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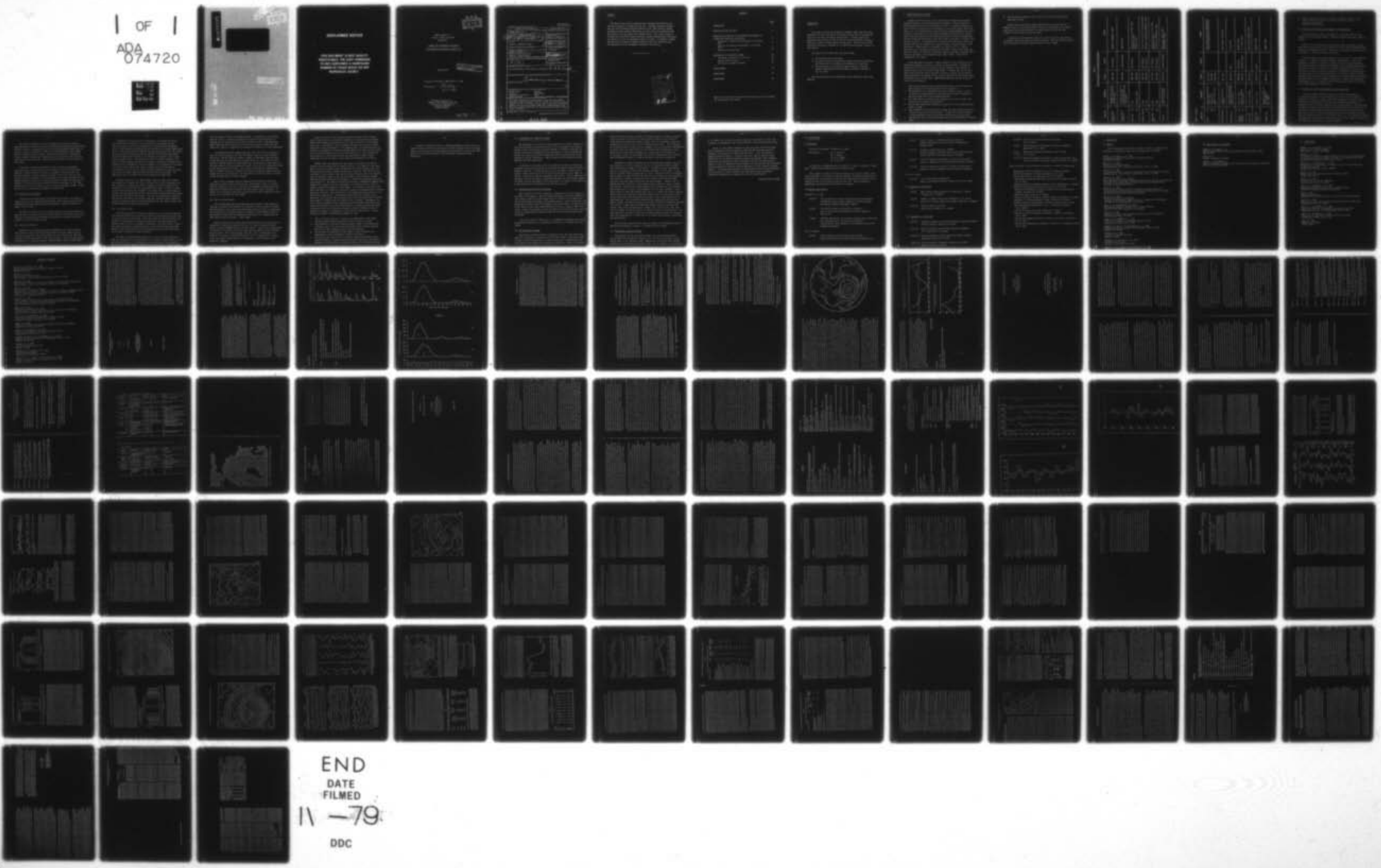

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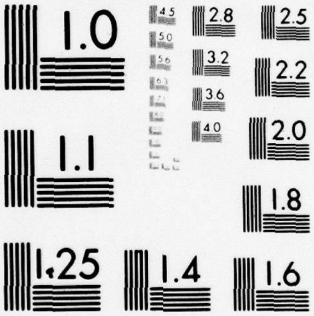

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A BASIS FOR FORECASTING THE ARCTIC SEA ICE OVER A FEW MONTHS TO MANY YEARS

January 1979

Principal Investigator: PROFESSOR H. H. LAMB

Co-ordinator: ....P. M. Kelly.........
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This report summarises research peformed under contract N00014-77-G-0074 during the period 1 Oct 77 - 31 Dec 78. Research topics include: (i) the collection of Arctic Sea ice data,(ii) statistical analyses of sea ice and climatic data,(iii) investigation of the physical mechanism responsible for inter-annual and longer changes in sea ice extent.

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ABSTRACT

An 80-year set of sea-ice data has been collected and digitized, and work is in progress to verify this data set. Principal component analysis has been used to identify "typical" mean sea level (MSL) pressure anomaly patterns and their temporal variations, and these have been correlated with long series of sea ice indices for various regions. Time series analysis of these sea ice and MSL pressure data has revealed characteristic time scales of variation, as well as significant long-term trends. In addition, studies have been made of various mechanisms which may have been responsible for the fluctuations in the atmospheric circulation and sea ice.

ABSTRACT

CONTENTS

Reprints and preprints of publications originating from this project are included with this report.

INTRODUCTION

This report, for the period ending 31 December 1978, covers the major achievements of the first year of the project "A basis for forecasting the Arctic sea ice over a few months to many years." Primary results are summarized and reference is made to articles, either published or pending publication, wherein further details can be found. The activities of the Principal Investigator, Professor H. H. LAMB, are detailed when relevant to this project.

The project can be broken down into three stages:

1. The collection of sea ice data.
2. The identification of associations between the sea ice variations and fluctuations in climate and the atmospheric circulation.
3. The development of a predictive scheme, based on a thorough physical understanding of the processes involved in changes in sea ice extent.

The following report lists achievements during 1978 under these three headings.

1. COLLECTION OF SEA ICE DATA

A major task of the first year of this project has been the collection and digitization of sea ice data for the 20th century. This extension of existing collections of sea ice data back in time is a necessary prerequisite to any attempt to predict sea ice variations on time scales longer than a few years. Dr. J. E. WALSH (University of Illinois at Urbana-Champaign) has kindly provided a digitized data set for the period 1953-76 and the charts for the period 1901-56, published by the Danish Meteorological Institute (*Isfolderene*) have been digitized and gridded in the same format, resulting in a 76-year data set for the Arctic. The Danish data is currently being verified as there are obvious problems with reliability in certain regions, and particularly in the early years. These matters are discussed in a paper by Dr. P. M. KELLY, delivered at the "Workshop on Mapping and Archiving of Data on Snow Cover and Sea Ice", held at the WDC-A for Glaciology, Boulder, Colorado in November 1978, and to be published in *Glaciological Data*,5 (April 1979). A preprint is included with this report.

Since that paper was written, further evidence of the reliability of the Danish Meteorological Institute ice charts has been obtained. Although the statistical verification of the data is not yet complete, from comments by various authors, and in particular KOCH (1945), it appears that the ice limit that we have digitized can be considered relatively reliable in the Atlantic sector and much of the eastern Arctic, but that the data for the Pacific sector are unlikely to be of much value. KOCH (1945) summarises various sources of error in the ice charts:

1. The data were gathered rather indiscriminately and, in later years, the chart analysts had little experience of ice navigation.
2. The estimates of ice encountered near the ice edge or further into the ice belt were highly subjective, and there were certainly variations in the terminology used by the different observers.
3. The impression of ice severity was affected by the size of vessel, and particularly the height of observation.
4. The ice edge reported may have been a narrow belt of ice removed from the actual ice edge.
5. Fog, frequently occurring near the ice edge, may have caused difficulties in determining the position accurately. In addition, the determination of longitude before radio became widely available was prone to error, and detailed maps of the East Greenland coast were not available in earlier years.

6. The estimation procedures used in areas of little or no data may not have been reliable.

Despite these reservations, KOCH regards the data, at least for the Atlantic sector, as being sufficiently reliable to incorporate in his authoritative tract on the East Greenland ice, and we therefore feel that the reliability of the data will meet our needs.

In addition to the hemispheric data set, various series of sea ice data at locations around the Arctic have been collected. These are listed in Table I; full references to the data sources are given in KELLY (1979).

TABLE I

Sea-ice data for the northern hemisphere

LOCATION		PARAMETER	PERIOD	SEASON	SOURCE
Arctic Ocean (eastern)		Weighted total of ice in Greenland, Barents and Kara Seas.	1895-1924	April-August	BROOKS and QUENNEL (1928)
Arctic Ocean (eastern)		Index of ice severity in Greenland and Barents Sea and around Spitzbergen.	1897-1938	January-December	WALKER (1947)
Kara Sea	(a)	Area	1895-1915	April-August	State of the Ice in Arctic Seas: Supplement (1917)
	(b)	Severity index	1868-1946		NAZAROV (1947)
Barents Sea	(a)	Area	1895-1915	April-August	State of the Ice in Arctic Seas (1917)
	(b)	Area	1900-1960	April-August	MAKSIMOV, SMIRNOV and VOROB'EV (1964)
Greenland Sea	(a)	Area	1877-1915	April-August	State of the Ice in Arctic Seas: Supplement (1917)
	(b)	Area	1924-1968	April-August	KIRILOV and KHROMTSOVA (1972)
Iceland		Weeks per year with drift ice on coast	1600-1975	October-September	LAMB (1977), KOCH (1945), THORARINSSON (1956)

TABLE I (contd.)

LOCATION		PARAMETER	PERIOD	SEASON	SOURCE
Baltic	(a)	Date of final opening of Port Riga	1530-1958		LAMB (1977), BETIN and PREOBAZENSKY (1959), SPEERSCHNEIDER (1915, 1927)
	(b)	Maximum area	1720-1957		
	(c)	Number of days with ice	1763-1926		
West Greenland		Northward extent of "Storis"	1821-1939		KOCH (1945), LAMB (1977)
Newfoundland		Index based on maximum eastward and southward extent of ice	1920-1973	April	MILES (1974
Western Atlantic: icebergs	(a)	Severity index	1886-1939	March-July	WALKER (1947)
	(b)	Number of icebergs south of 48°N	1900-1976	September-August	U.S. Coast Guard
Baffin Bay		Date of clearing	1952-1974		KEEN (1977), DUNBAR (1972)
North Slope, Alaska		Severity index	1953-1976	Summer	BARNETT (1978)
Okhotsk Sea		Anomaly of drift ice period (days) at (a) Abashiri (b) Shana	1892-1945		SAWADA (1957)

II. ASSOCIATIONS BETWEEN SEA ICE VARIATIONS AND CHANGES IN CLIMATE AND ATMOSPHERIC CIRCULATION

2.1 Collection of climatic and atmospheric circulation data

The collection of climatic and atmospheric circulation data has been largely covered in previous reports. Two recent acquisitions deserve mention, however.

The first is a digitised set of MSL pressure data for January and July which extends back to 1750 and has been extracted from LAMB and JOHNSON (1966) by the U.K. Meteorological Office. These data will provide a valuable check on our analyses of the 106-year MSL pressure data.

The second data set has been produced by Dr. P. M. KELLY in collaboration with Dr. P. D. JONES (Data Manager, Climatic Research Unit). Station air temperature records at a variety of locations over the northern hemisphere have been extracted from *World Weather Records*, and interpolated onto the grid used in the analyses of atmospheric circulation data detailed in Section 2. This data set provides the best estimate of air temperature fluctuations over the land masses of the northern hemisphere as the gridding reduces problems stemming from the varying spatial concentration of station data and, through the averaging inherent in the interpolation procedure, reduces the influence of observational error. An account of the derivation and analysis of this data set is being prepared for publication.

2.2 Analysis of climatic and atmospheric circulation data

In order to obtain objective measures of climatic and atmospheric circulation variability for correlation with the sea ice data, principal component or eigenvector analysis (PCA) has been applied to sets of northern hemisphere data (MSL pressure, 500 mb height, 1000-500 mb thickness, air temperature, and sea surface temperature for various regions). PCA can be used to identify "typical" spatial patterns of anomalies, and the time series of the coefficients of these patterns which give a measure of the strength of the particular pattern in every year/season provide a set of parameters covering the most important variations in the spatial data sets. This method has distinct advantages over the alternate method of selecting various indices of climate and the atmospheric circulation on "a priori" grounds.

The analyses completed so far have completely borne out the value of this approach and the major results are currently being prepared for publication. Selective results are described in the article "Forecasting the Arctic sea ice on time scales of a few months to many years" (*Climate Monitor*, 7(3), 1978), which is included with this report. Of particular interest is the presence in the principal components of fluctuations on identical time scales to those identified in the sea ice data. These points are covered in later sections of this report.

In addition to these basic analyses of the climatic and atmospheric circulation data, various indices of the strength of the circumpolar vortex, blocking in the North Atlantic sector, the frequency of extremes over the northern hemisphere and the frequency of weather types of the British Isles and Europe have been analysed. An investigation of the Lamb catalogue of daily weather types has resulted in an interesting parallel between the behaviour of atmospheric circulation during the 1970s and the extreme decade of the 1780s, which may be of value in attempts to forecast by the 'analogue' method. A paper on this work is currently being prepared for publication.

2.3 Analysis of sea ice data

In order that the digitization of the major sea ice data set should not delay analysis of sea ice/climate correlations, various long series of sea ice information at various locations have been obtained. These are detailed in Table 1 of this report.

The major fluctuations evident in these data have been identified and the data have been correlated with the principal components of the MSL pressure data. This work is currently being prepared for publication; the major results are summarised in the following sections:

(a) Long-term variations:

Studies of sea ice extent and other oceanographic anc climatic characteristics of the north-east Atlantic have shown that great changes occurred between the so-called Little Ice Age (which was most severe in the late 17th century) and the early decades of the present century. Two recent publications by Professor H. H. Lamb are relevant: LAMB and MÖRTH (1978) and LAMB (1979).

The 80-year sea ice data set is being used to investigate the large-scale and long-term changes in sea ice extent over the present century, and certain long series of sea ice extent for locations around the Eastern Arctic are being used to provide additional information for the pre-1900 period. As far as the causes of these long-term fluctuations are concerned, the results of the correlations between the sea ice data and the MSL pressure principal components suggests that changes in the strength and position of the Iceland Low are a prime factor. The fluctuations in sea ice extent probably do not occur in direct response, however, but through the complicated response of the atmospheric and oceanographic climate to changes in the atmospheric circulation. In order to throw light on this point a detailed study is being made of fluctuations in sea ice extent, climate and the atmospheric circulation during the period since 1945, when relatively plentiful data are available. An exploratory study is complete and is being prepared for publication.

Previous work by Dr. P. M. KELLY (KELLY, 1977) has shown that a strong correlation exists between the level of volcanic dust in the stratosphere and the frequency of south-westerly winds at London (an indirect measure of the strength of the Iceland Low) over the period 1675 to date. In order to obtain a more direct measure of the strength of the Iceland Low, principal component analysis has been applied to the set of North Atlantic pressure data for January and July over the period 1750 to date. This work has confirmed the long-term fluctuations identified in the earlier study and, although further research is essential, provides evidence of a causal mechanism for the recovery from Little Ice Age conditions during the 19th century.

(b) 7- to 8-year cycle:

Spectral analyses of the time series employed in this study have revealed two strong and statistically significant spectral peaks which occur selectively in various parameters and regions. While such peaks are often considered to be evidence for quasi-regular sinusoidal fluctuations in the data series, our research shows that this is a premature conclusion. The term "cycle" is used in this report to describe a physical process in the climatic system which goes through a well-defined evolution with a characteristic time scale, but which is not necessarily repeated at regular intervals.

This point is clearly demonstrated by our research into the causes of a peak at 7 to 8 years in the power spectrum of a record of iceberg counts for the western North Atlantic. This fluctuation is also evident in the strength of the Iceland Low, and a physical reason for this co-variation is readily apparent will have a direct effect on iceberg advection. As discussed in the previous section, there is a striking correlation on longer time scales between the strength of the Iceland Low and the amount of volcanic dust in the atmosphere. KELLY (1977) has shown that there is a 7- to 8-year cycle in LAMB's Dust Veil Index (DVI), which is a measure of the amount of volcanic dust in the stratosphere.

In formulating the DVI, LAMB assumes that, after the initial injection of dust into the stratosphere, the dust load decays linearly over the following four years. The DVI therefore contains a number of superposed ramp functions; a ramp function takes the shape of a reversed shark fin. By a series of simulations of the DVI, based on random numbers but incorporating a linear decay, it has been found that this formulation will give rise to the 7- to 8-year peak found in the power spectrum of the DVI. This does not invalidate the importance of the 7- to 8-year cycle as an indicator of correlations between volcanic activity, climate and sea ice fluctuations, but shows that its predictive value is limited to the few years after a volcanic eruption.

Work is now in progress aimed at identifying the effects of particular eruptions on climate, and in clarifying the relationship of this 7- to 8-year cycle to a process on a similar time scale, which BRYSON and STARR (1977) have proposed as an explanation of much of the inter-annual climatic variance. A report on the stochastic experiment described above has been submitted for publication, and is included with this report.

(c) The 4- to 5-year cycle:

"It is a well-known fact that every four or five years a large number of 'icebergs', floating from Greenland, are stranded on the west coast of Iceland. The inhabitants are then aware that their crops of hay will fail, in consequence of the fogs which are generated almost incessantly; and the dearth of food is not confined to land, for the temperature of the water is so changed that the fish entirely desert the coast." LYELL (1872)

Spectral analysis of the three century-long record of ice on the coasts of Iceland has confirmed the existence of the 4- to 5-year fluctuation briefly referred to by SIR CHARLES LYELL in the last century. This cycle is also present in records of ice extent in the Arctic seas north of Iceland, and off the North Slope of Alaska. Our findings suggest that this cycle is, once again, not evidence of a regular sinusoidal fluctuation, but is a signature of a process within the climate system which has a characteristic time scale but is not necessarily repeated.

Using the results of the principal component analyses of MSL pressure and air temperature over the northern hemisphere and previous work by DICKSON (1971) which documents the presence of this cycle in salinity in the European shelf seas, a climatology of this fluctuation has been built up, and a causal mechanism is being investigated. It is suggested that this fluctuation has its origin in an atmospheric circulation-induced change in the ocean current systems of the north-east Atlantic and seas of the eastern Arctic. Once established, this alteration in the current systems, and concomitant changes in ocean temperature and sea ice extent, in turn affect the atmospheric circulation.

DICKSON (1971) has proposed that this cycle is initiated by periods of enhanced southerly winds over the eastern Atlantic. This anomaly in the atmospheric circulation produces increased advection of oceanic Atlantic water into the European shelf areas, thereby altering their salinity. The effects of the increased influx of Atlantic water can be traced northwards, and it is suggested that this produces changes in the sea ice boundary, either directly through altering the ocean temperature distribution, or indirectly by changing the ocean current patterns. The numerical modelling experiments of HERMAN and JOHNSON (1978) suggest that a change in the sea ice boundary in the Barents Sea will have an effect on depression frequency in that region. In particular, they note in the model experiments a tendency for reduced ice extent to be accompanied by increased depression frequency. This association is also suggested by our analysis of the MSL pressure eigenvectors. The component representing the strength of the depression track running from the Iceland Low up into the eastern Arctic contains the strong 4- to 5-year cycle, also found in sea ice extent. Furthermore, the first principal component of air temperature over the northern hemisphere landmasses also contains this cycle and this pattern: a contrast between the temperature deviations over the eastern and western northern hemisphere would be produced by changes in the depression track into the eastern Arctic. We are therefore currently investigating the hypothesis that:

1. The 4- to 5-year cycle has its origin in an enhancement of the middle-latitude eastern Atlantic southerlies, which may occur at random.
2. This atmospheric circulation anomaly produces changes in the penetration of Atlantic water into the seas of the eastern Arctic, thereby altering the sea ice, ocean temperature and current distribution.
3. The frequency of depressions in this region is then altered by the oceanographic change, and perhaps reinforces the latter.
4. This process has a chacteristic time scale, probably determined by the positive feedback in stage 3 and the differential heating of the northern hemisphere resulting from the intensified Eastern Arctic depression track.

It must be stressed that this is a working hypothesis, and has yet to be fully verified. The initial verification of LYELL's account of a 4- to 5-year cycle on the Iceland ice is being prepared for publication, and this will form the first of a series of papers on the climatology and causes of this periodicity.

III. DEVELOPMENT OF A PREDICTIVE SCHEME

The development of a predictive scheme specifically oriented towards sea-ice variations awaits the completion of the first two stages of this project. We have however initiated two reviews of methods of climate forecasting: one concerns the general methodology of existing methods of climate forecasting, and the other concerns forecasting techniques that have been applied to the problems of sea-ice fluctuations. These reviews should be complete by March 1979 and June 1979 respectively.

In addition to the research into the causes of the sea-ice fluctuations discussed in the previous sections, a review of the general causes of climatic change is under way. Arising from this review, two papers - concerning the possible almost-intransitivity of the Sun and the problem of man's impact on climate - have been written and accepted for publication. A paper completed in the early stages of the project, concerning the causes of the European drought of 1975/6, has been published, and the conclusions are relevant to the question of the feasibility of the prediction of the Arctic sea ice.

3.1 The almost-intransitivity of the Sun

Solar variability has been invoked as a mechanism for climatic change on a variety of time scales. The most convincing arguments have been proposed for time scales of about 10^2 to 10^4 years, which are relevant to the longer-term sea-ice fluctuations discussed in the previous section. These correlations are supported by historical and ^{14}C evidence of solar and climatic variability, and by the absence of any other viable mechanism of climatic change on these time scales. Despite the evidence of solar variability on these time scales, there is as yet no accepted physical process within the Sun which could produce these variations.

In a recent letter to *Nature*, Dr. R. K. TAVAKOL has suggested that the Sun may be almost-intransitive. A preprint of this article is included with this report.

3.2 CO_2 and climatic change

Any attempt to predict climatic fluctuations must take into account the potential interference of Mankind with the climate system. There are a number of ways in which this could occur, either deliberately or inadvertently, but the so-called "CO_2 problem" has received most attention. Whereas in the past

Mankind has been a passive recipient of the consequences of climatic variation, we are now actively involved in a unique climatic experiment, by returning large amounts of concentrated organic carbon, stored in sedimentary rocks over hundreds of millions of years, into the atmosphere and oceans. This injection of increasing amounts of CO_2 into the atmosphere due to our escalating consumption of fossil fuels, and interference with the biosphere by deforestation, could have severe climate-induced consequences, in particular on food supplies. It is therefore a matter of some concern that reliable estimates of the effects of such anthropogenic factors on climate, and hence on Society, be obtained.

Although the scientific problem can be formulated simply enough - how will the injection of a certain amount of CO_2 into the atmosphere affect climate? - its solution poses a number of difficulties. In order to answer the question fully, it is necessary to have more complete knowledge in three areas. First, the future global energy strategy and the rate of interference with the biosphere must be known, as these determine the amount of CO_2 released into the atmosphere. This problem is complex, involving not only a number of alternative energy scenarios, but also a mesh of political and socio-economic factors; not to mention possible alterations to the energy strategy imposed by future climatic fluctuations. Second, given a known amount of CO_2 released into the atmosphere, what proportion will reside in the atmosphere over the coming decades? Third, given a known resident CO_2 concentration, how will it affect the climatic system? Unfortunately, our knowledge of the global carbon cycle and the climate system is not sufficiently well-established to provide a clear, unambiguous answer to these questions, and to the basic problem of how projected CO_2 increases will affect climate. No clear prediction can be made; only order-of-magnitude estimates can be given. A great deal of research does however point to very grave and perhaps irreversible consequences on a global scale, occurring not later than the first decade of the next century, if remedial action is not taken soon. The "CO_2 problem" is the direct result of our technological evolution, for which we must take responsibility. A first step is to clarify the scientific certainties and uncertainties.

A brief review article on this topic will appear in a forthcoming issue of *Chemistry and Industry*; a preprint is included with this report.

3.3 The European drought of 1975/6

The occurrence of the most severe drought on record in Western Europe during 1975/6 has received much attention and, with the severe winters in the United States in the subsequent years, added weight to the claim that climatic variability has increased during recent times. Dr. P. M. KELLY, in collaboration

P. B. WRIGHT, has reviewed the possible causes of the drought of 1975/6 from a synoptic climatological angle. The review came to the following conclusions:

> *"First...if the climatic anomalies of the early 1970s did set the scene for the drought of 1975/6 by producing a distribution of thermal anomalies conducive to blocking in the North Atlantic sector, ...then this implies a limited forecasting ability. Limited in the sense that the precise timing and location of the blocking situation could not be forecast, but a tendency towards the establishment of such a situation could have been anticipated... Second, we note the importance of the synthesis of the empirical and theoretical, and particularly the numerical modelling approaches to the problem of climatic change... A problem underlying many of the hypotheses that have been discussed in this article is that of defining cause and effect between potentially interactive components of a system such as the ocean-atmosphere."*

KELLY and WRIGHT (1978)

IV MISCELLANEOUS

4.1 Personnel

Principal Investigator:	Professor H. H. Lamb
Assisted by:	Dr. P. M. Kelly Mr. A. Chance Dr. R. K. Tavakol Mr. C. B. Sear

In addition, we acknowledge the assistance of L. Shaw, S. Johnson, B. Cherry and J. Sadler with the digitization of the sea-ice data.

Arthur Chance is leaving the Climatic Research Unit in April 1979 to take up an appointment in the School of Computing Studies and Accountancy (University of East Anglia), and we would like to take this opportunity to thank him for his invaluable work on this project during the past year. We also gratefully acknowledge the secretarial help of Miss R. A. Wallace.

4.2 Lectures and Seminars

Professor H. H. Lamb:

24.4.78	"The variability of climate: observation and understanding" Introductory lecture, Nordic Symposium on Climatic Change and Related Problems; Copenhagen, Denmark.
6.6.78	"The Little Ice Age in the North-East Atlantic" Lecture, Institute of Oceanographic Sciences; Godalming, Surrey, U.K.
7.9.78	"Climatic fluctuations in historical times and their connections with transgressions of the sea and storm-floods" Invited lecture, Ghent Symposium of the Belgisch Centrum voor Landelijk Geschiednis.

Dr. P. M. Kelly:

6.4.78	"Solar influence on North Atlantic MSL pressure" Royal Astronomical Society (MIST) meeting; Southampton, U.K.

26.7.78	"Solar influence on North Atlantic MSL pressure" Symposium/Workshop on Solar-Terrestrial relationships; Columbus, Ohio.
3.11.78	"An Arctic sea-ice data set: 1901-56" Workshop on Mapping and Archiving of Data on Snow Cover and Sea-Ice; WDC-A for Glaciology, Boulder, Colorado.
6.11.78	"Climatic change and variations in Arctic sea-ice extent" Seminar at Laboratory of Tree-Ring Research; Tucson, Arizona.
15.11.78	"Climatic change and variations in Arctic sea-ice extent" Seminar at Naval Postgraduate School, Monterey, California.

Dr. R. K. Tavakol:

23.11.78	"Is the Sun almost-intransitive?" Royal Society Meeting on Solar Variability and ^{14}C; London.

4.3 Organisation of Meetings

14.5.78	Royal Society, meeting with Drs. W. Libby and L. Libby on ^{14}C impact (R. K. Tavakol)
12.6.78	"Models of global carbon cycle and wiggles in ^{14}C record" With Dr. H. E. Suess, Queen Mary College, London (R. K. Tavakol)
23.11.78	"Solar variability and ^{14}C" Royal Society, London (R. K. Tavakol)

4.4 Attendance at Conferences

28.10.77	"Scientific aspects of the 1975/76 drought in England and Wales" The Royal Society, London (P. M. Kelly)
6-7.4.78	Royal Astronomical Society (MIST) meeting; Southampton (P. M. Kelly and R. K. Tavakol)
24-28.7.78	Nordic Symposium on Climatic Change and Related Problems; Copenhagen, Denmark (H. H. Lamb)
24-28.7.78	"Solar-Terrestrial Influences on Weather and Climate" Columbus, Ohio (P. M. Kelly)

5-7.9.78	British Isles Tree-Ring Colloquium; London (R. K. Tavakol)
7.9.78	Ghent Symposium of the Belgisch Centrum voor Landelijk Geschiednis (H. H. Lamb)
31.10 - 1.11.78	NOAA Climate Diagnostics Workshop, Miami, Florida (P. M. Kelly)
2-3.11.78	Workshop of Mapping and Archiving of Data on Snow Cover and Sea-Ice; WDC-A for Glaciology, Boulder, Colorado (P. M. Kelly)

Visits were made to the following institutions for scientific consultation:

Meteorological Office, Bracknell, U.K. (P. M. Kelly, A. Chance)
Danish Meteorological Institute, Copenhagen (H. H. Lamb)
British Antarctic Survey, Cambridge, U.K. (P. M. Kelly)
Lamont-Doherty Geological Observatory, University of Columbia, New York (P. M. Kelly)
National Oceanic and Atmospheric Administration, Washington (P. M. Kelly)
Office of Naval Research, Arlington, Virginia (P. M. Kelly)
Institute of Environmental Studies, and Center for Climatic Research, Madison, Wisconsin (P. M. Kelly)
Imperial College, London (R. K. Tavakol)
Institute for Arctic and Alpine Research, Boulder, Colorado (P. M. Kelly)
Laboratory of Tree-Ring Research, Tucson, Arizona (P. M. Kelly)
Scripps Institute of Oceanography, La Jolla, California (P. M. Kelly)
Naval Postgraduate School and F. W. N. C., Monterey, California (P. M. Kelly)
Ministry of Defence, Bonn, West Germany (H. H. Lamb)
Institute for Forestry Research, Birmensdorf, (Zurich), Switzerland (H. H. Lamb)
Institute for Geography and Physics, University of Berne, Switzerland (H. H. Lamb)
Institute for Meteorology and Geophysics, University of Innsbruck, Austria (H. H. Lamb)

V. PUBLICATIONS

5.1 Current

The following papers are either published, in press or submitted for publication. Reprints or preprints are included with this report.

CHANCE, A. and KELLY, P. M., 1979
An apparent periodicity in an index of volcanic activity.
Submitted to *Nature*

KELLY, P. M., 1977
Volcanic activity and climate.
Climate Monitor, 6(2), Climatic Research Unit, Ed. P. D. Jones

KELLY, P. M., 1978
Forecasting the Arctic sea ice on time scales of a few months to many years
Climate Monitor, 7(3), Climatic Research Unit, Ed. P. D. Jones

KELLY, P. M., 1979
An Arctic sea-ice data set: 1901-56
Paper delivered at workshop, "Mapping and Archiving of Data on Snow Cover and Sea-Ice", WDC-A for Glaciology, Boulder, Colorado, 2-3 November 1978.
To appear in *Glaciological Data, 5.*

KELLY, P. M., 1979
Solar influence on North Atlantic MSL pressure (Extended abstract)
In *Solar-Terrestrial Influences on Weather and Climate,* Ed. B. M. McCormac and T. A. Seliga; D. Reidl, Dordrecht, Holland

KELLY, P. M., 1979
Historical perspectives and trends
In *Atlas of the Drought of 1975/76,* Ed. K. G. Gregory and J. Doornkamp, Institute of British Geographers, (in press).

