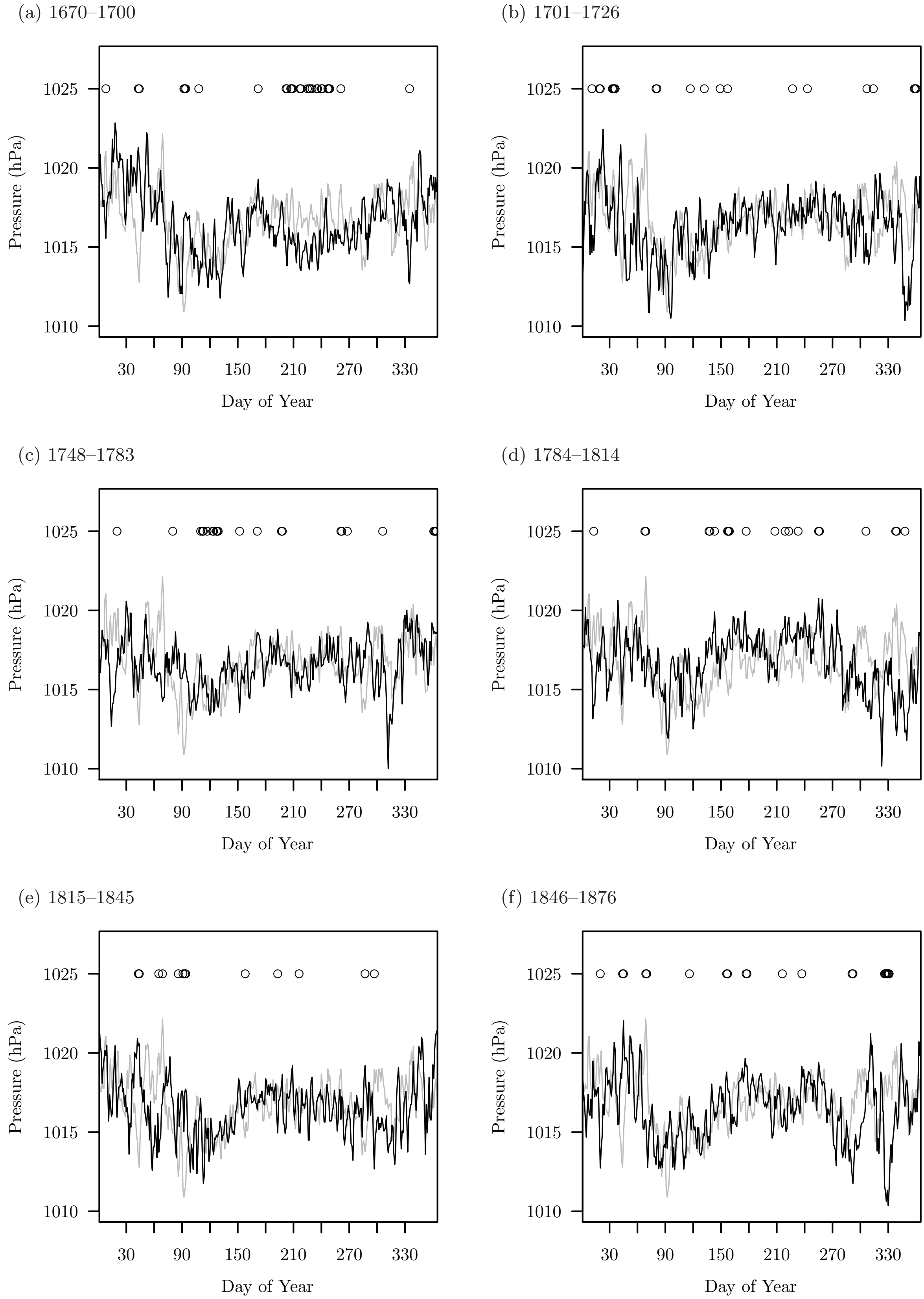

Figure 5.10: As Figure 5.9 but for Paris.

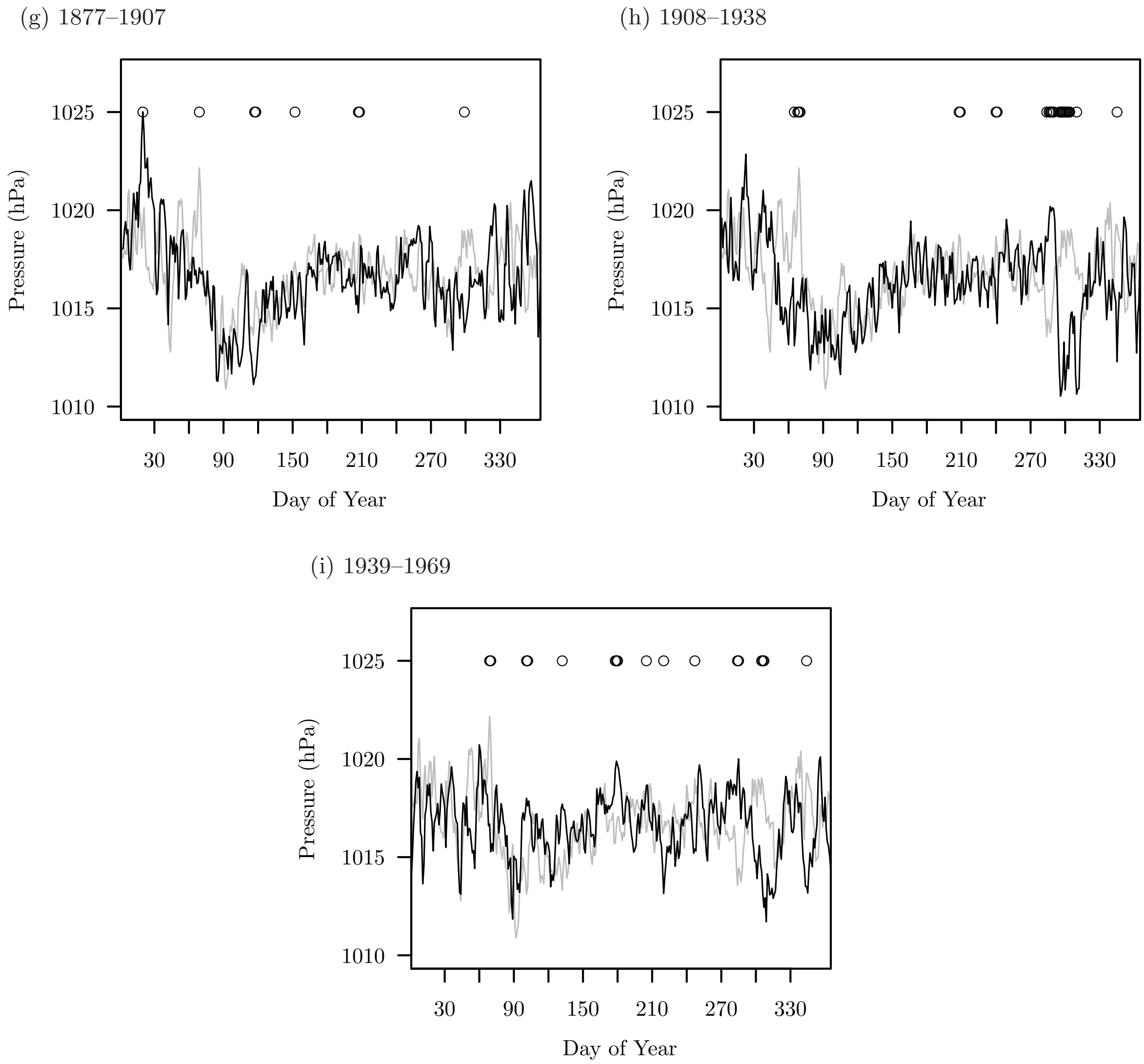

Figure 5.10: Continued.

stricter (and more usual) specification, which only considered the third element of Lamb's definition to be singularities.

A feature that appears frequently in work about singularities is that many of the identified weather spells are not statistically significant and can be generated using random series (Barry & Carleton, 2001). The pioneering studies on the subject often identified singularities as statistically significant because of the use of short data series. Brazell (1968) was sceptical about the concept of singularities for this reason, and found no basis for the association of weather types with specific Saints' days in his chronicle of weather in London over several centuries. Manley (1962, p.120) sums-up the situation by stating that "It will be interesting to see how many of these singularities are accepted after we have acquired a further fifty years of observations". Lamb (1950) was also conscious of this problem and sought to alleviate some of the doubt by using objective criteria to rank the significance of the events. As described above, however, Lamb's definition of singularities is broader than the more usual definition, and is more a description of the annual cycle of weather. More recently, Bissolli & Schönwiese (1990) have applied statistical tests to daily data recorded in Germany in an attempt to identify singularities in the temperature climate. Their approach defines singularities in the strictest sense, as being short-term departures of meteorological variables from the smoothed annual cycle. The methods of Bissolli & Schönwiese have been extended by Rezníčková *et al.* (2007), who identified 45 singularities in the Czech Republic using data from a range of stations recorded over 42 years (1961–2002). The authors note however that these weather spells vary considerably over time and space, and even record the occurrence of different singularities on the same calendar day when comparing data from different periods. Radová & Kyselý (2009) focused their attention to the temporal instability of singularities in the Czech Republic data by using a long series of data from Prague (1881–2000). They found that most of the singularities classed as statistical significant by Rezníčková *et al.* (2007) are not robust over time, and should therefore be considered as purely statistical artifacts.

5.6.3 Singularities in the London and Paris pressure data

In Section 5.6.1, the annual cycle of the Paris/London and Paris–London series was discussed. The patterns described there have certain similarities with Lamb's (1964) 'calendar of singularities'. Indeed, the annual cycle in the Paris–London westerly index (Figure 5.8c) bears a striking resemblance to Lamb's plot of the changing frequency of westerly weather types throughout the year (Lamb, 1964, page 145, figure 26). A noticeable feature in the London pressure series (Figure 5.8a) is the high mean pressure during mid-March which falls to an annual minimum at the start of April. The former event corresponds to Lamb's 'Mid-March Anticyclones' singularity in addition to Chaucer's description of the 'droghte[sic] of March', taking into account the difference between the Old Style (Julian) calendar (OS) and New Style (Gregorian) calendar (NS). Throughout April the pressure in London then rises, but remains low in Paris, and this leads to low values in the Paris–London index throughout April and May. This coincides with Lamb's 'Spring Northerlies' singularity, when the westerly winds are at their lowest frequency and AC, N and E weather types dominate. Throughout June the mean pressure in London remains constant, but rises in Paris, and this leads to increasing values in the Paris–London series, and accounts for Lamb's 'Return of the Westerlies' singularity and the onset of the so called 'European Monsoon'. An increase in pressure in London from late-August to mid-September leads to a decline in the westerlies, and coincides with the 'End of summer turning point' singularity. Beginning in mid-September and continuing to early-November the pressure falls at both London and Paris, although the trend is greater in London and this leads to a gradual increase in the Paris–London index, and corresponds to the 'Late Autumn rains' singularity when low pressure systems frequently cross southern Britain. In mid-November a short-term increase in pressure in London is evident, and to a lesser degree in Paris, and this corresponds to a distinct drop in the Paris–London index between the 16th and 19th November. Lamb (1964) records this event as the 'Mid-November anticyclone' singularity and leads to the foggiest period of the year in southern England. Following this the Paris–London index increases to a peak in early December (the 'Early winter storms and rain' singularity) but thereafter pressure in both London and Paris rises, which reduces the strength of the westerlies and leads to the 'December continental anticyclones' singularity. It must be noted however that the variance in barometric pressure quantified by the 10 and 90th percentiles for each day of the year is high. This indicates that there is a great deal of interannual variability in the mean.

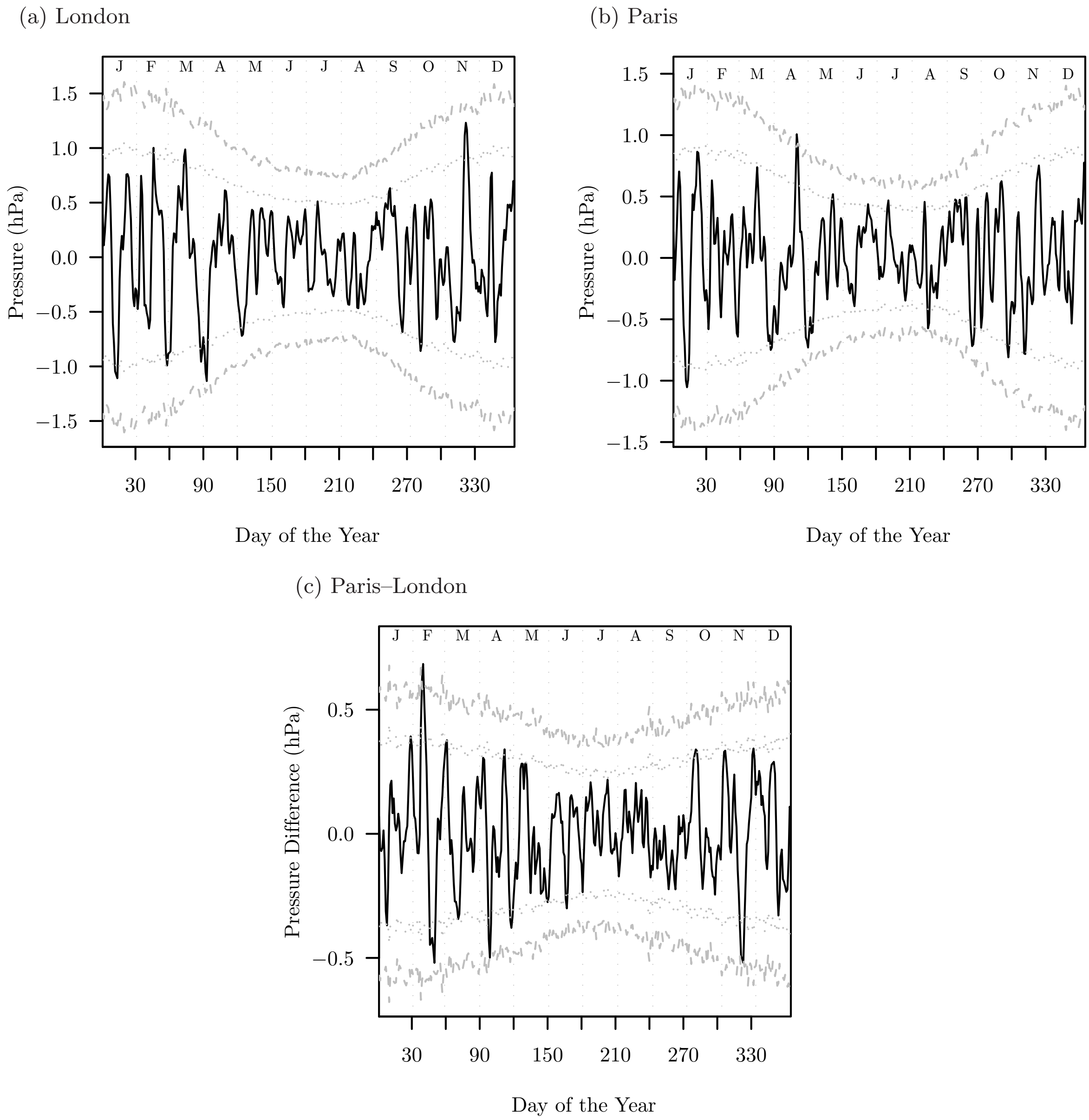

Figure 5.11: Deviations of the London (a) and Paris (b) pressure series, and the Paris–London westerly index (c), for each day of the year from the annual cycle. The grey lines represent levels of significance: dotted 80% and dashed 95%.

January	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
1692–2007												○□	○□	○□															▲		
1950–1999																															
1900–1949																					●△	●■	●■								○
1850–1899												△																■		▲	▲
1800–1849	●■	■					●△	△					□	□																	
1750–1799		△			■	●■	●	●△	△			▲	○□	○□	○□													▲			
1692–1749	▲								□	○	▲	□		▲	▲			■△	△	■△		■	■	■							
February	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
1692–2007								▲	▲	▲	▲				●△	△	△	△	△								○				
1950–1999			■								○□	○□	○□	○□△	△	△	△	△													
1900–1949	○														●■												○▲	○▲			
1850–1899																					△	●△	●■	●■△							
1800–1849							▲	■▲																▲		▲					
1750–1799				△		△			▲	▲	▲	▲						△	△					▲	▲		▲				
1692–1749	△	△			□	○□	○□	▲	▲	■▲	●■	●■▲	▲	▲		□	□	□					●	●△	△	△					
March	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
1692–2007	▲	▲												●	●													□	○	○	
1950–1999																									▲						
1900–1949																									△					▲	
1850–1899																			△	△	△	△			○□	○□	○□				
1800–1849													●	●■																	
1750–1799							△	△	△	△	△	△																			
1692–1749	○■	○■	○	○	△								□		●														□	○□	
April	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
1692–2007	○	○	○					△	△	△									■	■	■	▲					△	□△	□△	□	
1950–1999														●	●△	●△	●△	●△	●							△	△				
1900–1949																					●	■							□		
1850–1899																															
1800–1849																															
1750–1799									△												■							△	□△	□△	
1692–1749	○					□																■	■								

Table 5.4: Singularities identified in the London, Paris and Paris–London series that are significant at the 80% level. The circles (●, ○) represent the London series, squares (■, □) represent Paris and the triangles (▲, △) represent the Paris–London series. The filled symbols are positive singularities and open symbols negative singularities. It should be noted that due to the high number of missing data in the period 1692–1749 the results from this period are not directly comparable with the results from the 50-year sub-periods, which contain complete observations.

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
1692–2007	□		□	○□	○						▲											■									
1950–1999																														△	△
1900–1949					○	○▲				■									△	●	●										○□
1850–1899					△																										
1800–1849																						△	△								●■
1750–1799	□									○	▲	▲			■					■	●■	●■	●	△	△						□
1692–1749					○	○	▲	▲			●	●	●△	△											△	△	△	■	■	■	■
June	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
1692–2007															△	△															
1950–1999						○□	○□▲	○□▲	○□				●	●△	●△	●															
1900–1949																					■	■					■				
1850–1899					■																			■	●■	●■					
1800–1849	■		▲																												
1750–1799	□	□									□	□																			
1692–1749	△								▲	▲	▲				△	△											▲	▲			
July	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
1692–2007									■	●■																					
1950–1999													○▲	▲											■	●■					
1900–1949										●■														○□	○□	○□					
1850–1899																						▲	○▲	○	○□			●△	●△	●	●■
1800–1849																			○□▲	○□▲	○										
1750–1799																															
1692–1749				□		□						●	■	■													□	□	▲		
August	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
1692–2007											■			□	□																
1950–1999							□	□					○□	○		▲												●△	●		
1900–1949												●							○	○	○▲	○▲	○▲								
1850–1899	●						▲																								
1800–1849				○	○□												■	■													
1750–1799										●	●				○□	○□															
1692–1749									■	■			△												▲	▲	▲	▲			△

Table 5.4: Continued.

September	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
1692–2007								■			●■	●					■				□	□	○□	□							
1950–1999																	●	●■△	●△												
1900–1949						●■	●■	●■	●																		△	△	△	△	
1850–1899	▲											●■	●■				●				□					■▲	▲	▲		○□	
1800–1849	△	△							▲	▲							■													□	
1750–1799								△	●	■										□	○□	○□	○□								
1692–1749								■	■	●■	●					○	○	○			△	△	△	△			▲	▲			
October	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
1692–2007							▲	▲	○	○														□							
1950–1999												△	△	△																	
1900–1949											■	■	■	■	■	■	■						□	□	□	□	○□	○□	○□	□	
1850–1899																										□	□				
1800–1849																					▲	▲									
1750–1799										○▲	○▲					●■	●■	■					△								
1692–1749	●				▲														■	■	△	△	△	△	●△	●	●				
November	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
1692–2007																△	●△	●△	●△												
1950–1999	▲									○	○□	○□	□																		
1900–1949						□	□										△						■								
1850–1899				■	■	■	●■	●■										●△	●■△	●■				○□	○□	○□	○□				
1800–1849																			●										○▲	○▲	
1750–1799				▲			○□	○□			▲															■	■				
1692–1749				○□▲	○□▲	○□	□△	△	△			■	■		●	●	●■	●■													
December	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
1692–2007																															
1950–1999				●■	●■																										
1900–1949					▲	○	○			□						■	●■	●■	●△	●△								○□	○□		
1850–1899																															
1800–1849	▲																													●■	●■
1750–1799						△								○▲	○													●■	●■△	●	
1692–1749				△	△	■				●	●		□	○□	○□	□	□								△	■△	■△	■	■	■	▲

Table 5.4: Continued.

To identify statistically significant singularities in the data, the 'method of the mean' was used following Bissolli & Schönwiese (1990) and Rezníčková *et al.* (2007). This method consisted of smoothing the means of pressure on each day of the year with a 60-day Gaussian high-pass filter to remove the annual cycle. To remove transient atmospheric disturbances, the data were then smoothed with a three-day running mean filter to a produce a new series (m_t, Figure 5.11). Values in the series m_t that were significantly different from zero using a t-test at the 80% level were identified as singularities. The results from this test identify short-term departures of pressure from the smoothed annual mean and therefore quantify a different concept to the depiction of the annual cycle described above. To differentiate from the earlier description, these singularities are termed 'type-3' singularities after Lamb's (1964) specification. To test if the singularities are robust over time, the 'method of the mean' was applied to 50 year periods, along-with the entire 1692–2007 data.

The results (Table 5.4) indicate that there are certain statistically significant type-3 singularities in the London, Paris and Paris–London series. However, few of these singularities are robust over time, and in certain cases opposite singularities are apparent for different time periods. For example, in the Paris pressure series during the period 1900–49 negative pressure singularities are evident for 24–26 July, but in the period 1950–99 positive singularities occur on those days of the year.

A singularity that is worthy of further attention is the event of 17–19 November, which is associated with increased MSLP in London and reduced westerly conditions and relates to Lamb's 1964 'mid-November anticyclones'. This singularity is evident in the 1692–2007 data series and is significant at the 95% level. The event is also apparent during the 1850–99 period—when it is also associated with increased pressure in Paris—and the 1692–1749 period. However, despite the relatively high level of statistical significance it fails to appear in the remaining 50-year time segments.

To conclude this analysis of singularities in the London and Paris daily pressure series, two observations are made. If the strict definition of singularities is used, which only considers short-term deviations from the smoothed annual cycle, then there is no evidence for statistically significant singularities in the London/Paris daily pressure data. However, the annual cycle of MSLP at London and Paris, as well as the westerly index derived from the difference in MSLP between the two sites, agrees closely with Lamb's (1964) description of the march of the seasons. Yan *et al.* (2001) has more recently examined the change over time of the annual cycle in weather patterns in Europe, which marks a progression from Lamb's work. Continuing this line of investigation would seem more profitable than the search for short-term departures of weather conditions from the smoothed annual mean, which are probably little more than statistical curiosities.

5.7 Chapter summary

The purpose of this chapter has been to assess the results from the homogenization of the London and Paris daily pressure series. The two data series appear to have been successfully homogenized, with the values giving accurate indications of MSLP at the two sites over the last 300 years. However, the two series would still benefit from certain additional corrections.

The mean of the earliest data for Paris (approximately 1670–90) appears to be too high during the winter months and too low during the summer. This is almost certainly a consequence of the temperature corrections applied to the data, and the series would be improved through the acquisition of temperature corrections using Morin's temperature readings. The quality of the London data during the period 1765–70 appears to be low, with a much reduced variance of the data evident. This is most likely explained by the use of a poorly maintained barometer by the observer, and additional sources of data need to be sought for this period.

The seasonal cycle of pressure in London and Paris has also been analysed. Further work needs to be done on examining how the seasonal cycle has changed over time, and the length of the London and Paris data series are ideally suited to this application. The use of techniques such as Harmonics analysis (following the example of Jónsson & Miles, 2001) and wavelet analysis (Yan *et al.*, 2001) appear to be appropriate lines of further enquiry.

Part II

Data Series Analysis

Chapter 6

The Paris–London Westerly Index and its Relationship to the NAO

6.1 Introduction

In Part I of this thesis, the London and Paris daily pressure series have been presented. The corrections applied to the data to form homogeneous series of pressure have been described, and in the final chapter of Part I (Chapter 5) the statistical properties of the two series have been discussed. Chapter 5 ended with an examination of the annual cycle of westerly winds, which was quantified by the difference in daily pressure between London and Paris. This chapter explores the Paris–London index further by examining its relationship to the wider atmospheric circulation, and in particular its connection with the North Atlantic Oscillation (NAO).

The NAO is the dominant pattern of atmospheric circulation in the North Atlantic-Western European (NA-WE) region throughout the year and represents an alternation of atmospheric mass between the semi-permanent Azores High and Iceland Low centres (e.g. Barnston & Livezey, 1987; Hurrell *et al.*, 2003). An increase in the winter NAO since the 1970s to a peak in the 1990s has prompted questions regarding the role that greenhouse-gas forcing plays in the variability of the NAO, and specifically to what degree this recent trend is beyond the range of natural fluctuation (Gillett *et al.*, 2003a). To adequately answer that question, long time series of the NAO extending back to the early industrial or even pre-industrial era are required. Traditional indices of the NAO, which use the difference in Mean Sea-Level Pressure (MSLP) between the Azores and Iceland during the winter months of the year (DJF or DJFM), extend back to the mid-nineteenth century and indicate that the high positive values of the 1990s are unprecedented over that time period (Hurrell & van Loon, 1997). The use of MSLP recorded at Gibraltar allows extension of the NAO index back to 1823 with other Iberian stations allowing extension back to the 1780s (Jones *et al.*, 2003). The Gibraltar–Reykjavik index has indicated that the high NAO index values of the 1990s are not unprecedented but are of a similar magnitude to the values in the 1930s (Jones *et al.*, 1997; Slonosky & Yiou, 2001). Questions about the variability of the NAO further back in time remain only partially answered (Hurrell *et al.*, 2003). Proxy data are useful in this respect and have the potential to provide information on the state of the NAO over several hundreds of years (e.g. Cook *et al.*, 2002; Luterbacher *et al.*, 2002a). However, these indices are often limited by an inability to capture high-frequency variability, and by non-stationary relationships between the proxy and the atmospheric circulation (Schmutz *et al.*, 2000).

Early pressure data from mainland Europe have been used for many years to provide information on the state of the atmospheric circulation in previous centuries (e.g. Mossman, 1896; Lamb & Johnson, 1961, 1966; Kington, 1980; Jones *et al.*, 1987, 1999b). Using similar methods as these early studies, Slonosky *et al.* (2000) has recently shown that an index constructed from the difference in MSLP between London and Paris has a close relationship to the traditional NAO indices, particularly during the winter months of the year, by providing a measure of westerly flow across western Europe. The Paris–London index was extended back to 1774 and supported the assertion of Slonosky & Yiou (2001) that the high values of the NAO during the 1990s are not unprecedented in the context of the last 200 years. Slonosky *et al.* (2001b) demonstrated that a similar index could be constructed for the period 1698–1708 by using early instrumental observations recorded in the two cities. Jones *et al.* (2003) extended these studies by examining the relationship of the Paris–London index (1774–2000) to several NAO indices and surface temperature data series. They concluded that the Paris–London index can provide a reliable extension to the traditional NAO indices and suggested that the series could be extended back to the late seventeenth century.

This chapter extends the work of Slonosky *et al.* (2000), Slonosky *et al.* (2001b) and Jones *et al.* (2003) by using the newly recovered/homogenized daily London and Paris MSLP series to provide information on the state of the NAO back to 1748 and on a fragmentary basis back to 1692. In addition to the increased length of the series, the results presented in this chapter extend previous studies by examining the Paris–London index for all seasons of the year. The seasonal and annual Paris–London index time series are compared against various NAO indices (instrumental and proxy) in Section 6.4, and in accordance with the previous studies it is found that the index generally compares well with the NAO indices. These associations are quantified in Section 6.5 by calculating interannual and decadal correlations. The durability of these relationships is also examined in that section by calculating running correlations between the indices. The chapter concludes with an examination of the extremes of zonal flow from the Paris–London index, by calculating the number of extreme westerly and easterly days over the 1692–2007 period. This tests the assertions of Kington (1980) and Slonosky *et al.* (2000) that the atmospheric circulation was more variable before ca. 1860 than afterwards. Before any of these results are presented however, an overview of the NAO is provided. Over recent years there have been several very good review papers on this subject (Marshall *et al.*, 2001; Wanner *et al.*, 2001; Hurrell *et al.*, 2003) and rather than compete with these papers Section 6.2 presents a summary of the main themes of the papers, with particular emphasis on ways of extending the NAO series back in time.

6.2 The NAO: an overview

6.2.1 A definition of the NAO

The NAO is the dominant pattern of atmospheric circulation in the NA-WE region throughout the year and is based on an alternation of atmospheric mass between the subpolar Arctic low and the subtropical Atlantic high (Marshall *et al.*, 2001; Hurrell *et al.*, 2003). The NAO was formally defined in the 1920s by Gilbert Walker (Walker, 1924), who extended a body of research from the late 1890s/early 1900s that had examined the statistical relationships between circulation patterns and temperature anomalies across Europe (Wanner *et al.*, 2001). These seminal studies identified that MSLP in the Azores is inversely correlated with that in Iceland, and this finding is fundamental in defining an index of the NAO (Jones *et al.*, 1997, 2003). The major advance that Walker in particular made was to use statistical significance to extract the dominant modes of circulation variability from the data (Wanner *et al.*, 2001). In a later paper, Walker & Bliss (1932) used the weighted cross-correlation of pressure and temperature series selected in an iterative procedure to produce an index of the NAO. A similar technique is employed in modern-day measures of the NAO through the application of rotated Principal Component Analysis (PCA) to gridded MSLP, and while this technique removes some of the subjectivity regarding station selection, it produces a result similar to Walker & Bliss's study (Wallace, 2000).

The NAO displays a high rate of interannual variability, which is almost equivalent to white noise (Stephenson *et al.*, 2000). During years when both of the 'centres-of-action' are well developed, the NAO assumes a high-phase (NAO+). Given that air rotates in an anti-clockwise (clockwise) direction around low (high) pressure systems in the northern hemisphere, a high phase of the NAO leads to more vigorous westerly flow in the eastern Atlantic region and across Europe due to the increased meridional pressure gradient. During a low-phase (NAO–), both of the 'centres-of-action' of the NAO are weaker than normal and reduced westerly flow results (Wanner *et al.*, 2001; Hurrell *et al.*, 2003). An extreme situation of the NAO– phase may also occur on occasions when the pressure gradient in the North Atlantic is reversed; this leads to vigorous easterly flow across Europe (Moses *et al.*, 1987).

The spatial distribution of pressure anomalies during positive and negative phases of the NAO are not simply the reverse of each other but are somewhat asymmetric. Cassou *et al.* (2004) and Hurrell & Deser (2009) have shown through the clustering of daily MSLP over the Atlantic domain that during a negative phase of the NAO the southern node is located slightly further north and extends further eastwards compared to NAO+ conditions. Differences in the position of the northern node are also evident, with the centre-of-action shifted slightly northwestwards during NAO– conditions compared to NAO+ conditions. This asymmetry is not captured by the common PCA definition of the NAO, which defines opposite polarities of the NAO as simply the reverse of each other (Hurrell *et al.*, 2003). However, this asymmetry has important implications during the comparison of different NAO indices, and is explored further in Section 6.4.1.

As well as varying on an interannual basis, the location and strength of the 'centres-of-action' of the NAO vary on a seasonal basis. The leading component derived from PCA of North Atlantic MSLP assessed on a seasonal basis by Hurrell *et al.* (2003) demonstrates this feature. During the winter, the southern node is situated in the east Atlantic basin area and the northern node is situated to the east of Greenland. The meridional pressure gradient is large, compared to other seasons, and the spatial distribution of MSLP is coherent. These factors mean that the leading PC explains a large proportion (36.7%) of the variance of MSLP in the North Atlantic domain. Similar patterns are also found in the spring although the loadings tend to be weaker, and the pattern explains a smaller percentage of the total variance of North Atlantic atmospheric pressure (29.6%) compared to the winter. During the summer, the leading component explains only 22.1% of total MSLP variance, which is the lowest value of any season. The southern node is located much further north in this season and is situated over northwest Europe; the northern node, while still located to the east of Greenland, is more elongated in a northerly direction. Both the north and south nodes in summer have a limited spatial extent compared to winter and the pressure gradients are much weaker. It has been noted by Folland *et al.* (2009) that the circulation pattern in June is quite different to that in July and August, and this may lead to a weaker definition of the NAO if the mean value for the months of June, July and August is used. They argue that the NAO is best defined for high summer (July and August). In the autumn, the southern node of the NAO is located in a similar position to winter but the northern node is shifted eastwards and is centred to the east of Iceland. During the autumn the leading PC explains 23.3% of the variance in MSLP in the North Atlantic region.

The description of the NAO provided so far in this chapter highlights the fact that the NAO is typically considered by assessing the mean state of the North Atlantic pressure field at monthly, seasonal or annual timescales. However, the use of mean values fails to capture the dynamic nature of the NAO. Investigations into the intra-seasonal variance of the North Atlantic MSLP field have revealed that seasons are rarely dominated by a particular circulation regime and the pattern depicted by PCA is experienced on only a fraction of days (Hurrell & Deser, 2009). Consistent with this intra-seasonal variability is the association between the NAO and north Atlantic storm tracks. NAO+ conditions arise when the storm track is oriented in a north-eastward direction and deep, frequent low-pressure systems travel across north-west Europe. In contrast NAO– conditions are associated with weaker depressions that are oriented in a west-east direction and which travel into Mediterranean regions (Osborn, 2006). Accordingly, the number of blocked days in the North Atlantic region is higher during NAO– winters in the North Atlantic and the mean length of blocking episodes is increased, although the length is more variable than during NAO+ conditions (Shabbar *et al.*, 2001).

The association between the NAO and extratropical storm tracks leads to an effect on precipitation patterns across Europe (Ulbrich *et al.*, 1999; McGregor & Phillips, 2004). This is due to the storms transporting large quantities of water vapour from the Atlantic, but also because they provide suitable atmospheric conditions to precipitate this moisture (Osborn, 2006). However, studies that compare precipitation data with station-pair NAO indices report low correlations. This appears to be attributable to the fact that station-pair indices only capture the zonal character of the NAO (Slonosky & Yiou, 2002), which suggests that precipitation variability in western Europe is more closely connected with the position of North Atlantic storm tracks rather than advection of moisture (Yiou & Nogaj, 2004; Yiou & Masson-Delmotte, 2005).

In addition to having a direct effect on precipitation, the NAO also has a major influence on the surface temperature climatology of landmasses surrounding the Atlantic basin. As the NAO is most spatially coherent during the winter months and the pressure gradients are stronger compared to the other seasons, the NAO is the most important control on interannual climate variability in Europe during the winter (Hurrell & van Loon, 1997). Van Loon & Rogers (1978) describe the influence that the NAO has on temperature anomalies in Norway and Greenland. During NAO+ winters, the advection of warm air across the Atlantic as a result of the increased westerly flow causes temperatures to be above average in Norway. Conversely, the deepening of the Icelandic low-pressure system causes cold northerly air to be advected across Greenland. The opposite of this seesaw in temperatures is true for NAO– winters. The association between western European temperatures and atmospheric circulation is the subject of Chapter 7 and more information is provided there.

The configuration of the upper atmosphere is directly connected to the paths and intensities of extratropical storms. Hence a signature of the NAO is also apparent in the upper-atmosphere (Hurrell *et al.*, 2003). During NAO+ winters, the jet stream is located poleward of its mean state, whereas in NAO– winters it is located further south and accounts for the steering of storms into Mediterranean regions (Wallace & Hobbs, 2006). In this sense the NAO is a teleconnection pattern and is part of the wider hemispheric atmospheric circulation.

The definition of the NAO as a teleconnection pattern is at the centre of a debate over the connection between the NAO and another pattern of atmospheric circulation called the Northern Annular Mode (NAM).[1] The NAM, as described by Thompson & Wallace (2000), consists of positive components in the Atlantic and Pacific regions, and a negative component in the Arctic region. The NAM therefore assumes a symmetric pattern in the Pacific and Atlantic regions and is defined through the use of the full northern Hemisphere pressure dataset. In contrast the NAO only uses data from the North Atlantic domain and this difference between the two modes of circulation has led to suggestions that the NAO is just a regional expression of the wider hemispheric-scale atmospheric circulation (Thompson & Wallace, 1998). Other arguments have been put forward that the NAM is an artifact of the statistical methods used (Ambaum *et al.*, 2001). In support of that view Huth (2007) has suggested that the NAM appears to be a product of using unrotated Principal Components, whereas the NAO derived from rotated PCs has greater physical meaning. However, Christiansen (2002) performed rotated PCA on the 500hPa geopotential height field and concluded that the NAM is not a result of rotation. Other studies have concluded that the two patterns are "nearly indistinguishable" and the symmetric pattern of the NAM in the northern hemisphere is a result of a common relationship to the Arctic pressure pattern rather than a relationship between the Pacific and Atlantic "centres-of-action" (Deser, 2000, p782). Feldstein & Franzke (2006) have supported this view by showing that there is no statistically significant difference between the NAO and NAM. They also indicated that the same wave-breaking processes are associated with both patterns. The debate regarding the connection between the NAM and NAO will surely continue, but for the purposes of this thesis the advice of Wallace (2000) is taken, and as the focus is on the climate of western Europe, the results are presented under the paradigm of the NAO.

6.2.2 The value of NAO station-pair indices

The use of PCA to provide a measure of the NAO is restricted to the period for which reliable gridded MSLP data are available (typically from the late nineteenth century; Osborn *et al.*, 1999a). A simple way of quantifying the NAO, which allows extension of the index further back in time, is to subtract a barometric pressure observation recorded in the vicinity of the Icelandic

[1] The term Arctic Oscillation (AO) was used to describe this hemispheric mode of atmospheric circulation variability until Thompson & Wallace (2000) placed a greater emphasis on the annular pattern of the phenomenon. Since then the term North Annular Mode (NAM) has been used increasingly. The term NAM is used throughout this thesis.

low-pressure system from a contemporary observation recorded close to the Azores high-pressure centre. The horizontal pressure gradient between the two stations ($k \cdot \nabla p$) provides a measure that is proportional to the horizontal geostrophic wind vector (V_g) on a line perpendicular to the two stations, according to

$$V_g = \frac{1}{\rho f}(k \cdot \nabla p), \tag{6.1}$$

where ρ is the density of air and f is the Coriolis parameter (Slonosky & Yiou, 2002). Frictional forces that are apparent in the lower kilometre of the atmosphere retard the wind speed and allow the pressure gradient force ($k \cdot \nabla p$) to slightly dominant the Coriolis force (f) such that the actual wind direction at the surface differs from the geostrophic wind by approximately -15° in the mid-latitude northern hemisphere (Wallace & Hobbs, 2006). Despite this difference between the actual and geostrophic wind direction at the surface, the geostrophic wind is sufficient for the quantification of the NAO by station-pair indices. The index is usually calculated from the (normalized) pressure gradient (∇p), given that $V_g \propto \nabla p$.

Station-pair NAO indices are usually only calculated for the winter season, which is often defined as the mean of the months from December to March, rather than the usual meteorological season of December to February. Osborn *et al.* (1999a) explain the reason for this by showing that the NAO index (Gibraltar–Iceland) for DJF is significantly correlated on decadal timescales with the index in March but not in November or April. The NAO is therefore coherent on decadal timescales during the months of DJFM. Despite this information the DJFM mean is not used exclusively in studies, with various other means used, such as DJF or ONDJF. Slonosky & Yiou (2002) demonstrate that large differences can occur between different seasonal definitions of the NAO, especially in relation to the examination of long-term trends. These differences inhibit the cross-comparison of results from different studies.

Two stations commonly chosen to construct a station-pair NAO index have been Ponta-Delgada in the Azores and Stykkisholmur in Iceland, which forms a simplified version of Walker & Bliss's (1932) original NAO index (Hurrell *et al.*, 2003). The calculation of anomalies from the respective monthly mean eliminates problems associated with the annual cycle in pressure and normalization of the data ensures that the high variability of the Icelandic data does not bias the index. This index can be extended back to 1865, although there is little chance of extending it further back in time due to a lack of pressure observations recorded at (or available from) Ponta-Delgada (Jones *et al.*, 2003). There is also little chance of extending the series forward, beyond March 2003, due to the suspension of data keeping at Ponta-Delgada (Hurrell, 2009).

Hurrell (1995) managed to extend the NAO series back to 1864 by using MSLP recorded at Lisbon in Portugal, along with the Stykkisholmur series from Iceland. The Lisbon station data can successfully be used during the winter season because the southern node of the NAO extends to the Iberian peninsula during that season. Following the same reasoning, Jones *et al.* (1997) extended the NAO series back to 1823 using Gibraltar as the southern station. Jones *et al.* have shown that the anticorrelation of MSLP between Gibraltar and Iceland is higher than between Ponta-Delgada and Iceland, which would suggest that the NAO signal is clearer in the Gibraltar–Iceland index compared to Pont-Delgada–Stykkisholmur. However, at least some of the success of these results may be attributed to the changing positions of the NAO 'centres-of-action' over time (Mächel *et al.*, 1998). Since the publication of the paper by Jones *et al.* (1997), further corrections have been applied to the Gibraltar data to resolve inhomogeneities in the original series (Slonosky & Yiou, 2001). Vinther *et al.* (2003a) have more recently applied additional corrections to the Gibraltar data to remove further inhomogeneities, primarily in the summer months. This dataset has been shown to be an improvement on the original series (Li & Wang, 2003). However, it is shown below (§6.5) that the corrections applied during the spring and summer months may have actually impaired the index.

