CLIMATIC FLUCTUATIONS ON THE CENTURY TIME SCALE: A REVIEW OF HIGH-RESOLUTION PROXY DATA AND POSSIBLE MECHANISMS

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Abstract. We review the century time scale climatic variability that is observed in high-resolution proxy data records covering the past 10 000 yr. Cyclic variations with time scales ranging from 50 to 400 yr occur in oxygen isotope ratios derived from ice cores, tree-ring index series, pollen records and sea-ice extents. Century time scale cycles can also be identified in some biological and historical records and in long-term instrumental observations. In order to appreciate the century scale cycles in the context of climatic variability in general, a brief survey of all climatic time scales is presented.

The traditional interpretation that decadal-to-century scale fluctuations in the climate system are externally forced, e.g. by variations in solar properties, is questioned. A different mechanism for these fluctuations is proposed on the basis of recent findings of numerical models of the ocean's thermohaline circulation. The results indicate that this oceanic circulation exhibits *natural variability* on the century time scale which produces oscillations in the ocean-to-atmosphere heat flux. Although global in extent, these fluctuations are largest in the Atlantic Ocean.

1. Introduction

In view of the growing concern over a CO_2-enhanced greenhouse effect, there is a pressing need to have a better understanding of natural climatic variability on two fundamental time scales: decadal and century. On the decadal time scale, there are natural climatic fluctuations that centrally involve air-sea-ice interactions as well as mankind-induced changes to the atmosphere and to the land surface. On the century time scale, substantial global warming is likely to occur due to the cumulative effects of anthropogenic forcing. However, many records of Holocene proxy data show that there is also natural variability on a century time scale in the atmosphere, oceans, ice and the biosphere. Thus in order to identify a greenhouse global warming trend in observed climatic records, a greater understanding of natural variability on the decadal and century time scales is required.

The main purpose of this paper is to review the evidence for natural climatic variations on the century time scale during the Holocene, i.e., the past 10 000 yr. These variations occur as peaks corresponding to periods that range from 50 to 400 yr in many spectra calculated by various authors (e.g. Stuiver, 1980) and in spectra presented here for the first time. From the available proxy data as well as some historical and instrumental records we show, however, that a single, well-defined periodicity does not exist.

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A second purpose of this paper is to suggest that climatic variability on a century time scale may have its origin in the thermohaline circulation of the ocean. Recent results from three-dimensional numerical ocean models suggest that decadal and century time scale fluctuations form part of the *natural variability* of the thermohaline circulation (Mikolajewicz and Maier-Reimer, 1990; Weaver and Sarachik, 1991a). They also appear in a simpler, two-dimensional thermohaline circulation model (Stocker and Wright, 1991), as will be discussed below.

There are a number of different techniques used for analyzing proxy (non-instrumental) data (Lamb, 1972, 1977; Bradley, 1985). However, the time scale of interest here (50–400 yr) dictates which of these methods are the most suitable. Because proxy data records with annual resolution provide an absolute time scale, two methods are most relevant in this context: analysis of ice cores and analysis of tree rings.

The correlation of the oxygen isotope ratio $\delta^{18}O$ of ice cores with air temperature and its spatial representativeness depends on the path a water parcel was following from formation (evaporation from the ocean or land surface) until its actual location of deposition (e.g. as snow on an ice sheet). Thus, both the temperature conditions and the atmospheric circulation pattern operating along this path are reflected in the final oxygen isotope ratio. Correlation formulae between $\delta^{18}O$ and temperature are usually linear and strongly location dependent (Bradley, 1985). Due to this linearity, relative power spectra are not affected by spatially varying correlation formulae. The method is widely used in climate reconstruction and is one of the few techniques by which time series with annual resolution can be obtained. Proxy data sets compiled from some biological records and historical sources can also yield important information on climatic variations on the century time scale.

This paper is organized as follows. In Section 2 the century time scale fluctuations are put into the context of climatic variations on decreasing time scales ranging over eight orders of magnitude. This helps us to understand century scale fluctuations and their amplitude as an aspect of a wide range of climatic variability. Various examples of proxy data that demonstrate cycles on scales of 50–400 yr are reviewed in Section 3; in addition, new spectra of some recently obtained proxy data are presented. In Section 4 the results are summarized and a critique is given of the solar forcing theories of century time scale climate variability. In Section 5 we show some model results which indicate that decadal-to-century time scale cycles may be due to natural variability of the thermohaline circulation of the ocean.

2. Climate Variability on Decreasing Time Scales

Figure 1, which was originally compiled by Mitchell (1976), is a schematic of the dominant time scales of climatic variability. The time scales can be roughly characterized as tectonic (10^8 yr), orbital (10^5 yr), oceanic (10^3 yr) and atmospheric

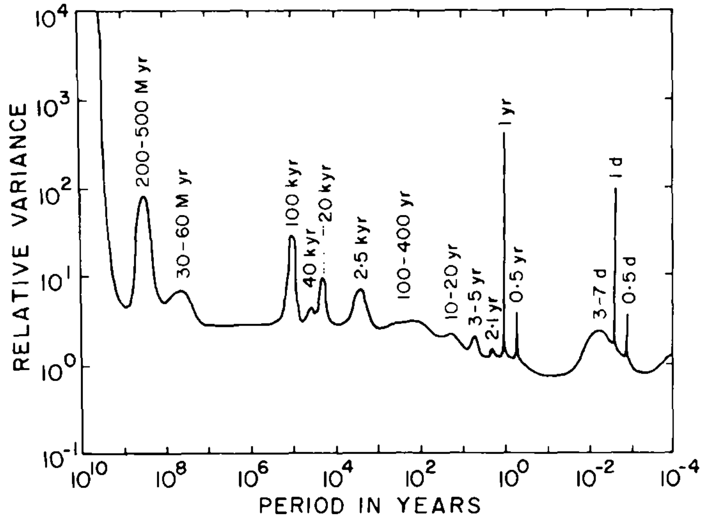

Fig. 1. Sketch of global climatic variability on all time scales (after Mitchell, 1976). The position of the peaks is relatively well known, but not their relative height and width. Units of time are abbreviated as 10^3 yr = 1 kyr and 10^6 yr = 1 Myr.

(10^0 yr). Climatic variability also contains a stochastic component involving a certain degree of nonpredictability. This is indicated by the continuous background underlying the variance spectrum.

Climate varies significantly on time scales exceeding 10^7 yr due to the tectonic changes of the earth's surface. Clear evidence is provided by fossil animals and plants. Continental drift alters the global distribution of land and water masses; the Atlantic basin was not yet formed 200 million yr ago. With a supercontinent and a superocean, climate fluctuations are expected to be substantially different from those which occurred during the Quaternary (the past two million years) with the current land-ocean distribution (Crowley, 1988).

Figure 2 illustrates the cascade of time scales and estimated amplitudes of climatic variations from 10^5 to 10^0 yr as seen in oxygen isotope records from sea sediments (a), and ice cores (b)–(d), and in direct air temperature measurements (e). Large negative values of the $\delta^{18}O$ isotope ratio in (a) correspond to relatively large ice volumes and to cold temperatures in (b)–(d). Time scale variations of 10^5 yr (Figure 2(a)) are associated with ice ages of the Quarternary in response to periodic changes of the solar irradiation caused by the variation of the orbital parameters (Berger *et al.*, 1984; Berger, 1988). While this mechanism is well accepted for the 19 000, 23 000 and 41 000-yr cycles, the origin of the strongest signal of 100 000 years is still uncertain (Hyde and Peltier, 1985; Saltzman *et al.*, 1982).