KELLY, P. M. and WRIGHT, P. B., 1978
The European drought of 1975/76 and its climatic context.
Progress in Physical Geography, 2(2), 237-263

LAMB, H. H., 1979
Studies of climate, wind and ocean currents over the last 1000 years.
Quaternary Research, (in press)

LAMB, H. H. and MÖRTH, H. T., 1978
Arctic ice, atmospheric circulation and world climate.
Geographical Journal, 144(1), 1-22

NICHOLS, H., KELLY, P. M. and ANDREWS, J. T., 1978
Holocene palaeo-wind evidence from palynology in Baffin Island.
Nature, 273, 140-142

TAVAKOL, R. K., 1978
Is the Sun almost-intransitive?
Nature, 276, 802

TAVAKOL, R. K. and KELLY, P. M., 1979
CO_2 and climatic changes.
Chemistry and Industry, (in press)

WIGLEY, T. M. L., GRAY, B. M. and KELLY, P. M., 1978
Climatic interpretation of $\delta^{18}O$ and δD in tree rings.

5.2 Manuscripts in Preparation

JONES, P.D. and KELLY, P. M.
An eigenvector analysis of the Lamb catalogue of daily weather types: 1861 to 1978

KELLY, P. M.
Climate forecasting in Europe.

KELLY, P. M. and CHANCE, A.
Spatial and temporal characteristics of mean sea level pressure fluctuations over the northern hemisphere.

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HERMAN, G. F. and JOHNSON, W. T., 1978
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Progress in Physical Geography, 2(2), 237-263

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Geographical Journal, 144(1), 1-22

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CURRENT PUBLICATIONS

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CO_2 and climatic changes.
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WIGLEY, T. M. L., GRAY, B. M. and KELLY, P. M., 1978
Climatic interpretation of $\delta^{18}O$ and δD in tree rings.
Nature, 271, 92-94

AN APPARENT PERIODICITY IN AN INDEX OF VOLCANIC ACTIVITY

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March 1979

Unpublished Manuscript

We demonstrate in this paper, by means of a stochastic simulation of LAMB's Dust Veil Index[1,2] (DVI), that statistically significant peaks in the variance spectrum of geophysical or climatic data are not necessarily evidence of regular, or even quasi-regular, oscillations. The DVI is an annual measure of the amount of volcanic dust in the stratosphere, based on a variety of information, for the period 1500 to date. KELLY[3] has noted the significant correlation of the DVI with various aspects of climatic change in the North Atlantic European sector on time scales of 50 years and more, and has shown that the variance spectrum of the DVI contains a statistically significant peak at 7 to 8 years. This peak is also present in the spectra of certain climatic and atmospheric circulation parameters. KELLY has suggested that this apparent periodicity in stratospheric dust content is more likely to be due to the chance occurrence of volcanic eruptions at 7 to 8 year intervals during the limited period of record, rather than to a forced, regular cycle in volcanic activity. We now propose an alternate explanation: that the formulation of the DVI produces the spectral peak.

In his formulation of the DVI, LAMB assumes, unless there is evidence to the contrary, that after an explosive volcanic eruption the dust remains in the stratosphere in sufficient quantities to affect the radiation received at the Earth's surface, and hence climate, for four years, and that the dust amount decays linearly over that time. This assessment is largely based on the observed radiation deficits following the major eruptions of the last 100 years and on the limited number of direct observations of the stratospheric dust load made in recent decades. Most studies of stratospheric dust loading due to volcanic activity assume an exponential, not linear, decay of the original dust injection with a relaxation time of about one year.[4] The linear decay approximates the period of most rapid fall-off of the exponential decay, integrated in yearly steps. Our results are *not* however valid for the case of an exponential decay, and the applicability of the general statistical point made in this paper to the question of associations between volcanic activity and climate will be discussed elsewhere. The characteristic signature of a single eruption, as it appears in the DVI, is a decaying *ramp* function, and the *complete* DVI record has an *irregularly* spaced saw-toothed and at times cyclical appearance due to the superposition of many such events, (Fig. 1a; the isolated eruptions about 1860 show the ramp formulation clearly).

Our hypothesis is that this formulation alone will produce a peak in the variance spectrum of the DVI at about 8 years: twice the length of the ramp function. A stochastic simulation technique was employed in order to test this hypothesis. Two parameters were allowed to vary in the stochastic simulations:

the probability of an eruption within a particular year, and the ramp length. Simulated DVI records for a realistic range of values of the two parameters were produced by a computer program using a random number generating routine. If the random number (in the range 0.0 to 1.0) assigned to a particular year was less than or equal to the eruption probability, an 'eruption' took place with a strength given by a second exponentially-distributed random number. This distribution approximates to that of the actual DVI. This simulated dust-load was then linearly decayed over a period of years: the ramp length. The length of the simulated records was 117 years in order to facilitate comparison with the spectral analysis of the actual DVI given by KELLY.[3] For each parameter pair, 1000 records of length 117 years were generated, the variance spectrum of each record was calculated, and a count was made of the number of peaks that were significant at the 5% level in each frequency band. The spectra were calculated using a Fast Fourier Transform algorithm, the spectral estimates were smoothed, and a white or red noise null continuum was assumed in a significance testing depending on whether or not the lag one autocorrelation coefficient departed significantly from zero.

It was found that varying the eruption probability over a wide range (0.1 to 0.9) produced little change in the resulting histograms (Fig. 2). This implies that a degree of superposition of the ramp functions does not obscure the spectral signal with a ramp of a few years' length. The following discussion is therefore restricted to the case of an eruption probability of 0.3, corresponding to that of the actual DVI. (While this value is representative of the most reliable portion of the DVI record from 1800 to date, the eruption probability does in fact vary widely). The resulting histograms for ramp lengths of 4 and 6 years are shown in Fig. 3. The case of zero ramp length, i.e. randomly distributed eruptions with zero decay time, is also shown as a control. It is clear that, as hypothesised, a spectral peak occurs at a period of twice the length of the ramp function. Note that the odd harmonics of twice the length of the ramp function also appear in the histograms. With no ramp the histogram is smooth, as expected from a large sample of white noise spectra.

Two conclusions are drawn from this analysis. First, the 7 to 8 year peak in the variance spectrum of the DVI is not necessarily evidence of a regular, predictable cycle in volcanic activity. It arises from the formulation of the DVI and indicates the existence of ramp functions of length 4 years in the data. A 7 to 8 year cycle will not necessarily appear in the DVI when filtered, as the DVI is a summation of such ramp functions with random phase. This does not however detract from the value of the 7 to 8 year spectral peak as a statistical characteristic of the DVI. It is the interpretation of this signal that is under

discussion, not its reality, and it can still be validly used for comparison with climatic data. The question of whether or not the linear decay is a realistic approximation to the fall-out of stratospheric dust does however warrant further investigation. Secondly, we note that if there is a mechanism within the climate system which has the decay characteristic of a ramp function, for example ocean-atmosphere interaction, then this could give rise to a spectral peak which may be misinterpreted as evidence of a regular climatic cycle.

We acknowledge useful discussions with Ms. B. M. Gray and Dr. T. M. L. Wigley (Climatic Research Unit) and Dr. G. J. Janacek (University of East Anglia), and the original suggestion of Dr. T. H. Tarling (University of Newcastle-upon-Tyne) which prompted this analysis.

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   Nature, 268, 616-617, (1977)

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   Journal Appl. Met., 15, 933-950, (1976)

FIGURE CAPTIONS

Fig. 1 (a) LAMB's Dust Veil Index: 1800 to 1976.[1,2]

(b) Stochastic simulation of the Dust Veil Index.

Fig. 2 Count of number of significant peaks per frequency band in the spectra of 1,000 simulations with ramp length of 4 years and eruption probabilities of:

(a) 0.9

(b) 0.1

Arrows indicate hypothesized location of spectral peaks.

Fig. 3 Count of number of significant peaks per frequency band in the spectra of 1,000 simulations with an eruption probability of 0.3 and ramp lengths of:

(a) 6 years

(b) 4 years

(c) 0 years

Arrows indicate hypothesized location of spectral peaks.

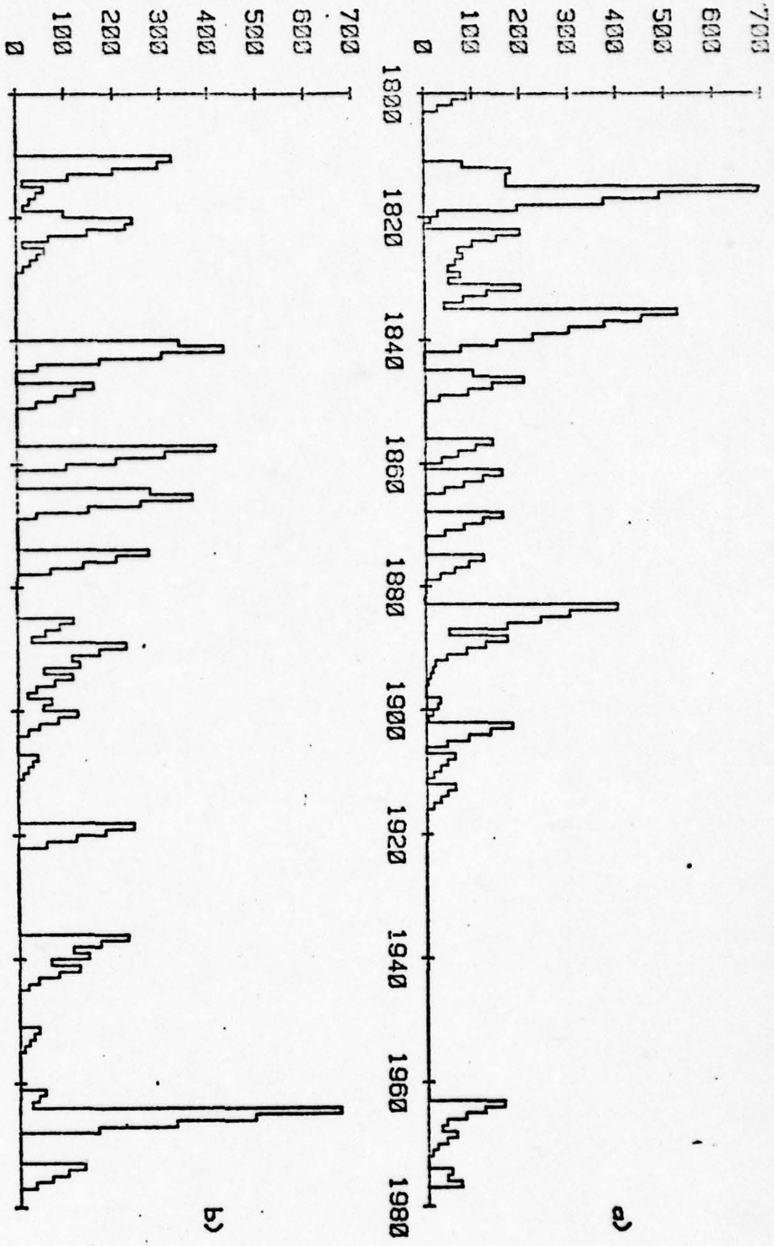


FIGURE 2

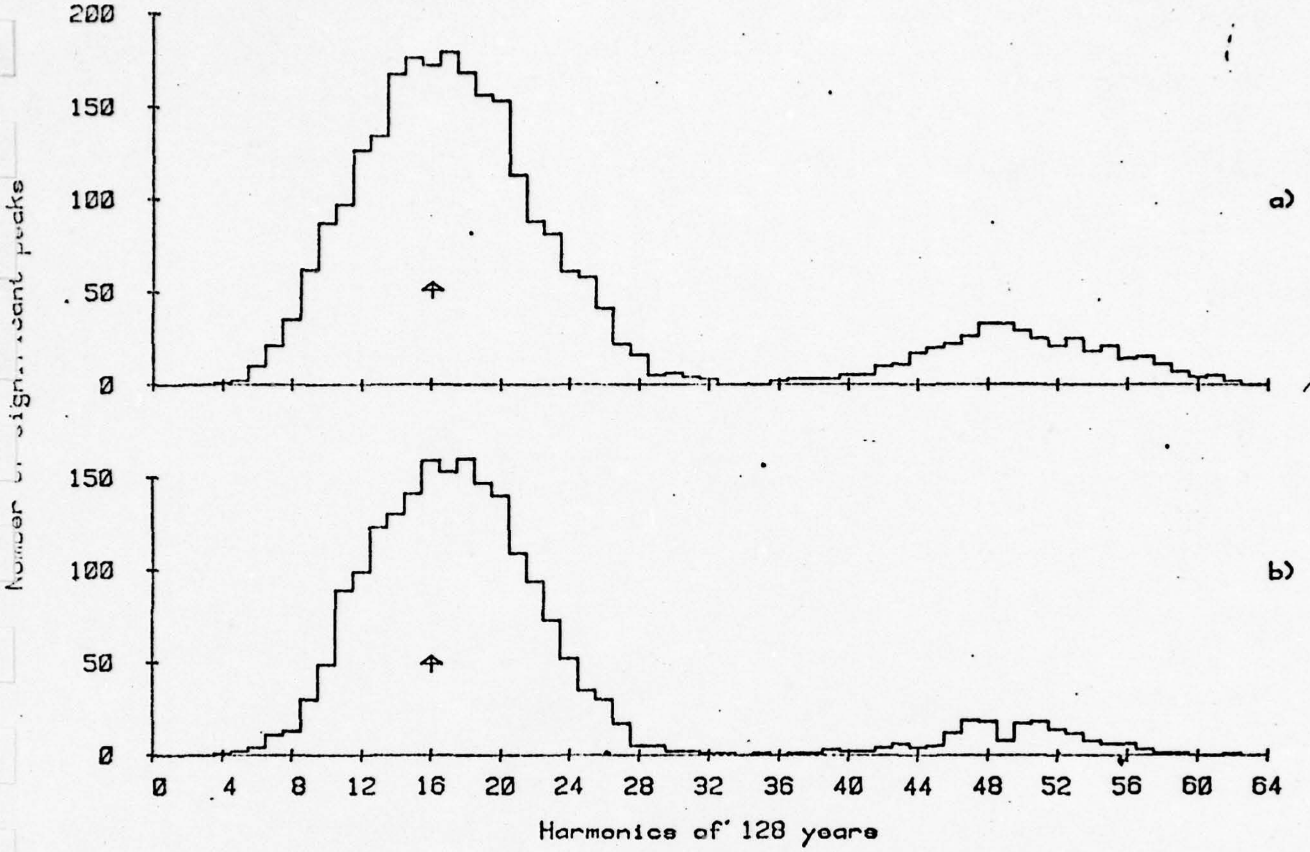
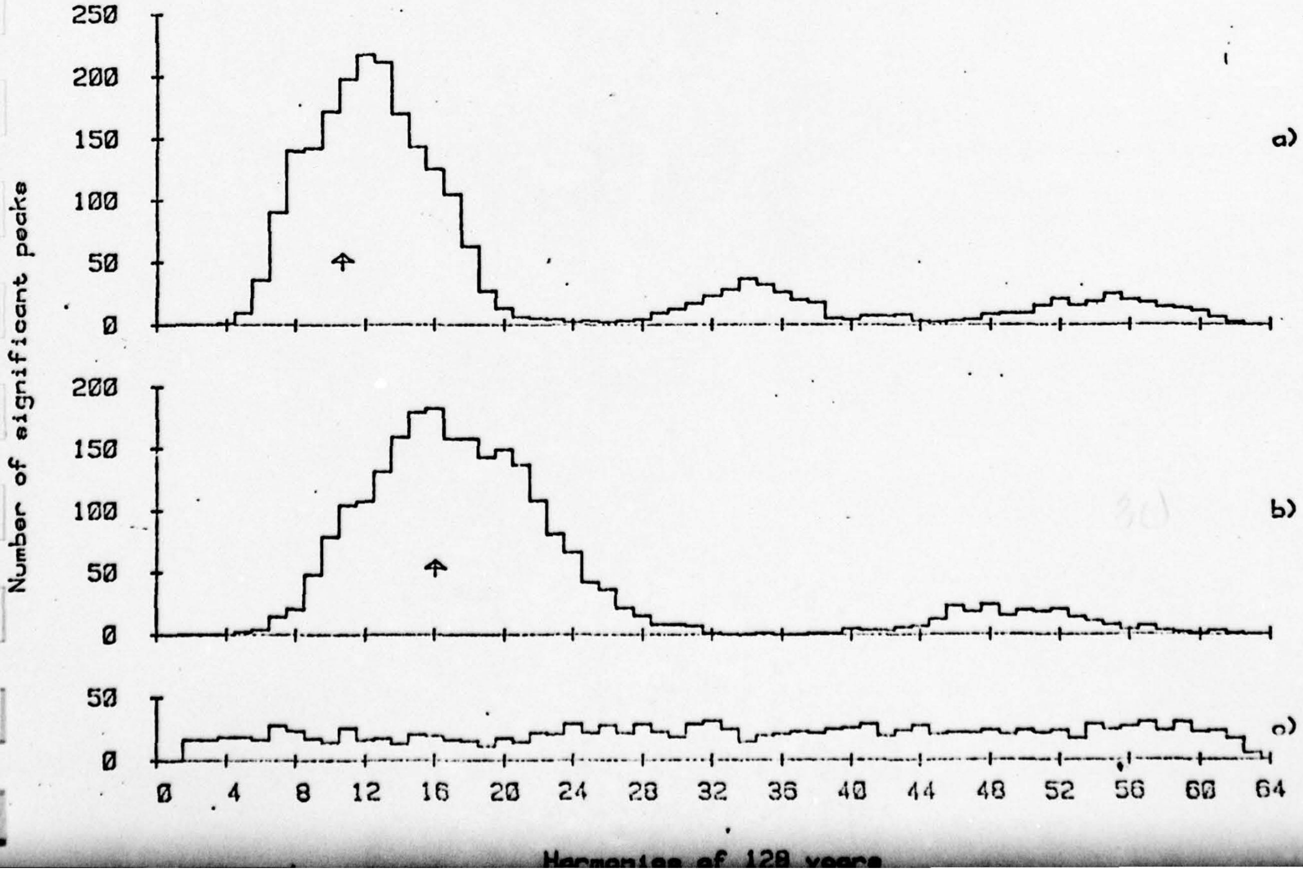


FIGURE 3



Volcanic Activity and Climate

The dust thrown into the high atmosphere during explosive volcanic eruptions has long been regarded as a possible cause of climatic change. In the late 18th century, Benjamin Franklin proposed that the severe winters of 1783-84 and 1784-85 were due to the eruption of the Icelandic volcano Hekla during 1783. Every major volcanic eruption since that time has stimulated interest in the hypothesis. During the early years of the present century, changes in solar radiation receipt at the earth's surface were noticed after the Katmai eruption. HUMPHREYS (1940) devoted much time to theoretical and empirical studies of the effects of volcanic activity on climate. The concentration on short term weather forecasting in the atmospheric sciences during the first half of the 20th century led to some neglect of the topic but in recent years revived interest has been shown. This can be partially attributed to the ever increasing demand for long term climatic forecasts for which greater understanding of the mechanisms of climatic change is essential. The renewal of widespread volcanic activity during the 1960s, following a remarkable lull during early decades of the 20th century (Fig. 1), and the development of new techniques for the study of volcanic emissions have also played a part.

When dust is thrown into the stratosphere by explosive volcanic eruptions it can persist for several years and cause notable optical effects. Dust veils often produce a brilliant red coloured glow which lingers near the horizon for some time after sunset. A blue sun or moon is often observed through a veil and a corona (Bishop's Ring) sometimes surrounds the sun. The dust spreads from the point of injection and gradually accumulates in polar regions under the action of the stratospheric wind system. The extent and development of the dust veil is dependent on the latitude of injection and also on the state of the stratospheric circulation High latitude eruptions tend to produce veils that are limited to polar regions whereas low latitude eruptions may result in hemispheric or global veils. The amount of solar energy reaching the earth's surface is depleted by back scattering and absorption in the dust layer and the earth's albedo is affected. The magnitude of these effects is, however, open to question. Although the response of the atmospheric circulation to changes in the energy budget caused by volcanic dust veils is not fully known, it is argued that the interception of solar energy in the stratospheric dust layers should lead to weakening of the flow in the troposphere as less energy reaches the earth's surface where it is available to drive the atmospheric circulation. Climatic variations can arise directly due to changes in the energy budget or indirectly as the atmospheric circulation is altered.

In order to provide the physical understanding of the causes of climatic change that is a necessary prerequisite to reliable climate forecasting, the Climatic Research Unit is engaged in assessing the importance of varying volcanic activity as a climatic control. Professor H. H. Lamb continues to update the volcanic dust veil index (DVI); data for recent years are given in this issue of CLIMATE MONITOR. Dr. P. M. Kelly is attempting to link the variations in the DVI to those shown by climatic data. As a preliminary stage to this analysis, time series analysis has been applied to the DVI and various characteristics of its variation noted and compared with those shown by various climatic data series. For example, 7 or 8 years appears to be a characteristic interval, perhaps arising by chance, between volcanic eruptions during the last few centuries and many climatic parameters in the North Atlantic sector show a similar variation. There is strong correlation between variations in the DVI, central England winter temperature and the frequency of southwesterly surface winds at London on time scales of 50 years and more over the last three centuries. The most notable features of these variations are the low levels of stratospheric dust and the corresponding periods of relative warmth and high frequency of southwesterly winds during the early 16th, 18th and 20th centuries.

Mean sea level pressure data for the northern hemisphere are being analysed in order to identify typical anomaly patterns of the atmospheric circulation. The time series of the pattern contributions in each season are being examined for evidence of volcanic influence so that the response of the atmospheric circulation to a varying stratospheric dust load can be determined. Most encouraging results are being obtained for the winter season and the North Atlantic sector. The atmospheric circulation appears to react in two ways to changes in the degree of volcanic activity. In the two years following an eruption, the effect of the injection of large quantities of dust into the stratosphere is to displace the North Atlantic westerlies and cyclone tracks equatorwards. On longer time scales, the slow accumulation and depletion of stratospheric dust produces a corresponding slow fall and rise, respectively, in the strength of the westerlies. Extension of the analysis to the linked North Pacific and North Atlantic sectors suggests that these two responses correspond to a longitudinal displacement and overall *in situ* strengthening of the Canadian upper air trough. High levels of volcanic dust in the stratosphere apparently displace the Canadian trough eastwards.

It is worth noting in conclusion that if volcanic activity proves to be a major climatic control, forecasts of climate on decade and longer time scales will require prior predictions of volcanic activity.

HUMPHREYS, W. J. (1940) Physics of the air. New York and London: McGraw Hill.

INTRODUCTION TO THE VOLCANIC DUST VEIL INDEX

This is a brief explanation of the Dust Veil Index (DVI) proposed by LAMB (1970) in order to relate the effects of different volcanic eruptions to one another.

There are three differing formulae which can be used to compute the DVI. They are each scaled so that the Krakatau eruption of 1883 produces a value of 1000.

(i) $DVI = 0.97\ R_{Dmax}\ E_{max}\ t_{mo}$

where R_{Dmax} is the greatest percentage depletion of the direct radiation as registered by monthly averages in middle latitudes of the hemisphere concerned after the eruption. (A considerable lag must be allowed to realise maximum depletion, as the spread of dust appears to be associated to seasonal changes of circulation occurring once or twice a year.)

E_{max} is a coefficient describing the maximum extent of the dust veil, according to this empirical scale.

1. Eruptions between 20°N and 20°S $E_{max} = 1$
2. Eruptions in extratropical latitudes in either hemisphere 20°-35° $E_{max} = 0.7$
3. Eruptions in latitudes 35°-42° $E_{max} = 0.5$
4. Eruptions in latitudes greater than 42° $E_{max} = 0.3$

t_{mo} is the total time in months between the eruption and the last observation of the dust veil or its effect on monthly radiation (temperature) in middle latitudes.

(ii) $DVI = 52.5\ T_{Dmax}\ E_{max}\ t_{mo}$

where T_{Dmax} is the estimated lowering of the average temperature in °C over the middle latitude zone of the hemisphere affected, during the worst year.

(iii) $DVI = 4.4\ q\ E_{max}\ t_{mo}$

where q is the estimated total volume of solid matter dispersed as dust into the atmosphere in cubic kilometres. The best estimates should be obtained from dust deposits over a wide area, down-wind of the volcano.

Estimates from (iii) are subject to uncertainty in estimating q. Reasonably accurate estimations for q have been developed by study of volcanic eruptions where the DVI could be independently derived from (i) and (ii). Tables and the associated graph are limited to DVI's greater than 100 of which 40% is allocated to the year of the eruption, 30% to the next year, 20% to the third year and 10% to the fourth, except in cases where the duration is known to be longer.

FORECASTING THE ARCTIC SEA ICE ON TIME SCALES OF A FEW MONTHS TO MANY YEARS

The southernmost limit of the Arctic ice responds rapidly to variations in the climate of the oceans and atmosphere. Notable fluctuations in sea ice extent have occurred during the present century, and historical reports suggest that even greater variations have occurred over the last few centuries. Man's increasing activity in ice-affected regions would benefit greatly from some anticipation of future variations in sea ice extent.

The Climatic Research Unit is currently engaged in a study of the predictability of the Arctic sea ice on time scales of a few months to many years. The project is funded by the Office of Naval Research, Washington, D.C. This task is to be undertaken in three stages:

1. The collection and digitization of ice data for the Arctic and the identification of significant trends and fluctuations during the twentieth century.

2. The search for associations between these sea ice fluctuations and variations in climate and the atmospheric circulation.

3. The application of climate forecasting techniques to the proble of sea ice variability, based on a thorough understanding of the physical mechanisms involved.

The first year of the project has been largely concerned with the collection and digitization of Arctic sea ice data. By late 1978 an approximately 80-year series of monthly ice charts will have been digitized. The information is obviously variable in reliabilit and quantity, ranging from the sparse Danish Meteorological Service data for April to August in the early decades of the twentieth century to the relatively abundant satellite data of recent years. When complete, this data set will form a unique compilation of existing sea ice information. At present, various long records of ice extent for various regions are being employed in the investigation of sea ice/climate correlations.

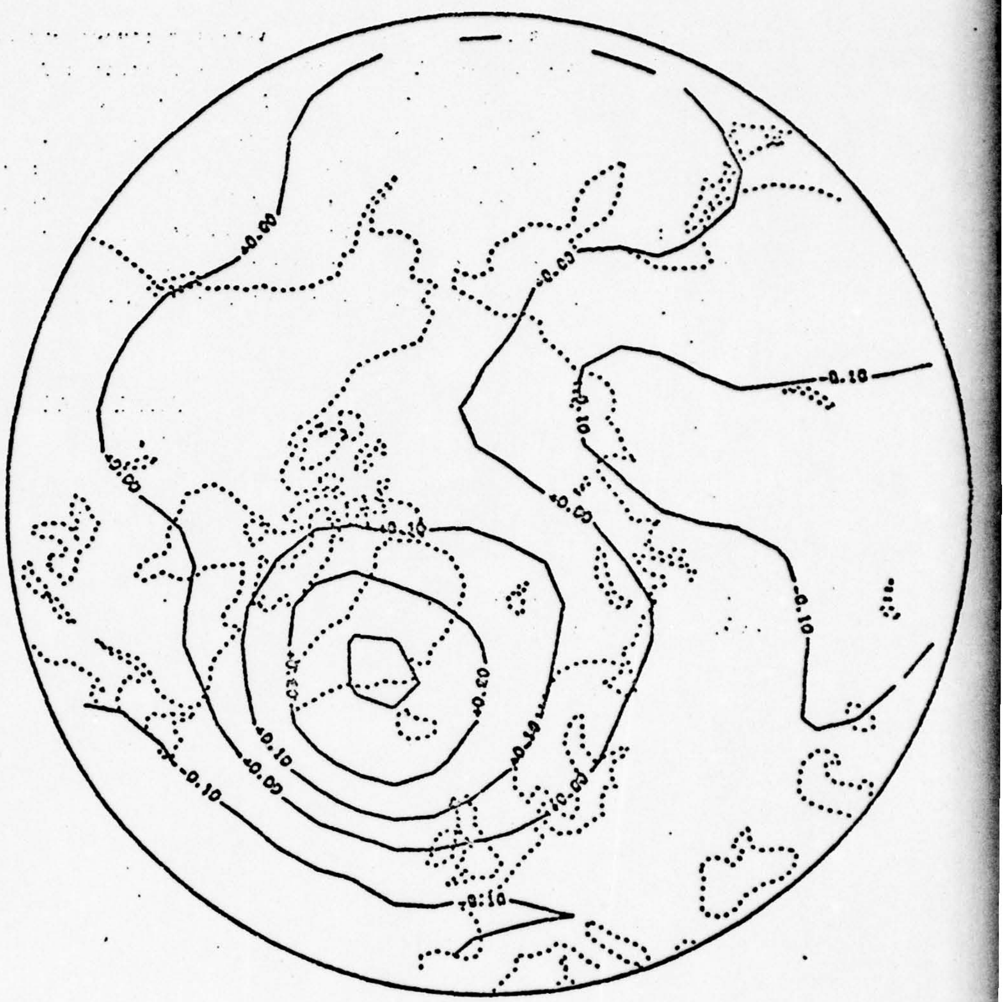
From: Climate Monitor, 7(3), 1978. Ed. P.D. Jones.

Climatic Research Unit: Norwich.

In order to determine the major patterns of atmospheric circulation variation, for correlation with the sea ice data, principal component analysis has been applied to a century-long set of mean sea level pressure data for the northern hemisphere. A set of "typical" anomaly patterns has been identified and their fluctuation in time has been studied. The major patterns, which are present, though of varying importance, in all seasons, relate to variations in the pressure over the central Arctic; the strength of the Iceland Low (Fig. 1); the incidence of depressions in the Kara Sea region; the latitude of the Siberian High and the pressure in middle latitudes right round the hemisphere. Other patterns, though statistically significant, relate to smaller spatial scale anomalies in the circulation, e.g. the location of blocking anticyclones in the North Atlantic-European sector. Certain of the patterns show quasi-regular fluctuations with time, as evidenced by significant peaks in the variance spectra of their temporal coefficients. For example, the strength of the Iceland Low undergoes a quasi-regular fluctuation on a 7 to 8-year time scale, which may be related to the occurrence of volcanic activity (KELLY, 1977). Fluctuations in the incidence of depressions in the Kara Sea region, caused by changes in the strength of the depression track which runs northwest from the Iceland Low, occur with a 4 to 5-year periodicity. This latter cycle has been noted in the amount of ice on the coasts of Iceland and off west Greenland, and in other parameters of the oceanic and atmospheric climate. If physical mechanisms for these quasi-periodic fluctuations can be established, they may provide a useful forecasting tool. Preliminary research suggests that they are not regular cycles forced by periodic external disturbances, but that they may arise from characteristic response times of the climate system to randomly-occurring disturbances.