Station-pair indices have been employed in many studies, primarily because they are easy to compute and can be extended back into the early nineteenth century. While simple circulation indices such as these are capable of yielding as much information as more complex classification methods when used properly (Yarnal *et al.*, 2001), there are certain limitations to their use. As the 'centres-of-action' of the NAO undergo interannual variation (Sahsamanoglou, 1990; Mächel *et al.*, 1998), station-pair indices will always fail to represent the true nature of the NAO. This leads to the high noise to signal ratio in station-pair indices that has been quantified by Hurrell & van Loon (1997). Station-pair indices are also poor at quantifying the seasonal progression of the NAO 'centres-of-action', and may explain why studies have considered the NAO as only a winter phenomenon (Portis *et al.*, 2001; Li & Wang, 2003). Principal Component analyses remedy the problems associated with the interannual and seasonal variations in the position of the 'centres-of-action', although are limited as other modes of variability may be represented in the results. To avoid this problem, while retaining an expression of the seasonal variation of the NAO, Portis *et al.* (2001) performed a PCA on MSLP data from restricted longitudinal/latitudinal ranges, to create the 'mobile NAO index'. However, it has been noted by Folland *et al.* (2009) that this mobile NAO index fails to capture the positions of the NAO during high summer (July and August), when the nodes of the circulation pattern extend beyond the latitudinal/longitudinal ranges used to construct the index. Despite the benefits of the 'mobile NAO index', it is restricted—as with all PCA indices—to a start date of the 1880s by the availability of gridded MSLP data.

A different way of quantifying the NAO is to develop a zonal index by using the pressure difference between two latitudinal bands. This resolves the problem of interannual variations in the position of the 'centres-of-action'. Defant (1924) used the pressure difference between north Africa and northern Europe (60–70°N and 25–35°N averaged over 10–60°W). Makrogiannis (1984) developed a zonal index for Europe for the years 1873–1972 by calculating the difference in pressure between latitudes 55°N and 35°N, in the region 20°W and 40°E. Li & Wang (2003) developed a similar index from the pressure difference between two latitudinal bands, in the region 80°W–30°E: 35°N and 65°N. Interestingly, the authors of that study failed to recognize the previous similar work by Defant (1924) and Makrogiannis (1984). In addition, Lamb & Johnson (1959) used the pressure difference between 40–50°N, 40°W to calculate an index of westerlies across the North Atlantic for the period 1820–1959.

The various NAO indices described so far have revealed that superimposed upon a high rate of interannual variability the NAO has experienced pronounced decadal variability. Makrogiannis (1984) identified three sub-periods in his zonal index as having experienced prevailing high or low indices: the period 1873–1902 was characterized as low index, with a reduction in westerly winds and an increased frequency of blocking anticyclones; the period 1903–1932 was predominately high index, with an increased frequency of westerly flow; the period 1933–1972 experienced an alternation of both high and low frequencies of westerly flow. In contrast to this latter observation by Makrogiannis (1984), most NAO indices have indicated that the 1930–70 period was typified by a marked decline in the westerly flow, which is attributable to a gradual increase in pressure to the south of Greenland (Rogers, 1984). A marked reversal has been commented upon frequently in the literature during the period following the mid 1970s, with the 1990s being dominated by stronger-than-normal westerly conditions. Indeed using the Lisbon-Stykkisholmur index, Hurrell & van Loon (1997) cited the winters of 1982/3, 1988/9 and 1989/90 as experiencing the highest positive values of the NAO in the period between 1864 and 1995. These remarkably high values are not apparent in the Gibraltar-Iceland NAO index and the values during the 1980s/90s appear as large as those during the 1930s (Jones *et al.*, 1997; Slonosky & Yiou, 2001). This discrepancy highlights the problems that confound attempts to extend NAO indices back in time and relate to the changing positions of the 'centres-of-action' of the NAO. These discrepancies may also be linked to different months used in the indices (DJF, DJFM or ONDJFM) or the normalization period used (Slonosky & Yiou, 2001).

The upward trend observed in the NAO over the last 30 years has prompted research into the influence of greenhouse gas forcing on the oscillation. Gillett *et al.* (2003b) provide a thorough review of the relative influence of various external forcing mechanisms on the recent increase in the NAO through the use of GCM simulations. The authors concluded that while changes in solar radiation can influence the NAO on interdecadal timescales and volcanic aerosols may promote a westerly phase in the one or two years following an eruption, the trend of the NAO over recent decades is probably due to increased greenhouse gas concentrations. However, it was also shown that while most climate models are able to replicate the trend in the NAO, the magnitude of change is smaller compared to observations. Progress is being made by incorporating a stratospheric component into the models (Scaife *et al.*, 2005) but work still remains to be done to resolve this problem. Central to these studies on the influence of climate change on the trend of the NAO over recent decades is the question about whether the increase is beyond the range of natural variability. The short time series used to quantify the NAO limit conclusions to this question and many studies have sought to use other data sources to analyse the past variability of the NAO: these are reviewed in the following three subsections.

6.2.3 The value of early European barometric pressure observations

The station-pair NAO indices described above can only provide an indication of the state of the NAO on a continuous basis back to 1823, at the earliest. To extend the series further back in time, MSLP data from mainland Europe can be used and many studies over the last 100 years have focused on this topic although they are often not cited in connection with the NAO (Stephenson *et al.*, 2003). Lamb & Johnson (1966) reconstructed a series of synoptic maps of MSLP for the months of January and July for the period 1750–1962 by using pressure observations from across Europe in the earliest periods, and globally in later periods.[2] In assessing the results from Lamb & Johnson's charts it should be remembered that they were drawn to be representative of the mean conditions of the season and not the particular month

[2]The charts actually extend back to 1650 and are archived at the Climatic Research Unit, although most of the charts remain unpublished (Jones & Briffa, 2006).

in question (Jones & Briffa, 2006). Using these maps, Lamb (1977) contrasted Januaries in the period 1790–1829 when reduced westerly winds were experienced over Europe, with those in the period 1900–39, during which the highest frequency of westerly winds in the entire series were experienced. This latter NAO+ period corresponds to the results from the NAO indices described above, although of course the high values of 1990s were not covered by the series. The conditions during the 1790–1829 period are typical of a NAO– configuration, and indeed Lamb attributed the episode to a reduced pressure gradient between the Azores high and Iceland low. In addition to this, he suggested that the continental high pressure system across eastern Europe was apparent to the north, which led to greater variation in the wind direction compared to the 1900–39 period and increased the frequency of easterly winds. In the months of July, Lamb (1977) noted that the period 1840–79 was dominated by increased west-north-west wind flow, whereas the period 1900–39 experienced increased anticycloncity. The traditional station-pair indices fail to capture this feature of the summer circulation due to the fixed positions of the stations, which are outside the 'centres-of-action' of the NAO in the summer months.

The state of the NAO during the 1690s and 1730s can be gleaned from the synoptic maps provided by Lamb (1977) for the months of January and July, which were reconstructed in a similar manner to his earlier work. The 1690s were typified by NAO– conditions during January, with a low pressure trough in the east Atlantic and the Azores high extending across Europe; a well developed Scandinavian high compounded the situation. During the July months in that early decade a low-pressure system centred to the north of the British Isles and a retarded Azores high caused a predominance of north-westerly winds across western Europe. In contrast, the 1730s experienced a high frequency of westerly (NAO+) conditions in both winter and summer.

Kington (1980, 1988) extended the example of Lamb & Johnson (1966) and Lamb (1977) by reconstructing daily synoptic charts for Europe for the 1780–85 period. These charts indicate that the early 1780s experienced a low frequency of westerly weather types, which was compensated by an increased frequency of blocking. This suggests that the first half of the 1780s was dominated by NAO– conditions. A more in depth analysis of the data led Kington (1980) to the conclusion that atmospheric circulation in the 1780s was extremely variable, with a high frequency of both cyclonic and anticyclonic days.

In an extension to the work of Lamb & Johnson (1966) and Kington (1980, 1988), Jones *et al.* (1987) used a database of long pressure series to reconstruct pressure over Europe since 1780. An update to that study was provided by Jones *et al.* (1999b), who used more homogeneous data series and more stations than the previous study. The data series had been recovered and homogenized during the ADVICE (1998) project, and Jones *et al.* used the data to produce a gridded pressure dataset for Europe. The results were compared to the digitized charts published by Lamb & Johnson (1966) and Kington (1988). While there were quite large differences between the new and old reconstructions, particularly in the earliest periods, Jones *et al.* (1999b) refrained from stating that the new series is an improvement. It is reasonable to suggest however that the greater coverage of data and the systematic homogenization of the series would produce better results.

To extract the dominant modes of atmospheric circulation variability from the station data recovered during the ADVICE (1998) project, Slonosky *et al.* (2000) applied a PCA to the station data. The first three components from the analysis indicated conditions of central pressure tendency throughout Europe, zonal conditions and blocking conditions respectively. The authors concluded that the NAO may be a better indication of east Atlantic blocking than zonal flow outside of the winter months of the year. However, the authors used the Gibraltar–Reykjavik NAO index for comparison. As has been discussed above, the movement of the 'centres-of-action' of the NAO in the summer months are shifted northwards, with the southern node situated over northwest Europe. Therefore the Gibraltar data will cease to provide a measure of the Summer North Atlantic Oscillation (SNAO) as defined by Folland *et al.* (2009)). Given the more northerly location of the southern node of the SNAO compared to the winter NAO, positive values of the SNAO would be expected to give weak easterly flow across Europe in the summer months and hence if anything a negative correlation with Slonosky *et al.*'s zonal index would be expected in the summer. However, the results from Slonosky *et al.* during the winter months were important and showed that data from a limited number of European stations are able to represent zonal flow and therefore the winter NAO. This provided the basis of extending the NAO series back in time by using historic pressure data.

Slonosky *et al.* (2000) constructed two indices by using selected station data from the ADVICE data series: a 'western European zonal' was constructed back to 1774 by taking the difference in the mean pressure between Trondheim and Lund from the mean of Madrid and Barcelona, and a second index was constructed back to 1774 by subtracting the monthly London series from the Paris series. Slonosky *et al.* (2001b) extended their earlier study and demonstrated that barometric pressure data recorded in London and Paris at the turn of the eighteenth century (1697–1708) could also be used to extend their measure of westerly flow. As the NAO directly affects westerly flow strength across Europe, the Paris–London index—and indeed any similar station-pair index for western Europe—can be viewed as a proxy for the NAO. Slonosky *et al.* showed that a strong correlation exists between the Paris–London index (1774–2000) and zonal flow across Europe especially during the winter months when the atmospheric flow is more coherent, although the relationship is maintained throughout the year. As the Paris–London index is a regional circulation index that is highly correlated with the larger scale North Atlantic atmospheric circulation, it is likely to provide an important link between the NAO and the surface climate parameters of temperature and precipitation. In analysing this relationship the Paris–London index is not influenced by the changing positions of the 'centres-of-action' of the NAO, which is a limitation of using the typical fixed-point indices of the NAO described above.

The construction of station-pair indices using pressure series from selected sites in mainland Europe is not a new research occupation, with Short (1767) performing such analyses in the mid-eighteenth century. The earliest station-pair comparison that used data series of a useful length was conducted by Mossman (1896) who used the difference in MSLP recorded at London and Edinburgh.[3] Brooks & Hunt (1933) used the pressure difference between Edinburgh and Paris to assess the reliability of their long wind direction series. Later, during the 1950s, the construction of these indices became a popular research occupation (Hurrell *et al.*, 2003). For example, according to Lamb & Johnson (1959), Lysgaard (1949) developed indices using Valentia–Edinburgh, and Copenhagen-Edinburgh: Schove (1950) developed a pressure gradient index for the British Isles by subtracting station data recorded in the Scottish Lowlands from ob-

[3] See also Mossman (1900).

servations in the Thames valley. However, the Paris–London data used by Slonosky *et al.* (2000) are longer and more homogeneous than the data used in these previous studies and allowed the authors to view the variability of the NAO in recent decades in a longer-term perspective. The results indicated increased variability in the index prior to 1830, which the authors interpreted as a real phenomenon rather than a data inhomogeneity. The recent positive trend in the NAO observed in other indices did not appear as particularly significant when viewed in the context of the last 200 years. This leads to the conclusion that the recent upward trend in the NAO is within the bounds of natural variability. The results of Slonosky *et al.* (2001b) for the 1697–1708 period are particularly valuable given the general lack of data for this early period. Although the data sequence is short, the results indicated that reversals in the pressure gradient between London and Paris was more common in the 1690s than in modern times, which caused a greater frequency of easterly winds.

In assessing the Paris–London index, the results should be compared against the weather-type catalogue for the British Isles produced by Lamb (1972). In this well known catalogue, each day from 1 January 1863 to 3 February 1997 was categorized by Lamb into one of 11 categories (see Kelly *et al.*, 1997, for detailed information). Kington (1980, 1988) produced a series of Lamb weather types by classifying his reconstructed daily synoptic charts over the 1781–5 period. Of particular interest in connection with the NAO/Paris–London index is the frequency of westerly and easterly winds in the British Isles. Jones & Hulme (1997) showed that the index of westerly days during winter is highly correlated with the Ponta-Delgada–Iceland NAO index. In accordance with this NAO index, the 1900–30 period experienced an increased frequency of westerly weather types. The series for the 1781–85 period showed that the low-frequency of westerly weather types was second only to the low values of the 1968–72 five-year period. In addition Kington (1980, 1988) showed that the climate during the 1780–85 period was more variable than in the nineteenth and twentieth centuries, with an unprecedented number of cyclonic or anticyclonic days. Of particular note in Lamb's catalogue is the decline in the westerlies from 1950 to a minimum in the 1980s, which contravenes the upward trend that has been observed in the NAO indices over this period. In Jones *et al.*'s (1993) objective classification of weather types using grid-point MSLP, the decline in the westerlies is less evident. The authors speculate that this difference may be due to subjectivity in Lamb's original catalogue. This suggests therefore that the low values of westerly weather types during 1780–85 may actually have been the lowest in the entire series. The assessment of conditions during this period in the Paris–London index by Slonosky *et al.* (2000) is limited by missing data for London for certain years, which were completed using the Paris–Edinburgh average.

A more sophisticated objective clustering technique has been developed by Philipp *et al.* (2007), who assigned every day from 1850 to 2003 to a circulation category, using the daily gridded data series produced by Ansell *et al.* (2006). The use of daily resolution data allows more information to be gained than is permitted by monthly or seasonal means. The results indicate that their NAO-type pattern (cluster 1) in winter showed no overall trend, but did display high frequencies in the 1850–70 period. Significant differences are apparent however between this index and a 'true' NAO pattern, which has been attributed to the weighting of the clusters to European locations. Interestingly their cluster 4, which is a European westerly pattern, displayed a statistically significant increase over time.

6.2.4 The value of wind observations

Observations of wind direction were recorded in Europe much earlier than barometer observations and these data may therefore be used to give an indication of the state of the NAO in earlier times. As the NAO directly affects westerly wind flow over Europe, at least during the winter season, a westerly index derived from wind direction observations may serve as a NAO proxy. Several studies have analysed the interannual to decadal variability of westerly flow across western Europe using historic wind direction observations, although in many cases an explicit connection to the NAO has not been made. Brooks & Hunt (1933) gathered together daily wind observations recorded in various sources to provide a wind direction series for the British Isles beginning in the fourteenth century. Using these data the authors concluded that the 1730s experienced an increased frequency of westerly winds, while the 1740s were dominated by easterly flow. In southern Britain the 1794–1810 period also experienced predominately easterly winds. The remaining periods were characterized by westerly flow across Britain with the first 30 years of the twentieth century being notably characterized by south-westerly flow. Lamb (1967) analysed a dataset of daily wind direction observations from London beginning in 1670 and reached conclusions similar to Brooks & Hunt (1933). This may be partly explained by an overlap in the data sources used, but Lamb added the observation that the frequency of westerly winds was at a minimum in the 1690s. Jönsson & Holmquist (1995) used wind direction observations over the period 1740–1992 recorded at Lund in southern Sweden, and showed that a shift occurred during the 1860s from a dominant west-east (termed the 'Continental Low Zonality Period'), bi-directional pattern to a wind climate characterized by flow from the western and south-western directions. These results broadly correspond to the findings from the pressure-based NAO indices described in previous sections.

A major limitation of land-based wind direction data series is that the observations are susceptible to local wind anomalies that may not be indicative of the general synoptic flow. It is for this reason that ship log wind direction data series are primarily valued as the observations are not so influenced by boundary layer conditions (Wheeler & García-Herrera, 2008). Wheeler & Suarez-Dominguez (2006) reconstructed wind flow indices for the English Channel for the 1680s/90s using wind direction data recorded in naval logbooks. Considering only the period coincidental to the Paris–London series pressure series (1692–1700), the year 1695 stands out in the reconstructed series as experiencing reduced westerly flow, which was compensated by increased easterly flow. This series has recently been extended to 1750 by Wheeler *et al.* (2009). These new results provide further evidence of the dominance of westerly conditions in the relatively warm decade of the 1730s, and the dominant easterly conditions during the 1740s. Jones & Salmon (2005) attempted to use wind strength/direction data recorded onboard ships over the 1750–1850 period to reconstruct the NAO. The results from that study were disappointing with lower correlations achieved against proxy and instrumental series than have been achieved using other data series. The study concluded that this was most likely a result of the small number of observations in certain areas of the Atlantic. Progress is being made in combining ship logbook wind data with terrestrial pressure data to form gridded pressure data series for the Atlantic region back to 1750 (Gallego *et al.*, 2005; Küttel *et al.*, 2009b). However, such analyses are currently limited to the seasonal timescale and conclusions concerning the variability of the NAO are yet to be presented. The usefulness of this dataset may also be limited by the problem recognized by Jones & Salmon (2005) in that for a given 8°× 8° grid square there may be too few observations to give a reliable measure of the state of the wind.

6.2.5 The value of proxy data

To extend the NAO time series further back in time from the early/mid-nineteenth century, a variety of proxy data have been used, including ice cores (Appenzeller *et al.*, 1998; Vinther *et al.*, 2003b; Fischer & Mieding, 2005), tree-rings (Cook *et al.*, 1998), mollusk shells (Schöne *et al.*, 2003) and snow cover (Chu *et al.*, 2008). The potential for grape harvest dates has also been assessed, mainly as a check on paleo-reconstructions (Souriau & Yiou, 2001). Cook *et al.* (2002) combined a variety of tree-ring and ice-core series from north America, Greenland and Europe to produce a winter (DJFM) NAO proxy series for the years 1400–1979. This multi-proxy approach gave results that were more highly correlated with overlapping instrumental series compared to previous tree-ring only reconstructions. Their reconstruction indicated that while the multi-decadal variability of the NAO during the twentieth century is unusual in the context of the last 400 years, it is not unprecedented, with similar variability apparent in the fifteenth and sixteenth centuries . The multi-decadal variability of the NAO in the period 1640–1880 was greatly reduced.

In a more recent study, Trouet *et al.* (2009) have produced a 947-year-long multidecadal NAO reconstruction by using a tree-ring series from Morocco, which is indicative of drought conditions, and a speleothem-based proxy for precipitation in Scotland. The headline results from this reconstruction indicate that the NAO was in a persistent positive phase on multidecadal timescales in the period ca. 800–1450, but declined to a low phase during the Little Ice Age. A comparison with other proxies, which begin in 1500, reveal quite large differences particularly during the late seventeenth and eighteenth centuries, although the proxy appears to replicate the multi-decadal variation of the last 200 years reasonably well. Many of these discrepancies may be attributable to dating uncertainties, which are an inherent problem when dealing with speleothems and make the comparison with other proxies problematic (Jones *et al.*, 2009).

In an attempt to extend the NAO series back in time, while removing the terrestrial biases that occur when using European proxies, Goodkin *et al.* (2008) used a proxy series of sea surface temperature derived from Sr/Ca coral deposits in Bermuda for the period 1781–1999. Goodkin *et al.*'s reconstruction showed increased multidecadal variability in the twentieth century compared to the 1800–50 period. These results therefore correspond to the findings of Cook *et al.*'s (2002) multiproxy reconstruction, but Goodkin *et al.* have suggested that the increase in variability in the twentieth century may be linked to anthropogenic warming. However, the physical basis for a NAO signal in the coral deposits is not entirely understood. On interannual timescale the NAO reconstruction is positively correlated with NAO indices, while on multi-decadal timescales an inverse correlation has been observed. In the 7–10 year frequency no significant relationship is found. While this proxy is useful in understanding the effect of NAO variability on ocean dynamics, pressure observations remain the most useful way of assessing NAO variability over this time period.

An indication of the state of the NAO in earlier times can also be inferred from documentary data. Wanner *et al.* (1995) combined documentary information from the Euro-Climhist database with a variety of early instrumental (temperature, pressure and rainfall) and tree-ring data to examine the state of the North Atlantic circulation during the Late Maunder Minimum (LMM). The results indicated that during the 1675–1704 period the winter and spring seasons were characterized by strong reversals of MSLP that were akin to the extreme NAO– phase described by Moses *et al.* (1987). This was particularly the case during the 1690s when blocking in the Scandinavia/North Sea area led to frequent outbursts of cold continental air. The validity of these reconstructions have recently been questioned, on account of the lack of data for northern Europe (Camuffo *et al.*, 2010). Nonetheless, it seems reasonable to suggest that blocking was a major cause of the coldness experienced during this period. In addition, these assertions correspond to the results from wind-direction analyses (Lamb, 1967; Wheeler & Suarez-Dominguez, 2006) and pressure reconstructions (Lamb, 1977; Slonosky *et al.*, 2001b).

Also using documentary data, Rodrigo *et al.* (2001) reconstructed a winter NAO series back to 1501. That study used a variety of documentary sources from southern Spain to derive a rainfall index, which the authors linked to the NAO given the relationship of the oscillation to rainfall in modern times. The results indicate that the periods 1580–1650 and 1750–1810 were typified by NAO– conditions, with extremes in rainfall experienced in Iberia. NAO+ conditions, and a dearth of rainfall, were identified for most of the sixteenth century, and in the periods 1700–10 and 1900–50.

In keeping with the focus of most research studies on the NAO during the winter half of the year, few studies have attempted to reconstruct proxies that pertain to dominant modes of circulation during the summer months. The Luterbacher *et al.* (1999, 2002a) NAO reconstruction is an exception, and data have been reconstructed for all months back to 1659 and all seasons back to 1500. This index has been constructed by taking the average of 4×5° grid-squares located in the vicinity of Iceland and the Azores from the reconstructed pressure series of Luterbacher *et al.* (2002b). Given that this series was reconstructed mainly from European mainland documentary and instrumental series, especially prior to the late eighteenth century, the skill of the reconstruction is lowest at the extremities of the region. Indeed, a large part of the success of this reconstruction back to the late seventeenth century rests with the use of pressure series. During the LMM period (1675–1715) the early barometer readings of Louis Morin in Paris are the most important component of the reconstruction in all seasons (Luterbacher *et al.*, 2000). In the winter months the skill of the NAO reconstruction is high due to the coherence of the atmospheric circulation. In the remaining seasons, and especially in the summer months, the NAO reconstruction is weaker and the index is more likely to represent atmospheric circulation over Europe rather than in the Azores/Iceland areas. However, as has been described above (§6.2), the 'centres-of-action' of the NAO are shifted in the summer and therefore even an accurate reconstruction in these areas would fail to depict the NAO.

A more successful summer NAO reconstruction has been described by Folland *et al.* (2009), who extended their SNAO pattern of atmospheric circulation variability back to 1706 by using tree-ring chronologies from trees in Norway and the United Kingdom. This reconstruction of the SNAO displays pronounced multidecadal variability, with a permanent negative phase occurring in the period 1780–1810 indicating a higher frequency of westerly flow over western Europe during that period. Since the 1850s a gradual increase in the SNAO was noted, with sustained positive values occurring since the 1970s, which indicate a dominance of blocked conditions. The European Northwesterly index defined by Lamb & Johnson (1961) as the pressure difference at

50°N 0°E and 60°N 15°E for every July from 1750 to 1949, is comparable as a measure of the SNAO. The pattern of multidecadal variability displayed by this northwesterly index bears a striking resemblance to the variability observed in the Folland *et al.* (2009) reconstruction, with a minimum of the index occurring at ca. 1800. Lamb & Johnson (1961) attribute the strength in the pressure gradient at the turn of the nineteenth century to the frequent occurrence of a strong ridge extending from the Azores high into central Europe.

This dominance of westerly flow during the summer at the end of the eighteenth century has also been shown in the results of Jacobeit *et al.* (2003), who used the reconstructed dataset of Luterbacher *et al.* (2002b) to obtain dynamical modes of atmospheric circulation variability for the period 1659–1999 for the NA-WE region. The results for July indicate a high frequency of westerly conditions during the late eighteenth century, which is unique in the 340 year period. Unexpectedly, this was a time of milder July temperatures in the NA-WE, and the authors attributed this to changes within the westerly classification.

Proxy series are the only way of examining the variability of the NAO in the pre-instrumental period. However, the use of such indices are not without problems. A limitation of all proxy-based reconstructions of the NAO is that the relationship of the local proxy to large-scale atmospheric forcing is assumed to be stationary. Several studies have shown that strong non-stationarities exist in the relationship between temperature/precipitation and atmospheric circulation (Jacobeit *et al.*, 2001; Slonosky *et al.*, 2001a). Schmutz *et al.* (2000) compared several proxy based measures of the NAO and found that the correlations with the Gibraltar–Reykjavik NAO index were not high at either the interannual or decadal time scales, although the Luterbacher *et al.* (1999, 2002a) NAO reconstruction constantly provided the highest correlations. The results presented by Cook (2003) broadly confirm the findings of Schmutz *et al.* (2000), although Cook suggests that the inability of many proxy indices to reproduce reliable measures of the NAO may occur from a bias in the selection of proxies and in the calibration procedure through the use of instrumental data from the anomalous twentieth century. It is suggested by Cook that improvements can be made to proxy reconstructions of the NAO by extending the calibration into the nineteenth century. However, the problem remains with all proxies that the relationship between the derived NAO index and temperature and precipitation data can not be assessed due to the proxies themselves being derived from temperature and/or precipitation relationships. In relation to this it must be emphasized that NAO proxies do not respond directly to atmospheric circulation or wind direction, but rather to the effects of these on temperature and/or precipitation (Cook, 2003). It is for this reason that Jones *et al.* (2003) concluded that the NAO would be best reconstructed, where possible, by using pressure series alone.

6.3 The Paris–London westerly index

6.3.1 The construction of the Paris–London index

To extend the work of Slonosky *et al.* (2000), Slonosky *et al.* (2001b) and Jones *et al.* (2003) a westerly index was constructed from the daily London and Paris pressure series in the same manner as these previous studies. However, the Paris–London index used in this study covers a longer timespan, as it extends back to 1748 on a near-continuous basis and back to 1692 on a more fragmentary basis. In addition, the quality of the data is considered higher than that of the data used in the previous work (see Chapter 5). Further, consideration is given here to all seasons, while the previous studies only analysed the winter and annual time series.

To construct the Paris–London index, the daily values were first reduced to monthly means but where the number of missing days in a month exceeded 40% the month was marked as missing. Anomalies were then calculated from these monthly data by subtracting the monthly mean for the period 1961–90 to provide an index that represented deviations from modern-day conditions. These data were then normalized by dividing by the monthly standard deviation, which was also calculated from the 1961–90 period. Both of these procedures were conducted on a month-by-month basis. Several different base periods were tested but the results from all tests were very similar.[4] This process of normalizing the data is necessary to eliminate the annual cycle from the data and to ensure that a high variance in either station does not bias the series. This procedure has been used extensively in the calculation of station-pair indices for the Southern Oscillation Index (SOI) (Ropelewski & Jones, 1987) and for the North Atlantic Oscillation Index (NAOI) (Jones *et al.*, 1997). As the standard deviation value for London and Paris is similar (see Table 5.1) compared with, for example, the large difference between Ponta Delgada and Stykkisholmur in the North Atlantic Oscillation Index (NAOI), it may be considered an unnecessary step. However, the derivation of indices both with and without normalization were tested and it was discovered that without normalization the variability of the index was very slightly reduced. The seasonal and annual values of the index were simply calculated as the mean of the months in the respective seasons/years.

6.3.2 The relationship of the Paris–London index to hemispheric MSLP

Slonosky *et al.* (2000) have suggested that the Paris–London index is a zonal index for western Europe, which is downstream of the NAO 'centres-of-action'. As the pressure gradient between London and Paris over climatological timescales declines from south to north, the Paris–London index provides a measure of geostrophic flow on a line that approximates the position and direction of the English Channel, according to Equation 6.1.

To provide further information on the exact pattern of atmospheric circulation that the Paris–London index describes, correlation maps have been produced between gridded MSLP and the Paris–London index (Figure 6.1). In all seasons except summer, high values of the Paris–London index are associated with low pressure centred to the east of Iceland and high pressure in an area encompassing the southern Mediterranean and north Africa; the reverse is true for negative values of the index. The axis of this dipole follows the Greenwich Meridian and hence positive values are associated with westerly flow over Europe, with negative values associated with easterly flow or less strong westerlies. These results confirm the assertions of Slonosky *et al.* (2000) that the Paris–London index is a westerly index for Europe, which is downstream of the NAO 'centres-of-action'. It is important to note, however, that the pattern is most coherent in the winter (DJF) when the correlation coefficients are highest. During winter the circulation pattern has elements of clusters 4 (a European westerly pattern) and 5 (a NAO-type pattern) following the classification by Philipp *et al.* (2007). It also includes elements of the East Atlantic pattern as defined by Barnston & Livezey (1987). During the summer in

[4] It should be noted that Slonosky *et al.* (2000, 2001a) used a normalization period of 1871–1995 in their Paris–London index but given this information the differences between the indices is likely to be slight.

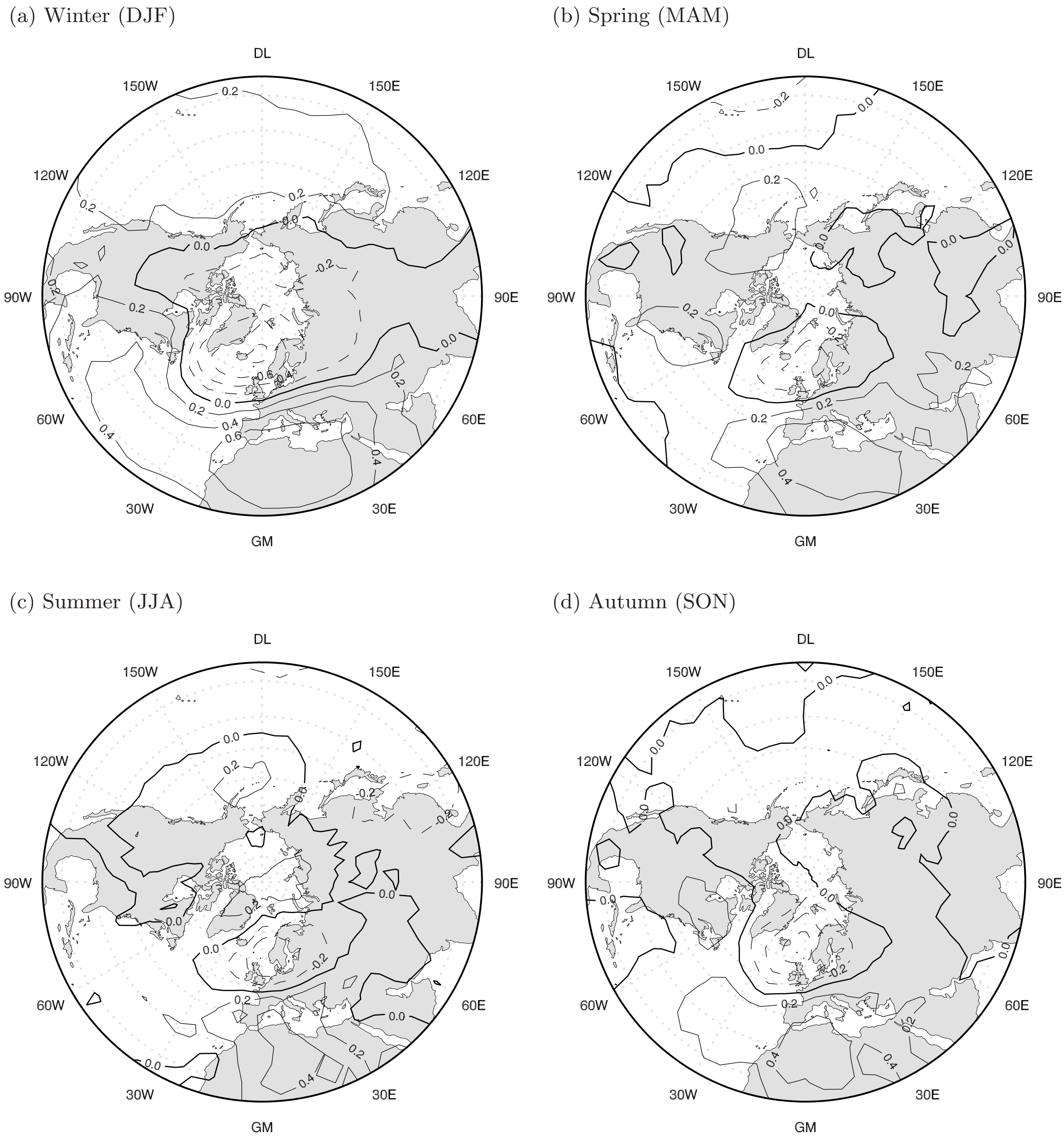

Figure 6.1: Point correlation maps between gridded hemispheric MSLP and the Paris–London index over the period 1881–2004. The values of n during the winter and spring are 123 and 124 respectively; for summer and autumn n = 121. The contour interval is 0.2. The HadSLP2 pressure data series was used and the data were converted to anomalies from the 1961–90 mean. Although the HadSLP2 data series begins in 1850, the data prior to 1881 were excluded due to their lower quality (see Allan & Ansell, 2006).

particular the pattern of the southern node is complicated and although the correlations are much weaker than during the other seasons the area of negative correlations is shifted south and is centred on the North Sea. Two areas of positive correlation are evident: one area is located near to Tunisia and a second, weaker, area is located in the Arctic. These results for summer indicate that the Paris–London index produces a measure of the SNAO as defined by Folland *et al.* (2009), with the weak Arctic node and the North Sea node corresponding to the north and south nodes of the SNAO respectively. However, the Paris–London index primarily quantifies the southern node of the SNAO, and remains a westerly index. Therefore an inverse

Period	Data	Abbreviation	Source
1865–2003	Ponta-Delgada–Stykkisholmur	PD–Styk	Rogers (1984)
1821–2007	Gibraltar–Reykjavik	Gib–Reyk	Jones *et al.* (1997)
1821–2007	Gibraltar–Reykjavik	Vinther	Vinther *et al.* (2003a)
1864–2007	Lisbon–Stykkisholmur/Reykjavik	Lis–Styk	Hurrell (1995)
1873–2007	Zonal pressure difference (35°N and 65°N)	Li/Wang	Li & Wang (2003)
1899–2007	First eigenvector of North Atlantic MSLP	NAO PC	Hurrell (1995)
1692–2000	Reconstructed MSLP* (Azores/Iceland)	Luterbacher	Luterbacher *et al.* (1999)
1692–1979	Multiproxy reconstruction	Cook	Cook *et al.* (2002)
1692–1984	Multiproxy reconstruction	Glueck	Glueck & Stockton (2001)

Table 6.1: The NAO indices used in this chapter for comparison with the Paris–London index. The two Gibraltar indices (Gib/Reyk and Vinther) have been extended to 2007 using Tim Osborn's update available at `http://www.cru.uea.ac.uk/~timo/datapages/naoi.htm`. The dates in the Glueck series have been amended so that the year reflects the January of the winter season and therefore differs from the years quoted by the authors, who took the winter dated from the December month. The DJFM mean values for the Li/Wang series has also been adjusted so the season is dated by the January year. * The data after December 1900 are an updated version of the gridded dataset developed by Trenberth & Paolino (1980).

relationship would be expected between the SNAO and the Paris–London index. It must also be remembered that the SNAO is primarily a feature of high summer (July and August) and a different pattern is evident in June (Folland *et al.*, 2009). The consideration of the mean of JJA would therefore be likely to weaken the depiction of the SNAO in the results.

6.4 Temporal variations in the Paris–London and NAO indices

In this section the Paris–London index is compared with various NAO indices (Table 6.1). Both proxy and instrumental indices were used in the comparison, following the example set by Cook (2003). The following five subsections compare the seasonal and annual indices.

6.4.1 Winter

Two definitions of the winter season are used in this section: the conventional mean of December to February, and the mean of December to March. Common to all of the time series (Figures 6.2 and 6.3) is the persistence of positive values during the 1900–30 period. As has been described above (§6.2), this period of predominately westerly flow has previously been recognized in many studies. However, it must be noted that while the 1900–30 period was dominated by strong westerly flow, it was punctuated by very strong easterly conditions during the winter of 1916/17.

The NAO indices in Figures 6.2 and 6.3 all show a decline in index values from the 1940s to the early 1970s, and a recovery thereafter to a consistently high period during the late 1980s/early 1990s. However, the Paris–London index shows a more suppressed variability, with generally low negative values during the 1940–80s and a dominant period of high positive values during the 1990s. This low-frequency variability is also suppressed in the Gibraltar–Stykkisholmur index compared to the other NAO indices and this feature is most likely a result of the asymmetry in the spatial distribution of MSLP during positive and negative phases of the NAO, as described above (§6.2). As has been shown in Figure 6.1, the pattern of MSLP in the North Atlantic associated with the Paris–London index is similar to the NAO+ conditions described in the regime analyses by Cassou *et al.* (2004) and Hurrell & Deser (2009). However, this pattern is somewhat different to the NAO– conditions when the northern node is shifted northwestward

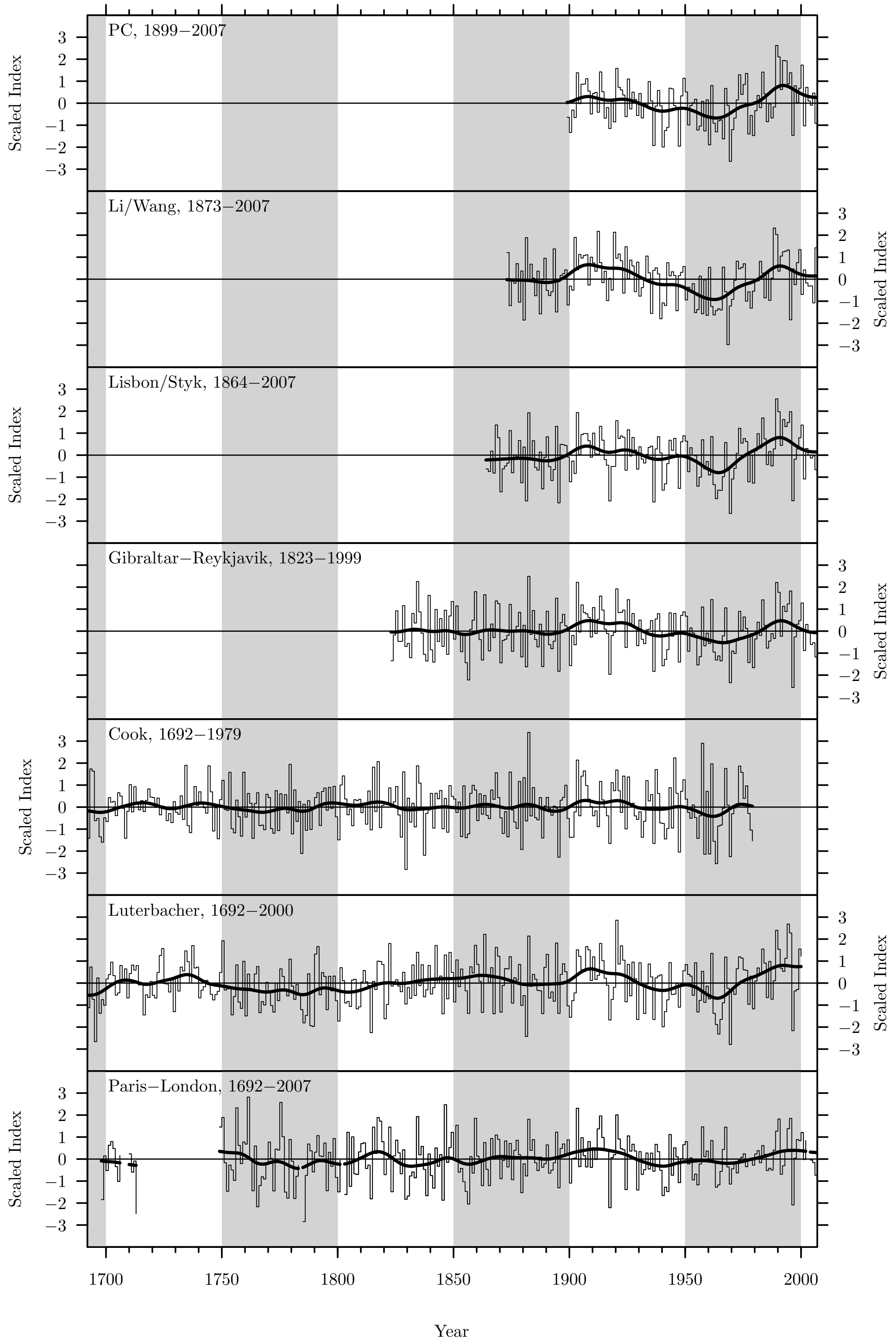

Figure 6.2: Time series plots of the NAO series listed in Table 6.1 and the Paris–London series during the extended winter season (DJFM). The Glueck series was not included in this plot as it has been reconstructed for the winter season expressed as DJF and is therefore not comparable with the other series. It should be noted that the data after 1901 in the Luterbacher series are derived from instrumental data. The thick black line shows the data smoothed with a 30-year Gaussian weighted filter.

