The History of Scientific Research on the North Atlantic Oscillation

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The North Atlantic Oscillation is one of the most dominant and oldest known world weather patterns. This article will briefly review the intriguing discovery and history of scientific research of this fascinating phenomenon. By reviewing previous scientific investigations, it can be seen that several contemporary themes have recurred ever since the early scientific studies. The review will conclude with a brief speculation on how these themes are likely to develop with future research.

1. INTRODUCTION

It is not possible in a short article like this to present a fully comprehensive review of all research on the North Atlantic Oscillation (NAO) – an extremely complex phenomenon that has been the subject of scientific attention for more than two centuries. Instead, we hope to present a stimulating account of the major scientific landmarks, and refer readers to other studies for more detailed historical accounts [e.g., *Wallace*, 2000; *Stephenson et al*., 2000; *Wanner et al*., 2001]. By reviewing the earlier scientific literature, it can be noted that many of the contemporary issues concerning the North Atlantic Oscillation have been around for a long time. It is our hope that future historical reviews will be able to say that many of these issues were satisfactorily resolved in the 21st century!

2. DISCOVERY OF NORTH ATLANTIC TELECONNECTIONS AD 1000-1780

Perhaps because of the volatility of their local weather, the people of Northern Europe have always had a deep fascination for weather and climate. In the "ragnarok" (twilight of the Gods) legend, Norse mythology predicts that the end of the world will begin with the occurrence of a severe "fimbul-winter", when "snow drives from all quarters, the frosts are so severe, the winds so keen and piercing, that there is no joy in the sun. There will be three such winters in succession, without any intervening summer" [*Sturluson*, 1984]. This long-term prognosis could be taken to imply a run of three years in which the phase of the North Atlantic Oscillation was strongly negative.

It is not surprising, therefore, that the earliest descriptions of North Atlantic Oscillation were first noted by seafaring Scandinavians. Because of their excursions to Greenland, they were well aware of the relationship between climate in different regions of the North Atlantic and surrounding landmasses. The history of Greenland and its climate, fauna, and flora were carefully documented by the Danish missionary Hans Egede Saabye [*Egede*, 1745]. Figure 1 shows a map of Greenland published in an English translation of this book showing the main settlements and coastal features. As described in *van Loon and Rogers* [1978], Hans Egede Saabye also made the following revealing remarks in a diary that he kept in Greenland:

"In Greenland, all winters are severe, yet they are not alike. The Danes have noticed that when the winter in Denmark was severe, as we perceive it, the winter in Greenland in its manner was mild, and conversely."

The fact that this relationship was common knowledge at the time was commented upon by the editor of Saabye's diary [*Ostermann*, 1942]. It was also known and discussed by physical geographers in 19th century Germany [*Gilbert*, 1819].

It is natural to speculate whether earlier visitors such as the Norse colonizers of Greenland might also have noticed this teleconnection between climates in different regions of the North Atlantic basin. Since their first settlement of

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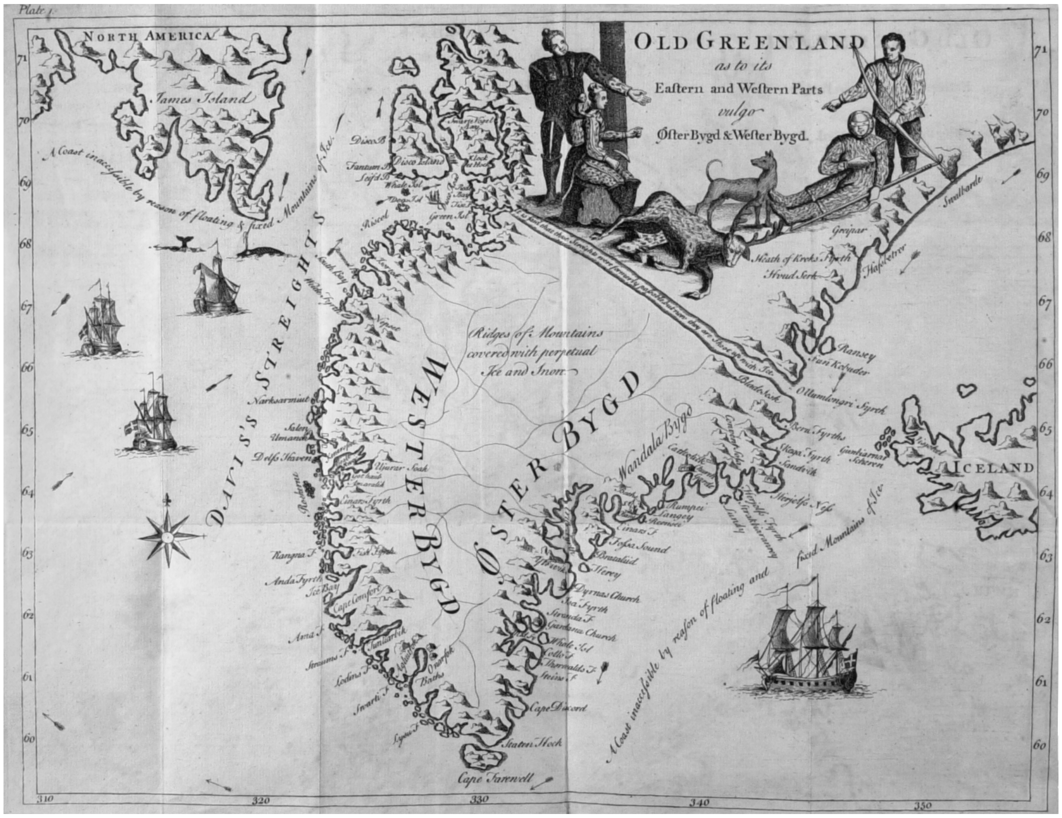

Figure 1. Vintage map of Old Greenland circa 1745 from an English translation of Hans Egede Saabye's History of Greenland. The original colour map of Greenland drawn by Egede in 1737 is on display in the Royal Library in Demark and a copy of it can be seen at http://www.kb.dk/kultur/expo/klenod/.