In the eastern Arctic, a number of these patterns have been found to be related to fluctuations in sea ice extent. On time scales of the order of decades, sea ice in the Iceland region responds to, and perhaps may influence, the strength of the Iceland Low. During the early decades of the present century, the Iceland Low was notably enhanced in strength and the sea ice retreated from the coasts of Iceland. During the 1960s, a much weaker Iceland Low, and a greater frequency of blocking situations over the northeast Atlantic and northern Europe accompanied by increased northerly air flow over the

Fig. 1 Principal component No. 2,
Annual : A measure of the strength of the Iceland low



Greenland Sea, brought the ice back to the Icelandic coasts (see Figs. 2 and 3). On shorter time scales, the ice around Iceland responds to changes in the degree of northerly air flow over the Greenland Sea.

When the full sea ice data set is complete, a detailed investigation of correlations between sea ice, the atmospheric circulation and climate is to be made. Particular attention will be paid to identifying critical times of year when events may determine the character of the whole ice season, and also lag relationships which may be of value for prediction. The physical mechanisms underlying the associations will be investigated, and attempts will be made to determine the causes of the fluctuations in the atmospheric circulation which are responsible for the variations in sea ice extent.

<u>Dr. P. M. Kelly</u>

Fig. 2 Decadal averages of the coefficients of principal component No. 2.

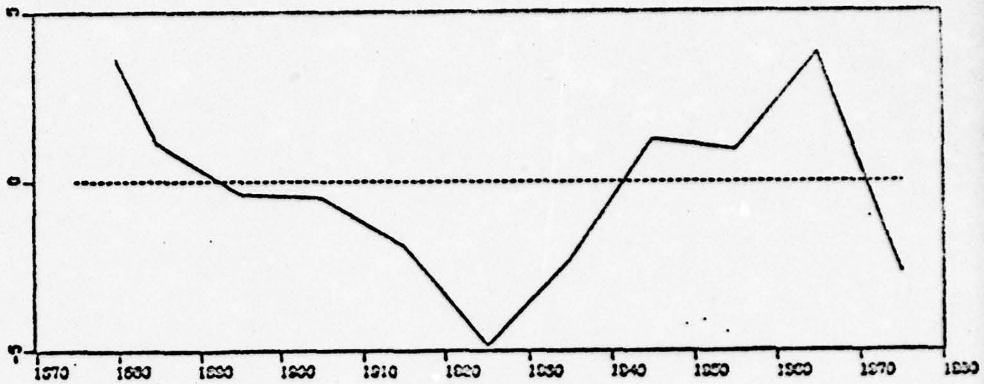
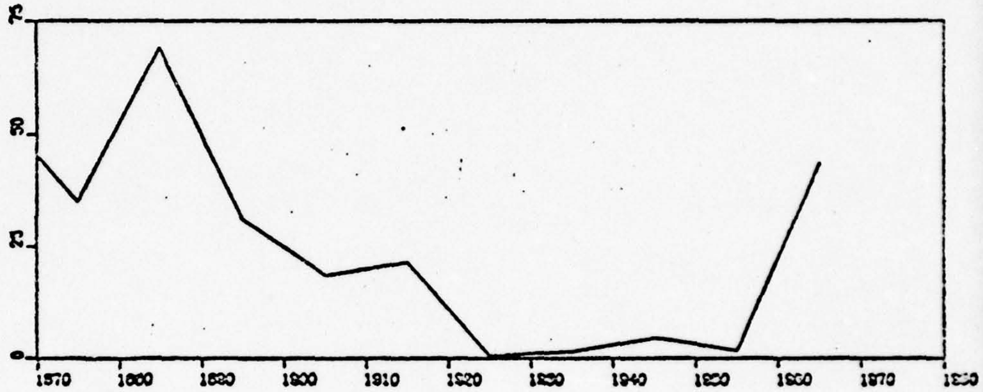


Fig 3. Decadal averages of an index of ice amount on the Iceland coast



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Nature, 268, pp. 616-617

AN ARCTIC SEA ICE DATA SET: 1901-1956

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Paper presented at the

WORKSHOP ON MAPPING AND ARCHIVING OF
DATA ON SNOW COVER AND SEA ICE

WDC-A for Glaciology,
Boulder, Colorado, U.S.A.

2 - 3 November 1978

The Climatic Research Unit is engaged in a feasibility study of the potential for Arctic sea ice prediction on climatic time scales. The main stages in this research are summarised in Table 1. The program includes the collection of sea ice data for the Arctic covering the 20th century; the statistical analysis of these data to identify the major fluctuations in sea ice extent, both spatially and temporally; correlation with climatic and atmospheric circulation data to determine the immediate causes of these sea ice variations, not excluding the possibility of feedback; and research, both theoretical and empirical, aimed at achieving the degree of understanding of the causes of these variations in climate and sea ice which is a necessary prerequisite to any predictive effort. This paper deals with the first stage in this research: the collection of Arctic sea ice data for the 20th century.

Ongoing digitising projects by WALSH (1978) and KUKLA (1978) are concerned with data for the last 25 years or so, but little digitised data is available for the first half of the 20th century. Pronounced changes in sea ice extent occurred during this period, which is considered to be without a climatic parallel during the last few hundred years (KELLY, 1975; LAMB and MORTH, 1978). In order to extend the existing sea ice data base, we have digitised, and are currently assessing the reliability of, the circumpolar ice limit contained in a chart series produced by the Danish Meteorological Institute for the period 1901 to 1956 (THOMSEN, 1947).

During the 1890s, the Danish Meteorological Institute published reports of ice conditions in the Davis Strait, and later between Greenland and Novaya Zemlya, in the Institute's Year-Book. In 1900, this work was extended to cover all Arctic regions where data were available. Information was obtained from sources in Canada, Germany, Great Britain, Norway, Sweden, USA and USSR; these observations originated from naval and merchant shipping, shore observers and, in later years, aircraft reconnaissance. During the periods 1901-39 and 1946-50, the Institute published an annual report, "The State of the Ice in the Arctic Seas", which contained, as text, summaries of the ice extent in the months and regions for which observations were available and, on multi-coloured charts, compilations of these observations for the months of April to August (occasionally September) when most information was available.

The observations were plotted on a polar stereographic projection of the Arctic. Direct observations of polar fast-ice, winter fast-ice, big ice floes, close drift-ice, open drift-ice, icebergs and bergy-bits were plotted in red, with the date of observation occasionally given. In addition, a red curve indicated observed limits between open sea and ice where available; a dashed line gave a climatological "normal" ice limit (for a period of years which changed during the chart series); and, as defined by a change from a white to a blue-green background to the chart, an ice limit based partially on direct observations and partially on supposition. This final ice limit is henceforward referred to as the estimated ice limit; it indicates the edge of the DMI classification "open drift-ice". In certain regions and in certain months, the charts contain the phrase "state of the ice unknown" or "no data", although an estimated ice limit is generally given for such areas regardless.

The number of direct observations plotted on these charts is not great, even in the later years. The coverage is reasonable around Greenland, Iceland and Spitzburgen. Elsewhere, and particularly in the western Arctic, the coverage is at best poor. The question of which information to digitise from the DMI charts posed some problems. Whereas obviously the direct observations, plotted in red, must be considered the most reliable, their variable coverage in space and time precludes rigorous statistical analysis. It was decided therefore to digitise the estimated ice limit initially, and perhaps to add to this at a later stage. In regions of good data coverage the estimated limit conveniently synthesises the direct observations, and even in regions of poor coverage may contain some reliable information.

The latitude and longitude co-ordinates of the estimated ice limit were digitised at a spatial resolution of about 100 kms depending on the distance of the particular set of points from the pole. It was felt that the accuracy of the data and the coarseness of the definition of the limit on the charts did not warrant increased spatial resolution. These co-ordinates are currently being transferred onto the grid shown in Fig. 1. This grid, over the area analysed in the DMI charts, corresponds to that used by WALSH in his digitisation of recent data (WALSH, 1978). The resulting data set will give an ice/no ice indicator for each square in the grid. At a later stage details of ice concentration may be substituted for the simple ice/no ice indicator where data are available. Also various regions are to be selected for close study, and a finer grid employed.

As we have digitised the full circumpolar limit, including the estimated limit in regions of little or no data, the question of data reliability or homogeneity is of great importance and is currently being assessed. The following points are being studied:

1. How does the Danish sea ice terminology correspond to recently developed conventions?
2. How reliable were the original shipping and shore observations of sea ice?
3. How, and by whom, were the charts compiled from the direct observations?
4. How was the ice limit estimated in regions of scarce or non-existent data?

This final question is perhaps the most important. It is obvious that at certain times and in certain regions, the estimated ice limit follows the climatological "normal" also given on the charts. At other times, this is not the case; an extrapolation has somehow been made. There are three fairly obvious possibilities:

a. extrapolation in space, from adjacent areas where data were available,
b. extrapolation in time, using data from previous months,
c. using auxiliary information; perhaps unplotted ice data or possibly climatic or atmospheric circulation data.

The reliability of these estimation methods depends to a great extent on the experience of the chart analyst and, given the wide variations in sea ice extent during the present century, upon the period of years on which this experience is based. Hence, the importance of determining how, and by whom, the charts were compiled. The preparation of the reports was undertaken by four people during the period 1901-56 - V. GARDE, C.J.H. SPEERSCHNEIDER, H. THOMSEN and M.V.L. LORCK - well-known names in the history of sea ice investigations.

In order to resolve these problems, two approaches are being taken. First, information pertaining to the compilation of the charts is being sought from the Danish Meteorological Institute and in the relevant scientific literature. Second, various statistical analyses are being undertaken. Principal component or eigenvector analysis is being used to identify the most important spatial patterns of variability in the sea ice and climatic data sets, and this technique can also be used to highlight gross errors (KELLY and CHANCE, 1978). A number of long series of sea extent data at various locations have been collected (see Table 2) and these, if based on independent data, will be used to verify the DMI data set. The data set produced by WALSH (1978) overlaps with the DMI data set during the period 1953 to 1956 (although it is not strictly independent), and will also be used for comparison purposes.

After this assessment is complete, gross errors will be removed from the DMI data set, the data will be flagged with a reliability rating, and will then be made available to other investigators. A detailed description of the data set will be prepared for publication at that time.

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TABLE 1

A BASIS FOR FORECASTING THE ARCTIC SEA ICE OVER A FEW MONTHS TO MANY YEARS

THE PROJECT, WHICH IS FUNDED BY THE U.S. OFFICE OF NAVAL RESEARCH, COMMENCED IN SEPTEMBER 1977. THE OBJECTIVE IS TO LAY THE FOUNDATIONS OF A SCIENTIFIC FORECASTING ABILITY FOR THE ARCTIC SEA ICE ON TIME SCALES OF A FRACTION OF A YEAR TO DECADES.

THIS IS TO BE ACCOMPLISHED IN THREE STAGES:

(A) THE COLLECTION AND DIGITISATION OF AVAILABLE SEA ICE DATA FOR THE ARCTIC EXTENDING BACK TO THE 19TH CENTURY.

(B) THE IDENTIFICATION OF PAST VARIATIONS IN SEA ICE EXTENT AND ASSOCIATED FLUCTUATIONS IN CLIMATE AND THE ATMOSPHERIC CIRCULATION.

(C) IF FEASIBLE, THE DEVELOPMENT OF A FORECASTING SCHEME BASED ON A THOROUGH UNDERSTANDING OF THE MECHANISMS UNDERLYING THE VARIATIONS IN SEA ICE, CLIMATE AND THE ATMOSPHERIC CIRCULATION.

Table 2. Sea ice data for the northern hemisphere.

LOCATION	PARAMETER	PERIOD	SEASON	SOURCE
Arctic Ocean (eastern)	Weighted total of ice in Greenland, Barents and Kara Seas.	1895-1924	April-August	BROOKS and QUENNEL (1928)
Arctic Ocean (eastern)	Index of ice severity in Greenland and Barents Sea and around Spitzbergen.	1897-1938	January-December	WALKER (1947)
Kara Sea (a)	Area	1895-1915	April-August	State of the Ice in Arctic Seas: Supplement (1917)
(b)	Severity index	1868-1946		NAZAROV (1947)
Barents Sea (a)	Area	1895-1915	April-August	State of the Ice in Arctic Seas (1917)
(b)	Area	1900-1960	April-August	MAKSIMOV, SMIRNOV and VOROB'EV (1964)
Greenland Sea (a)	Area	1877-1915	April-August	State of the Ice in Arctic Seas: Supplement (1917)
(b)	Area	1924-1968	April-August	KIRILLOV and KHROMTSOVA (1972)
Iceland	Weeks per year with drift ice on coast	1600-1975	October-September	LAMB (1977), KOCH (1945), THORARINSSON (1956)
Baltic (a)	Date of final opening of Port Riga	1530-1958		LAMB (1977), BETIN and PREOBRAZENSKY (1959), SPEERSCHNEIDER (1915, 1927).
(b)	Maximum area	1720-1957		
(c)	Number of days with ice.	1763-1926		
West Greenland	Northward extent of "Storis"	1821-1939		KOCH (1945), LAMB (1977)

Table 2. (Continued)

LOCATION	PARAMETER	PERIOD	SEASON	SOURCE
Newfoundland	Index based on maximum eastward and southward extent of ice	1920-1973	April	MILES (1974)
Western Atlantic: icebergs (a)	Severity index	1886-1939	March-July	WALKER (1947)
(b)	Number of icebergs south of 48°N.	1900-1976	September-August	U.S. Coast Guard
Baffin Bay	Date of clearing	1952-1974		KEEN (1977), DUNBAR (1972)
North Slope, Alaska	Severity index	1953-1976	Summer	BARNETT (1978)
Okhotsk Sea	Anomaly of drift ice period (days) at (a) Abashiri (b) Shana	1892-1945		SAWADA (1957)

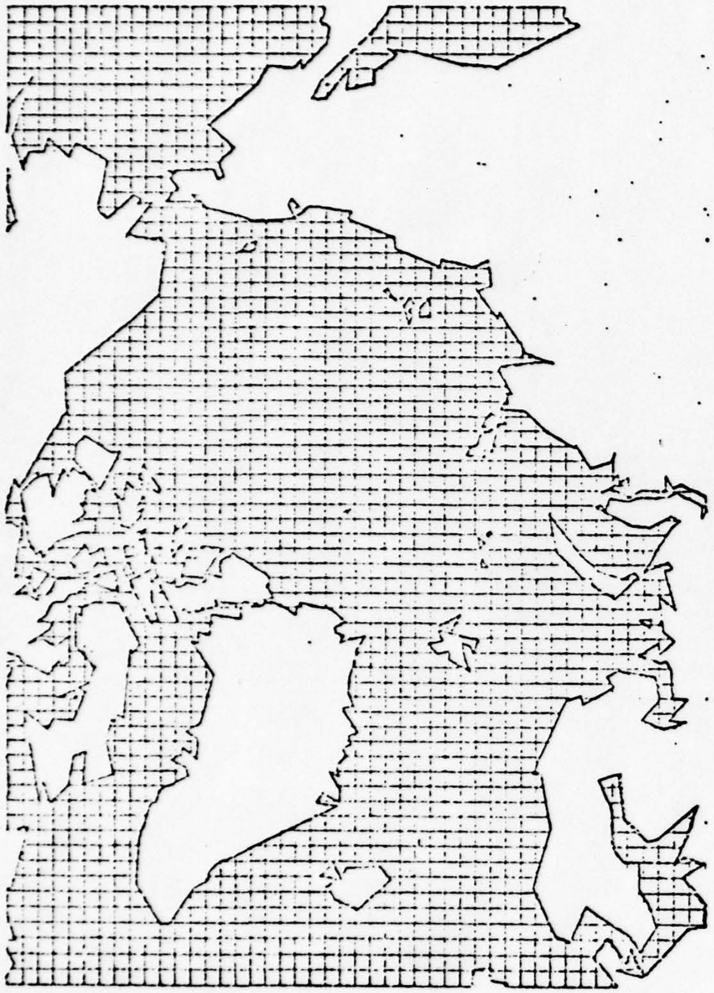

Fig. 1 Standard one-degree ice data grid

SOLAR INFLUENCE ON NORTH ATLANTIC MEAN SEA LEVEL PRESSURE

ABSTRACT

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A principal component analysis of a 101 year set of winter mean sea level pressure anomalies for the North Atlantic-European sector has revealed evidence of an 11 year cycle. This cycle is apparently related to the long-term modulation of solar flare activity during the sunspot cycle.

The principal components represent independent atmospheric circulation anomaly patterns. The variation of the strength of these patterns with time is given by a series of coefficients.

The variance spectrum of the coefficients of the second principal component (PC2) contains statistically significant peaks at 11, 5 and 3½ years, indicating the presence of a non-sinusoidal 11 year fluctuation. The main feature of the spatial pattern of PC2 is an area of intensified cyclonic activity to the [illegible] of the British Isles. This pattern, identified in [illegible], is consistent with the pattern of <u>24 hour</u> 500 mb height change following solar flare events reported elsewhere in this volume. The cyclonic intensification is located beneath a region of divergence ahead of an anomalous upper air trough. It is proposed that the 11 year fluctuation arises as the frequency of solar flares, and the atmospheric responses on the day to day time scale, changes with the sunspot cycle.

This compatibility between the short term solar-weather and long term solar-climate relationships suggests an approach which may avoid a problem frequently encountered in investigations of the latter. Although the data length may be sufficient to generate a hypothesis, there is rarely additional data available to test that hypothesis rigorously. This approach would be to base hypotheses not on analysis of the limited climatic data, but on the results of short term solar-weather investigations, i.e. to deduce their implications, or integrated effects, on climatic time scales.

The phase locking between the sunspot cycle and the 11 year fluctuation in PC2 was reasonable during the period 1920 to date, but broke down about the turn of the century. Although no firm conclusions can be drawn from the limited data available, three possible explanations felt worthy of further investigation are advanced. First, sunspot numbers may not be a good indicator of the component of the solar output affecting the atmospheric circulation. Second, the volcanic dust loading of the stratosphere was minimal during the period 1920 to 1960. This may have resulted in a stronger solar control on the atmospheric circulation during that period; at other times, the volcanic control may mask the solar effects. Third, the amplitude of the sunspot cycle was far greater after 1920 than it was before.

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CLIMATE: HISTORICAL PERSPECTIVE AND TRENDS

Contribution to

"ATLAS OF THE DROUGHT OF 1975/76"

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8. CLIMATE: HISTORICAL PERSPECTIVE AND TRENDS

During the early decades of the present century climatology was regarded as little more than an exercise in data collection and storage. If a long enough record of any climatic parameter was available, and thirty years was generally considered sufficient, statistical averages based on this record were considered representative of the climate of coming years. This complacency was shaken by the severe British winters of the 1940s. It became apparent that climatic statistics meant more than plain averages; extreme events had also to be considered. For some time, however, a limited sample of years was still considered sufficient to evaluate the statistics of these extremes. Increased knowledge of the vagaries of climate has now shown that it is dangerous to base any statistics on a limited record; it cannot be guaranteed that the period of record selected will be representative of years to come.

Awareness of the impact of climatic change on human affairs has been heightened as the need to manage the Earth's resources wisely has become more acute, and various extreme climatic events during the early 1970s have stressed the need to incorporate the potential of climatic change in socio-economic planning. This has led to a demand for greater understanding of climatic variation: the past record, the causes and, if possible, future climatic developments. This demand is not restricted to the slow climatic shifts on time scales of decades and longer, but also encompasses short-lived extremes such as the drought of 1975/76. As far as the impact of climatic change on man in concerned, it can be reasonably argued that the occurrence of such short-lived climatic extremes is of greater importance than the slower, smaller amplitude shifts in climate. While slow changes in climate allow time for adaptation, extreme events, however short their duration, may produce an unbearable stress. Nevertheless, climatic fluctuations on these two time scales are intrinsically linked. Longer period climatic changes may either cause variations in the frequency and intensity of short-lived extremes, or may arise through the varying frequency and intensity of the latter. Short-lived extremes must be considered in the context of longer-term climatic variations.

Unfortunately many of the questions concerning the past climatic record cannot be answered in detail at this time, and there can be no certainty about future developments. Knowledge of the past record is fragmentary. Instrumental records are limited in their spatial coverage and are, moreover, generally restricted to the twentieth century - a period of particularly unusual climate in the light of the European climatic history of the past millenium. An important taśk for climatologists today is to extend the climatic record and, in particular, provide information for the pre-instrumental era. Evidence of climatic change can be gleaned from a variety of sources: historical, biological and geological. In this section, various techniques that are being used to extend the record of rainfall fluctuations and drought frequency back in time are described, and the need to consider events such as the drought of 1975/76 in the context of longer-term rainfall variations is demonstrated.

Scattered instrumental observations of rainfall can be found dating from as early as the late seventeenth or early eighteenth centuries. In most cases these observations were made by country gentlemen, doctors of medicine, or clergymen; many of whom took their "hobby" seriously and frequently followed the scientific literature where a standard of observational practice was slowly being developed. There were, however, many differences of opinion regarding the dimensions, exposure and height of the primitive rain gauges. In many cases, records of the nature of the instrument, conditions of exposure and other aspects of observational practice were not kept or have not survived. Such factors must be taken into consideration when these early observations are employed. The uncritical acceptance of measurements made under unknown or non-standard conditions has led to many misconceptions regarding past rainfall fluctuations. Two centuries after the first regular observations were taken, rainfall is still considered one of the most difficult climatic parameters to measure accurately. The homogenisation of rainfall records has to be an exhaustive exercise. To the unwary a change in instrument, exposure or observational routine can easily be confused with a change in climate. An excellent discussion of the complex nature of the homogenisation of early rainfall records has been given by CRADDOCK (1976).

A selection of long rainfall records is shown in Fig. 1. The record for England and Wales is from NICHOLAS and GLASSPOOLE (1932) and has been updated by the U.K. Meteorological Office. It is considered to be unsatisfactory prior to 1850 as earlier data are based on a limited number of, in some cases, highly doubtful observations. It has, however, frequently been used in studies of drought frequency and long-term rainfall variations. The slow rise evident throughout this record is most likely to be due to errors in the early data rather than a genuine climatic change. Despite these errors, the decade-to-decade fluctuations are probably accurate in direction if not magnitude. The Manchester data (MANLEY, 1972) suggest that the nineteenth century was wetter than the twentieth century, with a prolonged period of notably decreased rainfall about the turn of the century. This contrast between the nineteenth and twentieth centuries is supported by the Pode Hole record (CRADDOCK and WALES-SMITH, 1976). The earliest decades of this long record show a prolonged period of decreased rainfall. The records for Oxford (SMITH, 1974) and Kew (WALES-SMITH, 1971) do not contain evidence of rainfall fluctuations on a century-to-century time scale. The Oxford series, from the Radcliffe Observatory, is particularly reliable, as excellent documentation is available throughout the period of the record. A few notably dry decades appear in nearly all of these records: the 1970s, 1940s, 1890s, 1850s, 1800s and 1740s. The gap of roughly fifty years between these dry decades has been discussed by BROOKS and GLASSPOOLE (1929) and BROOKS and CARRUTHERS (1953, p.330), and a similar fluctuation in a rainfall record for south-east England has been noted by GRAY (1976).

The occurrence of drought can be defined in a number of ways. For example, WIGLEY and ATKINSON (1977) distinguish between three types of drought: 'meteorological drought', which is defined solely by precipitation deficiency; 'hydrological drought', which arises from a deficiency in excess precipitation (i.e. that which neither evaporates nor is used up in soil moisture deficits) resulting in reduced surface run-off and/or groundwater recharge; and 'agricultural drought', which is determined by high soil moisture deficits over the growing season. These working distinctions allow one to determine quantitatively past drought frequency and severity; but even then it must be realized that the perception of what constitutes a drought will vary according to the impact on the individual. To avoid confusion, the 'agricultural drought' defined above will be referred to as soil moisture deficit (SMD) drought in the following discussion.

WIGLEY and ATKINSON (1977) have constructed a long series of growing season soil moisture deficits for Kew based on data given by WALES-SMITH (1971, 1973a, 1973b). They show that the SMD drought during 1976 ranks as the most severe since 1698, although 1934 was a close contender. They stress that the slow climatic variations on time scales of decades and longer cannot be neglected when considering the likelihood of the recurrence of short-lived events such as the drought of 1975/76. All but one of the seven worst SMD droughts on record have occurred during the last sixty years, and two have occurred during the period 1971 to 1976. The average frequency of soil moisture deficits exceeding 100 mm for the twentieth century is almost twice that of the preceding two centuries, and the frequency for the period 1960 to 1976 surpasses that of all previous twenty-year intervals. This change in the frequency of severe droughts is reflected in the long-term shifts in the decadal data (Fig. 2). The three-century record has seen five periods of prolonged soil moisture deficit at Kew on the decadal time scale: about 1750, 1800, 1850, 1890 and from about 1930 onwards.

The first four dry periods correspond to those commented on earlier (see Fig. 2). Th period of marked deficits since 1930 has no parallel in the record, and the contrast between the present and earlier centuries is striking. WIGLEY and ATKINSON (1977) note that these long-term changes seriously affect the calculation of recurrence intervals. The recurrence interval of the SMD drought that occurred in 1944 (the third worst on record), calculated from all the available data, was found to be about thirteen decades; but three droughts of similar magnitude have occurred in the last five decades. The probability of this occurring by chance is less than 0.4%, pointing again to a significant change in drought frequency in recent times.

For times before the instrumental era, knowledge of the occurrence of drought is dependent on historical reports and "proxy" indicators of climate. While historical material has been used as a source of medieval climatic information for many years, modern historical techniques are slowly refining the picture gleaned by pioneers in this field (BELL and OGILVIE, 1978; INGRAM et al, 1978). To date, workers have relied on compilations of material published some time after the events described (secondary sources). Rigorous testing of the authenticity of these records, by reference to the original or primary source, has revealed much unreliable information. Erroneous reports, frequently due to misquotation or duplication of the original writings, tend to exaggerate the severity of certain climatic events or epochs, and sometimes describe completely fictitious events. An example of this distortion is given by a previously accepted description of the period 988 to 1000 AD (LAMB and JOHNSON, 1961). The claim that this period was one of numerous unusually hot and dry summers appears to be supported by references to eighteen sources in HENNIG (1904). However, only two of these sources are contemporary to the event and, in fact, these mention only a single hot summer. The other sources are mainly from the seventeenth or eighteenth centuries and represent inaccurate multiplication of the one authenticated event.

An example of the type of historical information available for one year during the thirteenth century is given in Table 1, (from WIGLEY et al, 1978). A glance at this table will convey the difficulties arising in the climatic interpretation of such data. In particular, medieval writers in northern Europe were prone to comment more frequently on abnormally wet seasons than dry. This was due to the greater susceptibility of their agricultural economy to such conditions, rather than a lack of drought occurrence, (UNDERHILL, personal communication). Nevertheless, a general impression of warmth and cold or wetness and drought can be gained from historical information. In Fig. 3, a decadal index of summer wetness in Belgium compiled by ALEXANDRE (1976) is shown. Note the dry conditions of the late twelfth and early thirteenth centuries, which were interrupted by the notably wet decade of the 1190s, and the prolonged rainy period of the fourteenth century.

Historical reports are restricted to those events of importance to man: usually short-lived extreme climatic events. The tendency for people to judge extreme events against an ever-changing "normal" based on the experience of recent years results in a filtering out of longer time scale changes. Information concerning the slow, underlying fluctuations can be gained from biological indicators of climate such as tree growth. Trees such as oak, elm and ask lay down annual growth rings which can be dated precisely. In winter practically no growth takes place, although storage of moisture during this season can play an important part in the growth during the following year. Each spring, growth is initiated by a complex of internal and external factors, including climate. Trees such as oak lay down large, thin-walled cells as early wood, followed, as the growing season progresses, by thicker-walled, smaller cells which make up the late wood. The sharp transition between the late wood of one year and the early wood of the next is used to delimit the measurement of one year's growth. In middle latitudes and at low elevation, growth ends in late summer. By matching cross-sections of ring width from trees in the same, or similar, sites, a composite chronology of tree growth can be obtained. An age trend is generally removed from the ring width series. This process filters out fluctuations on time scales of the tree's life span; these fluctuations may be due to age, climatic variations or other factors. Just as the historical record provides a filtered view of climatic fluctuations, emphasising those on an inter-annual time scale, so tree ring data provide a filtered view of climate on inter-annual to inter-decadal time scales. Information on century-to-century changes can only be extracted in rare cases (see, for example, LAMARCHE, 1974).

The degree to which growth, and therefore tree ring width, varies with climate depends on location. Marked correlations with climate have been found in the semi-arid southwest of North America, where trees are often stressed by extreme climatic conditions. This has enabled the reconstruction of pressure anomaly patterns for the whole Pacific sector from tree ring data for the western United States (FRITTS, 1977), the derivation of a long climatic history for the White Mountains (LAMARCHE, ~~1974~~ 1973) and the extension back in time of drought indices for the western United States (STOCKTON and MEKO, 1975). In the British Isles oak, largely because of the lack of "missing rings" which can seriously complicate dating, has been considered most likely to provide climatic information. It was thought, however, that the climatic signal would be weak and masked by other factors, such as disease. Nonetheless, using modern analytical methods,

HUGHES et al (1978) have recently demonstrated that oak chronologies at carefully selected sites in the British Isles show a climatic response of similar magnitude to the trees selected in the semi-arid American south-west. They conclude that the application of dendroclimatological techniques in the British Isles is feasible. If this proves to be the case, such climate reconstruction will provide a valuable extension to the three century-long records shown in Fig. 1.

There are some important conclusions to be drawn from the climatic record of the last 1000 years, even though the record is limited and the potential of many of the techniques of climatic reconstruction has yet to be realized. It is clear that pronounced changes in climate occur on all time scales. Records for the instrumental and pre-instrumental period show that changes in rainfall amount and drought frequency have occurred throughout the present millenium, and it is reasonable to conclude that they will continue to occur in future years. It has been demonstrated that the estimation of recurrence intervals for events such as severe drought can be seriously affected by long-term shifts in climate, i.e. the frequency of short-lived climatic extremes and long-term fluctuations in climate are interlinked. KELLY and WRIGHT (1978) have shown that the severity of the drought of 1975/76 was associated with a tendency towards low rainfall totals that was characteristic of the early 1970s. The selection of the period of years upon which statistics for planning purposes are to be based should therefore be made carefully. This selection involves an implicit climatic prediction, for it is assumed that the period selected will be representative of years to come.. Yet a recent report by the NATIONAL DEFENCE UNIVERSITY (1978) has shown that even experienced climatologists vary significantly in their estimates of future climate. The causes of the climatic changes that occurred in the past are not well understood, and there is uncertainty about the degree to which the activities of man will affect climate in the future. Finally, it should be noted that the climate of the first half of the present century is considered to be unrepresentative of the experience of the last few hundred years; and yet this period is perhaps the one most frequently used as a climatic "normal"

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FIGURE CAPTIONS

Fig. 1

Decade average anomalies of annual rainfall totals (mm) for:

(a) England and Wales;
(b) Manchester;
(c) Pode Hole, Lincolnshire;
(d) Oxford;
(e) Kew.

For sources of data, see text. Averages for the 1970s contain all available data as of September 1978.

Fig. 2

Decade average anomalies of the growing season soil moisture deficit at Kew (mm). Data from WIGLEY and ATKINSON (1977).

Fig. 3

Decadal index of summer wetness/dryness for Belgium. There is some doubt as to the reliability of the data for the eleventh and late thirteenth centuries. Data from ALEXANDRE (1976).