Figure 2(b) displays variations on the scale of 10^4 yr in the oxygen isotope ratio from Dye 3 (left, southern Greenland) and Camp Century (right, northwestern Greenland). The records extend from the last interglacial to the Holocene. An estimate for the temperature change is about 4 °C globally averaged (Kutzbach and

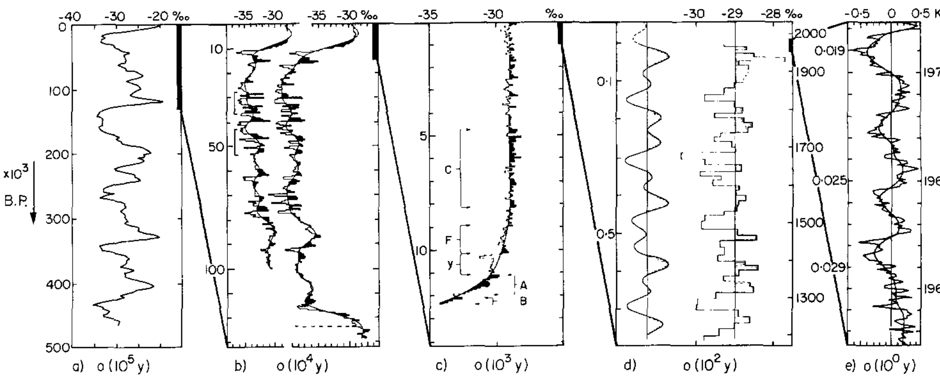

Fig. 2. Climatic variations on time scales from 10^5 to 10^0 yr as exhibited in oxygen isotope ratios (a)–(d), and in temperature measurements (e). Large negative $\delta^{18}O$ values in (b), (c) and (d) indicate cooler conditions; in (a) they indicate larger ice volumes. The $\delta^{18}O$ profile for the past 500 000 yr in (a) is derived from two sea-sediment cores from the Indian Ocean. The last glacial with its transitions is tracked in the Greenland ice cores from Dye 3 (b, left) and Camp Century (b, right) and shows the strong Wisconsin oscillations around 30 000 and 50 000 B.P. The $\delta^{18}O$ profile for the past 12 000 yr of the Camp Century core are displayed in (c), where distinct climatic events (A-Y, see text) with a time scale of 10^3 yr can be identified. In (d) the profile of the past 800 yr of (c) is given (d, right) with the synthesis of the two dominating harmonics (d, left). Interannual variability associated with El Niño events appear in measured air-temperature anomalies averaged vertically and horizontally over the Northern Hemisphere (e). [Figure compiled from Imbrie and Imbrie, 1979; Dansgaard *et al.*, 1970, 1984; and Peixóto and Oort, 1984.]

Guetter, 1986) with regional amplitudes being much larger (12 °C in South Greenland; see Dahl-Jensen and Johnsen, 1986). Climate changes on the time scale of 10^3 yr (Figure 2(c)) are illustrated in the past 14 000 yr of the oxygen isotope record of Camp Century (Dansgaard *et al.*, 1970). Superposed on the rapid transition into the present warm period are weaker and more regional excursions like the Bølling (B), Allerød (A) and Friesland oscillations (F) and the Postglacial Climatic Optimum (C; Lamb, 1977). An intensive cool period of only a few hundred years occurred just over 10 000 yr ago (Y, Younger Dryas). Its causation and abrupt termination are the subject of much current research (Berger and Labeyrie, 1987; Dansgaard *et al.*, 1989; Broecker and Denton, 1989; Maier-Reimer and Mikolajewicz, 1989; Stocker *et al.*, 1990). Several investigators have proposed that the Younger Dryas started just after North Atlantic deep water formation was inhibited by glacial melt water from the Laurentide ice sheet. This would have weakened the basin-scale thermohaline circulation and hence the poleward transport of heat in this region.

Variations on the century time scale, the central topic of this paper, are shown in Figure 2(d). Decadal averages of $\delta^{18}O$ in the Camp Century ice core are shown for the past 800 yr (Johnsen *et al.*, 1970). A cold period at the end of the 13th century and the Medieval Optimum (Lamb, 1977) of the 14th century are visible. The Little Ice Age (Grove, 1988) appears as two cold periods around 1500 AD and in the 17th century; the warm conditions around 1930 are also evident. Although the amplitudes of these fluctuations are much smaller than glacial-to-interglacial variations, historical documents reveal a strong impact on the extent of vegetation and living conditions in the Northern Hemisphere (Dansgaard *et al.*, 1975; Lamb, 1977; Pfister, 1984; Grove, 1988).

Climatic fluctuations on short time scales of 30 yr or less are related to decadal variability (e.g., Trenberth, 1990; Mysak *et al.*, 1990) and interannual El Niño events (Enfield, 1989). With amplitudes of less than 0.5 °C in a hemispheric average (Figure 2(e)), these air-temperature anomalies are weak compared to the amplitudes for the longer time scale fluctuations but can still be identified in instrumental records.

3. Variations on the Century Time Scale

From the above perspective, century time scale oscillations appear to be near the high-frequency end of the spectrum of climate variation and have amplitudes that are smaller than those for ice age cycles. Nevertheless, they can be clearly detected in many proxy data records and in some historical and instrumental data. The widespread distribution of these signals suggests that century time scale climatic variations may be an internal or forced oscillation of the climate system rather than just random noise.

The time series presented in this paper are analysed using the same method throughout. First, a linear trend was removed from the raw data to avoid a possible long term bias in the spectrum. The power spectrum was then calculated according to standard procedures (e.g. Priestley, 1989). We then tested the hypothesis whether or not the variance of the observed signal could be explained by a first-order autoregressive process. The hypothesis was rejected if the spectral power of the analysed data exceeded the power of the random process on a selected significance level (Mitchell *et al.*, 1966).

3.1. *Evidence in Ice Cores*

Ice cores from several sites in the Arctic have been analysed with a resolution that allows us to identify climatic variations on the century time scale. The first such core was retrieved from Camp Century (northwest Greenland) and provides a climate record of the past 800 yr. This part of the ice core has been sampled in 10–20-yr averages by Johnsen *et al.* (1970) and Dansgaard *et al.* (1970) and was spectrally analysed by these authors and Stuiver (1980). The former found that two large peaks, at 78 and 181 yr, account for much of the observed variance (cf. Figure 2(d), whereas Stuiver (1980) reports somewhat different near-significant peaks (see Figure 3(a)). Johnsen and Dansgaard conjecture that these cycles are due to changing conditions of the sun, and therefore attribute the fluctuations to external forcing. The 78-yr signal is close to the Gleissberg cycle (Gleissberg, 1965) observed in sunspot records. Figure 3(b) (Stuiver, 1980) displays the power spectrum for the Crête (central Greenland) record and exhibits significant cyclic variations

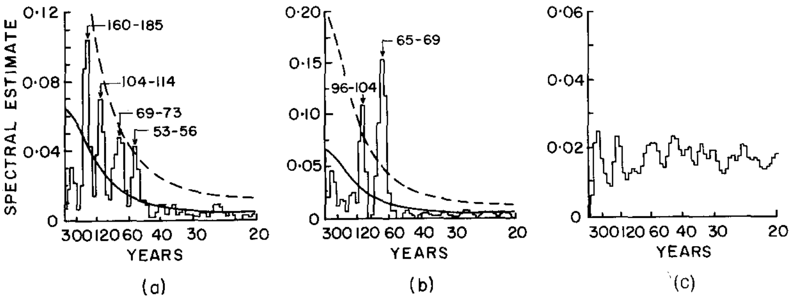

Fig. 3. Power spectra of the oxygen-isotope records covering the past 800 yr from Camp Century (a), Crête (b) and Devon (c). The Greenland cores (a) and (b) show peaks of the century time scale that are close to or exceeding the 95% confidence limit (dashed line) of the corresponding first-order autorgressive process (solid line). The record of Devon Island (northern Canada) shows no cycles and resembles white noise. [From Stuiver, 1980.]

with periods around 100 and 68 yr. Schönwiese (1981) analysed the same record but reported only a 50-yr peak that is significant at the 80% level. Records of oxygen isotope ratios and ice-melt features from the Dye 3 core were spectrally decomposed by Hibler and Langway (1977); they found spectral power at 80 and 30 yr.

