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Observed Climate Variations and Change

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CONTENTS

EXECUTIVE SUMMARY

***** There has been a real, but irregular, increase of global surface temperature since the late nineteenth century.

***** There has been a marked, but irregular, recession of the majority of mountain glaciers over the same period.

***** Precipitation has varied greatly in sub-Saharan Africa on time scales of decades.

*** Precipitation has progressively increased in the Soviet Union over the last century.

*** A steady increase of cloudiness of a few percent has been observed since 1950 over the USA.

* A larger, more sudden, but less certain increase of cloudiness has been observed over Australia.

Observational and palaeo-climatic evidence indicates that the Earth's climate has varied in the past on time scales ranging from many millions of years down to a few years. Over the last two million years, glacial-interglacial cycles have occurred on a time scale of 100,000 years, with large changes in ice volume and sea level. During this time, average global surface temperatures appear to have varied by about 5-7°C. Since the end of the last ice age, about 10,000 BP, globally averaged surface temperatures have fluctuated over a range of up to 2°C on time scales of centuries or more. Such fluctuations include the Holocene Optimum around 5,000-6,000 years ago, the shorter Medieval Warm Period around 1000 AD (which may not have been global) and the Little Ice Age which ended only in the middle to late nineteenth century. Details are often poorly known because palaeo-climatic data are frequently sparse.

The instrumental record of surface temperatures over the land and oceans remains sparse until after the middle of the nineteenth century. It is common, therefore, to emphasize trends in the global instrumental record from the late nineteenth century. The record suggests a global (combined land and ocean) average warming of 0.45±0.15°C since the late nineteenth century, with an estimated small (less than 0.05°C) exaggeration due to urbanisation in the land component. The greater part of the global temperature increase was measured prior to the mid-1940s. Global warming is indicated by three independent data sets: air temperatures over land, air temperatures over the ocean, and sea surface temperatures. The latter two data sets show only a small lag compared with land temperatures. A marked retreat of mountain glaciers in all parts of the world since the end of the nineteenth century provides further evidence of warming.

The temperature record of the last 100 years shows significant differences in behaviour between the Northern and Southern Hemispheres. A cooling of the Northern Hemisphere occurred between the 1940s and the early 1970s, while Southern Hemisphere temperatures remained nearly constant from the 1940s to about 1970. Since 1970 in the Southern Hemisphere and 1975 in the Northern Hemisphere, a more general warming has been observed, concentrated into the period 1975-1982, with little global warming between 1982 and 1989. However, changes of surface temperature in different regions of the two hemispheres have shown considerable contrasts for periods as long as decades throughout the last century, notably in the Northern Hemisphere

Over periods as short as a few years, fluctuations of global or hemispheric temperatures of a few tenths of a degree are common. Some of these are related to the El Niño-Southern Oscillation phenomenon in the tropical Pacific. Evidence is also emerging of decadal time scale variability of ocean circulation and deep ocean heat content that is likely to be an important factor in climate change.

It is not yet possible to deduce changes in precipitation on global or even hemispheric scales. Some regions have, however, experienced real changes over the past few decades. A large decline in summer seasonal rainfall has been observed in sub-Saharan Africa since the 1950s but precipitation appears to have increased progressively over the Soviet Union during the last century.

Reliable records of sea-ice and snow are too short to discern long-term changes. Systematic changes in the number and intensity of tropical cyclones are not apparent, though fluctuations may occur on decadal time scales. There is no evidence yet of global scale changes in the frequency of extreme temperatures Increases in cloud cover have been reported from the oceans and some land areas Uncertainties in these records are mostly too large to allow firm conclusions to be drawn Some of the changes are artificial, but increases of cloudiness over the USA and Australia over the last forty years may be real.

We conclude that despite great limitations in the quantity and quality of the available historical temperature data, the evidence points consistently to a real but irregular warming over the last century. A global warming of larger size has almost certainly occurred at least once since the end of the last glaciation without any appreciable increase in greenhouse gases. Because we do not understand the reasons for these past warming events it is not yet possible to attribute a specific proportion of the recent, smaller, warming to an increase of greenhouse gases.

7.1 Introduction

This Section focuses on changes and variations in the modern climate record. To gain a longer term perspective and to provide a background to the discussion of the palaeo-analogue forecasting technique in Section 3, variations in palaeo-climate are also described. Analyses of the climate record can provide important information about natural climate variations and variability. A major difficulty in using observed records to make deductions about changes resulting from recent increases in greenhouse gases (Sections 1 and 2) is the existence of natural climatic forcing factors that may add to, or subtract from, such changes. Unforced internal variability of the climate system will also occur, further obscuring any signal induced by greenhouse gases.

Observing the weather, and converting weather data to information about climate and climate change, is a very complex endeavour. Virtually all our information about modern climate has been derived from measurements which were designed to monitor weather rather than climate change. Even greater difficulties arise with the proxy data (natural records of climate sensitive phenomena, mainly pollen remains, lake varves and ocean sediments, insect and animal remains, glacier termini) which must be used to deduce the characteristics of climate before the modern instrumental period began. So special attention is given to a critical discussion of the quality of the data on climate change and variability and our confidence in making deductions from these data. Note that we have not made much use of several kinds of proxy data, for example tree ring data, that can provide information on climate change over the last millennium. We recognise that these data have an increasing potential, however their indications are not yet sufficiently easy to assess nor sufficiently integrated with indications from other data to be used in this report.

A brief discussion of the basic concepts of climate, climate change, climate trends etc, together with references to material containing more precise definitions of terms, is found in the Introduction at the beginning of this Report.

7.2 Palaeo-Climatic Variations and Change

7.2.1 Climate Of The Past 5,000,000 Years

Climate varies naturally on all time scales from hundreds of millions of years to a few years. Prominent in recent Earth's history have been the 100,000 year Pleistocene glacial-interglacial cycles when climate was mostly cooler than at present (Imbrie and Imbrie, 1979). This period began about 2,000,000 years before the present time (BP) and was preceded by a warmer epoch having only limited glaciation, mainly over Antarctica, called the Pliocene. Global surface temperatures have typically varied by 5-7°C through the Pleistocene ice age cycles, with large changes in ice volume and sea level, and temperature variations as great as 10-15°C in some middle and high latitude regions of the Northern Hemisphere. Since the beginning of the current interglacial epoch about 10 000 BP, global temperatures have fluctuated within a much smaller range. Some fluctuations have nevertheless lasted several centuries, including the Little Ice Age which ended in the nineteenth century and which was global in extent.

Proxy data clearly indicate that the Earth emerged from the last ice age 10,000 to 15,000 BP (Figure 7.1). During this glacial period, continental size ice sheets covered much of North America and Scandinavia, and world sea level was about 120m below present values. An important cause of the recurring glaciations is believed to be variations in seasonal radiation receipts in the Northern Hemisphere. These variations are due to small changes in the distance of the Earth from the sun in given seasons and slow changes in the angle of the tilt of the Earth's axis which affects the amplitude of the seasonal insolation. These Milankovitch orbital effects (Berger, 1980) appear to be correlated with the glacial-interglacial cycle since glacials arise when solar radiation is least in the extratropical Northern Hemisphere summer.

Variations in carbon dioxide and methane in ice age cycles are also very important factors, they served to modify and perhaps amplify the other forcing effects (see Section 1). However, there is evidence that rapid changes in climate have occurred on time scales of about a century which cannot be directly related to orbital forcing or to changes in atmospheric composition. The most dramatic of these events was the Younger Dryas cold episode which involved an abrupt reversal of the general warming trend in progress around 10 500 BP as the last episode of continental glaciation came to a close. The Younger Dryas was an event of global significance, it was clearly observed in New Zealand (Salinger, 1989) though its influence may not have extended to all parts of the globe (Rind et al., 1986). There is, as yet, no consensus on the reasons for this climatic reversal, which lasted about 500 years and ended very suddenly. However, because the signal was strongest around the North Atlantic Ocean, suggestions have been made that the climatic reversal had its physical origin in large changes in the sea surface temperature (SST) of the North Atlantic Ocean. One possibility is that the cooling may have resulted from reduced deep water production in the North Atlantic following large scale melting of the Laurentide Ice sheet and the resulting influx of huge amounts of low density freshwater into the northern North Atlantic ocean (Broecker et al., 1985). Consequential changes in the global oceanic circulation may have occurred (Street-Perrott and Perrott, 1990) which may have involved variations in the strength of the thermohaline circulation in the Atlantic This closed oceanic circulation involves northward flow of water near the ocean surface sinking in the sub-Arctic and a return flow at depth The relevance of the Younger Dryas to today s conditions is that it is possible that changes in the thermohaline circulation of a qualitatively similar character might occur quite quickly during a warming of the climate induced by greenhouse gases A possible trigger might be an increase of precipitation over the extratropical North Atlantic (Broecker, 1987), though the changes in ocean circulation are most likely to be considerably smaller than in the Younger Dryas Section 6 gives further details

The period since the end of the last glaciation has been characterized by small changes in global average temperature with a range of probably less than 2°C (Figure 7 1), though it is still not clear whether all the fluctuations indicated were truly global However, large regional changes in hydrological conditions have occurred, particularly in the tropics Wetter conditions in the Sahara from 12 000 to 4,000 years BP enabled cultural groups to survive by hunting and fishing in what are today almost the most arid regions on Earth During this time Lake Chad expanded to become as large as the Caspian Sea is today (several hundred thousand km^2, Grove and Warren, 1968) Drier conditions became established after 4,000 BP and many former lake basins became completely dry (Street-Perrot and Harrison 1985) Pollen sequences from lake beds of northwest India suggest that periods with subdued monsoon activity existed during the recent glacial maximum (Singh et al 1974) but the epoch 8,000 to 2,500 BP experienced a humid climate with frequent floods

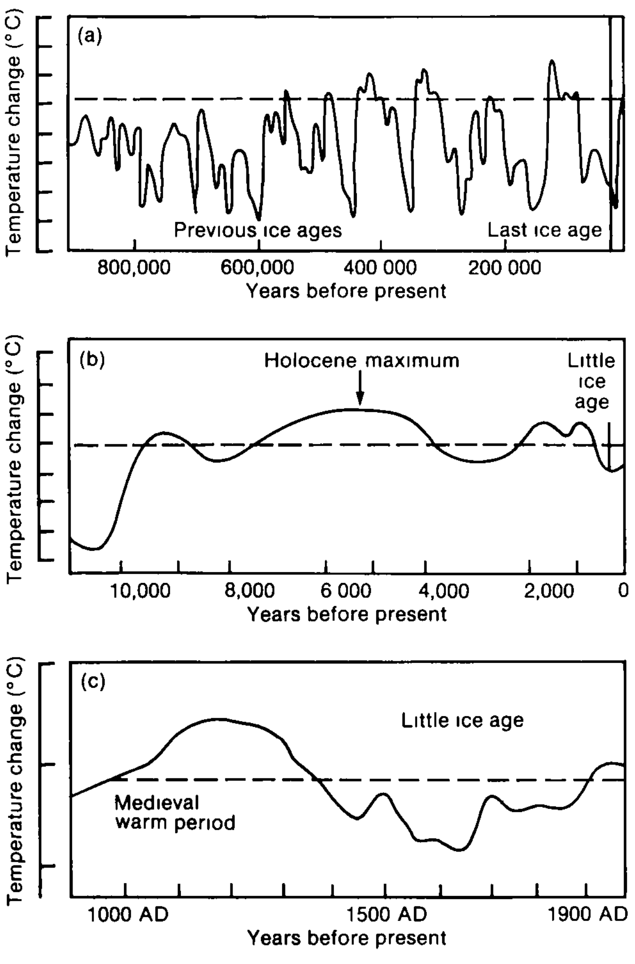


Figure 7.1: Schematic diagrams of global temperature variations since the Pleistocene on three time scales (a) the last million years (b) the last ten thousand years and (c) the last thousand years The dotted line nominally represents conditions near the beginning of the twentieth century

There is growing evidence that worldwide temperatures were higher than at present during the mid-Holocene (especially 5 000-6 000 BP), at least in summer, though carbon dioxide levels appear to have been quite similar to those of the pre-industrial era at this time (Section 1 Thus parts of western Europe China, Japan, the eastern USA were a few degrees warmer in July during the mid-Holocene than in recent decades (Yoshino and Urushibara, 1978, Webb et al 1987, Huntley and Prentice, 1988, Zhang and Wang 1990) Parts of Australasia and Chile were also warmer The late tenth to early thirteenth centuries (about AD 950-1250) appear to have been exceptionally warm in western Europe, Iceland and Greenland (Alexandre 1987, Lamb, 1988) This period is known as the Medieval Climatic Optimum China was, however, cold at this time (mainly in winter) but South Japan was warm (Yoshino, 1978) This period of widespread warmth is notable in that there is no evidence that it was accompanied by an increase of greenhouse gases

Cooler episodes have been associated with glacial advances in alpine regions of the world, such neo-glacial' episodes have been increasingly common in the last few thousand years Of particular interest is the most recent cold event, the Little Ice Age , which resulted in extensive glacial advances in almost all alpine regions of the world between 150 and 450 years ago (Grove, 1988) so that glaciers were more extensive 100-200 years ago than now nearly everywhere (Figure 7 2) Although not a period of continuously cold climate, the Little Ice Age was probably the coolest and most globally extensive cool period since the Younger Dryas In a few regions, alpine glaciers advanced down-valley even further than during the last glaciation (for example, Miller, 1976) Some have argued that an increase in explosive volcanism was responsible for the coolness (for example Hammer, 1977, Porter, 1986), others claim a connection between glacier advances and reductions in solar activity (Wigley and Kelly, 1989) such as the Maunder and Sporer solar activity minima (Eddy, 1976), but see also Pittock (1983) At present, there is no

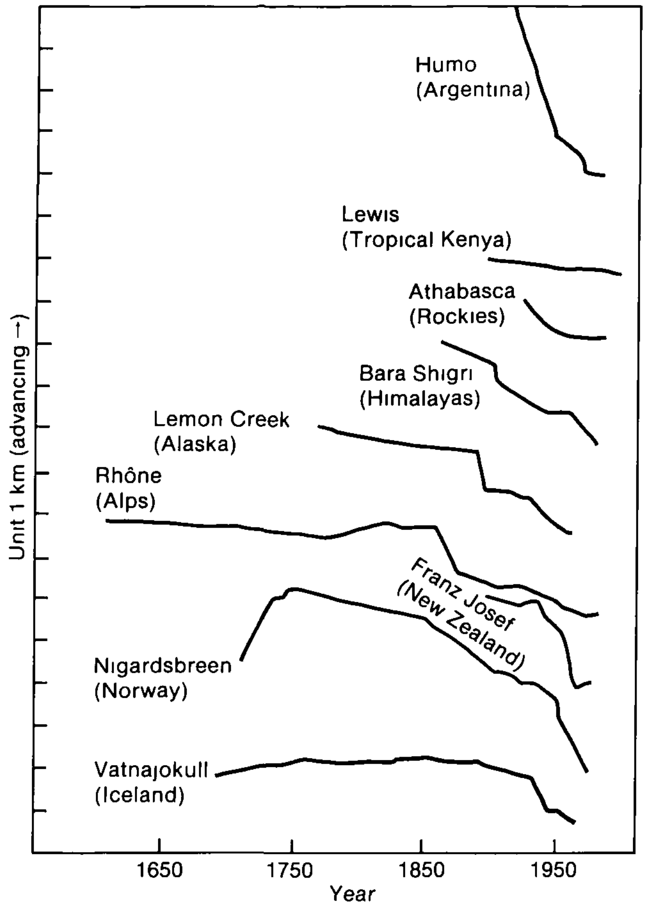


Figure 7.2: Worldwide glacier termini fluctuations over the last three centuries (after Grove, 1988, and other sources)

agreed explanation for these recurrent cooler episodes The Little Ice Age came to an end only in the nineteenth century Thus some of the global warming since 1850 could be a recovery from the Little Ice Age rather than a direct result of human activities So it is important to recognise that natural variations of climate are appreciable and will modulate any future changes induced by man

7.2.2 Palaeo-Climate Analogues from Three Warm Epochs

Three periods from the past have been suggested by Budyko and Izrael (1987) as analogues of a future warm climate For the second and third periods listed below, however, it can be argued that the changed seasonal distribution of incoming solar radiation existing at those times may not necessarily have produced the same climate as would result from a globally-averaged increase in greenhouse gases

1) The climate optimum of the Pliocene (about 3,300,000 to 4,300,000 years BP)
2) The Eemian interglacial optimum (125,000 to 130,000 years BP),
3) The mid-Holocene (5,000 to 6,000 years BP)

Note that the word optimum" is used here for convenience and is taken to imply a warm climate However such a climate may not be "optimal" in all senses

7 2 2 1 Pliocene climatic optimum (about 3,300,000 to 4,300,000 BP)

Reconstructions of summer and winter mean temperatures and total annual precipitation have been made for this

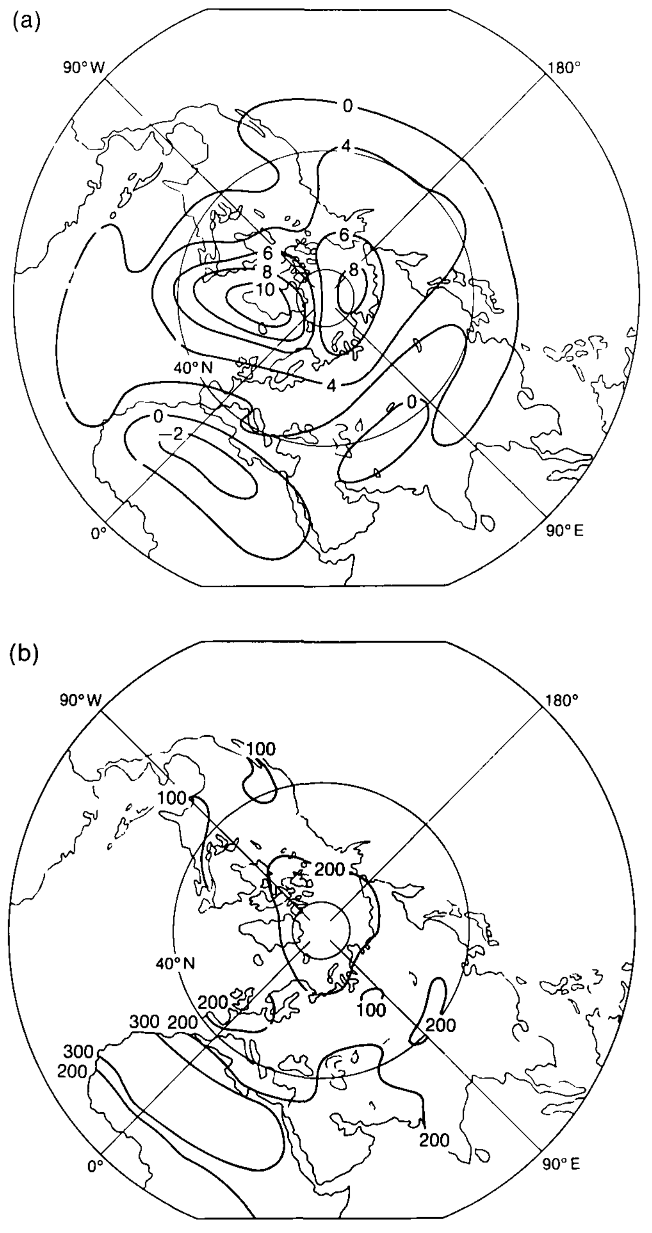


Figure 7.3: (a) Departures of summer air temperature (°C) from modern values for the Pliocene climatic optimum (4 3 to 3 3 million years BP) (from Budyko and Izrael 1987)
(b) Departures of annual precipitation (mm) from modern values for the Pliocene climatic optimum (from Budyko and Izrael 1987 Peshy and Velichko 1990)

period by scientists in the USSR Many types of proxy data were used to develop temperature and precipitation patterns over the land masses of the Northern Hemisphere (Budyko and Izrael 1987) Over the oceans, the main sources of information were cores drilled in the bed of the deep ocean by the American Deep sea Ocean Core Drilling Project Some of these reconstructions are shown in Figure 7 3a and b

Figure 7 3a suggests that mid-latitude Northern Hemisphere summer temperatures averaged about 3-4°C higher than present-day values Atmospheric concentrations of carbon dioxide are estimated by Budyko et al (1985) to have been near 600 ppm, i e twice as large as immediately pre industrial values However Berner et al (1983) show lower carbon dioxide concentrations So there is some doubt about the extent to which atmospheric carbon dioxide concentrations were higher than present values during the Pliocene Figure 7 3b is a partial re construction of Northern Hemisphere annual precipitation, this was generally greater during the Pliocene Of special interest is increased annual precipitation in the arid regions of Middle Asia and Northern Africa where temperatures were lower than at present in summer

Uncertainties associated with the interpretation of these reconstructions are considerable and include

1) Imprecise dating of the records, especially those from the continents (uncertainties of 100,000 years or more),
2) Differences from the present day surface geography, including changes in topography thus Tibet was at least 1000m lower than now and the Greenland ice sheet may have been much smaller,
3) The ecology of life on Earth from which many of the proxy data are derived was significantly different

See also Sections 5 5 3 and 4 10

7 2 2 2 Eemian interglacial optimum (125 000 130 000 years BP)

Palaeo-botanic oxygen-isotope and other geological data show that the climates of the warmest parts of some of the Pleistocene interglacials were considerably warmer (1 to 2°C) than the modern climate They have been considered as analogues of future climate (Budyko and Izrael, 1987, Zubakov and Borzenkova, 1990) Atmospheric carbon dioxide reached about 300 ppm during the Eemian optimum (Section 1) but a more important cause of the warmth may have been that the eccentricity of the Earth s orbit around the sun was about twice the modern value, giving markedly more radiation in the northern hemisphere summer The last interglacial optimum (125 000 130 000 years BP) has sufficient information (Velichko et al 1982 1983 1984 and CLIMAP 1984) to allow quantitative reconstructions to be made of annual and seasonal air

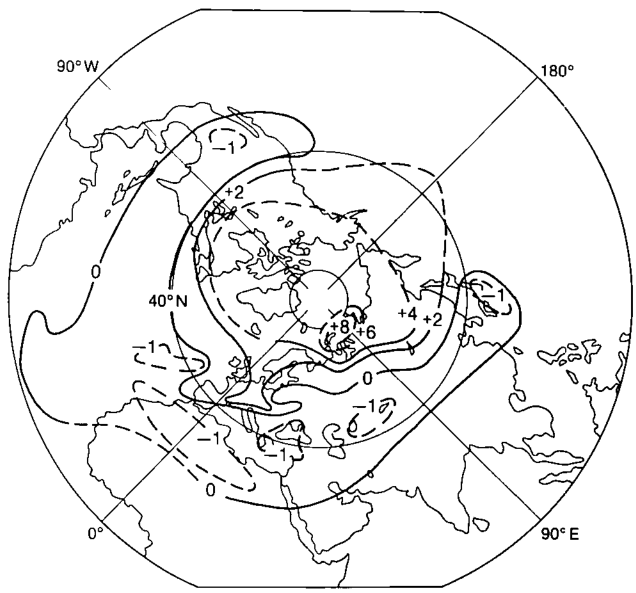


Figure 7.4: Departures of summer air temperature (°C) from modern values for the Eemian interglacial (Velichko et al , 1982, 1983 1984)

temperature and annual precipitation for part of the Northern Hemisphere For the Northern Hemisphere as a whole, mean annual surface air temperature was about 2°C above its immediately pre-industrial value Figure 7 4 shows differences of summer air temperature, largest (by 4-8°C) in northern Siberia, Canada and Greenland Over most of the USSR and Western Europe north of 50-60°N, temperatures were about 1-3°C warmer than present South of these areas temperatures were similar to those of today, and precipitation was substantially larger over most parts of the continents of the Northern Hemisphere In individual regions of Western Europe the north of Eurasia and Soviet Central Asia and Kazakhstan annual precipitation has been estimated to have been 30-50% higher than modern values

It is difficult to assess quantitatively the uncertainties associated with these climate reconstructions The problems include

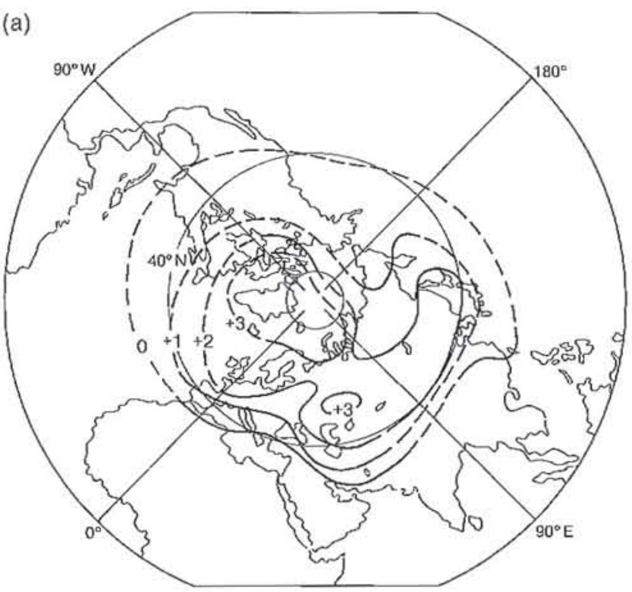
1) Variations between the timing of the deduced thermal maximum in different records,
2) The difficulties of obtaining proxy data in arid areas,
3) The absence of data from North America and many other continental regions in both Hemispheres

7 2 2 3 Climate of the Holocene Optimum (5 000-6 000 years BP)

The Early and Middle Holocene was characterized by a relatively warm climate with summer temperatures in high northern latitudes about 3 4°C above modern values Between 9 000 and 5 000 years BP, there were several short-lived warm epochs, the last of which, the mid Holocene optimum, lasted from about 6,200 to 5,300 years BP (Varushchenko et al., 1980). Each warm epoch was accompanied by increased precipitation and higher lake levels in subtropical and high latitudes (Singh et al., 1974; Swain et al., 1983). However, the level of such mid-latitude lakes as the Caspian Sea, Lake Geneva and the Great Basin lakes in the USA was lowered (COHMAP, 1988; Borzenkova and Zubakov, 1984).