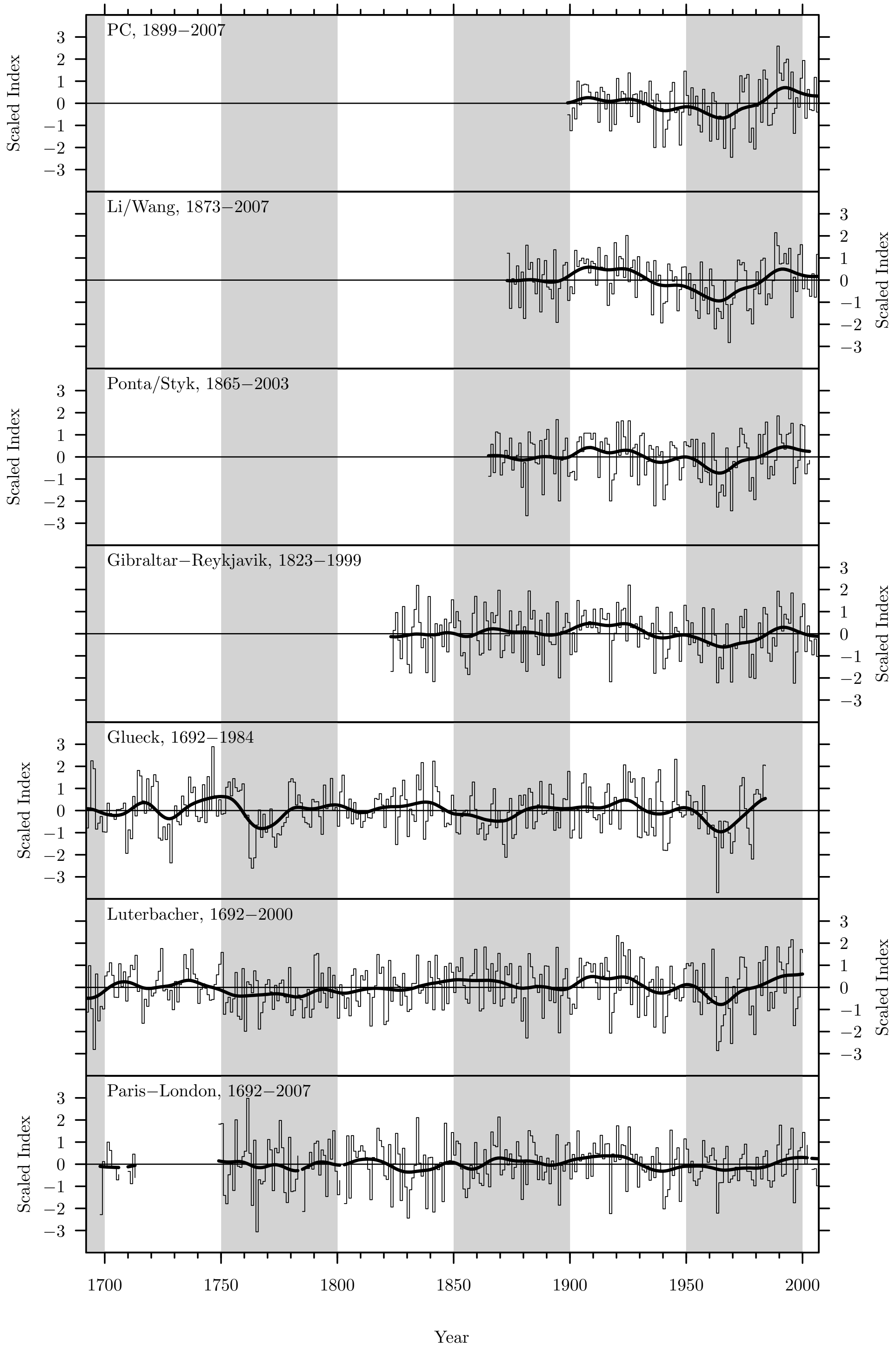

Figure 6.3: As Figure 6.2 but for winter (DJF). The Cook series has been excluded from this plot as it has been reconstructed for the extended winter season (DJFM) and is shown in Figure 6.2.

and the southern node is shifted northeastwards. This bias towards NAO+ conditions is also evident in the Ponta-Delgada/Stykkisholmur index but the positions of these two stations still reside within the 'centres-of-action' during NAO– conditions. On the other hand the Li/Wang and PC indices are able to capture this asymmetry more successfully given the positions of the data used.

The latter half of the nineteenth century did not experience any significant features of the NAO, with generally zero values evident in all of the indices. The winter of 1881/82 does stand out, however, in most NAO indices as experiencing very high values, with this winter having the highest long-term value in the Gibraltar/Stykkisholmur and Cook DJFM series. In the Paris–London series this winter experienced strong westerly values but of a magnitude similar to those during the 1990s.

The results for the first half of the nineteenth show interesting features, and are particularly worthy of investigation as this is the first period described so far that is outside the range of most of the instrumental NAO series. In the Paris–London index, the 1820–45 period generally experienced weak westerly conditions, and the index was in a negative phase apart from the westerly conditions of the mid 1830s. The 1800s and 1810s were typified by strong westerly conditions, which was of a similar magnitude to the strong westerlies experienced during the 1900–39 period, although the winter of 1814/15 experienced strong easterly conditions. The results for the 1800–10 period are quite different from those of the Luterbacher and Glueck reconstructions, which show generally normal conditions during this period.

The synoptic situation at the turn of the nineteenth century has been described in several studies as being dominated by easterly conditions (Kington, 1988). In the Paris–London index, the 1780s experienced anomalously weak westerly/easterly conditions, with the lowest negative value of the entire DJFM series being experienced during the winter of 1784/5. In the representation of winter as DJF this winter does not show a very low index value, which would indicate that the seasonal mean during that year is strongly affected by easterly conditions during March 1785. Indeed the weather maps of Kington (1988) indicate a dominant anticyclone over the British Isles. In addition, the *London Weather Diary (LWD)* indicates predominantly easterly winds in London during that month (Manley, 1964). Justification for this reconstruction also comes from temperature data, as March 1785 was the coldest March in the CET series (Lamb, 1995). The Luterbacher and Cook reconstructions also display negative values throughout the 1780s, although the Glueck index indicates negative values in the second half of the 1780s.

In the Paris–London index, the 1760s are shown to have experienced extremes of values, with the highest positive value of the entire DJF(M) series during the winter of 1760/61 and the lowest negative value in the DJF series experienced during the winter of 1764/65. This results contrast sharply with the results from the Luterbacher and Cook indices, which show generally negative values throughout the period. It is possible that errors in the London and Paris data may have led to these results. Indeed the transcription of the alternation of temperatures between Greenland and Germany published by van Loon & Rogers (1978) indicates that the winter of 1764/65 should be NAO+, with temperatures in Greenland very cold and in Germany moderate. It should be noted, however, that not all of the Greenland-above (below) winters described by van Loon & Rogers (1978) are negative (positive) in the Paris–London index. Furthermore, the interannual variability in the Paris–London index during the 1760s bears a close relationship to that shown in the Central England Temperature (CET) series, as shown in the following chapter (especially Section 7.4 and Figure 7.5). This independent information suggests that the Paris–London index is reliable during the 1760s.

The results at the turn of the eighteenth century are limited by the high number of missing values in the Paris–London index. There is an indication from those months that can be represented that generally negative values of the index were experienced during the winter months. This supports the results from documentary sources

6.4.2 Spring

Large differences between the various NAO time series and the Paris–London series are apparent during the spring (Figure 6.4). Most notably, the NAO indices show that the 1890–1930 period was dominated by strong westerly flow, whereas the Paris–London index displays near neutral conditions during that period. In the twentieth century the 1950–70 period was dominated by strong westerly flow in the Paris–London index, but this is only evident in the Gibraltar–Reykjavik NAO index, and to a less extent the Luterbacher series. Further back in time, the 1830–50 period was dominated by negative values in the Paris–London index, and this is also apparent although at a reduced rate in the Luterbacher reconstruction. Prior to this, the late eighteenth/early nineteenth century experienced predominately strong westerly conditions. This differs from the Luterbacher reconstruction, which shows strongly negative values in that period.

The 1780s are shown to have experienced strong negative values in the Paris–London index during the spring season; negative values are also evident in the Luterbacher reconstruction during that time. This agrees well with the easterly conditions described by Le Roy Ladurie (1972), which did great harm to the vine harvests in France at the time.

The strongest negative value in the spring season occurred in 1713, with the surrounding years also experiencing negative values. This extreme value is most probably a result of the low quality of the London pressure data during this period, which were obtained from the anonymous Holborn weather diary. However, the Luterbacher reconstruction shows this short period to have experienced negative values, although the magnitude is much less than that in the Paris–London index.

The 1700s are shown to have experienced strongly positive values in the Paris–London index, although prior to this there is an indication of predominately negative values. As with the winter series, the large number of missing values in the London pressure series during the 1690s preclude any definite conclusions. However, the spring season in the 1690s have been shown to have experienced strong easterly conditions (Wanner *et al.*, 1995), and these results tentatively appear to support this view.

6.4.3 Summer

During the summer months of the year (Figure 6.5), the Paris–London index bears little relation to the instrumental NAO indices. There is, however, close agreement between the Luterbacher reconstruction prior to 1900 and the Paris–London index. Of particular note is the high positive phase during the period 1770–1825, with a peak ca. 1800. This multidecadal variability is very similar to that shown in Folland *et al.*'s (2009) tree-ring reconstruction of the SNAO (especially

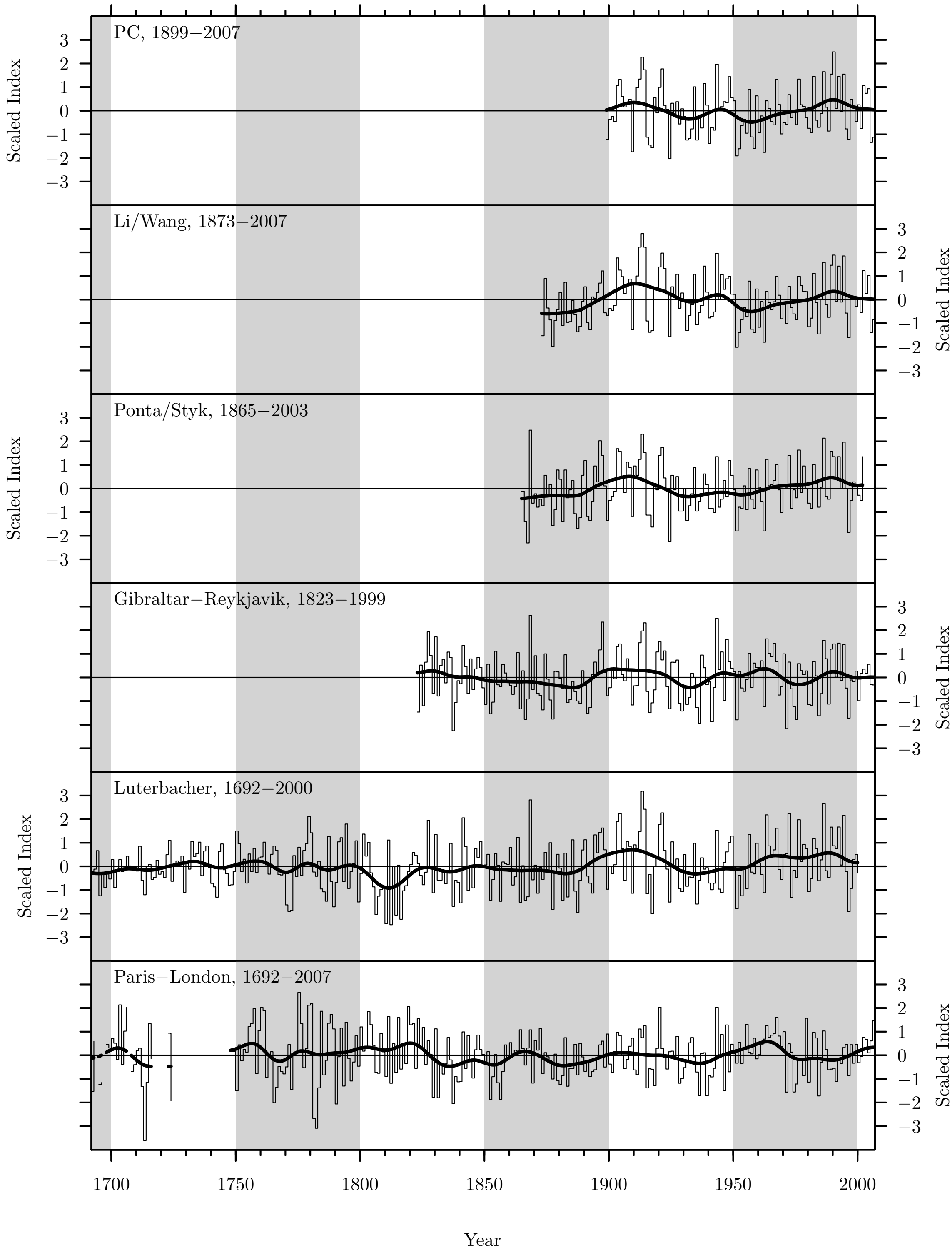

Figure 6.4: As Figure 6.2 but for spring (MAM).

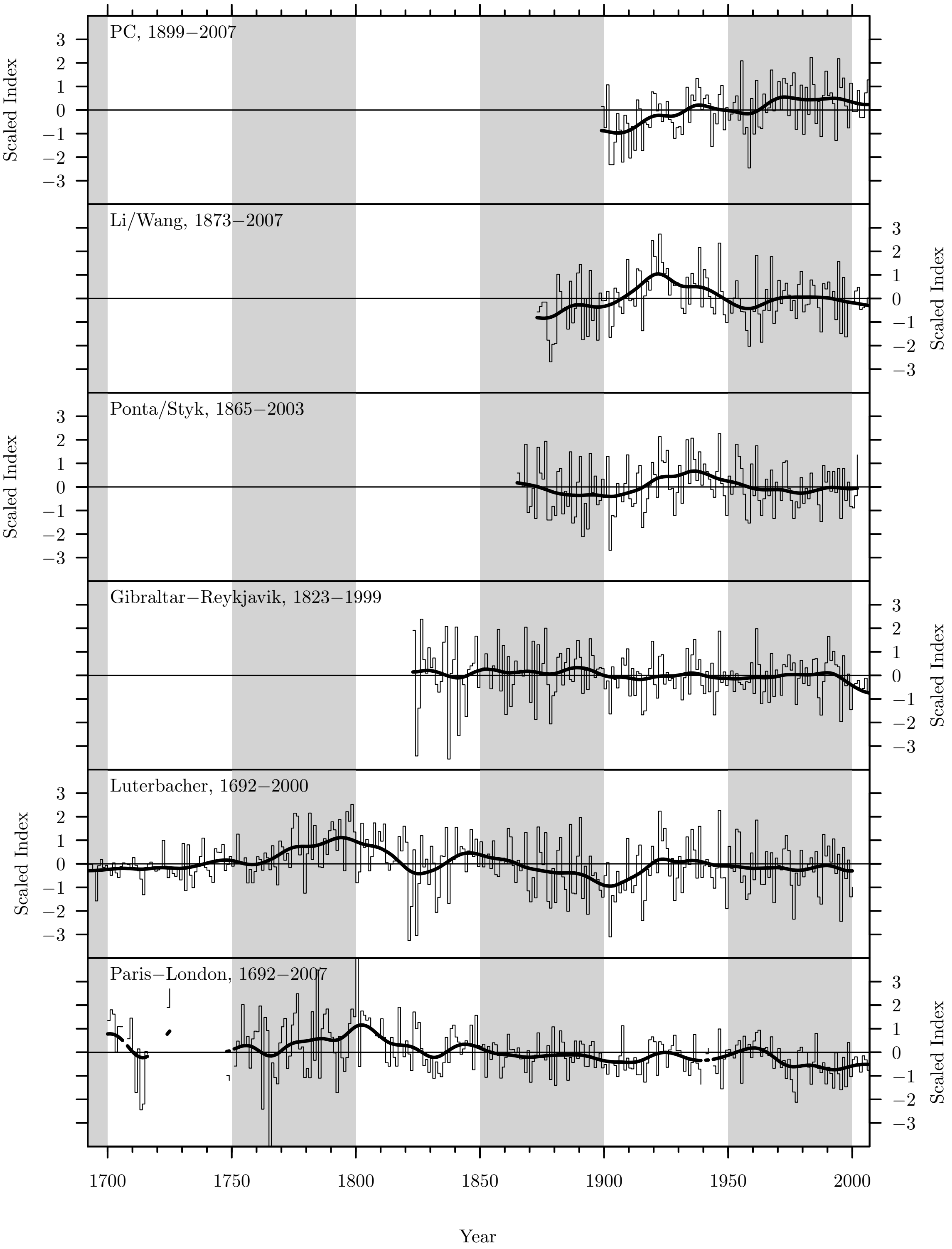

Figure 6.5: As Figure 6.2 but for summer (JJA).

their figure 3, where the index is inverted so that positive values indicate westerly flow). Briffa *et al.* (2009) have also indicated that this was a period of predominately high summer rainfall, with a persistence unprecedented in the 300-year series. The feature was most marked in Briffa *et al.*'s rainfall record from Kew, and given the proximity of the Paris–London index a close agreement would be hoped for. These findings also agree with the findings of Lamb & Johnson (1961), who attributed high values of their northwesterly index in summers during the late eighteenth century to the frequent occurrence of a strong ridge of pressure extending from the Azores high into central Europe. Jacobeit *et al.* (2003) also noted this increase in the frequency of westerly weather types during July and attributed the coincidental milder conditions across the NA-WE region at the time to negative vorticity anomalies within the broad westerly circulation.

In contrast to the Luterbacher reconstruction, this 50-year period of predominately strong positive values was also a period of high interannual variability in the Paris–London index. This difference may be attributable to the temperature corrections applied to the barometer observations in the London and Paris series. The quality of the temperature data in all seasons is likely to be low (see Chapters 2 and 3), and there is the additional problem that in some cases the temperature data were not always recorded near to the barometer but were outside temperatures. In the winter months when the temperatures are lowest the corrections and hence the errors transferred to the pressure data are small. In the summer months the temperature corrections applied to the barometer observations reach a maximum and hence the errors are also larger.

A notable feature of the Paris–London index is that in the period since ca. 1970 the index has been in a predominately negative phase, and there have been only three summers when the index was positive. This feature agrees well with the results from the Central European zonal index developed by Jacobeit *et al.* (2001) for the years 1780–1995 and the tree-ring based SNAO reconstruction by Folland *et al.* (2009). These results also correspond closely to the results of Briffa *et al.* (2009), which have indicated that this period is associated with a period of dryness in Europe that is anomalous in the context of the last 300 years.

6.4.4 Autumn

The time series for the autumn season (Figure 6.6) show some interesting results for the period 1690–1710. The Luterbacher reconstruction indicates that this period experienced weakly negative NAO conditions during the 1690s and zero conditions during the 1710s. In contrast the Paris–London index indicates that strong westerly conditions were experienced in the 1690–1700 period, followed by strongly negative conditions in the 1710s. Indeed, the westerly conditions experienced during the autumns of the 1690s and 1700s were the highest recorded in the series. It has been suggested by Lamb (1967) that there was an increase in the frequency of wet autumns in the British Isles during the 1690s, which would accord well with an increased frequency of westerly conditions across Europe.

6.4.5 Annual

To conclude this section, the annual mean time series are plotted in Figure 6.7. The results for the Paris–London index agree with the findings of Slonosky *et al.* (2000), in that the variability in the Paris–London is much greater before 1830 than afterwards. This is attributable to the high variance apparent in the index during the summer months. As has been mentioned in Section 6.4.3, the quality of the pressure data is likely to be at a minimum during the summer on account of the lower quality of the thermometer data used in the temperature corrections. However, other studies (Kington, 1980) have indicated that the atmospheric circulation in the

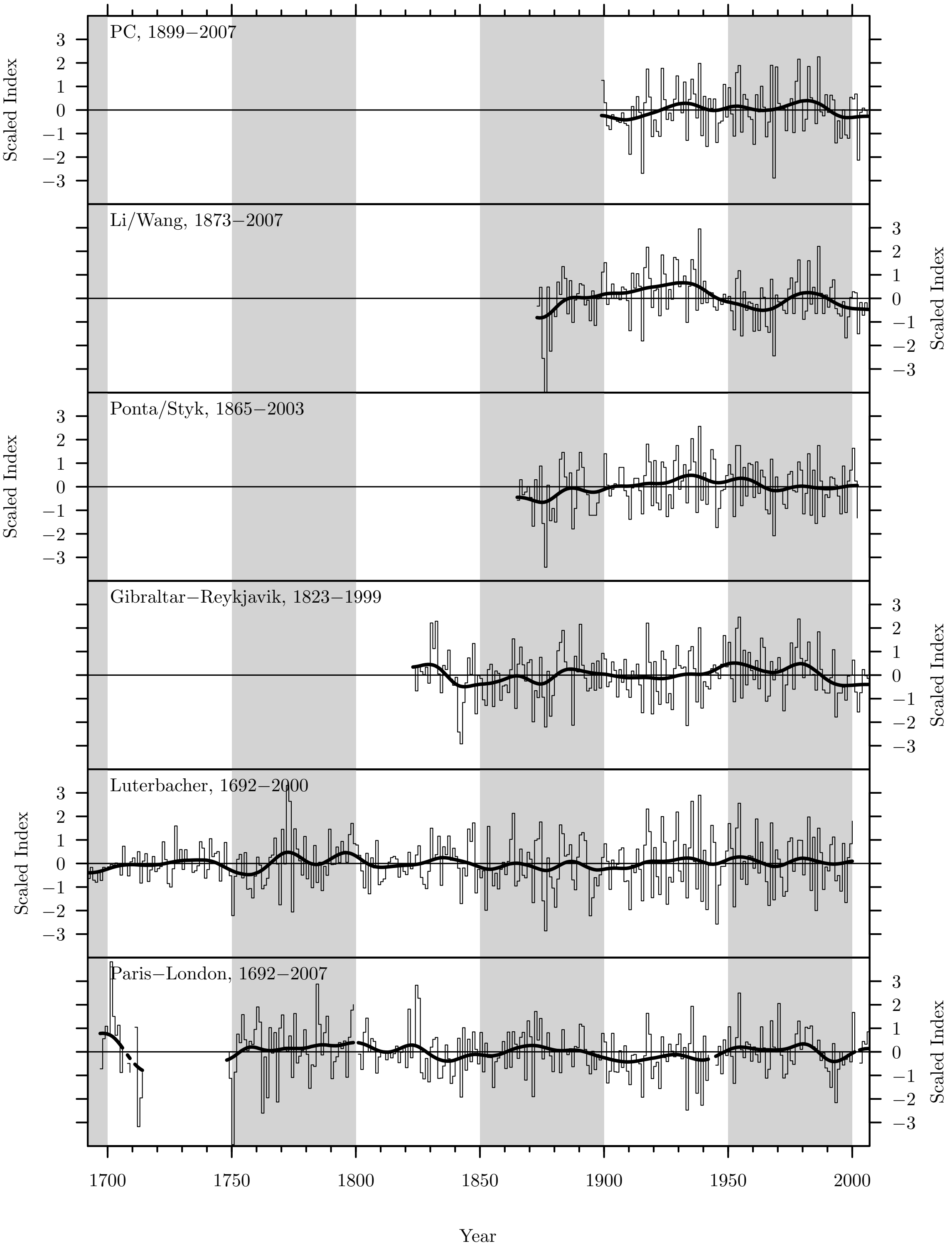

Figure 6.6: As Figure 6.2 but for autumn (SON).

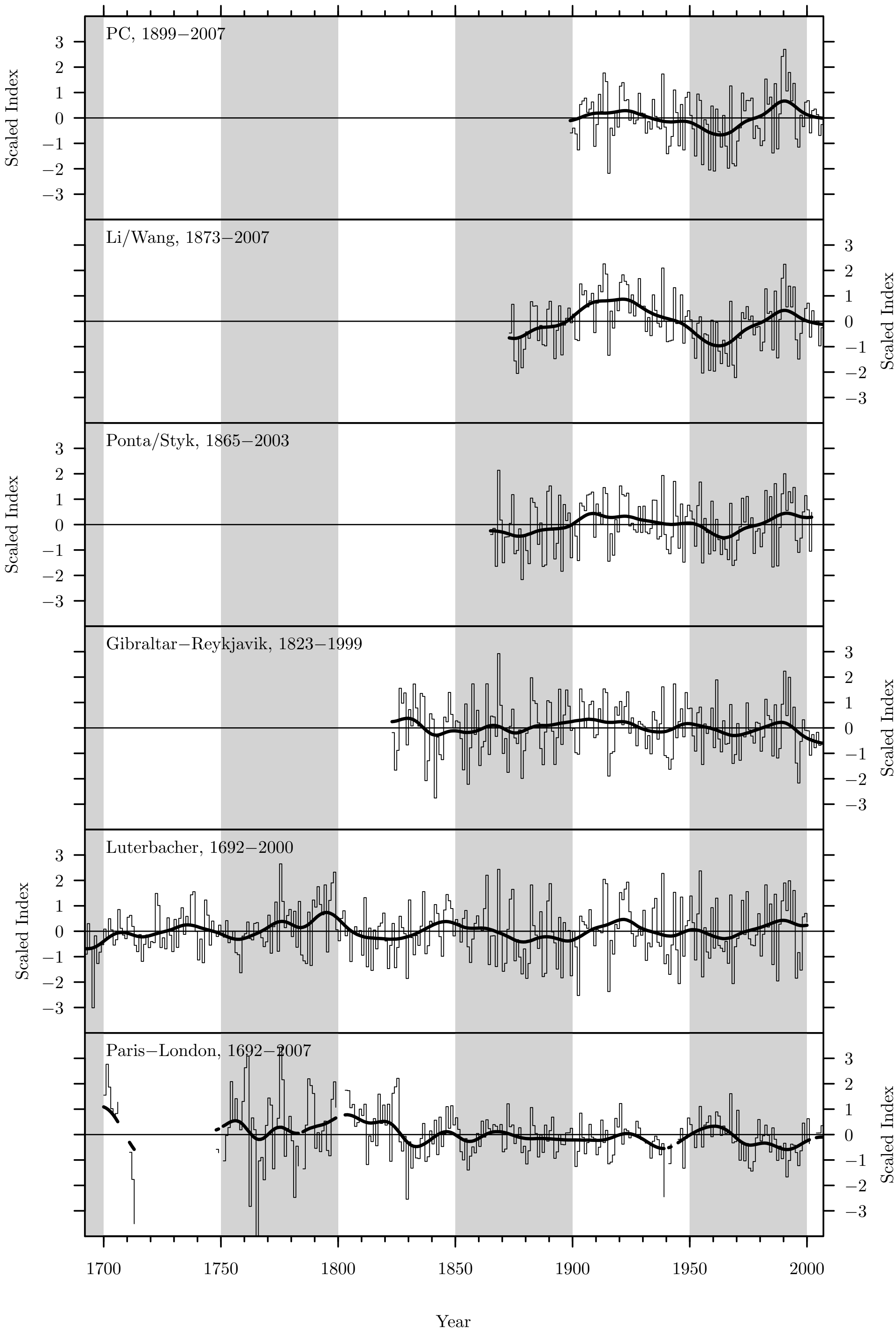

Figure 6.7: As Figure 6.2 but for annual means.

	Lisbon/Styk	PC	PD/Styk	Li/Wang	Gib/Reyk	Vinther	Glueck	Cook	Luterbacher
Jan	–	–	0.64	0.75	0.83	0.84	–	–	0.67
Feb	–	–	0.71	0.84	0.89	0.89	–	–	0.74
Mar	–	–	0.62	0.59	0.76	0.76	–	–	0.68
Apr	–	–	0.34	0.48	0.61	0.58	–	–	0.50
May	–	–	0.28	0.40	0.62	0.56	–	–	0.39
Jun	–	–	0.26	0.36	0.43	0.44	–	–	0.38
Jul	–	–	0.22	0.23	0.40	0.37	–	–	0.38
Aug	–	–	0.22	0.30	0.53	0.47	–	–	0.30
Sep	–	–	0.38	0.44	0.57	0.56	–	–	0.36
Oct	–	–	0.51	0.60	0.68	0.65	–	–	0.51
Nov	–	–	0.54	0.59	0.72	0.73	–	–	0.50
Dec	–	–	0.49	0.66	0.71	0.74	–	–	0.66
DJFM	0.77	0.64	0.68	0.76	0.81	0.83	–	0.52	0.57
DJF	–	0.60	0.66	0.76	0.81	0.84	0.18	–	0.59
MAM	–	0.19*	0.30	0.35	0.58	0.52	–	–	0.39
JJA	–	-0.27	0.14*	0.18	0.29	0.22	–	–	0.29
SON	–	0.61	0.43	0.40	0.58	0.54	–	–	0.32
Annual	–	0.10*	0.25	0.17*	0.39	0.28	–	–	0.23

Table 6.2: Monthly, seasonal and annual correlations between the Paris–London index and various NAO indices. All correlations are significant at the 95% level unless marked by an asterisk. Correlation coefficients greater than 0.7 are underlined for clarity. The DJFM value for the Ponta-Delgada/Stykkisholmur index has been calculated from the mean of the component months (dated by the January) and therefore differs from the calculation of the values during the other seasons. The values from January 1901 to December 2000 in the Luterbacher series, which were pressure data, have been excluded from the series in the calculation of the correlation coefficients. The full-length of each series have been used to compute these correlations. Caution should therefore be exercised when cross-comparing results from the different NAO indices as the sample sizes differ between the series. The difference is most marked between the instrumental and proxy series.

period before the mid-nineteenth century was more variable than the period after. This may therefore be a real feature of the atmospheric circulation and not a data inhomogeneity.

6.5 Correlations between the Paris–London and NAO indices

6.5.1 Interannual correlations

The interannual correlation between various NAO indices is well established (Osborn *et al.*, 1999a; Wallace, 2000; Wanner *et al.*, 2001; Li & Wang, 2003). To gauge the relationship between the Paris–London index and the NAO indices, a table of correlation coefficients is shown in Table 6.2. The highest correlations are achieved with the NAO indices that take data from the Iberian peninsula for the southern station (Gib/Reyk and Vinther). The weakest correlations are achieved for the indices that are furthest west, in particular the Ponta-Delgada–Stykkisholmur index. These results would be expected, given that the axis of the dipole quantified by the Paris–London index roughly follows the Greenwich Meridian (see Figure 6.1). Interestingly the improvements made to the Gibraltar–Reykjavik index by Vinther *et al.* (2003a) appear to have been justified only during the winter months. In the summer months lower correlation values are achieved than for the original Jones *et al.* (1997) series and this is probably due to the temperature correction that Vinther *et al.* applied to the Cadiz/San Fernando barometer readings. In the absence of barometer temperatures, contemporary outdoor temperatures were used, and it seems likely that these temperatures were too high in the summer months compared to the true barometer temperature, which led to an over-correction of the pressure data.

The correlations in all series are at a maximum in the winter months, particularly in February, and show a minimum during the summer. This would be expected given that the atmospheric circulation is most coherent during the winter. During the summer season (JJA) the correlation between the PC NAO index and the Paris–London index is weakly, although statistically significant, negative. This is a reflection of the position of the southern node of the NAO during these months, which is shifted northwards and is situated over the British Isles. Thus in a positive phase of this index, weak eastern flow is experienced across Europe.

The correlations between the Paris–London and the three proxy indices show some interesting results. The Cook multiproxy reconstruction shows a much higher correlation than the Glueck reconstruction. However, the highest correlations are evident for the Luterbacher reconstruction, particularly during the winter months when the correlation coefficients are comparable to those obtained for the Ponta-Delgada/Stykkisholmur series. However, during the summer months the correlations between the Luterbacher series are much higher than the Ponta-Delgada/Stykkisholmur index. Caution must be exercised when cross-comparing the results because the correlations were derived over different time periods and because the sample sizes differ. However, this feature of the Luterbacher correlations would suggest that the reconstruction is biased towards mainland Europe. This is reflected in the results of Luterbacher *et al.* (2002b), which show that the highest skill in the reconstruction is achieved over Europe during the summer. In the winter when the atmospheric circulation is most coherent the reconstruction has a closer link to the pressure centres of the NAO.

6.5.2 Running correlations

As an extension to the series-long correlation analysis above, running correlations have been calculated between the Paris–London series and the NAO series (Figure 6.8). The running correlations during the winter (DJM and DJFM) are generally similar between the series. In the summer, large differences are apparent. This would be expected given the series-long correlations listed in Table 6.2.

The correlation between the Paris–London and Gibraltar-Reykjavik index is consistently the highest with values ranging between 0.7 and 0.9 during winter. Compared to the results of Jones *et al.* (2003), the running correlation between the Paris–London index and Gibraltar–Reykjavik here is more consistent over time, which is probably a reflection of the greater homogeneity of the Paris–London index, but also the improvements made to the Gibraltar–Reykjavik index by Vinther *et al.* (2003a). In the summer the earliest correlations are below 0.2 but rise to between 0.3 and 0.5 during the early twentieth century but gradually decline thereafter. A similar trend, although with higher values of r are evident during the autumn. As has been discussed above (§6.5.1) the correlations during the earliest period may be due to an over-correction of the Gibraltar station data by Vinther *et al.* (2003a).

A significant feature of the running correlations during the winter (DJF and DJFM) is the decline in the correlations beginning in 1930, which reaches a minimum at the 31-year period

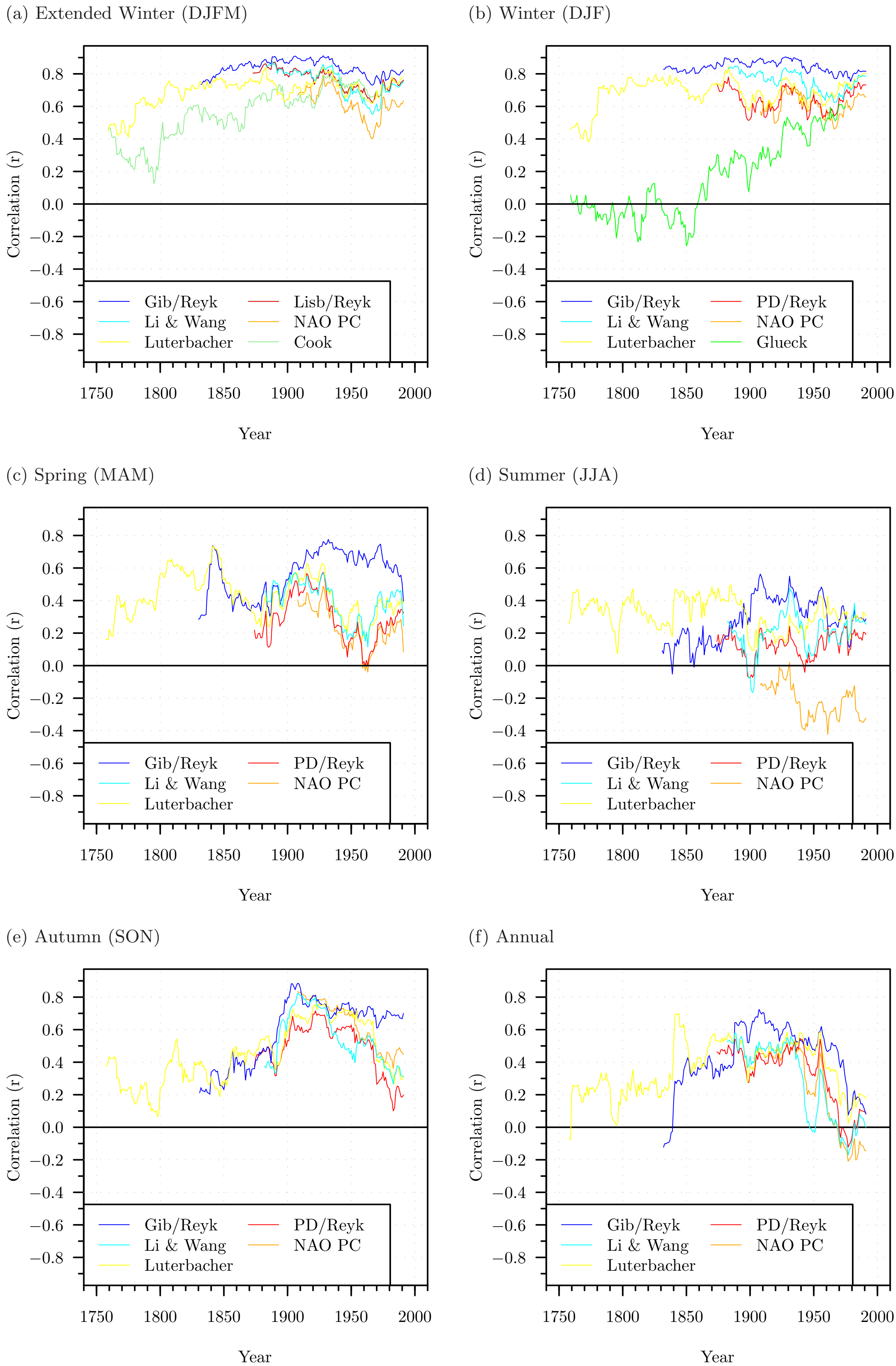

Figure 6.8: Running correlations (31-year centred) between the Paris–London index and various NAO indices. The sources of the NAO series are listed in Table 6.1. Correlations with the proxy series before 1748 are not possible given the large numbers of missing values in the Paris–London index. Where the number of missing values in a particular 31-year segment exceeded 20% the correlation was not computed.

centred around 1970; a recovery in the strength of the relationship can be observed thereafter. This feature is most marked in the extended winter season (DJFM). Jones *et al.* (2003) also commented upon this feature of their running correlation analyses using their Paris–London index.

The two proxy NAO indices (Cook and Glueck) have consistently the lowest correlations compared to the other indices until around 1950, when they are comparable with the instrumental NAO indices. The Cook index is consistently more highly correlated to the Paris–London index than the Glueck index, which is weak (and generally negative) throughout much of the eighteenth and nineteenth centuries. In contrast to these two proxy series, the correlations for the Luterbacher series are generally high throughout the eighteenth and nineteenth centuries during the winter months. Interestingly the correlations for the Luterbacher series from 1900 are consistently higher compared to the Ponta-Delgada series in the winter (DJF) season. The Luterbacher series during this time uses the National Center for Atmospheric Research (NCAR) five-degree gridded pressure data (Trenberth & Paolino, 1980), and the higher correlations may be attributed to the index being centred slightly to the east and hence nearer to the Paris–London index than the Ponta-Delgada series.

During the winter season (DJF and to a lesser degree DJFM) a clear step can be observed at around 1780 in the correlations with the Luterbacher *et al.* reconstruction. This is most likely attributable to the increase in the number of predictors included in the reconstruction during this period and in particular the inclusion of more instrumental pressure series (Luterbacher *et al.*, 1999, 2002a). It must also be noted that the London and Paris pressure series that were homogenized during the ADVICE (1998) project were also included in the Luterbacher *et al.* reconstruction, beginning in 1774 and 1760 respectively. As the same sources of data were used in the ADVICE London/Paris series and the daily London/Paris series during much of the late eighteenth/early nineteenth century, the potential for circularity in this comparison can not be ruled out. However, as demonstrated in Chapter 5 the series differ during that period due to the different corrections that were applied to the data. This would suggest that the strong correlations are a feature of the improving quality of the Luterbacher *et al.* reconstruction at this time and are not due to a circular relationship.

Before 1900 during the summer, the Luterbacher *et al.* series has consistently the highest values with the Paris–London series compared to the other NAO indices, although the relationship is weak with coefficients at around 0.35. With the incorporation of the updated Trenberth & Paolino (1980) data in 1900, the correlations suddenly drop to values around 0.2. This supplements the assertions made above (§6.5.1) that there appears to be a terrestrial bias in the Luterbacher reconstruction that is most apparent during the summer months. The incorporation of ship-log data, as demonstrated by Küttel *et al.* (2009b), would give the reconstruction less of a European bias and more of an indication of the state of the wider scale north Atlantic circulation.