Paterson *et al.* (1977) have analyzed two cores from Devon Island (northern Canada) which cover the past 125 000 yr. Although the core locations are only 27 m apart, the cross-correlation between various segments from each core varied from 0.45 to 0.72. They argued that these low values are due to annual 'noise'. The correlation for only the past 1000 yr, where the time scale is accurate, is not mentioned. For the past 800 yr a record is given with a resolution of 10 yr, and the authors remark that most of the features of the Camp Century record are reproduced. However, the spectral analysis by Stuiver (1980) demonstrated that there are no significant peaks (Figure 3(c)) and that the record resembles white noise. This qualitatively different behavior could be due to the geographic location of Devon Island. Whereas the Greenland stations are under the influence of the North Atlantic deep water formation and the northern branch of the Gulf Stream, Devon Island is exposed to cold polar outflow and is isolated from such direct oceanic effects.

A proxy data record that is clearly not under the direct influence of the North Atlantic circulation was constructed by Thompson *et al.* (1986) and Thompson and Mosley-Thompson (1989). Time series of particle concentration, conductivity, $\delta^{18}O$ and accumulation (with annual resolution from 1476 to 1984 AD) were obtained from an ice core of the Quelccaya ice cap of the Peruvian Andes. Figure 4 shows the spectra of the time series of particle concentration (a), conductivity (b), $\delta^{18}O$ (c) and accumulation (d). Dust, conductivity and the oxygen isotope series exhibit significant power on the decadal scale with various cycles of 10–50 yr. Conductivity and particle size show variability with periods around 110 yr significant on the 99% level, whereas power in the oxygen isotope spectrum is low for cycles

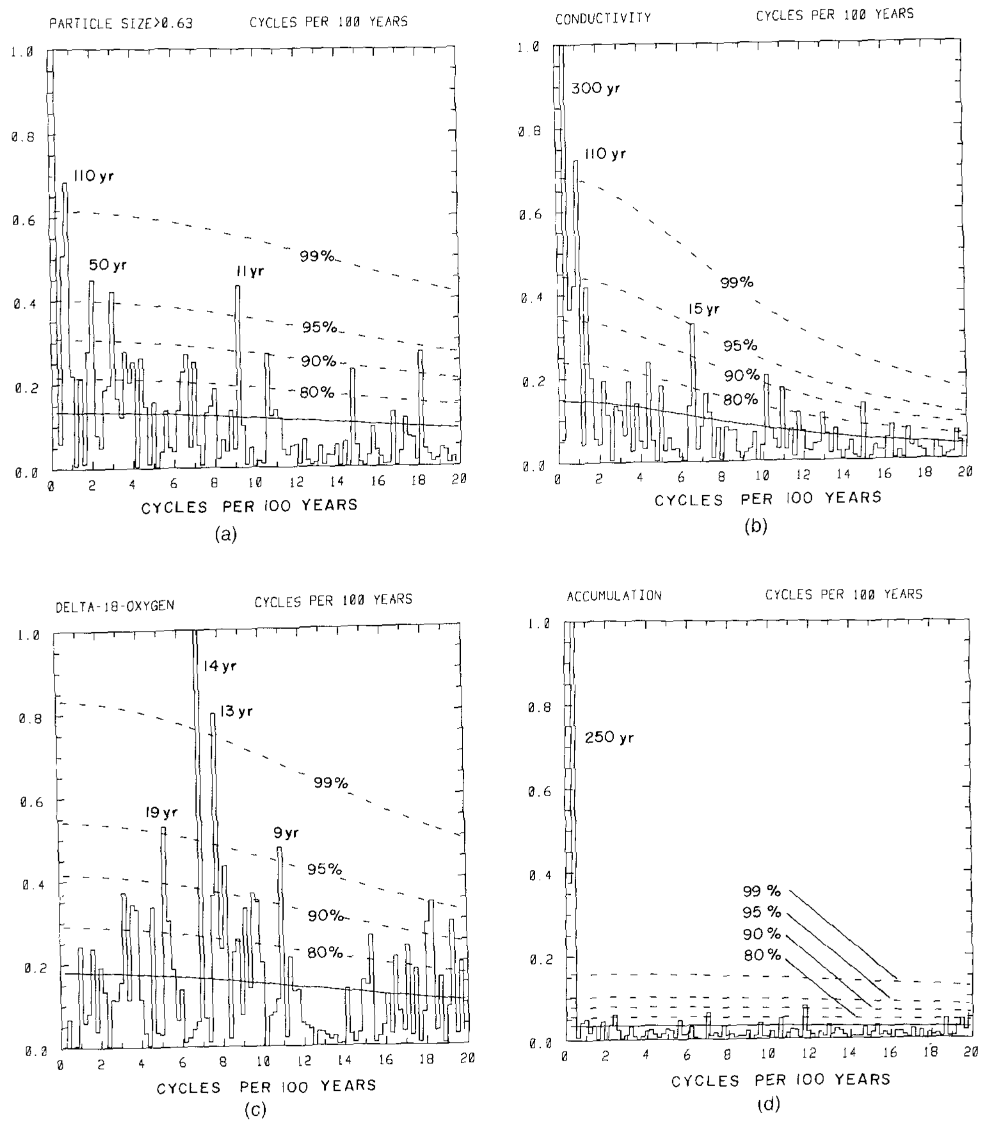

Fig. 4. Normalized spectra of total particle concentration (a), conductivity (b), $\delta^{18}O$ (c) and accumulation (d) from an ice core of the Quelccaya ice sheet (Peru; data from Thompson and Mosley-Thompson, 1989) covering the last 500 yr (1475–1984). Confidence limits (dashed) are obtained assuming a first-order autoregressive process (solid).

longer than 30 yr. Most of the variability for accumulation, which is closely linked to the hydrological cycle, is contained in a significant peak around 250 yr (Figure 4(d)).

It is remarkable that century time scale cycles are observed in oxygen isotope records from locations influenced by the North Atlantic circulation (Figure 3(a), (b)), while no signal occurs at other sites (Figures 3(c), 4(c)). We mentioned in Section 1 that the oxygen isotope ratio of a water parcel reflects the air-temperature history along the path of evaporation to deposition. Because Greenland, Devon and Quelccaya are under the influence of different atmospheric circulation patterns, one could expect different signals in the associated isotope records. The accumulation and dust series of the Quelccaya ice cap, on the other hand, are a proxy for the variability of the hydrological cycle and the wind regime. In Section 5 we propose a hypothesis that may qualitatively explain these observations.

Ice cores have been sampled from two other locations (Siple Station, Antarctica by Mosley-Thompson *et al.* (1990) and Dunde ice cap, China, by Thompson *et al.* (1988)) with sufficiently high accumulation rates such that an annual resolution for the last 1000 yr is possible. These data, however, have not yet been analysed to identify century time scale variability at these locations.

3.2. *Evidence in Tree Ring Records*

Hughes *et al.* (1982) have reviewed earlier developments in the study of variations in tree ring widths as a potential source of paleoclimatic information. Jacoby and D'Arrigo (1989) reconstructed a temperature series starting in 1671 by analysing tree ring widths from 11 high latitude sites along the boreal forest line in North America; only two locations are close to the Atlantic Ocean. A spectral analysis of the data did not reveal any significant cycles in their composite record.

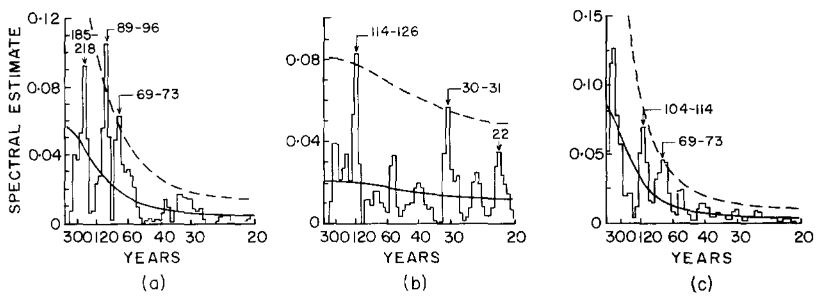

Fig. 5. Spectra of the tree ring width records from Lapland (a), Switzerland (b) and Nevada (c). The solid line represents a first-order autoregressive process and the associated 95% confidence limit (dashed). [From Stuiver, 1980.]