Figures 7.5a and b show maps of summer surface air temperature (as departures from immediately pre-industrial values) and annual precipitation for the mid-Holocene optimum in the Northern Hemisphere. This epoch is

(a)



(b)

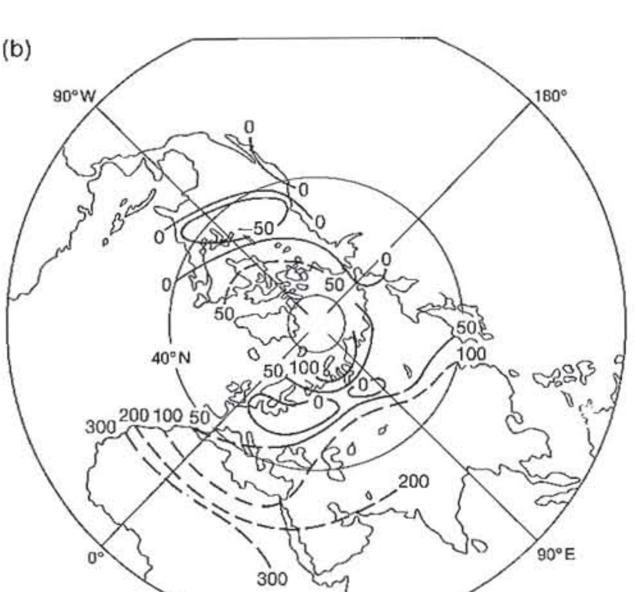


Figure 7.5: Departures of: (a) summer temperature (°C), (b) annual precipitation (mm), from modern values for the Holocene climatic optimum (Borzenkova and Zubakov, 1984; Budyko and Izrael, 1987).

(c)

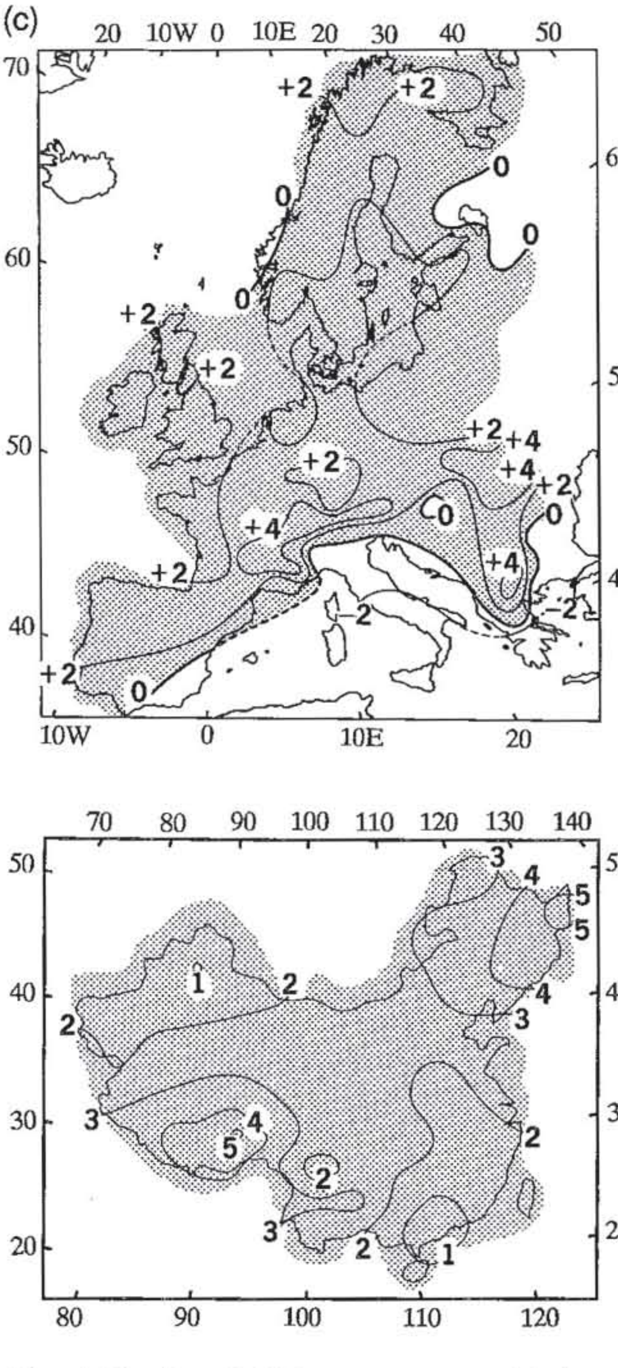


Figure 7.5 (continued): (c) Summer temperatures (relative to the mid-twentieth century) in Europe and China between 5,000 and 6,000 BP (after Huntley and Prentice, 1988; Wang et al., personal communication).

sometimes used as an analogue of expected early-21st century climate. The greatest relative warmth in summer (up to 4°C) was in high latitudes north of 70°N (Lozhkin and Vazhenin, 1987). In middle latitudes, summer temperatures were only 1-2°C higher and further south summer temperatures were often lower than today, for example in Soviet Central Asia, the Sahara, and Arabia. These areas also had increased annual precipitation. Annual precipitation was about 50-100 mm higher than at present in the Northern regions of Eurasia and Canada but in central regions of Western Europe and in southern regions of the European USSR and West Siberia there were small decreases of annual precipitation. The largest decrease in annual precipitation took place in the USA, especially in central and eastern regions (COHMAP, 1988).

The above reconstructions are rather uncertain; thus Figure 7.5a disagrees with reconstructions of temperature over north east Canada given by Bartlein and Webb (1985). However the accuracy of reconstructions is increasing as more detailed information for individual regions in both hemispheres becomes available. For instance, the CLIMANZ project has given quantitative estimates of Holocene temperature and precipitation in areas from New Guinea to Antarctica for selected times (Chappell and Grindrod, 1983). Detailed mid-Holocene reconstructions of summer temperature in Europe and China are shown in Figure 7.5c.

7.3 The Modern Instrumental Record

The clearest signal of an enhanced greenhouse effect in the climate system, as indicated by atmosphere/ocean general circulation models, would be a widespread, substantial increase of near-surface temperatures. This section gives special attention to variations and changes of land surface air temperatures (typically measured at about two metres above the ground surface) and sea surface temperatures (SSTs) since the mid-nineteenth century. Although earlier temperature, precipitation, and surface pressure data are available (Lamb, 1977), spatial coverage is very poor. We focus on changes over the globe and over the individual hemispheres but considerable detail on regional space scales is also given.

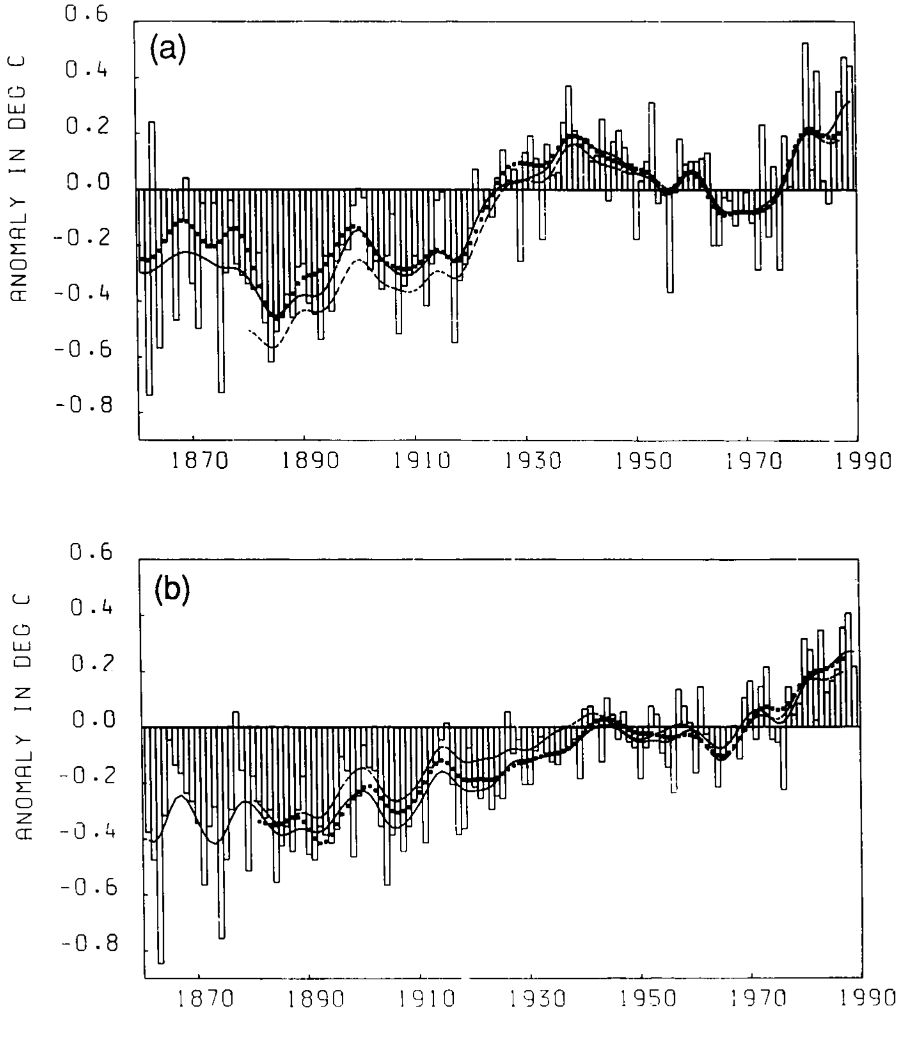


Figure 7.6: Land air temperatures, expressed as anomalies relative to 1951-80. Annual values from P.D. Jones. Smoothed curves of values from P.D. Jones (1861-1989) (solid lines), Hansen and Lebedeff (1880-1987) (dashed lines), and Vinnikov et al. (1861-1987 NH and 1881-1987 SH) (dots). (a) Northern Hemisphere, (b) Southern Hemisphere.

7.4 Surface Temperature Variations and Change

7.4.1 Hemispheric and Global

7.4.1.1 Land

Three research groups (Jones et al 1986a,b, Jones, 1988, Hansen and Lebedeff, 1987, 1988, and Vinnikov et al , 1987, 1990) have produced similar analyses of hemispheric land surface air temperature variations (Figure 7 6) from broadly the same data All three analyses indicate that during the last decade globally-averaged land temperatures have been higher than in any decade in the past 100 to 140 years (The smoothed lines in Figure 7 6, as for all the longer time series shown in this Section, are produced by a low pass binomial filter with 21 terms operating on the annual data The filter passes fluctuations having a period of 20 years or more almost unattenuated)

Figure 7 6 shows that temperature increased from the relatively cool late nineteenth century to the relatively warm 1980s, but the pattern of change differed between the two hemispheres In the Northern Hemisphere the temperature changes over land are irregular and an abrupt warming of about 0 3°C appears to have occurred during the early 1920s This climatic discontinuity has been pointed out by Ellsaesser et al (1986) in their interpretation of the thermometric record Northern Hemisphere temperatures prior to the climatic discontinuity in the 1920s could be interpreted as varying about a stationary mean climate as shown by the smoothed curve The nearest approach to a monotonic trend in the Northern Hemisphere time series is the decrease of temperature from the late 1930s to the mid-1960s of about 0 2°C The most recent warming has been dominated by a relatively sudden increase of nearly 0 3°C over less than ten years before 1982 Of course, it is possible to fit a monotonic trend line to the entire time series such a trend fitted to the current version of the Jones (1988) data gives a rate of warming of 0 53°C/100 years when the trend is calculated from 1881 to 1989 or the reduced if less reliable value of 0 45°C/100 years if it is calculated from 1861 Clearly this is a gross oversimplification of the observed variations even though the computed linear trends are highly significant in a statistical sense

The data for the Southern Hemisphere include the Antarctic land mass since 1957 except for the data of Vinnikov et al (1987 1990) Like the Northern Hemisphere, the climate appears stationary throughout the latter half of the nineteenth century and into the early part of the twentieth century Subsequently there is an upward trend in the data until the late 1930s but in the next three decades the mean temperature remains essentially stationary again A fairly steady increase of temperature resumes before 1970 though it may have slowed recently Linear trends for the Southern Hemisphere are 0 52 C/100 years from 1881 to 1989 but somewhat less and less reliable, at 0 45°C/100 years for the period 1861 1989

The interpretation of the rise in temperature shown in Figure 7 6 is a key issue for global warming so the accuracy of these data needs careful consideration A number of problems may have affected the record discussed in turn below

1) Spatial coverage of the data is incomplete and varies greatly,
2) Changes have occurred in observing schedules and practices,
3) Changes have occurred in the exposures of thermometers,
4) Stations have changed their locations
5) Changes in the environment especially urbanisation have taken place around many stations

Land areas with sufficient data to estimate seasonal anomalies of temperature in the 1860s and 1980s are shown (with ocean areas) in Figure 7 7 Decades between these times have an intermediate coverage There are obvious gaps and changes in coverage Prior to 1957 data for Antarctica are absent while some other parts of the global land mass lack data as late as the 1920s for example many parts of Africa parts of China the Russian and Canadian Arctic and the tropics of South America In the 1860s coverage is sparsest thus Africa has little or no data and much of North America is not covered The effect of this drastically changing spatial coverage on hemispheric temperature variations has been tested by Jones et al (1986a b) who find that sparse spatial coverage exaggerates the variability of the annual averages The reduction in variability of the Northern Hemisphere annual time series after about 1880 (Figure 7 6) is attributed to this effect Remarkably their analysis using a frozen grid experiment (see Section 7 4 1 3 for a detailed discussion for the combined land and ocean data) suggests that changes of station density since 1900 have had relatively little impact on estimates of hemispheric land temperature anomalies However prior to 1900 the decadal uncertainty could be up to 0 1°C This is quite small relative to the overall change Thus varying data coverage does not seem to have had a serious impact on the magnitude of the perceived warming over land over the last 125 years

Another potential bias arises from changes in observation schedules Even today there is no international standard for the calculation of mean daily temperature Thus each country calculates mean daily temperature by a method of its choice such as the average of the maximum and the minimum, or some combination of hourly readings weighted according to a fixed formula As long as each country continues the same practice the **shape** of the temperature record is unaffected Unfortunately few countries have maintained the same practice over the past century biases have therefore been introduced into the climate record some of which have been corrected for in

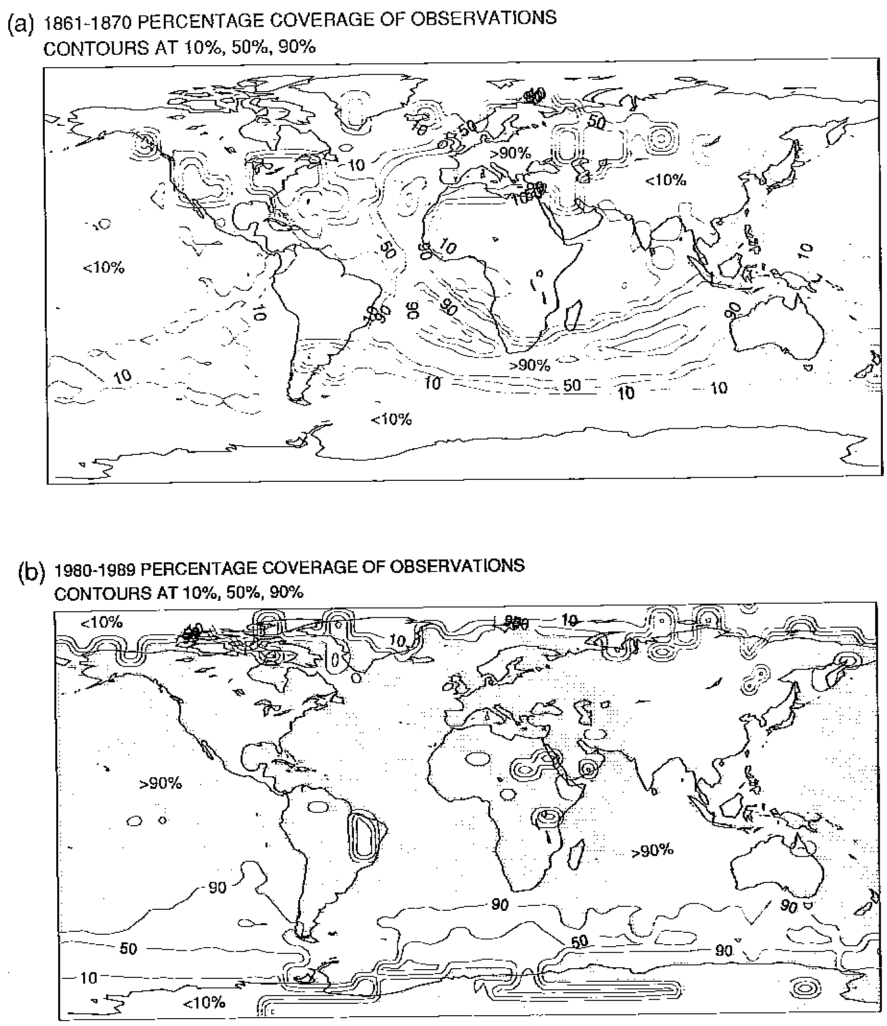


Figure 7.7: Coverage of land surface air (P.D. Jones) and sea surface (UK Meteorological Office) temperature data. Isopleths are percentage of seasons with one or more month's data in 5° x 5° boxes in a given decade. Contours drawn for 90%, 50% and 10% coverage. (a) 1861-70, (b) 1980-89.

existing global data sets, but some have not. These biases can be significant; in the USA a systematic change in observing times has led to a nominal 0.2°C decrease of temperature in the climate record since the 1930s (Karl et al., 1986). The effects of changing observation time have only been partly allowed for in the USA temperature data used in analyses presented here. So an artificial component of **cooling** of rather less than 0.2°C may exist in the USA part of the temperature analyses for this reason, offsetting the warming effects of increasing urbanisation in that country. Artificial changes of temperature of either sign may exist in other parts of the world due to changes in observation time but have not been investigated.

Substantial systematic changes in the exposure of thermometers have occurred. Because thermo-meters can be affected by the direct rays of the sun, reflected solar radiation, extraneous heat sources and precipitation, there has been a continuous effort to improve their exposures over the last 150 years. Additional biases must accompany these changes in the thermometric record. Since many of the changes in exposure took place during the nineteenth and early twentieth centuries, that part of the record is most likely to be affected. Recently, Parker (1990) has reviewed the earlier thermometer exposures, and how they evolved, in many different countries. The effects of exposure changes vary regionally (by country) and seasonally. Thus tropical temperatures prior to the late 1920s appear to be too high because of the placement of thermometers in cages situated in open sheds. There is also evidence that for the mid-latitudes prior to about 1880 summer temperatures may be too high and winter temperatures too low due to the use of poorly screened exposures. This includes the widespread practice of exposing thermometers on the north walls of buildings. These effects have not yet been accounted for in existing analyses (see Section 7.4.2.2).

Changes in station environment can seriously affect temperature records (Salinger, 1981) Over the years, stations often have minor (usually under 10 km) relocations and some stations have been moved from rooftop to ground level Even today, international practice allows for a variation of thermometer heights above ground from 1 25 to 2 metres Because large vertical temperature gradients exist near the ground, such changes could seriously affect thermometer records When relocations occur in a random manner, they do not have a serious impact on hemispheric or global temperature anomalies, though they impair our ability to develop information about much smaller scale temperature variations A bias on the large scale can emerge when the character of the changes is not random An example is the systematic relocations of some observing stations from inside cities in many countries to more rural airport locations that occurred several decades ago Because of the heat island effect within cities such moves tend to introduce artificial cooling into the climate record Jones et al (1986a, b) attempt in some detail to adjust for station relocations when these appear to have introduced a significant bias in the data but Hansen and Lebedeff (1988) do not believing that such station moves cancel out over large time and space averages Vinnikov et al (1990) do adjust for some of these moves There are several possible correction procedures that have been or could be, applied to the Jones (1988) data set (Bradley and Jones, 1985, Karl and Williams 1987) All depend on denser networks of stations than are usually available except in the USA Europe the Western Soviet Union and a few other areas

Of the above problems increasing urbanisation around fixed stations is the most serious source of systematic error for hemispheric land temperature time series that has so far been identified A number of researchers have tried to ascertain the impact of urbanisation on the temperature record Hansen and Lebedeff (1987) found that when they removed all stations having a population in 1970 of greater than 100,000, the trend of temperature was reduced by 0 1°C over 100 years They speculated that perhaps an additional 0 1°C of bias might remain due to increases in urbanisation around stations in smaller cities and towns Jones et al (1989) estimate that the effect of urbanisation in their quality-controlled data is no more than 0 1°C over the past 100 years This conclusion is based on a comparison of their data with a dense network of mostly rural stations over the USA Groisman and Koknaeva (1990) compare the data from Vinnikov et al (1990) with the rural American data set and with rural stations in the Soviet Union and find very small warm relative biases of less than 0 05°C per 100 years In the USA Karl et al (1988) find that increases due to urbanisation can be significant (0 1°C), even when urban areas have populations as low as 10 000 Other areas of the globe are now being studied Preliminary results indicate that the effects of urbanisation are highly regional and time dependent Changes in urban warming in China (Wang et al , 1990) appear to be quite large over the past decade, but in Australia they are rather less than is observed in the USA (Coughlan et al , 1990) Recently Jones and co workers (paper in preparation) have compared trends derived from their quality-controlled data and those of Vinnikov et al (1990), with specially selected data from more rural stations in the USSR, eastern China, and Australia When compared with trends from the more rural stations only small (positive) differences of temperature trend exist in the data used in Jones (1988) and Vinnikov et al (1990) in Australia and the USSR (of magnitude less than 0 05°C/100 years) In eastern China the data used by Vinnikov et al (1990) and Jones (1988) give **smaller** warming trends than those derived from the more rural stations This is an unexpected result It suggests that either (1) the more rural set is sometimes affected by urbanisation or, (2) other changes in station characteristics over compensate for urban warming bias Thus it is known that the effects of biases due to increased urbanisation in the Hansen and Lebedeff (1987) and the Vinnikov et al (1990) data sets are partly offset by the artificial cooling introduced by the movement of stations from city centres to more rural airport locations during the 1940s to 1960s (Karl and Jones 1990) Despite this, some of these new rural airport locations may have suffered recently from increasing urbanisation

In light of this evidence, the estimate provided by Jones et al (1989) of a maximum overall warming bias in all three land data sets due to urbanisation of 0 1°C/100 years or less is plausible but not conclusive

7 4 1 2 Sea

The oceans comprise about 61% of the Northern Hemisphere and 81% of the Southern Hemisphere Obviously a compilation of global temperature variations must include ocean temperatures Farmer et al (1989) and Bottomley et al (1990) have each created historical analyses of global ocean SSTs which are derived mostly from observations taken by commercial ships These data are supplemented by weather ship data and in recent years by an increasing number of drifting and moored buoys The Farmer et al (1989) analyses are derived from a collection of about 80 million observations assembled in the Comprehensive Ocean-Atmosphere Data Set (COADS) in the USA (Woodruff et al , 1987) The data set used by Bottomley et al (1990) is based on a slightly smaller collection of over 60 million observations assembled by the United Kingdom Meteorological Office Most but not all of the observations in the latter are contained in the COADS data set