Despite the observed temporal changes between the Paris–London and NAO indices, the results must be assessed with extreme caution. Robinson *et al.* (2008), amongst others, have clearly demonstrated that sample correlations can display low-frequency variability that is an artifact of the statistical method and may not necessarily imply a change in the relationship over time between two variables. To test this, the correlation coefficients were normalized

	Lisbon/Styk	PC	PD/Styk	Li/Wang	Vinther	Glueck	Cook	Luterbacher
DJFM	0.62**	0.65**	–	0.55*	0.73**	–	0.45**	0.25
DJF	–	0.62*	0.57**	0.69**	0.77**	0.09	–	0.31
MAM	–	-0.04	0.16	0.16	0.42	–	–	-0.08
JJA	–	-0.29	0.12	-0.01	0.00	–	–	0.41*
SON	–	0.55	0.00	-0.24	0.31	–	–	0.13
Annual	–	-0.47	-0.26	-0.33	-0.03	–	–	0.11

Table 6.3: Paris–London/NAO Decadal Correlations. In the calculation of these correlation coefficients, the data have been filtered using a 10-year Gaussian weighted low-pass filter. * indicates correlation coefficients significant at the 90% level, and ** at the 95% level. The significance levels have been adjusted following Wilks (1995) to account for autocorrelation in the filtered series.

using Fisher's variance-stabilizing transformation (Wilks, 1995). The statistical significance of successive correlations in each series of Figures 6.8a to 6.8f were assessed using the $2-\sigma$ limits, with N adjusted to account for autocorrelation in the method described by Slonosky *et al.* (2001a). This revealed that none of the temporal variations—even the large steps observed for the Luterbacher series—are beyond the range of statistical sampling variance at the 95% level.

6.5.3 Decadal correlations

The low-pass filtered series (30-year Gaussian weighted) from Figures 6.2 to 6.7 have been plotted separately in Figure 6.9 to emphasise the relationship between the indices at multi-decadal timescales. The similarity of the indices during the early twentieth century in the winter is clearly defined in this figure. A feature that also stands out is the failure of the Paris–London index to indicate the strong negative value of the NAO in the 1950–70 period. Further back in time the NAO indices diverge greatly, although the Paris–London index does show similar temporal variance to the Luterbacher series. This feature is most marked in the summer season, due to the predominant positive values during the 1760–1820 period.

Decadal correlations have been calculated by smoothing the seasonal Paris–London and NAO indices with a 10-year Gaussian weighted filter to quantify the low-frequency variations between the series (Table 6.3). These results indicate that there is agreement during the winter season between the instrumental NAO indices and the Paris–London series at decadal timescales. During the other seasons there is less agreement. In the case of the NAO proxy series during the winter, a relatively strong relationship can be observed for the Cook series but not the Glueck or Luterbacher series. However, a high correlation coefficient can be observed between the Luterbacher and the Paris–London series during the summer. Again, this is attributable to the common low-frequency variance that is displayed in the two series during the late eighteenth/early nineteenth century. However, this correlation is only significant at the 90% level.

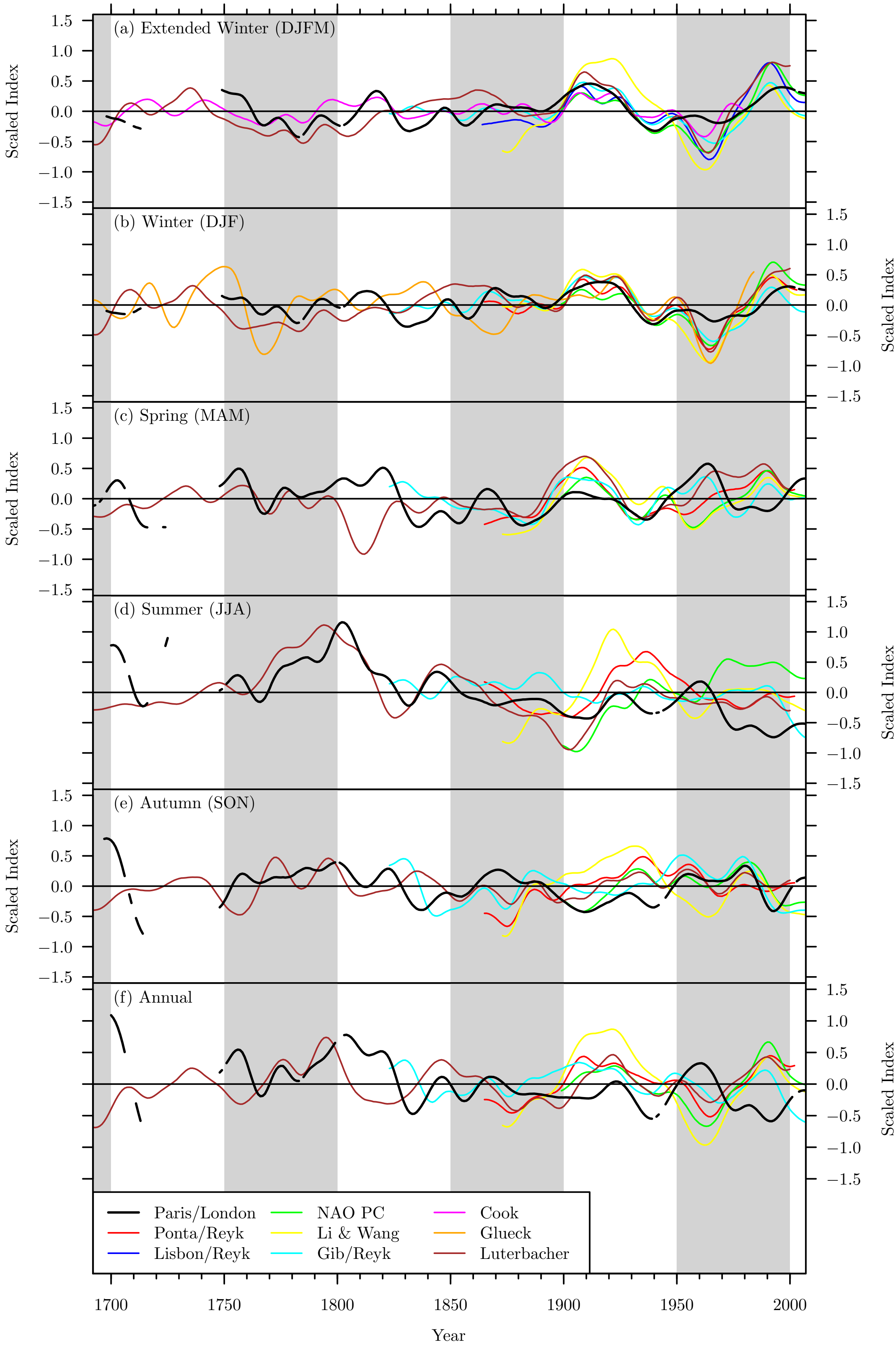

Figure 6.9: The smoothed values of the NAO indices from Figures 6.2 to 6.7.

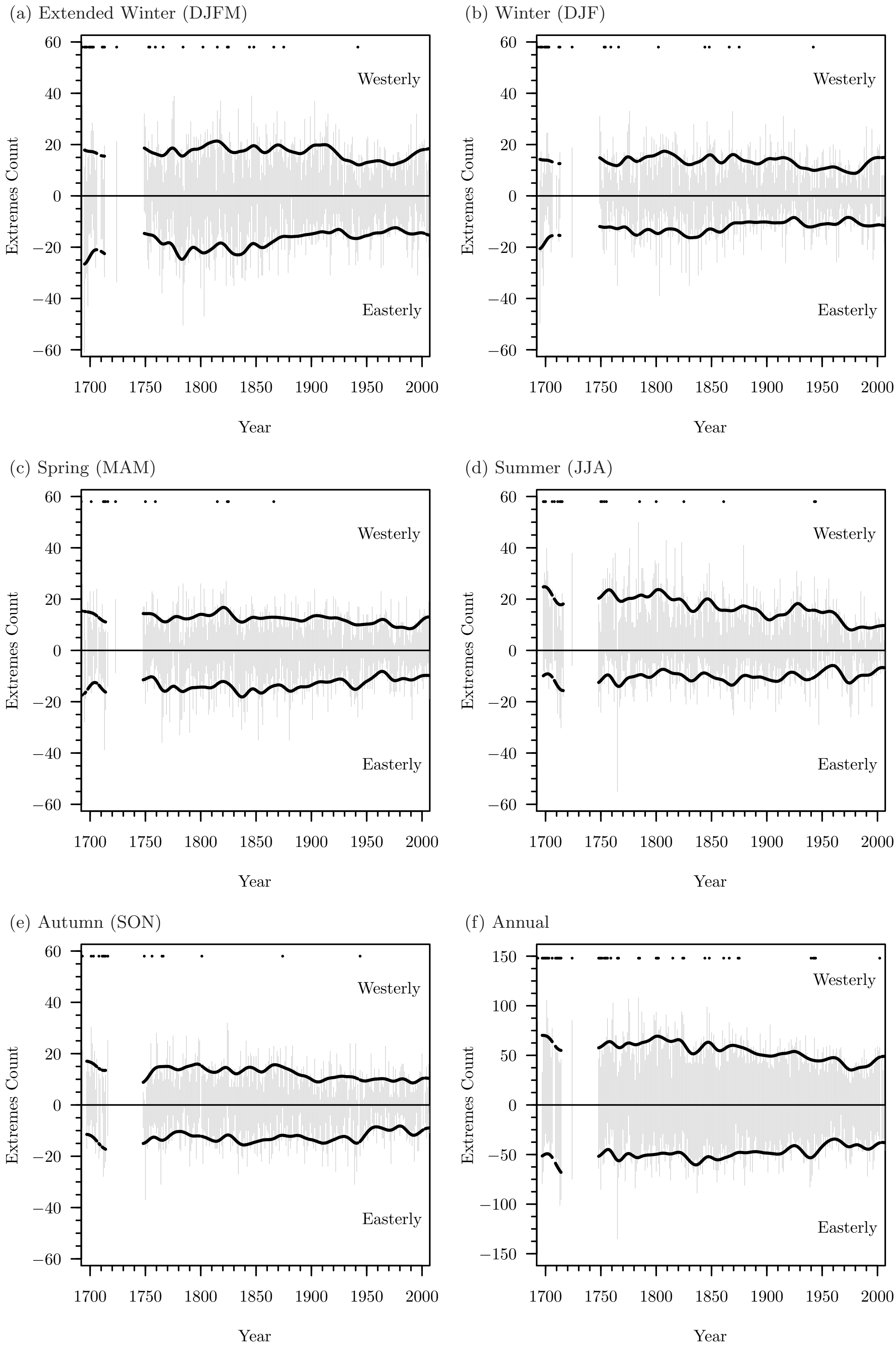

Figure 6.10: Extreme westerly/easterly days in the Paris–London index. The annual totals are calculated as the sum of the component seasons and therefore the year runs from December to November. The values for the easterly days have been reversed. Periods with $n < 80\%$ are not shown. The black circles indicate those years where there are missing values (<20%) and that the value has been adjusted pro-rata. The black line indicates the 30-year Gaussian filtered values. Note the different scale used in Figure 6.10f.

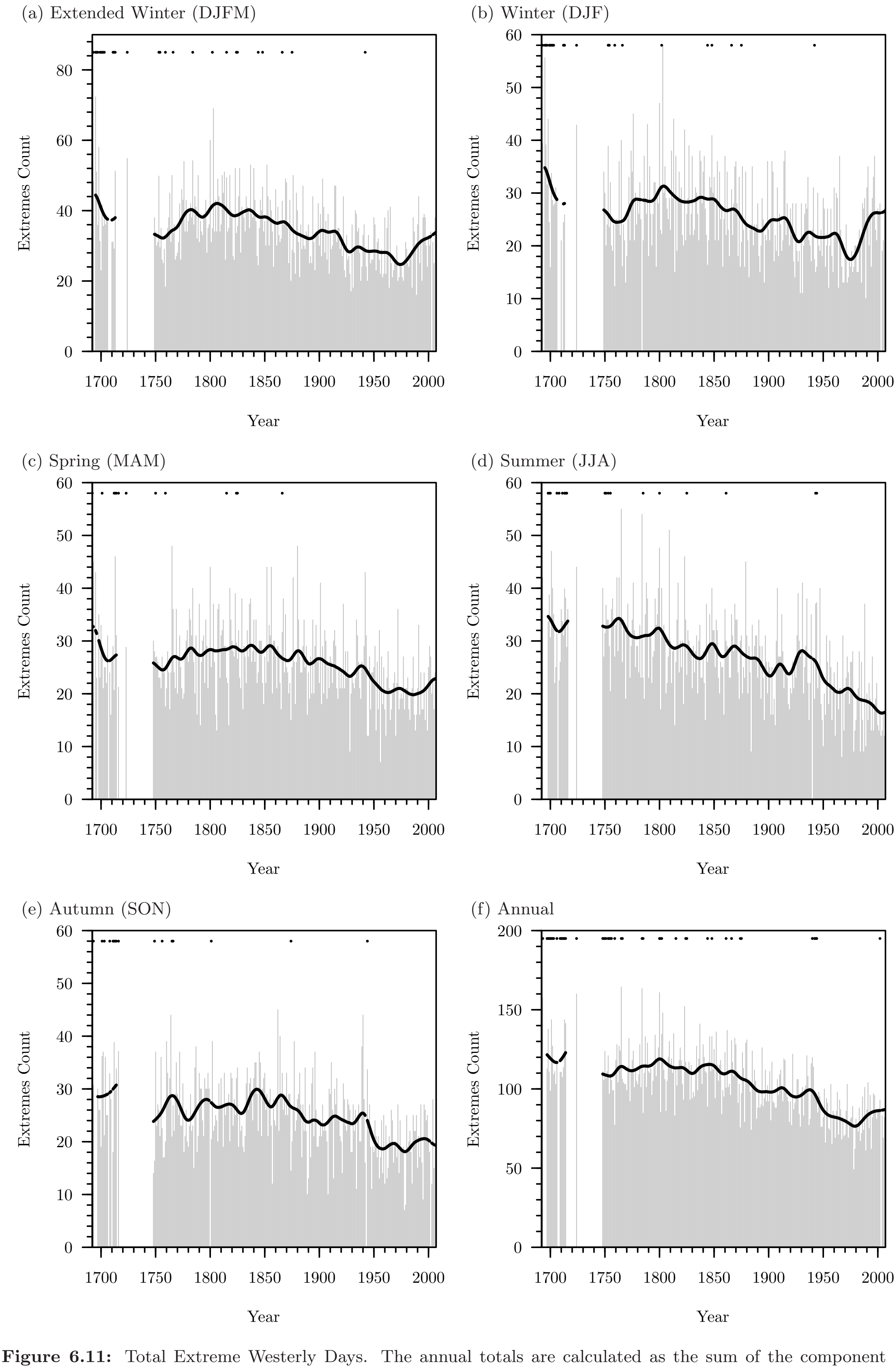

Figure 6.11: Total Extreme Westerly Days. The annual totals are calculated as the sum of the component seasons and therefore the year runs from December to November.

6.6 Extremes of zonal flow

The Paris–London index used in the previous sections of this chapter emphasize the monthly, seasonal and annual means of anomalous zonal flow across Europe. A different perspective is afforded by the use of the daily resolution of the Paris and London data, and in particular by an analysis of the extremes of the zonal flow.

To calculate extremes in the Paris–London index, a new series was formed by subtracting the pressure at London from the pressure in Paris on a day-by-day basis. As demonstrated in the previous chapter, this forms a measure of westerly flow for each day, but the series has an annual cycle which confounds the comparison of extreme westerly/easterly days throughout the year by simple fixed-threshold exceedance values. To avoid this problem, the method developed by Jones *et al.* (1999a) was applied to the daily Paris–London index to calculate the frequency of extremely westerly and extremely easterly days on a seasonal basis. In brief, this involves calculating the mean for each day of the year over the period 1961–90. These data are then smoothed with an 11-term binomial filter. Anomalies are then calculated as the difference between the daily Paris–London index value and the filtered mean for the respective day of the year. For each day in the Paris–London series, a 3-parameter gamma distribution is formed from a series of 150 values, centred on the specific day spaced at 5-day intervals. Using this distribution, each day is then transformed to a percentile, and the number of days above (below) the 90th (10th) percentile is calculated. The resulting index presents the extreme values relative to the 1961–90 reference period. In contrast to Jones *et al.* (1999a) who only considered annual frequencies, the data here have been divided into seasons. On average, approximately 9 days out of the 90 total during the season would be classed as extremely westerly, relative to the base period, with 9 also classed as extremely easterly; for the annual totals the averages would be approximately 30 days.

The conventional Paris–London index (see §6.3) and the extremes index are closely connected, with correlations in the winter (DJF) of 0.72 for the number of extreme westerly days and -0.78 for number of easterly days; in the summer the correlations are 0.75 (westerly) and -0.68 (easterly).[5] Nonetheless, this extremes index supplements the information provided by the 'conventional' Paris–London index.

The results (Figure 6.10) for winter, spring and autumn show no overall trend in the frequency of extreme westerly or easterly days. However, during the summer a gradual decline in the number of extreme westerly days is evident, and notably there is a step around 1960 to many fewer days classified as extreme; this is only partly compensated for by an increased number of extreme easterly days. This step has been commented upon in Section 6.4.3 for the seasonal mean Paris–London index, but is clearly defined in the extremes index used here.

During the winter, a definite high frequency of extremely easterly days are apparent from 1692 until 1700. This was also noted by Slonosky *et al.* (2001a), who used the same data sources. The winters of 1693/4 and 1694/5 are noteworthy given that approximately two thirds of the days in those seasons are classified as being extremely easterly. While the potential for inhomogeneities in these early data cannot be ruled out, the results appear to agree with the findings of previous studies, which have indicated that strong easterly flow occurred during the

[5] All of these correlations are significant at the 99% level.

winters of 1695–96–97 over Europe as a result of a strong Scandinavian high-pressure system (Kington, 1995, 1997b; Luterbacher *et al.*, 2000; Können & Brandsma, 2005). Documentary data suggest that the period of severe winters ended abruptly at around the year 1700 in England (Pfister, 1994) and this is clearly defined in Figure 6.10a as a drop in the frequency of extremely easterly days. Despite this trend, cold conditions were experienced throughout 1708, with the winter of 1708–09 being exceptionally cold (Bouant, 1880; Legrand & Le Goff, 1992; Lamb, 1995). Slonosky *et al.* (2001b) used their Paris–London index to interpret the causes of the extreme conditions during 1708, although the zonal nature of the Paris–London index means that correlations with extremely cold conditions would be strongest for those events occurring in early spring (February/March). Previous atmospheric circulation reconstructions as well as wind direction information have indicated that the coldest period of the winter was attributable to a northerly airflow (Pfister, 1994), which would not be detected in the Paris–London index. In accordance with that information, the winter of 1708–9 does not appear exceptional in terms of the number of extreme easterlies.

A notable feature of Figures 6.10a and 6.10b is the increase in the frequency of extreme easterly days in winter from 1748 to a peak at ca.1800 and a decline to ca.1850. This is most apparent in the DJFM series.

The example of Jones *et al.* (1999a) has been followed further, by constructing a total extremes index as the sum of the number of extreme easterly and westerly days (Figure 6.11). The frequency of extremes was higher before 1860, particularly in the winter and summer. Given this information, it would appear that while the conclusions of Kington (1980) that the 1780–85 period was affected by high variability in the atmospheric circulation were correct, they were limited by a lack of data for the 1785–1859 and pre-1780 periods. While the 1780s were indeed a period of increased variability, those years were part of a longer period of increased variability, which lasted until the mid-nineteenth century.

6.7 Chapter summary

In this chapter the daily London and Paris pressure series have been used to develop a European westerly index. The index was constructed at the monthly resolution by subtracting the normalized monthly mean London data from the normalized monthly mean Paris data. Although similar Paris–London indices have been presented by Slonosky (1999), Slonosky *et al.* (2000) and Jones *et al.* (2003), the series presented here is nearly continuous from the year 1748, and is semi-continuous back to 1692. Those studies have also been extended by analysing the Paris–London series for all months of the year.

In accordance with the findings of the previous studies, it has been discovered that during the winter months the Paris–London index is closely connected with the traditional NAO indices and that the high values in the 1990s are of a similar magnitude to the values during the 1920s. However, the decline in the index during the 1950–70s, which is a prominent feature in most NAO indices, does not appear as large in the Paris–London index. It is suspected that this is due to the asymmetric difference between positive and negative phases of the NAO. The most interesting results were apparent during the summer months of the year. A high positive phase is observed in the index during the 1770–1825 period, which corroborates the results from NAO proxy indices and which may explain the higher incidence of summer rainfall during that period (Briffa *et al.*, 2009).

To quantify the relationships between the Paris–London index and the NAO indices correlation analyses were performed.The Paris–London index is highly correlated with both instrumental and proxy NAO indices on an inter-annual basis. These correlations are highest during the winter months of the year. Running correlations indicate that certain relationships are variable over time, with an indication that in the case of the Luterbacher *et al.* (2002a) index this may be related to an increase in the number of predictors used in the reconstruction. The Paris–London index is also significantly correlated with the instrumental NAO indices on decadal timescales but only during the winter. Decadal correlations with the proxy NAO indices are generally not statistically significant, although a significant and strong decadal correlation has been observed with the Luterbacher *et al.* (2002a) index during the summer (JJA) season.

In the final section of the chapter a different perspective was presented by examining the frequency of extremely westerly and easterly days on a seasonal basis over the 1692–2007 period. The frequency of extremely easterly days during the winter in the 1690s appears unprecedented in the 1692–2007 period, which is consistent with the 1690s being the 'climax of the Little Ice Age (LIA)' in Europe (Luterbacher *et al.*, 2001, p.442). A second maximum of extremely easterly days in winter was observed at the turn of the nineteenth century. In contrast, the frequency of extremely westerly days in winter has remained constant over the 300-year period. However, in the summer the frequency of extreme westerly days was at a maximum prior to ca. 1860. During the summer months, an unprecedented low frequency of extremely westerly days are observed in the period after ca. 1970, which is partly compensated by an increased frequency of extremely easterly days.

Chapter 7

The Relationship of Surface Air Temperature to the Paris–London Index

7.1 Introduction

The science regarding global mean temperature increases over the last 100 years, and the connection to human activity is now well established (Trenberth *et al.*, 2007; Hegerl *et al.*, 2007). However, while improvements can undoubtedly be made to the global-scale average record (Jones, 2001b), a different branch of research is concerned with examining regional-scale temperature variations that have occurred in the past. Mann *et al.* (2009), for example, have recently examined regional-scale temperature changes in the pre-instrumental era. Regional temperature and precipitation variations are closely linked to the atmospheric circulation, with the key to understanding past and future spatial variability resting with an improved understanding of the circulation-temperature/precipitation relationship (Trenberth *et al.*, 2007).

In Europe, the variability of the surface climate on interannual to decadal timescales is largely governed by the state of the North Atlantic Oscillation (NAO) (Hurrell *et al.*, 2003). In the case of surface temperature, for example, the increasing trend that was experienced between the 1970s and 1990s was closely connected to an increase in the mid-latitude Mean Sea-Level Pressure (MSLP) gradient and the resulting increase in westerly flow (Trenberth *et al.*, 2007). The influence of the NAO on air temperature is most profound during the winter months of the year when advection is the main determinant, although a connection can also be established during the summer (Folland *et al.*, 2009). However, as has been discussed at length in the previous chapter (Chapter 6) the state of the NAO, and hence the relationship to surface temperature, can only be ascertained back to the mid-nineteenth century using traditional station-pair indices. There is a need to analyse this relationship further back in time to better understand the mechanisms of both past and future climate variability in Europe (Küttel *et al.*, 2009a).

Proxy measures of the NAO cannot generally be used to study the connection between atmospheric circulation and temperature or precipitation, because the proxies themselves are often inferred directly or indirectly from temperature or precipitation data. This is a limitation of, for example, the NAO reconstruction of Luterbacher *et al.* (1999, 2002a). Conversely, the gridded MSLP reconstruction of Küttel *et al.* (2009b) stretching back to 1750 can be used to investigate this relationship given the independence of the proxies used from any temperature or precipitation data (Küttel *et al.*, 2009a). The Paris–London westerly index can also be used to examine this relationship, as it too is independent from temperature and precipitation data, and while the Paris–London index lacks the spatial detail of the Küttel *et al.* (2009b) reconstruction, a westerly index can be constructed to span the longer 1692–2007 period using the daily Paris and London MSLP data.

Several previous studies have used the Paris–London westerly index to examine the circulation-temperature relationship in the North Atlantic-Western European (NA-WE) region (Slonosky, 1999; Slonosky *et al.*, 2001a; Slonosky & Yiou, 2002; Jones *et al.*, 2003). The merit of this index primarily rests with its extended length compared to more usual NAO time series, and has previously been used to indicate the relationship between surface temperature in the NA-WE region and the atmospheric circulation back to the year 1774. However, the index also provides a useful bridge between the atmospheric circulation at regional and hemispheric scales in the manner described by Jacobeit *et al.* (2001) and Jones & Lister (2009). The relationship between the Paris–London index and surface temperature is strongest in a region encompassing southern England and the Low Countries but also bears a signature of the larger-scale NAO (Slonosky & Yiou, 2002).

This chapter aims to extend the work of Slonosky (1999), Slonosky *et al.* (2001a), Slonosky & Yiou (2002) and Jones *et al.* (2003) by relating the Paris–London westerly index, as described at length in the previous chapter, to surface temperature series from across Europe. In a similar vein to the earlier studies the strength of the relationship is quantified using correlation analyses, with the data series at monthly and seasonal timescales. The analysis here, however, extends further back in time: back to 1748 on a semi-continuous basis and on a more fragmentary basis back to 1692. Further, the improved quality of the London and Paris MSLP data, especially during the 1780s (see Chapter 5), should allow an improved analysis. The chapter opens (§7.2) with a review of previous studies that have used the Paris–London index to analyse the temperature–circulation relationship back to the late eighteenth century. The review places that body of work in the context of recent research that has linked temperature variability in Europe to regional weather-type classifications. In Section 7.3 the Paris–London index is correlated against the Luterbacher *et al.* (2004) temperature reconstruction to provide an indication of the spatial extent of the relationship and how this has changed over the 1692–2007 period. This is followed in Section 7.4 with an assessment of the connection between the Paris–London index and three long temperature series (Central England Temperature (CET), Berlin and Debilt). The final results section in this chapter (§7.5) analyses the changing relationship between the Paris–London index and the three temperature series using running correlations. The chapter concludes (§7.6) with a summary of the results.

7.2 Background information

7.2.1 The use of the Paris–London index in previous studies

The relationship between an index of westerly flow quantified by the difference in MSLP at London and Paris (Paris *minus* London), and surface temperature in Europe has previously been analysed in several studies. Slonosky (1999) and Slonosky *et al.* (2001a) used the Paris and London monthly MSLP series that had been corrected as part of the ADVICE (1998) project, to develop an index covering the period 1774–1995 (see §6.2.2). The results from correlating temperature recorded at several sites across Europe against this westerly index revealed that correlations were highest (and positive) in the months from October to March, and weakest during the remaining spring and summer months. During high summer (July and August) the correlations were weakly negative. This seasonal variation in correlations can be explained by the dominance of temperature advection affecting surface temperature during winter, and to a lesser extent summer (Parker, 2009a). The lower correlations during the transition seasons of autumn and spring may have resulted from the seasonality in the temperature series (see Jones *et al.*, 1999a; Jones & Lister, 2009, for discussions about this).

Spatial variations in the correlations between the Paris–London index and surface temperature were also shown in the results of Slonosky *et al.* (2001a), with the strongest correlations throughout the year generally achieved for those station series closest to London and Paris, i.e. Central England, De Bilt and Berlin. A close relationship between these stations and the Paris–London index would be expected given the proximity of the series, and this identifies that the Paris–London index is a regional index of westerly flow. Indeed during the winter months the correlations were stronger than those between the Gibraltar/Reykjavik North Atlantic Oscillation Index (NAOI) and the temperature series, although both analyses showed a similar seasonal variation. This result is explained partly by a failing of fixed station-pair indices to capture the asymmetry during different phases of the NAO. As has been discussed in the previous chapter (§6.2), during NAO- conditions the southern node of the NAO is located slightly further north and is more elongated compared to NAO+ conditions. This asymmetry has only a small effect on the zonal wind vector across western Europe but will affect the quantification of the NAO by station-pair indices. Thus a variance appears in the NAOI that may not have an effect on the surface temperature of western Europe.

Slonosky & Yiou (2002) explored the spatial variation in correlations between surface temperature over the NA-WE region and the Paris–London index as part of a wider enquiry into the degree to which temperature variability across the region can be explained by changes in temperature advection resulting from zonal atmospheric flow. To achieve this, correlations between gridded temperature data and several atmospheric circulation indices (including the Paris–London index) were calculated over the period 1856–2000 for all seasons of the year. The results for the Paris–London index during the months of January and February indicated high positive correlations over the British Isles and northern Europe, and weaker correlations over the remainder of the NA-WE domain. These results correspond to the findings of Slonosky *et al.* (2001a) who identified the same general delineation of temperature/index correspondence using individual station series. The results of Slonosky & Yiou (2002) more clearly defined the spatial extent of the relationship, but also showed that a quadrapole pattern emerges when the entire North Atlantic region is considered. This pattern had strong negative correlations over northwest Africa and the Greenland/Labrador Sea area and weak positive correlations over southeastern North America, along with the strong positive correlations across northwest Europe. A similar pattern was observed for the NAO index, which indicates that the Paris–London index quantifies the same general circulation pattern as the NAO, but is more local to western Europe.

Running correlation results presented by Slonosky *et al.* (2001a) indicated that the relationship between the Paris–London index and surface temperature may not be constant over time. Running correlations between the Paris–London index and the CET series during February over the 1774–1995 period indicated that there were certain changes in the strength of the relationship over time. The correlations were generally weak in the 1780s but rose to a peak of 0.95 in the 1870s. Thereafter the correlations gradually fell to values around 0.7 during the 1910/20s, but increased again to values of 0.9 in the 1950s. Running correlations were calculated by Slonosky & Yiou (2002) between the Paris–London index in January and the second Principal Component of surface temperature derived from gridded temperature, which displayed a dipole pattern with strong positive loadings in the middle North Atlantic and negative loadings over the north and northwestern North Atlantic. The running correlation results indicated a strong positive relationship through the period 1915–80, with values around 0.8 and little temporal variation, although there was a slight dip in correlations (to 0.5) centred around 1960.

Jones *et al.* (2003) produced running correlations between the Paris–London index, derived from the same data as Slonosky *et al.* (2001a) and Slonosky & Yiou (2002), but used the following five European temperature series: the average of northern hemisphere land temperatures north of 20°N (NH20N), the average of central and northern European temperatures (EUR), the average of six temperature series from Finland/Scandinavia (FennScan), the average of five central European temperature series (CEUR) and the CET series. The pattern of running correlations between these temperature series and the Paris–London index for the extended winter season (DJFM) showed a good deal variability over time. Prior to 1830 the correlations were generally low (0.4) with the three temperature series FennScan, CEUR and CET, with variations in the Paris–London index explaining only around 16% of the variation in temperature. After 1830 the correlations with these three temperature series was higher, with values around 0.7 ($R^2 = 49\%$). The most marked feature in the running correlations was a drop in correlations for the NH20N series during the period 1930–70, from a peak of 0.7 in the 1910s to values around 0.1 and even negative values; after ca. 1970 the values recovered to around 0.3. A similar pattern of correlations was observed for the CEUR temperature series, and to a lesser extent for the other temperature series. In examining the running correlations between the five temperature series and indices of the NAO, the authors noted a gradual increase in correlation coefficients between the years 1830 and 2000, which was not apparent in the results for the Paris–London index. This was attributed to a gradual shift in the structure of the NAO over time.

Slonosky *et al.* (2001b) turned their attention to the relationship between the CET series and a Paris–London westerly index for the period 1697–1708. Due to the small sample of data, no definite conclusions could be reached about the relationship between surface temperature and the Paris–London index in this early period. However, the results suggested that there may have been a different seasonal cycle in the correlations compared to more recent observations, with the highest correlations during 1697–1708 occurring during the months of January and March, whereas during the period 1774–1995 the strongest correlations were found in February.

7.2.2 Studies using weather-type classification techniques

In establishing the relationship between the Paris–London index and European temperature, the studies described above provide a good example of the 'circulation to environment' theme of synoptic climatology defined by Yarnal (1993) and Yarnal *et al.* (2001). However, the consolidation of the complex 4-D atmospheric circulation to simple station-pair indices inevitably limits the depiction of the underlying dynamics of the relationship. Other studies have used time series of weather types in an attempt to better understand the relationship between European temperature and the regional-scale atmospheric circulation. The well known Lamb Weather Type catalogue for the British Isles (Lamb, 1972) and for Europe the "Grosswetterlagen" are examples of subjectively derived weather-type indices that have been used in this way (Buishand & Brandsma, 1997; Kelly *et al.*, 1997; Cahynová & Huth, 2009). The results from assessing the connection between frequencies of weather types and the temperature climate indicated that inter-annual variations in winter (and to a lesser extent summer) temperature are closely related to the proportion of 'warm' and 'cold' weather types experienced. However, studies that have derived weather-types using objective classification schemes (Osborn & Jones, 2000; Osborn *et al.*, 1999b; van Oldenborgh & van Ulden, 2003) and air sourcing techniques (Parker, 2009a) have indicated that low-frequency temperature variation (decadal or longer) has only a weak relationship to the frequency of weather-types. This raises the question as to the proportion of temperature change that can be explained by a change in the frequency of weather types as opposed to temperature changes within the classification types (Beck *et al.*, 2007; Jones & Lister, 2009). This concept is the same as the 'dynamic' and 'background' components of the temperature-circulation relationship described by Slonosky & Yiou (2001), where a 'dynamic' NAO-related warming and cooling on inter-annual to decadal timescales is superimposed upon a background mode that is related to the long-term warming trend. Recent further advances have been made in answering this question, along with better interpretations of the connections between circulation and temperature, using weather-type classifications for Europe obtained from daily gridded MSLP data (Huth *et al.*, 2008). Philipp *et al.* (2007) used a clustering algorithm (simulated annealing clustering) to classify the daily gridded MSLP dataset produced by Ansell *et al.* (2006), with a view to analysing the connection between European temperature variability and the atmospheric circulation. On the seasonal basis, cluster frequency explained a large proportion of both summer and winter temperature variability. Their results also indicated that the long-term rising trend in European temperatures was connected to an increasing frequency of warm weather types, which would appear to contradict the dynamic/background concept described by Slonosky & Yiou (2001). However, Philipp *et al.* were keen to point-out that their results need not indicate that a changing frequency of 'warm' weather types was primarily responsible for the long-term (centennial) warming because of the consideration of regional temperature change.

Further studies that have used the simulated annealing clustering algorithm to classify daily weather types over Europe have shown that much of the increase in temperature over the last 100 years has occurred within weather-types, as opposed to an increasing frequency of 'warm' types. Jones & Lister (2009) used the clustering algorithm to obtain a catalogue of daily weather types for the standard three-month (DJF, MAM etc.) seasons over a slightly wider European domain than that considered by Philipp *et al.* (2007). The circulation types were related to mean temperature, diurnal temperature range and precipitation. Their results indicated that the long-term warming in Europe over the course of the twentieth century was mostly attributable to warming within weather types, although this was not evident in all of the weather types. The results of a study by Küttel *et al.* (2009a) also reveal the dominance of within-circulation type variability in explaining multidecadal temperature variability in Europe. That study also used the clustering algorithm developed by Philipp *et al.* (2007), but by using the MSLP data from Küttel *et al.* (2009b) were able to produce a classification scheme for each winter season (DJF) back to 1750.

The dominance of within-type variability in explaining low-frequency changes in European surface temperature is directly related to the de-coupling that has been observed between the Paris–London westerly index and temperature in the studies of Slonosky (1999), Slonosky *et al.* (2001a), Slonosky & Yiou (2002) and Jones *et al.* (2003) described above (§7.2.1). Other studies have also identified non-stationary relationships between the temperature climate in Europe and the regional-scale atmospheric circulation (Jacobeit *et al.*, 2001). These non-stationarities arise from a combination of dynamic changes within circulation conditions, such as vorticity and intensity, but also synoptic-scale variations not resolved by monthly/seasonal mean indices and local-scale effects such as oceanic influences (Beck *et al.*, 2007). As has been mentioned by Jones & Lister (2009), amongst many others, this non-stationarity in the relationship between the atmospheric circulation and surface temperature has important implications for downscaling studies, which often assume a constant relationship between predictor and predictand.

7.3 Spatial correlations between the Paris–London index and surface temperature

In this section the relationship between the Paris–London index, calculated from the daily Paris and London MSLP series, and temperature across Europe is assessed. The method of constructing the Paris–London index is described in Section 6.3. In a similar manner to Slonosky & Yiou (2002), correlation maps between the Paris–London index and surface temperature have been calculated (Figures 7.1 to 7.4). However, the analysis here differs in two respects: correlation maps have been produced for all seasons of the year, whereas Slonosky & Yiou only considered maps for the mean of January and February; secondly, the maps have been produced for six time segments, whereas Slonosky & Yiou only produced the maps for the entire 1856–2000 period. To allow the examination of correlation maps for several time periods, the seasonally reconstructed gridded (0.5°×0.5°) temperature series of Luterbacher *et al.* (2004) was used. Although only available at the seasonal resolution, this dataset has the benefit of covering the time span of the Paris–London index constructed from the daily MSLP series, i.e. the period 1692–2007. It should be noted, however, that while the temperature series is a multiproxy reconstruction for most of the series (in this case 1692–1900), over the period 1901–1998 it is composed of the instrumental-based series produced by New *et al.* (2000), and from 1999–2007 by Hansen *et al.* (2001).

During the winter (Figure 7.1) strong positive correlations are achieved across the British Isles and central Europe for most of the time periods. Indeed, compared to the plots of the other seasons (Figures 7.2 to 7.4) much of the year-to-year winter temperature variability across the European domain is locally significantly correlated with the Paris–London index at the 95% level. There is also an indication of variations in this significant zone over different time periods. Within the twentieth century, when the temperature data are purely from instrumental obser-

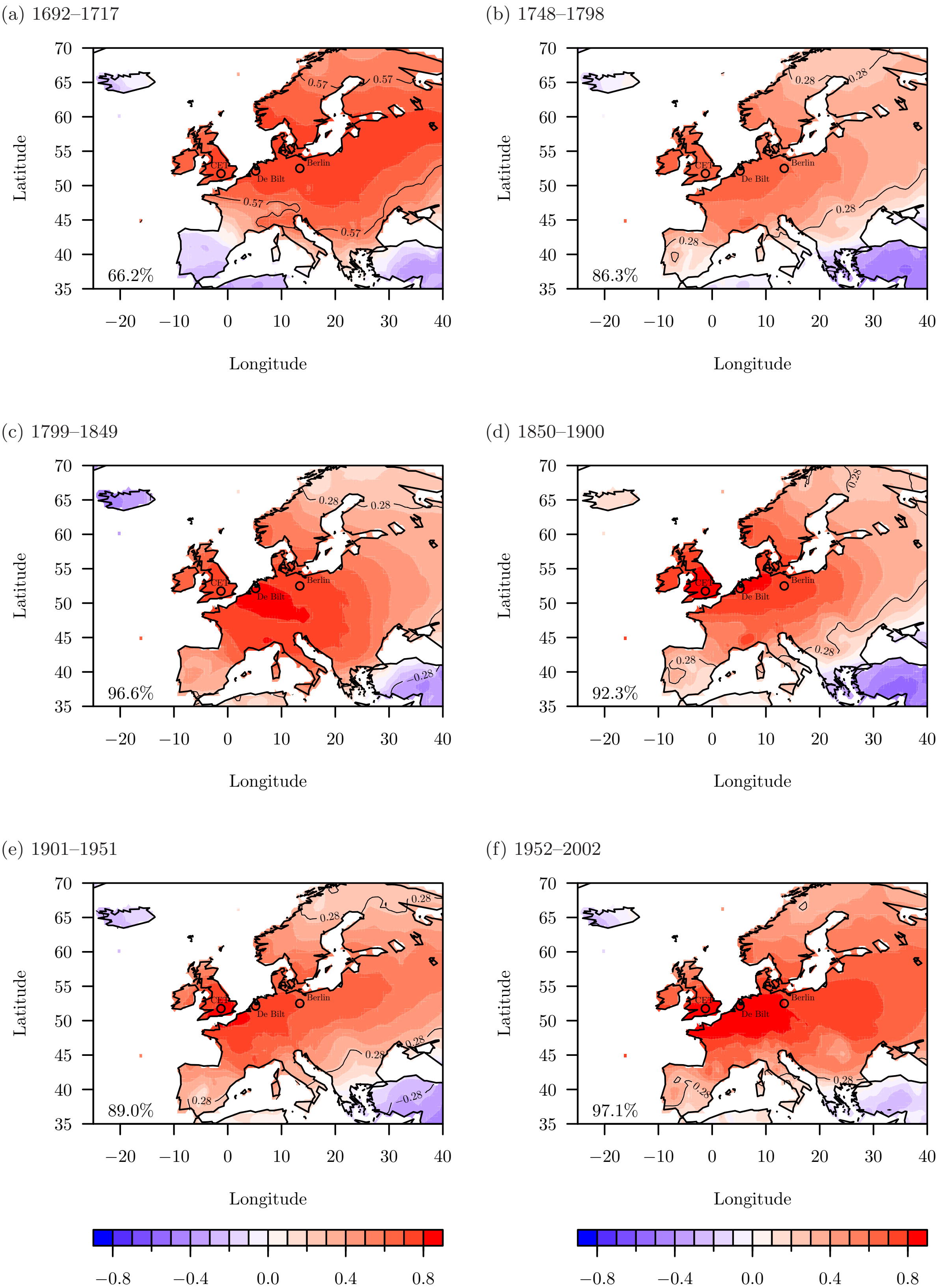

Figure 7.1: Correlations between the Paris–London index and the Luterbacher *et al.* (2004) temperature series for winter (DJF). The time-spans for each plot after 1748 are 51 years, although the earliest period is 26 years. The values of n are 12, 48 and 50 for the periods 1692–1717, 1748–98 and 1799–1849 respectively. During the time periods after 1748, correlations greater/less than ±0.28 can be declared locally significant at the 95% level, following Wilks (1995), taking into account the variable n values. During the period 1692–1717 the critical value is ±0.57. No corrections have been applied for spatial correlation. These critical significance levels are marked on the maps. The value printed in the bottom-left of the figures indicates the percentage of grid-squares that exceed the critical significance level. The three sites marked on the maps refer to the stations used in sections 7.4 and 7.5 below.

