Observed Climate Variability and Change

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CONTENTS

SUMMARY

Has the climate warmed?

- The estimate of warming since the late 19th century has not significantly changed since the estimates in IPCC (1990) and IPCC (1992), although the data have been reanalysed, and more data are now available. Global surface temperatures have increased by about 0.3 to 0.6°C since the late-19th century, and by about 0.2 to 0.3°C over the last 40 years (the period with most credible data). The warming has not been globally uniform. Some areas have cooled. The recent warming has been greatest over the continents between 40° and 70°N.

- The general, but not global, tendency to reduced diurnal temperature range over land, at least since the middle of the 20th century, noted in IPCC (1992), has been confirmed with more data (representing more than 40% of the global land mass). The range has decreased in many areas because nights have warmed more than days. Cloud cover has increased in many of the areas with reduced diurnal temperature range. Minimum temperature increases have been about twice those in maximum temperatures.

- Radiosonde and Microwave Sounding Unit observations of tropospheric temperature show slight overall cooling since 1979, whereas global surface temperature has warmed slightly over this period. There are statistical and physical reasons (e.g., short record lengths; the different transient effects of volcanic activity and El Niño-Southern Oscillation) for expecting different recent trends in surface and tropospheric temperatures. After adjustment for these transient effects, which can strongly influence trends calculated from short periods of record, both tropospheric and surface data show slight warming since 1979. Longer term trends in the radiosonde data, since the 1950s, have been similar to those in the surface record.

- Cooling of the lower stratosphere since 1979 is shown by both Microwave Sounding Unit and radiosonde data (as noted in IPCC, 1992), but is larger (and probably exaggerated because of changes in instrumentation) in the radiosonde data. The current (1994) global stratospheric temperatures are the coolest since the start of the instrumental record (in both the satellite and radiosonde data).

- As predicted in IPCC (1992), relatively cool surface and tropospheric temperatures, and a relatively warmer lower stratosphere, were observed in 1992 and 1993, following the 1991 eruption of Mt. Pinatubo. Warmer surface and tropospheric temperatures reappeared in 1994. Surface temperatures for 1994, averaged globally, were in the warmest 5% of all years since 1860.

- Further work on indirect indicators of warming such as borehole temperatures, snow cover, and glacier recession data, confirm the IPCC (1990) and (1992) findings that they are in substantial agreement with the direct indicators of recent warmth. Variations in sub-surface ocean temperatures have been consistent with the geographical pattern of surface temperature variations and trends.

- As noted in IPCC (1992) no consistent changes can be identified in global or hemispheric sea ice cover since 1973 when satellite measurements began. Northern Hemisphere sea ice extent has, however, been generally below average in the early 1990s.

Has the climate become wetter?

- There has been a small positive (1%) global trend in precipitation over land during the 20th century, although precipitation has been relatively low since about 1980. Precipitation has increased over land in

high latitudes of the Northern Hemisphere, especially during the cold season, concomitant with temperature increases. A step-like decrease of precipitation occurred after the 1960s over the subtropics and tropics from Africa to Indonesia, as temperatures in this region increased. The various regional changes are consistent with changes in streamflow, lake levels, and soil moisture (where data are available and have been analysed).

- There is evidence to suggest increased precipitation over the central equatorial Pacific Ocean, in recent decades, with decreases to the north and south. Little can be said about precipitation changes elsewhere over the ocean.

- Northern Hemisphere snow cover extent has been consistently below the 21 year (1974-1994) average since 1988. Snow-radiation feedback has amplified spring-time warming over mid- to high latitude Northern Hemisphere land areas.

- Evaporation appears to have decreased since 1951 over much of the former Soviet Union, and possibly also in the USA. Evaporation appears to have increased over the tropical oceans (although not everywhere).

- The evidence still suggests an increase of atmospheric water vapour in the tropics, at least since 1973, as noted in IPCC (1992).

- In general, cloud amount has increased over the ocean in recent decades, with increases in convective and middle and high-level clouds. Over many land areas, cloud increased at least up to the 1970s. IPCC (1990) and (1992) also reported cloud increases.

Has the atmospheric/oceanic circulation changed?