TABLE 1

Example of historical climate evidence. The bracketed sources in Part 1 are verified data from BRITTON (1937), while those in Part 2 are the names of particular manors. The data in Part 2 were collected by Dr. D. Stern, Climatic Research Unit, University of East Anglia.

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1. Annals and Chronicles

WINTER : Gale on Jan. 26 (N.S.) (Bartholomew de Cotton)

SPRING : Wind and snow in north of England around Apr. 18 (N.S.) (Lanercost Chronicle)

SUMMER : Wet (Worcester Annals)

Continual rains in August in East Anglia (Everisden)

AUTUMN : Continual rains in Sept. in East Anglia (Everisden)

Wet (Worcester Annals)

Possible flooding of the R. Thames around Oct. 24 (N.S.) (Bermondsey Annals; not a contemporary source)

2. Manorial Accounts, Bishopric of Westminster

WINTER : Peas for pigs and vetch for doves because of frost and snow (Feering)

Sheep deaths rather high, mainly ewes before lambing: indirect evidence of cold weather (Feering and Kelvedon)

Peas and beans for doves on 11 days because of snow: oats for poultry because of snow and frost (Birdbrook)

Roofs of barns damaged by gale (Kelvedon and Birdbrook)

Oats sowing rate increased because of rainy weather, late winter - early spring (Feering)

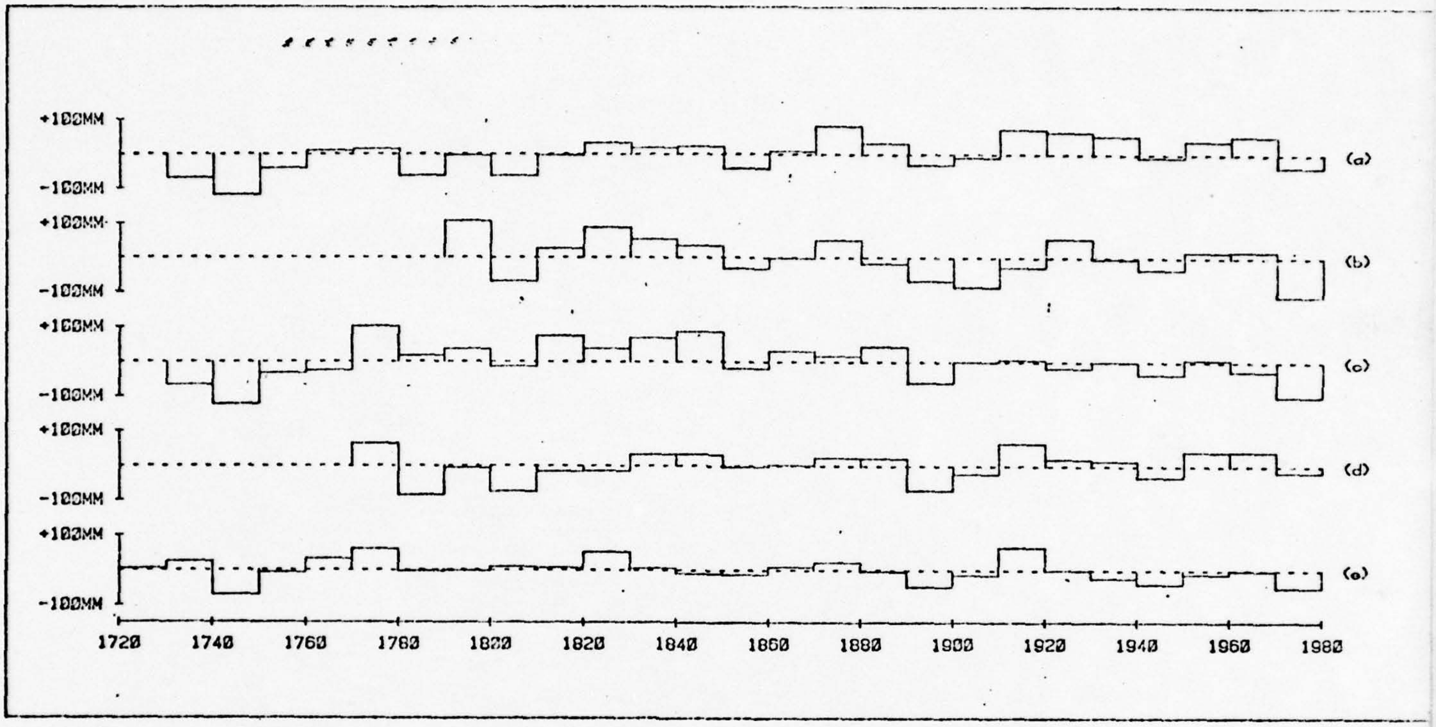
Oats ration for plough-horses augmented for 32 nights because of very muddy conditions, late winter to early May (Birdbrook)

SPRING :
SUMMER : Extra hoeing needed due to thistles, mowing delayed to early July: indirect evidence of wet weather from late spring to early summer (Feering and Kelvedon)

AUTUMN : Rainy weather October to early December (Kinsbourne)

Plough-oxen require extra shoeing because of muddy conditions in October and November

Fig 1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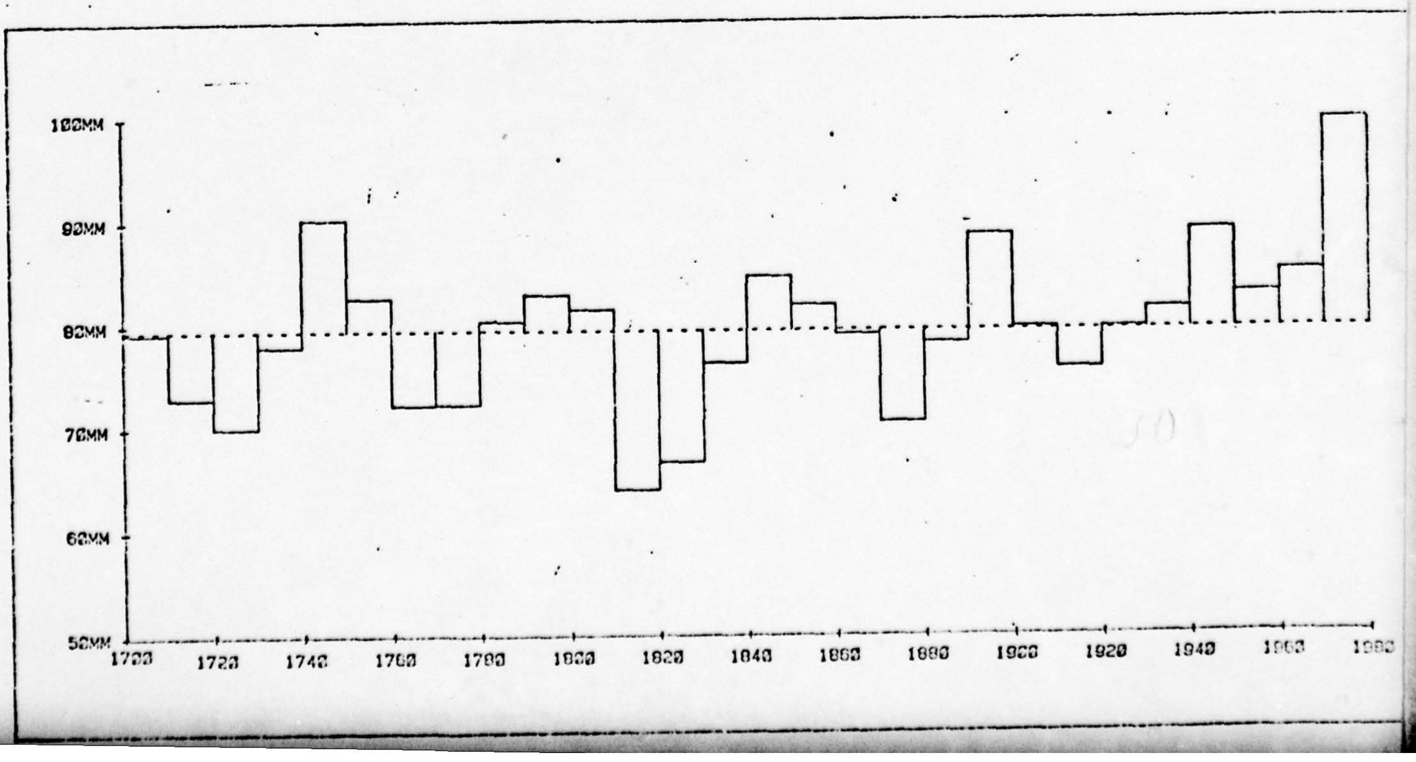
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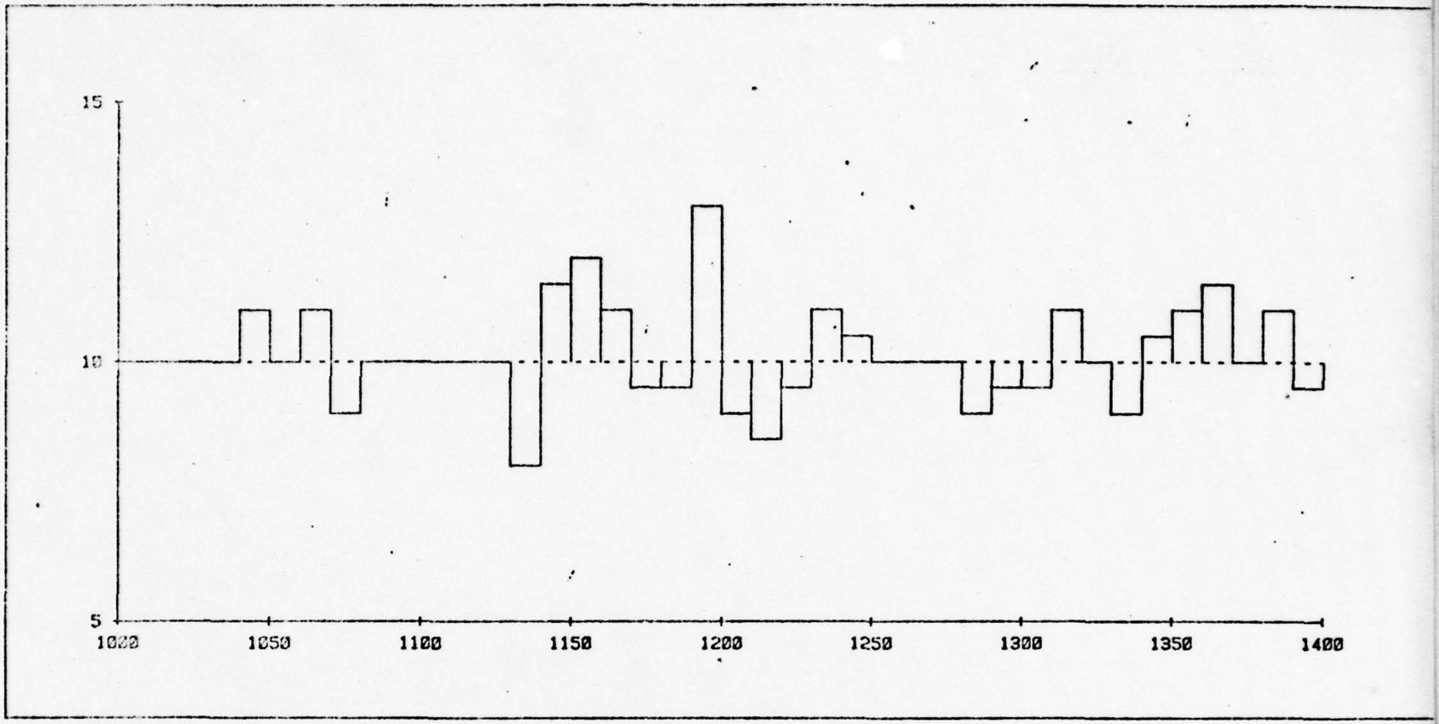

The European drought of 1975–76 and its climatic context

by P. M. Kelly and P. B. Wright

> Drought is undoubtedly one of man's worst natural enemies. Its beginning is subtle, its progress is insidious and its effects can be devastating. Drought may start any time, last indefinitely and attain many degrees of severity. It can also occur in any region of the world, with an impact ranging from slight personal inconvenience to endangering nationhood (*Hounam et al., 1975*)

The drought that affected most of western Europe during 1975 and 1976 was one of the most severe on record and it highlighted the need for more complete understanding of the nature and causes of such short-lived climatic extremes. In this article, we review research concerning the drought of 1975–76 and other similar events in the past.

We first discuss the magnitude of the drought of 1975–76 and place it in the context of certain historical droughts and other long-period rainfall variations. The behaviour of the atmospheric circulation during the drought period is then described, and the drought is seen as the result of a period of persistent and repetitive blocking in the North Atlantic sector. Finally, although it is not possible to define one particular cause of the drought as the atmosphere forms part of a complex system of interactive processes, factors that may have favoured the establishment, maintenance and breakdown of this particular mode of the atmospheric circulation are discussed.

The study of the nature and causes of climatic change is complex, involving not only many disciplines, for possible climatic controls are located in the Earth's crust, oceans, atmosphere and beyond, but also a variety of approaches. We illustrate the importance of the synthesis of the many different approaches, both empirical and theoretical, to such problems as the drought of 1975–76.

I Rainfall variations in England and Wales

1 *General*

The drought lasted from May 1975 to August 1976. During that period, southern England received less than 50 per cent of its normal rainfall and much of England and Wales received less than 70 per cent. Most of western

2 *The drought of 1975–76 and other severe droughts of the past*

In Figure 2, monthly percentages of the rainfall averaged over England and Wales are shown for recent years. The average percentage for the period May 1975 to August 1976 (henceforward know as the drought period) was about 65. The rainfall only surpassed the 1916–50 average in two months: September 1975 and May 1976. During the latter month however there was great variation within the England and Wales region; southern England received about 50 per cent of its usual rainfall whilst northern England received 150 per cent. This is a striking example of how an areal average can obscure an important gradient within the region. It is not possible to find a rainfall deficit of similar magnitude and duration in the England and Wales record which began in 1727. The previous lowest rainfall over a 16-month period ending in August occurred in 1749–50 (CWPU, 1976). During the present century, the dry period of April 1933 to September 1934 was similar in duration but less intense (Glasspoole, 1934). The intensity of the 1975–76 drought was matched in 1921 but that drought only lasted 10 months (Brooks and Glasspoole, 1922). Table 1 clearly shows that the drought of 1975–76 was without parallel during the previous two-and-a-half centuries.

3 *Rainfall variations on longer time scales*

Short-term climatic extremes are intrinsically linked to longer period climatic changes. Longer period climatic changes can be regarded as modulating the frequency and intensity of shorter period extremes and may arise through the varying frequency and intensity of the latter. The drought of 1975–76 was no exception. It represents an intensification of a rainfall deficit of 10 to 15 per cent that has been a feature of the early 1970s (Figures 2 and 3). The average annual rainfall over England and Wales during the five-year period 1971–75 was 826 mm: the lowest five-year average since the 1850s (Ratcliffe, 1976). In the map of global rainfall anomalies for the period 1970–72 presented by Lamb (1974), an area of deficient rainfall (10 to 15 per cent below the 1931–60 standard) covers the British Isles and extends into central Europe and around the Baltic Sea: the region most affected by the 1975–76 drought. It can be seen in Figure 2 that an earlier intensification of the longer period deficit occurred in 1972–73 (Jerome, 1975); the average rainfall over England and Wales during the nine-month period July 1972 to March 1973 was 65 per cent of the 1916–50 standard.

In fact, the rainfall deficit of the early 1970s marks the culmination of a consistent decline in annual rainfall totals over England and Wales that started in the mid 1960s (Figure 3). Although it does not represent a continuation of a longer period trend, nevertheless it is a feature without parallel in earlier years (Figure 4). The characteristic variability of rainfall totals from year to year ceases in the mid-1960s.

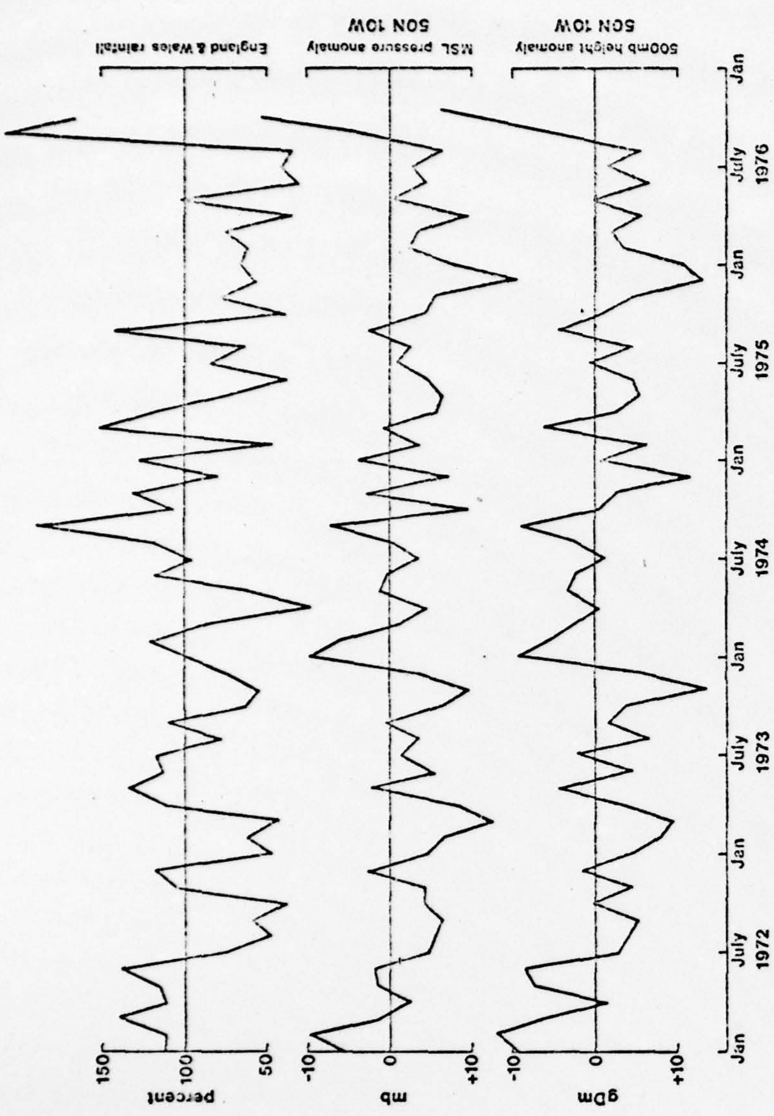

Figure 2 Monthly values for the period January 1972 to October 1976. a) England and Wales rainfall as percentages of 1916–50 monthly averages. *Data from the Meteorological Office, UK.* b) MSL pressure at 50 N 10 W, anomalies from 1900–39 monthly averages. Vertical scale inverted. c) 500 mb height at 50 N 10 W, anomalies from 1949–68 monthly averages. Vertical scale inverted.

On longer time scales, there is a great problem in obtaining reliable rainfall records (Craddock, 1976), although a dendroclimatological approach may prove of value (Fritts, 1977). The England and Wales rainfall record does exhibit a fluctuation with a characteristic time scale of about 50 years with periods of deficient rainfall of 10 to 20 years duration occurring about 1745, 1800, 1855, 1900 and 1945. But the record is too short to determine its statistical significance. This fluctuation has also been seen in rainfall over southeast England (Gray, 1976), the frequency of mild European winters during the first half of the present millennium (Lamb, 1964) and drought frequency during the second half (Brooks and Glasspoole, 1928). Brooks and Carruthers (1953, 330) demonstrate that the probability of a wet year was nearly twice that of a dry year around the maxima of the 50-year fluctuation and less than half around the minima; thereby emphasizing the link between the occurrence of short-period climatic extremes and longer-period climatic change.

Table 1 Rainfall over England and Wales to end of August 1976. *From CWPU (1976).*

Period in months ending August 1976	Provisional rainfall (mm)	% of average (1916-50)	Frequency of occurrence[1] (1 in X years)	Previous lowest on record 1727-1975		
				Ending August		Ending any month
				(year)	(mm)	(mm)
3	77	36	300	1800	74	45
6	205	52	400	1741	184	155
9	355[2]	55	1000	1731	400	343
12	571[2]	63	650	1750	608	556
16	757[3]	64	1000+	1750	809	779
18	909[2]	70	500	1742	914	885
24	1497	83	30	1741	1259	1259
36	2314	85	45	1742	1987	1938

Notes: 1 Starting in a given month
2 New lowest for period ending in August
3 New lowest for period ending in any month.

4 *Conclusion*

It has been demonstrated first that the drought was one of the worst on record, and second, that it was a short-period intensification of a tendency towards below-normal rainfall characteristic of the early 1970s and without parallel during the present century.

The fact that the drought of 1975–76 was unique in the context of

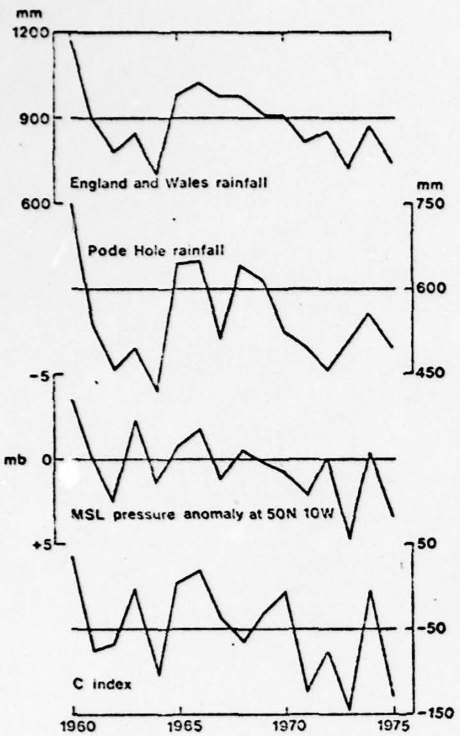

Figure 3 Annual values for the period 1960–75. a) England and Wales rainfall. *Data from the Meteorological Office, UK.* b) Rainfall at Pode Hole in eastern England. *Data from Craddock (1970).* c) MSL pressure at 50 N 10 W, anomalies from the 1900–39 average. Vertical scale inverted. d) C index. *For derivation see Murray and Lewis (1966).*

present rainfall records places a considerable restriction on the use of statistical analyses of such records to determine the likelihood of future recurrences. Furthermore, it emphasises the need for the collection of longer, reliable series of rainfall data, perhaps based on proxy information from the pre-instrumental era. It is possible however to arrive at some understanding of the causes of the drought by studying the behaviour of the atmospheric circulation. The identification of conditions favourable for the establishment, maintenance and breakdown of the drought-producing atmospheric circulation pattern may then lead to a limited forecasting ability.

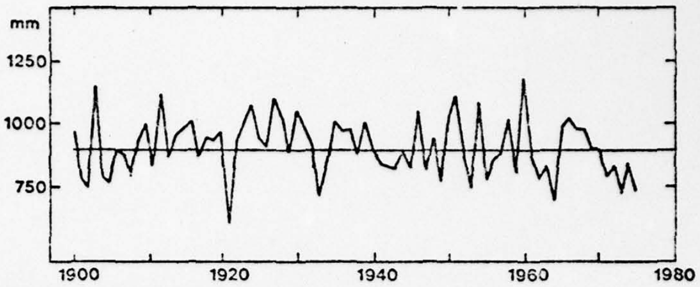

Figure 4 Annual England and Wales rainfall for the period 1900–75. *Data from the Meteorological Office, UK.*

II The behaviour of the atmospheric circulation during the drought of 1975–76

1 *Introduction*

The immediate cause of most climatic change can be found in the atmospheric circulation. Drought in middle latitudes is usually associated with persistent anticyclonic systems, the rain-giving depressions being steered elsewhere. This was the case during the drought of 1975–76.

It can be seen in Figure 2 that there is a close correspondence between the month-to-month fluctuations in rainfall over England and Wales and local mean sea level pressure and 500 mb height (an indicator of the characteristics of the mid-tropospheric circulation). During the drought, depressions were repeatedly diverted north, and sometimes south, of persistent anticyclones located over the British Isles and western Europe. This behaviour of the atmospheric circulation is known as *blocking*. The decline in rainfall totals during the late 1960s and rainfall deficit of the early 1970s were accompanied by similar changes in the frequency of anticyclones and depressions over the British Isles (Figure 3).

Before looking in detail at the behaviour of the atmospheric circulation during the drought of 1975–76, the main features of blocking in the North Atlantic–European sector are described.

2 *Blocking*

Synoptic meteorologists long ago identified the tendency for surface anticyclones to linger in regions usually occupied by the dominant westerly flow in middle latitudes, temporarily preventing the progression of depressions embedded in the westerly flow and diverting that flow to the north or south. Hence the use of the term blocking anticyclone, which perhaps places too much emphasis on one feature of a complex system. This however could not be recognized until the advent of widespread upper air observations during the 1940s permitted a fuller, three-dimensional view of blocking events.

The circulation through the lower atmosphere in middle latitudes is generally zonal, forming a broad, and in places intense, westerly current around the circumpolar vortex with high pressure cells to the south. The flow meanders and contains quasi-stationary troughs and ridges. Variations in the strength and location of the westerly flow and circumpolar vortex occur on all time scales. An extreme example of this is blocking. It can occur in any sector, although most frequently in the Pacific and North Atlantic–European sectors. In the North Atlantic–European sector, the westerly flow occasionally breaks down over the eastern Atlantic and western Europe and high pressure cells or ridges move into the region usually occupied by westerlies. The westerly flow and the depressions moving in it are diverted north and sometimes south of the high pressure cell or ridge. This can persist for periods of days to weeks, often disappearing for a time only to reappear later, resulting in an apparent succession of waves of blocking activity. At the surface, a persistent anticyclone is usually located in middle to high latitudes.

The climatic effects of blocking are largely dependent on the location of the persistent anticyclone. In the British Isles, for example, both positive and negative temperature extremes can result from blocking over the eastern Atlantic and Europe. If the persistent anticyclone is located south of Iceland to the west of the British Isles, the anomalous northerly flow *around its eastern flank gives rise to negative temperature extremes.* If it is located over central Europe, the anomalous southerly flow gives rise to positive temperature extremes. During winter, severe weather may be experienced due to the easterly flow round the southern flank of a Scandinavian blocking anticyclone. The region beneath the blocking anticyclone experiences low rainfall in all seasons, although temperature effects vary from season to season.

There is a seasonal variation in the preferred location of surface blocking anticyclones. They are usually located over northern Europe in the winter half of the year and the northeastern Atlantic during spring. A major maximum in blocking frequency occurs during spring and a secondary maximum occurs in late October. There is some evidence of long-period variation in the frequency and preferred location blocking anticyclones (Brezowsky *et al.*, 1951). For more detailed discussions of blocking, see Berggren *et al.* (1949), Namias (1950), Rex (1950, 1951) and Sumner (1959).

3 *The atmospheric circulation during the drought of 1975–76*

We now describe the atmospheric circulation during the drought period. It is important to consider the whole northern hemisphere as the circulation over the North Atlantic sector may have been influenced by events elsewhere. In this section, we identify the major circulation anomalies that persisted throughout the drought period as shown by atmospheric circulation charts and statistics averaged over that period. All anomalies are relative to the 1951–70 standard. Miles (1977) has provided a comprehensive account of the northern hemisphere circulation during the drought period and we extract the following summary from his study.

On average, during the drought period, the Iceland low was centred to the southeast of Greenland and depressions penetrated further into Arctic regions than normal. The pressure anomaly map for the sixteen-month period (Figure 5) shows a region of negative anomalies over Greenland and near Novaya Zemlya and a region of positive anomalies over the British Isles, indicating the prevalence of anticyclonic conditions during the drought. The Azores high was located north of its usual position, particularly over the eastern Atlantic. The strength of the zonal flow through the mid-troposphere in the latitude band 35–55°N was above average in the Pacific sector and below average over the rest of the hemisphere; averaged over the whole hemisphere it was about normal. Further north, in latitude band 55–75°N, the hemispheric zonal flow was about 15 per cent above its normal strength. The major deviation in the latitude of the circumpolar zonal flow occurred near the Greenwich meridian where it was displaced about 10° latitude north. Most of the features of the mid-troposphere wave pattern were displaced slightly east during the drought period with the exception of the greatly intensified ridge over the eastern Atlantic, which was about 10° longitude west of normal.

Many characteristics of blocking can be found in the atmospheric circulation during the drought period: the northward displacement of the westerly zonal flow over the eastern Atlantic, the prevalence of anticyclonic systems over the British Isles, the intensification of the ridge over the eastern Atlantic. Deviations from this pattern did occur on shorter time scales within the sixteen-month period. Blocking occasionally gave way to periods of westerly flow over western Europe, and the precise location of the surface blocking anticyclone varied. On average, however, it was located over the British Isles, resulting in the considerable rainfall deficit as the depressions were steered elsewhere.

The drought can therefore be seen as a local response to a much larger scale abnormality in the atmospheric circulation: the blocking system which affected much of the North Atlantic–European sector. The enhancement of the North Pacific zonal flow was also a persistent feature of the drought period and we shall investigate whether this was related to events in the North Atlantic sector. Blocking is a fairly common phenomenon, although it is not usually as persistent and repetitive as it was during the drought period, and various hypotheses have been advanced in order to explain its occurrence. In section IV, we examine certain of these hypotheses and apply them to the drought of 1975–76. First, we look at the background to the problem of why climate changes.

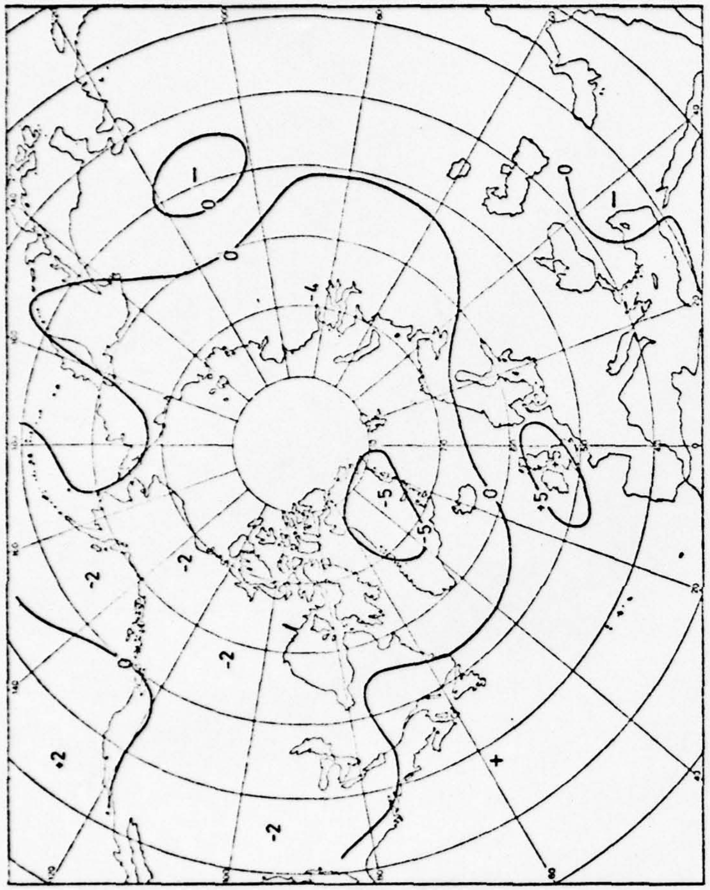

Figure 5 Surface pressure anomalies (mb) from the 1951–70 average for the period May 1975 to August 1976. *After Miles (1977).*

III The causes of climatic change

The main source of energy that drives the atmospheric circulation and shapes climate is the sun. The strength of the solar constant, that is the amount of energy reaching the top of the Earth's atmosphere, has only been measured directly for a limited period and it is not yet clear whether significant variations in this parameter occur. The distribution of solar radiation depends on latitude and time of year. On entering the atmosphere, the incoming solar radiation is subject to a series of transformations. About 50 per cent is absorbed by dust, water vapour, ozone or clouds, backscattered by air or reflected from clouds or the Earth's surface. On reaching the Earth's surface, the remaining solar energy is made available to the atmospheric circulation. It is either re-emitted as long wave radiation, which may be absorbed by water vapour and carbon dioxide, or transferred through the sensible and latent heat fluxes. Much of the outgoing long-wave radiation is emitted from clouds, water vapour and carbon dioxide. The net effect on the atmosphere is modified by geography. Topography constrains the wind flow, the characteristics of the Earth's surface affect the transfer of energy and the oceans act as mobile heat reservoirs. There is, therefore, a complex chain of events linking the solar output to the atmospheric circulation and variation in any component of this chain may disturb the energy balance and cause a climatic change. Even without a major change in the amount of energy made available to the atmospheric circulation at the Earth's surface (the boundary conditions), fluctuations may occur in the distribution of energy within the atmospheric circulation. It has been suggested that several stable modes of the atmospheric circulation can occur, given approximately similar boundary conditions.