Three tree ring width records that were spectrally analysed by Stuiver (1980) are reproduced in Figure 5. The Lapland tree ring index (Sirén, 1961; Lamb, 1977) covers the past 780 yr and shows significant cycles around 90 and 70 yr (Figure 5(a)). Near significant power appears at 200 yr. Century time scale variations are also present in an Alpine record of tree ring widths from Switzerland for the past 700 yr (Schweingruber *et al.*, 1976). In addition to the peak around 120 yr, Figure 5(b) shows a significant interdecadal cycle of 30 yr. Power at century scales, although weaker, is observed in the 1100-yr record of tree ring widths from the White Mountains, Nevada (LaMarche, 1974), where 110- and 70-yr peaks appear

(Figure 5(c)); they are absent in the deuterium record of the same time series (Stuiver, 1980).

Briffa *et al.* (1990) present a 1400-yr reconstruction of summer temperatures in Fennoschandia and report fluctuations on time scales ranging from annual to century. A spectral analysis (Briffa, pers. comm.) showed that variability in the band of 150–50 yr was significant (95%) in the chronology. Although individual peaks are present only during parts of the time series (e.g. the first 700 yr) significant broad-band century scale fluctuations were present in all the investigated subintervals.

Radiocarbon isotope ratios were analysed for the tree ring record from La Jolla by Neftel *et al.* (1981) and Sonett (1984). The time series goes back to 6000 BC and comprises 8000 years. The spectrum for the whole period is shown in Figure 6.

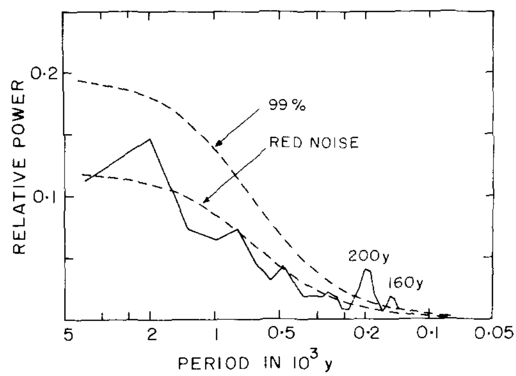

Fig. 6. Spectrum of the La Jolla tree ring $\delta^{14}C$ record (solid line) with the spectrum of the first-order autoregressive process and the associated 99% confidence limit. [From Neftel *et al.*, 1981.]

Apart from an autoregressive component, peaks exceed the 99%-confidence limit at about 200 and 160 yr. Sonett (1984) reports strong nonstationarity when spectrally analysing subintervals of the time series. Whereas 200 yr seems to be an average value of cyclic behavior during the past 8000 years, periods range from 1300 to 100 yr in various subintervals of the data. Figure 7 demonstrates that periods of 300–150 yr appear in $\delta^{14}C$ records from different sites in the Northern Hemisphere during 3900–3200 BC. Neftel *et al.* (1981) and Sonett (1984) link changes of $\delta^{14}C$ to varying intensity of the cosmic ray flux, which is suggestive of external forcing operating on the century time scale.

A recent study by Stuiver and Braziunas (1989) concentrates on this issue. A record of $\delta^{14}C$ from a 9600-yr tree ring chronology compiled from several sites yielded a high-quality time series with a 20-yr resolution. The power spectrum exhibits peaks at 420, 218 and 143 yr and weaker power at 67-, 52-, and 45-yr periods, which they interpret as a fundamental cycle of 420 yr and its higher harmonics. Stuiver and Braziunas (1989) mention the spectral analysis of ten other climatic records (tree rings and glacier fluctuations) from Röthlisberger (1986), where they found 'significant power in the 123 to 143-year interval for six records,

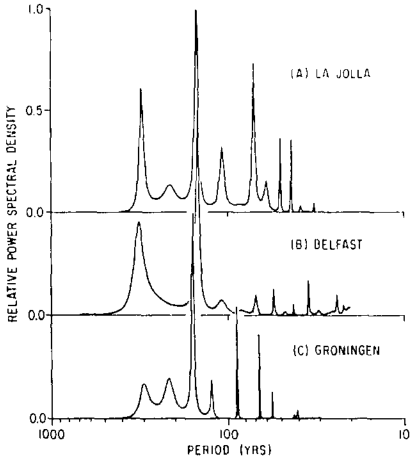

Fig. 7. Spectra of $\delta^{14}C$ records from tree ring data from three Northern Hemisphere sites. Due to the length of the $\delta^{14}C$ Belfast record only the subinterval 3900–3200 B.C. is analysed. [From Sonett, 1984.]

in the 102 to 104-year range for three, and near 88 years for two.' Thus it appears that there may exist a link between solar activity and climate for the third harmonic. Fisher (1982) cross-correlates the ^{14}C-production rates determined by Stuiver (1980) with the $\delta^{18}O$ records from Camp Century and Devon. He finds a coherent anti-phase correlation in the period range 100–400 yr between the two records; this may hint at a sun-climate relation.

3.3. *Evidence in Biological Records*

The impact of climatic conditions (e.g. ENSO) on fisheries is well documented (Cushing, 1982). Some records of animal populations also show century scale variability that may be driven by climate changes. Although such fluctuations in the fauna exhibit cyclic behavior, two problems should be mentioned concerning a climate-related interpretation. First, the population of a species can fluctuate due to effects of self-control or linked to the state of prey and predator. Second, if the climate influences animal populations, how then could a set of physical climate variables be related to the observed proxy? One can think of a statistical approach as in the analysis of tree-ring indices or pollen counts (Bradley, 1985). The lifetime of an animal seems to be an important factor in determining the usefulness of animal records as climate proxy data. High resolution records may be obtained from short-living populations (e.g. insects), which are more sensitive to changes of the environment.

Cyclic variations are evident in Figure 8, which shows the spectrum of the Pacific hake population estimated by Soutar and Isaacs (1969). The 1800-yr time series was obtained by counting the number of scales in a sea sediment core from the

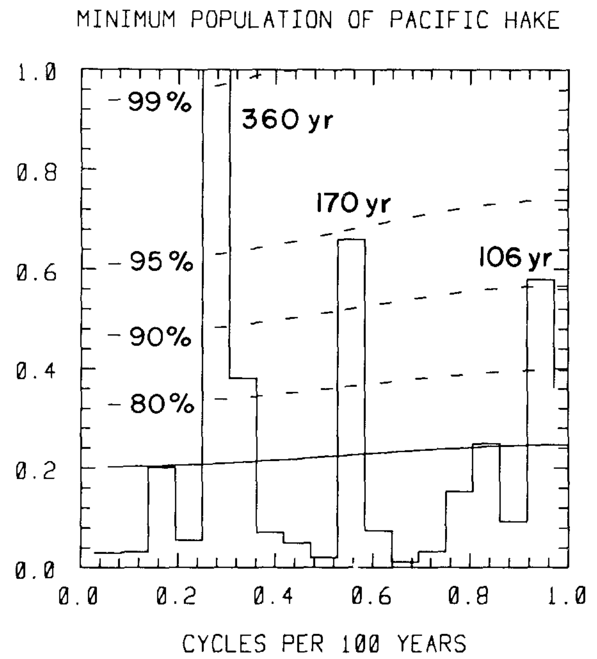

Fig. 8. Normalized spectrum of the minimum population of Pacific hake as estimated by Soutar and Isaacs (1969) using sedimented scales from the Santa Barbara Basin (California).