Greenland in AD 985, the Norse made regular summer transatlantic sailings between Norway and Greenland until around AD 1370, and as such were keen observers of North Atlantic weather. Around AD 1230, a remarkable book appeared in Norway known as the "King's Mirror" [*Anonymous*, 1917] – alternatively sometimes referred to as "Speculum Regale" (Latin) or "Konungs skuggsjá" (Old Norse). It provides fascinating descriptions and insight into several scientific topics including the Northern Lights, the spherical geometry of the Earth, and the climate of Greenland. The book is presented in the form of a dialogue between a son and his father, and one of the most revealing meteorological replies by the father is as follows:

"*In reply to your remark about the climate of Greenland, that you think it strange that it is called a good climate, I shall tell you something about the nature of the land. When storms do come, they are more severe than in most other places, both with respect to keen winds and vast masses of ice and snow. But usually these spells of rough weather last only a short while and come at long intervals only. In the meantime the weather is fair, though the cold is intense. For it is in the nature of the glacier to emit a cold and continuous breath which drives the storm clouds away from its face so that the sky above is usually clear. But the neighbouring lands often have to suffer because of this; for all the regions that lie near get severe weather from this ice, inasmuch as all the storms that the glacier drives away from itself come upon others with keen blasts.*"

This passage demonstrates that the Norse knew from their observations that colder than normal conditions in Greenland were associated with more storminess elsewhere – an important aspect of the North Atlantic Oscillation [*Rogers*, 1997]. Their great expertise in transatlantic navigation and keen sense of observation made it possible for the Norse to be able to discover nonlocal relationships between weather in different parts of the North Atlantic. The Norse colony had been in Greenland almost 300 years before the King's Mirror book was written, which is much longer than it took the later Danish colonizers to note the seesaw relationship based on qualitative observations.

3. EARLY SCIENTIFIC EXPLORATION AD 1811-1905

The temperature seesaw between winters in Greenland and Germany was first documented in tables of above and below normal winters (1709-1800) published by *Gronau* [1811] – see *van Loon and Rogers* [1978] for a copy of one of these tables. The anomalous temperatures in Greenland were not actually measured but were inferred from general impressions of the state of the sea ice, which was important for the then flourishing whaling and sealing industries in Greenland waters. These qualitative observations were used in several seesaw studies [e.g., *Gronau*, 1811; *Dove*, 1839; *Dannmeyer*, 1948].

Some of the earliest regular observations were first taken at Ny Herrnhut near Godthaab on the west coast of Greenland in 1767-8 [*Loewe*, 1966]. Ny Herrnhut was established by the "herrnhuts", a catholic Moravian mission from Germany, who had been given a permit by the Danish king in 1733 to assist Hans Egede in his conversion of the Greenlanders [*Crantz*, 1765]. Temperature observations made at Greenland stations were used in the first meteorological observing network with uniform instrumentation – the Societas Meteorologica Palatina established in 1780 [*Loewe*, 1966]. During 1783, the Moravian brothers made meteorological observations at Godthaab (Nuuk). Later, from 1806 to 1813, Dr. Giesecke at Godthaab (personal communication, Dr Trausti Jonsson, Iceland Met. Office) made regular observations three times a day. The availability of long records of observed temperature measurements made it possible for 19th century climatologists to start scientifically exploring the spatial and temporal variations in climates of different regions.

Dove [1839; 1841] investigated 60 temperature time series of up to 40-yr length from all over the Northern Hemisphere, and noted that east-west variations in temperatures were often more pronounced than north-south variations. He noted an opposition of the monthly and seasonal temperature anomalies of northern Europe with respect to both North America and Siberia, and thereby scientifically confirmed the statement made by Hans Egede Saabye. The famous Austrian climatologist, *Julius Hann* [1890], later demonstrated the east-west temperature seesaw by using 42 years of monthly mean temperatures from Jakobshavn on the west coast of Greenland (69°N, 51°W) and Vienna, Austria (48°N, 16°E). Later studies used Oslo, Norway (60°N, 11°E) instead of Vienna [*Hann*, 1906].

A major stimulus for the research came from severe climate events in Europe such as the anomalously cold winter of 1879/80. In a pioneering study, *Teisserenc de Bort* [1883] compared European climate during different anomalous winters. He investigated the positions of large pressure centers (which he called "centres d'action"), and distinguished five types of anomalous winters according to the position of the Azores High and the Russian High and to some extent also the Icelandic Low. He suggested that surface influences (such as Eurasian snow cover) were possibly responsible for these displacements. Figure 2 shows some of the pressure maps for various winters published in *Teisserenc de Bort* [1883].

Inspired by the concept of "centres of action" introduced by Teisserenc de Bort, *Hildebrandsson* [1897] then investigated sea-level pressure time series from different sites and found a distinct inverse relation between the pressure at Iceland and the Azores. He also noted that series from the Azores and Siberia ran "parallel", whereas Alaska and Siberia showed an opposite behaviour. This study was the forerunner for all future studies that have used sea-level pressures at Iceland and Azores to characterise the North Atlantic Oscillation.

Several authors of the late 19th century also addressed the relation between ocean and atmosphere in the North Atlantic region. In a study of sea surface temperatures near Norwegian lighthouses, *Pettersson* [1896] noted that milder winters were associated with warmer sea surface temperatures, and speculated that the climate of Western Europe was influenced by the Gulf Stream. *Meinardus* [1898] suggested that interannual fluctuations in the Gulf Stream might be responsible for anomalous winters, and that these fluctuations could affect the weather in western Iceland and Greenland in the opposite way than in Europe. With the benefit of hindsight, it is now known that coastal sea surface temperature anomalies are a local wind-induced response rather than the cause of variations in the North Atlantic Oscillation. A comprehensive review of these early theories of North Atlantic climate variability is given by *Helland-Hansen and Nansen* [1920].

4. DESCRIPTIVE CORRELATION STUDIES AD 1908-1937

The early explorations based on visual inspection of time series led to many mechanisms being proposed for explaining climate variations, for example, solar cycles, number of icebergs advected by the Gulf stream, etc. [*Helland-Hansen and Nansen*, 1920]. Many of these relationships were spurious and had arisen purely due to sampling uncertainty caused by the small length of available time series.