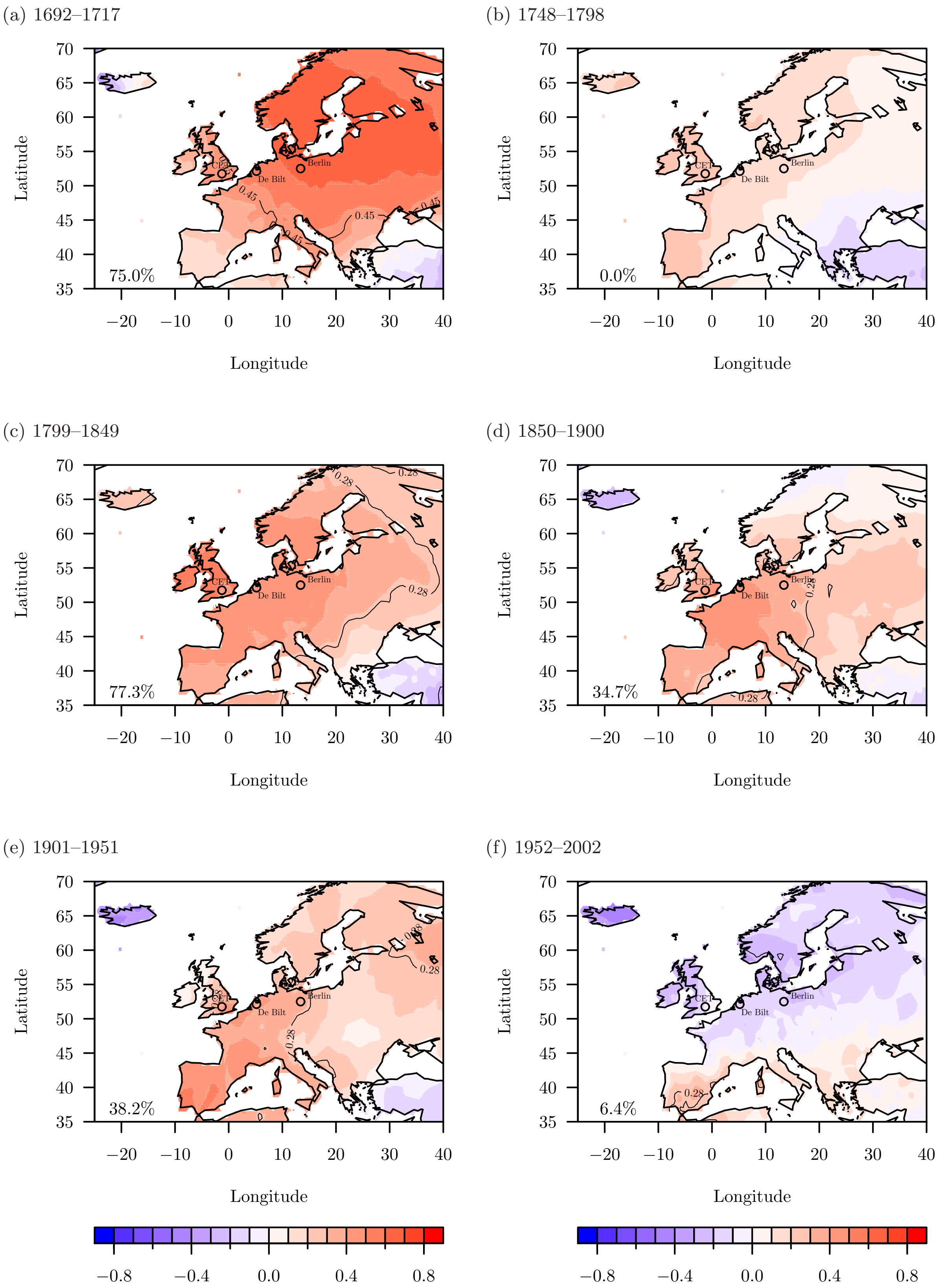

Figure 7.2: As Figure 7.1 but for spring (MAM). In this season the Paris–London index over the period 1692–1717 is 73% complete, giving a critical value of 0.45 at the 95% level with $n = 19$. In the periods from 1748, $n = 51$ giving a critical r value of 0.28 at the 95% level.

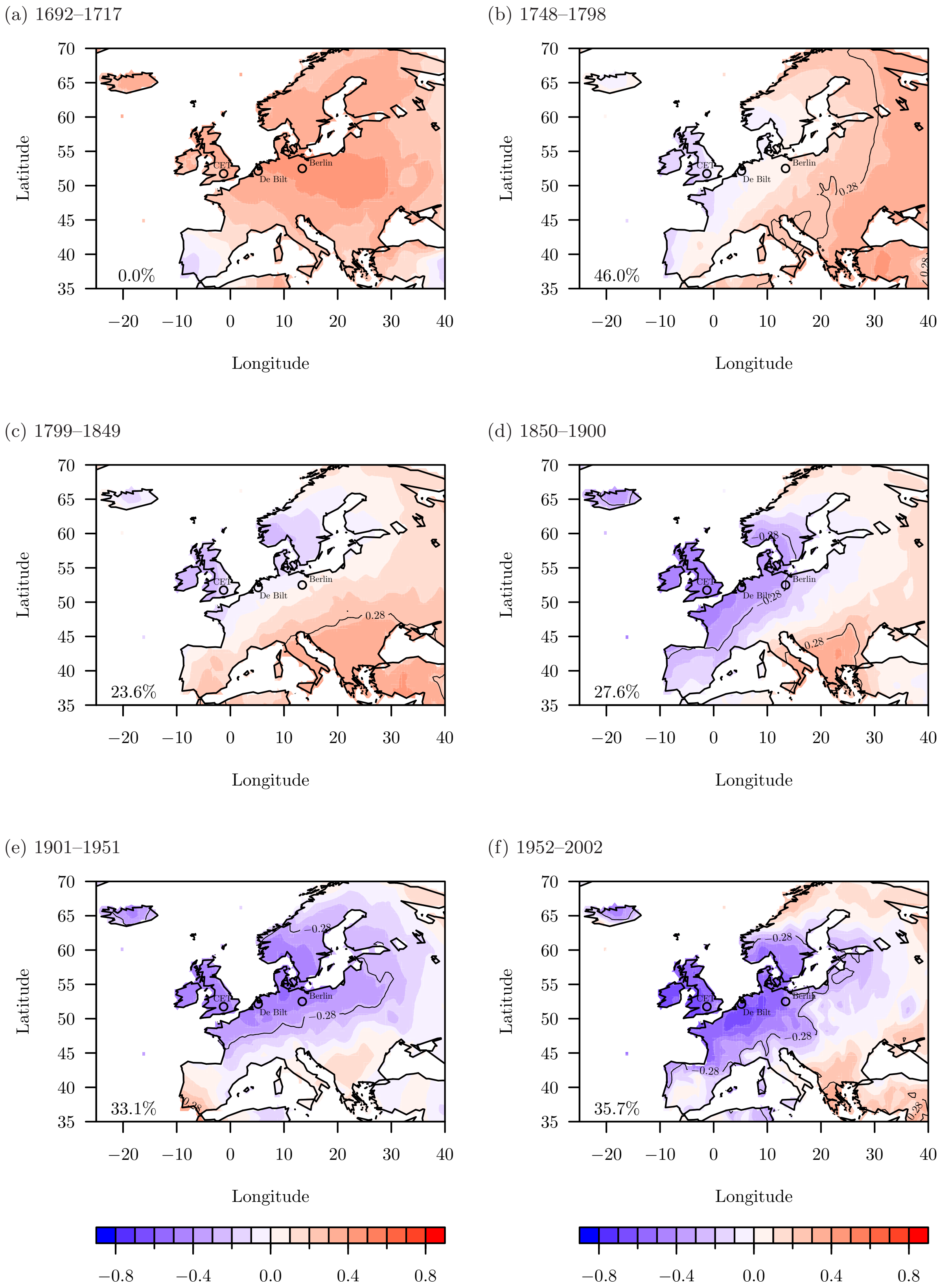

Figure 7.3: As Figure 7.1 but for summer (JJA). In this season the Paris–London index during the period 1692–1717 is 62% complete with $n = 16$, giving a critical value of 0.50 at the 95% level. The values of n for the periods 1748–98, 1799–1849, and 1901–51 are 50, 50 and 48 respectively; for the remaining periods $n = 51$. The critical values after 1748 are not affected by these varying sample sizes, and remain at 0.28 at the 95% level.

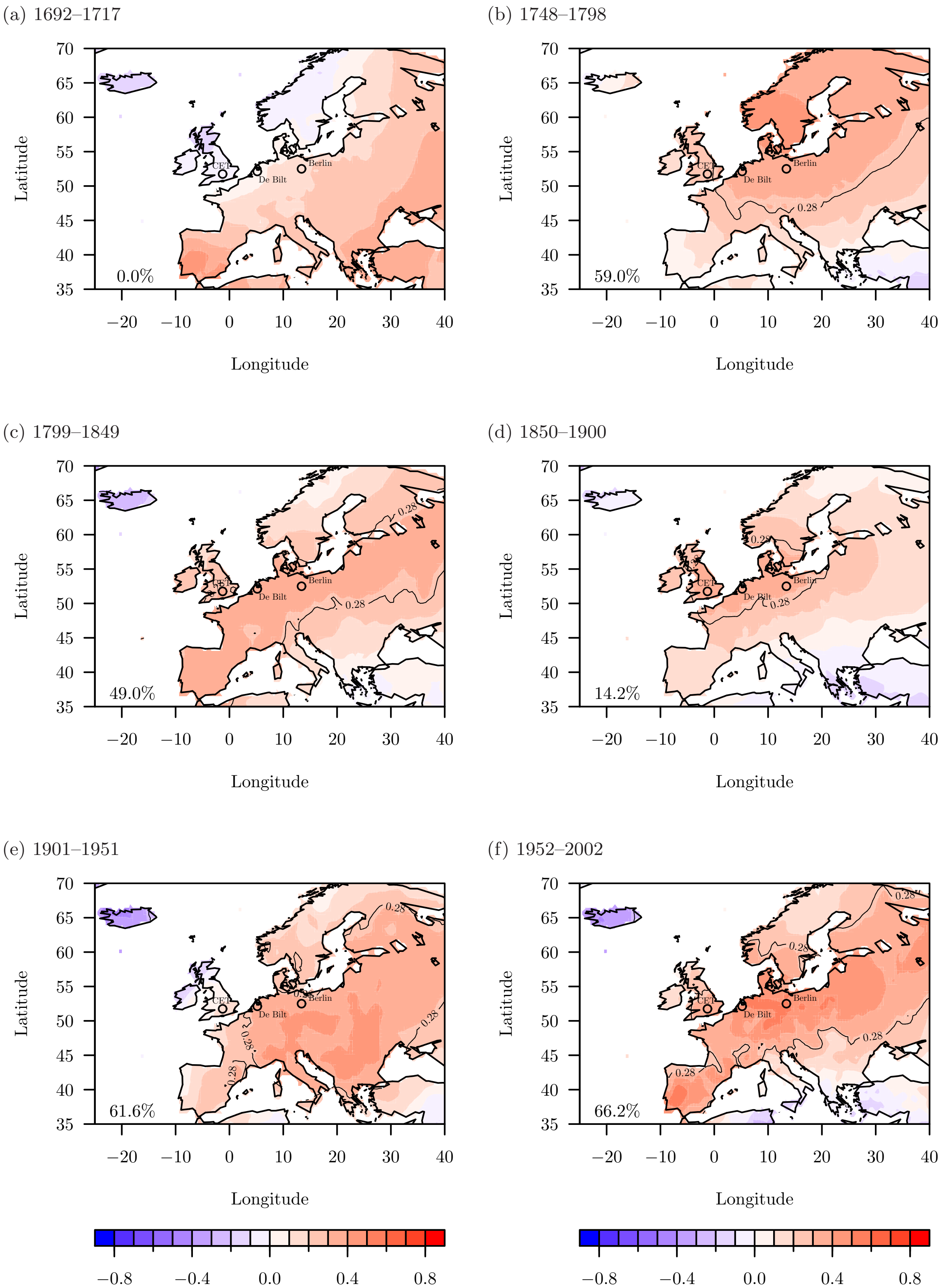

Figure 7.4: As Figure 7.1 but for autumn (SON). In this season the Paris–London index during the period 1692–1717 is 50% complete, giving a critical value of 0.55 at the 95% level, with $n = 13$. The values of n for the periods 1799–1849, 1901–51 and 1952–2002 are 50, 49 and 50 respectively; the critical value remains at 0.28 during these periods at the 95% level.

vations, the area of highest correlations is more confined compared to the other time periods. However, even during this period there is evidence of a change in the relationship between the Paris–London and surface temperature over time, with high correlations extending over a wider area in the period 1952–2002 compared to 1901–51. Similar results were achieved by Jones *et al.* (2003), who correlated the Ponta-Delgada/Reykjavik NAOI with surface temperature and concluded that this was a real environmental feature and not a result of reduced data homogeneity in the earlier time period. There is also an indication of a changing spatial pattern with time during the period of reconstructed data (1692–1899) in the results shown in Figure 7.1. During the period 1748–98, weak positive correlations are observed across the British Isles and central Europe. In the earliest period considered here (1692–1717) the positive correlations stretch much further eastwards across Europe. These latter results must be viewed with suspicion, however, on account of a high number of missing observations in the Paris–London index, and also because the error in the temperature reconstruction is larger before ca. 1750 due to a lack of instrumental data (Luterbacher *et al.*, 2004).

These results for the winter season (DJF) correspond well to the findings of Slonosky & Yiou (2002) who similarly showed the highest correlations between their Paris–London index and surface temperature in January and February to be restricted to the British Isles and central Europe. The results presented in Figure 7.1 also show the Greenland Above–Scandinavia Below pattern described by van Loon & Rogers (1978) with negative correlations across Iceland and positive correlations across northwest Europe. These results also partially confirm the quadrapole pattern shown by Slonosky & Yiou (2002), although the restricted domain considered here can not capture the other aspects of the quadrapole patters in northwest Africa and the northeast US. Interestingly, during the 1850–1900 period the correlations between the Paris–London index and the reconstructed surface temperature in Iceland is weakly positive. Given that the Iceland temperature data can be considered reliable, this probably indicates a change in the shape of the wider-scale atmospheric circulation at that time.

During the summer (JJA, Figure 7.3) negative correlations can be observed between the Paris–London index and surface temperatures across the British Isles, northern France and the Low Countries. At that time of the year westerly conditions bring relatively cold air from the North Atlantic Ocean compared to the land mass; easterly winds have the opposite effect. The strongest relationship occurs during the last time period considered (1952–2002) and declines for each of the earlier time periods. During the earliest period (1692–1717) weak positive correlations are observed across most of northwestern Europe, although again the high number of missing values during the period limits the drawing of definite conclusions.

During the spring (MAM) and autumn (SON) seasons the correlations between the Paris–London index and surface temperature is generally weakly positive for all time periods across much of Europe, with values in the range of 0.4. However, during spring in the period 1952–2002 the correlations switch to being weakly negative.

7.4 Series-long correlations

The three longest temperature series in Europe were selected for comparison with the Paris–London westerly index: CET (1692–2007, Manley, 1974; Parker *et al.*, 1992; Parker, 2009b),

	Berlin	CET	De Bilt
Jan	**0.74** (**0.73**)	**0.79** (**0.77**)	**0.76** (**0.72**)
Feb	**0.70** (**0.61**)	**0.80** (**0.73**)	**0.76** (**0.66**)
Mar	**0.58** (**0.59**)	**0.58** (*0.52*)	**0.61** (**0.59**)
Apr	**0.23** (0.47)	**0.44** (*0.56*)	**0.25** (0.36)
May	**0.20** (0.06)	**0.20** (0.17)	**0.16** (0.05)
Jun	-0.09 (-0.11)	-0.05 (0.27)	-0.11 (-0.08)
Jul	*-0.14* (-0.21)	**-0.28** (-0.22)	**-0.23** (-0.29)
Aug	-0.12 (-0.13)	**-0.21** (-0.25)	**-0.22** (-0.29)
Sep	**0.20** (0.42)	0.11 (0.08)	*0.16* (0.22)
Oct	**0.51** (*0.44*)	**0.37** (0.22)	**0.53** (*0.43*)
Nov	**0.57** (*0.55*)	**0.50** (0.37)	**0.63** (**0.56**)
Dec	**0.66** (*0.49*)	**0.68** (*0.51*)	**0.76** (**0.56**)
DJF	**0.68** (**0.49**)	**0.75** (**0.54**)	**0.75** (**0.54**)
MAM	**0.20** (0.26)	**0.32** (0.34)	**0.20** (0.18)
JJA	**-0.22** (-0.21)	**-0.27** (-0.14)	**-0.31** (-0.35)
SON	**0.35** (0.32)	**0.21** (0.06)	**0.36** (0.24)
Year	0.07 (-0.15)	0.07 (-0.11)	0.02 (-0.22)

Table 7.1: Correlations between the Paris–London westerly Index and three temperature series over the period 1748–2007. Decadal correlations are shown in brackets, for which the data have been smoothed with a 10-year Gaussian weighted low-pass filter. Correlations significant at $p = 0.01$ are shown in bold, and at $p = 0.05$ in italics. The values of n for the different months varies slightly due to missing values in the Paris–London index, but at the minimum $n = 251$. Temperature data for most months over the period 1752–55 are missing in the Berlin series. The significance thresholds take into account these missing values. In the calculation of the significance levels for the correlations from the low-pass filtered data, autocorrelation has been taken into account following the method described by Slonosky *et al.* (2001a, see §6.5.2).

Berlin (1701–2007, Schaak, 1982) and De Bilt (1706–2007, van Engelen & Nellestijn, 1995). These three locations are situated in the region of highest correlation between the Paris–London and European temperature, as shown in Figures 7.1 to 7.4 and also in the results of Slonosky *et al.* (2001a) and Slonosky & Yiou (2002). Table 7.1 lists the correlation coefficients achieved between the Paris–London index and the temperature series at the monthly, seasonal and annual resolutions over the period 1748–2007. The correlations have been computed at both the inter-annual and decadal scales. The results clearly show the annual variation in correlations that are evident in Figures 7.1 to 7.4 at the seasonal scale and also in the results presented by Slonosky *et al.* (2001a) and Slonosky *et al.* (2001b) at the monthly resolution. Strong positive correlations are evident between the months of December and March, with moderately strong negative correlations during high summer (July and August) but not in June. This latter observation corresponds to the information provided by Folland *et al.* (2009), which showed that the atmospheric circulation across the NA-WE region in June is somewhat different to that in July and August. Comparing the results across the three temperature series, the correlations throughout the year are generally higher for the CET series compared to the other two temperature series, with the correlations peaking in February when variations in the westerly flow quantified by the Paris–London index explain 64% of the variation in CET. The correlations during the transition seasons of spring and autumn represent relationships between the positive correlations of winter and negative correlations of summer. It should be noted that the annual cycle in the temperature records may influence this result as indicated by Jones & Lister (2009), who formed an anomaly series of daily temperature by subtracting the smoothed annual cycle. The use of monthly resolution data here means that such a transformation cannot be performed,

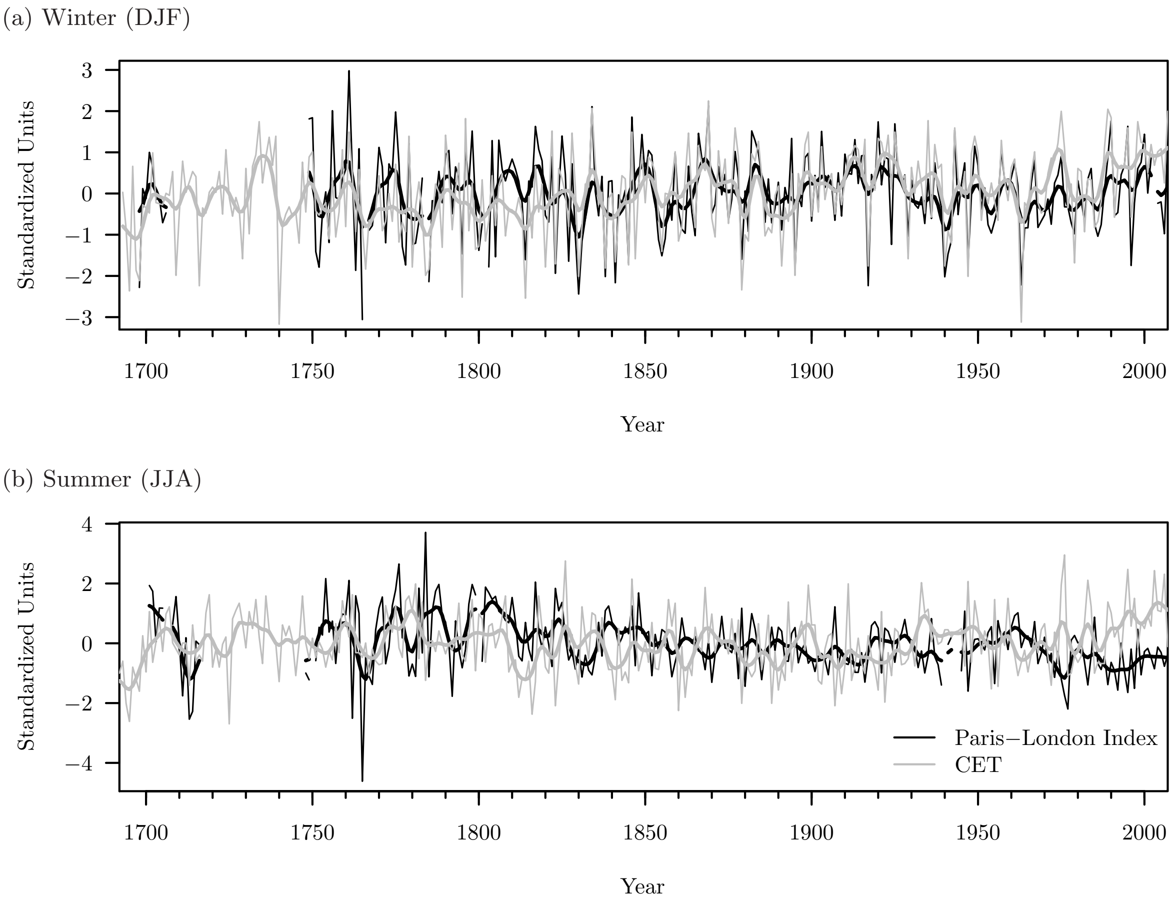

Figure 7.5: A comparison of the standardized Paris–London westerly index and CET series for the winter (DJF) and summer (JJA) seasons. Both series have been standardized over the 1692–2007 period. The thick lines indicate the data smoothed with a 10-year Gaussian-weighted low-pass filter.

but would lead to more comparable results in the spring and autumn compared to winter and summer.

The results for the low-pass filtered series in Table 7.1 indicate that during winter (December to February) there is a strong link between decadal changes in the degree of westerliness and temperature across south-central England and the Low Countries. Correlations are generally highest with the CET series, and for that series peak at 0.77 in January with decadal variations in the degree of westerliness explaining nearly 60% of the variation in temperature. During the other seasons of the year the decadal-scale correlations are generally not statistically significant.

A slightly different perspective on the series-long correlations is shown in Figure 7.5, where the Paris–London and CET time series have been plotted for winter (DJF) and summer (JJA). The plot for winter (Figure 7.5a) clearly shows the strong association between the degree of westerliness in western Europe and the mean winter temperature, at both the inter-annual and decadal timescales. During the summer (JJA, Figure 7.5b) the anti-correlation observed in the results presented in Table 7.1 is apparent at inter-annual and decadal timescales, although the relationship appears to fail prior to 1800. Similar results have been shown in the tree-ring based high-summer (July and August) NAO reconstruction by Folland *et al.* (2009). A further interesting feature is the rise in mean temperatures in the period after 1970, which corresponds to a significant reduction in the strength of the westerlies as identified in Chapter 6. These features are explored further in the following section using running correlations.

7.5 Running correlations

In this section 31-year centred running correlations are calculated between the Paris–London index and the three temperature series. In Figure 7.6 the running correlations have been computed for each month of the year and the results have been presented for each temperature series in the form of contour plots. Following the example of Jacobeit *et al.* (2001), the monthly series have been smoothed with a 10-year Gaussian weighted filter to reduce inter-annual variability in the results and to expose decadal relationships between the variables.

Beyond the simple seasonal differences in the correlations, and the stronger relationships for CET and De Bilt compared to Berlin, which can be ascertained from the results in Table 7.1 above, some interesting time evolving relationships are evident in the results shown in Figure 7.6. During the winter months (December, January and February) the correlations are weak for all seasons until the 1840s, when the correlation values increase to 0.85 in the case of the CET series. The correlations remain at this level until the 1910s when they drop, and remain at values around 0.65 until the 1940s, after which the values increase again. As has been described in Section 6.5.2 the attribution of these variations in correlation coefficients to environmental conditions is difficult because time-varying correlations can occur as a result of the sampling of portions of the data. However, a similar pattern during the extended winter season (DJFM) was observed in the comparison of the Paris–London index and several temperature series (different to those considered here) by Jones *et al.* (2003). The loss of correlation during the period 1910–40 is also evident in the results presented by Jacobeit *et al.* (2001) who compared the CET to a zonal index representing the NA-WE region.

Perhaps the most interesting results are achieved in the contour plots of Figure 7.6 during the summer months. Moderate negative correlations can be observed during the summer, and especially in July, during the period 1770–90. Thereafter, until the 1810s correlations are weak but gradually increase to a maximum during the 1940s. After the 1950s the correlations reduce slightly, especially during the 1970s. These expand the results shown above in the simple time series plots of Figure 7.5, and indicate that the same time-varying correlations feature in all three temperature series and not just CET. As mentioned above, a decoupling between atmospheric circulation and surface temperature during the period 1790–1810 has been shown in the results of Folland *et al.* (2009) who compared a tree-ring based Summer North Atlantic Oscillation (SNAO) reconstruction with the CET series. The authors avoided a direct attribution of these conditions to any particular mechanism but suggested that a similar loss of correlation observed in the period 1915–25 was likely due to a change in the pattern of atmospheric circulation, with the southern node of the SNAO lacking its usual east-west structure, which in turn affected cloudiness and hence the temperature in central England. The de-coupling during the 1790–1810 may also be attributable to the high rate of volcanic activity at the time. The prolonged eruption of the Laki volcano in Iceland in 1783 (Jones & Bradley, 1992), the anonymous tropical eruption in 1809 and the Tambora eruption in Indonesia in 1815 (Cole-Dai *et al.*, 2009) likely played a significant role in reducing the receipt of short-wave radiation across Europe. Parker (2009a) has shown that around 30–60% of the variation in CET in June, July and August

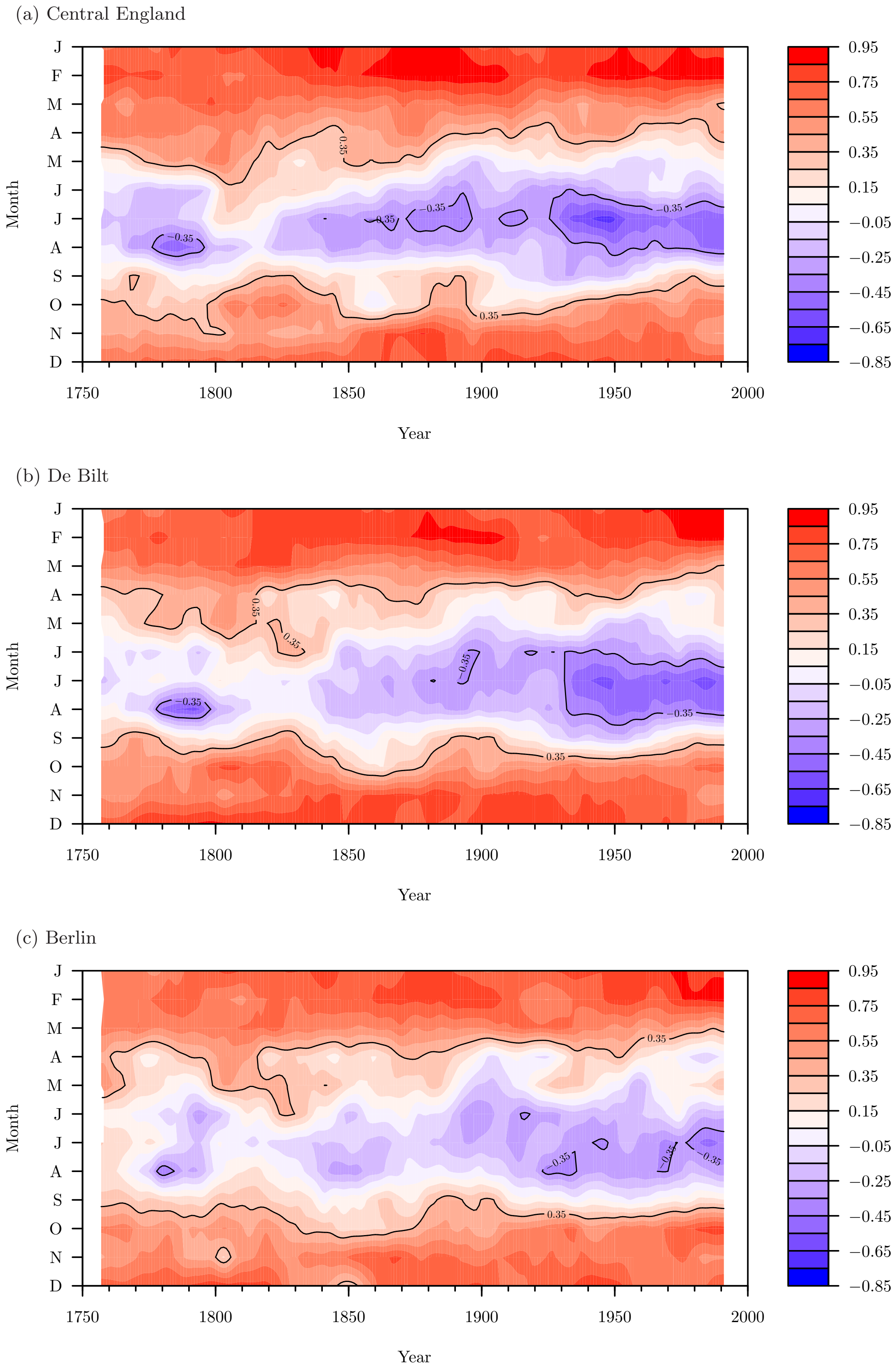

Figure 7.6: Contour plots showing the monthly running correlations (31-year centred) between the Paris–London westerly index and three temperature series over the period 1748–2007. The correlations have only been computed where there are < 20% missing values in each sample of the Paris–London series, and as there are no such samples before 1748 that period is no included in the plots. The individual monthly running correlations series have been smoothed with a 10-year Gaussian weighted low-pass filter in order to remove inter-annual variability and accentuate decadal-scale correlations. Correlations greater than approximately ±0.35 are significant at the 95% level.

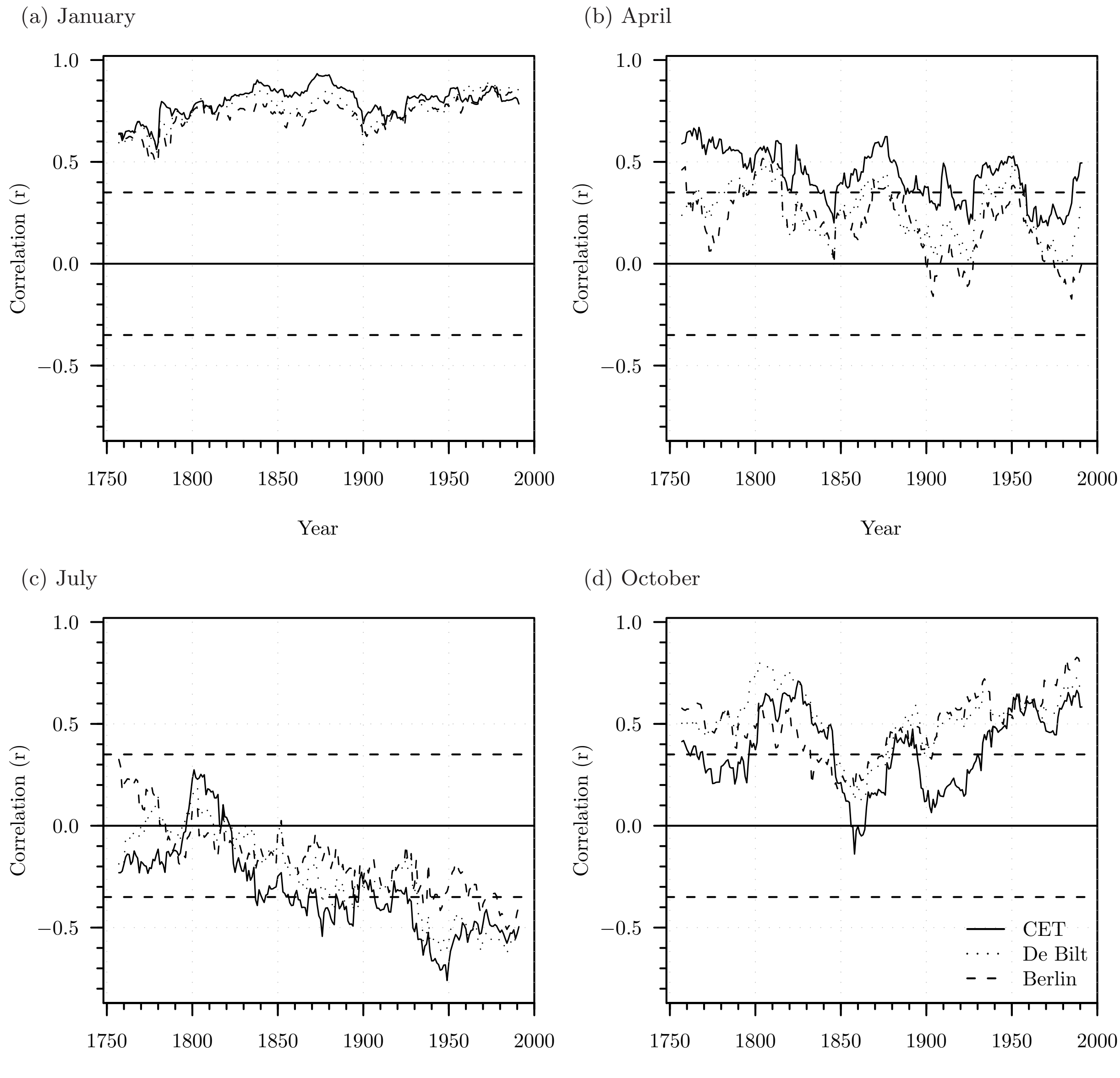

Figure 7.7: 31-year centred running correlations between the Paris–London index and three temperature series for the months of January, April, July and October. As with Figure 7.6, there are too many missing values in the Paris–London index before 1748 to calculate running correlations, and correlations have only been computed where there number of missing values is not greater than 20%. Correlations greater than approximately ±0.35 are significant at the 95% level. This significance level is marked in the plots by the horizontal dotted lines, and it should be noted that while this indicates the statistical significance of each 31-year sample, it does not indicate if the *variations* in the correlations are statistically significant.

is attributable to sunshine duration. Therefore the increase in aerosols resulting from these volcanic eruptions may have altered the relationship between the surface temperature and the atmospheric circulation during this period. However, much more work would be required to ascertain this relationship.

Running correlations for the central months of the four seasons of the year are plotted individually in Figure 7.7. The results for January show a consistency over time, compared to the other three months, and are higher than 0.5 for all of the three temperature series. The results for April and October show a great deal of variability over time, which is consistent for all three of the temperature series, although the correlations are generally weak for these two months. The most interesting results are apparent for July (Figure 7.7c), where a gradual increase in the strength of the negative correlation over the 1750–2000 period can be noted. This is due to the loss of correlation around the year 1800 as described above.

7.6 Chapter summary

This chapter has assessed the relationship of the Paris–London westerly index to surface temperature across Europe. The westerly index has been derived as monthly and seasonal normalized means of daily MSLP. The study expands the work of several authors by using the extended length of the London and Paris MSLP series, which allows the relationship to be studied back to 1748 on a near continuous basis and back to 1692 on a more fragmented basis. A correlation analysis between the Paris–London index and the Luterbacher *et al.* (2004) European temperature reconstruction has confirmed that the influence of the Paris–London index is highest across southern England and the Low Countries. However, there is also an indication that this regional-scale index is linked to the larger-scale NAO but also that the spatial pattern of this relationship has changed over the course of the last 300 years. It is difficult to say whether this is due to actual environmental causes, whether it is due to the use of running correlations or if it results from variations in the quality of the temperature or MSLP data.

Correlations between the Paris–London index and three long-temperature series (CET, De Bilt and Berlin) have shown the expected seasonal variation in correlations, with strongly positive correlations in the winter and weakly negative correlations in the summer. During the transition seasons of spring and autumn, the correlations are much weaker. These correlations appear to have varied over time, and running correlations were used to assess this. During the winter the correlations were most consistent with time. The correlations during the transition seasons of spring and autumn fluctuate greatly. During the summer a loss of correlation is evident during the period 1790–1810; after this period the correlations gradually increase.

Chapter 8

North Atlantic Storm Variability

8.1 Introduction

In Chapter 5, a list of the ten lowest barometric pressure readings in the London and Paris daily Mean Sea-Level Pressure (MSLP) series hinted at the variability of the storm climatology in the North Atlantic-Western European (NA-WE) region over the last 300 years. This chapter explores the subject in greater detail by extracting indices of storminess.[1] from the two series

The influence of human activity on the frequency and intensity of extreme events such as mid-latitude storms is a critical subject of current climatic research given the huge effects that such events have on society (Trenberth *et al.*, 2007). The analysis of storm variability, and especially the calculation of the return period of storms, is of particular interest to several industrial sectors, especially the insurance industry (Della-Marta *et al.*, 2009) and the offshore oil industry (Bijl *et al.*, 1999). Storms are also an important vehicle for the transportation of heat and momentum from the equator to more northern latitudes, and a greater knowledge of storm variability should aid the understanding of these dynamics (Wang *et al.*, 2006). Meehl *et al.* (2007) summarize the information from GCMs regarding the likely future changes in mid-latitude storms, by stating that fewer storms are likely as a result of poleward shifted storm track, but those that do occur will be more severe. However, the mechanisms behind these changes are generally poorly understood and different physical or dynamical processes can be either reinforcing or opposing. Weisse & von Storch (2010) describe three basic effects of global warming on storm activity, none of which has been established as the most likely. The first mechanism ascribes storm activity in the mid-latitudes to the meridional temperature gradient between the Equator and the Pole. A decrease in this gradient, through increased warming at the Pole, is likely to lead to a reduction in storm activity. However, an increased temperature gradient in the upper atmosphere would lead to increased storm activity, and the apparent storminess is therefore a balance between these two effects. The second mechanism relates changes in storm activity to the increased moisture content of a warmer atmosphere, as described by the Clausius-Clapeyron equation. Willett *et al.* (2007), amongst others, have shown that the global increase in specific humidity in recent decades is attributable to human activity, and Weisse & von Storch describe how this increased moisture content of the atmosphere may lead to more vigorous storm activity through an increased release of latent heat. However, Weisse & von Storch also describe a

[1]The term 'storminess' is used throughout this chapter to describe both the changing frequency and intensity of storms.

competing view in which the rise in humidity may lead to a preferable transport of heat, and with the available energy therefore spread over a wider latitudinal area reduced storm activity may be experienced in mid-latitude regions. The third possible effect of global warming on storminess in mid-latitudes described by Weisse & von Storch (2010) involves changes in the sea surface temperature. Increased temperatures may enhance cyclonicity, although the authors suggest that with other evidence disputing this, changes to sea surface temperature may rather influence the position of the storm track rather than the intensity or frequency of storms across the region.