Santa Barbara Basin (California); the resolution is 50 yr. Most of the variance is explained by three cycles of 360, 170 and 106 yr significant at the 99%, just below the 95% and the 90% level, respectively. Shorter time series are reconstructed by Vibe (1967), who links population changes of several species of Arctic animals to fluctuating climatic conditions.

Another type of biological data that is useful for climate reconstruction on the century scale consists of pollen counts in lake sediments (Gajewski, 1988). Gajewski analyzed the pollen content of these cores from sites close to the Great Lakes and the Atlantic coast. Using multiple regression, a continuous time series for the last 200 yr of summer temperature could be reconstructed with a resolution of 40 yr. Figure 9 shows the spectra for Hells Kitchen Lake (a, Wisconsin), Clear Pond (b, New York) and Conroy Lake (c, Maine). All three records have significant power exceeding the 95% level on the century time scale with 125 yr (a), 95 yr (b) and 330 yr (c). Also, very long periodic fluctuations are present. Significant power on the 90% level is concentrated around 90–120 and 230–250 yr in all three spectra.

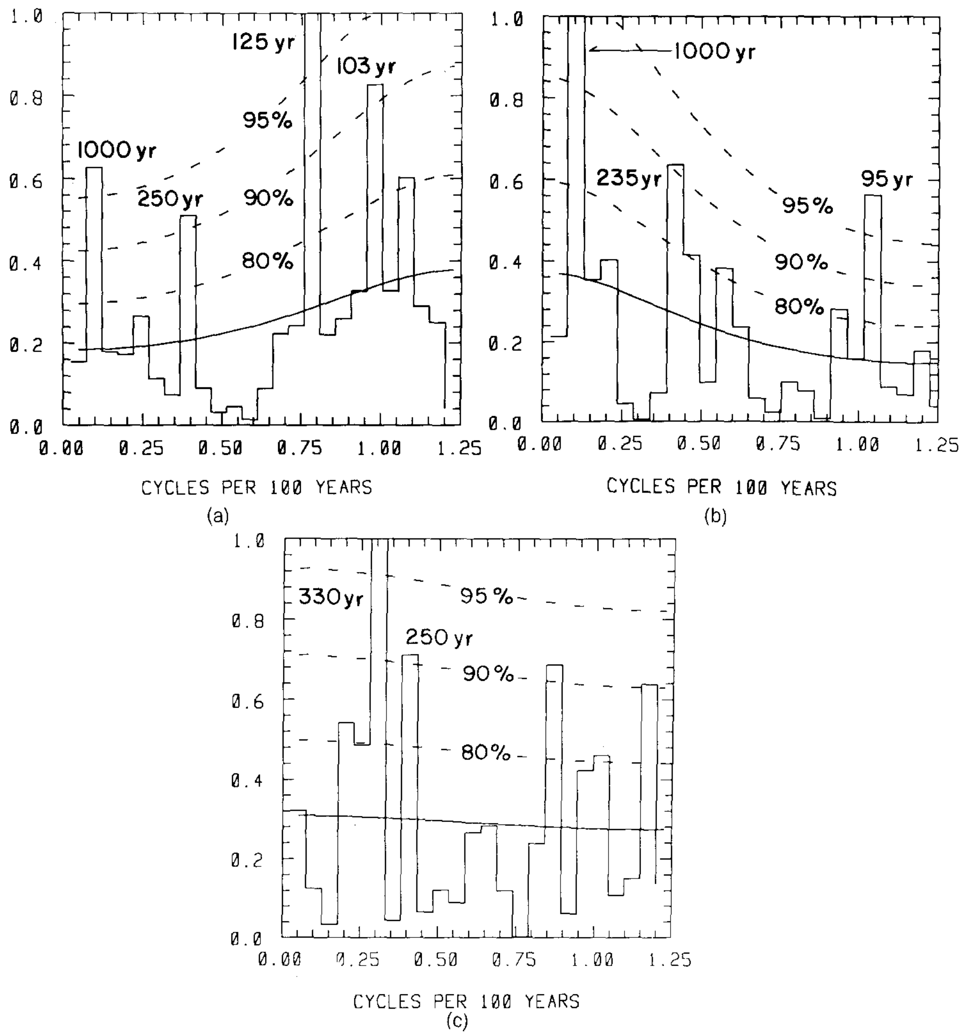

Fig. 9. Normalized spectra of the detrended temperature time series covering the last 2000 yr as obtained from pollen counts (Gajewski, 1988) in three lake-sediment cores: Hells Kitchen Lake (a, Wisconsin), Clear Pond (b, New York) and Conroy Lake (c, Maine).

3.4. *Evidence in Historical Records*

A number of studies using historical sources develop data sets which describe various properties of the cryosphere and the hydrosphere within the climate system. Among these, winter severity and sea-ice indices, lake level records, precipitation time series and wetness indices are particularly useful (Lamb, 1977). Cyclic behavior is evident from the Iceland ice-severity index (Koch, 1945; Lamb 1977), which is defined as the number of weeks per year that sea ice has been observed around the north coast of Iceland. The record goes back as early as 960

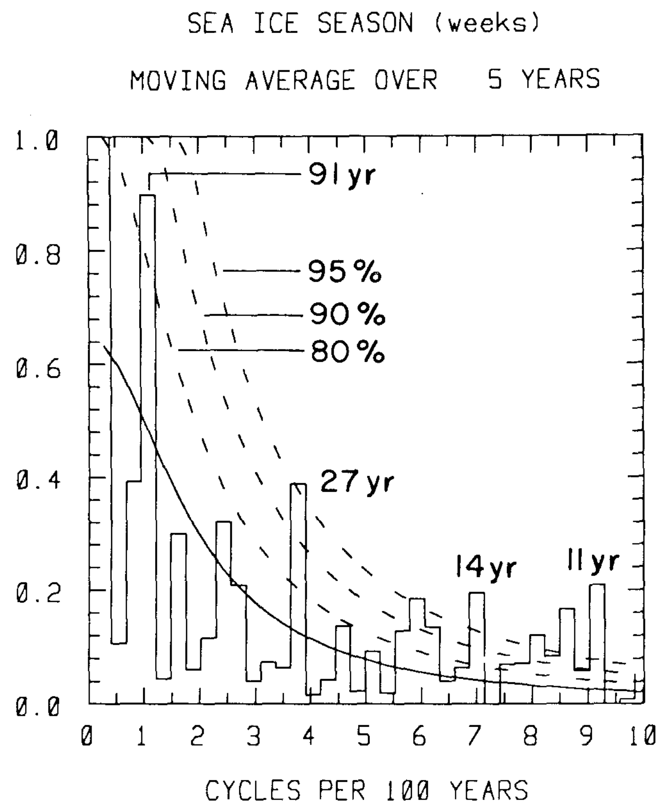

Fig. 10. Normalized spectrum of the time series of weeks of ice observed around the north coast of Iceland (Koch, 1945; Lamb, 1977) from 1600–1970. The data were smoothed with a 5-yr moving average.

AD, but Ogilvie (1984) argues that the part before 1600 is not reliable because of the difficulty in interpreting historical sources. Figure 10 displays the spectrum calculated from the 370 yr of data (Lamb, 1977), which was smoothed by a 5-yr moving average. Several cycles exceeding the 95% level are evident: decadal-scale fluctuations at 11, 14 and 27 yr are significant at the 95% level (see also Mysak *et al.*, 1990), while a peak at 91 yr is weaker and exceeds only the 80% level.

Using historical sources Lamb (1977) also constructed decadal winter severity indices for three well separated locations in Europe (England, Germany, Russia). The time series cover the past 860 yr, and their spectra (Stuiver, 1980) are given in Figure 11. In the England record, a significant cycle at more than 300 yr occurs as well as power at the interdecadal scale. The spectrum of the Russian index, however, shows near-significant power at a period over 100 yr as well as at the interdecadal time scale.