Felix Exner's comprehensive and accurate 1913 study of Northern Hemisphere sea-level pressure anomalies went one step further by producing the first correlation map showing the spatial structure of the North Atlantic

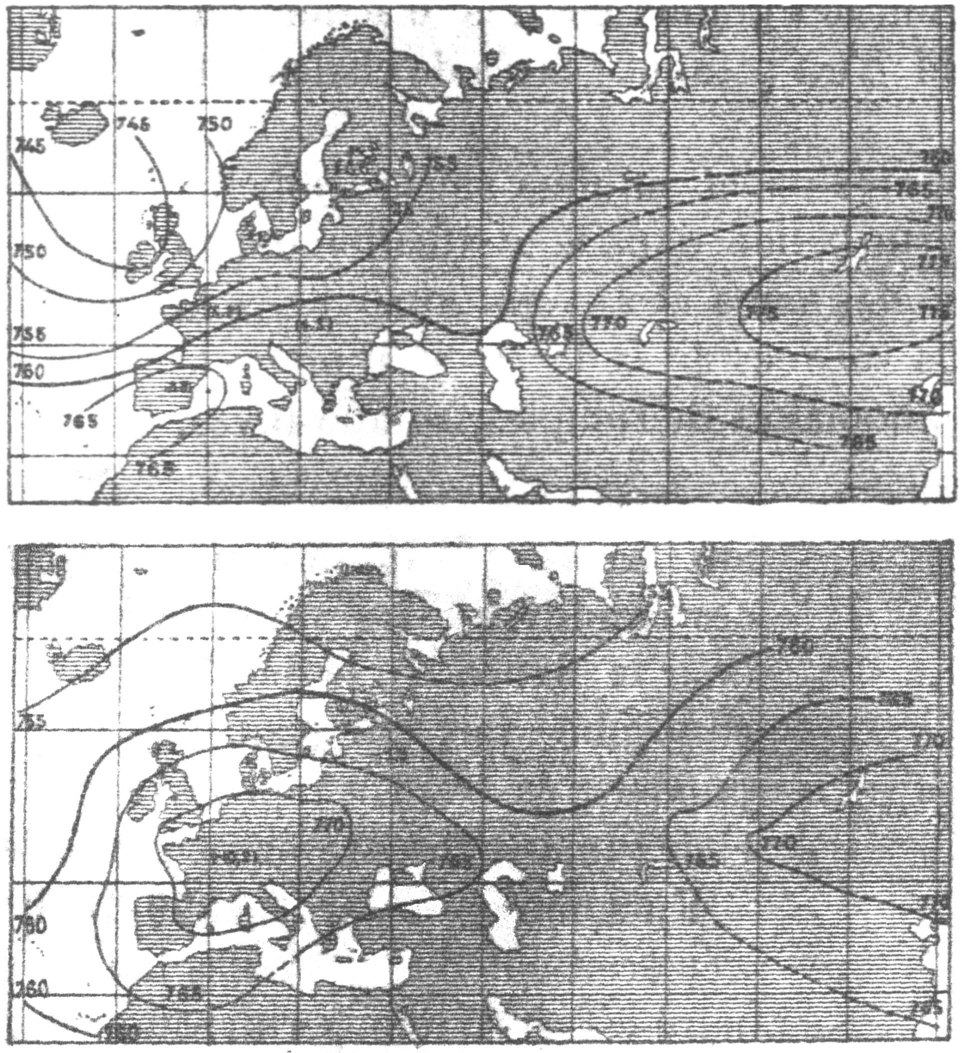

Figure 2. Vintage map showing early monthly mean sea level pressure (SLP) maps for December 1868 (top) and for December 1879 (bottom) (units in Torr; 1 Torr = 1.3332 hPa). From *Teisserenc de Bort* [1883].

Oscillation in the Northern Hemisphere. This map is reproduced in Figure 3a and shows the correlation between the monthly mean pressure anomalies at the North Pole (approximated by the mean of three time series from Greenland, northern Norway, and Northern Siberia) and some 50 sites in the Northern Hemisphere. Exner emphasised the annular appearance of the pattern and the strong signature in the North Atlantic and Mediterranean areas. In fact, his correlation pattern closely resembles the Northern Annular Mode (or Arctic Oscillation) found using principal component analysis of sea-level pressure [*Wallace*, 2000; *Deser*, 2000; *Ambaum et al.*, 2001; *Thompson et al.*, this volume]. Figure 3b shows Exner's later map of correlations of pressure anomalies between Stykkisholmur and some 70 sites [*Exner*, 1924]. This pattern is more regionally confined to the North Atlantic sector and resembles more closely the North Atlantic Oscillation pattern.

Felix Exner's studies used the statistical technique of correlation analysis introduced into climate research by Gilbert Walker [*Walker*, 1909; 1910]. As director of the Indian Meteorological Department in Pune, Walker was confronted with the problem of how to seasonally forecast ("foreshadow" in his words) the Indian summer monsoon and the flooding of the Nile. To do this he made expert use of the "regression" and "correlation" concepts that had been recently conceived by Francis Galton in 1877 [*Galton*, 1888]. It is possible that Walker learnt about these statistical techniques either directly from Galton or one of Galton's close acquaintances such as Richard Strachey (1817-1908) a