The statistical analysis of the variability of mid-latitude storminess is restricted by the small samples of available data. This problem arises primarily because there are usually only a limited number of storms per year from which to build a database, but is compounded by a lack of long homogeneous storm data. The most direct type of data for studying storminess is wind speed, although wind speed series are generally too short or are beset with inhomogeneities to be of use in studying long-term changes in storminess (Lamb & Weiss, 1979; The WASA Group, 1998). Geostrophic Wind (Geo-Wind) speed series are a useful proxy for the 'true' wind speed and can be calculated using gridded MSLP data or MSLP data from three stations in positions suitable for the construction of a 'pressure triangle' (e.g. Schmidt & von Storch, 1993). Given that MSLP data series are often longer than wind speed series, Geo-Wind analyses have enabled the extension of the storm record back into the late nineteenth century (Wang *et al.*, 2009). Barometric pressure data from stations that are not in positions suitable for the construction of 'pressure triangles' can also be used to study storminess in the NA-WE region by extracting local indices of storminess. Indices formulated from such stations have been used to extend the storm record back to the late eighteenth century and have the benefit of analysing storm activity in a pre-industrial environment when temperatures were cooler (e.g. Bärring & Fortuniak, 2009).

The London and Paris daily MSLP series have the potential to indicate changes in storminess in the NA-WE region over the last 300 years. Along with the increased database of storminess to aid statistical analyses, this would allow an assessment of the often cited conclusion that increased storminess (both frequency and intensity) was a significant feature of the Little Ice Age (LIA) climate (e.g. Lamb, 1984a, 1991; Wheeler & Mayes, 1997). This suggestion appears to contradict the relationship between human activity and storminess in the NA-WE region described above but is based on a greatly incomplete storm chronology and demands much more research (Pfister *et al.*, 2010). However, the relatively short distance between London and Paris provides a limited indication of storm-track changes and the comparison with other station series would be preferable; the calculation of a Geo-Wind series would be useful in this respect. The location of London and Paris, with the incorporation of data from de Bilt in the Netherlands, provide a triangle that is of a suitable size and location for the calculation of the Geo-Wind speed back to at least 1824. Unfortunately, inhomogeneities in the early part of the de Bilt series (T. Brandsma, pers. comm.) currently restrict this analysis. In addition, a further restriction on such analyses arises from the differing observation times used to complete the London and Paris MSLP series. The series have been constructed from a combination of once-daily, twice-daily and 24 hourly mean observations, which means that the data cannot be reduced to a common time. The situation is further complicated because the once-daily observations in the London and Paris series were recorded at different times of the day, e.g. mostly 9am for London and

12pm in Paris. However, local indices of storminess can be extracted from the London and Paris MSLP series, although the changing observation hours in the data means that the results should be viewed with caution because the detection of storms is determined by the resolution of the data, which varies throughout the series. The results presented in this chapter should therefore be considered a first attempt at the extraction of storm indices from the London and Paris MSLP data.

The chapter begins (§8.2) with a review of literature relating to storminess in the NA-WE region. This review focuses on those studies that use MSLP data to analyse storminess, given that the longest and arguably the most useful indices of storminess can be derived from such data. The literature review also refrains from including information on storminess derived from reanalysis data, which aim more at understanding the dynamics of the storm climate (e.g. Wang *et al.*, 2006). Section 8.3 describes the indices that have been used to calculate the storminess series from the London and Paris data, and includes a description of the problem of the changing observation hours in the data, which as briefly described above imposes a limit on an adequate assessment of storminess from the data. Section 8.4 follows with a discussion of the results, and the chapter ends (§8.5) with an outline of the main findings.

8.2 Previous studies about storminess in the Northeast Atlantic/Western European region

8.2.1 Geostrophic wind speed series

Wind speed observations provide a direct indication of storminess and several studies have attempted to use such data to analyse changes in storminess in the NA-WE region (e.g. Rodewald, 1965; Lamb & Weiss, 1979; Smith, 1982; Hammond, 1990; Dawson *et al.*, 2002; Smits *et al.*, 2005). Unfortunately, wind speed series are notoriously inhomogeneous due to an extreme sensitivity of the instruments to the immediate environment (Lamb & Weiss, 1979; The WASA Group, 1998; Jones *et al.*, 1999a). Along with this problem, the wind speed station-network tends to be sparse across much of Europe (Hewston, 2008) and the series are generally shorter than other meteorological series (Hulme & Jones, 1991; Alexandersson *et al.*, 1998; Schmith *et al.*, 1998). In the absence of suitably long homogeneous wind measurements, Geostrophic Wind (Geo-Wind) speed may be used as a proxy for the 'true' wind speed, and can be calculated using MSLP data (von Storch & Weisse, 2008). Gridded MSLP data are useful in this respect and may be used to derive indices of Geo-Wind and vorticity, with a threshold being set at a suitable level to extract storminess information from the data (Jenkinson & Collison, 1977; Hulme & Jones, 1991). Jones *et al.* (1999a) used 5° latitude by 10° longitude gridded MSLP data in this manner to derive an index of annual gale frequency over the British Isles for the period 1881–1997. Their results showed pronounced decadal variability, reaching a maximum during the 1990s but also with a suggestion of increased storminess during the late nineteenth century.

Geo-Wind series can also be obtained from instantaneous MSLP readings recorded from three suitably situated stations. This has the advantage over using gridded MSLP data of being able to extend the index of storminess slightly further back in time to the 1870s. Schmidt & von Storch (1993) were one of the first studies to demonstrate this 'pressure triangle' technique, and used it to analyse the annual frequency of storms crossing the German Bight over the 1876–

1990 period. The authors concluded from their results that there was no long-term change in storminess over the 1876–1990 period in the region. Alexandersson *et al.* (1998) extended the technique of Schmidt & von Storch by deriving Geo-Wind speed series for several triangles in the northeast Atlantic/northern Europe region. The results from the triangles were grouped into two regions: those from the British Isles, North Sea and Norwegian Sea were averaged into a western group, while those from Scandinavia, Finland and the Baltic Sea were amalgamated into an eastern group. Both of these series displayed a downward trend in 95th/99th percentiles of Geo-Wind from a series maximum in the late nineteenth century, to a minimum in the 1960s; thereafter an increase was noted, with values in the 1990s of a similar magnitude to those of the 1880s. Within this general 'flat-V-shaped' pattern, peaks were observed during the 1900s and 1940s, and for the eastern group during the 1900s, 1920s and 1950s. In a later study, Alexandersson *et al.* (2000) added three years of extra data to the analysis, and showed that the trend to increasing values from the 1960s peaked in the early 1990s and declined thereafter. This feature is more apparent in Trenberth *et al.*'s (2007) further extension of the series, which completed the series up to 2004.

The 'pressure triangle' technique has also been used by Matulla *et al.* (2008), who analysed Geo-Wind over the period 1874–2005 for the North Sea, Scandinavia and central Europe regions. Their results for the North Sea and Scandinavian areas showed the same 'V-shaped' trend evident in earlier studies, with maxima in the 1880s and 1990s and a minimum during the 1960s. The main development from the earlier studies, however, was the decadal-scale variability of Geo-Wind derived for the Central European pressure triangle. In comparison to the two northern regions, the central region lacked the declining trend to the 1960s, but rather showed high values in the 1890–1910 period, a sharp drop in values during the 1910s and a gradual increase to a subdued peak in the 1990s. Given the nature of these decadal trends, the difference in Geo-Wind speed between the northern and central European regions cannot be explained simply by a latitudinal shift in storm track, and points to a more complex situation.

Wang *et al.* (2009) have, more recently, extended the 'pressure triangle' technique further by calculating Geo-Wind speed for more triangles across the northeast Atlantic than Alexandersson *et al.* (1998, 2000), for a longer time period (1874–2007) and by breaking the results down into seasonal indices. The extended time series of this study confirmed the suspicions of earlier studies, that storminess in the northeast Atlantic peaked in the 1990s. However, the results went further and showed that large seasonal and regional differences exist in the results. The most important finding from this study is that the winter and summer conditions in the North Sea are often anti-correlated. Therefore while the Geo-Wind speed maxima of the 1880s and 1990s were shown to be of a similar magnitude in previous studies, the former peak mostly occurred during the summer while the latter mostly occurred during the winter. Therefore the peak in winter storminess in the North Sea during the 1990s is unprecedented in the 1874–2007 period, while in the summer a long-term decline in storminess is evident.

The studies by Alexandersson *et al.* (1998, 2000), Matulla *et al.* (2008) and Wang *et al.* (2009) demonstrate, therefore, the usefulness of Geo-Wind speed series in analysing storminess in the NA-WE region. The technique is not without problems, however, and Schmith *et al.* (1998) outline three main areas of consideration. Firstly, they argue that the Geo-Wind may not provide an adequate proxy for the true wind, due to the Rossby radius of deformation being of the same order of magnitude as mid-latitude cyclones. This argument essentially states that in order for the calculated Geo-Wind vector to be an accurate depiction of the true wind vector, the pressure triangle has to be of a suitable size. Triangle size is governed by the location of the stations, and in the North Atlantic the stations may be situated too far apart to provide triangles of an adequate size. Triangles of a more acceptable size can be constructed for the North Sea due to a higher number of stations in the area. A further criticism of Geo-Wind analyses presented by Schmith *et al.* (1998) is that different stations may have different observation times, which can affect the accuracy of the calculation. This problem is well known, and a common solution is to interpolate the data to a consistent time. When the hours are quite close together, for instance 3-hourly, then the error of this interpolation is likely to be small; for a time resolution greater than this, the errors may become unacceptably large. The third criticism of geo-wind analyses levelled by Schmith *et al.* (1998) is that inhomogeneities in the MSLP data are directly transferred to the Geo-Wind series. The geo-wind studies cited above have acknowledged this potential problem, and have sought to ensure the data are as homogeneous as possible. Wang *et al.* (2009) in particular went to great lengths to select homogeneous series, and to conduct a thorough quality control of the data. Nonetheless inhomogeneities may remain in the data, but the subject of inhomogeneities in the data becomes more important when earlier series are used, although in these early periods Geo-Wind series are likely to suffer from fewer inhomogeneities compared with the notoriously problematic wind speed data.

8.2.2 Local storminess indices

Storminess indices can also be calculated using pressure data recorded at a single location. These indices require daily (or higher) resolution pressure data from a particular station, but further demands of the data tend not to be as strict as those for geo-wind indices; this permits the extension of the storminess record further back in time.

The assumption of local storminess indices is that a particular state or rate of change of pressure at a station is an indication of storm activity. An example of this latter technique is the 24-hour absolute pressure changes (ΔP_{abs}) metric, which has been used in several studies. Schmith *et al.* (1998) developed winter indices of storminess using exceedance levels (at the 50%, 10% and 1% levels) of ΔP_{abs}, which were calculated for eight stations across the northeast Atlantic for the period 1875–1995. The results indicated a moderate increase in storminess in the northeast Atlantic from 1970 to 1990, but in general the results from the study were not conclusive. The authors suggested that inhomogeneities in the data may have affected the result. The ΔP_{abs} metric was used more successfully by Jónsson & Hanna (2007) to analyse the variability of storminess at stations in southern Greenland, Iceland and Denmark over the period 1823–2005. The authors concluded that there had not been an increase in storm activity since 1823 in the north Atlantic region. Hanna *et al.* (2008) extended the Jónsson & Hanna study by applying the ΔP_{abs} index to additional station pressure series from the United Kingdom, and include a detailed history of the use of the ΔP_{abs} metric which appears to have first been used by Kämtz (1832). The results indicated that there was no long-term increase in storminess, but there was pronounced interdecadal variability.

The strength in the ΔP_{abs} index lies in its ability to distinguish between mobile and blocked atmospheric conditions, and is not limited by inhomogeneities that cause shifts in the mean of the station data. Indeed, the index does not even require the station pressure data to be reduced to MSLP (Hanna *et al.*, 2008). However, Bärring & Fortuniak (2009) suggest that the index is limited by its inability to capture gradually developing cyclones. Further, if the cyclone is symmetrical in shape and does not change speed or direction when passing the station location there is a chance that the cyclone will be counted twice in the index: once on the leading edge of the cyclone and again on the flank.

Instead of restricting their analysis to just one storminess index, Bärring & von Storch (2004) used four indices to analyses storminess in southern Scandinavia using two pressure series from the south of Sweden. Use was made of the daily MSLP series from Lund (1780–2002) and Stockholm (1823–2002). In comparing the results from the two series, the authors concluded that there was no long-term trend evident in the annual series, but the results did indicate the pattern shown in the geo-wind analyses described above, with a peak in storminess in the 1990s, which was of comparable magnitude to the 1880s, and a quiescent period in the 1960s. Bärring & Fortuniak (2009) extended the study by analysing storminess in the Lund and Stockholm MSLP series over the period 1780–2006. As with the earlier study several indices were used, although they differed somewhat on account of the use of 24-hour time step data, as opposed to 12-hour in the earlier study. Four conventional indices of storminess were extracted from the series which used exceedance thresholds of daily MSLP and absolute day-to-day pressure changes. In addition, four new indices were developed using spectral and wavelet analyses in an attempt to better capture storm information from the MSLP series. The results for the twentieth century indicated a similar pattern of variability in storminess that has been identified in other studies, with a minimum in the 1960s and a maximum in the 1990s. However, in the context of the last 225 years these two periods were not exceptional and were within the range of long-term variability. It should be noted, however, that these findings may be somewhat misleading on account of the calculation of the indices at the annual resolution. It is known from the work of Wang *et al.* (2009) that the apparent lack of overall trend in previous Geo-Wind studies probably resulted from the consideration of annual resolution time series, which masked significant seasonal differences.

The changing frequency of severe storms is a subject that is particularly worthy of investigation given the potential huge socio-economic losses that may occur from such events. The detection of these fast moving weather systems requires sub-daily pressure data (ideally three-hourly or greater) and the reduced availability of such data limits the study of severe storms. Nonetheless suitable data are available for certain locations in Europe, and studies have extracted local indices from the data to analyse the changing frequency of severe storms. Alexander *et al.* (2005) recovered three-hourly pressure data for several sites across the United Kingdom and Iceland to analyse the variation of severe storms over the period 1950–2003. They detected a statistically significant increase in the number of severe storms over the United Kingdom since 1950, although the relatively short time-period used precluded any definite conclusions regarding the significance of this increase over longer time periods. Allan *et al.* (2009) extended the UK three-hourly pressure series back to 1920 by digitizing and correcting additional data. They discovered that the increase since the 1950s shown by Alexander *et al.* (2005) was still significant in the context of the last 70 years, although they also showed that the 1920s was a period of increased severe storminess that was of a similar magnitude to that observed during the 1990s.

8.2.3 Storminess during the Little Ice Age

A variety of studies using documentary, early instrumental and proxy data have suggested that increased storminess was a significant feature of the European climate during the LIA (Lamb, 1984a,b, 1988, 1991; Wheeler & Mayes, 1997). Lamb (1984a,b, 1988) used early instrumental data from across Europe to reconstruct individual storms during the period and combined this information with proxy data. Most notably, the incidence of sea-floods along the Dutch coast was reported as reaching a peak during the late seventeenth/early eighteenth centuries, which was attributed to an increased propensity for the storm track to reside in the 50–60°N latitudinal band (Lamb, 1984a). In a later study, Lamb (1991) reconstructed synoptic charts for many more storms for the extended 1570–1990 period, again using a variety of early instrumental and documentary data. In addition to a synoptic description of the storms, he also attempted to cross-compare the intensity of storms by assigning each storm a Storm Severity Index (SSI) rating. Lamb tentatively suggested from this SSI that there was an increase in storminess in northwest Europe during the two coldest periods (1690–1720 and 1790–1840) of the LIA but also reported that there was evidence for a rise in storminess in northwest Europe following the 1950s. However, Lamb was acutely aware of the difficulty in relating the degree of storminess during the LIA to conditions that followed due to a lack of data and the consideration of individual events. While the severity of individual storms during the period is probably reliable, the incomplete storm chronology for the period prior to the eighteenth century remains a problem in assessing the change of storminess over the last 300 years (Pfister *et al.*, 2010).

Relatively little further research has been conducted on storminess during the LIA in the context of the work of Lamb (1984b,a, 1991) probably as a result of the limited availability of storm data. A notable exception is van der Schrier & Barkmeijer (2005), who sought to explain the atmospheric dynamics responsible for the increased rate of storminess during the 1790–1820 period (Dalton minimum). To achieve this, they examined the results from a coupled ocean-atmosphere model and found that the mean atmospheric conditions that occurred during the Dalton Minimum could have led to an increase in storm intensity in northwest Europe due to increased baroclinicity. However, most of the increased storminess was attributable to a greater variability of the position of the storm track rather than increased cyclogenesis, i.e. an increase of blocking across northern Europe which forced more storms across central Europe. This meridional characteristic of the North Atlantic atmospheric circulation during the 1790–1820 period is also apparent in the reconstructed dataset of Luterbacher *et al.* (2002b) and a variety of other sources as described in Chapter 6.

The study by van der Schrier & Barkmeijer (2005) concerning storminess during the Dalton Minimum was extended by van der Schrier & Jones (2008a), who sought to ascertain whether the anomalous atmospheric conditions were attributable to regional atmospheric circulation anomalies, or rather to planetary-scale circulation anomalies. To measure regional-scale circulation anomalies the authors used pressure data recorded between 1786 and 1820 by an observer in the northeast US. In the absence of data suitable to quantify the planetary scale atmospheric circulation, the authors used a proxy consisting of the frequency of cold-air outbreaks, measured using temperature data recorded by the same observer. The study revealed that there was not generally a statistically significant difference between storminess in the northeastern USA during the 1786–1820 period compared to the 1973–2004, although there was an indication of an increased number of deep cyclones in the months from November to March in the early period. A distinct difference in the frequency of cold-air outbreaks between the two periods led the authors to the conclusion that the anomalous atmospheric conditions during the Dalton Minimum were attributable to planetary-scale atmospheric anomalies.

The storminess indices produced by Bärring & Fortuniak (2009) for southern Sweden stretch back to 1780, and are therefore able to place storminess during the Dalton Minimum in the context of 200 years of subsequent storm activity. Their results indicated that the early nineteenth century experienced a reduced frequency of storminess in Scandinavia, which corresponds well to the suggestion of blocked conditions in northwest Europe and a storm-track that adopted a more southerly route.

A further source of information regarding storminess during the late eighteenth century comes from the analysis of an annual series of maximum high water levels recorded in Liverpool (northwest England) from 1768 to 1999. Woodworth & Blackman (2002) discovered that the annual maximum surge at high water, which provides an indication of storminess, was high during the 1770s, 1880s and 1990s. The study also showed that there had not been a long-term trend in storminess over the ca. 230 period. Missing values during the early nineteenth century limited their study however.

Information on storminess during the Late Maunder Minimum (LMM) (1675–1715) beyond the work of Lamb (1984b,a, 1991) is greatly lacking, although progress is being made through the use of wind force data recorded in ship-logs. Wheeler & Suarez-Dominguez (2006) used daily observations of wind force taken on-board Royal Navy ships sailing in the English Channel during the period 1685–1700 to analyse storminess during the period. Their results indicated that the frequency of gale days in the region was higher in the late seventeenth century compared to the twentieth century, although a significant finding was that the seasonal distribution of gale frequency was somewhat different between the two time periods: an increase in the number of gale days was observed in the summer months, whereas a reduced frequency was noted during the winter. This latter observation was linked by the authors to an increased prevalence of atmospheric blocking in northwest Europe during winters in the late seventeenth century. Wheeler *et al.* (2009) have recently extended this study to the period 1685–1750, and these newer results supplement the earlier information by showing that the high number of storms passing through the English Channel during the LMM was exceptional in the 66 year period. These newly recovered data for the 1685–1750 period, also show the change in the annual cycle of storminess observed for the limited 1685–1700 period, with more storms occurring in the summer months and hence a more even cycle of storminess than that observed during the twentieth century.

Certain evidence to support the suggestion of increased storminess during the LIA has been found in changing sand movement in coastal areas of northwest Europe (e.g. Wilson *et al.*, 2004). Clarke & Rendell (2009) have thoroughly reviewed many of these studies and concluded that there is a general degree of agreement between the studies, which support the suggestions of increased storminess during the LIA. However, the use of coastal sediment as a proxy for storminess in Europe is fraught with difficulty and the data are only able to indicate multidecadal changes in storminess.

8.2.4 Storminess and the NAO

The storm climatology in the NA-WE region is strongly associated with the North Atlantic Oscillation (NAO), as identified in the previous chapter (§6.2). Positive NAO years are associated with the storm track situated in the north Atlantic/northern European region, whereas negative NAO conditions are associated with a more southerly storm track position across Europe. Indeed, Hurrell & van Loon (1997) have shown that anomalous transient eddy activity may actually maintain the anomalous mean circulation associated with the NAO. Other work has suggested that it remains unclear whether the storm activity drives or is driven by the mean circulation (Ulbrich & Christoph, 1999). Regardless of the direction of the relationship an association between storm activity and the NAO would be expected. However, the results from many studies have indicated that the relationship of the NAO, as quantified by station-pair indices, with storminess time series is not as strong as would be expected.

Alexandersson *et al.*'s (1998) pressure triangle indices displayed only moderate, albeit statistically significant, correlations with the North Atlantic Oscillation Index (NAOI) derived from MSLP data at Ponta-Delgada (Azores) and Stykkisholmur (Iceland). In particular, the low NAOI values during the late nineteenth century correspond to high values in the storminess indices. The authors offered the suggestion that this may be attributable to a decreased frequency of storms at the time, which affected the monthly mean NAO values, but which increased the severity of the events not detected in the NAO indices. Central to their argument is the question of how storminess contributes to the mean Icelandic low: either the Icelandic low is the average of storms moving into the region or it is part of the background hemispheric wave structure (Hoskins & Hodges, 2002). According to Hoskins & Hodges (2002), the actual situation may be a combination of both aspects. This suggests therefore that the NAO and storm activity can not be simply linked in the way described by Alexandersson *et al.*. In addition, at least part of the poor relationship between the storm and NAO indices may be attributable to the consideration of annual resolution data, which mask the important seasonal variations identified by Wang *et al.* (2009).

Other studies have avoided the problem of seasonal differences in the NAO and storm indices by correlating the storm series with the NAOI at the seasonal resolution. Hanna *et al.* (2008) showed that the highest correlations between winter storminess and the NAOI were achieved for those stations closest to the axis of the bi-polar NAO pattern, and especially for the Icelandic stations. Their results also indicated that the relationship between the NAOI and the storminess indices varied over time, which was attributed to the changing positions of the 'centres of action' of the NAO. Allan *et al.* (2009) have also indicated that the relationship between the NAO and severe storm activity over the British Isles varies over time, but is generally positively significantly correlated and that the NAO appears to have a moderating influence on severe storm activity in the region during the autumn (OND) and winter (JFM). It should be noted that most of the severe storms in the British Isles in their study occurred in the north of the British Isles, and this is hence where the largest association with the NAO is to be expected. The winter (October–March) gale day frequency for stations in northern Scotland correlated against the NAOI by Dawson *et al.* (2002) also demonstrates a similar changing relationship over time, although part of this may be attributable to a lower quality of the data in the nineteenth century. Wang *et al.* (2009) achieved high correlation coefficient values between their Geo-Wind speed series in the North-east Atlantic and North Sea regions and the Ponta-Delgada–Stykkisholmur NAOI during the winter (DJF) and spring (MAM) seasons. Their results indicate that high NAO conditions are associated with increased storminess in these two regions.

The correlations indicated in these studies highlight relationships at inter-annual timescales. Few studies have examined coherence at longer time scales. An exception is Bärring & Fortuniak (2009), who have tentatively indicated that there may also be a correlation between storminess and the NAO at decadal timescales.

8.3 Measuring storminess in the London and Paris MSLP series

8.3.1 The varying hours of observation in the series

A major limitation to the use of the London and Paris daily pressure series in the examination of storm variability is the changing observation hours of the barometer readings used to complete the series. The exact observation hours are listed in Tables 2.4 and 3.6 (Chapters 2 and 3), from which it is evident that prior to the nineteenth century the observations were generally recorded once per day (mostly 9am in London and 12pm in Paris). The once daily observations continued in Paris until the 1920s, but in London after the mid-nineteenth century the observations were mostly the average of 24 hourly observations. It should also be noted that the European and North Atlantic daily to MULtidecadal climATE variability (EMULATE) MSLP series for London were constructed from a combination of 24 hourly mean and 2–3 times daily observations (R. Allan, pers. comm.) and the problem of changing observation times has therefore been carried through to the London daily MSLP series during the 1850–81 period. In the Paris daily MSLP series, 24 hourly observations were only available after approximately 1950.

The changing observation times can cause inhomogeneities in the data, which affect the mean level, and therefore corrections were applied to remove this error (see §§2.3.6 and 3.3.4). On monthly or longer timescales this equivalent 24 hourly correction improves the accuracy of the data. However, the individual daily observations still have the variance properties linked to the observation hours, which affects the ability to quantify storm variability. Within the segments of consistent observation times, the comparison of inter-annual storm variability is valid but the comparison between segments of data with different numbers of observations per day is problematic. This difference is most marked when using storm indices that use day-to-day pressure tendencies.

The changing numbers of observations per day and the changing observation times also means that the data cannot be used to construct Geo-Wind speed indices, despite the distance between London and Paris, and the incorporation of MSLP data from de Bilt in the Netherlands, forming a triangle of a suitable size and position. The extraction of Geo-Wind indices from 'pressure triangles' is particularly vulnerable to different observation hours between the stations, and a common solution is to interpolate between observation to obtain a consistent data series (Wang *et al.*, 2009). However, the use of only one observation in most of the London and Paris data prior to the nineteenth century means that there are too few observations per day to effect such an estimation. Further, the use of 24 hourly observations in the later parts of the series means that this interpolation would not yield comparable data.

8.3.2 Index construction

Since Geo-Wind speed data cannot extracted from the London and Paris data, local indices have been constructed from each series. The rationale of Bärring & Fortuniak (2009), Bärring & von Storch (2004) and van der Schrier & Jones (2008a) has been repeated by extracting several indices of storminess from the two series. However, in contrast to these previous studies, index values for all seasons of the year were calculated, alongside annual values. Different indices from the previous studies were also calculated, namely:

N_{10pc} The frequency of observations below the 10th percentile of MSLP;

P_{Q1} The first quartile of MSLP;

Γ_{10} The number of days lower than the 10th percentile of MSLP, with seasonally varying thresholds developed through the application of a 3-parameter Gamma distribution to the data;

ΔP_{abs} The mean of absolute day-to-day MSLP variability;

ΔP_{abs99} The 99th percentile of absolute day-to-day MSLP variability.

The first index (N_{10pc}) is a simple threshold exceedance statistic. The calculation of the threshold value follows the example of van der Schrier & Jones (2008a), and differs between the two stations (1001.3hPa for London and 1004.3hPa for Paris). It can be considered comparable (although slightly less extreme) to the 'frequency of storms below 980hPa' index used for the Scandinavian stations by Bärring & von Storch (2004), Bärring & Fortuniak (2009) and The WASA Group (1998), but the higher threshold values reflect the higher mean MSLP values at London and Paris compared to the more northerly stations.

The P_{Q1} index has been used in several studies on storminess in the NA-WE region (e.g. Bärring & Fortuniak, 2009), and is included here for comparison purposes. It should be noted that this index is anti-correlated with the other storminess indices, with low index values being associated with increased storminess.

The third index (Γ_{10}) is a new index, which has not previously been used in the analysis of storms. The principles of the index are discussed in Section 6.6, where it was used to quantify extreme westerly/easterly conditions in the Paris–London index. The technique is applied here to the individual pressure series. The Γ_{10} index is very similar to the N_{10pc} index, but is constrained to the 1961–90 period and the annual cycle is removed. This is most important when considering annual frequencies of storms, when differing thresholds are necessary due to the annual cycle of MSLP; it is of no less importance in the analysis of seasonal storm frequencies. The values have been expressed as percentage of total days in the year or season.

The ΔP_{abs} index follows the example of Jónsson & Hanna (2007) and Hanna *et al.* (2008), and therefore allows comparison with their results, which were calculated from stations in the British Isles and Iceland. The ΔP_{abs99} is closely related to ΔP_{abs} although it quantifies very high absolute pressure changes between daily observations, and hence the deepest and probably quickest moving cyclones.

In the calculation of all of these indices, where the number of missing days in the season or year exceeded 20% the value was marked as missing.

8.4 Results and discussion

8.4.1 The annual cycle of storminess

The monthly distribution of values from the five storm indices are shown in Figure 8.1. The three indices N_{10pc}, ΔP_{abs} and ΔP_{abs99} all show a pronounced annual cycle, with maxima in the winter months (October to April) and minima during the summer months (May to September). The monthly values for the Paris series are lower than for London, indicating generally increased storminess in London. A similar annual cycle is shown in the storm indices produced for stations in southern Sweden by Bärring & Fortuniak (2009) and in the British Isles by Hanna *et al.* (2008). The annual cycle for the P_{Q1} index in London and Paris is somewhat different to these three indices, with a rise from the start of the year (most pronounced in Paris) to a peak in the spring. Thereafter the index declines to a minimum in June/July. This is followed by a rise to a second peak in November or December. The Γ_{10} index shows no annual cycle, which would be expected given the purpose of the index described above (§8.3.2).

The monthly distribution of values for the storm indices have also been calculated for various sub-periods (Figures 8.2 and 8.3). The annual cycles during the sub-periods at both London and Paris generally show the same pattern. An obvious difference is evident in the N_{10pc} index and particularly the P_{Q1} index for Paris during the period 1670–91, where the mean of the data during the summer appears too high while for the winter is too low. This is probably related to the inhomogeneity remaining in the earliest part of the Paris series identified in Chapter 5. The absence of this anomaly in the ΔP_{abs} and ΔP_{abs99} index results indicates the benefit of using these indices where pressure data have inhomogeneities which affect the mean value. However, these results correspond well to the findings of Wheeler *et al.* (2009), who noted a similar feature for the period 1685–1750 from wind force data derived from ship-logs recorded in the English Channel. There is also an indication from the results for the P_{Q1} and ΔP_{abs} indices that there was increased storminess in London over the period 1726–47 for the months of April through to June, although this pattern is not evident for the other storminess indices.

8.4.2 Time series of storminess

The time series plots for the storm indices N_{10pc}, P_{Q1} and Γ_{10} at the annual resolution (Figure 8.4) indicate a high degree of decadal variability in storminess but no long-term trend over the 300-year period. This is also true for these indices when broken down into seasonal time series (Figures 8.5 to 8.8). A trend test using ordinary least squares regression (not shown) has confirmed the lack of statistically significant ($\alpha = 0.05$) trends in the three indices. Despite the absence of a long-term trend, during autumn there is an indication of a decline in storminess between the 1830–40s and 1950s, which follows a large increase in storminess in the early 1830s. After the 1950s, storminess appears to have increased to a peak during the late 1990s. As this feature is apparent in both the London and Paris series it would seem to be a real feature, and cannot be explained as an inhomogeneity.

The results from the two absolute day-to-day pressure difference indices (ΔP_{abs} and ΔP_{abs99}) at both the annual and seasonal resolutions indicate that, as expected, the changing number of observations per day used to complete the London and Paris MSLP series has a large effect on the day-to-day variability of pressure. Large steps are apparent in the series at the time of the change

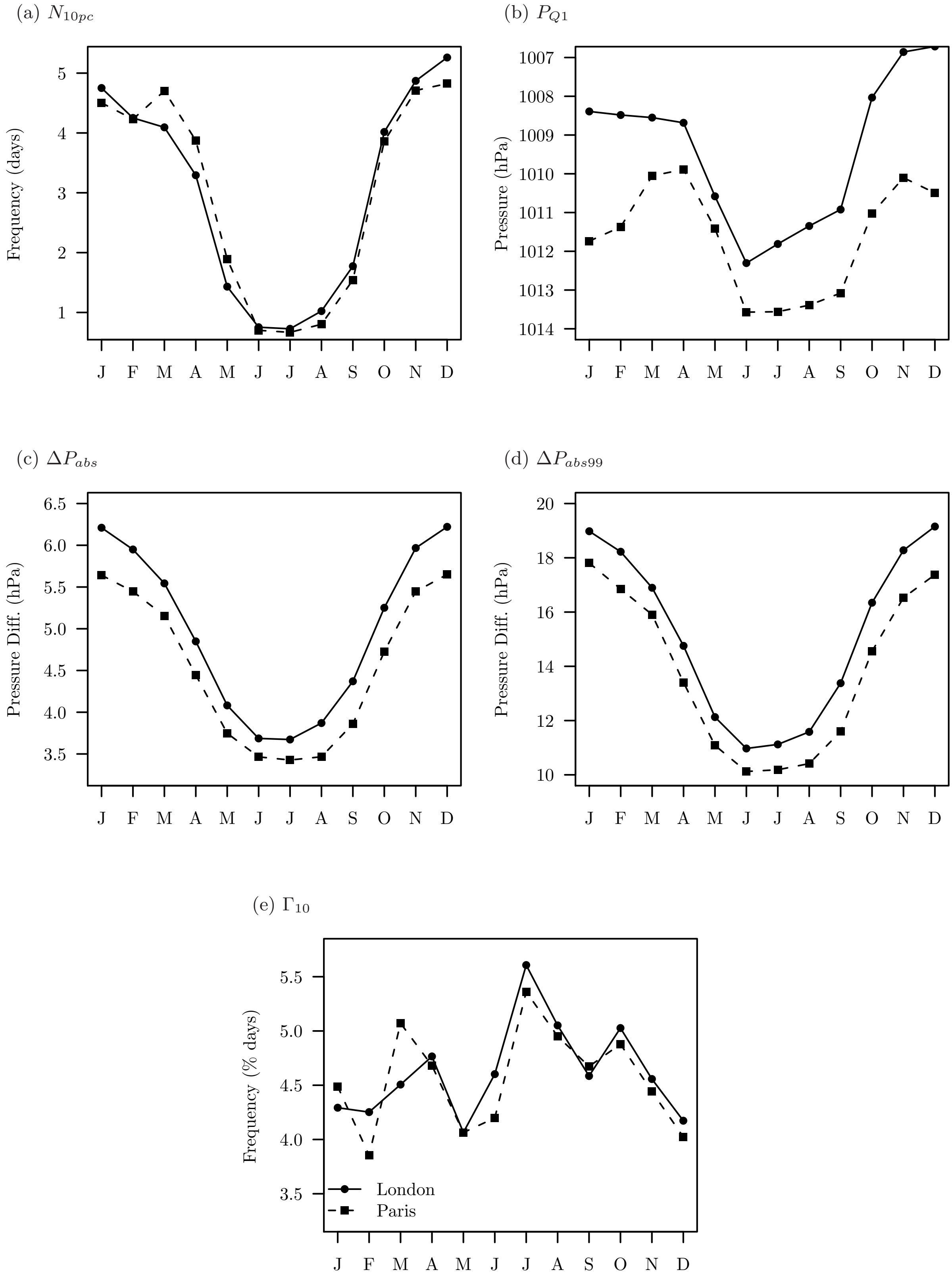

Figure 8.1: The monthly means of the storm indices.

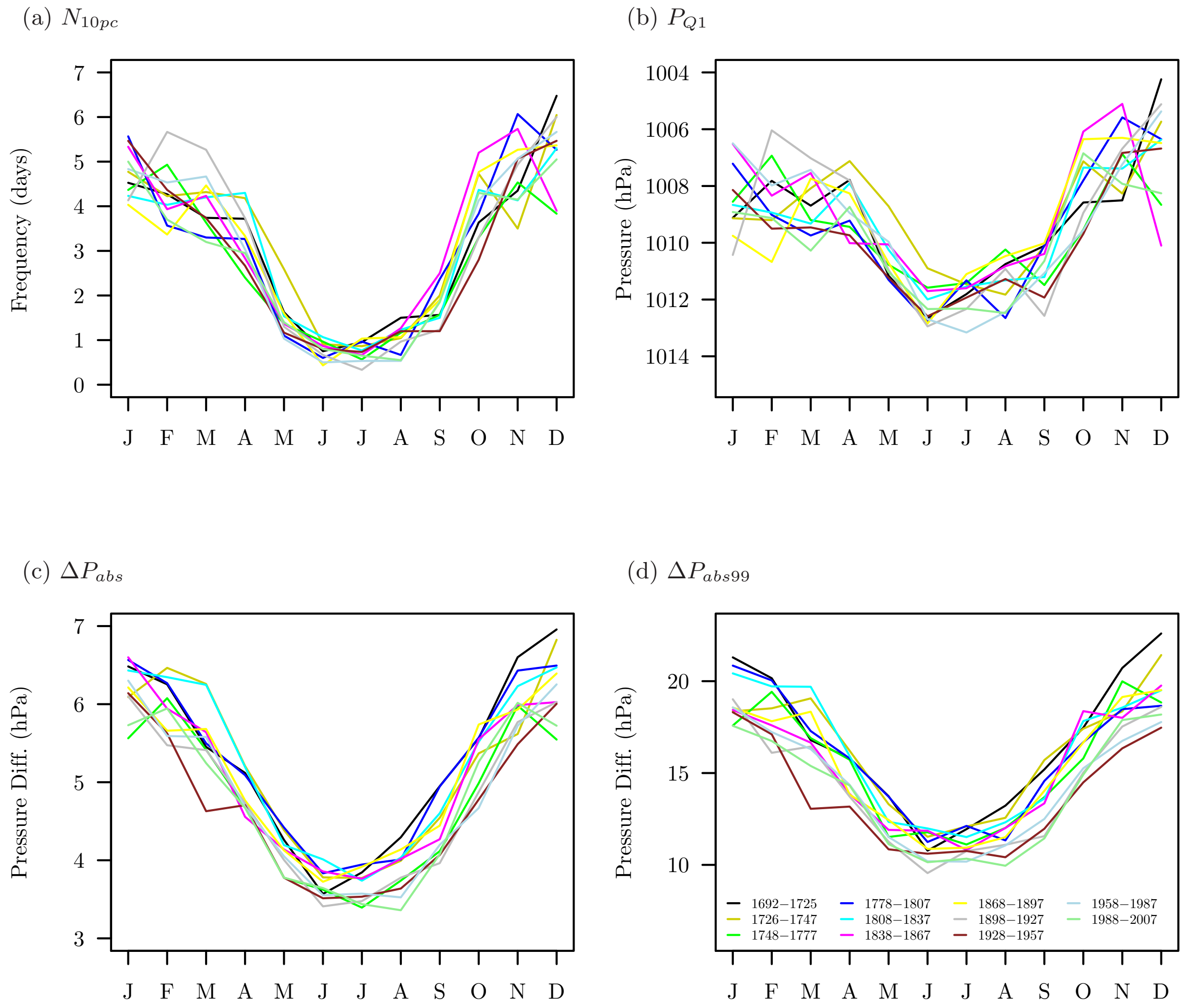

Figure 8.2: Monthly means of storminess in the London series during 30-year periods. The values for the Γ_{10} index have not been included due to the lack of an annual cycle in the results.

to different recording schedules, and are most marked at the annual resolution. The results for London over the 1765–73 period are greatly reduced, which indicates the susceptibility of the absolute day-to-day pressure different to poorly maintained barometers that suffer from reduced variability (see §5.5). After 1950, both the London and Paris MSLP series were constructed from the mean of 24 hourly MSLP data and are therefore consistent over the time period. However, even within that time period there is little change in storminess indicated in the two indices, which is in accordance with the other storminess indices. The 1990s do not appear to have experienced the level of increased storminess indicated in other studies, and while there is a slight indication of increased storminess in the late 1990s, this is not exceptional in either the twentieth century or the entire 300-year period.