Hameed *et al.* (1983) investigated a 500-yr precipitation index from Beijing and reported spectral power at 84 yr and weaker power at 126 and 56 yr. They conjectured that variations in insolation due to sunspot activity might be the cause of

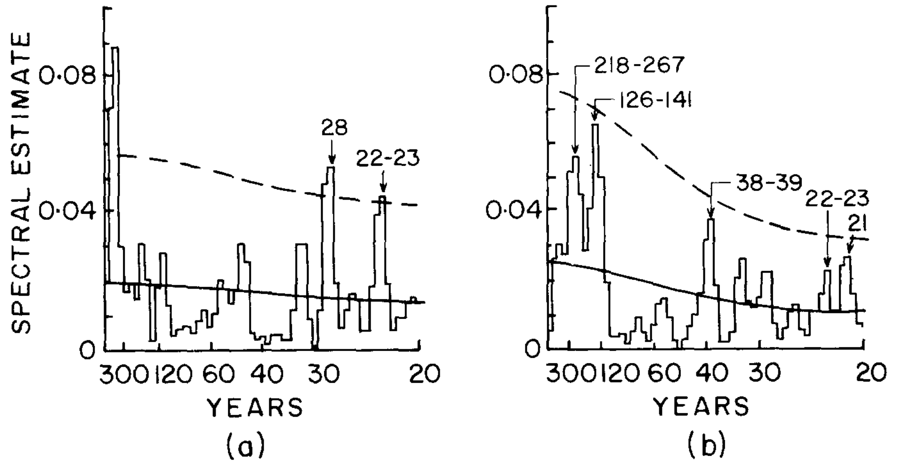

Fig. 11. Spectra of the decadal winter severity index series from 1100 AD–1960 AD of England (a) and Russia (b). [From Stuiver, 1980.]

the cycles. Clegg and Wigley (1984), however, re-analysed this record and six additional 510-yr series from various locations around Beijing. The only consistent and significant power present in all seven series is at 10 yr. The century-time-scale peak only occurs in one record and only for the past 250 yr. It is argued that the century scale cycle in the second half of the Beijing precipitation record is not characteristic for the area and may be an artifact of chance.

3.5. *Evidence in Instrumental Records*

Glaciers have been regularly monitored in Switzerland (Aellen, 1981) over the last 100 yr. At any one time, some glaciers advance while others retreat, indicating the importance of local climatology. The average over 50–100 glaciers, however, exhibits fluctuations that are representative of climatic variations. Major advances occurred around 1920 and 1980; maximum extension of Alpine glaciers was also recorded in 1850. A rough estimate yields a time scale of 60–70 yr for these fluctuations.

A dominant cycle of similar length, 83 yr, results from the spectral analysis of the global sea surface temperature and nighttime marine air temperature records over the last 130 yr constructed by Folland *et al.* (1984). It seems that this cycle is mostly due to the negative anomalies during the 45 yr from 1895 to 1940. It must be mentioned that the records by Jones *et al.* (1986) agree with these series only after 1900. In the 19th century, however, generally negative anomalies are observed which, over the past 130 yr, suggest a steady global warming.

Vinnikov *et al.* (1980) present global temperature anomalies for various latitude belts which span the period from 1880 until 1980. Their study shows generally negative anomalies before 1920 with a significant warming until 1940 followed by an equal cooling for the next 20 yr. Variance increases with latitude. The sequence of negative and positive anomalies could, again, be associated with cyclic processes. The glacier record and the temperature series described above cover only about 1.5 cycle lengths. The results should therefore be taken only as an indication of the possible presence of the century time scale fluctuation.

The well-known 'Central England' temperature record is considered to be the longest instrumental record of climatic variations. It dates back to 1659 AD and covers 318 yr (Manley, 1974; Lamb, 1977; Schönwiese, 1978). Most of the monthly data originate from an average of three observation sites in England. The spec-

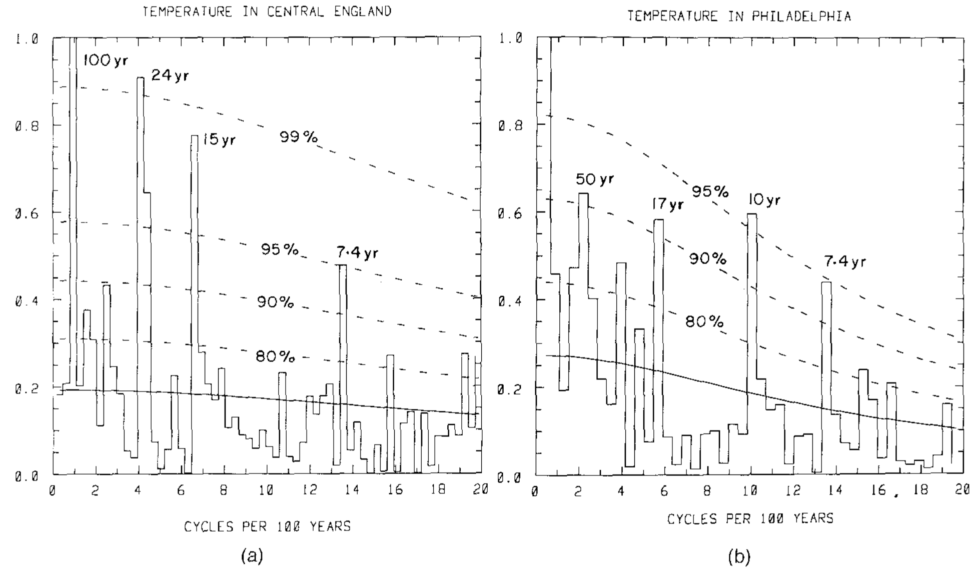

Fig. 12. Normalized spectrum of the annual means of the 'Central England' (a) and Philadelphia (b) temperature record.

trum in Figure 12(a) exhibits strong peaks at 100 and 24 yr, which both exceed the 99% confidence level; also a decadal cycle around 15 yr appears. Upon comparing Figure 12(a) with Figure 11(a) it is noted that the 100-yr cycle was strong during the past 300 yr for annual conditions, but does not appear in the seasonal proxy, the winter-severity index, over the past 850 yr. Another long temperature time series covering 230 yr is recorded at Philadelphia (Lamb, 1977) and is spectrally analysed in Figure 12(b). Again, decadal cycles are present at 10 and 17 yr; low-frequency signals are significant at 50 yr.

4. Summary and Discussion

The review of various records (proxy, historical and instrumental) has clearly shown that climate fluctuations on the century time scale, i.e., 50–400 yr, are an