The list of possible causes of climatic change is endless and there is as yet no consensus as to the most important factors. The solar output may vary. The atmospheric transmissivity may be altered by volcanic dust or pollution by man. The Earth's albedo may be altered by changes in snow and ice cover, vegetation, desert area. The distribution of cloudiness may vary. The carbon dioxide content of the atmosphere is being rapidly increased by human activity. Indeed, it is still held by some that climatic changes on the interannual time scale of the drought of 1975–76 are essentially random.

In the review of possible causes of the drought of 1975–76 in section IV, we concentrate on mechanisms within the climate system (the oceans, atmosphere and cryosphere) which could have led to or favoured the persistent blocking during the drought period. In particular, we discuss the contribution of sea temperature anomalies.

The top 100m or so of the ocean are thoroughly mixed by turbulence and convection, which means that any change in temperature is equalized through that depth; thus the ocean surface layer acts as a heat storage reservoir. Sea surface temperature anomalies sometimes persist for periods of months, allowing the atmospheric circulation time to adjust towards equilibrium with the changed boundary conditions. Snow and ice-cover anomalies can also persist for several weeks, due to the substantial latent heat required for melting. Long-lasting thermal anomalies at the Earth's surface, on land or sea, may affect climate directly, by modifying the overlying air masses, or indirectly, by the creation of anomalous thermal gradients, sources or sinks which may divert the track of the cyclones and enhance or weaken cyclonic development. Empirical studies of ocean-atmosphere interaction have led to the suggestion that *feedback* between ocean and atmosphere may play an important role in changing climate (see, for example, Namias, 1975a). If a similar pattern of sea temperature anomalies has occurred on a number of occasions in the past, a statistical analysis may be performed. Climatic parameters such as temperature, rainfall and pressure can be correlated with sea surface temperature anomalies in a particular region or composite maps of the atmospheric circulation can be formed for these periods when a similar sea surface temperature anomaly pattern occurred. In this way, theories of *positive feedback*, whereby a persistent oceanic thermal anomaly pattern reinforces the atmospheric circulation state that produced it, have been proposed. Such theories provide attractive explanations for the persistent nature of climatic events such as the drought of 1975–76.

It is, however, difficult to separate cause from effect in such situations. A pattern of sea temperature anomalies may occur in response to an atmospheric circulation abnormality, but may not reinforce that abnormality. It may act against and weaken the circulation pattern that produced it (*negative feedback*) or it may have no effect at all. Numerical modelling is providing a valuable means of assessing the importance of the ocean's role in climatic change.

Numerical models of climate and the atmospheric circulation are based on the fundamental equations of fluid dynamics and thermodynamics formulating the conservation of energy, mass and momentum. They vary greatly in sophistication. The simplest models use globally averaged parameters and consider only the vertical structure of the atmosphere. The most complex general circulation models consider the three spatial dimensions. The efficiency of these general circulation models is gradually being improved, although various problems have still to be solved (Barry, 1975). As far as ocean-atmosphere interaction studies are concerned, one of the most important defects is the lack of interaction between ocean and atmosphere in most models. The oceans can influence the atmosphere but cannot respond to changes in the atmospheric circulation. This problem is largely computational, arising out of the different time scales of oceanic and atmospheric motions. If a numerical model does provide an accurate simulation of the major features of climate or the atmospheric circulation, it can be used for climatic change experiments. The model can be run with a particular pattern of sea temperature anomaly included in the boundary conditions. The results can then be contrasted with those obtained from a control case: a run with the normal sea temperature distribution, or a different anomaly pattern, included. If there is a significant difference, it can be concluded that the particular sea temperature anomaly pattern is an important influence on the atmospheric circulation. There are however difficulties in assessing the significance of changes in the simulation results due to the lack of sensitivity in most models. Often unrealistically large anomalies have to be specified in order to obtain unequivocal results. One great advantage of numerical modelling lies in the detail of the simulations; the models produce far more information on the three-dimensional behaviour of the atmospheric circulation than it is possible to deduce from the limited data available for empirical studies.

The synthesis of the two approaches, one largely empirical and the other theoretical, is of great importance in the study of climatic change. Numerical models can be used to test hypotheses generated in empirical studies and empirical studies can be used to verify the numerical simulations of climate and the atmospheric circulation.

In the following section, we look in detail at the behaviour of the climate system during the 1970s. This system is so complex that it is impossible, and perhaps meaningless, to single out one cause of the drought of 1975–76. The best that can be done is to identify possible developments and interactions which may have been important and which warrant further investigation.

IV Possible causes of the drought of 1975–76

1 *Introduction*

The most comprehensive study of the causes of the drought of 1975–76 published to date has been presented by Ratcliffe (1977a). Ratcliffe has proposed that

> After the succession of mild European winters of the early 1970s with the main hemispheric coldness transferred to Canada and the North Pacific, the east Atlantic jet stream moved north and its apparent inertia aided by feedbacks from the Atlantic sea temperature and, perhaps also the excess ice cover in the North Pacific, maintained the situation. Another exceptional feedback may have arisen because of the extra sensible heating available to the atmosphere in the summer due to the greatly decreased evaporation and transpiration. The eventual break came with strong seasonal cooling in the Arctic initiating a discontinuous southward jump of the jet stream.

We use this hypothesis as a framework for the discussion of possible causes of the drought of 1975–76, and commence with a brief study of the events of the early 1970s which preceded, and may have set the scene for, the drought.

2 *The climate of the early 1970s*

Estimates of the mean temperature anomaly for the northern hemisphere indicate that during the early decades of the present century there was a net warming which culminated about 1940; during subsequent decades, cooling occurred (Mitchell, 1963; Budyko, 1969; Reitan, 1974). There have however been local and seasonal deviations from the hemispheric average. Van Loon and Williams (1976) have shown that the hemispheric average is dominated by changes in high latitudes in winter and middle latitudes in summer. Although evidence suggests that the hemispheric cooling trend has continued into the 1970s (Kukla *et al.*, 1977), Europe experienced a series of six mild or very mild winters from 1970–71 to 1975–76.

The immediate cause of this succession of mild winters lay in the strengthening of the North Atlantic atmospheric circulation, in particular the mid-latitude westerlies (Painting, 1977). In other seasons, however, the North Atlantic atmospheric circulation has not been enhanced during the early 1970s. In spring and autumn, pressure anomaly maps for the period 1971–74 (Painting, 1977) indicate increased blocking over the northeast Atlantic with positive pressure anomalies dominating the British Isles, in keeping with the rainfall deficit during this period discussed in section I. 3. Pressure was above normal over the northern North Pacific during the winters of the early 1970s implying a weakening of the Aleutian Low and decreased intensity of the mid-latitude westerlies. An anomalous northerly flow over the eastern Pacific produced cooling over Canada. This, coupled with the warmth of the European winters, tended to shift the main centre of polar cold towards the western hemisphere. The 1000–500 mb thickness anomaly map for the early 1970s has two main features: an extensive area of positive anomalies over Europe and the eastern Arctic and an area of negative anomalies over Canada (Figure 6).

Ratcliffe (1977a) has suggested that this large-scale shift in the position of the polar cold, and the temperature gradient between pole and equator, towards the western hemisphere may have eventually favoured a similar movement in the circumpolar vortex and mid-latitude westerly flow resulting in intensification of the North Pacific westerlies and the northward displacement of the North Atlantic westerlies which first became noticeable in the autumn of 1974 (Morris and Ratcliffe, 1976). This association, between a shift of the polar cold towards the western hemisphere and northward displacement of the westerlies and blocking in the North Atlantic–European sector, has been discussed on the day-to-day time scale by Flohn and Seidel (1958).

The hemispheric distribution of thermal anomalies in the atmosphere, shaped by the events of the early 1970s, was, therefore, such as to favour the intensification of the mid-latitude westerlies in the North Pacific sector, and the development of blocking with a high latitude westerly flow in the North Atlantic–European sector. Before considering possible relationships

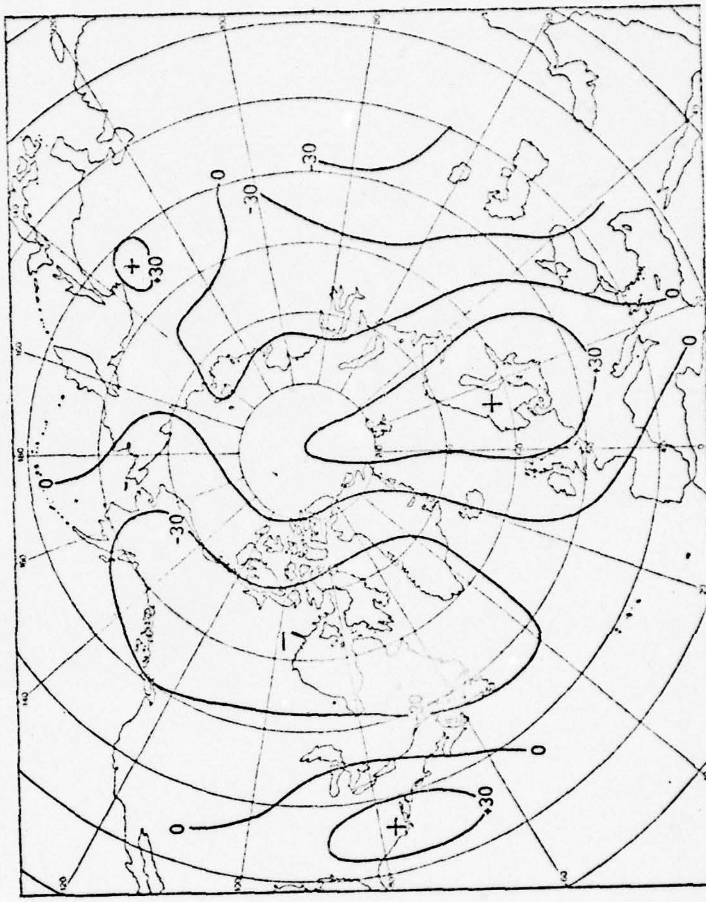

Figure 6 1000–500 mb thickness (gpm) in winter. Difference of averages, 1971–74 minus 1961–70. *After Painting (1977).*

between the atmospheric circulation in these two sectors, we discuss patterns of sea surface temperature anomaly in the North Pacific during the early 1970s and the drought period which may have also influenced the circulation in that sector.

3 *The temperature of the North Pacific Ocean*

The northern North Pacific was colder than usual throughout the 1970s and its temperature in 1976 dropped to the lowest August value since 1949 (Kukla *et al.*, 1978). This coldness was probably a result of the winter severity and enhanced anticyclonicity of the early 1970s in the Pacific sector: the enhanced anticyclonicity implying greater heat losses associated with decreased cloud cover. The coldness of the ocean may in turn have tended to reinforce the anticyclonicity. Namias (1969) has suggested that such an area of cold water could enhance anticyclogenesis, particularly in autumn, by increasing the stability of the overlying air and reducing the outflow of air from the anticyclone's friction layer. Rapid oceanic cooling experienced during mid-1975 and 1976 may have been due to the melting of the excessive ice covers of the previous winters (Ratcliffe, 1977a).

Ratcliffe (1977a) has noted the coldness of the northern North Pacific during the drought period and suggests that the area of large negative sea temperature anomalies in the northern North Pacific in conjunction with an area of positive anomalies to the south (Miles, 1977) strengthened the north–south 1000–500 mb thickness gradient in that sector, thereby enhancing the mid-latitude westerlies. Data were not available at the time of writing in order to trace the development of this pattern of sea temperature anomalies and it is therefore not possible to determine whether it was a feature of the early 1970s as a whole or the drought period alone. If the former, the effects of this pattern of strengthened north–south thermal gradient would tend to offset the action of the northern cold pool in stimulating anticyclogenesis throughout the early 1970s. If the latter, the development of the southern warm pool may have heralded a change in the atmospheric circulation of the Pacific sector from weak zonal flow, which characterized the pre-drought period, to the stronger zonal flow characteristic of the drought period.

Much attention has been given to variations in the temperature of the equatorial Pacific Ocean and their possible effects on the atmospheric circulation and climate. The sea in the Indonesia/West Pacific sector is always warmer than that in the central and eastern Pacific, and the resulting temperature gradient favours a *Walker circulation* in which air ascends over Indonesia giving rain, air descends over the East Pacific giving dry weather, and lower tropospheric easterly winds give dry weather in the intervening sector because they favour divergence (Gordon and Taylor, 1972). The cold sea is maintained by upwelling along the Equator together with advection from the southeast where winds blow from the cold Humboldt current flowing north along the South American coast. This region of relatively cold sea has interesting patterns of behaviour. It exhibits substantial surface temperature anomalies (up to 2 degC) coherently over the whole area 10N–10S, 90–180W, and these anomalies often persist for several seasons. When the ocean surface is warmer than usual, the temperature gradient along the Equator is reduced and so is the strength of the easterlies: the dry region receives more rainfall than usual, while Indonesia receives less. Conversely, when the sea is colder than usual, the normal rainfall contrasts are less. The variations in the atmospheric circulation and climate associated with variables in the equatorial sea surface temperature are known as the *Southern Oscillation*.

Correlation studies have revealed widespread associations with the Southern Oscillation, even as far away as the North Atlantic sector. Bjerknes (1966) has proposed that the temperature of the equatorial Pacific can affect the strength of the mid-latitude westerlies in the Pacific sector and that this may in turn influence events in the North Atlantic sector. During the winters of 1940–41, 1957–58, 1963–64 and 1965–66, the easterly winds over the eastern equatorial Pacific were abnormally weak and the consequent reduction in the upwelling of cold water resulted in a temperature anomaly of +2–3 degC in that region: the El Nino phenomenon, one aspect of the Southern Oscillation. The increased heating of the equatorial atmosphere strengthened the meridional trade circulation, and thermally driven Hadley cell, and led, Bjerknes argues, to an intensification of the zonal flow in Pacific mid-latitudes, anomalous troughing over the eastern Pacific and deepening of the Aleutian Low. In the North Atlantic sector, weakening of the *mid-latitude* westerlies was observed.

Bjerknes' hypothesis, based largely on case studies of a few extreme events, has been tested empirically by Namias (1975b) and in a numerical modelling experiment by Rowntree (1972). The model was run with warm and then cool equatorial Pacific sea temperatures; the anomalies were slightly larger than generally observed in order to intensify the model's response. The experimental results agreed well with Bjerknes' hypothesis and reproduced many features of the Southern Oscillation. Unfortunately, no firm conclusions could be drawn about downstream effects in the North Atlantic sector. The increased detail of the model's output, compared to the often scanty data available for empirical studies, allowed Rowntree to elaborate a mechanism through which interaction between the tropical and extra-tropical atmosphere could occur.

The equatorial Pacific experienced two warmings during the drought period of 1975–76 (Quinn, 1976) and this may therefore have been another factor contributing to the intensification of the Pacific zonal flow. Warming also occurred in 1972–73 (Miller and Laurs, 1975)—also a period of deficient rainfall in England and Wales (Figure 1).

The temperature of both the tropical and extra-tropical Pacific then tended to increase the strength of the mid-latitude westerlies in that sector during the drought period. We examine next whether this could have led to a decrease in the strength of the North Atlantic atmospheric circulation.

4 *Interaction between the North Pacific and North Atlantic sectors*

The atmospheric flow at mid-troposphere level takes the form of a circumpolar series of troughs and ridges. These waves are controlled to a large extent by surface geography and temperature. Mountains favour an overlying ridge and a trough downwind, providing a control throughout the year. The Rocky Mountains, for example, favour a trough over eastern Canada. It is present throughout the year, but greatly intensified during winter by the cold continental surface. For dynamical reasons, each trough favours another trough at some distance downwind. Sometimes a system of troughs and ridges will 'lock' into place with the surface features (such as a sea temperature anomaly pattern), resulting in a stable pattern which can persist for some time and may affect more than one sector of the hemisphere. In this way *teleconnections* can arise as forcing of the atmospheric circulation in one sector influences the flow in another, generally downstream.

Principal component or eigenvector analysis provides a useful means of determining such teleconnections. A set of data distributed in time and space (for example, a series of mean sea level pressure maps) can be transformed by this technique into a number of independent principal components or eigenvectors, which represent spatial anomaly patterns (typical pressure anomaly patterns), and a series of coefficients or scores, which represent the contribution of each anomaly pattern to the observed pattern at each time step.

Kutzbach (1970) calculated the principal components of 70 years of Northern Hemisphere mean sea level pressure data for January and July. The most frequent January anomaly pattern and the second most frequent July pattern represented an inverse relationship between the strength of the mid-latitude westerlies in the North Pacific and Atlantic sectors, providing a confirmation of part of Bjerknes' hypothesis. Ratcliffe (1977a) reports that when the flow in mid-latitudes of the east Pacific during summer was enhanced (a sample of 14 years), the mean summer rainfall over England and Wales was about 80 per cent of the average of 8 summers when the flow was below normal. The 'enhanced' sample of summers was also significantly more anticyclonic over the British Isles. Lamb and Johnson (1959) have also noted the inverse relationship between the flow in the two sectors and have suggested a physical explanation. When the Pacific circulation is strong, warm air may be repeatedly advected over North America and may lessen the normal wintertime intensification of the Canadian trough thereby weakening the atmospheric flow over the North Atlantic. This was apparently the situation during the drought period, although during the winters of the early 1970s, the opposite appears to have occurred. It should be noted however that Kidson (1975), in a principal component analysis of monthly pressure data on a global grid, found a weak tendency for the Southern Oscillation to be associated with weakening and strengthening in the *overall* circumpolar flow, in contradiction of Bjerknes' hypothesis. The analysis was based however on a limited sample of years and the association was not strong.

There is then a tendency for increased flow in the Pacific sector to be associated with weakened flow in the Atlantic sector. We now look at conditions in the Atlantic sector during the drought period and determine whether they were such as to favour and reinforce the weakening and northward displacement of the zonal flow.

5 *Surface conditions in middle latitudes of the North Atlantic–European sector*

Blocking patterns were particularly frequent over northern Europe during the late 1950s. A prolonged drought affected Scandinavia and was particularly intense during autumn months. Namias (1964) has studied this event in detail and concludes that two major factors contributed to the persistent nature of the blocking: an anomalous sea temperature gradient in mid-latitudes of the North Atlantic Ocean and anomalous snow cover over Scandinavia.

During the blocking period, which lasted from late 1958 until late 1960, an anomalous sea temperature gradient had been set up between the west (cold) and east (warm) Atlantic Ocean in middle latitudes. By altering the orientation of the baroclinic zone, this favoured an abnormal southerly component to the thermal wind over the central Atlantic. This would tend to increase cyclogenesis and steer the depressions along a more northward track. Inertial effects then produced an intensified ridge over the eastern Atlantic and blocking anticyclones over Scandinavia. This pattern of the atmospheric circulation would tend to reinforce the anomalous sea temperature gradient, by enhancing northward advection of warm water in the eastern Atlantic and through the increased cyclonicity and anticyclonicity over the western and eastern Atlantic respectively, resulting in positive feedback between atmosphere and ocean.

Other authors have noticed a tendency for sea temperature anomalies in the west and northeast Atlantic to vary in a contrasting way (Zverev, 1972; Rodewald, 1963). Dickson (1971) has studied the occurrence of a four to five-year cycle in the salinity of the European shelf seas. He shows that periods of high salinity were associated with the occurrence of the atmospheric circulation pattern discussed by Namias. The increased southerly wind component over the eastern Atlantic advected greater amounts of more saline oceanic water into the shelf seas and the reduction in precipitation and evaporation during the anticyclonic blocking spells also contributed to the salinity increases. The anomalous temperature contrast between the west and east North Atlantic Ocean during the period 1949 to

1976 is shown in Figure 7. It can be seen that there is fair agreement between the times of increased thermal gradient between the western and eastern sectors and the times of increased salinity in the European shelf seas (S) and drought in England and Wales (D). There is a significant correlation between this anomalous thermal gradient across the North Atlantic and the degree of cyclonicity over the British Isles (−0.52) and rainfall in England and Wales (−0.41). Since 1970, the east Atlantic has been consistently warmer (in an anomaly sense) than the west Atlantic. This may have been a factor contributing to the increased anticyclonicity and rainfall deficit of the early 1970s.

There is then a fair amount of evidence suggesting a link between this anomalous thermal gradient between west and east Atlantic and increased blocking over western Europe (see also Vinogradov (1967), Ratcliffe and Murray (1970), Oerlemans (1975)). This sea temperature anomaly pattern was present during the drought period (Perry, 1976; Miles, 1977). To what extent this distribution of sea temperature anomalies produced or was produced by the accompanying atmospheric circulation pattern is, however, difficult to resolve. Modelling experiments would certainly clarify the situation. Houghton *et al.* (1974) have modelled the atmosphere's response to North Atlantic sea temperature anomalies, but the anomalies they specify (in a limited region about 40°N 60°W) do not correspond well with those observed during the drought.

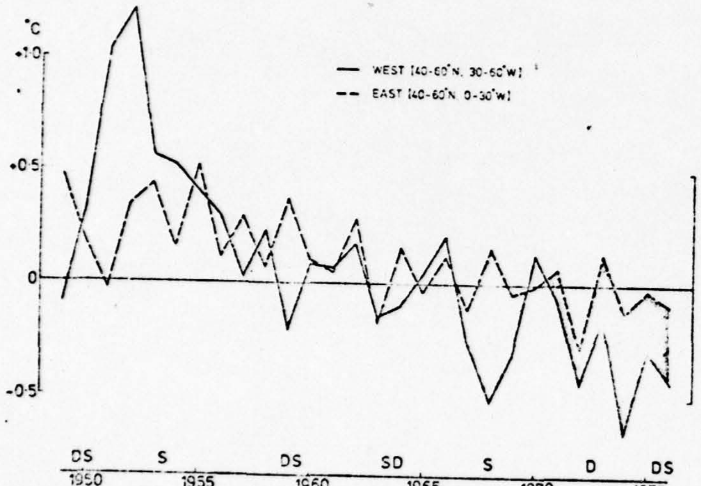

Figure 7 Sea temperature anomalies (degC) from the 1949–72 averages for the western and eastern North Atlantic. *Data from Meteorological Office, UK.*
Hatching indicates times when a notable gradient existed in the anomalies across the northern Atlantic.
D indicates times of drought in England. *From Tahony (1977).*
S indicates times of maximum salinity in the European shelf seas. *From Dickson (1971).*

Namias (1964) also suggested that reduced snow cover over the Scandinavian peninsula may have reinforced the blocking tendency during the late 1950s. Snow cover during the winter half-year was considerably reduced during the blocked period with the result that the Scandinavian peninsula warmed more than usual during the summer half-year. This increased warmth may have allowed a stronger monsoon effect to develop and the associated upper level anticyclone would have reinforced the blocking tendency. The series of mild European winters of the early 1970s may have produced a similar effect during the drought of 1975–76. Ratcliffe (1977a) suggests that the dryness of the ground during 1976 may have caused the blocking to persist. Eighty to ninety per cent of the incoming solar radiation was available to heat the ground during the summer of 1976 instead of the usual 50 per cent. (The dryness reduced the amount of radiation used in evaporation and transpiration.) The resulting atmospheric warming then increased the anomalous thermal gradient across the northern North Atlantic reinforcing the ridge over the eastern Atlantic and western Europe. Wright (1977) has argued in a similar fashion that the ridge favoured advection of warm air, clear skies and maximum insolation which maintained the ridge against its tendency to decline due to radiative cooling. Green (1977), however, argues that warming of the troposphere in this way should lead to increased cyclonicity, not anticyclonicity, at the surface.

The surface conditions in the North Atlantic sector were then such as to favour blocking during the drought period of 1975–76, although it is difficult to determine to what extent they were cause and to what extent effect. We now look at the possibility that the atmospheric circulation could be self-maintaining in a blocking configuration such as occurred during the drought period, regardless of surface conditions or other external forcing.

6 *Dynamical considerations*

In considering the state of the atmospheric circulation averaged over the drought period, features on much shorter time scales, such as the day-to-day development and progression of depressions and anticyclones (the transient eddies), have been smoothed out. These transient eddies are important in that they transfer heat from equator to pole thereby reducing the thermal imbalance. It has been argued that blocking occurs when the transient eddies can no longer cope with an increased thermal difference between equator and pole. The more meridional flow patterns common in blocking events, then take over the role of the transient eddies. Transient eddies also transfer momentum equatorwards at high latitudes. Green

(1977) has used this as a basis for an explanation of the maintenance of the blocking, once established, during the drought.

During July 1976, the westerly flow took two paths to the north and south of the British Isles. The British Isles was dominated by a persistent anticyclone. Green calculates that the transient eddies in the northern branch were injecting westerly momentum into the air north of the British Isles, where it was not being removed, thereby producing eastwards acceleration of the air. To the south of the British Isles, however, westerly momentum was being removed by the transient eddies in the southern branch of the westerly flow and not replaced, producing a westwards acceleration of the air. The net effect was an enhanced anticyclonic circulation over the British Isles. Green concludes that this mechanism was sufficiently powerful to establish the observed anticyclone in a few days.

7 *The end of the drought*

Ratcliffe (1977a, b) has described the dramatic changes in the atmospheric circulation that accompanied the ending of the drought. By August 1976, the main westerly flow over the North Atlantic was far north of its usual position. In late August, the first signs of seasonal cooling appeared over northern Canada as an outbreak of cold Arctic air presaged a shortening of the wavelength across the North Atlantic. Intense troughs formed over eastern Canada and western Europe during early September and the main westerly flow shifted abruptly south to about 50°N. These changes in regime heralded the exceptional rains of September and October: only surpassed in 1903 in recent times. The high sea temperatures around the British Isles, produced by the warm anticyclonic summer, probably contributed to the heavy rains of these months by increased sensible and latent heat and moisture transfer to the overlying unstable air.

The seasonal warming and cooling and the changes in the atmospheric circulation that result from the annual variation in the distribution of solar radiation at different latitudes are often neglected in studies of climatic change. These processes however operate continually and must interact with any climatic change. The end of the drought appears to have been a good example of this interaction. The northward displacement of the North Atlantic westerly flow could no longer be maintained against the 'normal' seasonal development of the atmospheric circulation. It is notable that the drought was also interrupted during September of the previous year when a shortening of the wavelength across the North Atlantic brought rain and cold air advection to western Europe.

Ratcliffe (1977b) also suggests that the sea temperature anomaly distribution may have aided the persistence of the new regime once it had been established. An anomalous thermal gradient had developed between 40°N 30°W (cold) and 35°N 20°W (warm), in such a position as to favour cyclogenesis in the region forward of the trough to the southwest of the British Isles. He also notes the simultaneous appearance of an area of positive sea temperature anomalies off northwest Africa. The results of a numerical modelling experiment suggest that such an anomaly in tropical regions tends to induce a fall of pressure about 45°N (Rowntree, 1976).

V Conclusion

The drought of 1975–76 in western Europe was a particularly severe event, unprecedented in the light of the longest rainfall records for the region. Nevertheless, it should not be viewed as an isolated event. There has been a tendency towards decreased rainfall, and increased anticyclonicity, throughout the early 1970s and the drought represented a short-term intensification of this regime. The immediate cause of the drought was *persistent and repetitive blocking in the North Atlantic–European sector* with a focus of enhanced anticyclonic activity centred over the British Isles.

The drought can be seen as a stage in the chain of climatic events that was initiated by the hemispheric wide climatic anomalies of the early 1970s. The cooling of the Pacific sector and the mildness of the European winters produced a thermal distribution on a hemispheric scale which was conducive to a northward displacement of the North Atlantic flow and blocking in that sector. Once this had been established, a number of factors then acted in concert to maintain this atmospheric circulation configuration:

1. The sea temperature anomaly distribution in the tropical and extratropical Pacific Ocean enhanced the zonal flow in that sector which then favoured blocking downstream over the North Atlantic and Europe.
2. The sea temperature anomaly distribution in the North Atlantic Ocean also favoured the maintenance of blocking over the eastern North Atlantic and Europe.
3. The characteristics of the surface in the region of British Isles (the dryness, in particular) increased the stability of the anticyclonic regime.

The relative importance of these factors is, however, difficult to establish. As well as possibly influencing the atmospheric circulation, they were all influenced *by* the atmospheric circulation.

During August 1976, the atmospheric circulation configuration responsible for the drought had reached an extreme stage and became unstable. With the onset of seasonal cooling during early autumn, the atmospheric circulation pattern could no longer maintain itself against the usual seasonal development of the atmospheric circulation; an abrupt transition occurred and the drought ended.

In reviewing possible causes of the drought, we have intentionally concentrated on mechanisms within the climate system. This is not to say that external factors such as volcanic activity, solar activity and pollution should be neglected in the search for the causes of climatic change. However, the lack of agreement amongst climatologists concerning the action of these factors on the atmospheric circulation and climate is such as to make it impossible to do justice to the topic in an article of this length. External factors may have been important in the development of the thermal anomalies of the early 1970s which set the scene for the drought. In particular, we note that the level of volcanic dust in the stratosphere was low throughout that period (Russell *et al.*, 1976 Lamb, 1977).

We draw two general conclusions from this study. First, we note that if the climatic anomalies of the early 1970s did set the scene for the drought of 1975–76, by producing a distribution of thermal anomalies conducive to blocking in the North Atlantic–European sector, as suggested by Ratcliffe (1977a), then this implies a limited forecasting ability. Limited in the sense that the precise timing and location of the blocking situation could not be forecast, but a tendency towards the establishment of such a situation could have been anticipated. We stress, therefore, the importance of continual monitoring of all aspects of the climate system. Second, we note the importance of the synthesis of the empirical and theoretical, and particularly the numerical modelling, approaches to the problem of climatic change. The application of numerical modelling to climatic change is still at an early stage but this approach is potentially of great value. A problem underlying many of the hypotheses that have been discussed in this article is that of defining cause and effect between potentially interactive components of a system such as the ocean-atmosphere. Numerical modelling can provide valuable additional evidence in determining the importance of changes in the atmosphere's boundary conditions.