This lack of long-term trend in storminess at London and Paris over the 300-year period corresponds to the findings of Bärring & Fortuniak (2009), who observed a similar lack of trend in storm indices calculated from MSLP recorded at Lund and Stockholm in southern Sweden over the shorter 1780–2005 period. The indices used by Bärring & Fortuniak were only calculated

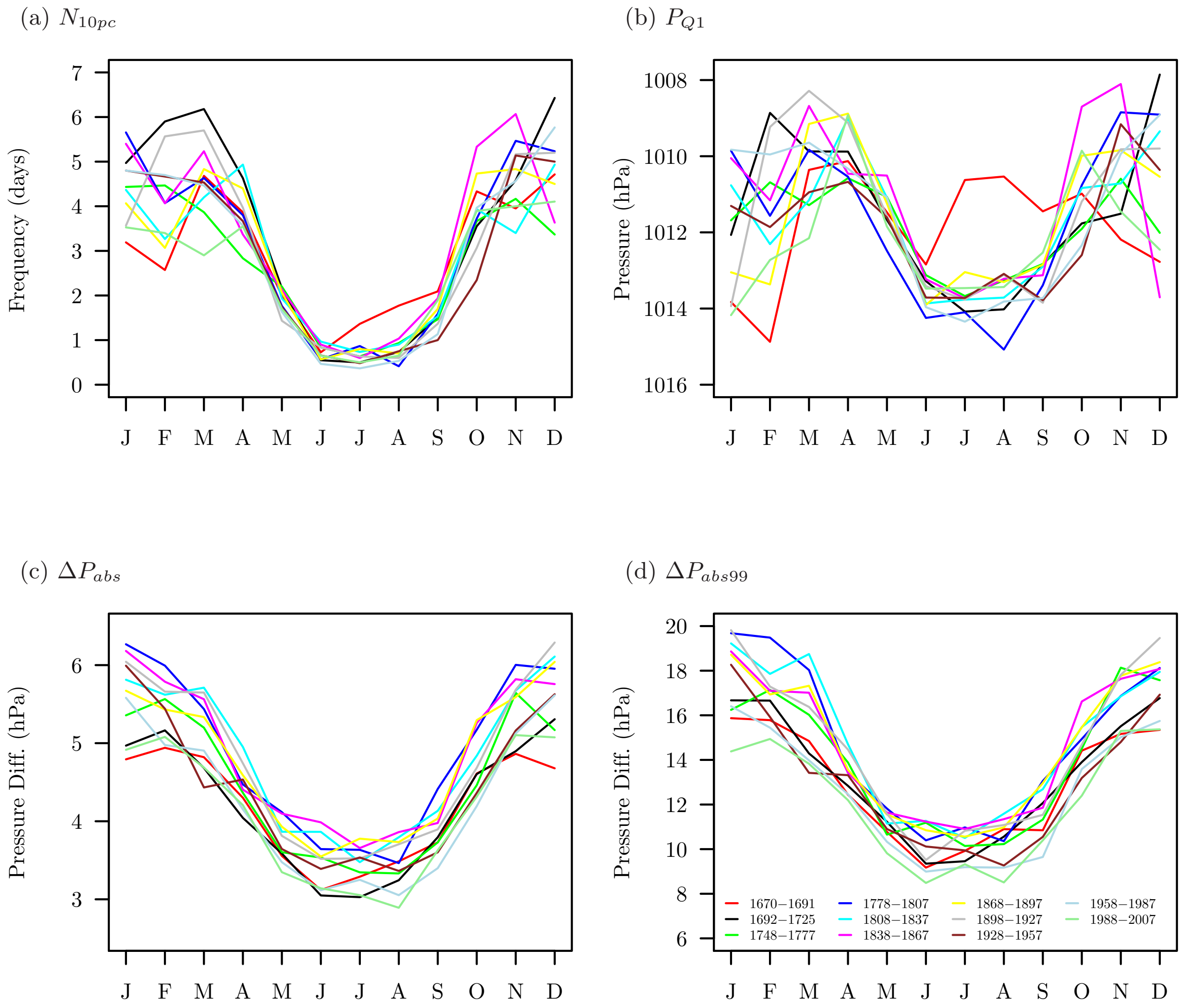

Figure 8.3: As Figure 8.2 but for Paris.

at the annual resolution but the results at the seasonal resolution presented here indicate that the lack of long-term trend observed in their study may not have resulted from the analysis of annually resolved data.

Wang *et al.* (2009) demonstrated that in the North Sea region, a decline in storminess was evident during the summer from 1874–2005, while an increase in storminess was evident over the same period during the winter. Specifically storminess during 1990s in the winter was exceptional in the 132 year period. The London and Paris data do not show these features of storminess, and this is most likely due to the calculation of storm indices for only two stations. The divergent information evident from the London and Paris data may also have occurred as a result of inconsistent observation times of the data. The least reliable series are the day-to-day absolute pressure difference series (ΔP_{abs} and ΔP_{abs99}). However, the period 1880–2007 in London and 1950–2007 in Paris are consistently the mean of 24 hourly observations. During the autumn (SON) and winter (DJF) the pattern of high values from 1880–1920, then low but increasing values to a peak in ca. 1982 is similar to that observed for Aberdeen by Hanna *et al.* (2008), who used the same ΔP_{abs} index.

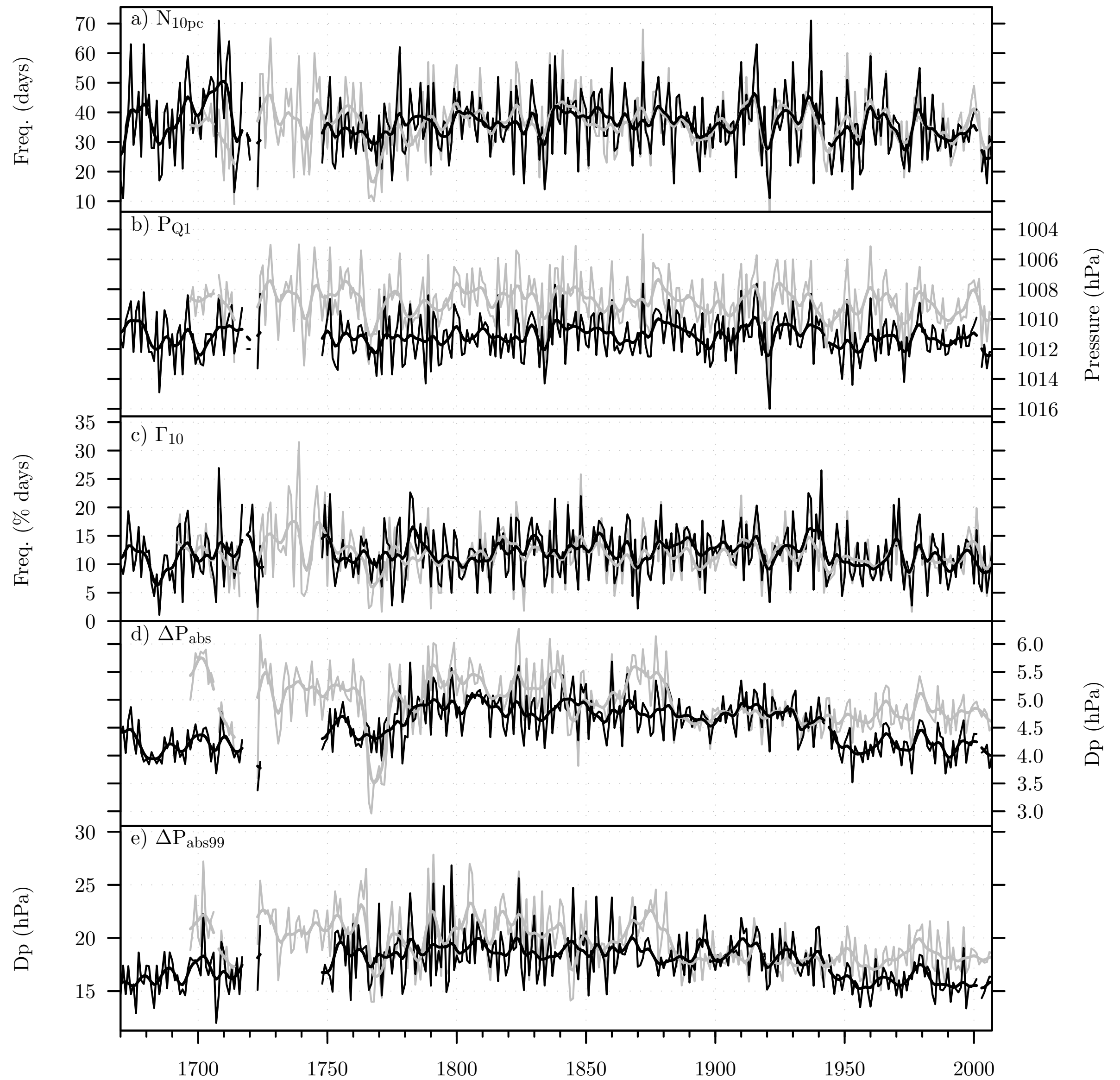

Figure 8.4: Annual time series of the storm indices. London is shown in grey and Paris in black. The thick lines show the 10-year Gaussian filtered values. The P_{Q1} index has been reversed to comply with the results of the other indices.

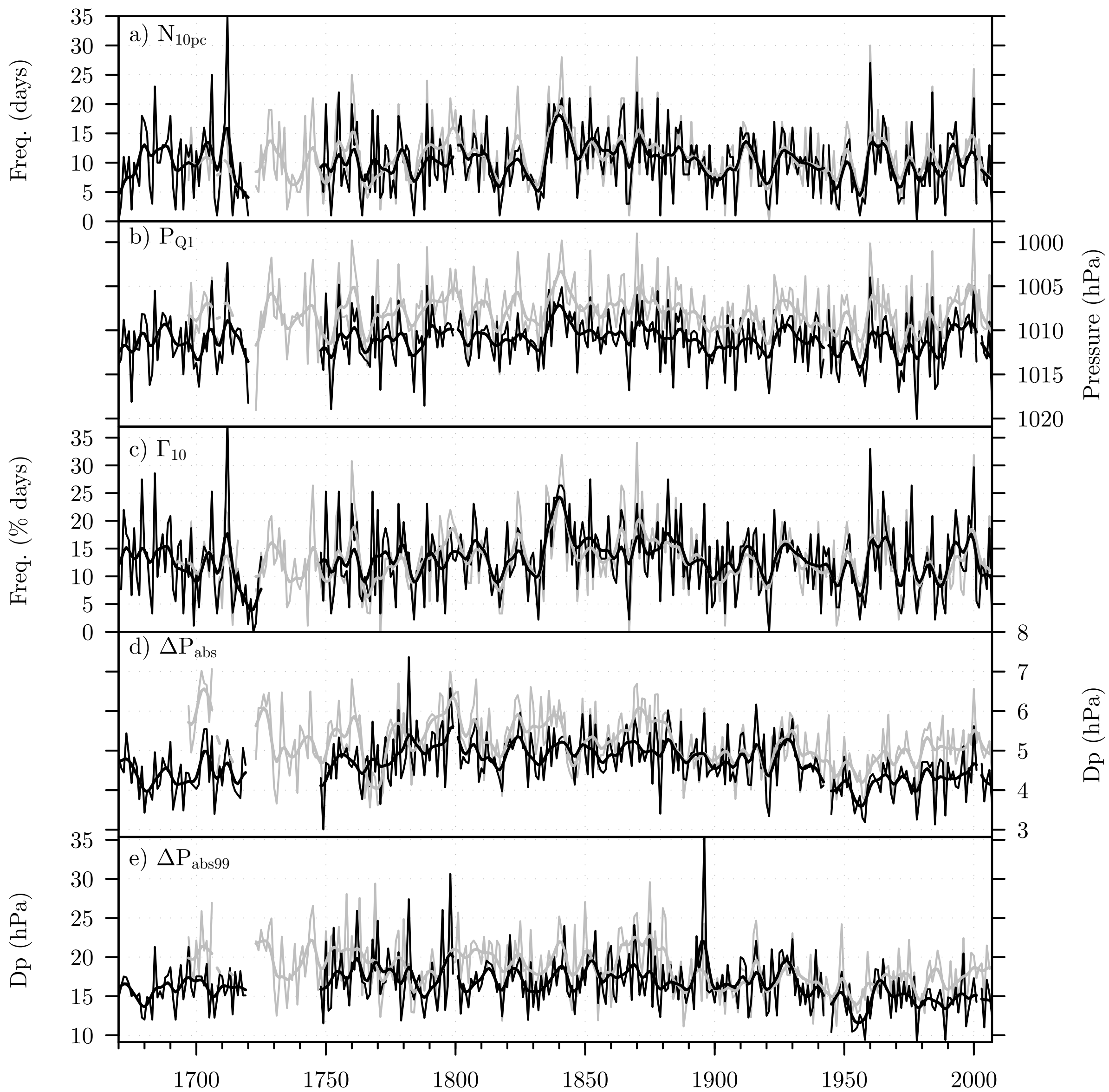

Figure 8.5: As Figure 8.4 but for autumn (SON).

The results prior to the nineteenth century are particularly interesting as few studies have shown series of storminess extending back that far. In the results from the N_{10pc} index, storminess appears slightly reduced at both London and Paris during the 1790s, although this reduction is not significant when viewed in the context of the entire series and it is not apparent in the other storminess indices. This corresponds to the findings of van der Schrier & Jones (2008a) who showed that there was no statistically significant difference between storm frequency in the 1790–1820 period compared to 1974–2004 in New England. Once again this conclusion may be reached by the consideration of local indices of storminess derived from a limited number of stations. If the conclusions of van der Schrier & Barkmeijer (2005) are correct, in that there was little change in the frequency and intensity of storms in the 1790–1820 period in the NA-WE region but there were considerable differences in storm track position, then more dispersed stations than London and Paris would be required to assess this feature.

Analysis of the annual storm data during the late seventeenth/early eighteenth century

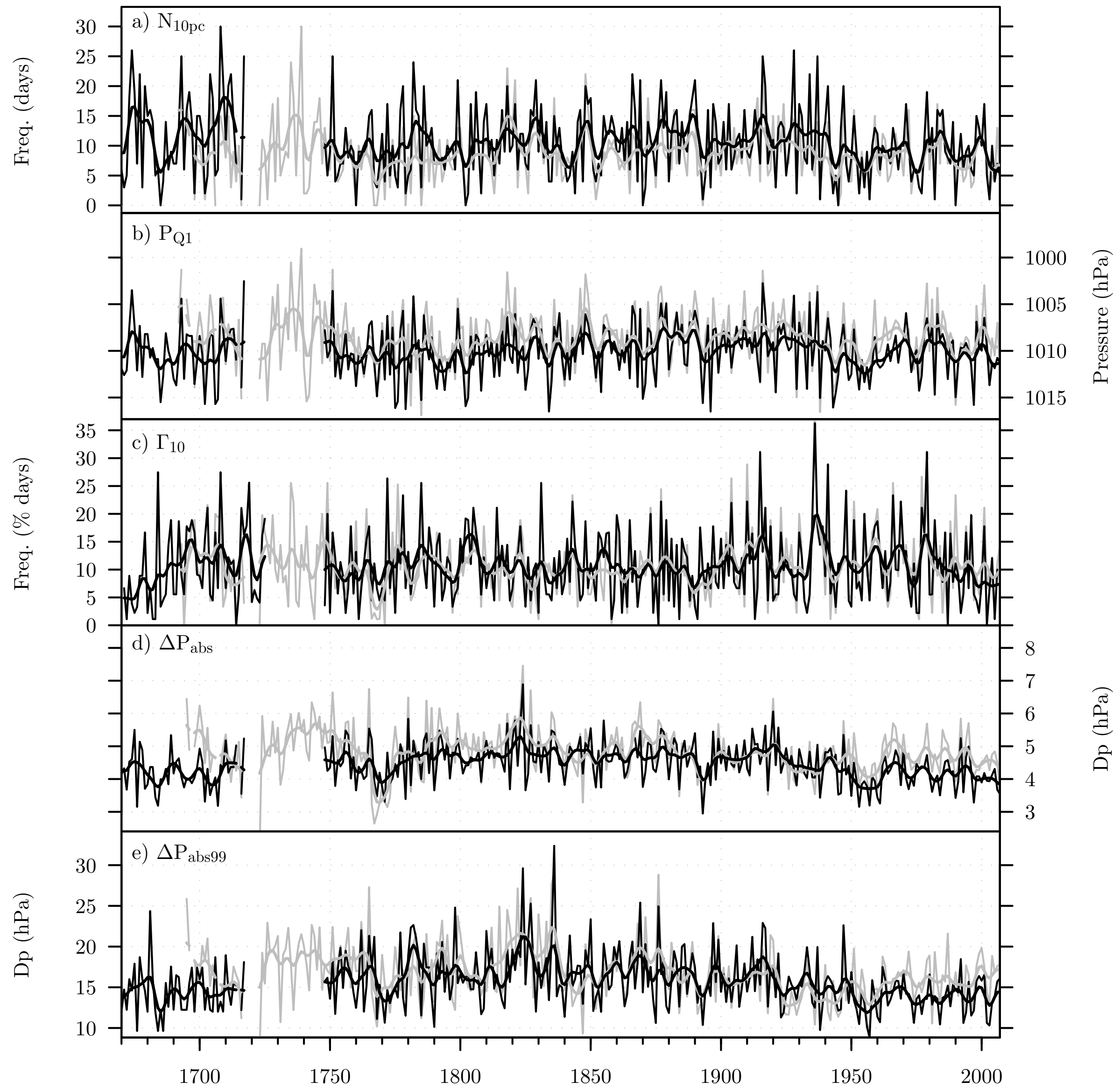

Figure 8.6: As Figure 8.4 but for winter (DJF).

reveals that there is no evidence of increased storminess, which appears contrary to the work of Lamb (1984a,b, 1988, 1991). Indeed analysis of the results from Paris indicates that the 1680s experienced reduced storminess. A review of the data at the seasonal resolution reveals something of a different story. Storminess in London in the period 1723–65 during the spring (MAM) but especially the summer (JJA) appears to have been much increased but also more variable compared to conditions both before and afterwards. The rate of storminess appears greatest in the results from the Γ_{10} index. There is also some evidence for this in the Paris data, although most of the data for this period in Paris are missing. These results generally correspond well to the findings of Wheeler *et al.* (2009) who showed increased storminess in the English channel, especially during the summer, over the 1685–1750 period using wind speed information gathered from ship log books. The information in the London and Paris MSLP data differ slightly by indicating that storminess only increased in summer and spring after ca. 1710.

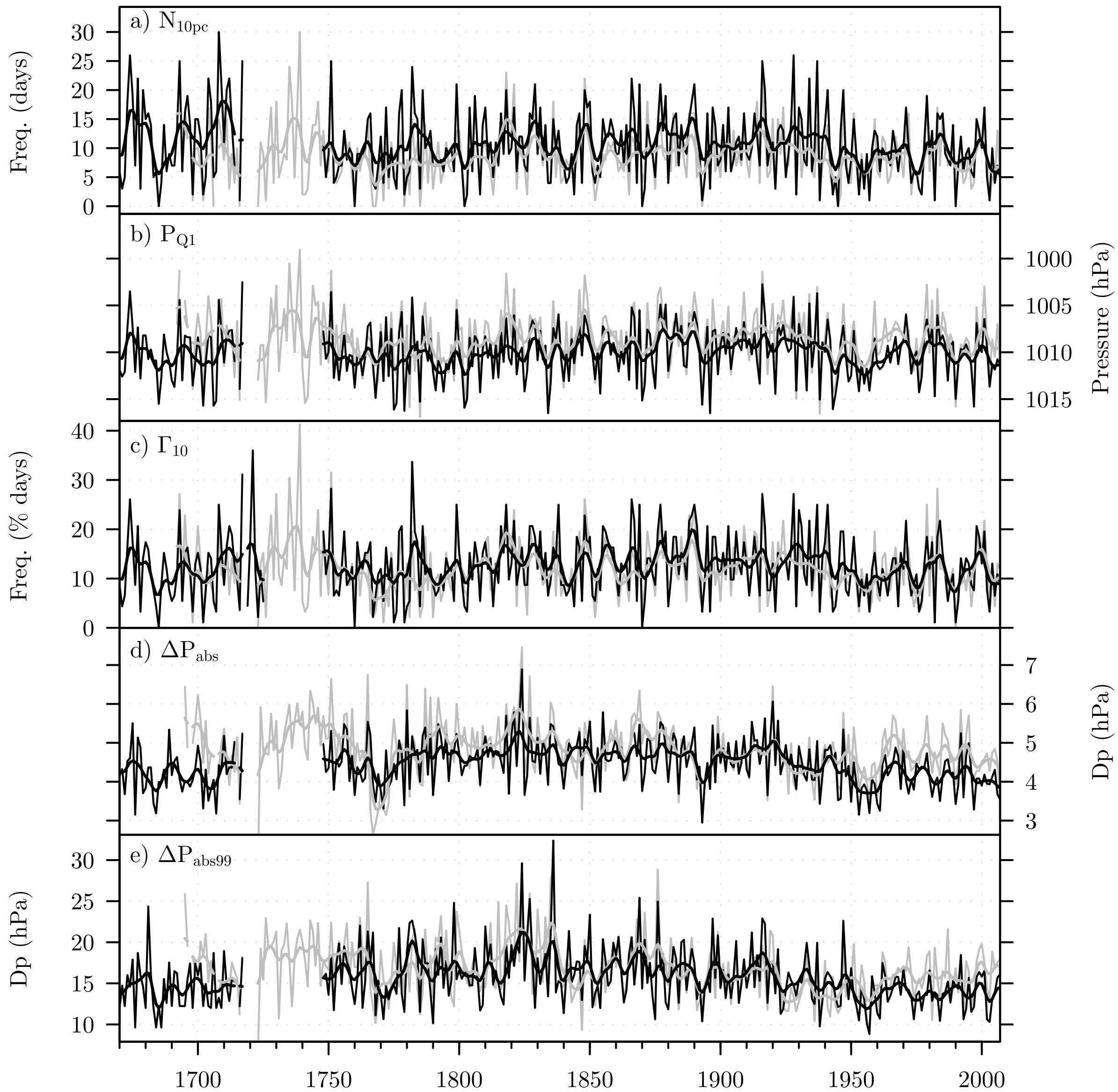

Figure 8.7: As Figure 8.4 but for spring (MAM).

8.4.3 Correlations between the storm indices

In Table 8.1 the correlations between the storminess indices are shown. The correlations between the indices for both London and Paris are generally high, but it should be noted that these statistics only indicate common inter-annual variability and include no information on the relationship between the indices at longer timescales. There is an indication of a changing relationship between the indices during different times of the year, with the strongest relationships being observed in the autumn and winter, and weakest during the spring and especially the summer.

The correlations between the ΔP_{abs} and ΔP_{abs99} indices are generally high, as too are the correlations between the N_{10pc} and P_{Q1} indices. Interestingly the highest correlations are achieved between the Γ_{10} and N_{10pc} indices. Between these two sets of indices the correlations are a good deal lower. This reasserts the message that the day-to-day absolute pressure difference indices

	N_{10pc}	P_{Q1}	ΔP_{abs}	ΔP_{abs99}	Γ_{10}
Annual					
N_{10pc}		**-0.86**	**0.50**	**0.30**	**0.70**
P_{Q1}	-0.86		**-0.51**	**-0.27**	**-0.62**
ΔP_{abs}	0.40	-0.41		**0.73**	**0.46**
ΔP_{abs99}	0.17*	-0.11*	0.63		**0.30**
Γ_{10}	0.62	-0.56	0.24	0.18	
Inter-station	0.86	0.87	0.62	0.45	0.81
Autumn (SON)					
N_{10pc}		**-0.83**	**0.51**	**0.31**	**0.89**
P_{Q1}	-0.86		**-0.46**	**-0.26**	**-0.86**
ΔP_{abs}	0.51	-0.47		**0.67**	**0.54**
ΔP_{abs99}	0.34	-0.28	0.59		**0.34**
Γ_{10}	0.92	-0.85	0.52	0.36	
Inter-station	0.82	0.88	0.69	0.54	0.83
Winter (DJF)					
N_{10pc}		**-0.88**	**0.43**	**0.20**	**0.92**
P_{Q1}	-0.89		**-0.49**	**-0.23**	**-0.83**
ΔP_{abs}	0.47	-0.47		**0.62**	**0.47**
ΔP_{abs99}	0.24	-0.21	0.61		**0.22**
Γ_{10}	0.93	-0.82	0.43	0.25	
Inter-station	0.84	0.89	0.67	0.49	0.83
Spring (MAM)					
N_{10pc}		**-0.87**	**0.46**	**0.33**	**0.91**
P_{Q1}	-0.84		**-0.48**	**-0.30**	**-0.88**
ΔP_{abs}	0.49	-0.44		**0.68**	**0.48**
ΔP_{abs99}	0.36	-0.27	0.71		**0.34**
Γ_{10}	0.89	-0.84	0.49	0.31	
Inter-station	0.78	0.86	0.72	0.58	0.75
Summer (JJA)					
N_{10pc}		**-0.53**	**0.40**	**0.38**	**0.67**
P_{Q1}	-0.65		**-0.35**	**-0.19**	**-0.86**
ΔP_{abs}	0.52	-0.51		**0.68**	**0.44**
ΔP_{abs99}	0.49	-0.34	0.65		**0.31**
Γ_{10}	0.73	-0.90	0.55	0.42	
Inter-station	0.69	0.80	0.64	0.41	0.71

Table 8.1: Correlation coefficients between the storminess indices for London and Paris over the period 1692–2007. Correlation coefficients ≥ |0.7| are underlined. The results for the Paris series are in bold typeface (the upper triangle), whereas those for London are indicated in normal typeface (the lower triangle). Correlations are significant at $\alpha = 0.01$ unless marked by an asterisk. The data have been converted to z-scores for the calculate of the correlation coefficients due to the large differences in the scales used.

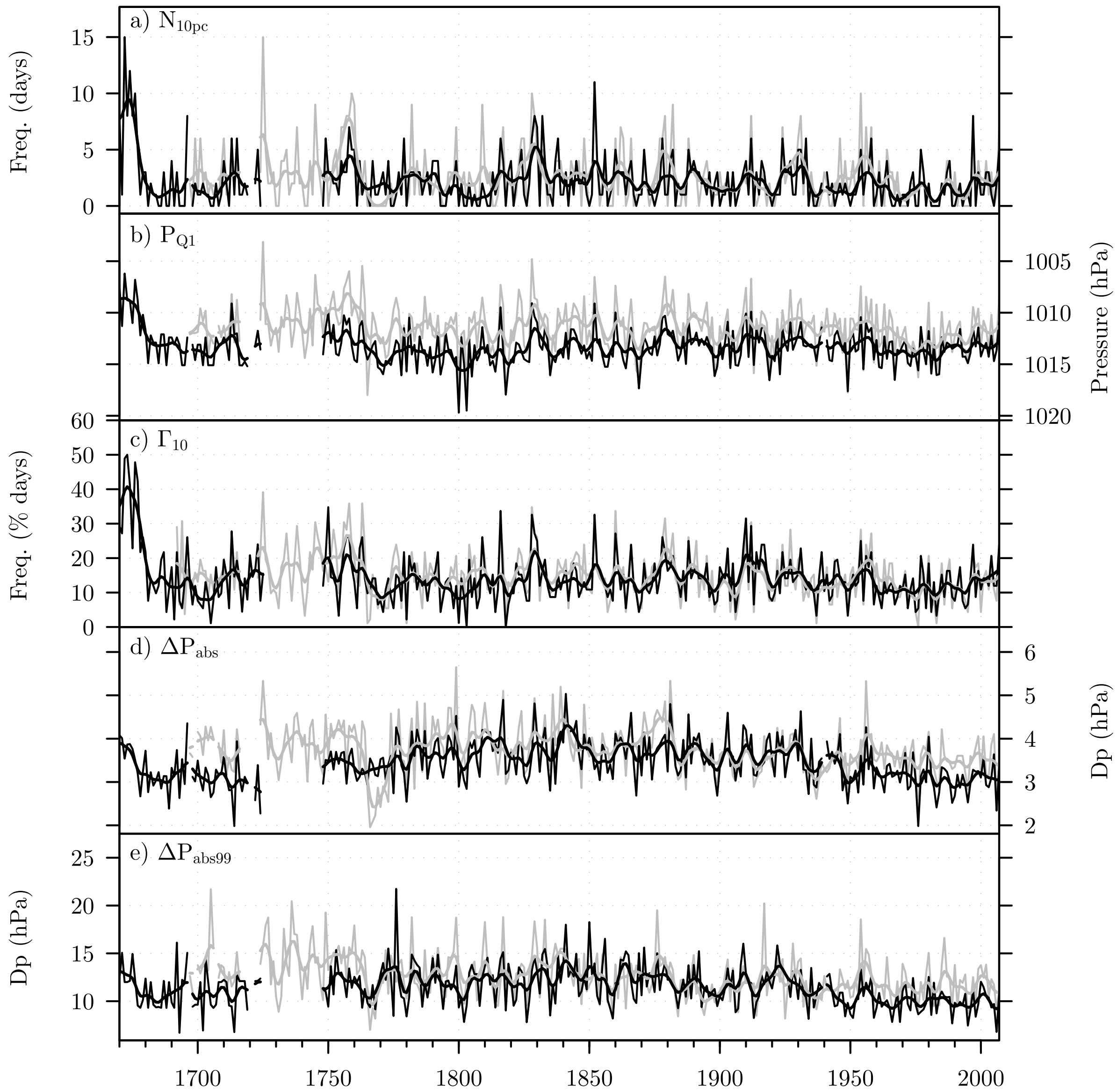

Figure 8.8: As Figure 8.4 but for summer (JJA).

and the threshold-type indices quantify different aspects of the storm climate: the threshold exceedance statistics focus on the core pressure of cyclones, whereas the absolute pressure change indices are more concerned with the rate of change of pressure.

The inter-stations correlations shown in Table 8.1 are generally strong, which indicates that the storm climatology between the two stations is similar.

8.4.4 Storminess indices and the NAO

The correlations between the various storm indices and the Gibraltar–Reykjavik NAOI for the extended winter season (DJFM) are shown in Table 8.2. In general, the correlations for London are not statistically significant at the 95% level. At Paris the correlations are higher and generally statistically significant, with high NAO conditions associated with decreased storminess, and low

	N_{10pc}	P_{Q1}	Γ_{10}	ΔP_{abs}	ΔP_{abs99}
			London		
1821–2006	**-0.21**	**0.22**	**-0.19**	0.03	0.00
1821–1851	-0.05	0.08	-0.09	0.09	-0.12
1852–1882	-0.27	0.32	-0.20	0.11	0.13
1883–1913	-0.19	0.28	-0.15	0.16	0.07
1914–1944	-0.12	0.04	-0.10	0.33	0.07
1945–1975	-0.34	0.33	**-0.40**	-0.29	0.12
1976–2006	-0.29	0.29	-0.27	-0.15	-0.06
			Paris		
1821–2006	-0.44	0.49	-0.40	-0.01	-0.02
1821–1851	-0.48	0.60	-0.29	-0.01	-0.06
1852–1882	-0.41	0.53	-0.36	-0.01	-0.00
1883–1913	**-0.46**	**0.56**	**-0.46**	0.11	0.11
1914–1944	**-0.36**	0.27	-0.32	0.09	-0.27
1945–1975	**-0.59**	**0.59**	**-0.57**	-0.29	-0.18
1976–2006	**-0.40**	**0.53**	**-0.45**	-0.19	-0.11

Table 8.2: Correlations between the storm indices and the extended-winter (DJFM) Gibraltar–Reykjavik NAOI of Jones *et al.* (1997) with additional corrections by Vinther *et al.* (2003a). Correlations that are significant at $\alpha = 0.05$ are shown in bold typeface.

NAO conditions associated with increased storminess.[2] These results can simply be explained as a shift in North Atlantic storm track associated with the NAO. During NAO+ conditions the storm track is situated to the north of the British Isles, whereas during NAO– conditions it lies across central Europe.

The correlations between the NAOI and the absolute day-to-day pressure change indices (ΔP_{abs} and ΔP_{abs99}) are very low and statistically insignificant. At least part of this result may be attributed to the changing hours of observations (particularly in the case of Paris) and the use of 24 hourly mean data (in the case of London). However, the results for these indices correspond well to the those published by Hanna *et al.* (2008), who showed a low and insignificant relationship between ΔP_{abs} in the Channel Islands (Jersey and Guernsey) and southwest Ireland (Valentia), and both the Gibraltar and Ponta-Delgada based NAOIs. Stations north of northern Ireland (Armagh) had increasing strong positive correlations to the NAOIs. This is a result of the stations lying on different sides of the mean jet-stream axis.

There is an indication of a changing relationship between the NAO and storminess over the time period, which corresponds to the findings of previous studies (Allan *et al.*, 2009; Hanna *et al.*, 2008). Specifically, the 1945–75 period stands out as being a period of strong association between the NAO and storminess in London and Paris, whereas the 31-year period prior to that (1914–44) was a time of weak correspondence. A similar result is evident for the Channel Islands ΔP_{abs} data presented by Hanna *et al.* (2008).

8.5 Chapter summary

In this chapter the London and Paris daily MSLP series have been used to examine changes in storminess in the North Atlantic region over the last 300 years. Information regarding storminess has been extracted from the data using five indices. Four of the indices have been used before

[2]Similar results are also achieved with the Ponta Delgada–Reykjavik NAOI (not shown), although the correlation coefficients are slightly lower.

in various studies, and include threshold exceedance statistics and measures that quantify the absolute day-to-day pressure variability. In addition to these indices, the Gamma index is used here for the first time to remove the annual cycle from the analysis of storminess. The threshold indices and the day-to-day pressure change indices appear to quantify slightly different aspects of the storm climate, and highlight the importance of using multiple indices of storminess in analyses.

Inhomogeneities in the London and Paris data—mostly relating to varying observation hours of the data—limit the application of the data to storm analyses. With these limitations in mind, certain cautious conclusions can be made. There appears to be no change in storminess at London or Paris over the last 300 years, although a good deal of decadal variability is evident. At the annual resolution, storminess during the LIA does not appear to have been significantly different from the long-term mean. However, storminess during the spring and summer months during the 1710–65 period appears to have been exceptionally high.

Chapter 9

Summary and Conclusions

9.1 Main research findings

9.1.1 Daily MSLP series for London and Paris

It has been shown in this thesis that daily Mean Sea-Level Pressure (MSLP) series can be constructed back to 1692 for London and back to 1670 for Paris through the digitization and correction of historic barometer observations. Observations earlier than 1692 were recorded by various prominent scientists working around London, such as Robert Boyle and Robert Hooke, but these series contain too many missing observations to be used in the daily MSLP series. Most of the observations for the late seventeenth and eighteenth centuries used in the London series were kept by individuals in private weather diaries. The majority of these observers were prominent scientists of the time who had close connections with the Royal Society. Manley (1964) collated sources of data recorded in eighteenth century London into the *London Weather Diary (LWD)*, and the pressure data from that source have been extracted to complete the London daily MSLP series over the period 1723–73. After 1774, data recorded at institutions were mostly used to complete the London daily series: the Royal Society series covered the periods 1774–81 and 1787–1842, the Royal Greenwich Observatory completed the series over the periods 1843–49 and 1882–1950 and the Met Office's Heathrow airport series completes the series to the present day (31 December 2007). Data recovered for London as part of the European and North Atlantic daily to MULtidecadal climATE variability (EMULATE) project (Ansell, 2004; Ansell *et al.*, 2006) were used to complete the 1850–81 period.

The Paris daily MSLP series covers a longer time period than London thanks to the remarkable series of observations kept by the physician Louis Morin. However, the Paris series also contains more missing values than London, with no observations that appear to have survived for the period 1726–47. Meteorological observations recorded at astronomical observatories form a major part of the Paris series during the eighteenth and nineteenth centuries. The observations from the Paris Observatory were used exclusively over the period 1783–1850, but also for the early part of the eighteenth century (1713–25). Another series of observations recorded from an astronomical observatory were those of Joseph Delisle, which are remarkably well kept and are very nearly complete for the period 1748–59. In the late-nineteenth century it is the observations recorded in connection with public health by medical practitioners that dominate the series. In addition, the observations recorded by the pioneering meteorologist Louis Cotte at his home in Montmorency were used to complete the period 1777–1782. As with the London series, meteorological observations during the late-nineteenth century were increasingly recorded at observatories operated by the newly founded national meteorological service (*le Bureau Central Météorologique* and later *Météo France*) and these observations complete the series to present day.

The majority of the barometer observations used in both the London and Paris MSLP series have not previously been converted to modern-day units or even extracted from the original sources. This meant that the data had to be corrected where necessary to represent measures of atmospheric pressure at standard modern-day conditions recommended by the World Meteorological Organization (1983). The data were also corrected to eliminate errors associated with different observation times, and were corrected to the equivalent of a 24-hourly mean when used at the monthly time resolution. Inhomogeneities were inevitable in the data given the patchwork nature of the two series. Further, the use of early unstandardized instruments along with instrument relocations would be expected to introduce additional changepoints. These series were therefore subjected to a statistical homogenization procedure using the RH-test (version 2, Wang & Feng, 2007) in order to identify statistically significant changepoints. Using this test the data were screened for both documented and undocumented inhomogeneities and corrections were applied to adjust the series to the most recent homogeneous segment. Meta-data proved vital in deciding on suitable adjustments, and to pinpoint the exact time of the changepoints. As many of the observers of the London and Paris observations were leading scientists of their time, a good deal of information had been published about the instruments and observation schedules used.

A significant improvement of the daily MSLP series for London and Paris compared to the earlier monthly-scale reconstructions by Jones *et al.* (1987) and ADVICE (1998) is that the long-term means of the new series—being approximately 1hPa lower than previous constructions—seem more in-keeping with the values that would be expected for the two locations given their mid-latitude location. While the internal homogeneity of the ADVICE series is adequate—and hence the data are suitable for many applications—when comparing with other series across Europe the relative mean value becomes important. The lower mean levels of the daily London and Paris MSLP series resolves the problem identified by Woodworth (2006) during the cross-comparison of the London and Edinburgh ADVICE series with a new series for Liverpool. The overall mean of the Liverpool series should be 50% of the London–Edinburgh difference, but Woodworth's results showed that the Liverpool data are actually 80% lower than London, which can be explained by the mean of the London series being too high. A further small improvement of the London daily series over the ADVICE series is that data observed in London were used throughout the series: the ADVICE series used the mean of the Edinburgh and Paris series for the years 1782 and 1790 due to missing data (ADVICE, 1998).

9.1.2 Limitations of the London and Paris MSLP data

Missing values in the London and Paris daily MSLP series restrict the use of the data. In the London series the longest gap occurs for the period 1717–22, although there are also gaps of less than a month's duration at other points in the series. The Paris series suffers from a longer gap in the early eighteenth century, which lasts throughout the period 1725–47. Other shorter gaps exist in the Paris series, even as late as 2002. A concerted effort was made to locate data to complete these gaps in both series, but it seems that the early eighteenth century was a low-point in the enthusiasm for keeping private weather diaries, as has previously been identified for London by Manley (1960). In the case of the large gap in the Paris series, it would appear that the data books were lost/destroyed in the late eighteenth century (Renou, 1881; Bigourdan, 1895). The missing periods in the London and Paris series mean that the westerly index constructed from the difference in pressure at the two locations (see below, §9.1.3) can not be completed during the 1730–40s. This is unfortunate given that this was an important period during the Little Ice Age (LIA), when large interannual and decadal variations in the climate of Europe were experienced (Jones & Briffa, 2006).

The differing observation times of the data used in the London and Paris series limits the usefulness of the data. In the case of the observations recorded at the Paris Observatory and used to complete the Paris series over the period 1713–26 there is some uncertainty connected with the measurement of time used: it may be that the astronomical time was used, which means for example that 12pm observations were actually 12am in civilian time. This may also be a problem in the Delisle series of 1748–59, although this seems less likely given the diurnal cycle of the accompanying temperature data. This uncertainty regarding the times of the data from the astronomical observatories is a problem for the correction of the data to 0°C and to sea-level but particularly for the diurnal correction. The diurnal correction reduces the error at monthly timescales associated with a limited number of observations per day. However, the diurnal correction itself is open to criticism, especially when series consisting of only one observation per day are combined with true 24-hourly mean values. This problem was shown particularly well in the results of Chapter 8, where the day-to-day absolute pressure change indices had steps evident at the change to different recording schedules. The monthly or seasonal means calculated from the daily data are not particularly affected by the different observations times/schedules, but this becomes an important limitation when the individual daily observations are analysed. However, the problem cannot be rectified without the inclusion of additional data.

The early part of the Paris series (approximately 1670–90) remains problematic. The readings during the winter months appear too high but during the summer seem to be too low. This is probably related to the estimated temperature corrections used but may also be due to an unsuitable positioning of the instruments. The homogenization procedure failed to correct for this error due to the testing being applied to the monthly data arranged sequentially. This technique has the advantage of having a larger number of data from which to test for breakpoints, but also relies on the size of the step in the data being applicable to data for all months of the year. Further testing needs to be applied to the data to obtain more suitable corrections.

In the London series, the data are of low-quality during the latter half of the 1760s. The observations over the period 1765–73 were published in the *Gentleman's Magazine*, and were extracted from Manley's *LWD* for use in the daily MSLP series. However, the variability of the data is too low across all months of the year and this appears to be due to the use of a poorly maintained barometer by the observer. Manley (1960) suspected that this was a problem with the data and suggested that the observer may have used a poorly maintained wheel barometer: the results from Chapter 5 prove Manley's suspicion.

In the reduction of the London and Paris pressure observations to 0°C, concurrent barometer temperatures were used where available. Where these data were missing or not recorded, estimated temperatures were used either from an annual model or from outdoor temperatures. As identified above for the Morin series in Paris, unsuitable temperature corrections can lead to large errors in the final MSLP series depending on the time of year. An examination of the annual cycle of pressure in the two series for different time segments has revealed that the temperature corrections on the whole seem adequate. However, individual daily observations may be quite inaccurate depending on the time of year as a result of the estimated temperature values. Errors may also have been introduced through the use of concurrent temperature observations which themselves have not be subjected to a detailed analysis. A good example is the temperature observations used to correct the Locke observations (1692–96) in the London series. The ideal situation would be to develop an homogeneous series of temperature alongside the MSLP series, as was done for the series constructed for the Improved Understanding of past climatic variability from early daily European instrumental sources (IMPROVE) project (Camuffo & Jones, 2002). Such a venture would unfortunately extend far beyond the time limit imposed on this project.