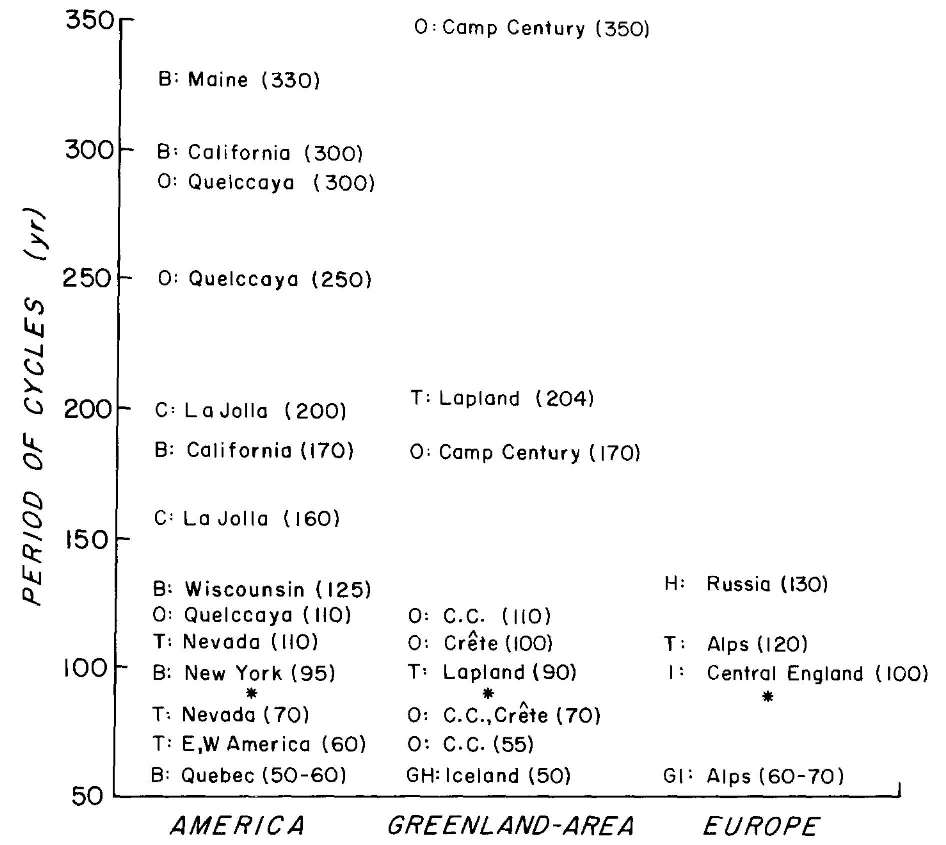

Fig. 13. Summary of climatic variations observed on the century time scale. The findings are spatially and temporally ordered in the horizontal and the vertical, respectively. The capital letters denote evidence in biological (B), radio carbon (C), glaciological (G), historical (H), instrumental (I), oxygen isotope and other parameters from ice cores (O), and tree-ring records (T). The observed cycle period is given in brackets. C.C. denotes the Camp Century $\delta^{18}O$ record and * indicates the 83-yr cycle observed in the globally averaged SST and MAT records by Folland *et al.* (1984).

ubiquitous phenomenon during the Holocene. Figure 13 shows a summary of most of the cycles discussed in this paper. The evidence is ordered both spatially and temporally. Notice that all the data plotted here originate from the Northern Hemisphere except the Quelccaya ice-core data and the global average temperature by Folland *et al.* (1984), which also contain some data from the Southern Hemisphere. Evidence of the century scale cycles is found in $\delta^{18}O$ records from ice cores, in tree ring indices and $\delta^{14}C$ records, in records of major glacier advance and sea-ice extent, in aquatic population records and pollen counts, in historical records and, finally, in records based on instrumental observations during the past 300 yr.

Cyclic fluctuations on the century (and shorter) time scale have often been attributed to varying solar conditions. Precision measurements of the solar radiative flux (the solar 'constant') are available only for the past 10 yr (Willson and Hudson, 1988). This is the first study directly demonstrating that the solar constant may have an 11-yr periodicity. They estimated the amplitude of this fluctuation to be only 0.04% of the solar constant, which calls for strong positive feedback mechanisms within the climate system if solar forcing were to have an effect on surface temperature.

Stuiver (1980) has spectrally analyzed 11 proxy data records (oxygen isotopes, tree ring widths and historical records) covering the last millennium. His objective was to identify signals of solar variability in climate records (sunspot cycle of 11 yr, Hale cycle of 22 yr, Gleissberg cycle of 84 yr and others), but he concluded that no support existed for a 'statistically significant relationship between the combined regional climate and the ^{14}C time series.' Many of the spectra, however, contain significant power on the century time scale. In particular, as we have shown above, power close to or exceeding the 95% level in the range of 90–140 years occurs in two oxygen isotope and four tree ring records and in one historical record.

The picture that the climate system is externally forced and responds in a linear fashion on these time scales is probably too simplistic. Inconsistencies using the solar explanation for century time scale variations have been noticed in the analyses of the proxy data records. If solar processes are important for the climate system on these time scales, they could most likely be detected globally. Why then is it that in a number of proxy data records only cycles of about 80 yr appear but not the well-known 11-yr and 22-yr cycles?

Clear evidence of a *physical mechanism* including amplifying feedbacks to support the hypothesis of direct solar forcing is still lacking. Recent results of ocean and climate models indicate that decadal and century time scale cycles need not be due to external (solar) forcing but may well be the manifestation of *natural variability* within the coupled atmosphere-ocean-ice system.

An important component of the climate system which is capable of exhibiting these time scales is the deep circulation of the ocean. We propose a *hypothesis* to illustrate this point using the example of the spectra obtained from the Quelccaya ice cap in the Peruvian Andes, a location which is well away from a direct influence of the North Atlantic. Deep water formation in the North Atlantic regulates the meridional oceanic heat transport in this ocean basin and the release of heat from the ocean to the atmosphere in high northern latitudes. A three-dimensional coupled atmosphere-ocean general circulation model (Manabe and Stouffer, 1988) and a simpler two-dimensional atmosphere-ocean model (Stocker *et al.*, 1990) shows that variability of the thermohaline flow is registered in regional surface air temperature with amplitudes that could be detected in proxy records. The regional evaporation-precipitation budget is also affected. As the Atlantic is the most important region of net evaporation in the world ocean (Baumgartner and Reichel, 1975), regional fluctuations there will enter the hydrological cycle and eventually have a global influence. This may explain why the Quelccaya data exhibits a century time scale signal only in the proxy for the hydrological cycle but not for temperature (Figure 4). How the wind regime may be influenced by the variability of the thermohaline circulation is not clear.

The model study by Manabe and Stouffer (1988) is consitent with and lends some support to our tentative explanation. Their model shows two states of the global climate, which are roughly characterized either by a weak or a strong thermohaline circulation in the Atlantic. Comparing the two states they find that the surface air temperatures change mainly in the region around the northern North Atlantic and very little at low latitudes of the Southern Hemisphere. Changes in the hydrological cycle at low southeren latitudes, however, show magnitudes similar to those in the high northern latitudes. Finally, changes in the mean meridional circulation of the atmosphere are strongest around the equator.

In the final section we give examples of cyclic decadal-to-century scale fluctuations involving the thermohaline circulation that have recently been found in numerical models.

5. A Possible Mechanism for Century Time Scale Fluctuations

Natural variability of the upper ocean has long been recognized as an important factor in our understanding of interannual fluctuations in the climate system. Possible variations of the deep ocean on glacial time scales, on the other hand, have been found in proxy data (Duplessy and Shackleton, 1985; Broecker *et al.*, 1985; Boyle and Keigwin, 1987; Broecker and Denton, 1989). On intermediate time scales of decades to millennia, however, the ocean has classically been considered as a mere reservoir of heat and water.

Over the last few years, several models of different complexity have been developed to study the thermohaline circulation of the ocean. Box models by Stommel (1961), Rooth (1982), Welander (1986) and Birchfield (1989) exhibit the possibility of multiple equilibria for the state of the thermohaline circulation. This property also carries over to two-dimensional models (Marotzke *et al.*, 1988; Wright and Stocker, 1991), and more realistic three-dimensional OGCMs (Bryan, 1986; Marotzke, 1989; Weaver and Sarachik, 1991b) and a coupled atmosphere-ocean GCM (Manabe and Stouffer, 1988).

Partly because of limited integration time of these models, very little attention could be paid to natural variability. The recent study by Mikolajewicz and Maier-Reimer (1990) shows variability with a peak around 320 yr in their global OCGM under stochastic forcing. Natural variability is also present in the two-basin version of a two-dimensional, zonally averaged ocean model (Wright and Stocker, 1991) under *steady* forcing. The model is based on the diagnostic balance equations of momentum and mass and the prognostic equations of heat and salt.