The importance of studies of extreme climatic events such as the drought of 1975–76 cannot be over-emphasized. Mankind may adapt to and cope with slow, low magnitude long-term shifts in climate but the ability to cope with changes in the frequency and magnitude of short-lived climatic extremes, which accompany many longer-term climatic changes, is considerably less.

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ABSTRACT

Studies of climate, wind and ocean currents over the last 1000 years

Prof. H.H. Lamb.   To be published in Quaternary Research

Study of the various sorts of data (thermometer measurements since 1867 and in 1789, ice reports and fisheries records) indicating the variations of surface temperature, currents and watermass in the sea areas between Iceland, Scotland and Norway has revealed long-term variations of 5-year mean water temperature about the Faeroe Islands which greatly exceeded the variations of air temperature over land in England and continental Europe in the last 100 to 300 years. Examination of the reported snow and ice conditions in northern Scotland and southern Norway appears to support the diagnosis, indicating that in the extreme phase between about 1675 and 1705 the ocean surface between Iceland and the Faeroes was dominated by the polar water from the East Greenland Current and was generally about 5°C colder than the twentieth century average. The lowering of average air temperatures in the upland regions of northern Scotland and southern Norway at that time seems to have been 2 to 2.5°C or about twice as great as in the lowlands of England and central Europe.

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ARCTIC ICE, ATMOSPHERIC CIRCULATION AND WORLD CLIMATE

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After a brief outline of the known history of the Arctic ice and of its interactions with the general wind circulation, an account is given of the transport and redistribution of heat over the Earth which largely determines the Arctic climate and the patterns of climate prevailing at any given time over the rest of the globe. The remaining sections are concerned with the Arctic ice and other variables as an indicator of the state of the current global climatic regime. Recent climatic fluctuations (and some historic ones) are briefly reviewed in the light of these considerations.

THE VARIATIONS of the Arctic sea ice have attracted much interest in recent years, both because the changes during this century have been big and because the era of satellite observations and transpolar flying has made it possible to keep the ice under continual survey. Apart from its importance to the northern fisheries, to shipping and to the economies of the countries closest to the ice-belt, there has long been a notion that the Arctic ice may provide a useful indicator of the state of world climate. It is the purpose of this paper to examine that proposition and particularly in relation to the changes in recent years.

The question is often raised nowadays because of the general concern about climatic change and the future of world climate (see, for instance, *National Academy of Sciences*, 1975). After many decades in which it was generally assumed—and taught—that climate could for practical purposes be treated as constant, it was Ahlmann who in this journal (*Geogrl J.* **112** (1949)) drew widespread public attention to the fact that a very significant warming of world climate had been *going on more or less* throughout the first half of this century, particularly from 1920 to 1940. The reversal of this trend that followed, particularly between 1955 and 1965, and the remarkable incidence since 1960 of many kinds of extreme weather in many parts of the world, going beyond the statistical expectations based on the data of the so-called climatic 'normal' periods between 1900 and 1960, have created concern amongst planners in agriculture, industry and trade. This confronts meteorology and climatology with demands for advice which the state of the science has been in no way ready to meet. There is also understandable anxiety about the possible impact of the increasing scale of Man's activities, mostly supposed to be in the direction of warming, upon the world climatic regime. In 1976, the World Meteorological Organization issued a statement suggesting that a drastic warming of world

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climates from this cause (especially Man's production of carbon dioxide) must be expected to set in before the end of the century, and might already have begun, leading ultimately to disappearance of the Arctic ice, melting of ice caps, rise of sea level and *great shifts of the natural vegetation and crop belts*. In this situation, there is much sense in looking for a reliable indicator (or indicators) of what is actually going on.

The past history of the Arctic ice has been described by many authors, for example Koch (1945), Ahlmann (1949) and Lamb (1972b, 1977). There is reasonable agreement (e.g. Manley, 1951; McIntyre *et al.*, 1976) about its very great extent in the last major glaciation 17–22 000 years ago, covering the North Atlantic at least seasonally to latitude 50°N (and in places farther south), though there was less change in the Pacific. At the other extreme, although it now appears that the central Arctic Ocean has never been ice-free in the last 70 000 years or more (Hunkins and Kutschale, 1965; Ku and Broecker, 1965), the marginal areas around the Canadian archipelago and Greenland, and off the Siberian coast, seem to have become ice-free during the warmest post-glacial times about 5000 years ago (e.g. Flohn, 1973; Koerner and Paterson, 1974). Similarly, the ice more or less disappeared from the sea areas around southern Greenland and Iceland in the warmest centuries of the early Middle Ages. Thereafter it increased again until, in 1695, Iceland was surrounded for some months by such a broad area of ice that open water could not be seen, even from the tops of the mountains. These great variations of climate within the past thousand years are known to have been essentially a world-wide phenomenon. Once again in the present century, a period of global warming—this time very fully documented—was accompanied between 1920 and the late 1930s by a dwindling of the Arctic ice area, generally estimated to have been by about 10 to 15 per cent. (An assessment of the total area of the ice yearly from 1901 to 1955 is given in Lamb (1977), as well as a tabulation of the incidence of the ice reported each year in Iceland up to 1975.) There is no reasonable doubt, therefore, that the extent of the Arctic sea ice has varied hand-in-hand with the gross changes of global temperature level.

It should, therefore, be worthwhile to examine the recent changes and build up some knowledge of the shorter-term variations to which the ice is liable. Not all of these may be of the same significance because of accidents caused by the interplay between the ice distribution and storm activity, which sometimes breaks away (and, in effect, destroys) more or less extensive marginal areas of ice. It is not certain yet how important the effects of such mechanical accidents may be, or how long they may last: but a persistent deficiency of the incoming radiation, due, for instance, to volcanic dust in the stratosphere, or to a solar fluctuation, would presumably sooner or later restore something like the previous balance. The strongest thermal gradients at the Earth's surface occur near the ice limit, and these affect the occurrence and intensity of jetstreams in that region in the overlying atmosphere. These in turn control and steer the development of anticyclones and cyclones, and some of the latter produce the storms that disturb the ice distribution. The influence upon the ice of changes in the large-scale atmospheric circulation, due to whatever cause, seems to be very marked; the distribution of the main floating mass of the Arctic polar ice seems to undergo shifts in response to shifts of the circumpolar vortex in the atmosphere. Through the rapid losses of ice blown away in storms, the rapid advances of the ice impelled by more moderate northerly surface winds, and the slow growth of ice in calm regions under low temperatures, the main Arctic pack-ice mass apparently tends, despite its obvious inertia, to develop a distribution concentric with the circumpolar vortex in the atmosphere, whatever shifts the latter undergoes. In this way, it becomes subject to shifts and changes over a few weeks, months or years at a time. These appear to be triggered by shifts of the atmospheric vortex, only some of which are attributable initially to storms generated near the ice margin.

To gain the perspective needed to understand this hierarchy of processes, we must consider briefly the global make-up of the climatic regime.

How the climatic regime is maintained

The main items that determine the climatic regime may be grouped as follows:

1. The balance between the heat gained and lost by incoming and outgoing radiation.
2. The heat and moisture transported about the Earth by the winds.
3. The heat transported by the ocean currents.
4. The water cycle—evaporation, transport, condensation, downput, seepage, storage, and runoff—the vigour of the cycle being controlled by the winds and ocean currents and temperature levels prevailing.
5. The characteristics of the surface: extent of land, water, snow and ice surfaces, vegetation, waterlogged and parched ground, and the topographical effects (friction, channelling, etc.) on the winds.

All these items vary with time and all are affected in various ways, over longer or shorter periods, by feedbacks produced by the weather itself, for example, the distribution of clouds, snow and ice.

Averaged over the seasonal round of the year, or any longer period, the polar regions lose more heat by radiation to space than they gain from the sun. There must therefore be a continual poleward transport of heat within the Earth-atmosphere system if polar temperatures are to be maintained at whatever level is characteristic of the epoch. This poleward transport of heat is effected largely by the general circulation of the winds, but partly also by the circulation of the oceans. Overall, the proportion of heat transfer accounted for by the oceans seems to be between a fifth and a quarter. Within the tropics, it is more than half of the whole, whereas at 55°N it is only about 10 per cent (Sverdrup, 1955; Vonder Haar, 1973). These figures are averages for the latitudes mentioned: in the Norwegian Sea, with its meridionally orientated ocean currents, the ocean heat transport must be substantial, but its amount and its proportion of the whole must also vary greatly with time, as the strength of the warm, saline North Atlantic Drift and of the polar current off East Greenland vary—the latter apparently by up to a factor of 10 (and probably more than that).

There are two kinds of mechanisms which achieve the poleward flux of heat in the atmosphere. One is large-scale air circulation in the vertical meridional (i.e. north-south) plane, a sort of massive overturning of the atmosphere over some range of latitudes; the other is the heat exchange associated with the horizontal eddies (cyclones, anticyclones etc. and the meandering of the main airstream over middle latitudes), in which the heat flux is not accompanied by any net flux of air in the meridional direction. The first kind of process is prominent in the transport of heat from equatorial to subtropical latitudes in the 'Hadley cells' of the general atmospheric circulation, as illustrated in Figure 1 for the Northern hemisphere. The circulation is also assisted by the release of large amounts of latent heat of condensation in the deep convective clouds over

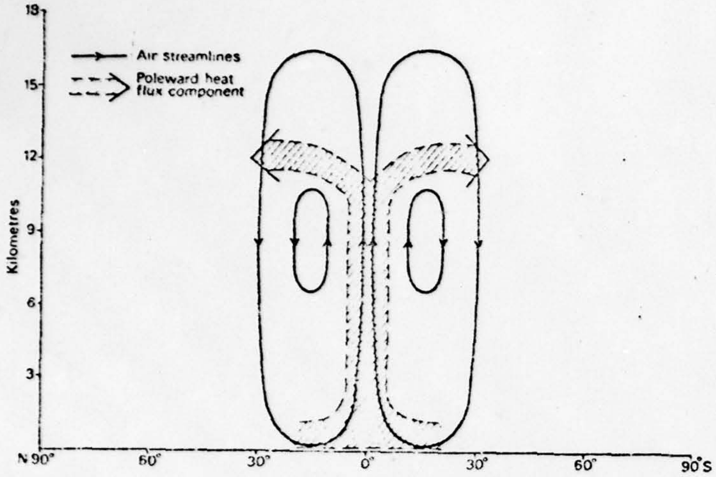

Fig. 1. The Hadley circulation and associated heat flux over tropical and subtropical latitudes (schematic north-south section)

low-latitude regions. The 'Hadley circulation' achieves a massive flux of heat from the surface to the upper troposphere of the tropics. No such direct meridional mass circulation cell exists across the middle latitudes. There, the atmosphere resorts to another mechanism for the transport of heat: horizontal eddies.

Owing to the mean temperature distribution set up in the lower atmosphere by the difference of heating between low and high latitudes, which raises the mass *of the upper atmosphere over the heated zone, there are* permanent upper westwind vortices around the poles. This huge wind circulation extends from near the pole to subtropical latitudes, but is strongest over middle latitudes. The strength and extent varies with season and altitude. The vortex is more extensive in winter and spring than in the other seasons. Wind speeds increase from the surface with increasing height up to 10–12 km above the ground, where they usually reach a maximum. This great wind system exhibits wave motions on various scales from small-amplitude waves up to huge meanders extending from high latitudes to the tropics. During periods of large-scale meandering, the horizontal waves interact with the Hadley circulation of the tropical zone, taking heat from the subtropical and tropical latitudes. Since the meandering has its greatest meridional extent at the level of maximum wind (about 12 km), a large proportion of the heat abstraction from the tropics occurs at high tropospheric levels. The resulting heat flux, due to the poleward-directed flow elements in the meanders, is indicated in Figure 2.

The poleward boundary of the meandering of the main flow of the circumpolar vortex is generally in subpolar, occasionally in even higher, latitudes. Thus, the mechanism of heat transport by horizontal eddies may extend over 40 degrees of latitude or more. The poleward heat flux is related directly to the number and amplitude of the waves, as well as to the strength of the wind in the circumpolar circulation. All over the belt of circumpolar 'westerlies'—the wind direction

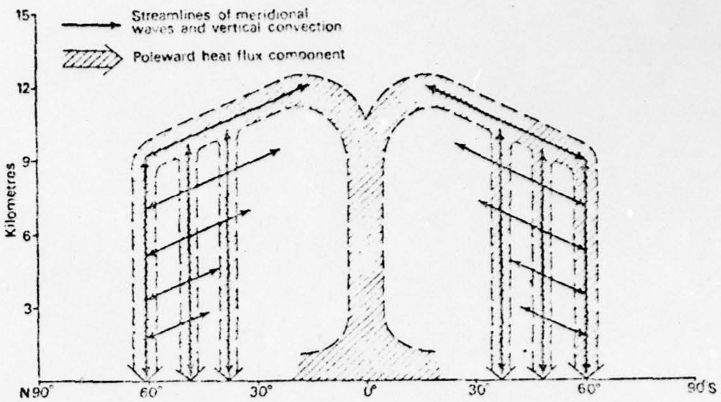

Fig. 2. Heat transport and atmospheric circulation over middle latitudes (schematic north-south section)

actually varies greatly in the course of the meanders—there occurs a redistribution of heat throughout the lower parts of the troposphere by vertical mixing in convective cells associated with individual clouds and with synoptic weather systems (cyclones, anticyclones etc.). *The vertical temperature distribution in the* lower atmosphere is mostly stable—the potential temperature* increases with height—so the heat flux in middle and high latitudes must be directed downwards. One might expect that the cumulative effect of heat detraction farther and farther from the equator would lead to a poleward decrease of temperatures at the level of maximum wind. However, this is commonly not observed. Generally, the temperatures are approximately constant from the equator to middle latitudes along the 250 mb level, because of the horizontal heat flux convergence towards the higher latitudes, due to the spherical nature of the Earth. Release of latent heat of condensation of the moisture carried contributes to the effect.

It now remains to discuss how the heat, which has been transported from the tropics by the meanders in the upper wind circulation and distributed through the troposphere over middle latitudes by convective motions, may reach the polar regions. Convective vertical transport of heat cannot play a major part, since the stability of the polar air usually does not allow deep convection, except over warm open seas, such as the Norwegian and Barents Seas and Gulf of Alaska. Also, daily upper windflow charts show that the meanders of the circumpolar upper windflow do not often reach the central Arctic near the pole. Rather, one must look for a mechanism of heat exchange between polar and middle latitudes through mass overturning of air, similar to the Hadley circulation of the tropics. One mechanism powerful enough to drive such a meridional heat exchange is provided by the disturbances developing along the polar front. This airmass boundary is a near-horizontal layer separating the cold polar air at the bottom from the warmer, middle latitudes air above. This frontal transi-

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* The potential temperature is the temperature the air would acquire if brought down adiabatically to the level of standard atmospheric pressure (1000 millibars) near sea level.

tion zone, which generally covers a width of a few degrees of latitude, meanders around the hemisphere in the same way as the upper windstream, with which it is in principle associated. There are marked seasonal variations in the mean *latitudinal position of the frontal zone*, and in the intensity of the temperature contrast across it. At the surface, the mean latitude varies from about 44–48°N in winter to 65–71°N in summer (Defant, 1976); the temperature contrast is greater in winter and spring than in summer and autumn.

Although the temperature stratification at the polar front is basically stable (cold air below, warm air above), instability can rapidly develop in the wave-like interactions of one airmass flowing alongside the other. Polar-front wave disturbances develop within a few days into major systems (polar-front cyclones), which bring together large volumes of air flowing on either side of the polar front, producing some mixing and modification of the airmasses within the frontal zone. (In comparison with the greater scale of the main circumpolar vortex, these individual cyclonic vortices are considered as eddies.) Polar-front cyclones thus provide for the exchange of large amounts of heat between middle and high latitudes across the polar front. The mass circulation and heat transport in a polar-front depression are sketched in Figure 3.

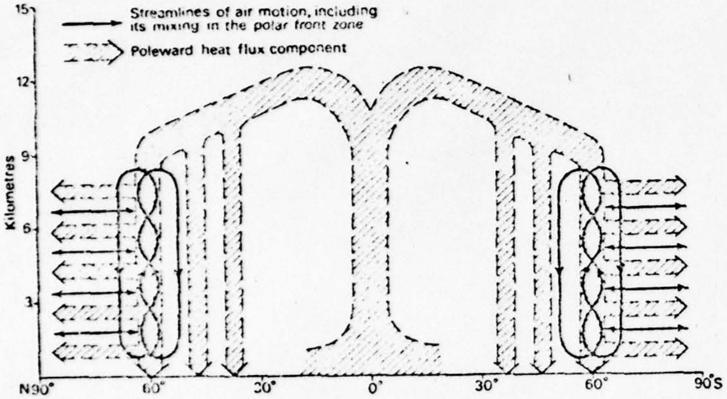

Fig. 3. Heat transport and atmospheric circulation over higher latitudes (schematic north-south section)

Since net uplifting of air takes place on a large scale within the polar-front cyclones, there must be equally massive sinking of air elsewhere to keep the mass balance. These sinking motions take place partly in the warm air to the equatorward side of the polar front and partly in the cold air, poleward of the polar front. In both the latter situations, the flux of heat is downward. In the presence in middle and higher latitudes of a number of large, polar-front cyclones, a large part of the polar regions may be dominated by compensatory subsident air motion. It is of interest to note that the flux of water vapour into the central Arctic is strongest in summer, when the ring of circumpolar westerlies has contracted most; and the water vapour contributes to the absorption of radiation there.

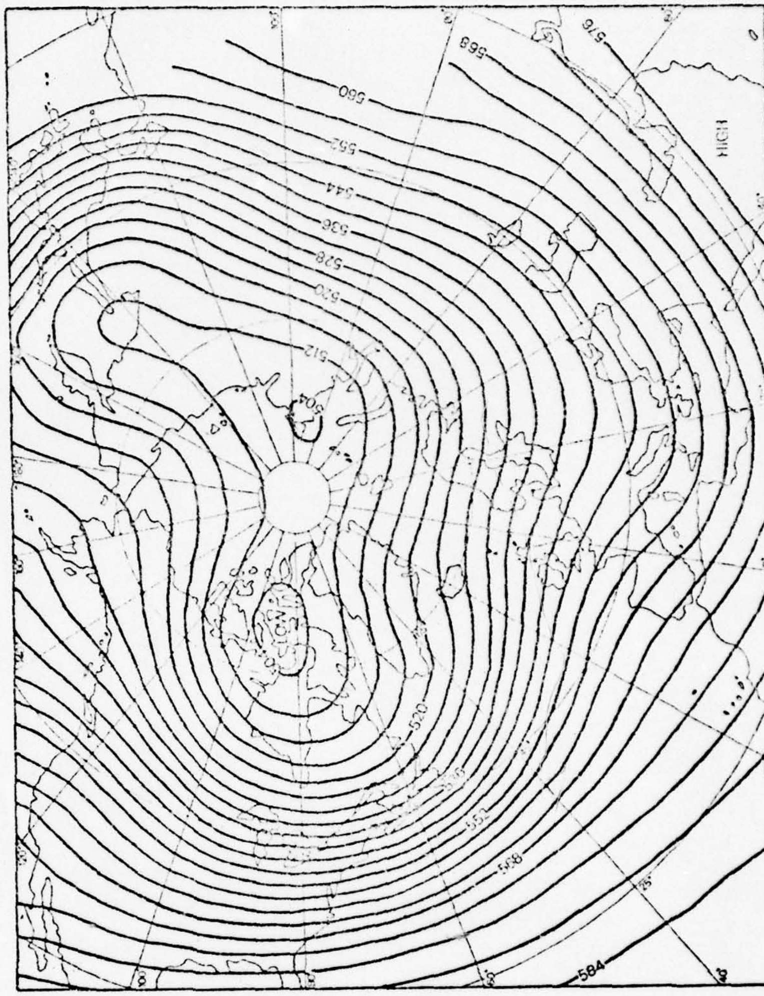

Fig. 4. Mean monthly height (in decametres) of the 500-millibar pressure level in January, Northern hemisphere map, 1949–73

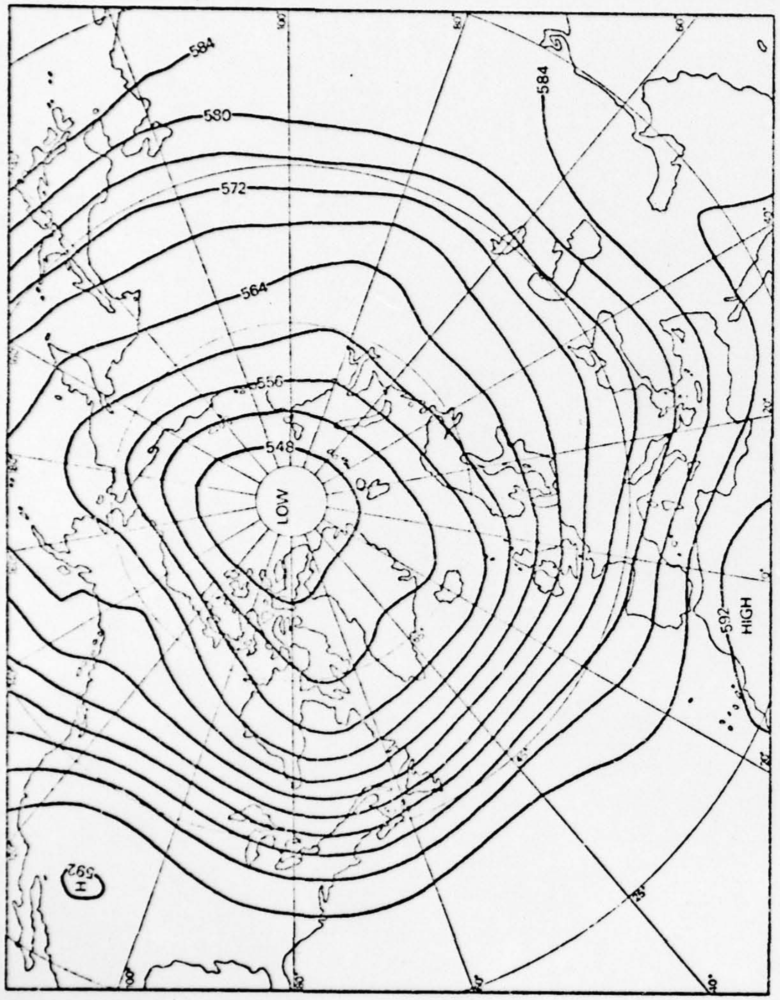

Fig. 5. Mean monthly height (in decametres) of the 500-millibar pressure level in July, Northern hemisphere map, 1949–73

Having identified the atmospheric circumpolar jetstream and the polar front as key features in the meridional transport of heat to the polar regions, we can now discuss the implications for the polar ice of variations in the general atmospheric circulation.

Apart from the systematic seasonal changes, the circumpolar circulation is subject to irregular variations on time scales ranging from a few hours to hundreds and thousands of years. Upper air data cover the Northern hemisphere only from the 1940s, and global coverage was attained just since the International Geophysical Year (1957–58); so any longer-period variations can only be deduced from surface wind circulation data, either from the era of instrument measurements (about 200 years), or as can be inferred from earlier weather diaries and other historical reports, or from the 'proxy' data afforded by various kinds of botanical, zoological, geomorphological and glaciological evidence and isotope measurements. An extensive account of these data and their uses in palaeoclimatology is given in Lamb (1977).

It is not yet known whether any general rules exist regarding the variations between the more zonal wind circulation patterns (i.e. with small-amplitude waves) and the more meridional patterns (with big-amplitude waves) over middle latitudes as to which variants, together with the associated transient eddies (the travelling cyclones and anticyclones), are most effective in transporting heat polewards. It does appear, however, that the cold Little Ice Age climate of recent centuries (particularly the seventeenth century) was associated with much blocking and big-amplitude waves, an expanded polar cap and reduced latitude-range of the Hadley circulation (see Lamb, 1977).

The majority of observations and deductions relevant to atmospheric circulation changes provide indications of the configuration of the quasi-stationary troughs and ridges in the circumpolar vortex. These 'stationary' waves tend to recur frequently in much the same positions over many years, and impress a distinct pattern on the long-term mean charts for any given month, such as those illustrated by the 1949–73 contours of average height of the 500 millibar pressure level for January and July in Figures 4 and 5. Such pressure maps are virtually mean flow maps, since the winds blow nearly along the contour lines.

Our longest data series indicate quite clearly that, even within the period of instrument observations, these patterns are subject to variations and displacements—changes of wave length and hence of the number of waves, also of wave amplitude and position and so on—over both shorter and longer periods. These must affect and alter the patterns of poleward heat transport, as do the seasonal changes and irregular changes of the intensity and mobility of the dominant wave features from time to time and from year to year. Figure 6 shows, by way of example, three basically different Northern hemisphere wave patterns which occurred over the Arctic fringe over periods of several weeks in 1946, 1947 and 1948:

(a) a situation with largely stationary (high-amplitude) waves;
(b) a situation with mobile progressive (eastward-moving) low amplitude waves: also shorter wave length and therefore more numerous waves;
(c) a situation with retrogressive (i.e. westward-moving) waves: these were of high amplitude.

Even situations (b) and (c) include some pauses in the movement and give hints of some preferred positions for the ridges and troughs.

Depending on the location of stationary waves (and, in the more extreme cases, cut-off vortices) in the circumpolar wind flow, different areas of the surface

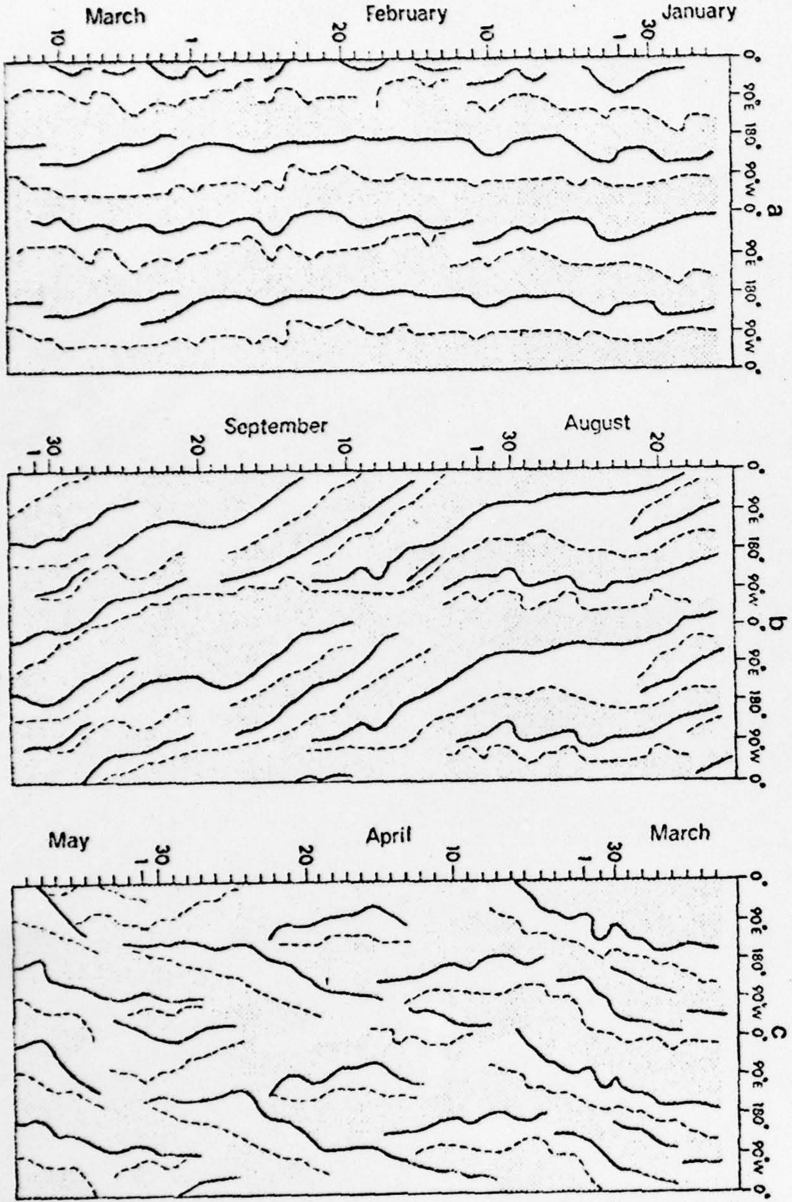

Fig. 6. Longitude positions of long waves in the circumpolar vortex of upper westerlies at 75°N. for three sample periods: (a) 26 January to 13 March 1948: stationary situation; (b) 16 August to 2 October 1946: progressive waves; (c) 23 March to 9 May 1951: retrogressive waves. (Solid lines represent ridges, pecked lines, troughs)

in high and middle latitudes experience periods of prolonged warming or cooling as a result of the meridional and vertical fluxes of heat in the atmosphere. Prolonged warming, as in the realm of the ridges (which mark extensions of the lower latitude regime) in the pattern of the circumpolar vortex, leads to retreat of the sea ice; and increased calving of icebergs from the edges of the inland icesheets reduces their extent also. Prolonged cooling, as in the realm of the upper cold troughs, results in extension of the Arctic sea ice and consolidation of the land-based icesheets in those areas. In either situation, there also occurs a pro-

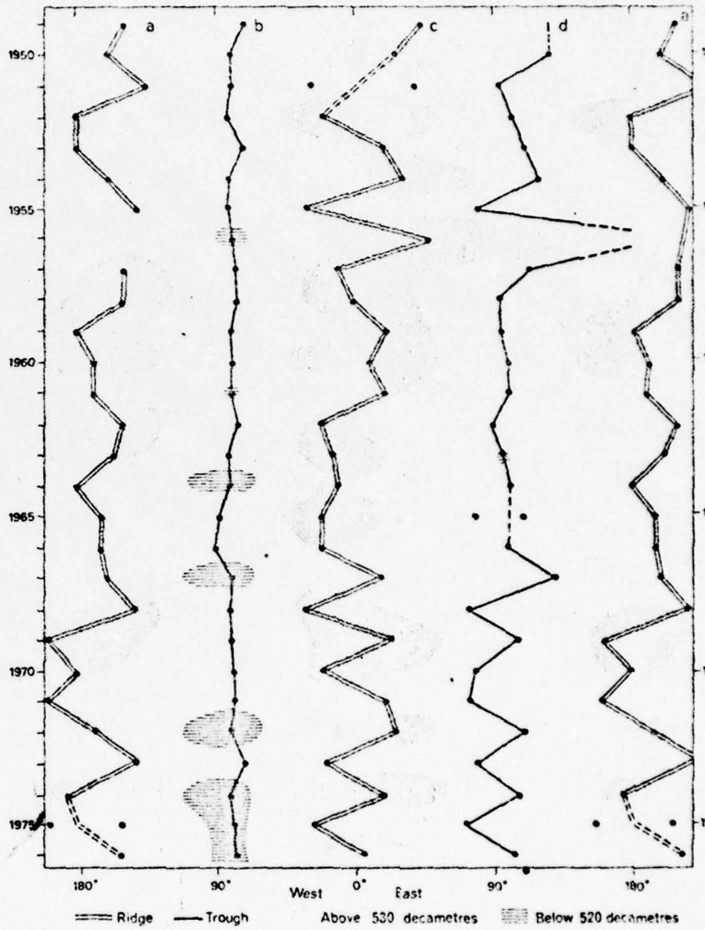

Fig. 7. Mean yearly positions of the main troughs and ridges in the circumpolar vortex at 75°N. from 1949 to 1976: (a) Pacific Ridge; (b) Canadian Trough; (c) Greenland—Barents Sea Ridge; (d) Siberian Trough; (e) Pacific Ridge

nounced modification of the distribution of sea temperatures, which, if it persists, may lead to changes in the strength and direction of the ocean currents, which play a part in extending the changed regime in time and to other latitudes.