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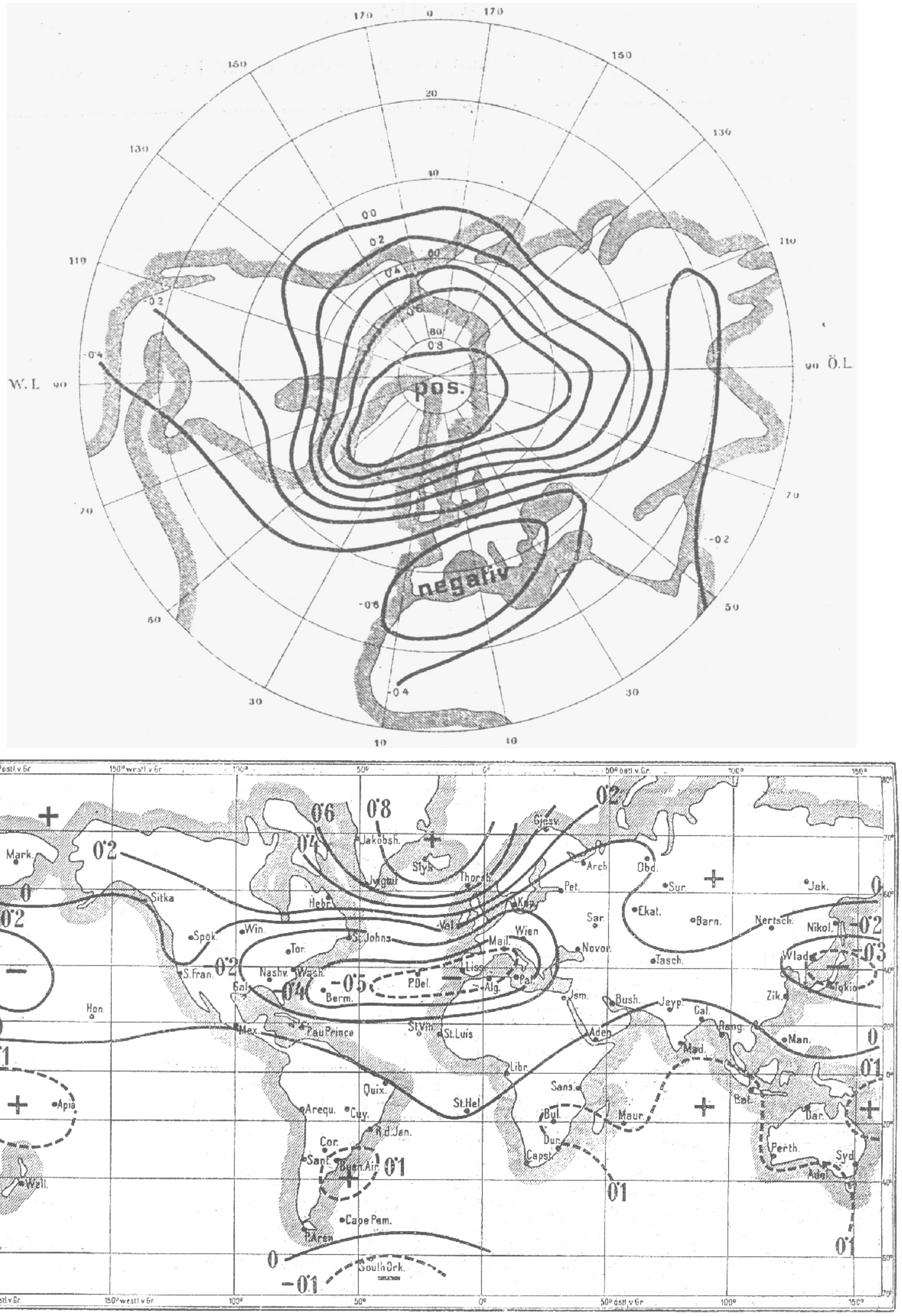

Figure 3. (a) Map of the correlation between monthly anomalies of "polar pressure" (average of three stations in northern Greenland, northern Norway, and northern Siberia, respectively) and pressure at around 50 sites of the Northern Hemisphere from 1887 to 1906 [from *Exner*, 1913]. (b) Map of the correlation between monthly anomalies of pressure at Stykkisholmur and pressure at about 70 sites for winter months (September to March) from 1887 to 1916 [from *Exner*, 1924].

who was heavily involved in public administration in India. Galton, himself, had an extremely strong interest in meteorology and was a founding member of the Meteorological Committee/Council from 1868-1902 responsible for establishing the UK Met Office after the death of its founder Admiral Fitzroy. By using statistical significance testing to reject spurious correlations, Walker was able to group world weather variations into several distinct patterns. His preliminary study of world weather published in 1923 summed up the situation by saying:

"there is a swaying of pressure on a big scale backwards and forwards between the Pacific ocean and the Indian ocean; and there are swayings, on a much smaller scale, between the Azores and Iceland and between the areas of high and low pressure in the North Pacific: further, there is a marked tendency for the "highs" of the last two swayings to be accentuated when pressure in the Pacific is raised and that in the Indian ocean lowered."

Walker [1923] also noted that the "Iceland Azores oscillation is not very closely related with that between the Pacific and Indian oceans" and suggested that "readers interested in northern relationships must in any case read Exner's interesting and important paper [*Exner*, 1913]". In *Walker* [1924] he extended his results to a comprehensive review of simultaneous and lag correlations for all four seasons for many worldwide stations. Most likely because of his mathematical training, Walker preferred to present his correlation results quantitatively as tables of numbers rather than as correlation maps. In *Walker* [1924] he classified the correlations into groups named the "Southern Oscillation" and the "Northern Oscillations". He further classified the Northern Oscillations into two distinct patterns, which he referred to as the "North Atlantic Oscillation" and the "North Pacific Oscillation". While the word "oscillation" is perhaps appropriate for the quasi-periodic Southern Oscillation, it remains a misnomer for the noisy and non-periodic (in time) Northern Oscillations – Northern Swayings might be a more accurate description! He discussed the relationship of the North Atlantic Oscillation to the Gulf Stream and the sea-ice dynamics in the North Atlantic, but he was skeptical about periodicities of 2 and 4.5 years of the sea-ice extent off Iceland and Iceland pressure that were discussed by other scientists at that time. Walker's concept of the NAO became popular among contemporary meteorologists and created the need for a quantitative measure of the strength of the NAO. *Walker and Bliss* [1932] constructed a robust multivariate index for the North Atlantic Oscillation using the following linear combination of variables

PVienna+ 0.7PBermuda PStykkisholmur PIvigtut +
TBodö + TStornoway + 0.7(THatteras + TWashington) /2
– 0.7TGodthaab

where P stands for surface air pressure and T for surface air temperature averaged over the winter period December to February (all series were standardised to have zero mean and a variance of 20). The weights were discovered using an early selection of variables regression procedure. The Azores pressure time series gave only a small coefficient less than 0.5 and so was not retained in the expression by *Walker and Bliss* [1932]. This rather surprising rejection of the Azores predictor is due to its strong collinearity with Iceland pressure etc. rather than it having too weak a correlation with the NAO. According to *Wallace* [2000], the *Walker and Bliss* [1932] procedure may be considered an iterative approximation to Principal Component Analysis (PCA). However, this is not the case since the Azores pressure is not similarly rejected in the principal component weights shown by *Wallace* [2000] for the Arctic Oscillation. Walker's approach is more akin to a "selection of variables" approach as often used to select explanatory variables for multiple regression. A photograph of Gilbert Walker is shown in Figure 4.