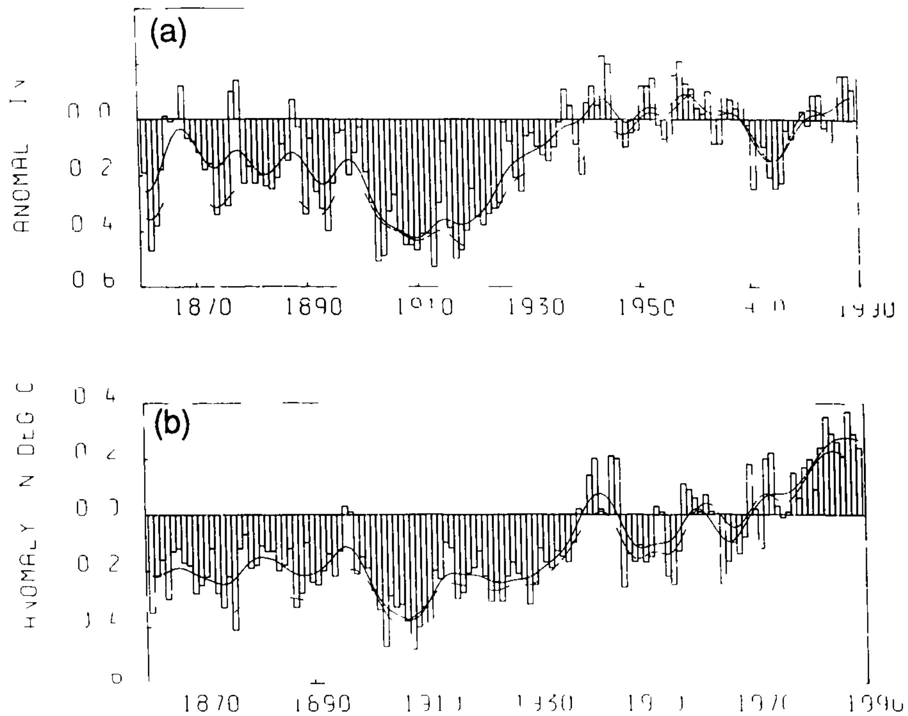


Figure 7.8: Sea surface temperature anomalies 1861 1989, relative to 1951 1980 Annual values (bars) and solid curves from UK Meteorological Office data Dashed curves from Farmer et al (1989) (a) Northern Hemisphere (b) Southern Hemisphere

Long-term variations of SSTs over the two hemispheres, shown in Figure 7 8, have been, in general, similar to their land counterparts The increase in temperature has not been continuous There is evidence for a fairly rapid cooling in SST of about 0 1 to 0 2°C at the beginning of the twentieth century in the Northern Hemisphere This is believed to be real because night marine air temperatures show a slightly larger cooling The cooling strongly affected the North Atlantic, especially after 1903 and is discussed at length by Helland-Hansen and Nansen (1920) The cool period was terminated by a rapid rise in temperature starting after 1920 This resembled the sudden warming of land temperatures, but lagged it by several years Subsequent cooling from the late 1950s to about 1975 lagged that over land by about five years, and was followed by renewed warming with almost no lag compared with land data Overall warming of the Northern Hemisphere oceans since the late nineteenth century appears to have been slightly smaller than that of the land (Figure 7 8a) and may not have exceeded 0 3°C

In the Southern Hemisphere ocean (remembering that the Southern Ocean has always been poorly measured) there appear to have been two distinct stable climatic periods the first lasting until the late 1920s the second lasting from the mid 1940s until the early 1960s Since the middle 1970s SSTs in the Southern Hemisphere have continued to rise to their highest levels of record Overall warming has certainly exceeded 0 3°C since the nineteenth century, but has probably been less than 0 5°C (Figure 7 8b), and has been slightly less than the warming of the land However if the increases of temperature are measured from the time of their minimum values around 1910, the warming of the oceans has been slightly larger than that of the land Despite data gaps over the Southern Ocean, the global mean ocean temperature variations (Figure 7 9) tend to take on the characteristics of the Southern Hemisphere because a larger area of ocean is often sampled in the Southern Hemisphere than the Northern Hemisphere Overall warming in the global oceans between the late nineteenth century and the latter half of the twentieth century appears to have been about 0 4°C

Significant differences between the two SST data sets presented in Figure 7 8 result mainly from differing assumptions concerning the correction of SST data for instrumental biases The biases arose chiefly from changes in the method of sampling the sea water for temperature measurement Several different types of bucket have been used for sampling made for example, of wood, canvas, rubber or metal but the largest bias arose from an apparently rather sudden transition from various un insulated buckets to ship engine intake tubes in World War II A complex correction procedure developed by Folland and Parker (1989) and Bottomley et al (1990) which

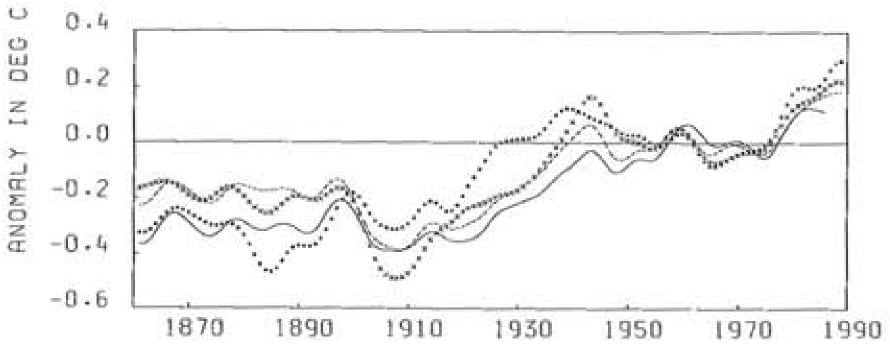


Figure 7.9: Global sea surface, night marine air (crosses) and land air temperature anomalies (dots) 1861-1989, relative to 1951-80. Sea surface temperatures are values from Farmer et al. (1989) (solid line) and the UK Meteorological Office (dashed line). Night marine air temperatures from UK Meteorological Office. Land air temperatures are equally weighted averages of data from Jones, Hansen and Lebedeff, and Vinnikov et al.

creates geographically varying corrections, has been also been used in nearly the same form by Farmer et al. Differences in the two data sets remain, however, primarily because of different assumptions about the mix of wooden versus canvas buckets used during the nineteenth century. Despite recommendations by Maury (1858) to use wooden buckets with the thermometer inserted for four to five minutes, such buckets may have been much less used in practice (Toynbee, 1874; correspondence with the Danish Meteorological Service, 1989) possibly because of damage iron-banded wooden buckets could inflict upon the hulls of ships. Some differences also result, even as recently as the 1970s, because the data are not always derived from identical sources (Woodruff, 1990).

No corrections have been applied to the SST data from 1942 to date. Despite published discussions about the differences between "bucket" and engine intake SST data in this period (for example James and Fox, 1972), there are several reasons why it is believed that no further corrections, with one reservation noted below, are needed. Firstly the anomalies in Figure 7.8 are calculated from the mean conditions in 1951-1980. So only **relative** changes in the mix of data since 1942 are important. Secondly many of the modern "buckets" are insulated (Folland and Parker, 1990) so that they cool much less than canvas buckets. A comparison of about two million bucket and four million engine intake data for 1975-1981 (Bottomley et al., 1990) reveals a global mean difference of only 0.08°C, the engine intake data being the warmer. Thus a substantial change in the mix of data types (currently about 25-30% buckets) must occur before an appreciable artificial change will occur in Figure 7.8. This conclusion is strongly supported by the great similarity between time series of globally-averaged anomalies of colocated SST and night marine air temperature data from 1955 to date (not shown). Less perfect agreement between 1946 and the early 1950s (SST colder) suggests that uninsulated bucket SST data may have been more numerous then than in 1951-80, yielding an overall cold bias of up to 0.1°C on a global average.

Marine air temperatures are a valuable test of the accuracy of SSTs after the early 1890s. Biases of day-time marine air temperatures are so numerous and difficult to overcome that only night-time marine air temperatures have been used. The biases arise during the day because overheating of the thermometers and screens by solar insolation has changed as ships have changed their physical characteristics (Folland et al., 1984). On the other hand appreciable biases of night-time data are currently believed to be confined to the nineteenth century and much of the Second World War. Night marine air temperatures have been found to be much too high relative to SST, or to modern values, in certain regions and seasons before 1894 (Bottomley et al., 1990). These values were corrected using SSTs, but subsequently (except in 1941-1945) night marine air temperature data constitute independent evidence everywhere, although corrections are also made for the increasing heights of ship decks (Bottomley et al., 1990). Figure 7.9 indicates that multi-decadal global variations of corrected night-time marine air temperature have been quite similar to those of SST. To provide a complete picture, Figure 7.9 shows the Farmer et al. and UK Meteorological Office global SST curves separately along with a global land air temperature series created by averaging the series of Jones, Hansen and Lebedeff and Vinnikov et al. Both SST and night marine air temperature data appear to lag the land data by at least five years during the period of warming from 1920 to the 1940s. However some of the apparent warmth of the land at this time may be erroneous due to the use of open shed screens in the tropics (Section 7.4.1.1).

The above results differ appreciably in the nineteenth century from those published by Oort et al (1987) who followed the much less detailed correction procedure of Folland et al (1984) to adjust the COADS SST and **all hours** marine air temperature data sets Newell et al (1989) also present an analysis quite similar to that of the above authors, based on a UK Meteorological Office data set that was current in early 1988 All these authors obtain higher values of global SST and marine air temperature in the middle to late nineteenth century typically by about 0 1°C and 0 15°C respectively than are indicated in this report It is our best judgement that the more recent analyses represent a real improvement but the discrepancies highlight the uncertainties in the interpretation of early marine temperature records Yamamoto et al (1990a) have tried to quantify changing biases in the COADS **all hours** marine air temperature data using a mixture of weather ship air temperature data from the 1940s to 1970s and selected land air temperature data mainly in three tropical coastal regions to calculate time varying corrections Based on these corrections Yamamoto et al (1990b) calculate a global air temperature anomaly curve for 1901-1986 of similar overall character to the night marine air temperature curve in Figure 7 9 but with typically 0 15°C warmer anomalies in the early part of the twentieth century, and typically 0 1°C cooler anomalies in the warm period around 1940 1950 Recent data are similar It could be argued that the corrections of Yamamoto et al may be influenced by biases in the land data including warm biases arising from the use of tropical open sheds earlier this century Warm biases may also exist in some ocean weather ship day-time air temperature data (Folland 1971) Although we believe that the night marine air temperature analysis in Figure 7 9 minimises the known sources of error the work of Yamamoto et al underlines the level of uncertainty that exists in trends derived from marine air temperature data

7 4 1 3 Land and sea combined

Combined land and sea surface temperatures show a significant increase of temperature from the late nineteenth to the late twentieth century (Figures 7 10a to c) These data are an average of two data sets a combination of the Jones land data and the Farmer et al SST data and a combination of the Jones land data and the UK Meteorological Office SST data Note that the relative contributions of land and sea to the combined data have varied according to changing data availability over land and ocean (bottom of Figure 7 10c) Over the globe the combined data gives an increase of temperature of 0 45°C between the average for the two decades 1881-1900 and the decade 1980 89 The comparable increase for the Northern Hemisphere is 0 42 C and for the Southern Hemisphere 0 48°C A similar calculation for the changes of temperature between 1861-1880 and 1980 89 gives 0 45°C 0 38°C and 0 53°C respectively A linear trend fitted between 1890 and 1989 gives values of 0 50°C/100 years (globe) 0 47°C/100 years (Northern Hemisphere) and 0 53°C/100 years (Southern Hemisphere), a linear trend fitted between 1870 and 1989 gives the reduced values of 0 41°C 0 39°C and 0 43°C/100 years respectively

Apparent decadal rates of change of smoothed global combined temperature have varied from an increase of 0 21°C between 1975 and 1985 (largely between 1975 and 1981) to a decrease of 0 19°C between 1898 and 1908 (though data coverage was quite poor around 1900) Surprisingly the maximum magnitudes of decadal change (warming or cooling) over land and ocean (SST) have been quite similar (Figure 7 9) at about 0 25°C Smoothed night global marine air temperature showed the largest apparent change around 1900 with a maximum cooling of 0 32°C between 1898 and 1908 though this value is very uncertain

Combined land and ocean temperature has increased rather differently in the Northern than in the Southern Hemisphere (Figure 7 10) A rapid increase in Northern Hemisphere temperature during the 1920s and into the 1930s contrasts with a more gradual increase in the Southern Hemisphere Both hemispheres had relatively stable temperatures from the 1940s to the 1970s though with some evidence of cooling in the Northern Hemisphere Since the 1960s in the Southern Hemisphere, but after 1975 in the Northern Hemisphere temperatures have risen with the overall rise being more pronounced in the Southern Hemisphere Only a small overall rise was observed between 1982 and 1989

An important problem concerns the varying spatial coverage of the combined marine and land observations Figure 7 7 indicates that this has been far from uniform in time or space and even today coverage is not comprehensive Ships have followed preferred navigational routes and large areas of the ocean have been inadequately sampled The effect that this may have on global estimates of SSTs has been tested in frozen grid analyses (Bottomley et al 1990) and in eigenvector analyses (Folland and Colman 1988) In the frozen grid analyses, global and hemispheric time series were recalculated using data from 5 x5° boxes having data in nominated earlier decades for example 1861 1870 Remarkably, the small coverage of this period (Figure 7 7a) appears surprisingly adequate to estimate long term trends probably because the data are distributed widely in both hemispheres throughout the last 125 years An eigenvector analysis of combined land and ocean data (Colman, personal communication) isolates an underlying signal of century time scale climate change which is surprisingly uniform geographically and very like Figure 7 10c even though gross regional changes vary because of other factors Figure 7 10d shows the

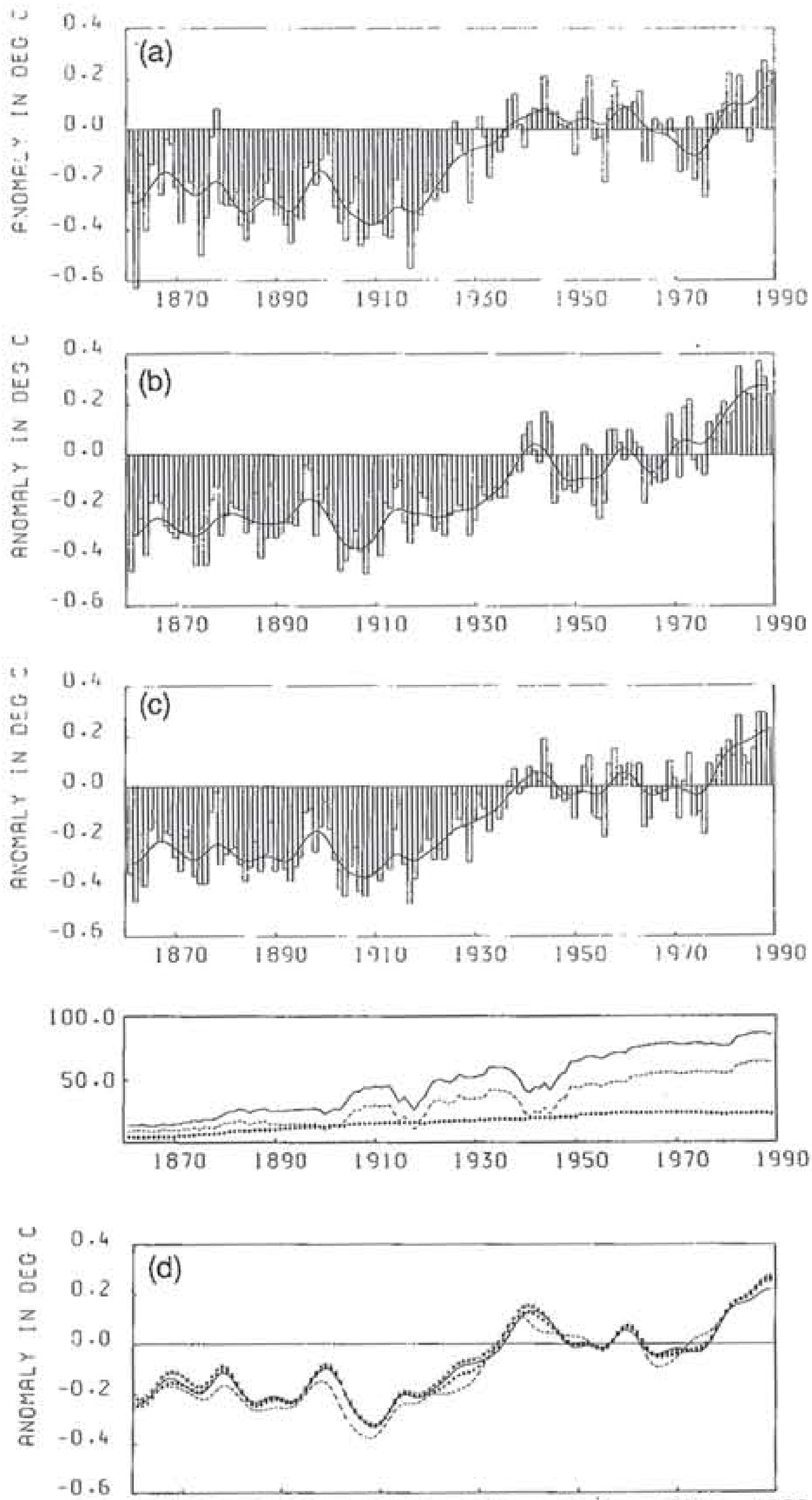


Figure 7.10: Combined land air and sea surface temperatures, 1861-1989, relative to 1951-1980. Land air temperatures from P.D. Jones and sea surface temperatures from the UK Meteorological Office and Farmer et al. (1989). Sea surface temperature component is the average of the two data sets. **(a)** Northern Hemisphere, **(b)** Southern Hemisphere, **(c)** Globe. Percentage coverage of the data is shown for Figure 7.10c, expressed as a percentage of total global surface area for land (dotted line) ocean (dashed line) separately, and for combined data (solid line) plotted annually. 100% coverage would imply that all 5° x 5° boxes had data in two or three months in each season of the year. **(d)** "Frozen grid" analyses for 1861-1989 for the globe, using land data as above and UK Meteorological Office SST data: 1861-70 coverage (dashed), 1901-10 coverage (dotted), 1921-30 coverage (crosses) and all data (solid line).

results of a frozen grid analysis applied to a combination of the Jones land data and the UK Meteorological Office SST data Frozen grids were defined for 1861-1870, 1901 1910, 1921-30 and global series using these were compared with that incorporating all data (also shown in Figure 7 9) Varying the data coverage has only a small effect on trends, confining the data to the 1861-70 grid augments the temperature increase since the late nineteenth century by about 0 05°C at most However, omission of much of the Southern Ocean in these tests, as well as air temperatures over the Arctic ocean north of 80°N, is a cause for concern So the uncertainties in trends due to varying data coverage may be underestimated by Figure 7 10d

In models forced with enhanced greenhouse gases (Sections 5 and 6), warming over the land is substantially greater than that over the ocean, so that the steadier and larger warming of the Southern Hemisphere in recent decades is not predicted The latter may be part of a global-scale natural fluctuation of the ocean circulation (Street-Perrott and Perrott, 1990) Comparing Northern Hemisphere land and ocean, Figure 7 11 shows that the land is now relatively warmer than the oceans by the about the same amount as in the period of global warming during the first half of this century Southern Hemisphere land (not shown) shows no recent warming relative to the oceans

In summary, the overall increase of temperature since the nineteenth century can be estimated as follows It is probable that a small residual positive bias remains in the land surface temperatures due to increasing urbanisation (Section 7 4 1 1) However, the contribution of the urbanisation bias is at least halved in recent decades in the combined ocean and land data, so it is unlikely to exceed 0 05°C From Figure 7 10d, allowing for areas never adequately sampled, we estimate that varying data coverage produces an uncertainty in trend of at least ±0 05°C We also recognise the existence of several other sources of bias, highlighted by some disagreements between individual analyses, but are uncertain as to their true sign Therefore our best estimates of the lower and upper limits of global warming between the late nineteenth century and the 1980s are about 0 3°C and not more than 0 6°C respectively, slightly less than most previous estimates

7.4.2 Regional, Seasonal, and Diurnal Space and Time Scales

We show that regional, including zonally-averaged, climate variations often do not match those of the globe as a whole Some apparent differences between large-scale variations of temperature in different seasons are shown Finally we discuss variations of maximum and minimum daily temperatures over the relatively restricted areas so far analysed

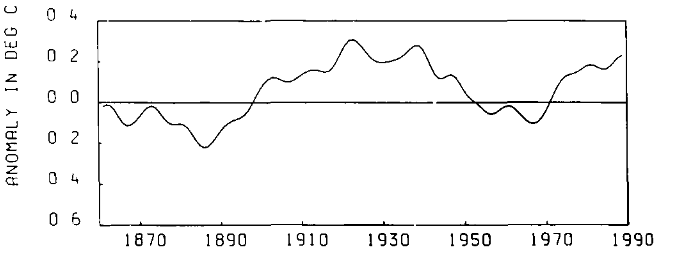


Figure 7.11: Differences between land air and sea surface temperature anomalies, relative to 1951 80, for the Northern Hemisphere 1861-1989 Land air temperatures from P D Jones Sea surface temperatures are averages of UK Meteorological Office and Farmer et al (1989) values

7 4 2 1 Land and Sea

Regional time series suffer from many near-random errors that can nearly cancel in analyses of global and hemispheric temperatures (Kleshchenko et al , 1988) The 20° latitude x 60° longitude areas analysed in Figure 7 12a have been chosen to be large enough to minimise random errors and yet be small enough to capture the individual character of regional temperature changes Figure 7 12a demonstrates considerable regional variability in temperature trends which nevertheless evolve coherently between adjacent regions Particularly striking is the peak warmth in the north east Atlantic and Scandinavian regions around 1940 45 followed by a sharp cooling, and the strong warming in the South Atlantic and much of the Indian Ocean since about 1965

Figure 7 12b shows zonally averaged land air temperature and SST anomalies using the same data as in Figure 7 12a Almost uniformly cooler conditions in the nineteenth century are clearly seen in all zones, extending into the early twentieth century Warming around 1920-1940 occurs in most zones, except perhaps over the northern part of the Southern Ocean, with a strong warming, exceeding 0 8°C occurring to the north of 60°N over this period Note that the polar cap (north of 80°N) has insufficient data for analysis and insufficient data exist to calculate representative zonal means south of 40°S until after 1950 The cooling after 1950 was mainly confined to the Northern Hemisphere, though weak cooling is evident in the Southern Hemisphere tropics between about 1940 and the early 1950s There was renewed warming in most Southern Hemisphere zones before 1970 This warming continued until the early 1980s but then slowed markedly However very little change of temperature is evident over Antarctica (south of 60°S) since records began there around 1957 Renewed warming is seen in the Northern Hemisphere in all zones after the early 1970s, **including small rises in high latitudes**, a fact hitherto little appreciated probably because of the marked cooling in the

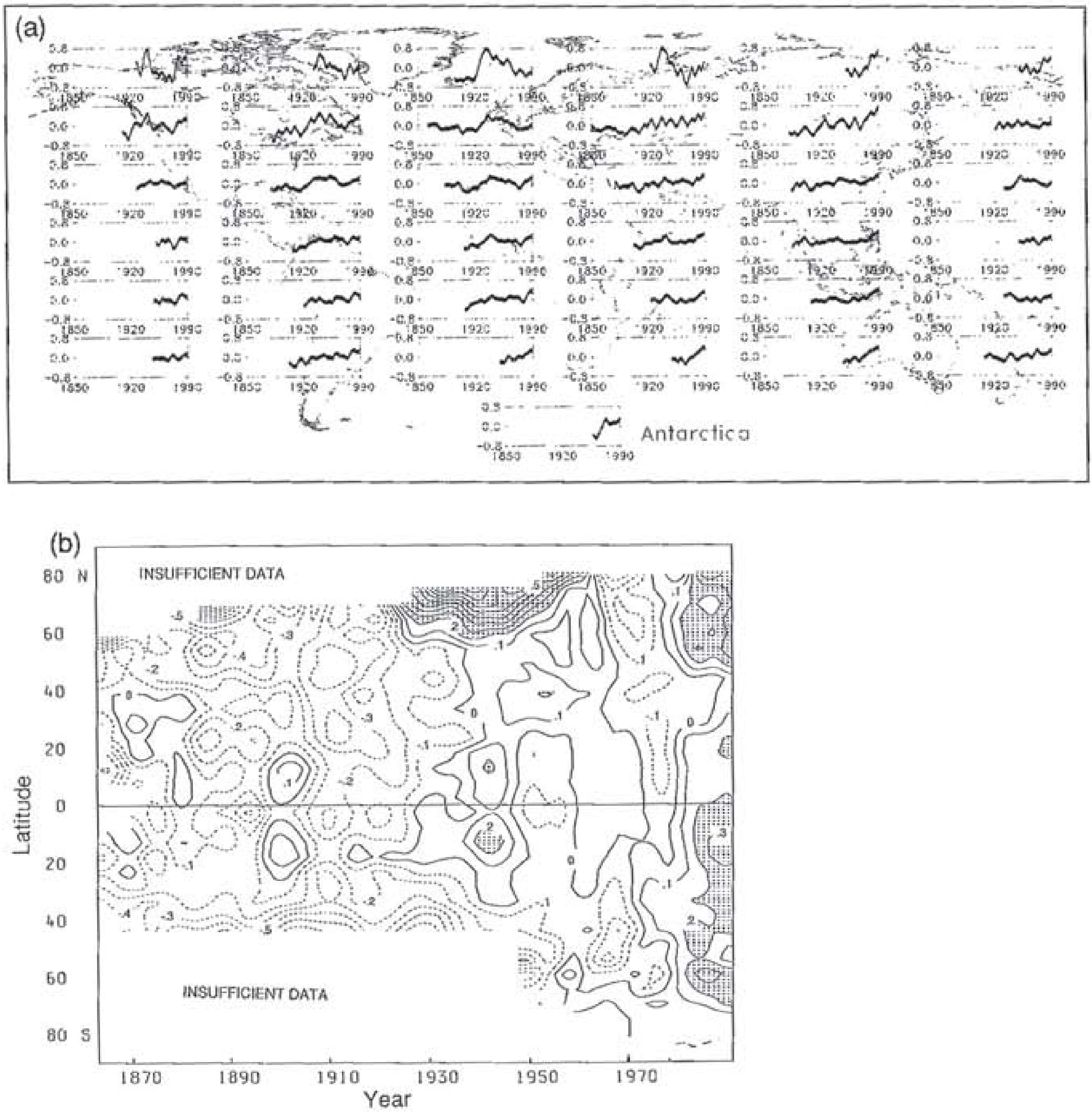


Figure 7.12: (a) Regional surface temperature anomaly variations over 20° latitude x 60° longitude boxes and Antarctica (regions south of 60°S). (b) Zonal averages of combined sea surface and land air temperature data, 1861-1989. Land air temperatures from P.D. Jones and sea surface temperatures from the UK Meteorological Office.