The situation in recent years

Figure 7 indicates the history of the most persistent features of the circumpolar vortex in the region of the Arctic fringe over a period of 28 years. The most noticeable feature is the constancy of the north-east Canadian cold trough, attributable to the downstream effect of the Rocky Mountains disturbance of the main flow of the upper westerly windstream and to the persistent cold of the abundant, largely cut-off, water surfaces there. Apart from this, the most notable things are (i) signs of a quasi-biennial oscillation in the Barents Sea (or east Atlantic-European sector) ridge and (ii) an apparent net westward shift of the preferred position of the trough in the Siberian sector of the Arctic: or this may mark a tendency to produce an extra trough, sometimes the deepest one, near Novaya Zemlya and north-west Siberia in all the colder months of the year, as seen on Figure 4. There also seems to be, despite considerable oscillations from year to year, a tendency for decline and westward displacement of the Atlantic-Norwegian Sea warm ridge. These changes are apparent in the summary figures given in Table I, which also indicate that the Canadian trough became deeper after 1970 and show falling heights for all features except the Pacific ridge. This trend registers the cooling of the Arctic about 1961. The effects became particularly notable in the Canadian sector in 1971 and after (but see Bradley *et al.*, 1972, 1973), having been more pronounced in the Greenland and Barents Seas and particularly around Novaya Zemlya and Franz Josefs Land in the 1960s (as shown for instance, in Rodewald, 1972, Figs. 21–24).

TABLE I

Mean positions of the features of the circumpolar vortex at lat. 75°N and corresponding heights (dekametres) of the 500 mb pressure level. (Averages for the year, though dominated by the 6 to 8 colder months.)

Years	Pacific warm ridge	Canadian cold trough	Atlantic warm ridge	Asian sector cold trough
1949–56	(158°W) absent in 1956 529·9	79°W 521·6	16°E 531·0	(118°E) absent in 1956 525·7
1959–61	170°W 530·9	80°W 522·2	17°E 533·0	98°E 525·2
1963–69	167°W 529·3	83°W 521·4	7°W 531·0	100°E 523·0
1970–75	172°W 529·3	77°W 519·7	0° 529·9	87°E 523·0

***Note:** At the time of writing data were not available for the omitted years.*

Important regional changes in middle and higher latitudes of the Northern hemisphere, lasting from a few months to a few years, are associated with changes in the relative depths of the Canadian and Siberian cold troughs and corresponding shifts of centre of the circumpolar vortex towards either side, or to the position mentioned near Novaya Zemlya–Franz Josefs Land (40° to 80°E). An effect of such changes is registered in Figure 8, which shows the distribution of mild winters 1971–74, i.e., in the period of notable depth of the Canadian cold trough and renewed warmth in Europe, which, however, seems to have made little difference to the mean temperature of the Northern hemisphere or of the Arctic as a whole (Fig. 9).

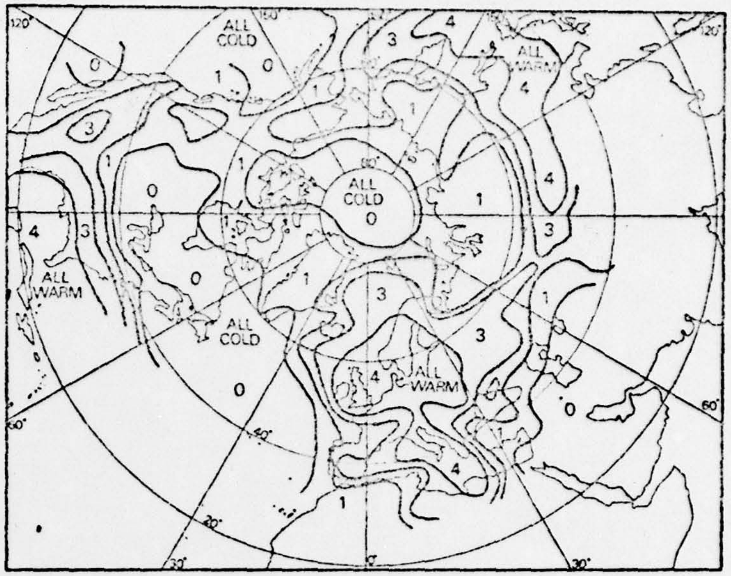

Fig. 8. Number of mild winters 1971 to 1974; Northern hemisphere map showing the number of those winters which gave mean temperatures above the 1931–60 average

The first half of the present century saw a great recession of the Arctic ice—reported in this journal by Ahlmann in 1949 (*Geogrl J.* **112**: 165–95)—giving Iceland a long period of near immunity and lengthening the average ice-free season for shipping in Spitsbergen from three to seven months of the year. The reduction of the ice at that time seems to have been associated with a period of remarkably sustained strength of the zonal circulation of the atmos-

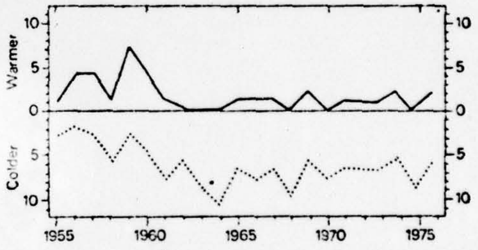

***Fig. 9.** Numbers of months warmer and colder than the 1931–60 average over the central Arctic area generally north of latitude 70°N*

phere (high values of the 'zonal index') with long wave length and eastern positions of the upper ridges and troughs affecting the eastern Atlantic-Europe and Asia. Correspondingly, the cyclonic storms of the sub-Arctic zone developed to a large size and intensity, many of them penetrating far into the Arctic, as the ice receded in the 1930s (Petterssen, 1949). There was a rather general warming of climates in most parts of the world during about the same decades, averaging *about 0·5°C from the 1880s to the 1940s* over the whole Earth (most carefully calculated by Mitchell, 1963), though the temperature rise was many times greater in the Arctic (about 4°C in northern parts of the Barents Sea), partly because of the retreat of the ice and its replacement by open water.

The tendency of the atmospheric circulation changed in the 1940s and after, perhaps in response to a general *cooling trend which seems to have begun* about the same time; and, by the late 1960s, the sea ice seems to have regained most of its former extent (see, for example, Lamb, 1972b, Fig. 7.3). In April 1968, Iceland was half surrounded by the ice, a position that had not occurred since 1888, and in 1969 the situation was again somewhat similar. S. H. Schneider has reported that a modelling experiment indicates that these *changes of global* temperature over the past hundred years could be accounted for by allocating suitable weight to just three variables: carbon dioxide and volcanic dust in the atmosphere and solar variation (Schneider and Mass, 1975).

The longest record which we have of the corresponding variations of the Arctic sea ice is from the observations of its reaching the coasts of Iceland and affecting the shipping lanes there. This position is probably a lucky accident, since, apart from the fluctuations of limited duration (from a few weeks to a few years) produced by shifts of centre of the circumpolar vortex, the biggest variations in the extent of ice and of ocean temperatures seem to occur in the North Atlantic near the watermass boundary between the water of Gulf Stream origin and the polar current, as in the Iceland region, and are probably indicative of global changes. This observation applies whether one considers variations within the present century or the Little Ice Age (e.g., the seventeenth century) or the greatest glaciations of the Quaternary. Table II gives the number of weeks a year with the Arctic drift ice at the coast of Iceland since 1860 (from Koch, 1945) and for the later years from the official records of the Iceland Weather Bureau, *Veðurstofan Íslands*, kindly supplied by Hlynur Sigtryggsson and Flosi Sigurðsson.

TABLE II

Number of weeks each year with drift ice at the coast of Iceland

Decade beginning	Year 0	1	2	3	4	5	6	7	8	9	Decade average
1860	14	0	3	16	0	6	29	16	20	25	12·9
1870	18	5	11	10	19	0	12	6	12	2	9·5
1880	6	20	19	10	0	5	15	20	29	0	12·4
1890	5	13	22	9	0	7	7	0	5	1	6·9
1900	0	5	20	9	0	0	6	7	4	0	5·1
1910	0	13	0	0	10	15	5	3	7	2	5·5
1920	1	3	0	2	1	0	0	0	2	6	1·5
1930	3	0	5	1	0	0	0	2	3	0	1·4
1940	0	0	0	7	10	0	4	0	2	7	3·0
1950	0	0	0	0	0	2	7	0	1	0	1·0
1960	0	0	0	4	4	23	2	11	27	22	9·3
1970	13	13	0	0	2	9	(9)				(6·6)

The figure for 1976 is a provisional estimate from the reports in the monthly issues of Veðratten.

Our study of the atmospheric circulation warns us that one cannot expect all the short-term details of the variations of the ice in one sector to indicate changes affecting the Arctic as a whole. After 1971, there was some improvement in conditions (less ice) east of Greenland and about Iceland, whereas the ice increased in the Canadian Arctic and on the *north-west Atlantic*. Ice in the Labrador Current had been diminishing more or less progressively in the 1940s, 1950s and 1960s, but increased again sharply after 1971; 1972 produced the greatest number of icebergs (1594) on the western Atlantic south of 48°N since such counts began in 1880. Kukla and Kukla (1974) report on the basis of very careful measurements from mosaics of satellite photographs that the total extent of ice and snow in the Northern hemisphere actually increased by 12 per cent from 1967 to 1972, and has declined only slightly since then (Fig. 10).

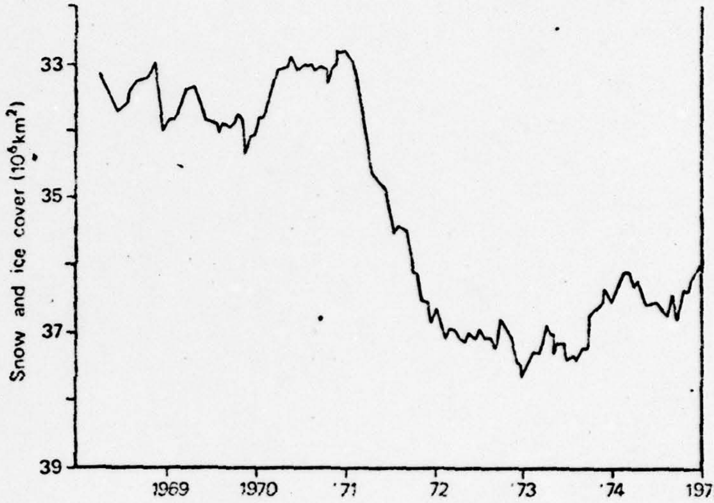

Fig. 10. Area of snow and ice in the Northern hemisphere (millions of square kilometres): running 12-month averages from 1968. (The curve is plotted inverted, to indicate the presumed implication as regards prevailing temperatures over the higher northern latitudes.) Data from Dr. G. J. Kukla of the Lamont-Doherty Geological Observatory, Columbia University, New York

(Most of the increase took place in 1972.) When this result is compared with the survey made by Wiesnet and Matson (1975) of the snow-cover on land alone, it appears that there was a great maximum of the extent of snow in 1972 and 1973 (despite the mild winters in western Europe), which more than compensated for a minor minimum in the overall extent of the sea ice. There were minima of the winter continental snow extent in 1970 and 1975. These surveys have, therefore, revealed shorter-term fluctuations on time-scales of, perhaps, five to six years superposed on the long-term trends that were already familiar, and the amplitude of the shorter-term changes is found to be much greater than had previously been suspected. These changes evidently have to do with shifts of centre of the circumpolar vortex, and of the positions of the great troughs and ridges in the upper wind flow.

Some of these changes in the circumpolar vortex take place more or less suddenly, and may be associated with changes of the preferred wave-number (which introduces a critical point), when the mainstream of the wind circulation strengthens or weakens, or when the same thing arises through a change of latitude of the mainstream. About 1961, the cooling of the Arctic, causing an expansion of the polar cap, seems to have reached a point where 3-wave patterns became commoner than before in the flow of the upper winds in high latitudes around the polar cap: previously 1- and 2-wave patterns had been dominant. The result was that troughs in the flow commonly occupied a position over the eastern Barents Sea and *Franz Josefs Land* (80°N 53°E), which had previously been that part of the Arctic most strongly affected by the twentieth-century warming: the same area became affected by the strongest surface cooling and, since 1960, has experienced many months with mean surface temperatures 10°C or more below the previous 30-year average, a situation which has, on the whole, continued even in the most recent years, although the main brunt of the colder regime has most recently been felt between about 80 and 120°E (cf. Angell and Korshover, 1976a).

The general persistence of the colder regime which set in in the Arctic in 1961 is seen in Figure 9. It seems, therefore, that despite the return to warmer conditions in the east Atlantic-European sector and in the eastern United States, associated with frequent southerly surface wind components, from 1971 to 1976, the warmth has not penetrated the Arctic on the scale that it did in the 1920s and 1930s, or even in the early 1950s. This is perhaps not surprising when the very different character of the prevailing wind circulation in middle latitudes in the two periods is considered.

In the first half of this century, the circulation of the atmosphere over middle latitudes had a strongly zonal character. The mean yearly number of days with general westerly winds over the British Isles (see Fig. 11) was 109 in the 1920s and 99 in the 1930s: the extreme range shown by the individual years was from 68 to 130 westerly days. Recent years (1970–76) have shown an average of 74 westerly days per year, the range being from 56 to 96. In these recent years, with frequent 'blocking' of the surface westerlies in middle latitudes, large-amplitude waves have affected the course of the upper westerlies around the hemisphere. Hence, zones of westerly winds have appeared in both high and low latitudes (typically about 65-80°N and 35–45°N), sometimes in limited sectors, now here and now there, and sometimes around much of the hemisphere. Often the cyclonic activity has been in the lower middle latitudes over the Atlantic and over the Mediterranean, but sometimes stationary in the central Atlantic or near Greenland; and there has been a greatly enhanced development of cyclonic activity around the fringe of the polar region; anticyclones have been common in middle latitudes, where droughts have been a notable feature. There have also been some very wet spells in places in middle latitudes, for example the US Middle West in 1970–74 and late 1976 in the British Isles—when the blocking/meridionally orientated waves in the upper westerlies occupied different longitudes, putting the places concerned near a persistent focus of cyclonic activity. Such regimes with reduced mobility in middle latitudes are conducive to long spells of weather and the build-up of extremes of very diverse character.

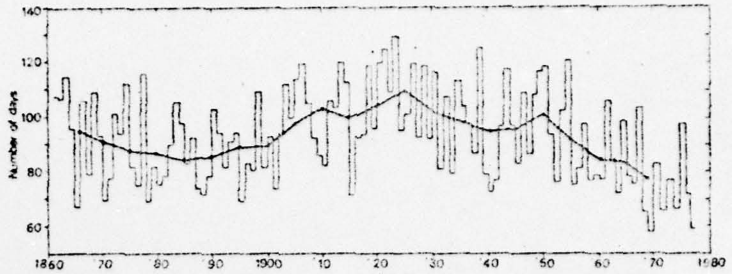

Fig. 11. Number of days with general westerly winds over the British Isles from 1861 to 1976. (The bold line shows the 10-year averages at 5-year intervals)

It seems from all this that clues to fundamental or long-term changes of climatic character are most clearly seen in terms of:

(a) temperature changes affecting the highest latitudes (where the changes are big),
(b) also probably temperature changes in the tropics and equatorial zone (where the changes are much smaller, and therefore harder to measure satisfactorily, but of greater horizontal extent) and
(c) changes in the wind circulation over middle latitudes.

Angell and Korshover (1976b) find that the prevailing temperatures averaged over the whole Earth fell by about 0·3°C (at the surface and in the upper troposphere) between 1958 and 1965, since when the overall changes have been slight, though there has been localized warming in some sectors in middle latitudes in both hemispheres associated with the large-amplitude excursions of the flow around the circumpolar vortex. The best available assessments of the changes of prevailing surface temperature over the Earth are shown in Figure 12.

It is reasonable to suppose, therefore, that—particularly when we consider the averages over 10 years or more—(i) the polar ice, (ii) Arctic temperatures, and (iii) the frequency of mobile westerly-wind (or of blocked, stationary) situations in middle latitudes may provide convenient indicators of the tendency of the world climatic regime. It is noticeable that the variations of the ice at

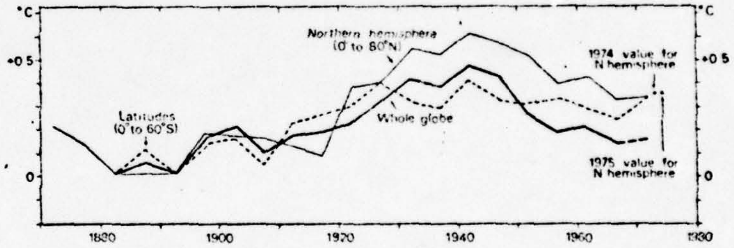

Fig. 12. Estimates of the changes of prevailing surface air temperature since 1870 for: (i) the whole earth (after Mitchell, extended through 1960s by NCAR, and to 1973 with changes from Angell and Korshover); (ii) averages for latitudes 0° to 80°N. (after Mitchell, adjusted and extended to 1973 by Brinkmann); (iii) averages for latitudes 0° to 60°S. (after Mitchell, extended to 1973 with changes indicated by Angell and Korshover)

Iceland, the frequency of westerly-wind situations over the British Isles and the assessment of global temperature changes, seen in Table II and Figures 9, 11 and 12, show a broad parallelism, which suggests a physical relationship affecting all three items. All three may be rather closely related, at least in their trends over a number of years, to variations in the most basic characteristic of the climatic regime expressible in terms of energy level. Because of the margins of uncertainty and error which must affect our assessments of the prevailing level of surface air temperature averaged over the whole Earth to a matter of one- or two-tenths of a degree, it may be that the other two indices mentioned could provide useful checks on our assessments of world temperature. (They are also certainly quicker to derive.) Equally, any of the three may be useful in deriving a predictive capacity for the probable future trend of the ice.

The amount of Arctic ice, even as registered in one small region by the long record of its occurrence at the coasts of Iceland, and the frequency of westerly wind situations over the British Isles* are found to have statistically significant associations with the variations of the weather prevailing in many parts of the world. This is illustrated by the correlation coefficients listed in Table III.

For the calculations reported in this Table, the long series of London south-westerly wind frequency and frequency of British Isles westerly days were extended by using a calibration curve, which appears to link the 10-year values of each satisfactorily as if they were a single series. That this is possible suggests that the correlation coefficients noted in the Table, linking the long history of the south-westerly winds at London with prevailing temperatures in England, and even with remote aspects of world weather, indicate that there is *in reality a link between the frequency of westerly situations* over the British Isles and world temperature.

If we make use of the extension of the central England temperature series (50-year averages) back to the early Middle Ages derived by Lamb (1965), and the more recent use of oxygen isotope measurements, to derive proxy climatic data, we may add further items to this list of associations. Two examples are given in Table IV below.

Conclusions

The approach to diagnosis of the current tendency of the global climatic trend, which suggests itself from this survey, may help to resolve the confusion which results from the multiplicity of recent published contributions to the subject, particularly those which are based on the data of some limited area of the world chosen at random.

A good deal has been written in recent years about the warming trends observed in New Zealand and in the Antarctic (e.g. Trenberth, 1976, and the partly similar diagnosis by Wollin *et al.*, 1972), where it is clear that a substantial rise of the long-term mean temperatures by about 0·5°C has taken place over the years since 1950, just when the Northern hemisphere (and particularly the Arctic) has been cooling down. In the case of New Zealand, as Trenberth has pointed out, the remarkable magnitude of the warming is attributable to a persistent anomaly of the atmospheric circulation in that sector of the Southern hemisphere over the past 20–25 years, associated with north-easterly winds over the country.

The present study has drawn attention to the differences of climatic experience that may arise in different longitudes of either hemisphere, over periods from a few weeks to some years, due to changes of prevailing wave length and wave positions in the flow of the upper westerlies (circumpolar vortex). These differences are likely to be particularly strong in periods when large amplitude waves and blocking are common, as since about 1955 and also in the 1940s. The

TABLE III

Correlation coefficients indicating associations in world weather

Items and period surveyed	Time units	Number of values in series compared	Correlation coefficient	Significance level (per cent)
Iceland ice and world temperature 1880–1974	5 yr	19	−0·64	1
Iceland ice and Northern hemisphere temperature 1870–1974	5 yr	21	−0·61	1
Iceland ice and central England temperature 1870–1974	5 yr	21	−0·53	about 1
Iceland ice and British Isles westerly days 1861–1974	5 yr	23	−0·54	1
Iceland ice and days with SW surface wind at London 1780–1976[1]	10 yr	20	−0·47	5
Iceland ice and tree-ring widths in northern Finland 1900–55	1 yr	56	−0·35	about 1
Central England temperature and world temperature 1880–1974	5 yr	19	+0·67	1
Central England temperature and Northern hemisphere temperature 1870–1974	5 yr	21	+0·71	0·1
British Isles westerly days and world temperature 1880–1974	5 yr	19	+0·31	–
British Isles westerly days and rainfall in the *Sahel* zone of Africa *(10–20°N) 1900–73*[2]	1 yr	74	+0·56	1
British Isles westerly days and rainfall in the *Sahel* zone of Africa (10–20°N) 1900–73[1]	20 yr	4	+0·80	–
Days with SW surface wind at London and central England temperature 1730–1976[1]	10 yr	25	+0·39	about 5
Days with SW surface wind at London and snow at the South Pole 1760–1957[1,3]	10 yr	20	+0·75	0·1

[1] *incomplete final period taken as if complete.*
[2] *from Winstanley (1974).*
[3] *data from Giovinetto and Schwerdtfeger (1966).*

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* Other workers, who have explored far more correlation coefficients in world weather than the selection here listed, report that the frequency of westerly situations over the British Isles has more statistically significant associations with world weather than has the standard Zonal Index, which measures the development of the westerly wind belt between 35 and 55°N around the entire Northern hemisphere. This is also true of the comparison of the frequency of westerly days in the British Isles with most alternative ways of measuring the west wind belt around the hemisphere or in other sectors of the hemisphere. This is probably because the British Isles are situated in or near the middle of that part of the middle latitudes west-wind belt which is most commonly subject to blocking development, i.e. *most sensitive to interruption and variation*. It also appears that the British Isles circulation pattern classification used (Lamb, 1972a) is less affected by accidental or subjective distortions than other pattern classifications, which cover greater areas of the Northern hemisphere or which do not recognize that some days' patterns are unclassifiable.

TABLE IV

Correlation coefficients indicating associations in world weather

Items and period surveyed	Time units	Number of values in series compared	Correlation coefficient	Significance level (per cent)
Central England temperature and tree-ring widths in northern Finland¹ 1200–1949	50 yr	15	+0·79	0·1
Central England temperature and temperatures in North Island, New Zealand, indicated by oxygen *isotope measurements*² 1150–1949	50 yr	16	+0·62	about 1

¹data from Sirén (1961).
²data kindly supplied by Professor A. T. Wilson.

long spells, sometimes of northerly, sometimes of southerly, and sometimes of easterly winds, sometimes of anticyclonic, sometimes of cyclonic weather, which then prevail are liable to produce a great diversity of extremes of both temperature and rainfall in the middle latitudes of either hemisphere. There have been many examples since 1960, including the coldest winter (1963) in 223 years and one of the warmest winters (1975) in England; also periods of great wetness, as in the summer of 1968, and of prolonged drought (1975–76) in the lowlands of England. In the same period, the Baltic had two of its greatest ice winters (1963 and 1966) and one winter (1975) with virtually no ice at all (and roses blooming in Copenhagen in late January). It may be a similar symptom of the diversity of extremes in periods of frequent blocking of the westerlies that, prior to these recent experiences, the winters with most and with least ice recorded on the Baltic both occurred in the same decade, the 1650s, and that the famous hot summers associated with the last great outbreak of bubonic plague and the fire of London in the successive years 1665 and 1666 also took place in or near the period of climax development of the Little Ice Age, when the Arctic sea ice and glaciers all over the world were nearing their greatest extensions in postglacial times.

This enhanced year-to-year, and possibly even decade-to-decade, variability, which seems to go with periods of blocking, and which affects rainfall as well as temperature, may be one of the aspects of climatic change which has the most serious agricultural and economic consequences.

We have also drawn attention in this survey to some differences which characterize different latitudes. One of us (Lamb, 1972b, 1977; see also Fletcher, 1969) has noted signs that, in the climatic variations of the past three centuries, all the climatic zones (and the accompanying zones of the wind circulation) have tended to move south or north together, with important responses in the ocean circulation also. Thus, in the time of Captain Cook's voyages in the 1770s and about 1820, the limits of the Antarctic sea-ice seem to have been farther south than in our own century, approximately when the Arctic ice was most prominent (farthest south) about Iceland, and both attained northern positions around 1930 or in the 1930s. Similarly, Willett's survey (1950) of the changes of prevailing temperature over the Earth during the first 40 years of the twentieth century revealed an opposite tendency south of about 40°S. It may be that on these time scales there is a rather general tendency for the higher southern latitudes, south of about 40°S, to go in antiphase to the temperature trend over most of the rest of the Earth.

The indicators which we have mainly examined in the present study seem to confirm those assessments of recent global temperature change, seen in Figure 12, which indicate that, although the cooling trend which set in around 1950 has levelled off in recent years, there is, as yet, no sign of a return to the warmer regime which dominated the first half of the century (and especially the period between about 1933 and 1952). Since the side-effects of most human activities, particularly the output of carbon dioxide and of the waste heat from industrial (and domestic) processes, are believed to tend to warm the Earth (Matthews *et al.*, 1971, Schneider, 1976), the indications of this study suggest that natural causes are, so far, still dominant in producing the climatic changes observed.

Nevertheless, the rapid development of technology and changes in the environment produced by Man are a proper cause of concern in connexion with their possible, or even expected, impact on climate. The indications of the present study do not provide any ground for complacency about this. It must be assumed that the effect of Man's output of carbon dioxide (estimated as a global warming of 0·3 to 0·5°C since the industrial revolution, over half of this within the present century, and the rate increasing in the latest decades) is already sufficient to be moderating what would otherwise have been a more severe global cooling of the natural climate since 1950. Every effort and all reasonable approaches should be used to assess the probable magnitude and nature of the effects on climate of all human disturbances of the environment. Among those approaches, it is now necessary to monitor world climate in all appropriate ways, including the study of such indicators as we have here discussed.

The Climatic Research Unit at the University of East Anglia is indebted to the National Oceanic and Atmospheric Administration, Washington DC, for supporting a project to study the changes in the patterns of the atmospheric circulation, and the patterns of temperature and rainfall anomaly in the past, which have accompanied previous periods of global cooling and global warming of climate, with a view to recognition of any common characteristics.

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Holocene palaeo-wind evidence from palynology in Baffin Island

TRACE amounts of wind-blown tree pollen from the highly productive boreal coniferous forests are a characteristic component of arctic tundra sediments[1–4]. These exotic pollen are generally regarded as mere contamination or distractions in tundra pollen diagrams[5]. We report here that traces of exotic pollen in late Holocene sediments from Baffin Island can be used as palaeo-wind indicators, and may be associated with periodic shifts of a trough in the atmosphere.

In tundra sites 550 km from the forest, H.N.[4] found clear relationships between numbers of tree pollen in Holocene tundra peats and the climatic history of the arctic tree-line to the south. In 1972 and 1973 a line of Tauber[5] pollen traps was laid down along a 1,600-km transect from tree-line to the high Arctic to record relationships between synoptic meteorology and modern tree-pollen deposition in the tundra[6]; small numbers of pine, alder and spruce pollen (about one exotic pollen grain of each taxa cm⁻² yr⁻¹) were recorded on Baffin Island, more than 1,200 km from their most northerly tree limits.

H.N.[7] modified the standard pollen counting routines[3] to emphasise the exotic tree pollen: using both percentage and 'absolute' dry sediment weight approaches we established suitable totals comprising local, regional and exotic pollen for each sampled level[7]. At that stage of the pollen counts the exotic tree pollen were barely represented, but by prolonged further counting of only the exotic pollen, statistically satisfactory numbers of tree pollen were established and related to the microscope-slide area counted and thus to 'absolute' pollen values.

We have examined sub-fossil pollen grains preserved in late Holocene peats from Cumberland Peninsula in eastern Baffin Island (Fig. 1). This region lies below a major atmospheric standing (Rossby) wave formed by the northern Hemispheric circulation[8], with an average position of the trough axis at about 75° W longitude. A prolonged shift of the trough to the east or west of its normal position acts as a switching mechanism for airmass trajectories into the region; thus a westward shift of the trough increases southerly airflow into Cumberland Peninsula, while an eastward shift produces northerly and easterly windflows there. This is interesting because the trough position has significant consequences for past and present status of climate, ice cover, plant and animal life and human occupation in eastern Baffin Island[9], with likely impacts 'downstream' in Greenland, the north-east Atlantic and elsewhere.

The two monoliths of peat sediments collected by Miller and Boulton were dated by 16 radiocarbon assays[10]; the pollen sampling interval was 2.5 cm. Peats may accumulate at irregular sedimentation rates, and may cease to grow at times, but they experience less sediment mixing than many holomictic lakes normally used for palynology; absence of sediment homogenisation is of paramount concern in our study. The rate of peat accumulation at Windy Lake was nearly linear throughout, about 16.5 yr cm⁻¹, from 3,600 yr BP to 850 ± 65 yr BP, while the Maktak Glacier peat covered 2,560 ± 170 yr BP to 1,480 ± 165 yr BP and underwent nonlinear accumulation. Our sampling intervals from both were chosen to average 40 yr.

For the time series these studies were designed to investigate Holocene palaeo-wind vectors by counting exotic tree pollen deposition[7], and a fuller report on these data is in preparation. The analytical techniques[7] were not designed to examine fully with the necessary precision the short-term variations or periodicities which have unexpectedly emerged, so that we stress this latter aspect forms only an interim hypothesis, now in process of further testing by closer sampling (5-cm intervals) of other sections.

Fig. 1 Location of the two pollen sites on Cumberland Peninsula and relationship to average position of the trough axis and suggested direction of air flow for influx of alder, pine and spruce pollen into Cumberland Peninsula.

Our studies of ancient and modern pollen deposition in Keewatin, Mackenzie, Baffin Island and Labrador-Ungava suggest that the influx of exotic pollen in these peats was primarily due to winds of southerly origin passing over the boreal forest during the growing season. The exotic pollen peaks are composed of distinctive ratios of birch, alder to pine pollen (with alder usually an order of magnitude greater than pine pollen numbers) which for the central and eastern Canadian Arctic are unique matches for north-east Labrador-Ungava both in the Holocene and modern pollen counts. We therefore conclude that the winds responsible for the exotic pollen peaks in the sediments came from due south from their source in Labrador into eastern Baffin Island, a minimum distance from the northernmost pines, spruces and alders of 1,250 km.