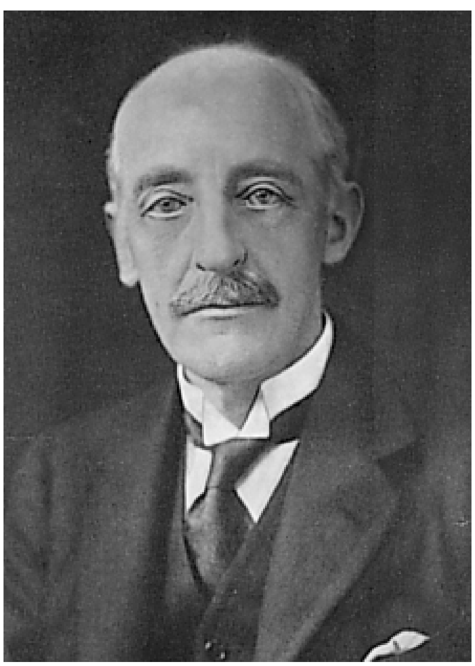

Figure 4. Photograph of Gilbert Thomas Walker (courtesy of E.M. Rasmussen, University of Maryland).

Defant [1924] also published an original study of the monthly pressure anomaly fields over the North Atlantic from 1881 to 1905. He distinguished two pairs (four types) of anomalies, where the first pair (83% of all months) corresponds to the NAO-pattern and the second pair to a strong anomaly at 55°N and a weak opposite anomaly between 10° and 30°N. By subjectively attributing to each month an anomaly type and strength and applying a weighting procedure he was able to draw annual time series. He considered these variations to be internal oscillations of the climate system disturbed by sea ice extent off Iceland and volcanic eruptions. *Defant* [1924] also pointed to possible relations between the North Atlantic climate and the "heat engine" of the tropical Atlantic, taking up older, speculative ideas of *Shaw* [1905] and *Hann* [1906].

Although Defant went further than Exner and Walker in his search for dynamical causes for the NAO-like anomalies, his study still remained primarily exploratory. Other descriptive studies based on longer time series were published in the 1930s and 40s on the temperature seesaw between Northern Europe and Greenland [*Angström*, 1935; *Loewe*, 1937; *Dannmeyer* 1948]. *Angström* [1935] invented the word "teleconnection" to describe the association of climatic variations between different regions.

5. MODERN STUDIES

Theoretical developments in understanding the dynamics of large-scale planetary waves opened up a new way of looking at climate patterns. A number of theoretically motivated studies about the interaction of the zonal circulation and pressure centers were published by a group of leading meteorologists that included Rossby, Willett, Namias, Lorenz and others [*Lorenz*, 1967]. *Rossby et al*. [1939] studied the structure and dynamics of the planetary waves in the presence of disturbances and deduced an influence of the strength of the zonal circulation on the temporal behaviour of the quasi-stationary centers of action. Apparently unaware of Exner's and Walker's climatological studies, they introduced a "zonal index" defined as the zonally averaged zonal wind at 45°N as a measure for the strength of the polar vortex in the free atmosphere to the north. *Rossby and Willett* [1948] focussed their studies on the polar vortex and addressed the issue of stratosphere-troposphere coupling. Rossby's zonal index became very popular, and many climatological studies of the zonal circulation were performed. *Namias* [1950], with a clear focus towards the improvement of forecasts, recognised the importance of latitudinal shifts in the zonal mean zonal wind. *Lorenz* [1951] studied the variability of the zonal mean circulation and the oscillations in the distribution of atmospheric mass. He introduced a new zonal index based on the zonal mean meridional pressure gradient at 55°N.

Another driving force in modern NAO studies has been the insight provided by the application of more advanced multivariate statistical techniques to grid point data sets. After visually exploring the correlation matrix between zonal mean sea-level pressure and zonal wind at various latitudes in *Lorenz* [1951], *Lorenz* [1956] went on to construct a less subjective zonal index by using "Empirical Orthogonal Functions" (EOFs) of the zonal means. EOFs are eigenvectors of the sample covariance matrix and were previously used in a weather forecasting study by *Fukuoka* [1951]. EOF analysis is equivalent to the widely used statistical technique known as Principal Component Analysis (PCA) invented by Karl Pearson in 1903. It is a descriptive multivariate technique for obtaining linear combinations of the variables (Principal Component indices) that explain maximum variance. The principal component time series are each associated with a set of constant weights, which in the case of grid point variables, define a spatial EOF pattern. With access to increased amounts of computer power, *Kutzbach* [1970] was able to demonstrate the power of PCA for studying large-scale circulation anomalies in two dimensional gridded pressure data. Many later studies have since adopted the same approach for pressure as well as for other fields e.g., *Trenberth and Paolino* [1980], *Barnett* [1985], and many subsequent studies. The intention of many of these studies was to identify the leading "modes" of the low-frequency atmospheric circulation. In a comprehensive review, *Wallace and Gutzler* [1981] noted the dominance of a zonally symmetric, global-scale seesaw between polar and temperate latitudes in Northern Hemisphere sea-level pressure, as well as to the more regional-scale pattern resembling the so-called Pacific North American (PNA) and Western Atlantic (WA) pressure patterns at mid-tropospheric levels. By applying similar techniques to a 700-hPa geopotential height, *Barnston and Livezey* [1987] demonstrated that the North Atlantic Oscillation is the only low-frequency circulation pattern, which is found in every month of the year. These studies confirmed that NAO is one of the most dominant and robust large-scale patterns of natural climate variability.