Atlantic/Barents Sea sector in recent decades (Figure 7.12a) which is not seen elsewhere in high latitudes. The temperature curve cited by Lindzen (1990) as showing recent Arctic cooling is in fact one representative of the North Atlantic Arctic sector only (much as Figure 7.12, third curve from the left, northernmost row) and is therefore not properly representative of high latitudes of the Northern Hemisphere as a whole. General circulation models with enhanced concentrations of carbon dioxide tend to show largest increases of annual mean temperature in Northern Hemisphere polar latitudes. The rate of warming has slowed again in many Northern Hemisphere zones in recent years and, almost simultaneously, cooling in the middle to high latitude Atlantic sector has ceased.

Figure 7.13 shows the pattern of temperature anomalies in 1950-59, 1967-76 and 1980-89. Much of the Southern Hemisphere has warmed steadily since 1950-59, with a few exceptions, for example, parts of Brazil and Antarctica. In the Northern Hemisphere the middle decade of those shown was coolest (see Figures 7.6, 7.8, 7.10). The most

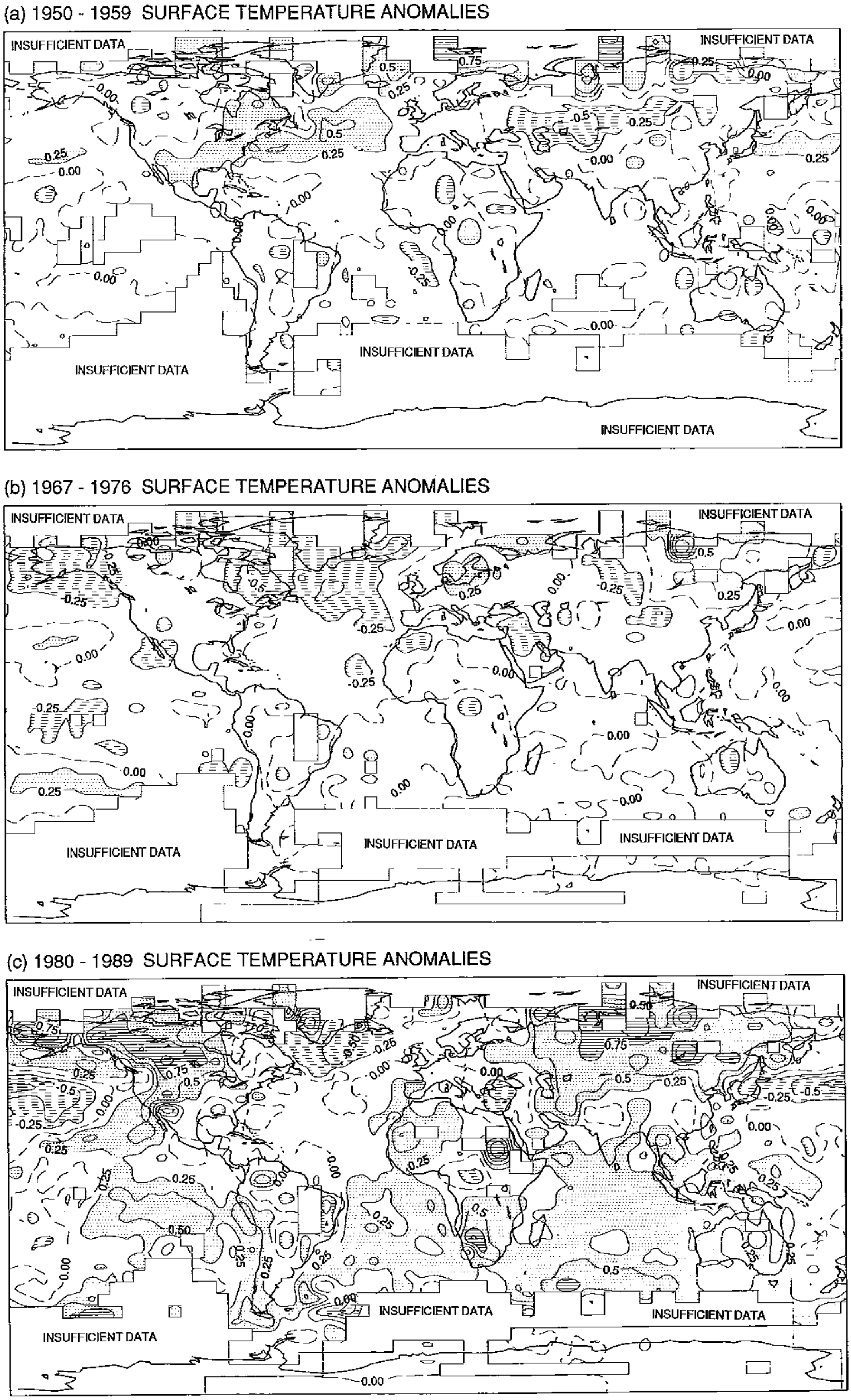


Figure 7.13: Decadal surface temperature anomalies, relative to 1951-80. Isopleths every 0.25°C; dashed isopleths are negative values; dotted positive anomalies 0.25 to 0.5°C; heavy-shaded greater than 0.5°C. Heavily shaded negative values less than -0.25°C. Land air temperatures from P.D. Jones and sea surface temperatures from the UK Meteorological Office. (a) 1950-59, (b) 1967-76, (c) 1980-89. Also shown in the colour section.

consistent recent warming is found in subtropical and tropical regions, especially the Indian Ocean and regions near to, and including, the tropical South Atlantic. By contrast, cooling occurred in parts of the extratropical North Pacific and North Atlantic, especially between 1970 and 1985. Recent warming has also been weak or absent over the Canadian archipelago, the Eastern Soviet Union, and Europe. In Section 7.9 it will be shown that some of these regional temperature variations are linked to regional-scale fluctuations in the circulation of the atmosphere, so it is not surprising that pronounced variations in regional temperature trends occur.

7.4.2.2 Seasonal variations and changes

Figure 7.14 indicates that the increase of land-based temperatures in the Northern Hemisphere since 1975 has largely consisted of an increase between December and May, but with little increase between June and November. In the Southern Hemisphere there is little difference in recent seasonal trends (not shown). Of some concern are substantial differences in seasonal trends before 1900 in the Northern Hemisphere. The relative warmth of summer and coolness of winter at that time reflect considerably greater seasonal differences of the same character in the continental interiors of North America and Asia (not shown). It is not clear whether a decrease in the seasonal cycle of temperature that commenced around 1880 is real; it could be due to changes in the circulation of the atmosphere or it may reflect large, seasonally dependent, biases in some nineteenth century land data. The latter might arise from the progressive changes of thermometer exposure known to have occurred then (Section 7.4.1.1). The Southern Hemisphere (not shown) shows a similar decrease in the seasonal cycle of temperature in the last part of the nineteenth century, but with less than half the amplitude of that in the Northern Hemisphere.

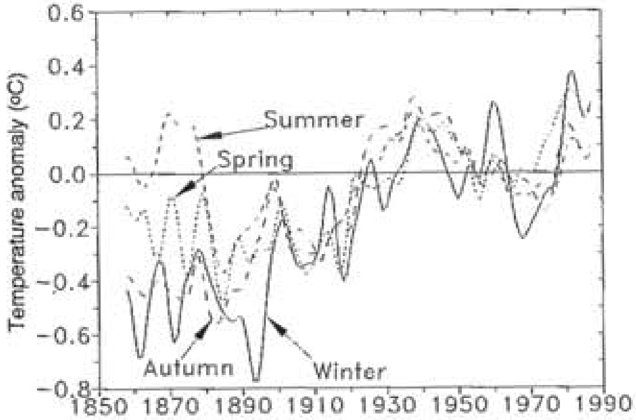


Figure 7.14: Smoothed seasonal land surface air temperature anomalies, relative to 1951-80, for the Northern Hemisphere. Data from P.D. Jones.

7.4.2.3 Day-time and Night-time

Because the ocean has a large heat capacity, diurnal temperature variations in the ocean and in the overlying air are considerably muted compared with those over land and, from a climatic point of view, are likely to change little. Over land, diurnal variations are much less restricted so the potential for relative variations in maximum and minimum temperature is much larger. Such relative changes might result from changes in cloudiness, humidity, atmospheric circulation patterns, windiness or even the amount of moisture in the ground. Unfortunately, it is not yet possible to assess variations of maximum and minimum temperature on a hemispheric or global scale. However in the regions discussed below, multi-decadal trends of day-time and night-time temperatures have been studied and do not always appear to be the same.

Figure 7.15a, second panel shows a rise of minimum temperatures (these usually occur around dawn) in the USA. The rise has not been reflected in maximum temperatures (which usually occur during mid-afternoon). (See also Section 7.10.1). Similar behaviour has been found in other parts of North America (Karl et al., 1984). Appreciably different variations of maximum and minimum temperatures on decadal time-scales are also observed at inland stations in Australia (Figure 7.15b). It is unlikely that urban heat islands play a significant role in these variations as the data for both countries have been extensively scrutinized for urban heat island biases. In China (Figure 7.15c), the minimum temperature also appears to have risen more than the maximum. It is uncertain to what extent increases in urbanisation contribute to the changes in China, especially as urban heat island biases tend to be greatest during the night. Over New Zealand, a strong influence of atmospheric circulation variations on variations in daily maxima relative to daily minima has been observed (Salinger, 1981). This is an indication that the above results can only be fully understood when changes in atmospheric circulation over these countries have been studied in some detail.

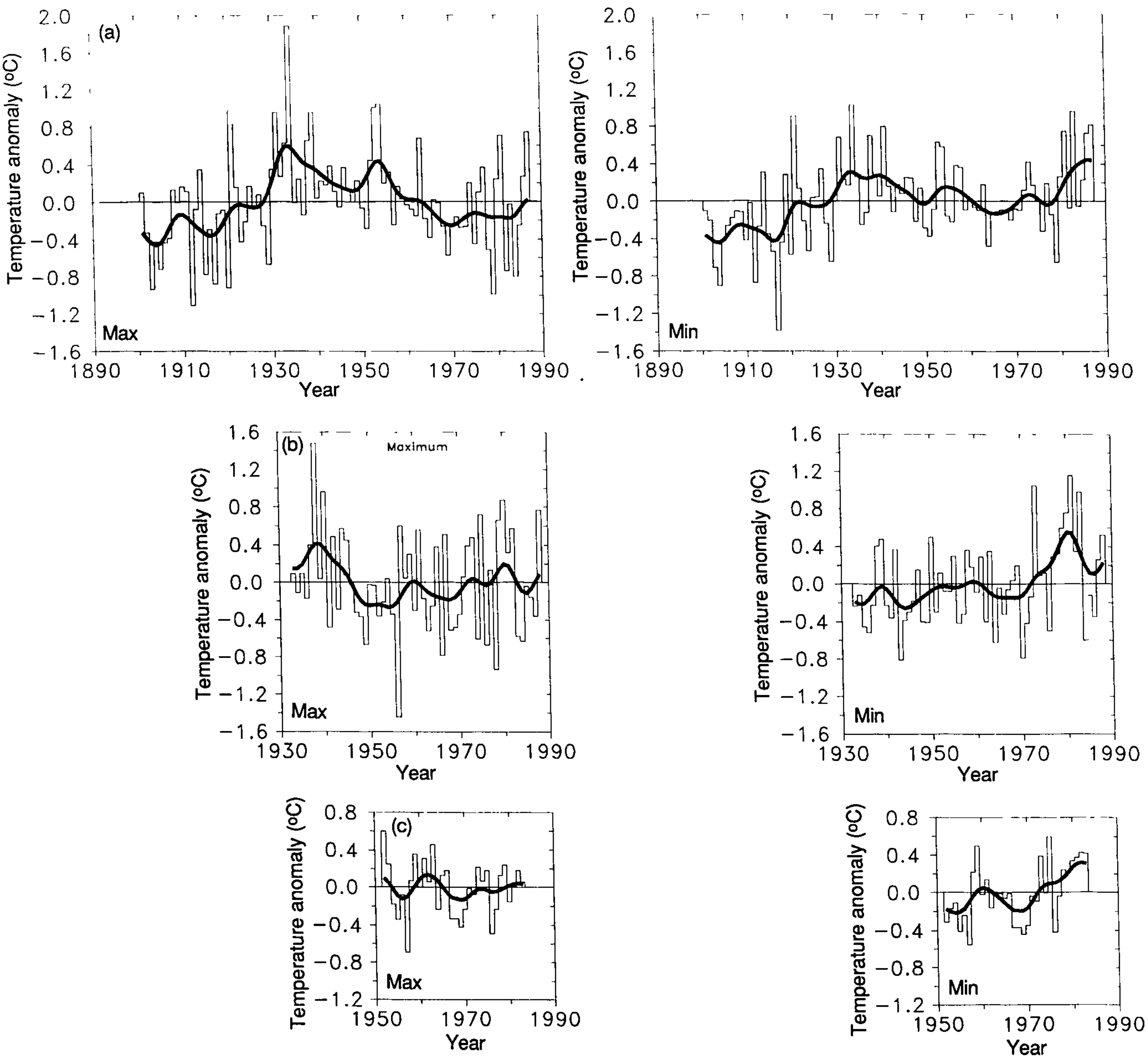


Figure 7.15: Changes of maximum (day-time) and minimum (night-time) temperatures. (a) United States, (b) South-eastern Australia, (c) China.

7.5 Precipitation and Evaporation Variations and Changes

7.5.1 Precipitation Over Land

Several large-scale analyses of precipitation changes over the Northern and Southern Hemisphere land masses have been carried out (Bradley et al., 1987; Diaz et al., 1989; Vinnikov et al., 1990). These have demonstrated that during the last few decades precipitation has tended to increase in the mid-latitudes, but decrease in the Northern Hemisphere subtropics and generally increase throughout the Southern Hemisphere. However, these large-scale features contain considerable spatial variability. Figure 7.16 illustrates this variability for three regions in the Northern Hemisphere and East Africa. Annual precipitation over the Soviet Union displays a remarkably consistent increase over the twentieth century (Figure 7.16a). An apparent increase in precipitation has been found over northern Europe (Schönweise and Birrong, 1990) with a suggestion of a decrease in extreme southern Europe, though these data have not yet been corrected for changing instrumental biases. In the tropics, East African rainfall departures from normal show significant decadal

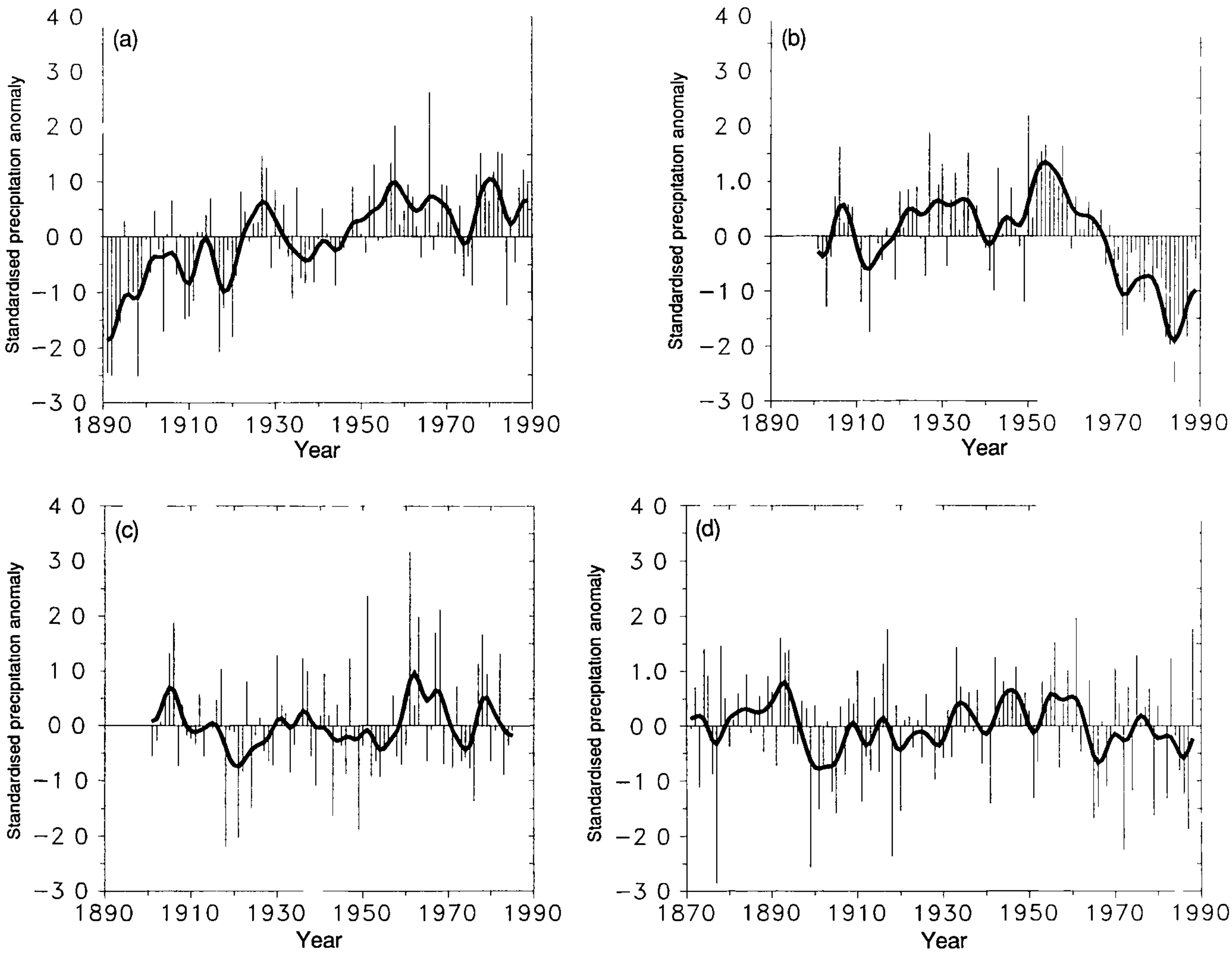


Figure 7.16: Standardised regional annual precipitation anomalies (a) USSR, (b) Sahel, (c) East Africa, (d) All India monsoon Note that Sahel values are annual averages of standardised **station** values restandardised to reflect the standard deviation of these annual averages

variability, but consistent trends are absent (Figure 7 16c) Summer monsoon rainfall in India also reflects multi decadal changes in climate (Figure 7 16d), but consistent trends are also absent The period 1890-1920 was characterised by a high frequency of droughts in India, while 1930-1964 had a much lower frequency Since 1965 the frequency of droughts has again been higher relative to 1930-1964 (Gadgil 1988), mostly in the wet areas of north eastern India (Gregory 1989)

The dramatic drying of sub Saharan Africa shown in Figure 7 16b deserves special comment Various explanations have been proposed reviewed in Druyan (1989), see also Semazzi et al (1988) and Wolter (1989) The most consistent result of these studies was to show over the last few decades a pattern of anomalously high SSTs in the Atlantic south of about 10°N lower than normal SSTs in the Atlantic to the north of 10°N and higher SSTs in the tropical Indian Ocean (Figure 7 13c) There has been a distinct weakening of some these patterns recently and a return to near normal rainfall in 1988 and 1989 Such large-scale changes of SST appear to have a major impact on the sub-Saharan atmospheric circulation (Folland et al 1990, Wolter, 1989) Although SST changes appear to be strongly related to the decreased rainfall since the 1950s they are probably not the only cause (Nicholson 1989) Folland et al (1990) show however that at least 60% of the variance of Sahel rainfall between 1901 and 1988 on time scales of one decade and longer is explained by worldwide SST variations Reductions of rainfall occurred at much the same time immediately south of the Sahel and over much of Ethiopia and the Caribbean

It is important to consider the accuracy of the precipitation data sets Precipitation is more difficult to monitor than temperature as it varies much more in time and space A higher spatial density of data is needed to provide an analysis of variations and trends of comparable accuracy High density data often reside within national meteorological centres, but there is no regular international exchange The number of stations required to sample a regional rainfall climate adequately varies with region and an adequate number may not always be available

A severe problem for analysing multi decadal variations of precipitation lies in the fact that the efficiency of the collection of precipitation by raingauges varies with gauge siting construction and climate (Sevruk 1982, Folland 1988, Legates and Willmott 1990) Major influences are the wind speed during rain, the size distribution of precipitation particle sizes, and the exposure of the raingauge site Fortunately, appropriate climatological averages of the first two, highly variable quantities can be used to assess usefully their effects over a long enough period (Folland, 1988, Appendix 1) Collection efficiency has tended to increase as operational practices have improved, often in poorly documented ways that may give artificial upward trends in precipitation in some regions Thus precipitation data are not completely compatible between countries due to the lack of agreed standards Of particular concern is the measurement of snowfall from conventional gauges where errors of at least 40% in long term collection efficiency can occur When precipitation errors are expressed as a percentage of the true rainfall it is not surprising that they tend to be greatest in high latitude windy, climates and least in wet equatorial regions

Vinnikov et al , (1990) have carried out detailed corrections to USSR data for the varying aerodynamic and wetting problems suffered by gauges These corrections are incorporated in the record shown in Figure 7 16a though no aerodynamic corrections were thought necessary in summer In winter the (positive) aerodynamic corrections can be large and vary from 5% to 40% (the latter for snow) Wetting corrections, which are also positive and tend to be largest in summer, varied typically in the range 4% to 10% and were applied after correction for aerodynamic effects Despite these large biases, comparisons of data sets over the USSR from Bradley et al (1987) who only partially corrected for biases, and Vinnikov et al who corrected more extensively show that most of the important long-term variations are apparent in both data sets (Bradley and Groisman, 1989) Many of the major variations apparent in precipitation records are evident in hydrological data such as the rise in the levels of the North American Great Lakes Great Salt Lake and the Caspian Sea during the early 1980s, and the severe desiccation of the Sahel Nevertheless the lack of bias corrections in most rainfall data outside the USSR is a severe impediment to quantitative assessments of rainfall trends