- The behaviour of the El Niño-Southern Oscillation (ENSO), which causes droughts or floods in many parts of the world, has been unusual since the mid-1970s and especially since 1989. Since the mid-1970s, warm (El Niño) episodes have been relatively more frequent or persistent than the opposite phase (La Niña) of the phenomenon. Recent variations in precipitation over the tropical Pacific and the surrounding land areas (e.g., the relatively low rainfall over the subtropical land areas in the last two decades) are related to this behaviour in the El Niño-Southern Oscillation, which has also affected the pattern and magnitude of surface temperatures.

Has the climate become more variable or extreme?

- The data on climate extremes and variability are inadequate to say anything about global changes, but in some regions, where data are available, there have been decreases or increases in extreme weather events and variability.

- Other than the few areas with longer term trends to lower rainfall (e.g., the Sahel), little evidence is available of changes in drought frequency or intensity.

- There have been few studies of variations in extreme rainfall events and flood frequency. In some areas with available data there is evidence of increases in the intensity of extreme rainfall events, but no clear, large-scale pattern has emerged.

- There is some evidence of recent (since 1988) increases in extreme extra-tropical cyclones over the North Atlantic. Intense tropical cyclone activity in the Atlantic has decreased over the past few decades although the 1995 season was more active than recent years. Elsewhere, changes in observing systems and analysis methods confound the detection of trends in the intensity or frequency of extreme synoptic systems.

- There has been a clear trend to fewer extremely low minimum temperatures in several widely separated areas in recent decades. Widespread significant changes in extreme high temperature events have not been observed.

- There have been decreases in daily temperature variability in recent decades, in the Northern Hemisphere mid-latitudes.

Is the 20th century warming unusual?

- Northern Hemisphere summer temperatures in recent decades appear to be the warmest since at least about 1400 AD, based on a variety of proxy records. The warming over the past century began during one of the colder periods of the last 600 years. Data prior to 1400 are too sparse to allow the reliable estimation of global mean temperature. However, ice core data from several sites around the world suggest that 20th century temperatures are at least as warm as any century since at least about 1400, and at some sites the 20th century appears to have been warmer than any century for some thousands of years.

- Large and rapid climatic changes affecting the atmospheric and oceanic circulation and temperature, and the hydrologic cycle, occurred during the last ice age and during the transition towards the present Holocene period. Changes of about 5°C occurred on time-scales of a few decades, at least in Greenland and the North Atlantic.

- Temperatures have been far less variable during the last 10,000 years (the Holocene), relative to the previous 100,000 years. Based on the incomplete observational and palaeoclimatic evidence available, it seems unlikely that global mean temperatures have increased by 1°C or more in a century at any time during the last 10,000 years.

3.1 Introduction

Observed climate change and variability are considered in this chapter by addressing six commonly asked questions related to the detection of climate change and sensitivity of the climate to anthropogenic activity. The questions are:

Has the climate warmed?
Has the climate become wetter?
Has the atmospheric/oceanic circulation changed?
Has the climate become more variable or extreme?
Is the 20th century warming unusual?
Are the observed trends internally consistent?

The conclusions from observations depend critically on the availability of accurate, complete, consistent series of observations. That conclusions regarding trends cannot always be drawn does not necessarily imply that trends are absent. It could reflect the inadequacy of the data, or the incomplete analysis of data. Karl *et al.* (1995a) demonstrate that, for many of the climate variables important in documenting, detecting, and attributing climate change, the data are not at present good enough for rigorous conclusions to be reached. This especially applies to global trends of variables with large regional variations, such as precipitation. The final section of this chapter attempts to indicate our confidence in the various trends observed in the less than complete data available.

3.2 Has the Climate Warmed?

3.2.1 Background

IPCC (1990) concluded that, on a global average, surface air and sea temperature had risen by between 0.3°C and 0.6°C since the mid-19th century. IPCC (1992) confirmed this. The recent warming is re-examined here, using updated and improved data, including the diurnal asymmetry of the warming, and the geographical and vertical structure of the warming. Conventional temperature observations are supplemented by indirect evidence and by satellite-based data.

Temperatures in this chapter are expressed relative to the 1961-90 averages, rather than the 1951-80 period used in IPCC (1990) and (1992). The new reference period has been used because it contains more sea surface temperature data, more data from currently operating land stations, and because it is the official reference period used by the World Meteorological Organisation and member states. Where series from IPCC (1992) are reproduced here they are expressed relative to the 1961 to 1990 mean, not the 1951 to 1980 mean used in IPCC (1992).