9.1.3 Conclusions from the analysis of the MSLP series

In searching for ways of extending the North Atlantic Oscillation (NAO) series back in time, Jones *et al.* (2003) asserted that the series is best extended, where possible, using pressure-only data series. This is due to the complications introduced for analysing the temperature/precipitation–circulation relationships with proxy reconstructions which themselves are constructed directly or indirectly from temperature and precipitation data but also because the predictor–predictand response may not be constant over time. The authors concluded that a westerly index derived from the difference in normalized pressure at London and Paris held the greatest potential for extending the NAO, rather than pressure measurements recorded in the 'centres-of-action' of the NAO, which can only probably be reconstructed back to the late-eighteenth century. The potential for a Paris–London westerly index had been demonstrated in previous studies using the monthly ADVICE (1998) MSLP series for London and Paris (Slonosky *et al.*, 2000, 2001b) and these studies prompted the further investigations by Jones *et al.* (2003).

In Chapter 6 of this thesis the new daily MSLP series for London and Paris were used in the same way as Slonosky *et al.* (2000), Slonosky *et al.* (2001b) and Jones *et al.* (2003) by developing a westerly index at the seasonal resolution. It was shown in that chapter that the consideration of the Paris–London index as a NAO proxy is complicated by the location of the index, which is somewhat downstream of the main flow associated with the NAO. This had also been shown in the results of Slonosky *et al.* (2000). However, more detailed information was provided in Chapter 6 about the exact pattern of atmospheric circulation that is described by the Paris–London index. The highest correlations with hemispheric MSLP showed a dipole pattern that was associated with the NAO, during all months of the year except summer (JJA). However, the 'centres-of-action' in the pattern were shifted somewhat eastwards compared to the NAO, with high negative correlations to the east of Iceland and positive correlations in an area encompassing the southern Mediterranean and north Africa. Thus the Paris–London also contains elements of the East Atlantic pattern of atmospheric circulation as defined by Barnston & Livezey (1987).

In the summer (JJA) the Paris–London index produces a pattern that is similar to the Summer North Atlantic Oscillation (SNAO) defined by Folland *et al.* (2009). The observed pattern has a weak Arctic node and a North Sea node, which correspond to the north and south nodes of the SNAO respectively.

The differences between the atmospheric circulation pattern depicted by the Paris–London index and that of the NAO are important when cross-comparing time series of the NAO with the Paris–London index. Most importantly, the asymmetry that is evident in the NAO (Cassou *et al.*, 2004; Hurrell & Deser, 2009) means that the correlations between the NAO and the Paris–London index are strongest during positive phases of the NAO but weaker during negative phases. As the Paris–London index remains a direct measure of westerly flow in the North Atlantic-Western European (NA-WE) region this may explain some of the temporal variations between temperature and precipitation series and the NAO station-pair indices that have been observed in previous studies and which have implications for the construction of NAO proxies and also for downscaling studies (e.g. Jones *et al.*, 2003).

Bearing in mind these differences between the Paris–London index and NAO indices, the time series of the Paris–London index has been analysed in relation to instrumental and proxy-based NAO indices in this thesis. The Paris–London index provides an indication of the state of the NAO back to 1748 (and back to 1692 on a fragmentary basis), which provides an extension to traditional 'station-pair' NAO indices but also the Paris–London index developed from the ADVICE (1998) data. The results from the Paris–London index constructed in this thesis confirm the findings of other studies, which have shown that the high values in the NAO during the 1990s were of a similar magnitude to those during the 1920–30s (Jones *et al.*, 1997; Slonosky & Yiou, 2001). However, the increase from negative values of the NAO during the 1950–70s to the high positive values in the 1990s does not appear so dramatic in the Paris–London index due to the asymmetry of the NAO described above.

The Paris–London westerly index was produced for all seasons of the year in Chapter 6. During the summer season (JJA) a prolonged positive phase was observed during the period 1770–1825, which has also been shown in the NAO reconstruction of Luterbacher *et al.* (2002b) but is missed in most other proxy series due to their reconstruction for the winter season only (e.g. Glueck & Stockton, 2001; Cook *et al.*, 2002). An exception is the tree-ring based SNAO reconstruction by Folland *et al.* (2009), which also showed similar positive values at the turn of the nineteenth century. The prolonged westerliness during this period may well explain the higher incidence of summer rainfall during that period observed in the results of Briffa *et al.* (2009). Further, a period of reduced summer rainfall has been noted since 1970 by Briffa *et al.* which is also indicated in the Paris–London index as a period of reduced westerliness/increased easterliness.

The daily resolution of the London and Paris MSLP series has also been put to use in Chapter 6, through the examination of extremes of westerly flow. This provides an extension to proxy-based reconstruction of the NAO, which are restricted to monthly or seasonal timescales. A high frequency of extreme easterly days are evident in the series during the 1690s which appears to be unprecedented in the 1692–2007 period. This relates well to the 1690s being extremely cold and the so-called 'climax of the LIA' in Europe (Luterbacher *et al.*, 2001, p.442). Another high frequency of extremely easterly days in winter was evident in the results at the turn of the nineteenth century; this supports the findings of Kington (1988). In contrast to the variability in the frequency of extreme easterly days, the frequency of extreme westerly days remained quite constant over the 1692–2007 period.

In Chapter 7 the relationship between the Paris–London westerly index and surface temperature was explored in an extension to the work of Slonosky (1999), Slonosky *et al.* (2001a), Slonosky & Yiou (2002) and Jones *et al.* (2003). The correlation between the Paris–London index and surface temperature is highest in a region that covers southern England and the Low Countries. The results showed that the extent of this correlation changes over time, although it is not certain whether this a physical feature of the temperature–circulation relationship or if it is a result of the use of running correlations, or a changing quality of the temperature or MSLP data over time. Running correlations between 'station' temperature series and the Paris–London index showed a changing relationship over time that has also been identified in other analyses (Jacobeit *et al.*, 2001; Jones *et al.*, 2003). An important result was apparent during the period 1790–1810, when the correlations between the westerly index and surface temperature during the summer months of the year were very low. The slightly extended length of the Paris–London index has been able to show that correlations before that time were higher, which with previous shorter series was uncertain (Jacobeit *et al.*, 2001). These results reaffirm the concern that proxy reconstructions of the atmospheric circulation may suffer from non-stationarities in the temperature-circulation relationship (Slonosky *et al.*, 2001a). Of particular note is the apparent gradual increase in the strength of the relationship between the Paris–London westerly index and surface temperature during the summer months.

In the final analysis chapter of this thesis (Chapter 8), the London and Paris MSLP series were used to analyse the variability in storminess in the NA-WE region over the last 300 years. Five 'local' indices of storminess were extracted from the data. Most of these indices have been in previous studies (Hanna *et al.*, 2008; Bärring & Fortuniak, 2009) although one—the Gamma Index—has not previously been used to analyse storms but has been used in the analysis of extremes of surface temperature (Jones *et al.*, 1999a). The results of the analysis were severely jeopardised by the changing number of observations per day used in the MSLP data. Steps occurred in some of the indices at the change-over from one schedule to another. Bearing this in mind, it was tentatively concluded that storminess during the LIA was not significantly different from the long-term mean. This appears to contravene the results from other studies (e.g. Lamb, 1984a, 1991; Wheeler & Mayes, 1997; Wheeler *et al.*, 2009) but may result from the use of data from only two sites in Europe, which are too close to each other to appreciate spatial changes in storminess.

9.2 Further research

9.2.1 Additional work to the MSLP series

The large gaps in the London and Paris series during the early eighteenth century need to be completed. Suitable data may be contained in manuscripts archived in private repositories and it is hoped that such data may eventually be available for use. Extension to the London series may also be possible further back than 1692. Manley (1960) conducted a thorough search for such data, but there may be other observations in private collections that may eventually come to light. In the absence of such data, the known sources—such as Robert Boyle's observations for the year 1684—cannot contribute to the London series due to the high number of missing observations. It seems unlikely that any extension to the Paris series can be made further back than the current 1670.

Several improvements can be made to the London and Paris daily MSLP series, especially regarding the earliest data. The data used in the Paris series prior to 1690 needs to be reappraised. Camuffo *et al.* (2010) have recently demonstrated that for the year 1693, a more suitable correction than the 'block' corrections used by Legrand & Le Goff (1992) and Slonosky *et al.* (2001b) can be effected using Morin's contemporary temperature observations. It seems likely that the early pressure data may also be better corrected to 0°C using those data.

For the London series, additional data need to be located to complete the 1765–73 period, which appear to be of a low quality, as described above. The late-eighteenth century was a time of increased attention to the keeping of regular meteorological observations (Kington, 1988), and it would seem likely that other series exist to complete this problematic period. These data need to be located, corrected and incorporated into the London series.

A problem with both the London and Paris MSLP datasets is the use of series constructed from single daily observations, but particularly the joining of these series to series constructed from 24-hourly mean data. This is a particular problem when the day-to-day variability of pressure is analysed, for example in the analysis of storms; at the monthly mean resolution this error becomes negligible. The analysis of storms, and in particular severe storms, requires sub-daily data at a resolution greater than 3-hourly (Alexander *et al.*, 2005; Allan *et al.*, 2009). Data with this resolution for both London and Paris are available at least back to the late-nineteenth century, but these have not been recovered from the paper manuscripts, and to do so would take a major research effort. In the case of London, Allan *et al.* (2009) report that 3-hourly data have been recovered back to 1920, and these may be incorporated into a sub-daily MSLP series for the location. Further efforts, organized under the Atmospheric Circulation Reconstructions over the Earth (ACRE) project, may contribute additional sub-daily data for London and Paris, which would make the construction of a sub-daily MSLP series for both locations feasible. To complete such a series for Paris would require more work than London, given that sub-daily pressure data are only currently available after 1945. However, 3-hourly observations between the hours of 9am and 9pm (local time) exist for Paris back to 1816. In the case of London, such sub-daily data are only available back to the start of the Greenwich series in 1841: before that time the highest resolution data (twice-daily observations) were recorded by the Royal Society. Throughout much of the eighteenth century in London and Paris, meteorological observations were recorded at a maximum of twice daily; an exception is Joseph Delisle's Paris series, which consists of three/four observations per day. Therefore sub-daily MSLP series, of an ideal resolution for the detection of severe storms, can only be potentially constructed for London and Paris back to the early nineteenth century.

Further improvements can be made to the London and Paris MSLP series in the detection of inhomogeneities. The Penalized Maximal t (PMT) and Penalized Maximal F (PMF) tests only detect shifts in the mean of the series and are unable to detect inhomogeneities related to higher moments of the distribution. As described above, in the case of the London series the inhomogeneity during the 1765–73 period affected the dispersion of the data more than the mean level and this went undetected in the homogeneity testing. Related problems were identified in the Paris and London series due to changing observation times/schedules of the data when the day-to-day variability of MSLP was used as a measure in the analysis of storm activity. Progress is being made in developing tests which identify these types of inhomogeneities (Della-Marta & Wanner, 2006), and an improved detection of inhomogeneities in the London and Paris series may arise from the use of these tests. A new version of the RH-test (version 3, Wang & Feng, 2010) has recently been released, which includes a quantile-matching algorithm to ensure that the empirical distributions of all segments of the corrected series are equal (Wang, 2009). Further work rests with testing the homogeneity of the two series using the new version of this software.

9.2.2 Additional work related to the analysis of atmospheric circulation variability

The use of wavelet analysis in analysing the variability of daily temperature series and westerly indices has been demonstrated by Yan *et al.* (2001). Their analysis quantified daily, weekly and seasonal variability and showed the relative variability during warm and cold periods at the three different timescales, the connection of these variations to the variability of the atmospheric circulation and how the variability has changed since the late-eighteenth century. A similar analysis should be conducted using a daily westerly index constructed from the London and Paris MSLP series. Such an analysis would cover a longer time span than that used by Yan *et al.* and would allow the previously observed features to be placed in a longer-term context. Such an analysis would seem to be more instructive than the analysis of singularities as conducted in Chapter 5, which as concluded in that chapter are probably little more than statistical curiosities.

A great deal of additional work needs to be done in analysing the relationship between the Paris–London westerly index and surface climate variables. In this thesis only monthly mean temperature was analysed but the relationship between the index and precipitation needs to be studied. This has previously been analysed using the Paris–London index derived from the ADVICE data by Jones *et al.* (2003) but only back to 1774. The Kew rainfall series extends back to 1697 (Briffa *et al.*, 2009) and may be compared with the Paris–London westerly index over that time period. Further work also needs to be done on examining the connection between the westerly index and temperature extremes. Jones *et al.* (1999a) and Jones & Lister (2009) have demonstrated the types of extreme indices that can be derived from daily temperature series and this provides a starting point for such an analysis. Analyses also need to be conducted regarding the connection between the westerly index and extremes of precipitation.

The results shown in Chapter 7 of apparent non-stationary relationships between the atmospheric circulation and surface temperature are particularly worthy of further investigation given the implications of these results for statistical downscaling and hence our understanding of the regional impacts of future climate change. Perhaps the most striking results in Chapter 7 were achieved during the summer months, for which a general increase in the strength of the relationship between surface temperature and the Paris–London westerly index was noted over the period 1750–2007. The reasons for this apparent change need to be investigated, particularly with regards to the importance of changes within weather types (Beck *et al.*, 2007) and the possible influence of changes in anthropogenic aerosols (Stjern *et al.*, 2009).

The results from the Paris–London westerly index need to be compared with the westerly indices that have been derived for the late seventeenth/early eighteenth century from wind measurements by Wheeler & Suarez-Dominguez (2006) and Wheeler *et al.* (2009). These data are entirely independent of the Paris and London MSLP data and such a comparison is very important given that so few directly measured climate data are available for this period. These data may also be used to complete the gaps in the Paris–London westerly index in the first half of the eighteenth century.

The analysis of storms in this thesis is only a first attempt at the use of the London and Paris MSLP data to analyse these events. Great restrictions on the analysis of storms are presented by the changing observation times/schedules used in the current data. It may be possible with a re-homogenization of the data and the addition of more sub-daily data for series to be constructed that are more suitable for the analysis of storminess. If suitable series can be constructed then the first line of enquiry should be the calculation of Geostrophic Wind (Geo-Wind) speed series from a ‘pressure-triangle’ with the incorporation of data from the Netherlands. Such an analysis would require the homogenization of the early Dutch data. Efforts that are currently underway to develop long sub-daily series of pressure for the Netherlands (T. Brandsma, pers. comm.) would also contribute to such an analysis and could potentially lead to a Geo-Wind speed series stretching back into the mid-eighteenth century, and possibly to the late-seventeenth century.

Appendix A

Data Sources

This appendix provides the reference information for the data sources used to complete the London and Paris series described in Chapters 2 and 3. A detailed catalogue of data sources for London can be found in Manley (1960) and for Paris in Renou (1881) and Angot (1897). A list of weather diaries in the British Isles, including London, for the years 1675–1715 are printed in Kington (1994), although that source does not distinguish between instrumental and non-instrumental observations.

A.1 London data sources

British Atmospheric Data Centre (BADC) [Online archive]

Heathrow Airport, 1950–2007
UK Meteorological Office. MIDAS Land Surface Stations data (1853-current).
`http://badc.nerc.ac.uk/data/ukmo-midas`

BnF Gallica [Online archive]

Royal Society Journal, 1774–1842.
Philosophical Transactions of the Royal Society (1665–1887), vols. 65–133. Used to supplement illegible or missing volumes in the Royal Society Publishing Online repository.

Climatic Research Unit Library, University of East Anglia

Holborn Weather Diary, 1709–16.
Meteorological Journals: Rawlinson. Microfilm CRU 43.
Reproduction of originals from the Bodleian Library, Oxford (ref: Rawlinson 1161 D)

London Weather Diary (LWD), 1723–1773 and 1784–6.
London Weather Diary, 1723–1805 (Prof. G. Manley). Copy of original.

Royal Observatory, Greenwich, 1880–1950.
Greenwich Magnetical and Meteorological Observations. Royal Observatory, Greenwich 1861–1952.

Climatic Research Unit, Digital Data Repository

EMULATE LONDON, 1850–1881
EMULATE mslp land-station daily data series (Deliverable D2).
http://www.cru.uea.ac.uk/cru/projects/emulate/LANDSTATION_MSLP/CORRECTED/EMULATE_LONDON_TS_DIURNAL_A.ASC

JSTOR [Online archive]

ROYAL SOCIETY JOURNAL, 1774–1842.
Philosophical Transactions of the Royal Society (1665–1887), vols. 65–133. Used to supplement illegible or missing volumes in the Royal Society Publishing Online repository.

National Meteorological Archive, Exeter

JOHN LOCKE'S WEATHER DIARY, 1692–1696.
Weather diary 1682-1703. Oates, Nr. Epping. Archive Y15.K5 ID5A. Copy of original. The observations for the year 1692 Old Style (Julian) calendar (OS) were published in the *Philosophical Transactions of the Royal Society (1665–1887)*, vol. 24, pp. 1917–1937

ROYAL OBSERVATORY, GREENWICH, 1843–49.
Results of the magnetical and meteorological observations made at the Royal Observatory, Greenwich, in the year 1836-1952. Archive Y36.B1-3

THOMAS HOY'S WEATHER DIARY, 1781–84.
Private weather diary for Muswell Hill/Syon House, Greater London. Archive Z11.E-Z10.B

Royal Society Archives

ROYAL SOCIETY JOURNAL, 1774–1842.
Philosophical Transactions of the Royal Society (1665–1887), vols. 65–133. Used to supplement illegible or missing volumes in the Royal Society Publishing Online repository.

WILLIAM CARY'S OBSERVATION 1826.
Taken from the Gentleman's Magazine, 1827. Used to complete missing observations in the Royal Society record.

Royal Society Publishing Online

GRESHAM COLLEGE WEATHER JOURNAL, 1693.
Philosophical Transactions of the Royal Society (1665–1887), vol. 18, pp. 183–190.

WILLIAM DERHAM'S WEATHER DIARY, 1708.
Philosophical Transactions of the Royal Society (1665–1887), vol. 26, pp. 334–366.
Derham's original diaries are available from the Royal Society's archive in London.

ROYAL SOCIETY JOURNAL, 1774–1842.
Philosophical Transactions of the Royal Society (1665–1887), vols. 65–133. Supplemented by copies in the JSTOR and Gallica Online archives and at the Royal Society Archives.

A.2 Paris data sources

Bibliothèque interuniversitaire de médecine (BIUM). [Online archive]

AUGUSTIN ROUX'S WEATHER DIARY, 1762–76.
Journal de médecine, chirurgie, pharmacie, etc. Vols. 12–46.
http://www.bium.univ-paris5.fr/histmed/medica.htm

PÉRE LOUIS COTTE'S WEATHER DIARY, MONTMORENCY, 1776–1782.
Journal de médecine, chirurgie, pharmacie, etc. Vols. 46–59.
http://www.bium.univ-paris5.fr/histmed/medica.htm

Climatic Research Unit, Digital Data Repository

EMULATE PARIS, 1851–1880
EMULATE mslp land-station daily data series (Deliverable D2).
http://www.cru.uea.ac.uk/cru/projects/emulate/LANDSTATION_MSLP/CORRECTED/EMULATE_PARIS_TS_DIURNAL_AD.ASC

GaleNet Database [Online archive]

AUGUSTIN ROUX'S WEATHER DIARY, 1760–62
Journal Œconomique, ou, Mémoires, notes et avis sur l'agriculture, etc.
Used to complete the period January 1760–May 1762.
Access to database via institutional subscription.

National Meteorological Archives, Exeter

PARC DE SAINT-MAUR, 1881–1920.
Annales du Bureau central météorologique de France. Archive Y23.H3–H5.
Used to supplement illegible or missing volumes in the NOAA Online archive.

PARC DE SAINT-MAUR, 1921–1922.
Daily weather report for France Archive Y39-Y36.
Also catalogued as 'Bulletin international / Bulletin quotidien—charts'.

LE BOURGET AIRPORT, 1923–2007.
Daily weather report for Germany (Täglicher Wetterbericht). Archive Y10–Y06.
Data used to complete missing observations in the digital data during the period 1939–45 obtained from Météo-France.

NOAA Central Library. Foreign climate data. [Online archive]

PARC SAINT MAUR, 1881–1920.
Annales du Bureau central météorologique de France.
http://docs.lib.noaa.gov/rescue/data_rescue_french.html.
Supplemented by volumes from the National Meteorological Archives, Exeter.

Paris Observatory Library/Archive, Paris[1]

Paris Observatory Journal, 1713–26.
Journal des observations faites à l'Observatoire de Paris, 1683–1798. Microfilm D3: 1–30 & D4: 1–29. Observations may be available before 1713.

Maraldi Diary 1718–25.
Maraldi I, Observations. Microfilm D2: 22.
Bigourdan (1895) indicates meteorological observations from 1/10/1718 to 22/1/1725, although only usable from 1721 as the microfilm is very faint

Joseph Delisle's weather diary, 1748–59.
Observations météorologiques faites à Paris. Microfilm A7: 2.

Paris Observatory Journal, 1783.
Journal des Observations faites a lObservatoire de Paris. Microfilm D4: 23.
Data provided by M. Barriendos, University of Barcelona.

Paris Observatory Journal, 1784.
Observations météorologiques faites a Paris. Extretes del Journal General de la France. Microfilm D6: 39.
Data provided by M. Barriendos, University of Barcelona.

Paris Observatory Journal, 1785–1850.
Journal des Observations Météorologique & Magnetique faites a l'observatoire de Paris, 1785-1798. Manuscripts F1: 9–21, F1: 1–8.
Data provided by M. Barriendos, University of Barcelona.

[1]Catalogue references provided by Bigourdan (1895)

Appendix B

London/Paris Time Series Plots

The time series plots in this appendix are a continuation to Figures 5.6 and 5.7.

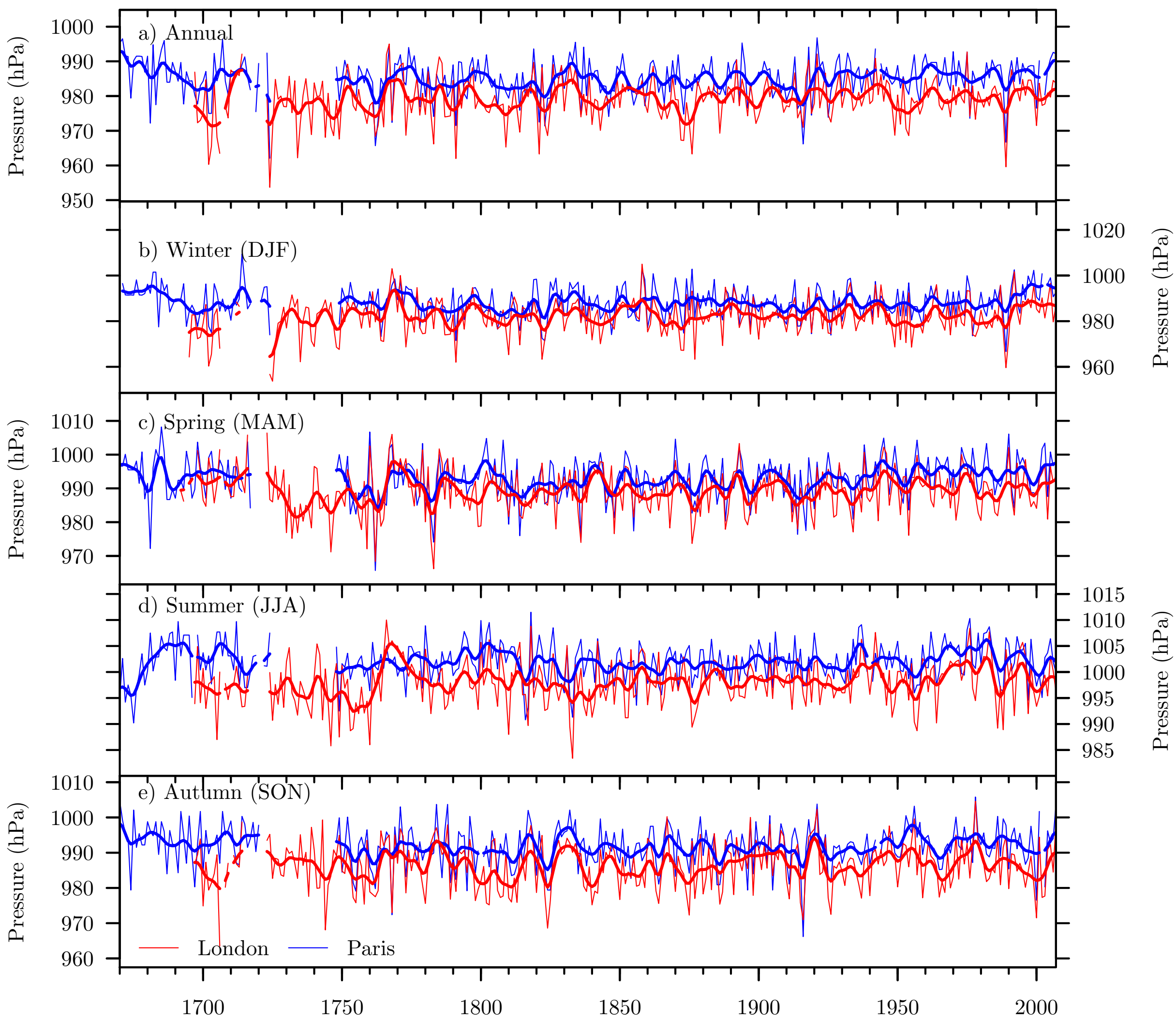

Figure B.1: As Figure 5.6 but for the minumum values.

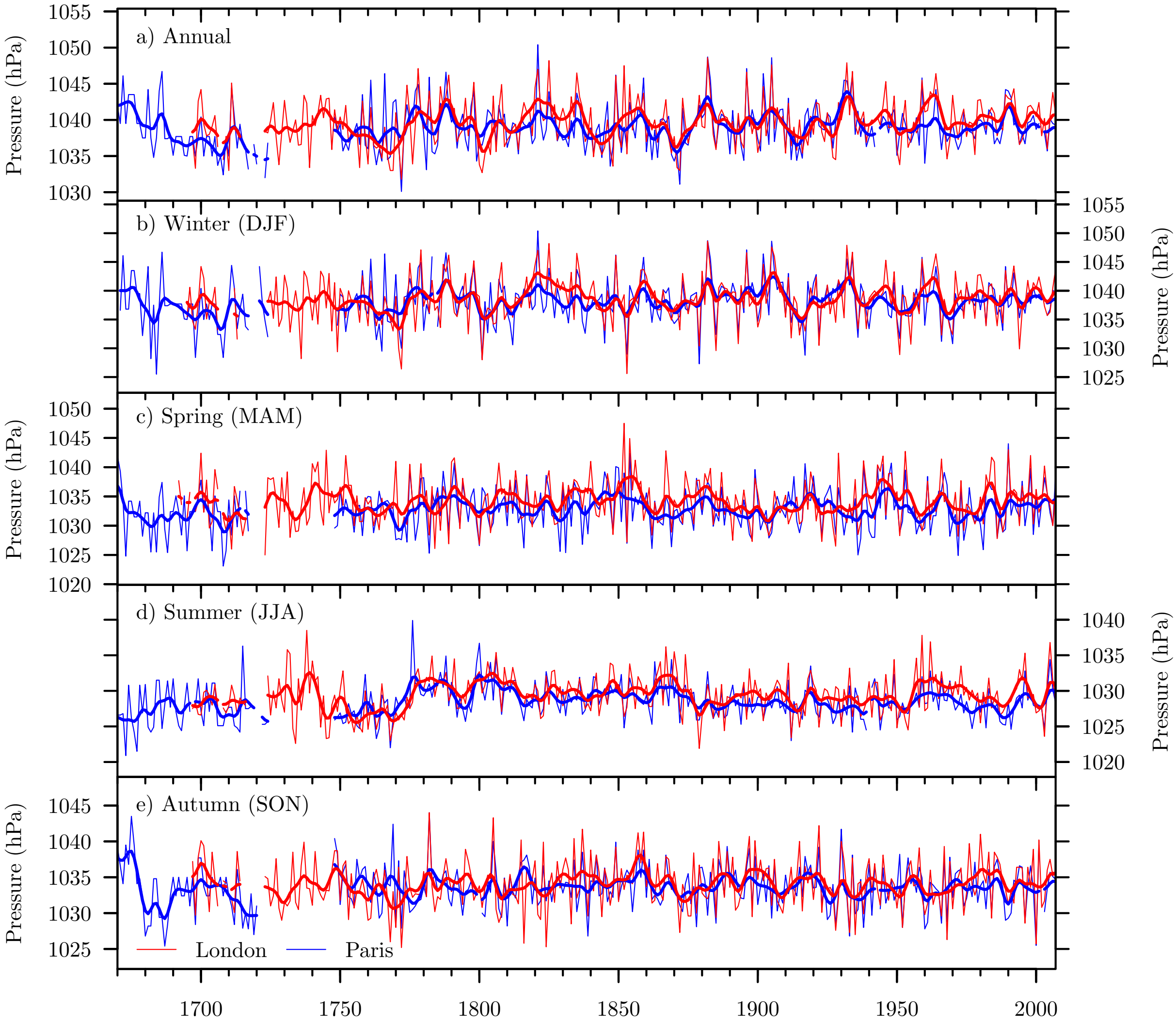

Figure B.2: As Figure 5.6 but for the maximum values.

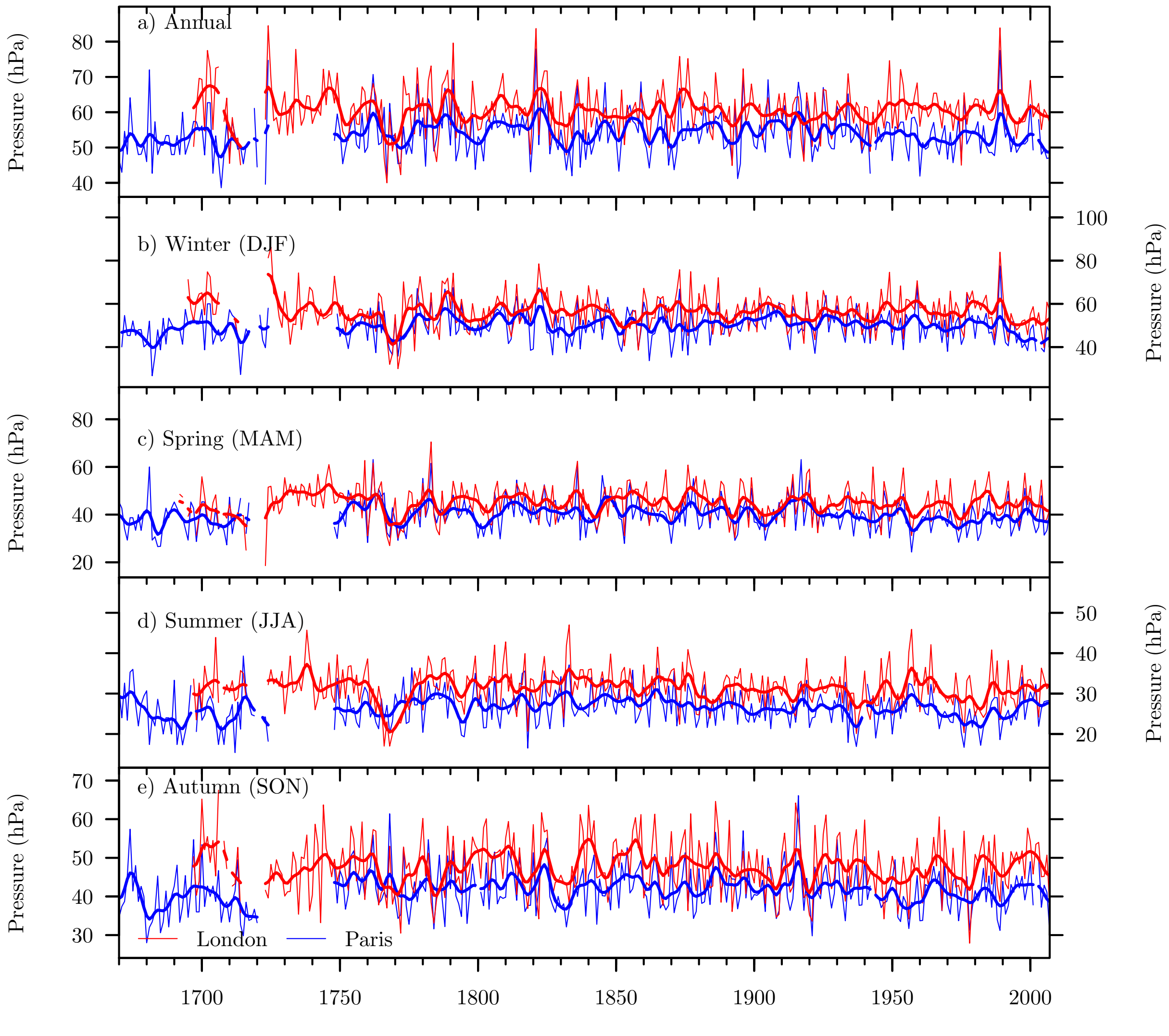

Figure B.3: As Figure 5.6 but for the range.

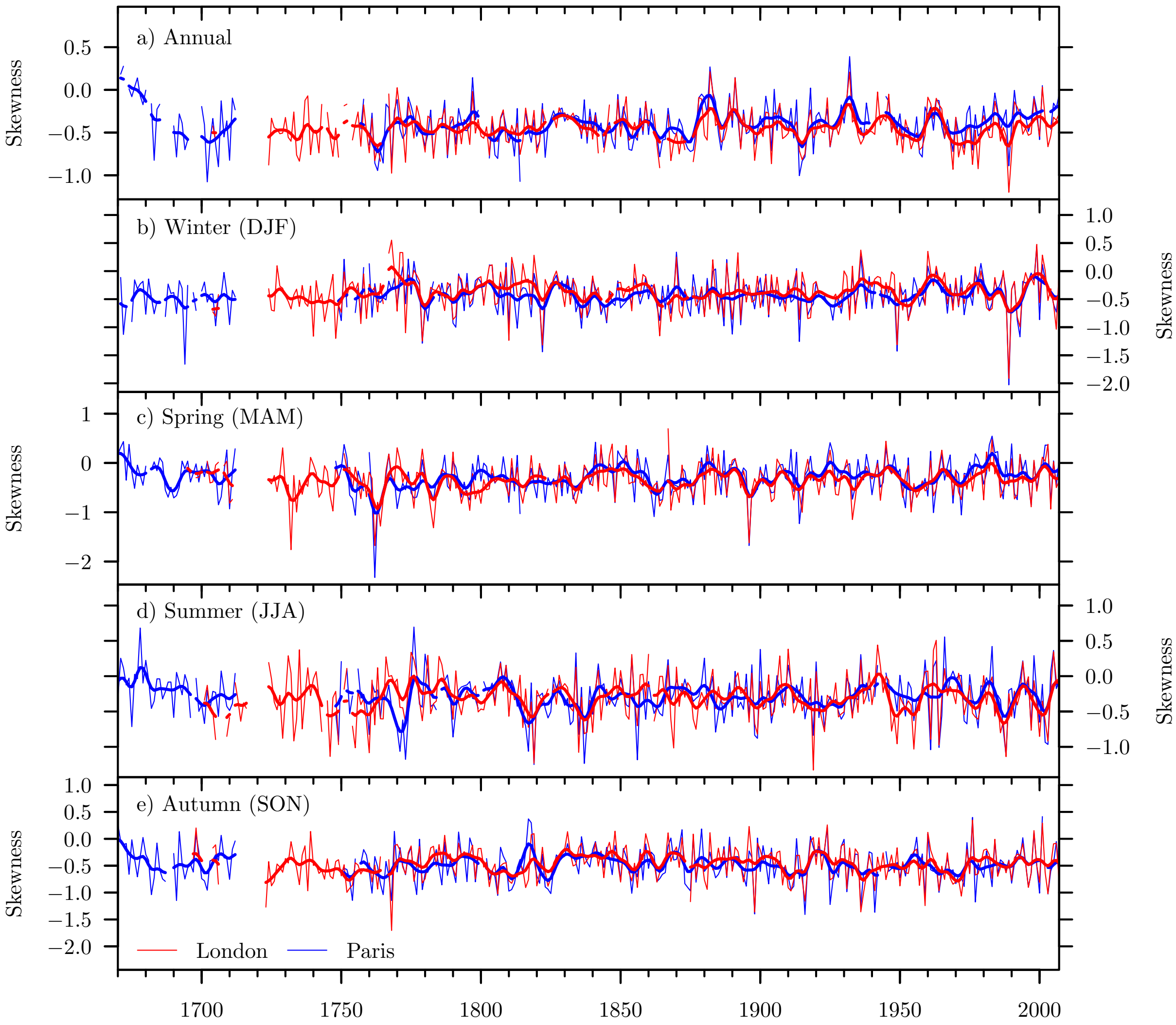

Figure B.4: As Figure 5.6 but for the skewness.

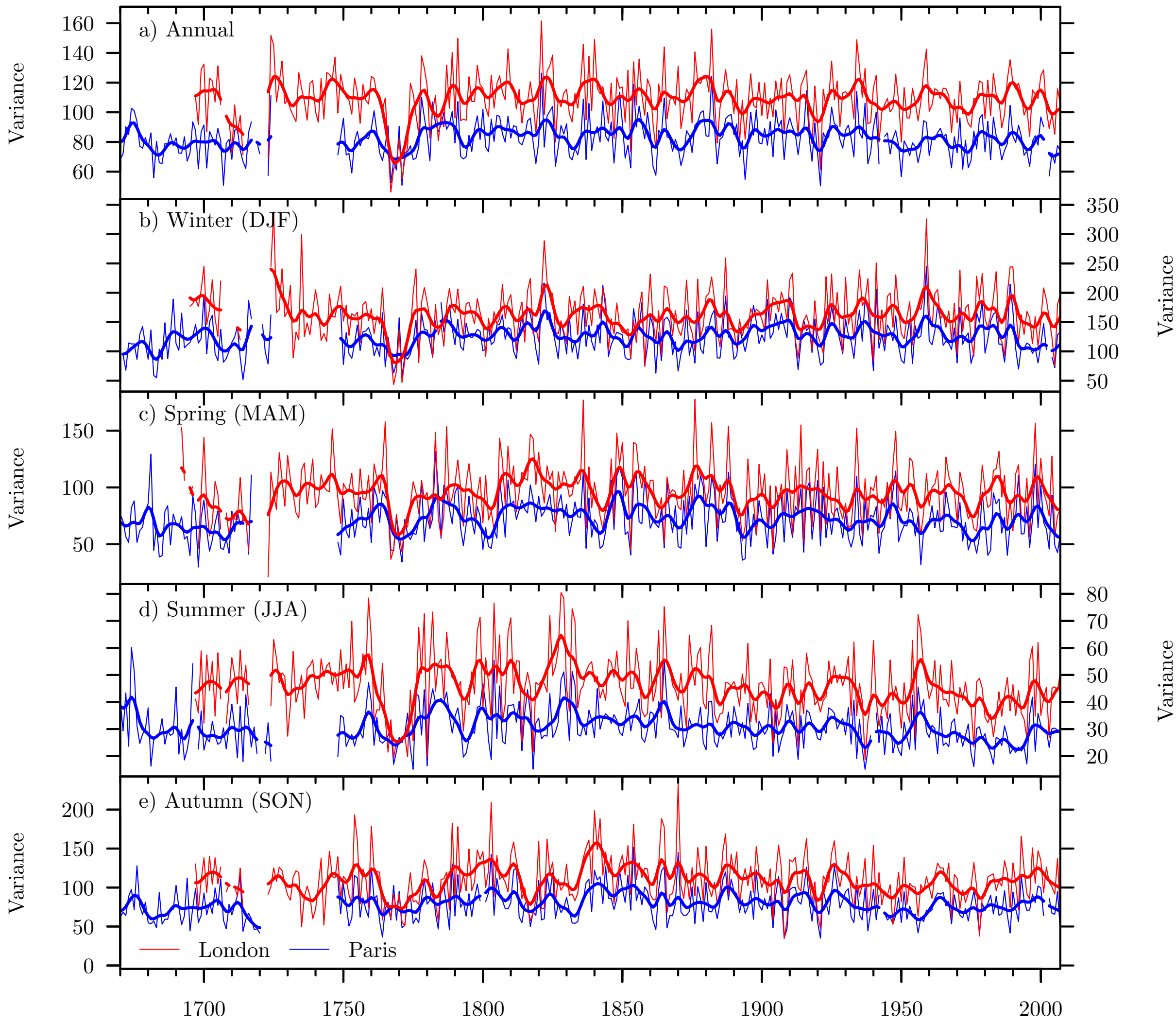

Figure B.5: As Figure 5.6 but for the variance.

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