7 5 2 *Rainfall Over The Oceans*

Quantitative estimates of precipitation over the oceans are limited to the tropics where they are still very approximate The mean temperature of the upper surfaces of convective clouds deduced from satellite measurements of outgoing long wave thermal radiation (OLR) are used to estimate mean rainfall over periods of days upwards The colder the clouds the less is OLR and the heavier the rainfall (Section 4 gives references) Nitta and Yamada (1989) found a significant downward trend in OLR averaged over the global equatorial belt 10°N to 10°S between 1974 and 1987, implying an increase of equatorial rainfall over that time Arkin and Chelliah (1990) have investigated Nitta and Yamada s results for this Report They find that inhomogeneities in the OLR data are sufficiently serious to cast doubt on Nitta and Yamada s conclusions However the latter s claim that equatorial SST has risen over this period seems justified (Flohn and Kapala, 1989, and Figures 7 12 and 7 13) This trend is likely to result in increased deep convection and more rainfall there (Gadgil et al 1984, Graham and Barnett, 1987)

Section 7 5 has shown that some regional scale rainfall trends have occurred over land However much more attention needs to be paid to data quality and to improving data coverage before more comprehensive conclusions can be drawn about precipitation variations over the global land surface Precipitation cannot yet be measured with sufficient accuracy over the oceans to reliably estimate trends, even though quite modest changes in SST in the tropics could give rise to important changes in the distribution of tropical rainfall (see also Section 7 9 1)

7 5 3 *Evaporation from the Ocean Surface*

It is difficult to estimate trends in evaporation from the oceans An increase is however, expected as a result of an increase in greenhouse gases (Section 5) The most important problem concerns the reliability of measurements of wind speed that are an essential component of evaporation estimates Oceanic wind speeds have apparently increased in recent decades However, Cardone et al (1990) have demonstrated that much of this increase can be explained by changes in the methods of estimating wind speed from the state of the sea surface, and changes in the heights of anemometers used to measure wind speed on ships Until these problems are substantially reduced, it is considered that estimates of trends in evaporation are unlikely to be reliable

7.6 Tropospheric Variations and Change

7.6.1 *Temperature*

Tropospheric and stratospheric temperatures are central to the problem of greenhouse warming because general circulation models (Section 5) predict that temperature change with enhanced concentrations of greenhouse gases will have a characteristic profile in these layers, with more warming in the mid-troposphere than at the surface over many parts of the globe, and cooling in much of the stratosphere One of the "fingerprint" techniques (Section 8) for detecting anthropogenic climate change depends in part on an ability to discriminate between tropospheric

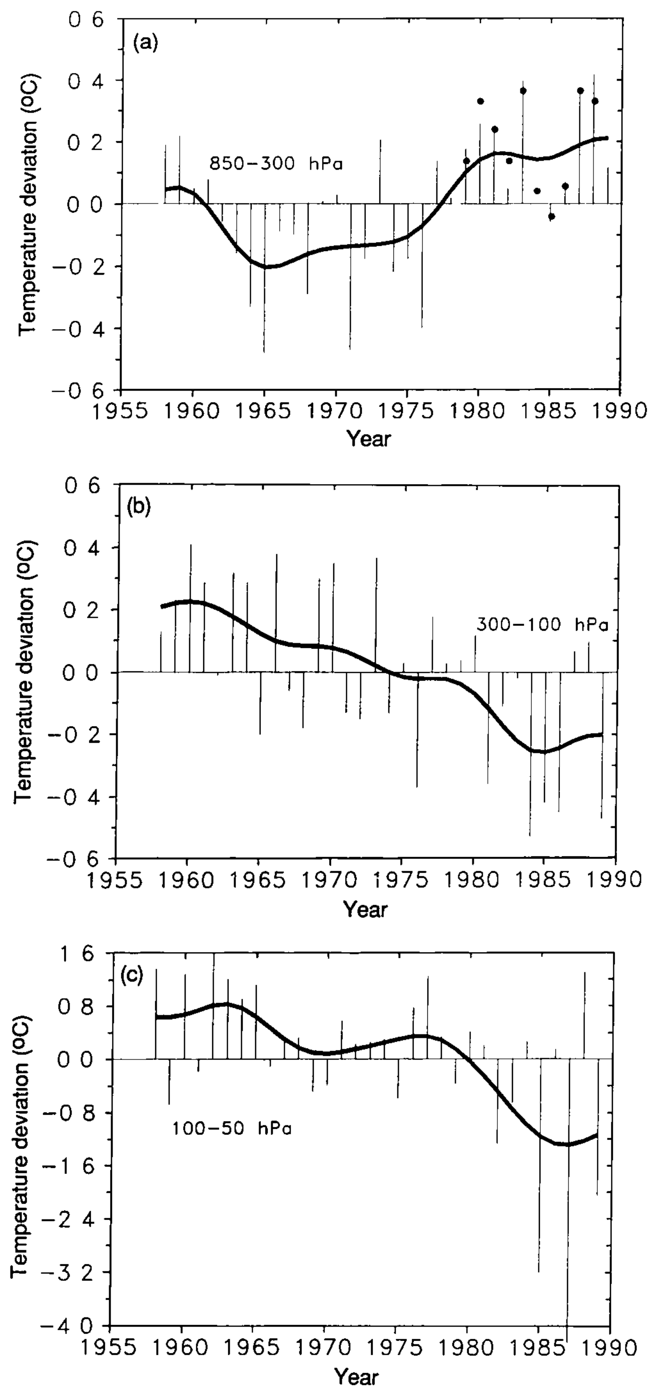


Figure 7.17: Temperature anomalies in the troposphere and lower stratosphere 1958-1989, based on Angell (1988)
(a) Annual global values for 850-300mb Dots are values from Spencer and Christy (1990) (b) 300-100mb (c) Annual values for Antarctic (60°S-90°S) for 100-50mb

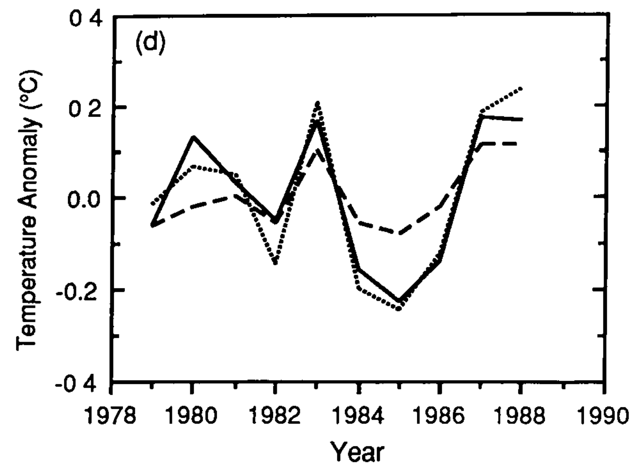


Figure 7.17 (continued): (d) Annual global anomalies for 1979-1988 tropospheric satellite temperatures from Spencer and Christy (1990) (solid line), 850 300mb radiosonde temperatures based on Angell (1988) (dots), combined land and sea surface temperatures as in Figure 7 10 (dashed line) All anomalies are referred to the average of their respective data sets for **1979-1988**

warming and stratospheric cooling (Barnett and Schlesinger, 1987) Observational studies of variations in recent temperature changes with height have been made by numerous authors, for example Parker (1985), Barnett (1986), Sellers and Liu (1988) and Karoly (1989) Layer mean temperatures from a set of 63 radiosonde stations covering the globe have been derived by Angell (1988) Most stations have operated continuously only since about 1958 (the International Geophysical Year) The network is zonally well distributed, but about 60% of the stations are in the Northern Hemisphere and only 40% in the Southern Hemisphere Layer mean temperatures from this network have been integrated for the globe Figure 7 17a shows that over the globe as a whole, mid-tropospheric (850 300 mb) temperatures increased by about 0 4°C between the late 1960s and mid-1980s, with much of the rise concentrated between 1975 and the early 1980s as at the surface Zonal average anomalies for 850-300mb (not shown) indicate that the largest changes occurred in the zone 10°S to 60°S followed by the equatorial region (10°N to 10°S) with little trend north of 60°N or south of 60°S This finding is in good agreement with surface data (Figures 7 12a and b)

In the upper troposphere (300 100 mb) Figure 7 17b shows that there has been a rather steady decline in temperature since the late 1950s and early 1960s in general **disagreement** with model simulations that show warming at these levels when the concentration of greenhouse gases is increased (Section 5) The greatest change in temperature has been in the lower stratosphere (100-50 mb) where the decrease after 1980 is much beyond the variability of the previous decades. It is mostly attributed to changes over and around Antarctica (Figure 7.17c) where the cooling since 1973 has reached nearly 10°C in austral spring and 2°C in summer (Angell, 1988) but with small values of cooling in other seasons. A small amount of lower stratospheric cooling has been observed elsewhere in the Southern Hemisphere, mainly in the tropics, and also in the equatorial belt (10°N to 10°S). The abrupt decrease over Antarctica in spring may at least be partly related to the formation of the "ozone hole".

Temperatures derived from radiosondes are subject to instrumental biases. These biases have not been assessed in the data used by Angell (1988), although there have been many changes in radiosonde instrumentation over the last 31 years. In 1984-85, international radiosonde comparisons were carried out (Nash and Schmidlin, 1987). Systematic differences between various types of radiosonde were determined for a series of flights which penetrated the tropopause. The estimated heights of the 100mb surface generally differed by up to 10-20 geopotential metres which is equivalent to average differences of 0.25°C in the layer from the surface to 100 mb.

7.6.2 Comparisons of Recent Tropospheric and Surface Temperature Data

A measure of the robustness of the tropospheric data derived by Angell (1988), at least in recent years, can be obtained by comparing his 850-300mb data with ten years of independent satellite measurements analysed by Spencer and Christy (1990) for 1979-1988. Spencer and Christy have used the average of measurements from microwave sounding units (MSU) aboard two USA National Oceanographic and Atmospheric Administration (NOAA) TIROS-N series of satellites to derive global temperatures in the mid troposphere. Although surface and mid-tropospheric data are likely to show rather different changes in their values over individual regions, better but not perfect, coupling is expected when the data are averaged over the globe as a whole. Figure 7.17d compares the annual global combined land air temperature and SST data used in Figure 7.10 with annual values of these two tropospheric data sets for the period 1979-1988. In each case the 10 annual anomalies are calculated from their respective 1979-1988 averages. The agreement between the three data sets is surprisingly good, despite recent suggestions that it is poor. Thus the correlations and root mean squared differences between the surface and MSU data are 0.85 and 0.08°C respectively, while the correlation between the surface and the radiosonde data is 0.91. The correlation between the two tropospheric data sets is, as expected, slightly higher at 0.96 with a root mean squared difference of 0.02°C. The latter represents excellent agreement given the relatively sparse network of radiosondes. Note that annual values in both tropospheric data sets have nearly twice the variability of the surface values, as measured by their standard deviation. This partly explains why the root mean square difference between the MSU and surface data is appreciably larger than that between the two tropospheric data sets, despite the high correlation. This is, arguably, an indication of genuine climatological differences between the interannual variability of mid-troposphere temperatures and those of the surface. All three data sets show a small positive trend over the period 1979-1988, varying from 0.04°C/decade for the MSU data to 0.13°C/decade for the surface data. These trends are not significantly different over this short period and again reflect surprisingly great agreement. Further discussion of these results is given in Jones and Wigley (1990).

7.6.3 Moisture

Water vapour is the most abundant greenhouse gas, and its increases are expected to augment the warming due to increases of other greenhouse gases by about 50%. Trenberth et al. (1987) estimate that doubling carbon dioxide concentrations would increase the global concentration of water vapour by about 20%, and Hansen et al. (1984) estimate a 33% increase.

There is evidence that global water vapour has been a few percent greater during the 1980s than during the 1970s (Elliott et al., 1990). Hense et al. (1988), and Flohn et al. (1990) find a 20% increase in water vapour content in the mid troposphere over the equatorial Pacific from 1965-1986 with at least a 10% rise between the surface and the 300mb level. Despite great uncertainties in these data some increase seems to have taken place. Because of numerous changes in radiosondes a global assessment of variations prior to 1973 is difficult and trends after 1973 have an uncertain accuracy. See also Section 8.

7.7 Sub-Surface Ocean Temperature and Salinity Variations

The sub-surface ocean data base is now just becoming sufficient for climate change studies in the North Atlantic and North Pacific basins to be carried out. A few, long, local time series of sub-surface measurements exist, sufficient to alert the scientific community to emerging evidence of decadal scale temperature variability in the Atlantic Ocean. Beginning about 1968, a fresh, cold water mass with its origins in the Arctic Ocean appears to have circulated around the sub-Arctic gyre of the North Atlantic Ocean. This event has been described by Dickson et al. (1988) as the "Great Salinity Anomaly". Some of this cold, fresh water penetrated to the deep waters of the North Atlantic (Brewer et al., 1983). The marked cool anomalies in the North Atlantic SST shown in Figure 7 13 for 1967-76 partly reflect this event

Recently, Levitus (1989a, b, c d) has carried out a major study of changes of sub surface temperature and salinity of the North Atlantic Ocean between 1955 59 and 1970 74 1955-59 was near the end of a very warm period of North Atlantic surface waters, but by 1970-74 the subsequent cool period was well developed (Figure 7 13) Cooler water extended from near the sea surface to 1400m depth in the subtropical gyre (30-50°N) Beneath the subtropical gyre, a warming occurred between the two periods North of this gyre there was an increase in the temperature and salinity of the western sub arctic gyre The density changes associated with these changes in temperature and salinity indicate that the transport of the Gulf Stream may have decreased between the two periods Temperature difference fields along 24 5°N and 36 5°N presented by Roemmich and Wunsch (1984) based on data gathered during 1981 and the late 1950s, are consistent with these ideas

Antonov (1990) has carried out a complementary study for the North Atlantic and North Pacific using subsurface temperature data held in the USSR and SST data from the UK Meteorological Office He finds that zonal averages of temperature changes between 1957 and 1981 show statistically significant cooling in the upper layers and a warming below 600m when averaged over the North Atlantic as a whole This agrees well with Levitus results for the North Atlantic Basin mean temperature changes (1957 to 1981) for the North Atlantic and North Pacific, as computed by Antonov, are shown in Figure 7 18

The reasons for some of these changes are partially understood For example, the cooling of the upper 1400m of the subtropical gyre was due to an upward displacement of cooler fresher water Why this displacement occurred is not definitely known but most probably is related to changes in the large scale wind field over the North Atlantic Of particular importance is the temperature increase of approximately 0 1°C over, on average, a thousand metre thick layer in the deep North Atlantic because it represents a relatively large heat storage Even the upper few metres of the ocean can store as much heat as the entire overlying atmospheric column of air Scientists have long recognized (Rossby, 1959) that the ocean could act to store large amounts of heat through small temperature changes in its sub-surface layers for hundreds or thousands of years When this heat returns to the atmosphere/cryosphere system it could also significantly affect climate Section 6 gives more details

The magnitude and extent of the observed changes in the temperature and salinity of the deep North Atlantic are thus large enough that they cannot be neglected in future theories of climate change

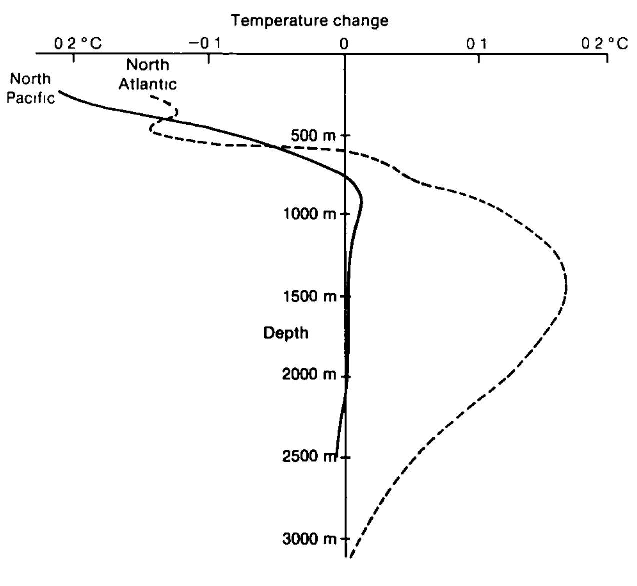


Figure 7.18: Sub-surface ocean temperature changes at depth between 1957 and 1981 in the North Atlantic and North Pacific Adapted from Antonov (1990)

7.8 Variations and Changes in the Cryosphere

Snow, ice, and glacial extent are key variables in the global climate system They can influence the global heat budget through regulation of the exchange of heat moisture, and momentum between the ocean, land, and atmosphere Accurate information on cryospheric changes is essential for full understanding of the climate system Cryospheric data are also integrators of the variations of several variables such as temperature, sunshine amount and precipitation, and for sea-ice, changes in wind stress Therefore caution must be exercised when interpreting a cryospheric change Variations in the Greenland and Antarctic ice sheets are discussed in Section 9

7.8.1 Snow Cover

Surface-based observations of snow cover are sufficiently dense for regional climate studies of the low lying areas of the Northern Hemisphere mid-latitudes Unfortunately, a hemisphere-wide data set of mid-latitude snow cover observations has not yet been assembled (Barry and Armstrong, 1987) In fact sustained high-quality measurements are generally incomplete (Karl et al , 1989) Since 1966 Northern Hemisphere snow cover maps have been produced operationally on a weekly basis using satellite imagery by NOAA The NOAA data contain snow/no-snow information for 7921 grid boxes covering the globe and were judged by Scialdone and Robock (1987) as the best of four data sets which they compared Deficiencies have been noted by Wiesnet et al (1987) such as until 1975 the charts did not consistently include Himalayan snow cover, there were occasional extensions of the southern edge of the snow cover beyond observed

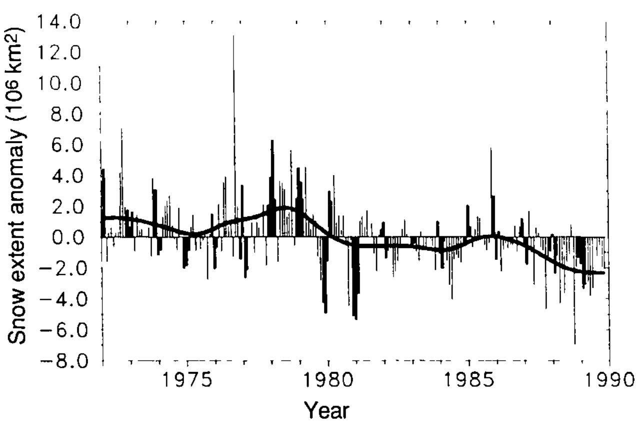


Figure 7.19: Northern Hemisphere snow extent anomalies. Data from NOAA (USA).

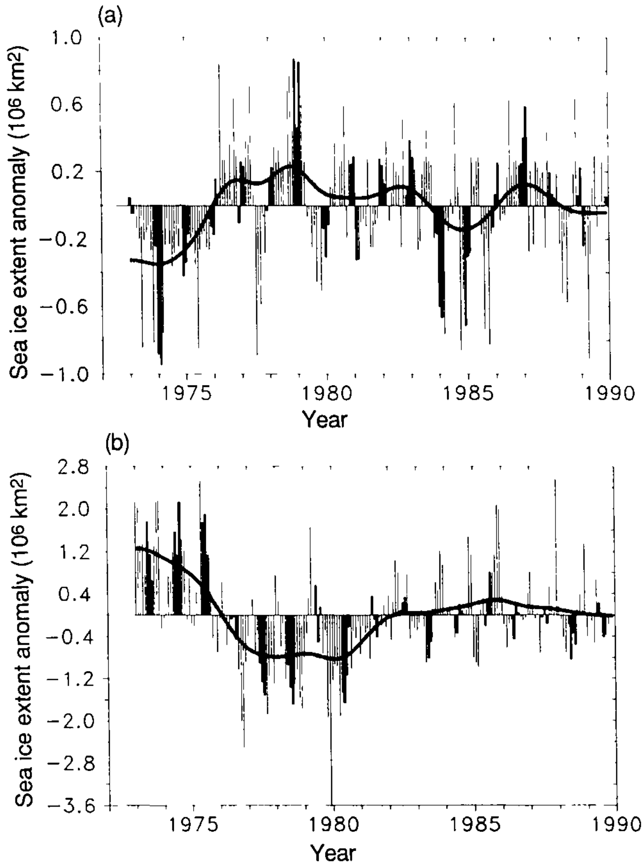


Figure 7.20: (a) Northern Hemisphere, and (b) Southern Hemisphere sea-ice extent anomalies. Data from NOAA (USA).

surface limits; the seasonal variation of sunlight limits polar coverage in the visible wavelengths; and scattered mountain snows are omitted because of the coarse grid resolution. Data are believed to be usable from 1972 with caution, but are better from 1975 onwards.

Consistent with the surface and tropospheric temperature measurements is the rapid decrease in snow cover extent around 1980 (Figure 7.19). This decrease is largest during the transition seasons. Robinson and Dewey (1990) note that the reduction in snow cover extent during the 1980s is largest in Eurasia where they calculate decreases during autumn and spring of about 13% and 9% respectively relative to the 1970s.

7.8.2 Sea-ice Extent and Thickness

There has been considerable interest in the temporal variability of global sea-ice in both the Arctic and Antarctic (for example, Walsh and Sater, 1981; Sturman and Anderson, 1985). This interest has been increased by general circulation model results suggesting that greenhouse warming may be largest at high latitudes in the Northern Hemisphere. It must be recognized, though, that sea-ice is strongly influenced by surface winds and ocean currents so that the consequences of global warming for changes in sea-ice extent and thickness are unlikely to be straightforward.

Sea-ice limits have long been observed by ships, and harbour logs often contain reported dates of the appearance and disappearance of harbour and coastal ice. These observations present many problems of interpretation (Barry, 1986) though they are thought to be more reliable after about 1950. Changes and fluctuations in Arctic sea-ice extent have been analysed by Mysak and Manak (1989); they find no long term trends in sea-ice extent between 1953 and 1984 in a number of Arctic ocean regions but substantial decadal time scale variability was evident in the Atlantic sector. These variations were found to be consistent with the development, movement and decay of the "Great Salinity Anomaly" noted in Section 7.7.

Sea-ice conditions are now reported regularly in marine synoptic observations, as well as by special reconnaissance flights, and coastal radar. Especially importantly, satellite observations have been used to map sea-ice extent routinely since the early 1970s. The American Navy Joint Ice Center has produced weekly charts which have been digitised by NOAA. These data are summarized in Figure 7.20 which is based on analyses carried out on a 1° latitude x 2.5° longitude grid. Sea-ice is defined to be present when its concentration exceeds 10% (Ropelewski, 1983). Since about 1976 the areal extent of sea-ice in the Northern Hemisphere has varied about a constant climatological level but in 1972-1975 sea-ice extent was significantly less. In the Southern Hemisphere since about 1981, sea-ice extent has also varied about a constant level. Between 1973 and 1980 there were periods of several years when Southern Hemisphere sea-ice extent was either appreciably more than or less than that typical in the 1980s.

Gloersen and Campbell (1988) have analysed the Scanning Multi-channel (dual polarization) Microwave Radiometer data from the Nimbus 7 satellite from 1978 1987. They find little change in total global ice area but a significant decrease of open water within the ice. Their time series is short, and it is uncertain whether the decrease is real.

Sea-ice thickness is an important parameter but it is much more difficult to measure than sea-ice extent. The heat flux from the underlying ocean into the atmosphere depends on sea-ice thickness. Trends in thickness over the Arctic Ocean as a whole could be a sensitive indicator of global warming. The only practical method of making extensive measurements is by upward-looking sonar from submarines. Apart from a very recent deployment of moorings, data gathering has been carried out on voyages by military submarines. In the past repeated tracks carried out in summer have either found no change in mean thickness (Wadhams 1989) or variations that can be ascribed to interannual variability in summer ice limits and ice concentration (McLaren 1989). Recently however, Wadhams (1990) found a 15% or larger decrease in mean sea-ice thickness between October 1976 and May 1987 over a large region north of Greenland. Lack of a continuous set of observations makes it impossible to assess whether the change is part of a long term trend. In the Antarctic no measurements of thickness variability exist and so far only one geographically extensive set of sea-ice thickness data is available (Wadhams et al 1987).

7.8.3 Land Ice (Mountain Glaciers)

Measurements of glacial ice volume and mass balance are more informative about climatic change than those of the extent of glacial ice, but they are considerably scarcer. Ice volume can be determined from transects of bedrock and ice surface elevation using airborne radio-echo sounding measurements. Mass balance studies performed by measuring winter accumulation and summer ablation are slow and approximate, though widely used. Section 9 discusses changes in the Greenland and Antarctic ice-caps so attention is confined here to mountain glaciers.