Figure 14 displays the meridional overturning stream function in $10^6 m^3/s$ in the model of the Pacific-Atlantic basin system (Stocker and Wright, 1991). A stable, quasi-steady state is reached after 7000 yr of spin-up under restoring surface boundary conditions on temperature and salt, followed by 14 000 yr of integration

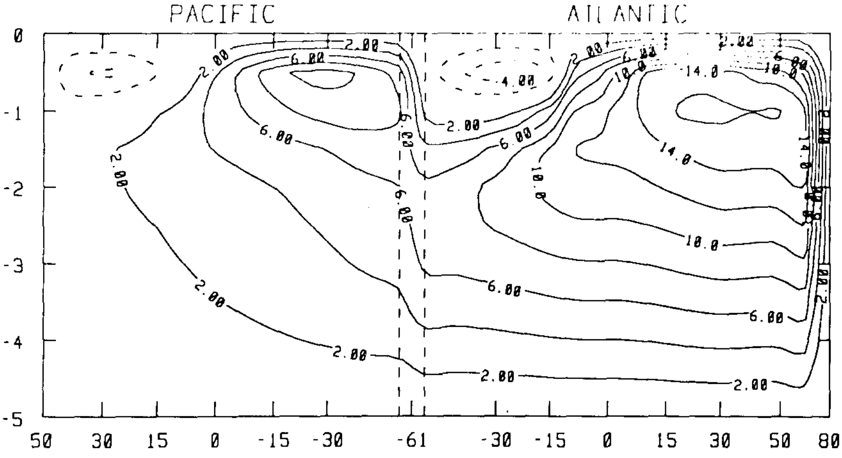

Fig. 14. Quasi-steady thermohaline circulation in the Pacific-Atlantic basin system. The Pacific (Atlantic) basin extends from 50° N to 61° S (80° N to 61° S) and is 5000 m deep; contours of the meridional stream function are in 10^6 m^3/s. The main region of sinking is in the North Atlantic from where the deep water spreads into the Pacific, where its upwells. The results are obtained using a two-basin version of the zonally averaged ocean model of Wright and Stocker (1991).

under mixed boundary conditions (temperature is still restored, salt flux is held fixed). Deep water is formed in the North Atlantic, from where it flows as a deep current into the Pacific to upwell. The model reproduces the global conveyor belt circulation proposed by Gordon (1986) and also gives temperature and salinity fields that are in fair agreement with observations.

This stable state is quasi-steady: the fields oscillate on different time scales about their mean value. As the forcing at the surface is constant in time, this variability is most likely a self-sustained oscillation of this nonlinear system. Figure 15(a) shows a time series of the average vertical ocean-to-atmosphere heat flux in the Atlantic (from 55° S to 80° N, solid) and Pacific (from 55° S to 50° N, dashed). Natural variability on decadal-to-century scales is evident in both fluxes, but the magnitude is much weaker in the Pacific. The average Atlantic heat flux fluctuates with a peak-to-peak amplitude of 1.4 W/m^2; in the Pacific this value is only 0.006 W/m^2. The oscillation seems to be linked to the shallow upwelling of South Atlantic thermocline water (see Figure 14, in the equatorial region of the Atlantic), where the surface heat fluxes assume very large amplitudes (>50 W/m^2).

A signal in the atmospheric temperature due to this natural variability must therefore be expected in regions under the climatic influence of the Atlantic but not in those under Pacific influence. The spectrum of the Atlantic heat flux is given in Figure 15(b). Most of the signal can be explained by two strong cycles of 110 and 38 yr and a weaker one at 19 yr; in the Pacific the 110-yr peak is dominant. A parameter study reveals that the natural variability in this model is extremely sensitive to vertical diffusivity of heat and salt; from observations one estimates values in the range of $0.1 – 5 \times 10^{-4}$ m^2/s. The result of Figures 14 and 15 are obtained with a

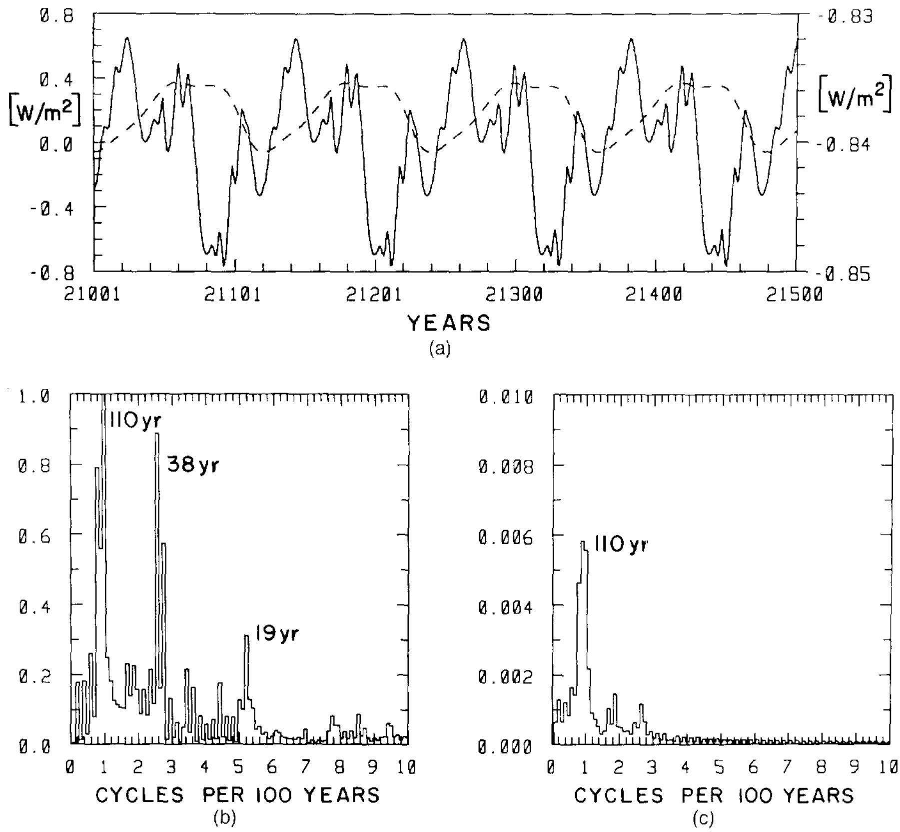

Fig. 15. (a) Time series of the average ocean-to-atmosphere heat flux in W/m^2 of the Atlantic (55° S to 80° N, solid, left ordinate) and Pacific (55° S to 50° N, dashed, right ordinate). Under steady surface forcing natural variability occurs in the form of a self-sustained oscillation. (b) Normalized power spectrum of the time series in (a) for the Atlantic. (c) Power spectrum of the time series in (a) for the Pacific. The total variance in the Pacific is about 100 times smaller than in the Atlantic.

uniform value of 0.3×10^{-4} m^2/s. A slight increase of the vertical diffusivity to 0.4×10^{-4} m^2/s does not affect the mean state of the global conveyor belt circulation but reduces the amplitude of the fluctuations. Also, the self-sustained oscillations in this case consists of the 38-yr cycle only. Further experiments with the same model but in a single basin have shown that century time scale variability of the meridional heat flux is also clearly present if a randomly varying perturbation is added to the surface freshwater flux.

These results suggest that cyclic century time scale fluctuations observed in various proxy data time series could therefore indeed be due to *natural variability* within the climate system. We have shown, using a two-dimensional ocean model, that the thermohaline circulation of the Pacific-Atlantic basin may exhibit such cycles. Their effect on the atmosphere is primarily felt in the Atlantic. This region is also characterized by a large net evaporation and hence plays an important role for the hydrological cycle of the globe. The fact that climatic variability is enhanced in this region is consistent with some aspects of the spatial pattern of the century time scale signals reported in this paper: (i) the signal is present in the proxies for wind and the hydrological cycle but not for temperature at Quelccaya, (ii) Camp Century exhibits a clear signal while it is absent at Devon, and (iii) century time scale fluctuations are significant in tree ring indices from Fennoscandia but are not found in records from Arctic sites in North America. Unlike with the solar forcing hypothesis, complicated feedback mechanisms, which would amplify a very weak signal, need not be invoked to explain century-time-scale variability.

Vertical diffusivity is crucial in determining both amplitudes and frequencies of these cycles, but it is, unfortunately, also a little understood parameter in ocean modelling. Further studies, especially long integrations of three-dimensional ocean and climate models, should provide a better under standing of how natural variability of the ocean influences the other components of the climate system on the longer time scales.

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