Many European studies relevant to NAO research were published in the latter half of the 20th century but, unfortunately, they remain relatively unknown and rarely cited in the NAO literature. Two main reasons for this obscurity were the preference for using (perceived to be less old-fashioned) expressions such as "westerly flow type" instead of "North Atlantic Oscillation", and their publication in not widely accessible international journals. A good example is provided by the studies of English climatologist, Hubert Lamb, who was fascinated by the variations in westerly flow and blocking that had greatly affected the UK and its society over the previous century and more – many interesting discussions and references can be found in his fascinating books on climate [*Lamb*, 1972; *Lamb*, 1977; *Lamb*, 1995]. Lamb [1972] devised a set of circulation types and associated indices for the UK and the nearby Atlantic that were later updated [*Hulme and Barrow*, 1977] and are still used today. One of Lamb's indices, the "westerly index", is very closely related to the NAO index and its variability since 1860 was discussed in detail in *Lamb* [1972] and *Hulme and Barrow* [1977]. Other westerly flow indices were also constructed such as the "PSCM" atmospheric circulation indices [*Murray and Benwell*, 1970] and the 500 hPa zonal index in the Atlantic/ European sector by H. Trenkle shown in Fig 7.9, p271 of *Lamb* [1972] – many of these and other zonal flow indices are reviewed in *Steinrücke* [1999]. An early study on the negative (blocked) phase of the NAO was published by *Sumner* [1959]. Several pioneering long-range forecasting studies at the UK Met Office attempted to use the NAO (westerly flow) to predict future circulation, temperatures, and precipitation in following seasons for the UK and the Atlantic region [*Hay*, 1967; *Murray*, 1972; *Murray and Lankester*, 1974]. *Miles* [1977] contains an interesting discussion of the annual cycle in the NAO.

In an attempt to find mechanisms explaining year-to-year and longer period variations in North Atlantic climate, *Bjerknes* [1964] used the pressure difference between Iceland and the Azores as a simple measure of westerly flow strength. This is in fact a simple North Atlantic Oscillation index, although Bjerknes used the term "zonal index". His studies were inspired by earlier investigations such as those of *Pettersson* [1896] *and Helland-Hansen and Nansen* [1920], and involved the dynamical analysis of past climate variability following *Lamb and Johnson* [1961]. Bjerknes noted that short-term variations in the zonal index were associated with latent cooling of North Atlantic sea surface temperatures (the tripole pattern) whereas long-term trends had a more complicated temperature pattern that he speculated were related to oceanic heat advection.

Several scientists in the 1970s attempted to exploit sea surface temperatures in order to make empirical long-range forecasts of European climate. *Ratcliffe and Murray* [1970] and *Ratcliffe* [1971, 1973] suggested that SST anomalies south of Newfoundland play a crucial role in this context and developed a classification, which could be used for long-range forecasts during winter. Cooler than normal SSTs south of Newfoundland were found to be followed one month later by positive SLP anomalies over the North Sea and the northern North Atlantic and negative SLP anomalies over the Atlantic south of 40°N (i.e. negative NAO index conditions). In a prescient seasonal forecast study of the causes of the extremely cold European winter of 1962/63, *Rowntree* [1976] investigated the influence of SST anomalies in the tropical Atlantic on the circulation of the northern extratropics by means of a set of climate model simulations including random perturbation experiments ("ensembles"). He prescribed a positive SST anomaly off the west coast of Africa at 16°N – 20°N, similar to that observed in the winter of 1962/1963, and then analysed days 41 to 80 of a 80 day model runs (seasonal hindcasts). Although the different experiments gave different results north of 50°N and in the western North Atlantic, all experiments consistently showed a negative SLP anomaly west of the Iberian Peninsula. This finding was in agreement with the SLP anomalies observed in the 1962/1963 winter as well as with composites of other SLP anomalies for anomalously warm winters in the tropical North Atlantic. *Folland* [1983] later confirmed that SSTs in the eastern tropical Atlantic (as estimated by Cap Verde surface air temperatures) were significantly negatively correlated with the westerly flow over the North Atlantic [see *Wanner et al*., 2001, for a comprehensive description of Atlantic SST anomalies related to the NAO]. To summarise, these early studies discovered the three main nodes of what is now known to be the North Atlantic SST tripole pattern associated with NAO [*Visbeck et al.*, this volume].

The papers by Fritz Loewe are worthy of further mention in that they provide an important historical bridge between the early German work and modern NAO studies. A polar explorer and meteorologist, Fritz Loewe experienced the severity of Greenland's temperatures first hand on the fateful expedition to Greenland in 1930, which led to the death of Alfred Wegener. Based on earlier German studies, he wrote about the temperature seesaw between Western Greenland and Europe in 1937, and then again in his retirement in 1966. Both *Loewe* [1937] and *Loewe* [1966] provided an important historical basis for the later studies of van Loon and coworkers in the late 1970s. With access to much longer historical data records, these studies were able to re-examine the winter temperature seesaw between Greenland and Northern Europe. *Loewe* [1966] confirmed beyond doubt that the seesaw in temperatures between western Greenland and Europe had been well established (stable) over a period of more than 200 years. The dynamical causes for the seesaw were then investigated in a series of pivotal studies by Harry van Loon and his PhD and masters students in Colorado [*van Loon and Rogers*, 1978; *Rogers and van Loon*, 1979; *Meehl and van Loon*, 1979]. They found significant correlations between atmospheric circulation and North Atlantic surface temperatures, and investigated the teleconnections with the Pacific region and with the tropical climate system. These studies significantly "shaped" the current concept of the NAO as a large-scale climate mode in the North Atlantic region with important impacts on European climate.

Rogers [1984] used a simple two-station NAO index based on sea-level pressures at Ponta Delgada, Azores and Akureyri, Iceland to assess the association between NAO and the Southern Oscillation. He confirmed *Walker's* [1924] earlier findings that the two phenomena are not strongly associated. *Rogers* [1984] also speculated on the long-term decreasing secular trend in the NAO index, which has since vanished due to the subsequent runs of positive NAO index winters. *Lamb and Peppler* [1987] successfully invoked the North Atlantc Oscillation for explaining the 1979-1984 droughts in Moroccan precipitation. This led to the (negative phase of the) North Atlantic Oscillation phenomenon being renamed "Al Moubarak" (the bountiful) by His Majesty King Hassan II of Morocco (personal communication, Dr El Hamly).