A substantial, but not continuous, recession of mountain glaciers has taken place almost everywhere since the latter half of the nineteenth century (Grove, 1988). This conclusion is based on a combination of mass balance analyses and changes in glacial terminus positions, mostly the latter. The recession is shown in Figure 7.2, evidence for glacial retreat is found in the Alps, Scandinavia, Iceland, the Canadian Rockies, Alaska, Central Asia, the Himalayas, on the Equator, in tropical South America, New Guinea, New Zealand, Patagonia, the sub Antarctic islands and the Antarctic Peninsula (Grove 1988). The rate of recession appears to have been generally largest between about 1920 and 1960.

Glacial advance and retreat is influenced by temperature, precipitation, and cloudiness. For example at a given latitude glaciers tend to extend to lower altitudes in wetter cloudier, maritime regions with cooler summers than in continental regions. The complex relation between glaciers and climate makes their ubiquitous recession since the nineteenth century remarkable; temperature changes appear to be the only plausible common factor (Oerlemans 1988). The response time of a glacier to changes in environmental conditions varies with its size so that the larger the glacier the slower is the response (Haeberli et al 1989). In recent decades glacial recession has slowed in some regions. Makarevich and Rototaeva (1986) show that between 1955 and 1980 about 27% of 104 North American glaciers were advancing and 53% were retreating, whereas over Asia only about 5% of nearly 350 glaciers were advancing. Wood (1988) found that from 1960 to 1980 the number of retreating glaciers decreased. This may be related to the relatively cool period in the Northern Hemisphere over much of this time (Figure 7.10). However Patzelt (1989) finds that the proportion of retreating Alpine glaciers has increased sharply since the early 1980s so that retreat has dominated since 1985 in this region. A similar analysis for other mountain regions after 1980 is not yet available.

7.8.4 Permafrost

Permafrost may occur where the mean annual air temperatures are less than −1°C and is generally continuous where mean annual temperature is less than −7°C. The vertical profile of temperature measurements in permafrost that is obtained by drilling boreholes can indicate integrated changes of temperature over decades and longer. However, interpretation of the profiles requires knowledge of the ground conditions as well as natural or human induced changes in vegetation cover. Lachenbruch and Marshall (1986) provide evidence that a 2 to 4°C warming has taken place in the coastal plain of Alaska at the permafrost surface over the last 75 to 100 years but much of this rise is probably associated with warming prior to the 1930s. Since the 1930s there is little evidence for sustained warming in the Alaskan Arctic (see Figure 7.12a and Michaels, 1990). A fuller understanding of the relationship between permafrost and temperature requires better information on changes in snow cover, seasonal variations of ground temperature, and the impact of the inevitable disturbances associated with the act of drilling the bore holes (Barry 1988).

7.9 Variations and Changes in Atmospheric Circulation

The atmospheric circulation is the main control behind regional changes in wind, temperature, precipitation, soil moisture and other climatic variables. Variations in many of these factors are quite strongly related through large scale features of the atmospheric circulation as well as through interactions involving the land and ocean surfaces One goal of research into regional changes of atmospheric circulation is to show that the changes of temperature rainfall and other climatic variables are consistent with the changes in frequency of various types of weather pattern

Climates at the same latitude vary considerably around the globe, while variations in regional temperatures that occur on decadal time scales are far from uniform but form distinctive large-scale patterns as indicated in Figure 7 13 The spatial scale of these climatic patterns is partly governed by the regional scales of atmospheric circulation patterns and of their variations Changes in weather patterns may involve changes in the quasi stationary atmospheric long waves in the extratropics or in monsoonal circulations (van Loon and Williams 1976) Both phenomena have a scale of several thousand kilometres Their large-scale features are related to the fixed spatial patterns of land and sea, topography, sea temperature patterns and the seasonal cycle of solar heating

Persistent large scale atmospheric patterns tend to be wavelike so that regional changes of atmospheric heating if powerful and persistent enough can give rise to a sequence of remote atmospheric disturbances Thus a number of well separated areas of anomalous temperature and precipitation of opposite character may be produced The best known examples are in part related to the large changes in SSTs that accompany the El Niño-Southern Oscillation (ENSO), whereby changes in the atmosphere over the tropical Pacific often associated with the SST changes there are linked to atmospheric circulation changes in higher latitudes (Wallace and Gutzler 1981) The 1988 North American drought has been claimed to be partly a response to persistent positive tropical SST anomalies located to the west of Mexico and to the north of the cold La Niña SST anomalies existing at that time (Trenberth et al 1988) Such localised SST anomalies may themselves have a much larger scale cause (Namias 1989)

An emerging topic concerns observational evidence that the 11 year solar cycle and the stratospheric quasi biennial oscillation (QBO) of wind direction near the equator are linked to changes in tropospheric circulation in the Northern Hemisphere (van Loon and Labitzke 1988) Coherent variations in tropospheric circulation are claimed to occur over each 11 year solar cycle in certain regions but their character depends crucially on the phase (easterly or westerly) of the QBO No mechanism has been proposed for this effect and the data on the QBO cover only about 3 5 solar cycles so that the reality of the effect is very uncertain However Barnston and Livezey (1989) in a careful study find evidence for statistically significant influences of these factors on atmospheric circulation patterns in the Northern Hemisphere extratropics in winter Many previous largely unsubstantiated claims of links between the 11 year, and other solar cycles, and climate are reviewed in Pittock (1983) Section 2 discusses current thinking about the possible magnitude of the physical forcing of global climate by solar radiation changes in some detail

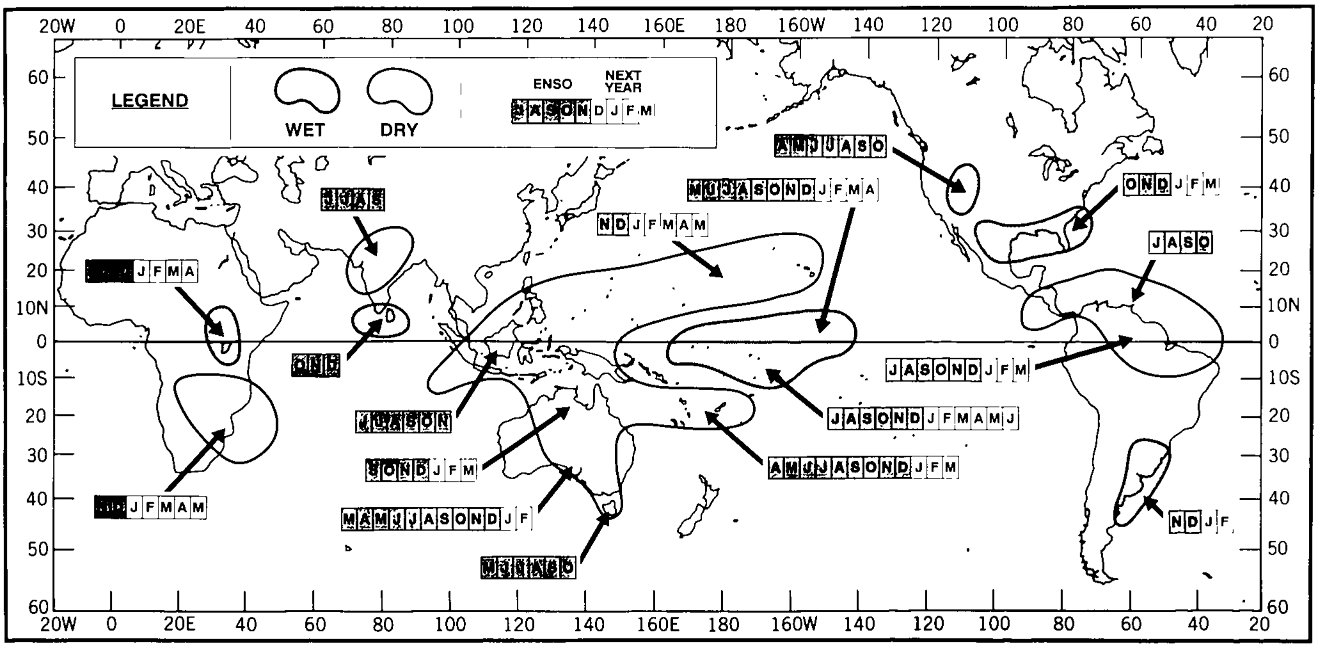
Several examples are now given of links between changes in atmospheric circulation over the last century and regional-scale variations or trends of temperature

7 9.1 El Niño-Southern Oscillation (ENSO) Influences

ENSO is the most prominent known source of interannual variability in weather and climate around the world, though not all areas are affected The Southern Oscillation (SO) component of ENSO is an atmospheric pattern that extends over most of the global tropics It principally involves a seesaw in atmospheric mass between regions near Indonesia and a tropical and sub-tropical south east Pacific Ocean region centred near Easter Island The influence of ENSO sometimes extends to higher latitudes (see Section 7 9 3) The El Nino component of ENSO is an anomalous warming of the eastern and central tropical Pacific Ocean In major Warm Events warming extends over much of the tropical Pacific and becomes clearly linked to the atmospheric SO pattern An opposite phase of Cold Events with opposite patterns of the SO is sometimes referred to as La Niña ENSO events occur every 3 to 10 years and have far reaching climatic and economic influences around the world (Figure 7 21a adapted from Ropelewski and Halpert 1987) Places especially affected include the tropical central and East Pacific islands, the coast of north Peru eastern Australia New Zealand (Salinger 1981) Indonesia India (Parthasarathy and Pant, 1985) and parts of eastern (Ogallo, 1989) and southern Africa (van Heerden et al 1988) A fuller description of ENSO can be found in Rasmusson and Carpenter (1982) and Zebiak and Cane (1987) Over India, the occurrence of ENSO and that of many droughts (see Section 7 5 1) is strikingly coincident Droughts tend to be much more frequent in the first year of an ENSO event though, intriguingly this is often before the ENSO event has fully developed However not all Indian droughts are associated with ENSO

While ENSO is a natural part of the Earth s climate, a major issue concerns whether the intensity or frequency of ENSO events might change as a result of global warming Until recently the models used to examine the climatic consequences of enhanced greenhouse forcing had such simplified oceans that ENSOs could not be simulated Some models now simulate ENSO like but not entirely realistic SST variations (Section 4) unfortunately long term variations in ENSO cannot be studied yet using models The observational record reveals that ENSO events have changed in frequency and intensity in the past The

(a)



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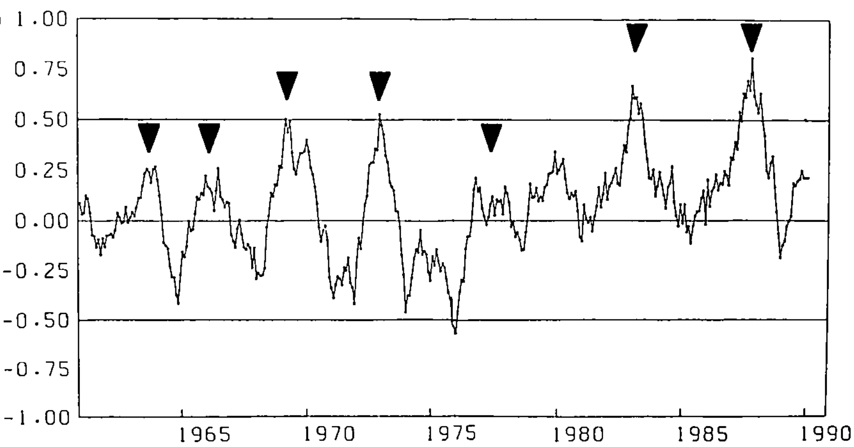

Figure 7.21: (a) Schematic diagram of areas and times of the year with a consistent ENSO precipitation signal (adapted from Ropelewski and Halpert, 1987). (b) Monthly tropical sea surface and land air temperature anomalies 1961-1989; land data from P.D. Jones and sea surface temperature data from the UK Meteorological Office. Tropics extend from 20°N to 20°S. Arrows mark maximum ENSO warmth in the tropics.

strong SO fluctuations from 1880 to 1920 led to the discovery and naming of the SO (Walker and Bliss, 1932) and strong SO events are clearly evident in recent decades. A much quieter period occurred from the late 1920s to about 1950, with the exception of a very strong multi-year ENSO in 1939-42 (Trenberth and Shea, 1987; Cooper et al., 1989). Quinn et al. (1987) (covering the past 450 years) and Ropelewski and Jones (1987) have documented historical ENSO events as seen on the northwest coast of South America. Therefore, the potential exists for a longer palaeo-record based on river deposits, ice cores, coral growth rings and tree rings.

During ENSO events, the heat stored in the warm tropical western Pacific is transferred directly or indirectly to many other parts of the tropical oceans. There is a greater than normal loss of heat by the tropical oceans, resulting in a short period warming of many, though not all, parts of the global atmosphere (Pan and Oort, 1983). Consequently, warm individual years in the record of global temperatures (Figure 7.10) are often associated with El Niños. Maxima in global temperatures tend to occur about three to six months after the peak warmth of the El Niño (Pan and Oort, 1983). Figure 7.21b shows monthly anomalies of combined land surface air temperatures and SST for the global tropics from 1961-1989. The strong, coherent, warming influence of the 1972-73, 1982-83 and 1986-88 ENSO events on the record of tropical temperature is very clear, as is the cold influence of the strong La Niña episodes of 1974-75 and 1988-89.

From an inter-decadal perspective, ENSO is a substantial source of climatic noise which can dominate the tropical temperature record. It is possible to remove ENSO signals statistically (for example Jones, 1989) to give a smoother global temperature curve; in this way 20 to 30% of decadal and shorter time scale variance is removed. The warming of the globe in the last 15 years then is reduced by about 0.1°C, i.e., by about one half. However other temperature signals might also be partly removed at the same time, for example those relating to the effects of volcanic eruptions, though some ability to separate these signals has recently been shown (Mass and Portman, 1989) (see also Section 2). As it is unclear whether ENSO might change with and contribute directly to long-term global warming, it seems preferable to retain ENSO variability as an integral part of the global climate record.

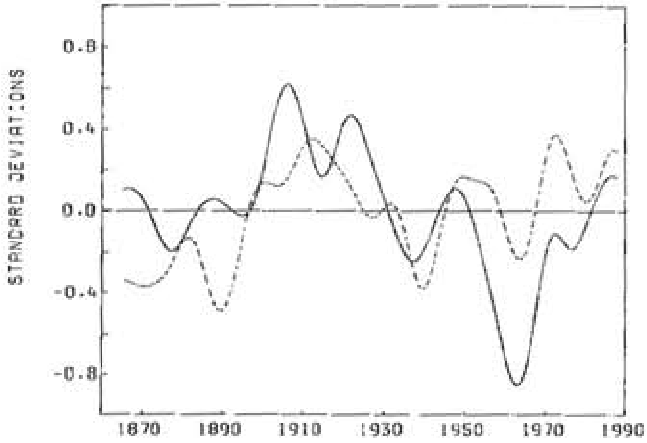

Figure 7.22: Smoothed standardised indices in winter (using binomial filter with 21 terms applied three times) of difference in atmospheric pressure at mean sea level between Ponta Delgada, Azores and Stykkisholmur, Iceland (solid line) and surface temperature for 45°-60°N, 5°W-35°E, based on land air (P.D. Jones) and night marine air temperature (UK Meteorological Office). December 1866-February 1867 to December 1989-February 1990.

7.9.2 The North Atlantic

The early twentieth century cooling of the Northern Hemisphere oceans (Figure 7.8) was accompanied by a period of intensified westerlies in the extratropical Northern Hemisphere, especially in the Atlantic sector, that affected most of the year. An extensive discussion is given in Lamb (1977). The global warming which took place in the 1920s and 1930s (Figure 7.10) was largest in the extratropical North Atlantic and in the Arctic (Figure 7.12), and coincided with the latter part of the period of intense westerlies. The westerly epoch is regarded as finishing around 1938 (Makrogiannis et al., 1982). The effects of the enhanced westerlies on surface climate were clearest in winter when there was an absence of very cold outbreaks over Europe and winters were persistently mild. Rogers (1985) noted that the best correlation between temperatures in Europe and wind direction is with the westerly component, largely reflecting whether or not the encroaching air masses have had an oceanic moderating influence imposed on them. Figure 7.22 shows an index of westerly flow expressed as the difference in atmospheric pressure measured at mean sea level between the Azores and Iceland in winter. High index epochs have stronger or more frequent westerly flow across the extratropical North Atlantic. Also shown is the air temperature anomaly over northern Europe and the adjacent seas from 45°N-60°N and 5°W-35°E in winter. The inter-decadal variations of the pressure index are strikingly large, with weakest flow centred around the late 1960s (less westerlies) and a return to a stronger westerlies recently (Flohn et al., 1990). Wallen (1986) notes that the period of intense westerly flow also affected summer temperatures in western Europe, making them generally cooler between the late 1890s and about 1920, giving striking decreases in the differences between July and January temperatures. This suggests that at least a small part of the decrease in the annual range of Northern Hemisphere land surface air temperature seen at this time in Figure 7.14 may be real.

Variations in the westerly index of Figure 7.22 are associated with changes in the depth of the Iceland low pressure centre both near the surface and in the troposphere (van Loon and Rogers, 1978). European temperatures well downstream are quite strongly related to this Atlantic pressure index, especially during winter, being warmest when the index is largest , i.e., pressure over Iceland is lowest relative to the Azores. Relative to the level of the westerly pressure index, there is a long-term increase of European winter surface air temperature in Figure 7.22, much as noted by Moses et al. (1987) for a small set of stations in western Europe. Above normal winter temperatures in Europe tend to go hand-in-hand with below normal temperatures in Greenland and the Canadian Arctic where there are increased northerlies as a result of the deeper Iceland Low. Stronger westerlies over the Atlantic, do not, therefore, account for the Arctic warming of the 1920s and 1930s on their own: in fact they preceded it by 20 years. Iceland (Einarsson, 1984) and Spitzbergen began to warm after about 1917 (Lamb, 1977), whereas Greenland and Northern Canada did not warm until the mid-1920s (Rogers, 1985). When both Greenland and Northern Europe had above normal temperature, especially in the winter half year, the atmospheric circulation was more zonal around most of the Arctic, not just in the Atlantic sector. This was associated with increased cyclonic activity over the whole Arctic basin which increased the frequency of zonal flows over the higher latitudes of the continents Note that the character of the warming experienced in the higher latitude Northern Hemisphere in the the 1920s and 1930s differs from that of the mid-1970s to early 1980s (Figure 7 10) when the North Atlantic and Arctic stayed cool, or in parts, cooled further

Inter-decadal changes in the west African monsoon circulation which have particularly affected Sub-Saharan African rainfall (Figure 7 16) were introduced in Section 7 5 1 The main change in atmospheric circulation has been in the convergence of winds into sub Saharan Africa in summer from the north and the south (Newell and Kidson, 1984), less intense convergence gives less rainfall (Folland et al , 1990) Drier years are also often accompanied by a slightly more southerly position of the main wind convergence (rain bearing) zone The North Atlantic subtropical high pressure belt also tended to extend further southward and eastward during the summer in the dry Sahel decades (Wolter and Hastenrath, 1989)

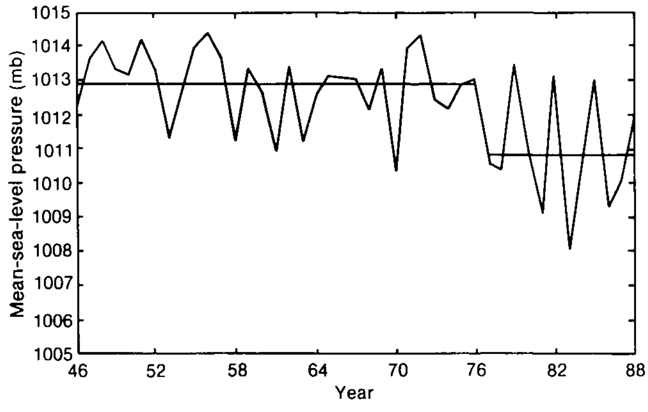

Figure 7.23: Time series of mean North Pacific sea level pressures averaged over 27 5 to 72 5°N, 147 5°E to 122 5°W for November through March Means for 1946 76 and 1977 87 are indicated

7.9.3 The North Pacific

Circulation changes in the North Pacific have recently been considerable and have been linked with regional temperature changes Figure 7 23 shows a time series of mean sea level pressure for the five winter months November to March averaged over most of the extra-tropical North Pacific for 1946 1988 (Trenberth 1990) This index is closely related to changes in the intensity of the Aleutian low pressure centre It is also quite strongly linked to a pattern of atmospheric circulation variability known as the Pacific North American (PNA) pattern (Wallace and Gutzler 1981) which is mostly confined to the North Pacific and to extratropical North America All five winter months showed a much deeper Aleutian Low in the period 1977 to 1988 with reduced pressure over nearly all the extratropical North Pacific north of about 32 N (Flohn et al 1990) The change in pressure in Figure 7 23 appears to have been unusually abrupt other examples of such climatic discontinuities have been analysed (Zhang et al 1983) though discontinuities can sometimes be artifacts of the statistical analysis of irregular time series The stronger Aleutian Low resulted in warmer moister air being carried into Alaska while much colder air moved south over the North Pacific These changes account for the large Pacific temperature anomalies for 1980-89 shown in Figure 7 13, which are even clearer for the decade 1977-86 (not shown) This decade had a positive anomaly (relative to 1951 80) of over 1 5°C in Alaska and negative anomaly of more than 0 75°C in the central and western North Pacific

The above changes are likely to have been related to conditions in the equatorial Pacific 1977 1987 was a period when much of the tropical Pacific and tropical Indian Oceans had persistently above normal SSTs (Nitta and Yamada, 1989, and Figure 7 12a) Very strong El Niño events and a lack of cold tropical La Niña events in the period 1977-1987 (Figure 7 21b) contributed to this situation

7.9.4 Southern Hemisphere

In Antarctica strong surface temperature inversions form in winter but elsewhere in the Southern Hemisphere maritime influences dominate The SO has a pronounced influence on precipitation over Australia (Pittock 1975) and also affects New Zealand temperatures and precipitation (Gordon 1986) However the best documented regional circulation-temperature relationship in the Southern Hemisphere is that between an index of the meridional (southerly and northerly) wind (Trenberth 1976) and New Zealand temperature The index is calculated by subtracting sea level pressure values measured at Hobart (Tasmania) from those at Chatham Island (east of New Zealand) A tendency for more northerly mean flow across New Zealand (Hobart pressure relatively low) especially from about 1952 to 1971 has been related to generally warmer conditions in New Zealand after 1950 However a return to more southerly (colder) flow after 1971 is not strongly reflected in New Zealand temperatures so the recent warmth may be related to the general increase in temperature in much of the Southern Hemisphere (Figures 7 10b, 7 12 and 7 13) This finding indicates that regional temperature changes due to a future greenhouse warming are likely to result from an interplay between large scale warming and changes in local weather patterns

7.10 Cloudiness

Clouds modify both the shortwave (solar) and longwave (terrestrial) radiation, the former by reflection and the latter by absorption Therefore they may cause a net warming or cooling of global temperature, depending on their type distribution, coverage, and radiative characteristics (Sommerville and Remer, 1984 Cess and Potter, 1987) Ramanathan et al (1989) show that with today's distribution and composition of clouds, their overall effect is to cool the Earth (Section 3 3 4) Changes in cloudiness are therefore likely to play a significant role in climate change Furthermore, local and regional climate variations can be strongly influenced by the amount of low middle and high clouds

Observations of cloudiness can be made from the Earth's surface by trained observers from land stations or ocean vessels, or by automated systems Above the Earth's surface, aircraft or space platforms are used (Rossow 1989, McGuffie and Henderson-Sellers 1989a) Surprisingly, surface-based observations of cloudiness give closely similar results to space based observations Careful and detailed intercomparisons, undertaken as a preliminary part of the International Satellite Cloud Climatology Project (ISCCP) by Sze et al (1986), have demonstrated conclusively that surface and space based observations are highly correlated Space-based observations of cloudiness from major international programs such as ISCCP are not yet available for periods sufficiently long to detect long-term changes

7.10.1 Cloudiness Over Land

Henderson Sellers (1986 1989) and McGuffie and Henderson-Sellers (1989b) have analyzed changes in total cloud cover over Europe and North America during the twentieth century It was found that annual mean cloudiness increased over both continents Preliminary analyses for Australia and the Indian sub-continent also give increases in cloudiness The increases are substantial 7% of initial cloudiness/50 years over India 6%/80 years over Europe 8%/80 years for Australia and about 10%/90 years for North America These changes may partly result from alterations in surface-based cloud observing practices and in the subsequent processing of cloud data This may be especially true of the large increase in cloudiness apparently observed in many areas in the 1940s and 1950s At this time (about 1949 or later, depending on the country) the synoptic meteorological code, from which many of these observations are derived generally underwent a major change but not in the USA USSR and Canada Observers began recording cloud cover in oktas (eighths) instead of in tenths When skies were partly cloudy it is possible that some observers who had been used to making observations in the decimal system converted decimal observations of cloud cover erroneously to the same number of oktas thereby overestimating the cloud cover

Recently Karl and Steurer (1990) have compared daytime cloudiness statistics over the USA with data from automated sunshine recorders They indicate that there was a much larger increase of annual cloud cover during the 1940s than can be accounted for by the small observed decrease in the percentage of possible sunshine The large increase of cloudiness may be attributed to the inclusion of the obscuring effects of smoke, haze, dust, and fog in cloud cover reports from the 1940s onward (there being no change in the recording practice from tenths to oktas in the USA) The increase in cloudiness after 1950 may be real because an increase is consistent with changes in the temperature and precipitation records in the USA, including the decreased diurnal temperature range seen in Figure 7 15

Observed land based changes in cloudiness are difficult to assess Nonetheless total cloud amount appears to have increased in some continental regions, a possibility supported by noticeable reductions in the diurnal range of temperature in some of these regions Elsewhere the cloudiness record cannot be interpreted reliably

7.10.2 Cloudiness Over The Oceans

Ocean-based observations of cloud cover since 1930 have been compiled by Warren et al (1988) The data are derived from maritime synoptic weather observations Their number varies between 100,000 and 2 000,000 each year increasing with time and the geographic coverage also changes The data indicate that an increase in marine cloudiness exceeding one percent in total sky covered on a global basis took place from the 1940s to the 1950s This increase is not reflected in the proportion of observations having a clear sky or a complete overcast The largest increases were in stratocumulus clouds in Northern Hemisphere mid-latitudes and in cumulonimbus in the tropics Since 1930 mean cloudiness has increased by 3-4 percent of the total area of sky in the Northern Hemisphere and by about half of this value in the Southern Hemisphere Fixed ocean weather ships placed after 1945 in the North Atlantic and North Pacific with well trained observers, showed no trends in cloudiness between the 1940s and 1950s when other ship data from nearby locations showed relatively large increases changes of the same sign as those in available land records (Section 7 10 1) It is clearly not possible to be confident that average global cloudiness has really increased

7.11 Changes of climate Variability and Climatic Extremes

Aspects of climate variability include those associated with day-to-day changes inter-seasonal and interannual variations, and the spatial variability associated with horizontal gradients. A pervasive problem for assessments of changes in the temporal variability of climate is the establishment of a reference level about which to calculate that variability. For example, the results of an investigation to determine whether the variability of monthly mean values was changing could give different results depending on how the average, or baseline, climate was calculated. If the climate was changing, calculations of variability would depend on whether a fixed baseline was used or whether it was allowed to change smoothly or discontinuously. Additionally, attempts to identify whether the number of extremes is decreasing or increasing may be critically dependent on the definition of the threshold value above which an extreme is defined. An attempt was made for this Report to estimate changes in the number of extremes of monthly average temperature values for a globally distributed set of about 150 stations, all having at least 60 years of record. The results were found to be very sensitive to the threshold chosen to define the extreme, and to the baseline climatology selected, so that no firm deductions about changes in extremes or variability were possible.