There presumably were Holocene variations in tree and shrub pollen production in the source region of north-east Labrador-Ungava due to plant succession, fires, and alterations in growing season climate. We expect the local short-term effects (such as succession and fire) would have been averaged out over the larger region and would not have affected the exotic pollen influx in Baffin Island, but regional variations in pollen production would imply regional climatic change in the source area, of comparable interest to the palaeowind changes we infer. Indeed it seems likely that the two effects (productivity changes in the forest of north-east Labrador-Ungava plus wind shifts over eastern Baffin Island) might be a common response to altered strength of the circumpolar vortex.

The exotic pollen record at the two sites is a series of brief episodes of relatively heavy influx of tree pollen ('spikes'), separated by longer intervals with little or no exotic pollen (Fig. 2). We have applied spectral analysis to the numbers of the three main exotic pollen taxa, *Pinus* (pine), *Alnus* (alder), and *Picea* (spruce), to test whether there are underlying periodicities. The possibility that the exotic pollen spikes might be 'noise' has been resolved by a standard significance test of the peaks in the power spectra[11]. For this we used the Fourier transform of the autocorrelation function with smoothing of the resulting estimates[12].

Power spectra of the pine, alder and spruce pollen profiles at Windy Lake exhibit peaks with a period of about 200 yr for all taxa (Fig. 3). The three exotic pollen taxa are statistically independent so that the similarities in the three spectral peaks offers considerable evidence for periodicities, apparently of ~200 yr. Alder, the most numerous of the exotic pollen, exhibits nine maxima in the 2,000-yr record at Windy Lake, with average intervals between spikes of 200–250 yr.

Several studies of late Quaternary and recent quasi-climatic data have identified periodic changes at approximately 200-yr intervals; these include analysis of peat bog growth over 5,500 yr (270-yr periodicity)[13], spectral analysis of ¹⁸O fluctuations in ice cores (180-yr periodicity)[14], stepwise changes in reconstructed climatic data for the last millennia[15–18], and tree-ring data from Lapland[19] and Japan[20]; the 200-yr climatic periods have sometimes been compared with volcanic[21] and solar[17] behaviour. These data are, however, not usually suited to rigorous statistical testing for periodicities of this length. Similarly, the evidence we present here for repeated incursions of southerly air in summer into eastern Baffin Island at approximately 200-yr intervals during the past 2,500 yr is insufficiently established to be used in long-term forecasting, but it is reassuring that these variations correlate well with the history of glaciation on northern Cumberland Peninsula[22].

Thus the two major findings of this paper, (1) the ability in at least some geographical areas of determining quite precisely the source of exotic pollen and thus the direction of growing season palaeo-winds, and (2) the possibility of past (and future?) periodicities in these southerly palaeo-winds, are of potential significance for the increasing interest of the climatological community in reconstructing past atmospheric circulation patterns. Our initial findings will be further tested by collection of lake sediments and peats in Baffin Island and in the supposed source region of the exotic tree pollen in Labrador-Ungava.

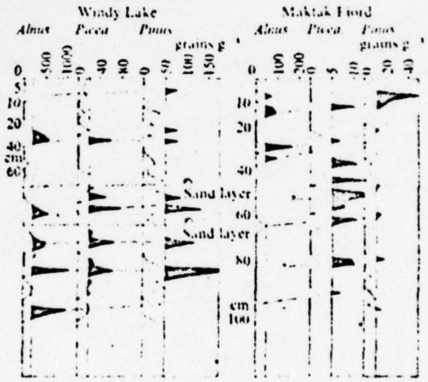

Fig. 2 Counts of *Alnus* (alder), *Picea* (spruce) and *Pinus* (pine) pollen as numbers of pollen grains per g dry weight of sediment from the Windy Lake and Maktak Fiord sites. The dashed lines are suggested correlations between exotic tree pollen influx peaks. The fastest growing sections of the Maktak diagram shows slightly metachronous influx peaks (out-of-phase by ~25 years, explanation in preparation). Full details of stratigraphies and radiocarbon chronologies in Nichols.[7]

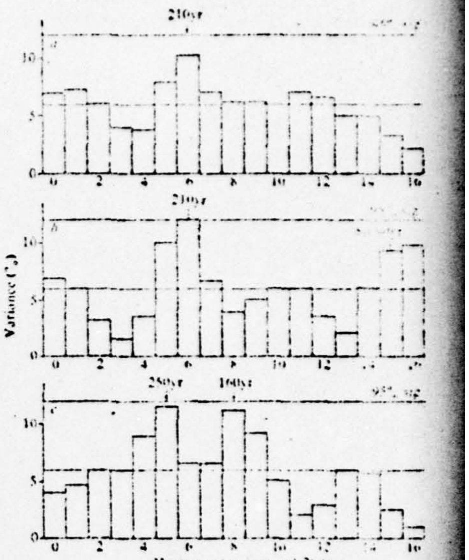

Fig. 3 Variance spectra of pine (*a*), spruce (*b*) and alder (*c*) pollen data for Windy Lake.

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Is the Sun almost-intransitive?

There is now ample instrumental, historical and proxy evidence for paleoclimatic variability over time scales ranging from 10^0 to 10^9 years (1). Although a great deal of research is still needed to establish more precisely the nature and finer spatial and temporal resolution of these changes, the main theoretical problem is to understand the mechanisms responsible for this variability over such a wide range of time scales. A large number of hypotheses have been advanced by researchers in various disciplines based on physical processes, both terrestrial and extra-terrestrial (1-8). Although there is no general consensus as to the causes of variability over various time scales, the common view among climatologists is, however, that the very long time scale fluctuations with periods of $\sim 10^8$ years could eventually be explained by causes of terrestrial origin, e.g. the changes in oceanic and continental geometries (3, 10). The intermediate time scale fluctuations with periods of $\sim 10^4 - 10^5$ years are thought to have been caused by variations in Earth's orbital elements (9). The relatively short time scale fluctuations with periods of $\sim 10^2 - 10^4$ years are on the other hand hard to explain, because of the clear lack of a physical process with the appropriate time scale. Solar variability is, however, accepted as a serious contender (3, 10). What all these hypotheses, whether terrestrial or extra-terrestrial, have in common is that they all assume the changes in climate to be deterministic, i.e. the causal response of the climatic system to a change in some environmental (internal or external) parameter, even though the actual mechanism of change is not usually understood.

A radically different hypothesis, put forward relatively recently by E. N. Lorenz, amounts to the possibility that the climatic variability over some time scales may turn out to be non-deterministic (14-16). This possibility arises, essentially, from the fact that the climate can be defined as a set of long-term statistics of the time-dependent solution of a set of appropriate non-linear differential equations. On the basis of ergodic theory, both transitive systems (ones in which long-term statistics of some time-dependent solution is independent of the choice of boundary conditions) and intransitive systems (ones in which the solution is dependent on the choice of the boundary conditions) can exist (16). Evidence for intransitive systems also exists both experimentally (17) and numerically (14). In addition to the above two modes of behaviour for a system, Lorenz has pointed out the very interesting possibility that a system of non-linear differential equations may have solutions which exhibit different statistical properties within different segments of a long time span, with a completely constant environment. Such systems he has termed almost-intransitive (14-16). As an example of these systems, he has constructed numerical models (which to some extent resemble the numerical models of the Earth's atmosphere, or for that matter any similar non-linear system of differential equations), which behave in an almost-intransitive fashion (16).

There is also some evidence to support the possibility that the climate may have behaved in an almost-intransitive fashion over time scales with periods of $\sim 10^4$ years (18). It would therefore seem likely that the possible almost-intransitivity of the climatic system could account for climatic variability over such time scales, without the need to invoke solar variability. This, however, does not appear to be the case, since there are some strong indications of solar variability over these time scales, both historical (12) and proxy. The latter evidence is based on the measurements of radiocarbon (^{14}C) fluctuations in tree rings which are thought to have been caused by the solar modulation of Galactic Cosmic rays (11). There is also some apparent correlation between the radiocarbon variations and the historical climatic record (10, 11, 19, 20). Solar variability over such time scales cannot, therefore, be ruled out in favour of almost-intransitivity of the climatic system.

There is, however, some difficulty in accounting for the solar variability over these time scales. This difficulty becomes apparent when one takes a closer look at the commonly accepted solar model (with its own difficulties (21)), and the time scales characteristic of the physical processes that are thought to be operative in the Sun. Such examination reveals a spectrum of time scales dominated on one end with very long time scales of $\sim 10^7 - 10^{13}$ years, and on the other with very short time scales of $\sim 10^{-4} - 10^{-1}$ years (13). Therefore within the context of the presently accepted solar model, the time scales of variability for which there is some evidence and are thought to be important climatologically, namely those with periods of $\sim 10^2 - 10^4$ years, are hard to explain. It appears, therefore, to be necessary to reconcile the evidence for solar variability over such periods, the lack of physical processes with appropriate time scales operative in the Sun and the possibility of the existence of systems which behave almost-intransitively.

We suggest that this could be achieved if the Sun itself (i.e. its coupled "convective zone-atmosphere") were almost-intransitive. In the following we summarise some of the arguments that support the plausibility of the above hypothesis and outline some of its consequences.

1. The complete, unapproximated fluid dynamical equations representing the convective zone-atmosphere of the Sun are highly non-linear and resemble to a great extent those representing the Earth's atmosphere. Lorenz's arguments regarding the plausibility of the almost-intransitivity of the climatic system

could therefore equally apply to the Sun, or for that matter to any physical system where similar highly non-linear differential equations are operative.

2. Almost-intransitivity of the Sun could account for the evidence of solar variability in radio carbon data and in the historical record, and also the climatic variability over these time scales. Almost-intransitivity of the climatic system on the other hand, although possible, cannot account for the independent evidence for solar variability over such time scales.

3. There is also the possibility, on the basis of dishpan experiments (17) with their limited similarity to the climatic system, that the climatic system may be intransitive (16). If so, it is hard to switch from one climatic regime to another without the presence of an external forcing mechanism (16). Almost-intransitivity of the Sun could act as such an external forcing agency.

In view of the above arguments, it seems plausible that the Sun could be almost-intransitive over some time scales. It should, however, be added that the climatic system is highly non-linear and complicated, and it is possible that even if the Sun is almost-intransitive, this need not be the sole cause of climatic variability over such time scales. Nevertheless, if the almost-intransitivity of the Sun turns out to be true, it could have astronomical as well as climatological significance.

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CO_2 PROBLEM - AN INTERDISCIPLINARY PERSPECTIVE

Review: "Carbon Dioxide, Climate and Society", J. Williams (Ed.);
IIASA Proceedings Series - Environment; Pergamon Press,
Oxford, 1978. 332 pp.

In the past, Mankind has been powerless in the face of the vagaries of climate. While it is possible to overstate the Impootance of climatic change in determining the course of history, a number of events in recent years (the droughts in the Sahel, Western Europe and California; the failure of the Russian wheat harvest in 1972; the severe winters in the United States in 1976/77 and 1977/78) have underlined the fact that at times climatic fluctuations, and particularly climatic extremes, can have a major effect of Society's well-being. In addition a further shift in the balance of Man's relationship to his environment may be about to occur: firstly due to the increasing population, and secondly to anthropogenic interference with the chemical composition of the atmosphere and the biosphere.

It is believed that the chemical composition of the atmosphere has played an important part in determining the global temperature regime of the Earth's climate over a variety of time scales. It is only with respect to the scale and character of this influence that opinions still differ. The most abundant constituent gases in the atmosphere and N and O, accounting for over 99% of the bulk of the gaseous atmosphere. These are also small traces of optically active minor constituents, such as water vapour, CO_2, O_3 and aerosols, which determine the radiation balance of the atmosphere. They are capable of changing the Earth's surface temperature through the 'greenhouse' effect; they tend to absorb terrestrial radiation peaking in the infra-red, but not solar radiation peaking in the visible. Over very long time scales ($\sim 10^9$ years), the chemical evolution of the atmosphere has probably been important in sustaining the climatic regime conducive to the evolution of life by counter-balancing the luminosity deficit of the younger Sun predicted by most solar models. On shorter time scales, natural phenomena, such as volcanic activity, large-scale changes in ocean temperature or climatic shifts, could have caused variations in the chemical composition of the atmosphere, which could in turn have been responsible for further climatic fluctuations.

Whereas in the past Mankind has been a passive recipient of the consequences of climatic variation, we are now actively involved in a unique climatic experiment, by returning a large amount of concentrated organic carbon, stored in sedimentary rocks over hundreds of millions of years, into the atmosphere and oceans. This injection of increasing amounts of CO_2 into the atmosphere due to our escalating consumption of fossil fuels, and interference with the biosphere by deforestation, could have severe climate-induced consequences, in particular on food supplies. It is therefore a matter of some concern that reliable estimated of the effects of such anthropogenic factors on climate and hence of Society be obtained.

Although the scientific problem can be formulated simply enough - How will the injection of a certain amount of CO_2 into the atmosphere affect climate? - its solution poses a number of difficulties. In order to answer the question fully, it is necessary to have more complete knowledge in three areas. First, the future global energy strategy and the rate of interference with the biosphere must be known, as these determine the amount of CO_2 released into the atmosphere. This problem is complex, involving not only a number of alternative energy scenarios, but also a mesh of political and socio-economic factors; not to mention possible alterations to the energy strategy imposed by future climatic fluctuations. Second, given a known amount of CO_2 released into the atmosphere, what porportion will reside in the atmosphere over the coming decades? Third, given a known resident CO_2 concentration, how will it affect the climatic system? Unfortunately, our knowledge of the global carbon cycle and the climate system is not sufficiently well-established to provide a clear, unambiguous answer to these questions, and to the basic problem of how projected CO_2 increases will affect climate. No clear prediction can be made; only order-of-magnitude estimates can be given. A great deal of research does however point to bery grave and perhaps irreversible consequences on a global scale, occurring not later than the first decade of the next century if remedial action is not taken soon. The 'CO_2 problem' is the direct result of our technological evolution for which we must take responsibility. A first step is to clarify the scientific certainties and uncertainties.

A recent landmark in this field was the organisation of an inter-disciplinary workshop by the International Institute for Applied Systems Analysis (IIASA) of Laxenburg, Austria. The proceedings of this "IIASA Energy Systems Program" workshop has now been published under the title "CO_2, Climate and Society." This is a comprehensive record of the meeting which was planned as a state-of-the-art analysis of the CO_2 problem. It consists of three sections, each of which is devoted to one of the three major problems outlined above.

The first section deals with the global carbon cycle. This section (as do the other two) consists of a review article covering the field, and a set of research papers presented in a readable form by active scientists in related [illegible]. The main carbon reservoirs relevant to the time scale of interest - i.e. a century ahead - are the atmosphere, biosphere and the oceans. The carbon content of these reservoirs is reasonably well known. It is however the net exchange between the reservoirs that determines the rate of accumulation of carbon in the atmosphere, and these exchange rates are not so well known. Within these limitations, however, all models predict a doubling of atmospheric CO_2 concentration by between AD 2025-2050, unless the growth rate is reduced or fossil fuels are replaced by alternative energy sources. Beyond an AD 2100 peak, the atmospheric CO_2 concentration might reach 4 to 8 times the pre-industrial level!

The second section is concerned with the impact on the climate and environment of increasing the atmospheric CO_2 concentration. The climatic system, like the global carbon cycle, is highly complicated and non-linear, and there is a great deal of uncertainty concerning the degree to which mathematical models of the climate are realistic. Nevertheless the consensus, on the basis of agreement between a variety of models, is that doubling the CO_2 concentration of the atmosphere will result in an increase of the mean surface temperature of about 2-3°C. It is also estimated that the local temperature variations could be much more dramatic; for example, about 10°C at the poles. Although this temperature change appears small, the effect on food supplies and the biosphere may be drastic. Indeed, in magnitude, it is comparable to about 50% of the change in the mean hemispheric temperature between inter-glacial and glacial conditions.

The last section deals with the interaction between future global energy strategies and the 'CO_2 problem'. This is extremely important since it is on the basis of such strategies that the future output of CO_2 into the atmosphere must be estimated. This in turn is fed into the global carbon cycle and the climatic models to calculate the climatological and biospheric impact. The proceedings also contains a summary of the reports and recommendations of the working groups on each individual aspect of the 'CO_2 problem'.

This book does represent a good state-of-the-art summary of the scientific aspects of the CO_2 problem. It is perhaps unfortunate that little attention is paid to the history of natural climatic fluctuations, as these provide a necessary context for the possible CO_2-induced changes. Natural fluctuations occurring in coming decades may drastically alter the climatic scenarios based on consideration of CO_2-induced effects alone. However, a more striking omission, in view of the gravity of the CO_2 problem, is a detailed discussion of the implications of such changes for Society: How serious is the problem for Society in general? Is the global political situation such that combined action could be taken in order to avoid the worst consequences? Should action be taken now, even

though the scientific uncertainties are great? Admittedly, two or three excellent papers do address these questions, and the omission of further discussion is not an oversight on the part of the organizers but arises from the worrying lack of research concerning the general impact of climatic change on Mankind.

It is to be hoped that these questions, as well as the scientific aspect of the problem, will be studied further in coming years. It is essential that those in a position to make policy decisions at a national and international level do not neglect this problem by arguing that action must wait until the scientific uncertainties are less. The scientific uncertainties will not be resolved until it is too late for action to be taken - until the experiment is over.

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Climatic interpretation of $\delta^{18}O$ and δD in tree rings

THERE has been considerable interest[1–8] in, and some controversy[5–7] over the use of the stable isotopes of oxygen and hydrogen in tree rings as measures of past climate. We point out here that variations in isotopic values from the whole ring (or a number of rings) may be in part a function of variations in ring width. As a consequence, whole ring isotope estimates of past climate will not be independent of ring width estimates of past climate. This is a direct result of the relative constancy of either early- or late-wood width in many tree species and of the differences in isotopic composition between early and late wood.

In many species of tree, much of the variation in ring width from year to year is in either the early-wood or the late-wood part of the ring. For instance, in oak[8] and elm (D. Brett, personal communication) the width of the early wood is *approximately constant, while in* most conifers the late-wood width is approximately constant[1]. Early wood and late wood generally have different isotopic composition. The cellulose analyses of Epstein and Yapp[5] and Wilson and Grinsted[4] both show differences of up to 50‰ in δD. The latter authors show lighter isotopic values in the early wood which they attribute to temperature-dependent fractionation effects. Epstein and Yapp[5] disagree with this interpretation. Their analyses show that early-wood isotopic values may be either *lighter or heavier* than those of the late-wood depending on the location of the tree, and their work suggests that late-wood is isotopically lighter (for Douglas Fir) in regions where there is winter snow cover.

Epstein and Yapp[5] note that "... differences in early- and late-wood δD could cause sampling problems...". We elaborate here on one way which such problems might arise, and on their possible implications. Approximate constancy of early- or late-wood width, and isotopic variation across a ring, when considered together, necessitate a relationship between ring width and the isotopic value ($\delta^{18}O$ or δD) of the whole ring. If E is the early-wood width, L the late-wood and W $(=E+L)$ the total ring width, and if δ_E, δ_L and δ_w are the corresponding mean stable isotope ($\delta^{18}O$ or δD) values, then

$$\delta_w = \delta_E + (\delta_L - \delta_E)\, L/W \qquad (1)$$

or

$$\delta_w = \delta_L - (\delta_L - \delta_E)\, E/W \qquad (2)$$

These alternative expressions for δ_w arise from the fact that δ_w is a weighted average of δ_E and δ_L. They both contain a term proportional to W^{-1} and thus imply a direct functionation dependence of δ_w on W. The sign of the relation between δ_w and W depends on the sign of $\delta_L - \delta_E$ and on whether the tree has relatively constant E or relatively constant L.

As ring width is determined partly by climate (although the relation is often complex[9]), these results imply a dependence of δ_w on climate which would occur even if δ_E and δ_L were constants. Thus, at least a part of any δ_w-climate relationship may be attributable to ring width variations.

Whether this 'ring width effect' contributes significantly to variations in δ_w depends on the magnitude of variations in δ_E, δ_L and either E/W or L/W. For oak, where E is approximately constant and equation (2) is the appropriate expression, Eckstein and Schmidt[8] give ring width data where E/W varies from 0.23 to 0.63 over the period 1880 to 1969. Since $\delta_L - \delta_E$ may be as high as 50‰ for δD, equation (2) shows that the ring width effect could give δD variations for single whole rings of up to 20‰.

Expected variations in $\delta^{18}O$ of whole rings due to the ring width effect are difficult to estimate because no suitable early-wood and late-wood isotopic data is available. The values would depend on whether precipitation or temperature-dependent fractionation effects are dominant in controlling tree ring isotopic composition, a subject on which there is considerable disagreement. If precipitation effects dominate then $\delta^{18}O$ variations of order 2.5‰ could be expected as a result of the ring-width effect. If fractionation effects dominated then even greater variations in $\delta^{18}O$ could occur.

Gray and Thompson[1] and Libby *et al.*[2] have found significant correlations between whole ring isotopic values and mean annual temperatures. Their results may be partly due to the ring width effect. Gray and Thompson's[1] data show a $\delta^{18}O$ range of about 3‰ with lower values corresponding to cooler mean annual temperatures. In their case we expect L to be relatively constant. If $\delta_L - \delta_E < 0$, as suggested by the results of Epstein and Yapp[5], then δ_w should be lower for narrower rings (see equation (1)), and hence, most probably, for colder years. Since Gray and Thompson use 5-yr means, the magnitude of variations due to the ring-width effect could be as much as 1.5‰ and could account for a significant part of the variation observed. If $\delta_L - \delta_E > 0$ then the ring-width effect would be in the opposite direction and the variation observed by Gray and Thompson[1] would be even more significant.

The results of Libby *et al.*[2] are more difficult to interpret. One of their oak samples shows variations in δD and $\delta^{18}O$ of approximately 180‰ and 9‰ respectively (for 30-yr means). This variability is much larger than one would expect from the ring-width effect. As Epstein and Yapp[5] point out, however, the magnitudes of the variations observed by Libby *et al.*[2] are much larger *than one would expect from precipitation* isotope variations (which Libby *et al.*[2] state to be the dominant control). Such large variability is even more unexpected when one recalls that Libby *et al.*[2] use 30-yr means. Nevertheless, their results do correlate reasonably well with central England temperature data.

Isotopic data from tree rings are potentially a powerful indicator of past climate. There is, however, considerable disagreement between the opinions of different workers in this field, and many of the results seem to be mutually incompatible. The simple analysis presented here suggests that variations in whole ring isotope data may be significantly influenced by variations in ring width, and that such isotope data need not be an independent climate indicator. This additional complicating factor may help to explain some of the incompatibilities. We suggest that a comparison between ring width and isotopic variations should be a first step in any analysis of whole ring isotopic data, whether the data comes from whole wood or chemically more specific isotope measurements.

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WILSON REPLIES—Wigley, Gray and Kelly make the valid point that isotopic measurements on whole wood may give results which merely reflect the ring width. One aspect of the problem was discussed by Wilson and Grinsted[1] who pointed out that whole wood contains a mixture of lignin and cellulose which have different isotope compositions. Since early and late wood can have different lignin to cellulose ratios, isotopic measurements on whole wood may merely reflect the ratio of late wood to early wood which may in turn be a simple reflection of ring width. Wilson and Grinsted suggested that this and other problems could be avoided if isotope dendroclimatologists measured only pure cellulose or pure lignin.

The comments of Wigley *et al.* on the climatic interpretation of the isotopic measurements on tree rings and the relationship of these to past climate involve the fundamental principles on which isotope dendroclimatology is based. Much of the controversy in this field stems from certain misconceptions of the aims of isotope dendroclimatology and the basic plant physiology involved.

Isotopic dendroclimatology studies face two problems. First, at what times of the year is the material that is ultimately formed into wood components fixed from the atmosphere? And second, how does the isotopic composition of a wood component such as cellulose vary with changing climate?

A conifer manufactures photosynthates at all times of the year except when climatic conditions are unsuitable, due for example to low temperatures or drought stress. These photosynthates are stored for short or extended periods before they are laid down as wood. Most conifers (*Pinus radiata* is one of the exceptions) lay down wood only during a brief period of the year. The actual period of wood deposition is not controlled by net photosynthesis but is under hormone control, the production of hormones being controlled principally by day length and to a lesser extent by temperature. For example, in trees suffering from drought stress wood can be laid down during periods when net photosynthesis is negative[2].

The above considerations apply to any isotopic work on trees. But in the case of isotopic work on oxygen and hydrogen another factor is important. The isotopic composition of rain or snow depends on many factors including the temperature history of the air masses which bring the precipitation to an area[3]. This is not the end of the problem, however. Once the water is taken into the tree transpiration processes in the leaves can cause very large fractionations particularly in arid environments[1].

Wigley *et al.* state that "early wood and late wood generally have different isotopic composition". Leaving aside the point, discussed above, that early and late wood generally have different D/H ratios because they are a variable mixture of more than one compound each with its own isotopic composition. Late-wood cellulose and early-wood cellulose generally have different isotope composition because they represent material fixed from the atmosphere at different times of the year and hence in different climatic conditions. For example in New Zealand *Pinus radiata* early wood is laid down in the spring and summer and late wood in the winter, that is, early wood is laid down at a warmer time than the late wood. On Mt Lemon, Arisona, *Pinus ponderosa* lays down early wood in the spring and late wood in the summer[2]. That is, early wood is laid down at the colder time than the late wood. The important point is that the isotopic composition is determined by the climate at the time the carbohydrate was fixed from the atmosphere and not whether it is early or late wood that is being formed.

Isotope dendroclimatology can never be expected to produce a mean annual temperature curve as might be produced by a meteorological observer or from measurements of speleothems[5]. It will only produce a curve representative of some period of the year for example 'a spring and early summer' temperature curve. Different trees may fix from the atmosphere the carbohydrate ultimately formed into wood at different times of the year and hence record climate at different periods of the year. Obviously a deciduous tree such as an oak growing in New Zealand only carries out photosynthesis in the spring and summer, whereas at the same site a conifer such as *Pinus radiata* can fix material from the atmosphere all times of the year. Thus the wealth of palaeoclimatic data recorded in the isotopic ratios of the constituents of tree rings and the superb time base provided by dendrochronology makes the potential of isotopic dendroclimatology very great indeed.

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GRAY AND THOMPSON REPLY—The 'ring width effect' discussed by Wigley *et al.* is relevant in two regards to our findings of significant correlation between $\delta^{18}O$ values in cellulose and mean annual temperatures[1]. First, as stated by Wigley *et al.*, there is a possibility that an appreciable fraction of the variation in the $\delta^{18}O$ values may be due to varying proportions of early and late wood in the tree rings used for analysis. Second, the possibility exists of a sampling error being introduced when a 5-yr group of rings is analysed.

To evaluate the first effect we have made measurements of late-wood width (L), early-wood width (E), and total ring width (W) for the entire section of tree used for production of the climate curve[1]. Values of L/W ranged from 0.05 for the largest value of W to 0.32 for the smallest W. Further, $^{18}O/^{16}O$ isotopic analyses were carried out on early and late wood from a number of selected rings from the tree. (These were necessarily rings having larger values for W due to difficulties associated with the sampling of narrow rings and insufficiency of material for analysis.) The range of values found for the difference in isotopic composition between early and late wood ($\delta E - \delta L$) was found to be 0.5 to 0.8‰.

Thus using equation (1) as stated by Wigley *et al.* with values of $\delta L - \delta E = -0.8$‰ and $L/W = 0.32$ the maximum variation in δW due to the term dependent on total ring width is found to be 0.26‰. Thus the maximum contribution to the variation is estimated at somewhat less than 10% of the total variation observed (3‰) in a 100-yr-old tree. Furthermore, by taking 5-yr groups of rings this effect will tend to be minimised since the tree in question contained few narrow rings and the effect is much less significant for wider rings (L/W of the order 0.05). In general, therefore, we expect the effect to be considerably less than the 10% suggested above.

The measured values of tree ring width (W) for the Edmonton spruce, after growth curve corrections were made, show little or no correlation with mean annual temperatures. We conclude that in this case, the contribution of ring-width effects to variation in $\delta^{18}O$ of the cellulose is minimal. This finding, however, does not detract from the potential significance of the effect for other trees in other climate zones. Care should be taken to select trees which are 'complacent', that is, those with ring widths showing little annual variation. (This is in contrast to the requirements of those establishing climate curves from ring-width measurements[2].)

The second possible effect of ring-width variation, that of introduction of a sampling error, arises because, when sampling 5-yr groups of rings[1], no attempt was made to normalise the amount of wood contributed by each of the rings to the material subsequently analysed. When calculating mean annual temperatures for each 5-yr period, however, an arithmetic mean was used, implying equal contribution from each ring and hence implying equal ring width throughout the 5-yr group. To estimate the error introduced by this procedure, we measured total ring widths for the entire tree. Using mean annual temperature (T) from climate records we calculated the expected isotopic composition of the cellulose in each ring using the relation $\delta^{18}O = 1.3T + 20.5$ (‰) (ref. 1). The mean $\delta^{18}O$ for each 5-yr group of rings was then calculated first using the ring-width data as a means of weighting the $\delta^{18}O$ contribution of each ring and second, assuming equal contributions for each ring in a given 5-yr group. The calculated weighted and unweighted means, together with measured values are shown in Table 1. The largest difference between weighted and unweighted calculated value is 0.4‰, approximately twice the estimated precision of the measured data (± 0.2‰). It seems that errors introduced elsewhere in the procedures used, are usually equal to or greater than those due to sampling errors. It should be pointed out, however, that trees showing marked variability of ring width with climate may well present sampling problems of this kind.

Table 1 Comparison of ring-width weighted mean, non-weighted mean and measured $\delta^{18}O$ values for cellulose extracted from 5-yr groups of tree rings

Period	$\delta^{18}O$ (‰) weighted mean	$\delta^{18}O$ (‰) unweighted mean	$\delta^{18}O$ (‰) measured
1894-99	23.4	23.5	23.4
1900-04	24.2	24.4	24.1
1905-09	24.7	24.6	24.7
1910-14	24.6	24.6	24.7
1915-19	24.0	24.0	24.1
1920-24	23.8	24.0	24.2
1925-29	23.7	23.5	23.6
1930-34	24.6	24.7	24.7
1935-39	23.2	23.3	22.9
1940-44	24.9	24.6	24.5
1945-49	23.8	23.7	23.3
1950-54	23.7	23.3	23.3
1955-59	24.4	24.5	24.5
1960-64	25.1	25.3	25.2
1965-68	23.5	23.7	24.0

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LIBBY AND PANDOLFI REPLY—Pandolfi has shown that isotope variations in tree rings are correlated with climate variations local to the trees. Wigley *et al.* speculate that isotope variations in tree rings may be correlated with ring widths. Then if they are correct, it must follow that ring widths are correlated with climate.

We consider that the master chronologies of ring widths from the European tree laboratories will not correlate with local climate variations. We found no correlation between isotope measurements for a German oak and B. Huber's master oak ring chronology.

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