6. THE LATE 20TH CENTURY RENAISSANCE

Since 1990, there has been a remarkable growth in scientific research on the North Atlantic Oscillation. This can be clearly seen in Figure 5, which shows the number of scientific articles in the Institute for Scientific Information (ISI, see http://www.wos.mimas.ac.uk) citation database with the expression "North Atlantic Oscillation" in either the title or the abstracts published between 1985 and 2001. Various factors contribute to this renaissance of interest; in particular, the abundance of positive NAO index winters since 1970 that are associated with recent European climate variations

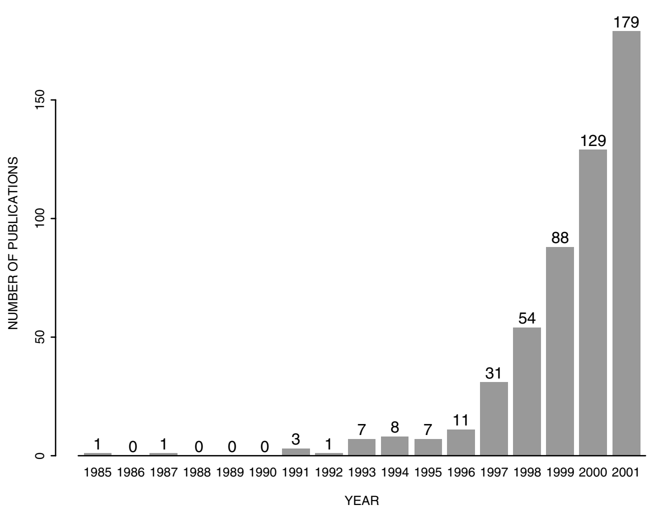

Figure 5. The increasing number of published articles containing the expression "North Atlantic Oscillation" either in the title or in the abstract during the period January 1985 and November 2001. Source: web of science bibliographic database.

and associated impacts [*Hurrell*, 1995]. In the year 2000, no fewer than 129 scientific papers were published on aspects of the North Atlantic Oscillation. In addition to these articles, a similar search for articles with titles and abstracts containing the words "Northern Annular Mode" and "Arctic Oscillation" revealed 1, 5, 22, and 41 articles published in the years 1998 to 2001. This great interest in the subject will undoubtedly lead to significant advances in the future. The rest of this section will briefly sketch some of the main developments that have occurred in this period, and we refer the reader to other articles in this volume for more in-depth reviews of the recent literature.

Hurrell [1995] investigated the influence of the NAO on interannual and decadal temperature and pressure variations over the European continent. He demonstrated that recent trends in the NAO could help explain climate trends over Europe. *Hurrell* [1996] used multiple regression to show that the NAO explained 31% of the total variance in wintertime mean surface temperatures averaged from 20N to 90N over the period 1935-94. In other words, a substantial fraction of recent extratropical warming in the Northern Hemisphere can be attributed to the recent upward trend in the NAO index from 1965 to 1995. However, using longer NAO indices shows that the 31% explained variance reduces to zero over 1895-1920 and is about 25% over the period 1851-1894 [*Osborn et al*., 1999]. A more comprehensive review of these findings was presented in *van Loon and Hurrell* [1997]. *Gillett et al*., this volume, discuss likely changes to NAO variability due to anthropogenic forcing in more detail.

Hurrell [1995] defined a new NAO index as the difference between the standardised station pressure series of Lisbon, Portugal minus Stykkisholmur, Iceland. This index has become one of the most commonly used NAO indices in climate research. *Jones et al.* [1997] further extended an instrumental NAO index back to 1821 by using station pressure observations from Gibraltar and the Reykjavik area [see also *Jones et al.*, this volume]. Despite their obvious advantages for historical studies, two-point station indices are not particularly robust to changes in the NAO spatial pattern [*Kapala et al*., 1998; *Wanner et al*., 1997]. They are also less representative and noisy for sampling the NAO over periods less than one season [*Stephenson et al*., in preparation]. For daily NAO studies, it is necessary to define the NAO index using data from the whole North Atlantic region [*Stephenson et al.,* in preparation]. Refer to *Jones et al*. [this volume] for more discussion of the recent work on historical NAO indices.

For studying long-term trends in the NAO, it is necessary to extend the index further back beyond the pre-instrumental period. Much current research has focussed on constructing "proxy" NAO indices using early instrumental pressure, temperature and precipitation station series and environmental proxy and documentary proxy data [e.g., *Cook*, this volume; *Appenzeller et al.*, 1998; *Luterbacher et al.*, 1999, 2002; *Glueck and Stockton,* 2001]. An important caveat of the proxy approach is that proxies can only be used to infer NAO by its assumed response rather than measure NAO directly via dynamical quantities such as pressure. Refer to *Cook* [this volume] for more discussion of the recent work on proxy indices.

In the 1990s, climate modellers also began to investigate the NAO in their model simulated climates. *Glowienka-Hense* [1990] showed that NAO variability was realistically simulated by an atmosphere-only general circulation model, confirming that atmospheric processes fundamentally cause the NAO. Several studies have also shown that NAO can be captured quite realistically by coupled ocean-atmosphere models [*Pittawala and Hameed*, 1991; *Davies et al.*, 1997; *Osborn et al.*, 1999]. *Davies et al.* [1997] showed that the HadAM1 atmospheric model gave low but significant predictability for the NAO from N. Atlantic SST in the model in winter and spring with likely El Niño/Southern Oscillation (ENSO) influences on at least the western half the NAO pattern. By comparing coupled simulations made using different ocean models, *Christoph et al.* [2000] demonstrated that the NAO in sea-level pressure variations simulated by the ECHAM4 coupled model was not sensitive to the choice of ocean model. *Stephenson and Pavan* [2002] reviewed the ability of 17 coupled models to simulate the NAO temperature pattern, and found a wide range of different model behaviour. Although the spatial NAO pattern was found to be generally well simulated, the simulated NAO time series was too strongly correlated with ENSO for several of the coupled models. More recently, *Hoerling et al.* [2001] have used a GCM to trace the origins of decadal NAO predictability to the tropical Indian ocean, thereby extending the earlier work of *Shaw* [1905], *Hann* [1906], *Defant* [1924], and *Rowntree* [1976].