Interest in climatic variability often includes that on daily time-scales: a common question concerns whether daily temperatures above or below given threshold values, for example frosts, are changing in their frequency. Although considerable local climatic information exists on daily time-scales in any national meteorological data centre, such information covering the globe as a whole is not readily available at any one centre. Thus many of the data needed for a comprehensive assessment of changes in variability still need to be assembled and a scientifically sound method of analysis needs to be developed. Nevertheless a few comments can be made about variability which are discussed below.

7.11.1 Temperature

Several researchers have assessed relationships between anomalously cold or warm seasons and daily temperature variability in the USA. Brinkmann (1983) and Agee (1982) both find reduced day-to-day variability in anomalously warm winters, though Brinkmann (1983) provides evidence of enhanced day-to-day variability during anomalously warm summers. It is likely, however, that these relat-

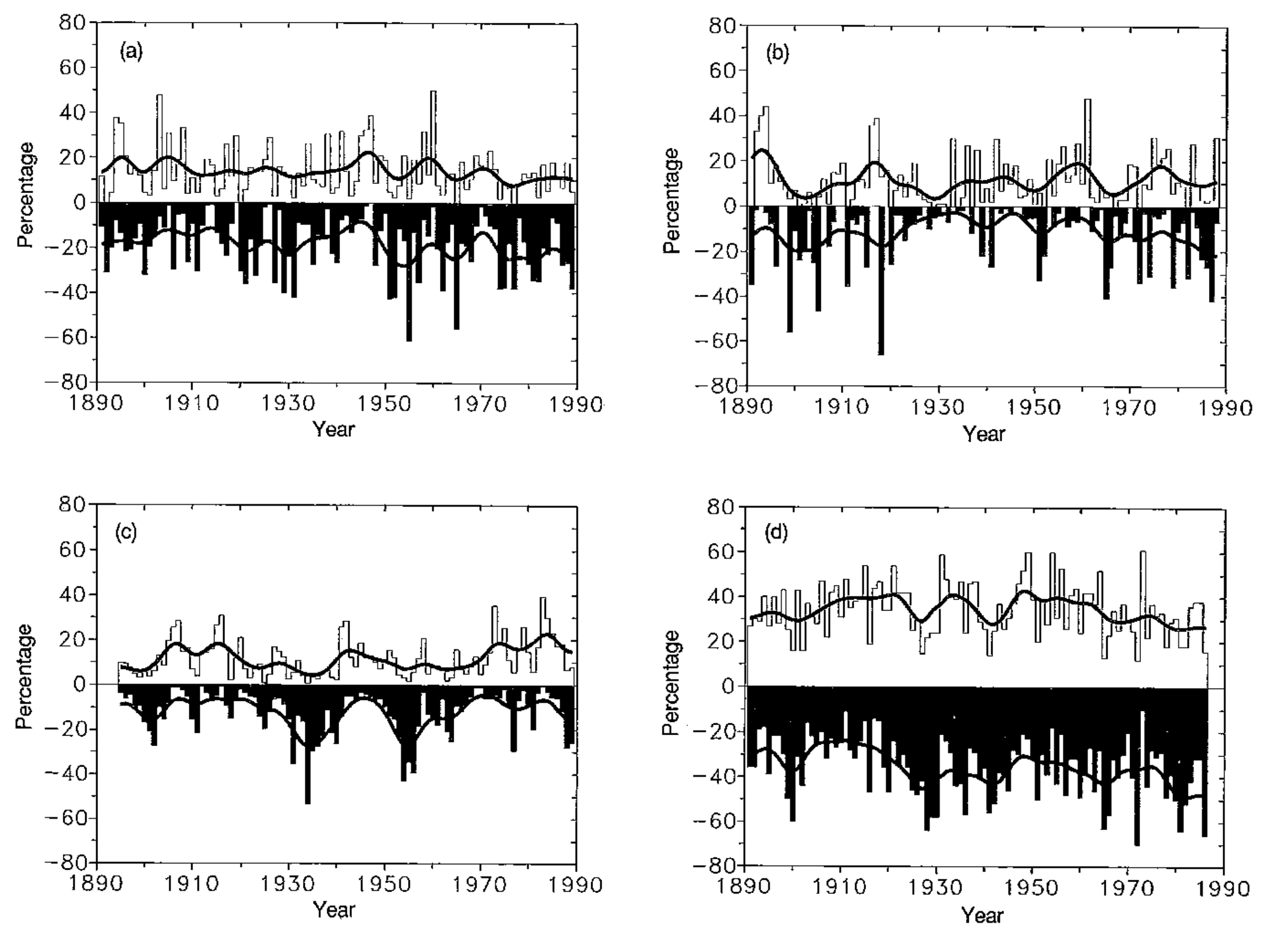

Figure 7.24: Regional drought and moisture index series. Unshaded region indicates excessive moisture. (a) Part of USSR (from Meshcherskaya and Blazhevich, 1977), (b) India, (c) USA, (d) China.

ionships are highly sensitive to the choice of region There appears to be little relation between interannual variability and the relative warmth or coldness of decadal averages Although Diaz and Quayle (1980) found a tendency for increased variability in the USA during the relatively warm years of the mid-twentieth century (1921-1955), Karl (1988) found evidence for sustained episodes (decades) of very high and low interannual variability with little change in baseline climate Furthermore, Balling et al (1990) found no relationship between mean and extreme values of temperature in the desert southwest of the USA

7.11.2 Droughts and Floods

An important question concerns variations in areas affected by severely wet ('flood) or drought conditions However, drought and moisture indices calculated for Australia (not shown), parts of the Soviet Union, India, the USA, and China (Figure 7 24, previous page) do not show systematic long-term changes Although this does not represent anything like a global picture, it would be difficult to envisage a worldwide systematic change in variability without any of these diverse regions participating It is noteworthy that the extended period of drought in the Sahel (Figure 7 16) between 1968 and 1987 exhibited a **decreased interannual** variability of rainfall compared with the previous 40 years even though the number of stations used remained nearly the same

7.11.3 Tropical Cyclones

Tropical cyclones derive their energy mainly from the latent heat contained in the water vapour evaporated from the oceans As a general rule, for tropical cyclones to be sustained, SSTs must be at or above 26°C to 27°C at the present time Such values are confined to the tropics, as well as some subtropical regions in summer and autumn The high temperatures must extend through a sufficient depth of ocean that the wind and wave action of the storm itself does not prematurely dissipate its energy source For a tropical cyclone to develop, its parent disturbance must be about 7° of latitude or more from the equator Many other influences on tropical cyclones exist which are only partly understood Thus ENSO modulates the frequency of tropical storms in some regions for example over the north-west Pacific, mainly south of Japan (Li, 1985, Yoshino, 1990), East China (Fu and Ye, 1988) and in the central and southwest Pacific (Revell and Gaulter 1986) The reader is referred to Nicholls (1984), Gray (1984), Emanuel (1987) and Raper (1990) for more detail

Have tropical cyclone frequencies or their intensities increased as the globe has warmed over this century? Current evidence does not support this idea perhaps because the warming is not yet large enough to make its impact felt In the North Indian Ocean the frequency of tropical storms has noticeably decreased since 1970 (Figure 7 25) while SSTs have risen here since 1970, probably more than in any other region (Figure 7 13) See also Raper (1990) There is little trend in the Atlantic, though pronounced decadal variability is evident over the last century There have been increases in the recorded frequency of tropical cyclones in the eastern North Pacific, the southwest Indian Ocean, and the Australian region since the late 1950s (not shown) However, these increases are thought to be predominantly artificial and to result from the introduction of better monitoring procedures Relatively good records of wind speed available from the North Atlantic and western Pacific oceans do not suggest that there has been a change toward more **intense** storms either

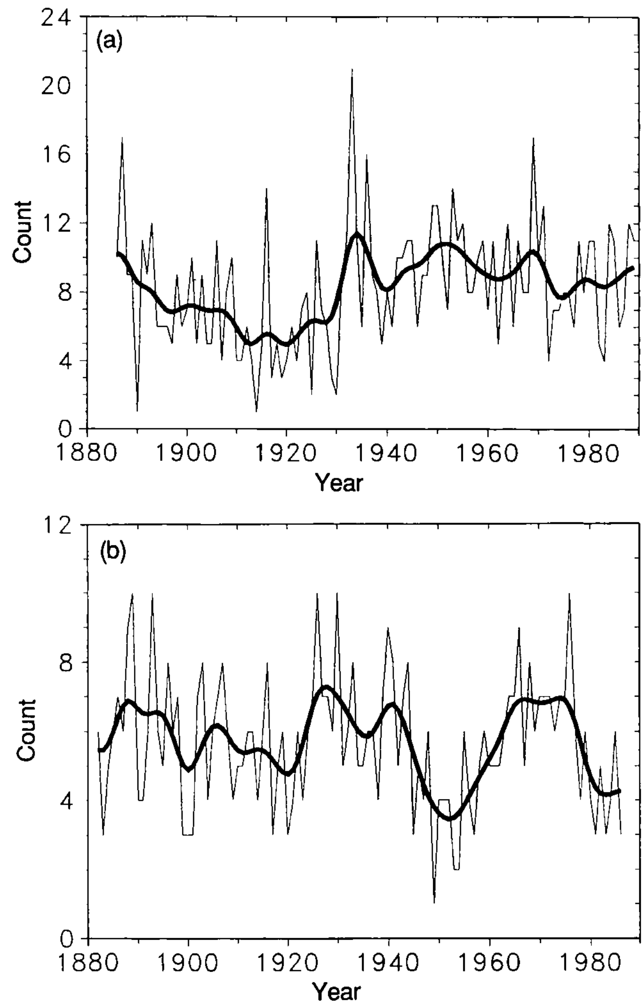

Figure 7.25: Estimated number of tropical cyclones in (a) Atlantic, and (b) North Indian Oceans over the last century Data in (b) is less reliable before about 1950

7.11.4 Temporales of Central America

Temporales are cyclonic tropical weather systems that affect the Pacific side of Central America and originate in the Pacific Inter-tropical Convergence Zone Very heavy rainfall totals over several days occur with these systems, but unlike hurricanes their winds are usually weak Their atmospheric structure is also quite different from that of hurricanes as they possess a cold mid-tropospheric core Temporales typically last several days, are slow moving and cause damaging floods and landslides in the mountainous regions of Central America Records of temporales are available since the 1950s They were markedly more frequent in the earlier than in the later part of this period Thus there was an average of 2 4 temporales per year in 1952 1961 (Hastenrath 1988) only 1959 had no temporales In 1964-1983 the average reduced to 0 45 temporales per year and in 12 of these years there were none

When the evidence in Section 7 11 is taken together, we conclude that there is no evidence of an increasing incidence of extreme events over the last few decades Indeed some of the evidence points to recent decreases, for example in cyclones over the North Indian Ocean and temporales over Central America

7.12 Conclusions

The most important finding is a warming of the globe since the late nineteenth century of 0 45 ± 0 15°C, supported by a worldwide recession of mountain glaciers A quite similar warming has occurred over both land and oceans This conclusion is based on an analysis of new evidence since previous assessments (SCOPE 29 1986) and represents a small reduction in previous best estimates of global temperature change The most important diagnosis that could **not** be made concerns temperature variations over the Southern Ocean Recent transient model results (Section 6) indicate that this region may be resistant to long term temperature change A data set of blended satellite and ship SST data is now becoming available and may soon provide an initial estimate of recent Southern Ocean temperature changes

Precipitation changes have occurred over some large land regions in the past century but the data sets are so poor that only changes of large size can be monitored with any confidence

Some substantial regional atmospheric circulation variations have occurred over the last century notably over the Atlantic and Europe Regional variations in temperature trends have also been quite substantial This indicates that, in future regional climatic changes may sometimes be quite diverse

Natural climate variations have occurred since the end of the last glaciation The Little Ice Age in particular involved global climate changes of comparable magnitude to the warming of the last century It is possible that some of the warming since the nineteenth century may reflect the cessation of Little Ice Age conditions The rather rapid changes in global temperature seen around 1920 -1940 are very likely to have had a mainly natural origin Thus a better understanding of past variations is essential if we are to estimate reliably the extent to which the warming over the last century, and future warming, is the result of an increase of greenhouse gases

References

Agee E M 1982 A diagnosis of twentieth century temperature records at West Lafayette *Indiana Clim Change* **4** 399 418

Alexandre P 1987 Le Climat en Europe au Moyen Age Contribution a l histoire des variations climatiques de 1000 a 1425 d apres les sources narratives de l Europe Occidentale Ec Hautes Etud Sci Soc *Rech Hist Sci Soc* **24** Paris 827pp

Angell J K 1988 Variations and trends in tropospheric and stratospheric global temperatures 1958 87 *J Clim* **1** 1296 1313

Antonov J I 1990 Recent climatic changes of vertical thermal structure of the North Atlantic and North Pacific Oceans *Meteorol i Gidrolog* **4** (in press)

Arkin P A and M Chelliah 1990 An assessment of variations of outgoing longwave radiation over the tropics 1974 1987 Draft Report to IPCC WG1 Section 7

Balling R C Jr J A Skindlow and D H Phillips 1990 The impact of increasing summer mean temperatures on extreme maximum and minimum temperatures at Phoenix Arizona *J Clim* (in press)

Barnett T P 1986 Detection of changes in the global tropospheric temperature field induced by greenhouse gases *J Geophys Res* **91** 6659 6667

Barnett T P and M E Schlesinger 1987 Detecting changes in global climate induced by greenhouse gases *J Geophys Res* **92** 14772 14780

Barnston A G and R E Livesey 1989 A closer look at the effect of the 11 year solar cycle and the quasi biennial oscillation on Northern Hemisphere 700mb height and extratropical North American surface temperature *J Clim* **2** 1295 1313

Barry R G 1988 Permafrost data and information status and needs In K Senneset (Ed) *Permafrost* Fifth International Conf Proc Vol 1 Tapir Publishers Trondheim pp119 122

Barry R G 1986 The sea ice data base In Untersteiner (Ed) *The Geophysics of Sea Ice* Plenum Press New York 1099 1134

Barry R G and R L Armstrong 1987 Snow cover data management The role of WDC A for Glaciology *Hydrol Sci J* **32** 281 295

Bartlein P J and T Webb III 1985 Mean July temperatures at 6000BP in eastern North America regression equations for estimates from fossil pollen data In *Climatic Change in Canada* 5 C R Harrington (Ed) Syllogeus 55 National Museum of Canada Ottawa 301 342

Berger A 1980 The Milankovitch astronomical theory of palaeoclimates a modern review *Vistas in Astronomy* **24** 103 122

Berner R A , A C Lasaga and R M Garrels 1983 The carbonate-silicate geochemical cycle and its effect on carbon dioxide over the past 110 million years *Am J Sc* , **283** 7, 641 683

Borzenkova, I I , and V A Zubakov, 1984 Climatic Optimum of the Holocene as a model of the global climate at the beginning of the 21st century *Meteorol i Gidrolog* **N8** 69 77 Also Sov Met Hydr , 8 52-58

Bottomley, M , C K Folland, J Hsiung R E Newell and D E Parker, 1990 Global Ocean Surface Temperature Atlas (GOSTA) Joint Meteorological Office/Massachusetts Institute of Technology Project Project supported by US Dept of Energy, US National Science Foundation and US Office of Naval Research Publication funded by UK Depts of Energy and Environment 20+iv pp and 313 Plates HMSO, London

Bradley, R S , and P D Jones, 1985 Data bases for isolating the effects of increasing carbon dioxide concentration In *Detecting the Climatic Effects of increasing carbon dioxide*, M C MacCracken and F M Luther (Eds) USA Dept of Energy Carbon Dioxide Research Division pp29 53

Bradley, R S H F Diaz, J K Eischeid P D Jones, P M Kelly and C M Goodess, 1987 Precipitation fluctuations over Northern Hemisphere land areas since the mid-19th century *Science*, **237**, 171 175

Bradley, R S , and P Ya Groisman 1989 Continental scale precipitation variations in the 20th century In *Proc Int Conf Precip Measurements*, WMO Geneva (in press)

Brewer, P G , W S Broecker, W J Jenkins P B Rhines, C G Rooth, J H Swift, T Takahashi and R T Williams, 1983 A climatic freshening of the deep Atlantic (north of 50^{o}N) over the past 20 years *Science*, **222**, 1237 1239

Brinkmann, W A R , 1983 Variability of temperature in Wisconsin *Mon Weath Rev* **111**, 172 180

Broecker, W S , 1987 Unpleasant surprises in the greenhouse *Nature*, **328**, 123 126

Broecker W S D Peteet and D Rind 1985 Does the ocean-atmosphere system have more than one stable mode of operation? *Nature*, **315**, 21 26

Budyko, M , A B Ronov and A L Yanshin 1985 *The history of the Earth's atmosphere* Leningrad Gidrometeoizdat, 209pp (English trans Springer-Verlag, 1987 139pp)

Budyko, M , and Yu A Izrael (Eds), 1987 *Anthropogenic Climatic Changes* L Gidrometeoizdat, 404pp

Cardone, V J , J G Greenwood and M A Cane 1990 On trends in historical marine wind data *J Clim* **3**, 113 127

Cess, R D , and G L Potter 1987 Exploratory studies of cloud radiative forcing with a general circulation model *Tellus* **39A** 460 473

Chappell, J M A , and Grindrod, A , (Eds), 1983 Proceedings of the first CLIMANZ conference, Howman's Gap, 1981 Dept of Biogeography and Geomorphology, Australian National University, Canberra, 2 vols

CLIMAP Project Members, 1984 The last interglacial ocean *Quatern Res* , **21**, 2, 123-224

COHMAP Members, 1988 Climate changes of the last 18,000 years observations and model simulations *Science*, **241**, 1043 1052

Cooper N S , K D B Whysall and G R Bigg, 1989 Recent decadal climate variations in the tropical Pacific *J Climatol* , **9** 221 242

Coughlan M J , R Tapp and W R Kininmonth, 1990 Trends in Australian temperature records Draft contribution to IPCC WGI, Section 7

Diaz, H F and R G Quayle, 1980 The climate of the United States since 1985 spatial and temporal changes *Mon Weath Rev* , **108**, 249 266

Diaz H F , R S Bradley and J K Eischeid, 1989 Precipitation fluctuations over global land areas since the late 1800s *J Geophys Res* , **94**, 1195 1210

Dickson, R R , J Meincke, S A Malmberg and A J Lee, 1988 The great salinity anomaly in the northern North Atlantic, 1968-82 *Prog Oceanogr* , **20**, 103 151

Druyan, L M , 1989 Advances in the study of Sub saharan drought *Int J Climatol* , **9** 77-90

Eddy, J , 1976 The Maunder Minimum *Science*, **192**, 1189-1202

Einarsson M A 1984 Climate of Iceland In Chapter 7 of *Climate of the Oceans, World Survey of Climatology*, 15, H van Loon (Ed), pp673 697

Ellsaesser, H W M C MacCracken, J J Walton, and S L Grotch, 1986 Global climatic trends as revealed by the recorded data *Rev Geophys* , **24**, 745 792

Elliott, W P M E Smith and J K Angell, 1990 On monitoring tropospheric water vapour changes using radiosonde data Proc Workshop on Greenhouse Gas Induced Climate Change, Amherst, MA, 8 12 May 1989, Elsevier , (in press)

Emanuel, K A , 1987 The dependence of hurricane intensity on climate *Nature*, **326** 483 485

Farmer, G , T M L Wigley, P D Jones and M Salmon, 1989 Documenting and explaining recent global mean temperature changes Climatic Research Unit, Norwich, Final Report to NERC, UK, Contract GR3/6565

Flohn, H , and A Kapala 1989 Changes in tropical sea-air interaction processes over a 30-year period *Nature*, **338**, 244-246

Flohn, H , A Kapala H R Knoche and H Machel, 1990 Recent changes of the tropical water and energy budget and of midlatitude circulations Submitted to *Climate Dynamics*

Folland, C K , 1971 Day time temperature measurements on weather ship Weather Reporter' *Met Mag* , **100**, 6-14

Folland, C K , 1988 Numerical models of the raingauge exposure problem, field experiments and an improved collector design *Q J Roy Met Soc* **114**, 1485-1516

Folland, C K and A W Colman, 1988 An interim analysis of the leading covariance eigenvectors of worldwide sea surface temperature anomalies for 1951-80 LRFC 20, available from National Meteorological Library, Meteorological Office, Bracknell, UK

Folland, C K , D E Parker and F E Kates, 1984 Worldwide marine temperature fluctuations 1856-1981 *Nature*, **310**, 670 673

Folland, C K , and D E Parker, 1989 Observed variations of sea surface temperature NATO Advanced Research Workshop on Climate Ocean Interaction, Oxford, UK, 26 30 Sept 1988 Kluwer Academic Press, pp 31 52

Folland, C K, J Owen, M N Ward and A Colman, 1990 Prediction of seasonal rainfall in the Sahel region using empirical and dynamical methods *J Forecasting*, (in press)

Fu, C, and D Ye, 1988 The tropical very low frequency oscillation on interannual scale *Adv Atmos Sci*, **5**, 369 388

Gadgil, S C, P V Joseph and N V Joshi, 1984 Ocean-atmosphere coupling over monsoon regions *Nature*, **312**, 141 143

Gadgil, S, 1988 Recent advances in monsoon research with particular reference to the Indian Ocean *Aust Met Mag*, **36**, 193-204

Gloersen, P, and W J Campbell, 1988 Variations in the Arctic Antarctic, and global sea ice covers during 1979-1987 as observed with the Nimbus 7 Scanning Multichannel Microwave Radiometer *J Geophys Res*, **93**, 10,666-10,674

Gordon, N D, 1986 The Southern Oscillation and New Zealand weather *Mon Weath Rev*, **114**, 371 387

Graham, N E, and T P Barnett, 1987 Sea surface temperature, surface wind divergence, and convection over tropical oceans *Science*, **238**, 657-659

Gray, W M, 1984 Atlantic seasonal hurricane frequency Part I El Niño and 30mb quasi-biennial oscillation influences *Mon Weath Rev*, **112**, 1649 1683

Gregory, S, 1989 The changing frequency of drought in India, 1871-1985 *J Geog*, **155**, 322 334

Groisman, P Ya, and V V Koknaeva, 1990 The influence of urbanisation on the estimate of the mean air temperature change in the 20th century over the USSR and USA territories obtained by State Hydrological Institute network Draft contribution to IPCC WGI, Section 7

Grove, A T, and A Warren, 1968 Quaternary landforms and climate on the south side of the Sahara *J Geog* **134**, 194-208

Grove, J M, 1988 *The Little Ice Age* Methuen London 498pp

Haeberli, W, P Mulle P Alean and H Bosch, 1989 Glacier changes following the Little Ice Age a survey of the international data bases and its perspectives In J Oerlemans (Ed), *Glacier Fluctuations and Climatic Change*, 77 101

Hammer, C, 1977 Past volcanism revealed by Greenland Ice Sheet impurities *Nature*, **270** 482-486

Hansen, J E, A Lacis D Rind G Russell, P Stone I Fung R Rudy and J Lerner, 1984 Climate sensitivity analysis of feedback mechanisms In *Climate Processes and Climate Sensitivity* J E Hansen and T Takahashi (Eds) *Geophys Monogr*, **29**, pp viii + 368, Washington

Hansen, J, and S Lebedeff, 1987 Global trends of measured surface air temperature *J Geophys Res* **92** 13345 13372

Hansen, J, and S Lebedeff 1988 Global surface temperatures update through 1987 *Geophys Res Letters*, **15**, 323 326

Hastenrath, S L, 1988 *Climate and Circulation in the Tropics* Second edition Reidel, Dordrecht, 455pp

Helland-Hansen B, and F Nansen 1920 Temperature variations in the North Atlantic Ocean and in the atmosphere introductory studies on the cause of climatological variations (Translated from German) *Smithsonian Misc*, Coll, **70**(4) 408pp

Henderson-Sellers, A 1986 Cloud changes in a warmer Europe *Clim Change*, **8**, 25-52

Henderson-Sellers, A, 1989 North American total cloud amount variations this century *Glob and Planet Change* **1**, 175 194

Hense A P Krahe and H Flohn, 1988 Recent fluctuations of tropospheric temperature and water vapour content in the tropics *J Meteor Atmos Phys* **38**, 215-227

Huntley B, and I C Prentice, 1988 July temperatures in Europe from pollen data 6000 years before present *Science* **241** 687 690

Imbrie, J and K P Imbrie, 1979 *Ice Ages solving the mystery* Macmillan, London 224pp

James, R W, and P T Fox, 1972 Comparative sea-surface temperature measurements Marine Science Affairs Report No 5, WMO 336, 27pp

Jones, P D, 1988 Hemispheric surface air temperature variations recent trends and an update to 1987 *J Clim* **1** 654-660

Jones P D, 1989 The influence of ENSO on global temperatures *Climate Monitor*, **17**, 80-89

Jones, P D, P M Kelly, G B Goodess and T R Karl 1989 The effect of urban warming on the Northern Hemisphere temperature average *J Clim*, **2**, 285 290

Jones, P D, S C B Raper, R S Bradley, H F Diaz P M Kelly and T M L Wigley, 1986a Northern Hemisphere surface air temperature variations, 1851 1984 *J Clim Appl Met* **25** 161-179

Jones P D S C B Raper, R S Bradley, H F Diaz P M Kelly and T M L Wigley, 1986b Southern Hemisphere surface air temperature variations, 1851-1984 *J Clim Appl Met* **25** 1213-1230

Jones P D and T M L Wigley, 1990 Satellite data under scrutiny *Nature*, **344** 711

Karl, T R, G Kukla and J Gavin, 1984 Decreasing diurnal temperature range in the United States and Canada from 1941 1980 *J Clim Appl Met*, **23**, 1489 1504

Karl T R, C N Williams Jr and P J Young 1986 A model to estimate the time of observation bias associated with monthly mean maximum minimum and mean temperatures for the United States *J Clim Appl Met* **25**, 145-160

Karl T R, and C N Williams, Jr, 1987 An approach to adjusting climatological time series for discontinuous inhomogeneities *J Clim Appl Met*, **26**, 1744 1763

Karl T R, 1988 Multi year fluctuations of temperature and precipitation The gray areas of climate change *Clim Change* **12** 179 197

Karl, T R, H F Diaz and G Kukla 1988 Urbanization its detection and effect in the United States climate record *J Clim* **1** 1099 1123

Karl T R, J D Tarpley, R G Quayle, H F Diaz D A Robinson and R S Bradley, 1989 The recent climate record What it can and cannot tell us *Rev Geophys*, **27**, 405 430

Karl, T R, and P M Steurer, 1990 Increased cloudiness in the United States during the first half of the twentieth century Fact or fiction In Review, *Geophys Res Lett*

Karl T R, and P D Jones, 1990 Reply to comments on Urban bias in area-averaged surface temperature trends *Bull Amer Met Soc*, **71**, (in press)

Karoly, D J, 1989 Northern Hemisphere temperature trends A possible greenhouse gas effect? *Geophys Res Lett* **16** 465 468

Kleshchenko L K, V T Radiuhin and R N Khostova 1988 On the comparison of Northern Hemisphere grid point mean monthly air temperature archives Proceedings of VNIIGMI-WDC, 153, (in Russian)

Lachenbruch, A H , and B Vaughn Marshall 1986 Changing climate geothermal evidence from permafrost in the Alaskan Arctic *Science*, **234**, 689 696

Lamb, H H , 1977 *Climate Present Past and Future* Vol 2, Methuen

Lamb, H H , 1988 Climate and life during the Middle Ages, studied especially in the mountains of Europe In *Weather Climate and Human Affairs* Routledge, London, 40-74

Legates, D R , and C J Willmott, 1990 Mean sesonal and spatial variability in gauge corrected, global precipitation *Int J Climatol* , **10**, 111 127

Levitus, S , 1989a Interpentadal variability of temperature and salinity at intermediate depths of the North Atlantic Ocean 1970-74 versus 1955-59 *J Geophys Res Oceans*, **94**, 6091 6131

Levitus, S , 1989b Interpentadal variability of salinity in the upper 150m of the North Atlantic Ocean 1970-74 versus 1955 59 *J Geophys Res Oceans*, **94**, (in press)

Levitus, S , 1989c Interpentadal variability of temperature and salinity in the deep North Atlantic Ocean, 1970 74 versus 1955 59 *J Geophys Res Oceans*, **94**, 16125 16131

Levitus, S , 1989d Interpentadal variability of steric sea level and geopotential thickness of the North Atlantic Ocean 1970-74 versus 1955-59 *J Geophys Res Oceans*, **94** , (in press)

Li C Y , 1985 El Niño and typhoon activities in the western Pacific *Kexue Tongbao*, **30**, 1087 1089

Lindzen, R S , 1990 Some coolness concerning global warming *Bull Am Met Soc* , **71**, 288-299

Lozhkin A B , and L H Vazhenin 1987 The features of the plant cover development in the Kolyma lowland in the Early Holocene In *The Quaternary Period in the North East of Asia* Magadan

Madden R A , and J Williams 1978 The correlation between temperature and precipitation in the United States and Europe *Mon Weath Rev* , **106**, 142 147

Makarevitch, K G , and O V Rototaeva, 1986 Present day fluctuations of mountain glaciers in the Northern Hemisphere Data of Glaciological Studies, Publ No 57, Soviet Geophysical Committee, Academy of Sciences of the USSR Moscow, 157 163

Makrogiannis, T J , A A Bloutsos and B D Giles, 1982 Zonal index and circulation change in the North Atlantic area, 1873 1972 *J Climatol* , **2**, 159 169

Mass, C F and D A Portman, 1989 Major volcanic eruptions and climate a critical evaluation *J Clim* , **2**, 566-593

Maury M F , 1858 Explanations and sailing directions to accompany the wind and current charts Vol 1, pp383 +51 plates W A Harris, Washington, DC

McGuffie, K , and A Henderson-Sellers, 1989a Almost a century of "imaging' clouds over the whole-sky dome *Bull Amer Met Soc* , **70**, 1243-1253

McGuffie, K , and A Henderson Sellers, 1989b Is Canadian cloudiness increasing?, *Atmos Ocean* **26** 608 633

Mechcherskaya A V and V G Blazhevich 1977 Catalogues of precipitation and temperature anomalies for basic agricultural regions of the southern part of the European territory of the USSR, Northern Kazakhstan and West Siberia *Meteorol i Gidrolog* , **9**, 76 84

Michaels, P T , 1990 Regional 500mb heights prior to the radiosonde era *Theoret and Appl Climat* , (in press)

Miller, G H 1976 Anomalous local glacier activity, Baffin Island, Canada palaeo climatic implications *Geology*, **4**, 502 504

McLaren, A S , 1989 The under ice thickness distribution of the Arctic Basin as recorded in 1958 and 1970 *J Geophys Res* , **94**, 4971 4983

Moses, T , G N Kiladis, H F Diaz and R G Barry, 1987 Characteristics and frequency of reversals in mean sea level pressure in the North Atlantic sector and their relationship to long term temperature trends *J Climatol* , **7**, 13 30

Mysak, L A and D A Manak 1989 Arctic sea ice extent and anomalies, 1953-1984 *Atmosphere Ocean*, **27**, 376-405

Namias J 1989 Cold winters and hot summers *Nature*, **338**, 15-16

Nash, J and F J Schmidlin, 1987 WMO International Radiosonde Comparison (UK 1984, USA 1985) Final Report WMO Instruments and Observing Methods Report No 30 WMO/TD No 195 103pp

Newell R E , and J W Kidson 1984 African mean wind changes between Sahelian wet and dry periods *J Climatol* , **4**, 27 33

Newell, N E , R E Newell J Hsiung and Z -X Wu, 1989 Global marine temperature variation and the solar magnetic cycle *Geophys Res Lett* , **16** 311 314

Nicholls, N , 1984 The Southern Oscillation, sea surface temperature, and interannual fluctuations in Australian tropical cyclone activity *J Climatol* **4**, 661 670

Nicholson, S E 1989 African drought characteristics, causal theories and global teleconnections *Geophys Monogr* , **52**, 79-100

Nitta, T , and S Yamada, 1989 Recent warming of tropical sea surface temperature and its relationship to the Northern Hemisphere circulation *J Met Soc Japan*, **67**, 375 383

Oerlemans, J 1988 Simulation of historical glacier variations with a simple climate-glacier model *J Glaciol* **34** 333-341

Ogallo L J 1989 The spatial and temporal patterns of the East African seasonal rainfall derived from principal component analysis *Int J Climatol* **9**, 145-167

Oort, A H Y -H Pan, R W Reynolds and C F Ropelewski, 1987 Historical trends in the surface temperature over the oceans based on the COADS *Clim Dynam* , **2**, 29-38

Pan, Y H , and A H Oort 1983 Global climate variations connected with sea surface temperature anomalies in the eastern equatorial Pacific Ocean for the 1958-1973 period *Mon Weath Rev* , **111**, 1244 1258

Parker, D E , 1985 On the detection of temperature changes induced by increasing atmospheric carbon dioxide *Q J Roy Met Soc* , **111**, 587 601

Parker, D E , 1990 Effects of changing exposure of thermometers at land stations Draft contribution to IPCC WGI, Section 7

Parthasarathy B and G B Pant 1985 Seasonal relationships between Indian summer monsoon rainfall and the Southern Oscillation *J Climatol* **5** 369-378

Patzelt, G 1989 Die 1980er Vorstossperiode der Alpengletcher *Oesterreicher Alpenverein*, **44** 14-15

Peshy, A and A A Velichko, 1990 (Eds) Palaeo-climatic and palaeo environment reconstruction from the late Pleistocene to Holocene In *Palaeo geographic Atlas for the Northern Hemisphere* Budapest (In press)

Pittock, A B , 1975 Climatic change and patterns of variation in Australian rainfall *Search*, **6**, 498-504

Pittock, A B , 1983 Solar variability, weather and climate an update *Q J Roy Met Soc* , **109**, 23 55

Porter, S C , 1986 Pattern and forcing of Northern Hemisphere glacier variations during the last millennium *Quat Res* , **26(1)**, 27-48

Quinn, W H , V T Neal and S E Antunez de Mayolo, 1987 El Niño occurrences over the past four and a half centuries *J Geophys Res* , **92**, 14449 14462

Ramanathan, V , R D Cess, E F Harrison, P Minnis, B R Barkstrom, E Ahmad and D Hartman, 1989 Cloud-radiative forcing and climate results from the Earth Radiation Budget Experiment *Science* **243** 57 63

Raper, S C B, 1990 Observational data on the relationships between climatic change and the frequency and magnitude of severe tropical storms In *Climate and sea level change Observations, Projections Implications* R A Warrick and T M L Wigley (Eds), Cambridge University Press (in press)

Rasmusson, E M , and T H Carpenter, 1982 Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño *Mon Weath Rev* , **110**, 354-384

Revell, C G , and S W Gaulter, 1986 South Pacific tropical cyclones and the Southern Oscillation *Mon Weath Rev* **114**, 1138-1145

Rind, D , D Peteet W Broecker, A McIntyre and W F Ruddiman, 1986 The impact of cold North Atlantic sea surface temperatures on climate implications for the Younger Dryas cooling (11 10K) *Clim Dynam* , **1**, 3-33

Robinson, D A , and K F Dewey, 1990 Recent secular variations in the extent of Northern Hemisphere snow cover Submitted to *Nature*

Roemmich, D , and C Wunsch, 1984 Apparent changes in the climatic state of the deep North Atlantic Ocean *Nature*, **307**, 447-450

Rogers, J C , 1985 Atmospheric circulation changes associated with the warming over the Northern North Atlantic in the 1920s *J Clim Appl Met* , **24**, 1303-1310

Ropelewski, C F , 1983 Spatial and temporal variations in Antarctic sea ice (1973 1982) *J Clim Appl Met* , **22** 470-473

Ropelewski, C F , and M S Halpert 1987 Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation *Mon Weath Rev* , **115**, 1606-1626

Ropelewski, C F , and P D Jones, 1987 An extension of the Tahiti-Darwin Southern Oscillation Index *Mon Weath Rev* , **115**, 2161 2165

Rossby, C G , 1959 Current problems in meteorology In *The Atmosphere and Sea in Motion*, Rockefeller Institute Press, New York, pp9-50

Rossow, W B , 1989 Measuring cloud properties from space a review *J Clim* , **2**, 201 213

Salinger, M J , 1981 New Zealand climate The instrumental record Victoria University of Wellington, 327pp

Salinger, M J 1989 New Zealand climate from ice age to present Environmental Monitoring in New Zealand 32 40

Schonwiese, C D , and W Birrong, 1990 European precipitation trend statistics 1851 1980 including multivariate assessments of the anthropogenic CO_2 signal *Z Meteorol* **40** 92 98

Scialdone, J , and A Robock, 1987 Comparisons of northern hemisphere snow cover data sets *J Clim Appl Met* **26** 53 68

SCOPE 29, 1986 *The greenhouse effect climatic change and ecosystems* B Bolin, B R Doos J Jager and R W Warrick (Eds) Wiley, Chichester

Sellers, W D , and W Liu, 1988 Temperature patterns and trends in the upper troposphere and lower stratosphere *J Clim* **1** 573 581

Semazzi, F H M , V Mehta and Y C Sud 1988 An investigation of the relationship between Sub saharan rainfall and global sea surface temperatures *Atmosphere-Ocean* **26** 118 138

Sevruk, B , 1982 Methods of correcting for systematic error in point precipitation measurement for operational use *Operational Hydrology Report* No 21, WMO No 589

Singh, G , R D Joshi, S K Chopra and A B Singh, 1974 Late quaternary history of vegetation and climate of the Rajasthan Desert India *Phil Trans Roy Soc Lond* Series B **267**, 179 195

Sommerville, R J , and L A Remer, 1984 Cloud optical thickness feedbacks in the CO_2 climate problem *J Geophys Res* , **89**, 9668 9672

Spencer, R W , and J R Christy, 1990 Precise monitoring of global temperature trends from satellites *Science*, **247** 1558 1562

Street-Perrott, F A and S P Harrison, 1985 Lake levels and climate reconstruction In *Palaeo climate Analysis and Modeling*, (Ed) A Hecht J Wiley, New York, pp291 340

Street-Perrott, F A , and R A Perrott 1990 Abrupt climate fluctuations in the tropics The influence of the Atlantic circulation *Nature*, **343**, 607 612

Sturman, A P , and M R Anderson, 1985 A comparison of Antarctic sea ice data sets and inferred trends in ice area *J Clim Appl Met* , **24**, 275 280

Swain, A M J E Kutzbach and S Hastenrath 1983 Estimates of Holocene precipitation for Rajasthan India based on pollen and lake level data *Quatern Res* **19** 1 17

Sze, G , F Drake, M Desbois and A Henderson Sellers 1986 Total and low cloud amounts over France and Southern Britain in the summer of 1983 comparison of surface observed and satellite retrieved values *Int J Rem Sens* **7** 1031 1050

Toynbee H 1874 Appendix D of Report of Proc Conf Maritime Meteorology, London, 1874 HMSO

Trenberth, K E , 1976 Fluctuations and trends in indices of the Southern Hemispheric circulation *Q J Roy Met Soc* **102** 65-75

Trenberth, K E G W Branstator and P A Arkin 1988 Origins of the 1988 North American Drought *Science* **242** 1640 1645

Trenberth, K E , and D J Shea 1987 On the evolution of the Southern Oscillation *Mon Weath Rev* **115** 3078 3096

Trenberth K E J R Christy and J G Olson 1987 Global atmospheric mass surface pressure and water vapour variations *J Geophys Res* , **92** 14 815-14 826

Trenberth, K E 1990 Recent observed interdecadal climate changes in the Northern Hemisphere *Bull Am Met Soc*, **71** (in press)

van Heerden, J , D E Terblanche and G C Schultze, 1988 The Southern Oscillation and South African summer rainfall *J Climatol*, **8**, 577-598

van Loon, H and J C Rogers, 1978 The seesaw in winter temperature between Greenland and northern Europe Part I General description *Mon Weath Rev* , **106**, 296-310

van Loon, H , and J Williams, 1976 The connection between trends of mean temperature and circulation at the surface Pt I Winter *Mon Weath Rev* , **104**, 365-380

van Loon, H , and K Labitzke 1988 Association between the 11 year solar cycle, the QBO and the atmosphere Part II Surface and 700mb in the Northern Hemisphere winter *J Climate*, **1**, 905-920

Varushchenko S I , A N Varushchenko and R K Klige, 1980 *Changes in the Caspian Sea regime and closed water bodies in palaeotimes* M Nauka, 238pp

Velichko A A , M P Grichuk, E E Gurtovaya, E M Zelikson and O K Borisova, 1982 Palaeo-climatic reconstructions for the optimum of the Mikulino Interglacial in Europe Izv Acad Sci USSR, *Ser Geogr* , **N1**, 15

Velichko A A , M P Grichuk, E E Gurtovaya and E M Zelikson 1983 Palaeo-climate of the USSR territory during the optimum of the last interglacial (Mikulino) Izv Acad Sci USSR, *Ser Geogr* **N1**, 5-18

Velichko A A , M S Barash, M P Grichuk Ye Ye Gurtoyova and E M Zelikson, 1984 Climate of the Northern Hemisphere in the last interglacial (Mikulino) Izv Acad Sci USSR, *Ser Geogr* **N6**, 30-45

Vinnikov, K Ya , P Ya Groisman, and K M Lugina, 1990 The empirical data on modern global climate changes (temperature and precipitation) *J Clim* , (in press)

Vinnikov, K Ya , P Ya Groisman, K M Lugina, and A A Golubev, 1987 Variations in Northern Hemisphere mean surface air temperature over 1881 1985 *Meteorology and Hydrology*, **1**, 45 53 (In Russian)

Wadhams, P , M A Lange and S F Ackley, 1987 The ice thickness distibution across the Atlantic sector of the Antarctic Ocean in midwinter *J Geophys Res* , **92**, 14535 14552

Wadhams, P , 1989 Sea-ice thickness distribution in the Trans Polar Drift Stream Rapp P v Reun Cons *Int Explor Mer* **188**, 59-65

Wadhams, P , 1990 Evidence for thinning of the Arctic sea ice cover north of Greenland *Nature* , (in press)

Walker, G T , and E W Bliss, 1932, World Weather Vol *Mem Roy Met Soc* , **4**, 53-84

Wallace, J M , and D S Gutzler, 1981 Teleconnections in the geopotential height field during the Northern Hemisphere winter *Mon Weath Rev* , **109**, 784 812

Wallen, C C , 1986 Impact of present century climate fluctuations in the Northern Hemisphere *Geograf Ann* , Ser A **68**, 245-278

Walsh J E and J E Sater, 1981 Monthly and seasonal variability in the ocean-ice-atmosphere systems of the North Pacific and the North Atlantic *J Geophys Res* **86** 7425-7445

Wang W C , Z Zeng, and T R Karl, 1990 Urban warming in China Draft contribution to IPCC WGI, Section 7

Warren, S G , C J Hahn, J London, R M Chervin and R L Jenne, 1988 Global distribution of total cloud cover and cloud type amounts over the ocean NCAR Tech Note TN 317+STR, 42pp

Webb, T III, P J Bartlein and J E Kutzbach, 1987 Climatic change in eastern North America during the past 18000 years comparisons of pollen data with model results In *The Geology of North America*, Vol K 3, North America and Adjacent Oceans During the Last Deglaciation (eds W F Ruddiman and H E Wright) Geol Soc of America, Boulder, pp447-462

Wiesnet, D R , C F Ropelewski G J Kukla, and D A Robinson, 1987 A discussion of the accuracy of NOAA satellite-derived global seasonal snow cover measurements In B E Goodison, R G Barry, and J Dozier, (Eds), *Large Scale Effects of Seasonal Snow Cover*, IAHS Publ 166, pp291 304 IAHS Press, Wallingford, UK

Wigley, T M L , and P M Kelly, 1989 Holocene climatic change, 14C wiggles and variations in solar irradiance *Phil Trans Roy Soc* Lond , (in press)

Wolter, K 1989 Modes of tropical circulation, Southern Oscillation and Sahel rainfall anomalies *J Clim* , **2**, 149-172

Wolter K and S Hastenrath, 1989 Annual Cycle and Long-Term Trends of Circulation and Climate Variability over the Tropical Oceans *J Clim* , **2**, 1329 1351

Wood, F B , 1988 Global alpine glacier trends, 1960s to 1980s *Arct Alp Res* , **20**, 404-413

Woodruff, S D , R J Slutz, R J Jenne, and P M Steurer, 1987 A Comprehensive Ocean-Atmosphere Data Set *Bull Am Met Soc* , **68**, 1239 1250

Woodruff, S D , 1990 Preliminary comparison of COADS (US) and MDB (UK) ship reports Draft contribution to IPCC WG1, Section 7

Yamamoto, R M , R M Hoshaio and N Nishi, 1990a An estimate of systematic errors in air temperature data in COADS *J Clim* , (in press)

Yamamoto, R M , R M Hoshaio, N Nishi and Y Kakuno, 1990b Interdecadal warming over the oceans *J Clim* , (in press)

Yoshino, M M , 1978 Regionality of climatic change in Monsoon Asia In *Climatic change and food production* K Takahashi and M M Yoshino (Eds), Univ Tokyo Press Tokyo, 331 342

Yoshino, M M , 1990 Climate related impact research activities-Japan Int Networkshop, Boulder, Co, March 14 17, 1989, (in press)

Yoshino, M M , and K Urushibara, 1978 Palaeoclimate in Japan since the Last Ice Age *Climatological Notes*, **22**, 1-24

Zebiak, S E , and M A Cane, 1987 A model El Niño--Southern Oscillation *Mon Weath Rev* , **115**, 2262-2278

Zhang, C , J Yang and Lin, X , 1983 The stages nature of long-term variations of the atmospheric centres of action *Sci Atmos Sinica* **7** 364 374

Zhang, Y and W C Wang, 1990 The surface temperature in China during the mid-Holocene In *Zhu Kezhen Centennial Memorial Collections* Science Press, Beijing, (in press)

Zubakov, V A , and I I Borzenkova, 1990 *Global Climate during the Cenozoic* Amsterdam, Elsevier, 453pp