Stimulated by the progress made in understanding the coupled processes controlling ENSO, several studies in the 1990s started to investigate North Atlantic ocean-atmosphere processes in more detail. The NAO was related to interdecadal variability of latent and sensible heat flux anomalies of the North Atlantic and the oceanic circulation [e.g. *Cayan*, 1992a, b; *Deser and Blackmon*, 1993; *Kushnir*, 1994]. More recent research with atmosphere-only models forced by observed prescribed sea surface temperatures demonstrated a small amount of ex-ante skill at hindcasting post 1950 decadal trends in the NAO [*Rodwell et al.*, 1999; *Mehta et al.*, 2000]. Whether this apparent skill is relevant to the fully coupled system is still a serious matter for debate [*Bretherton and Battisti*, 2000]. See *Rodwell et al.* and *Cjaza et al.* [this volume] for more discussion of recent research on these matters.

The 1990s have seen the emergence of a debate on the spatial structure of the North Atlantic Oscillation. Based on principal component analysis of hemispheric sea-level pressure north of 20°N, *Thompson and Wallace* [1998; 2000; 2001] isolated a large-scale pattern they referred to as the "Arctic Oscillation (AO)" or "Northern Annular Mode (NAM)". The AO/NAM pattern has striking resemblances to the NAO in the Atlantic sector, but is more zonally symmetric with a low pressure center of action over the Arctic region and an annular high pressure band in the subtropics. The AO/NAM index has strong correlations with the stratosphere [*Baldwin and Dunkerton*, 1999 and references therein], and shows more marked decadal trends than does the NAO index. However, according to *Deser* [2000] and *Ambaum et al.* [2001], the annular appearance of the AO/NAM is caused by the Arctic center of action, while there is no co-ordinated behaviour of the Atlantic and Pacific centers of action. *Ambaum et al.* [2001] showed that the NAO reflects the correlations between the surface pressure variability at all of its centers of action whereas this is not the case for the AO/NAM. The only significant correlation between centers of action in the AO/NAM pattern is between the Iceland and the Azores [*Ambaum et al.*, 2001]. For more discussion of this ongoing debate refer to these cited articles and to *Thompson et al.* [this volume].

A major contribution to the recent growth in publications on the NAO has been the rising awareness by researchers in other fields of the usefulness of the NAO for explaining weather related impacts. NAO provides a convenient (yet far from unique) aggregate index for summarizing seasonal weather in the North Atlantic and surrounding land mass regions. Because of its strong association with temperature, precipitation, and surface winds, the NAO has a strong influence on the biosphere. By relating impacts to recent changes in the NAO, it is possible to get an idea of how the biosphere may respond to future climate change. For a discussion of the large amount of recent NAO work on marine, terrestrial, and freshwater ecosystems refer to *Drinkwater et al.*, *Mysterud et al.*, and *Straile et al.* [this volume], respectively.

7. COMMON THREADS AND FUTURE DIRECTIONS

Several important threads can be discerned in previous research on the NAO.

Firstly, NAO is without doubt one of the most ancient, robust, and omnipresent climate teleconnections known to mankind. Scientific research has confirmed (and will undoubtedly continue to demonstrate) the role of NAO as a very useful aggregate factor for describing the variations of many diverse phenomena. NAO provides a macro-scale index that encapsulates a lot of information about climate and weather variations in the North Atlantic region.

Secondly, the overall spatial extent of the NAO pattern is still a debatable topic. Is the NAO primarily located in the North Atlantic region (and surrounding rim) or is it really part of a more global hemispheric pattern? In the absence of any dynamical arguments, the pattern has always been isolated using descriptive statistical techniques such as correlation mapping or principal component analysis. These methods do not provide any definitive answer to what is the most "physically" correct pattern for the NAO. In some ways, the recent debate on NAO versus AO [see *Ambaum et al*., 2001] has similarities with the debate in the first half of the 20th century on Spearman's g factor (leading principal component) for intelligence. After much heated debate, Spearman finally conceded that neither his principal component nor the alternative rotated principal components provided a definitive factor for intelligence – the problem of intelligence had to be considered multidimensional [see *Gould*, 1981 for a very interesting account]. Despite the obvious temptation, we should avoid falling into a similar trap by remembering that other teleconnection patterns also need to be carefully considered in order to fully understand the many facets of climate variability.

A third recurrent theme of NAO research has been concerned with understanding underlying long-term climate trends. Despite being quite noisy from year to year, the NAO index has also exhibited substantial long-term trends (both up and down) in the past. These trends are the result of runs of similar sign in the NAO index. Various mechanistic explanations have been sought for these trends such as oceanic forcing, and more recently stratospheric forcing. However, the trends might also be stochastic trends resulting from natural variability containing long-range dependence [*Wunsch*, 1999; *Stephenson et al*., 2000]. In order to discriminate likely future trends in the NAO induced by anthropogenic effects, it is necessary that we understand the behaviour and causes of the natural long-term variations in the NAO. Longer time series from both climate model simulations and proxy reconstruction are likely to help enormously in this endeavour.

A fourth theme in NAO research has been the search for statistically significant periodicities. This is a particularly difficult exercise that is prone to error due to the presence of noise and trends in the NAO time series [see *Wunsch*, 1999 for some warning remarks]. Perhaps the most significant periodicity (if any) in the NAO is the quasi-biennial one remarked upon by *Walker* [1924] and reviewed in more detail in *Stephenson et al.* [2000]. *Coughlin and Tung* [2001] discuss the earlier QBO literature reviewed by *Stephenson et a.l* [2000] and present a reanalysis of this robust feature of the NAO. It should be remembered, however, that NAO is a broad band phenomena with an almost white noise power spectrum and so, unlike ENSO, individual periodicities will never account for large fractions of the total variance.

Perhaps the most challenging thread in NAO research relates to our ability to understand its underlying dynamical mechanisms. Although we can describe its features, we still have very little conceptual understanding of why this particular pattern emerges out of weather variations or how it evolves prognostically. Without a dynamical understanding of how it ticks, it is difficult to define the "mode" unambiguously and thereby assess its predictability. To make progress, it will be necessary to develop conceptual understanding of the key mechanisms controlling the evolution of the North Atlantic Oscillation as has been achieved spectacularly in recent decades for the Southern Oscillation.

Rather than being merely a recent bandwagon phenomenon, the history of the last few centuries shows that NAO research waxes and wanes but always seems to come back again. There is no doubt that in the future the complex NAO phenomenon will continue to attract the curiosity of scientists as it has repeatedly done so in the past.

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