3.2.2 Surface Temperature

3.2.2.1 Land-surface air temperature

The land-surface air temperature data base developed by Jones *et al.* (1986a,b) and Jones (1988), and used by IPCC (1990) and IPCC (1992), has been substantially expanded and reanalysed (Jones, 1994a). Coverage in recent decades has benefited most from this expansion. The resulting global anomaly time-series are very similar, on decadal time-scales, to those in the previous (IPCC, 1990, 1992) analyses (Figure 3.1a). The small differences in the time-series are mainly due to the addition of a few extra Australian stations which resulted in warmer late 19th century temperatures, relative to the earlier time-series. The 19th century Australian temperatures may be biased warm relative to modern recordings, because of different methods of exposure (Nicholls *et al.*, 1996). Figure 3.1b shows time-series of global land temperatures updated from Hansen and Lebedeff (1988) and Vinnikov *et al.* (1990), for comparison with the Jones (1994a) time-series.

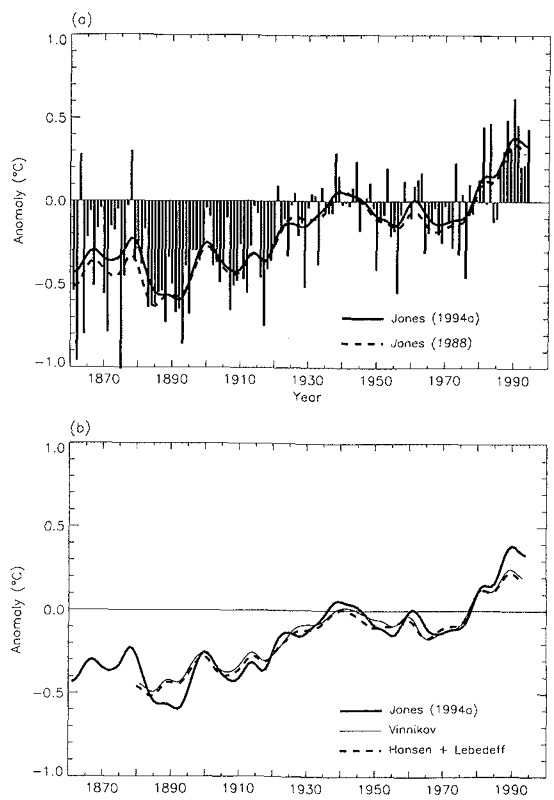


Figure 3.1: **(a)** Annual global average surface air temperature anomalies (°C) for land areas, 1861 to 1994, relative to 1961 to 1990. Bars and solid curve from Jones (1994a); dashed curve from Jones (1988). The smoothed curves were created using a 21-point binomial filter. (b) As (a) but updated from Hansen and Lebedeff (1988) – dashed line; Vinnikov *et al.* (1990) – thin line. Thick solid line is from Jones (1994a), as in (a).

IPCC (1992) cited results of Jones *et al.* (1990) which indicated that urbanisation influences have yielded, on average, a warming of less than 0.05°C during the 20th century in their data over the global land. In specific regions, however, urbanisation influences may be significant. Portman (1993) found that the average warming of 0.22°C between 1954 and 1983 over northern China in the gridded data of Jones *et al.* (1986a) was nearly as large as the 0.25°C warming in this period averaged over seven uncorrected large urban stations; Portman's adjustments using rural stations, however, suggested that there was in fact a regional cooling of about 0.05°C. The urbanisation warming trends were greatest in spring. Differences from Jones *et al.* (1990) and Wang *et al.* (1990), who found a smaller or no urbanisation warming trend in eastern China, may have resulted from the different, though overlapping, region covered. Hulme *et al.* (1994) note that urbanisation cannot fully account for the significant warming trends over eastern Asia. Christy and Goodridge (1994) found that the five longest term Californian stations used by Hansen and Lebedeff (1988) all had more positive temperature trends in 1910–89 than the median of 112 Californian stations. Moberg and Alexandersson (1995) found evidence of urban warming affecting apparent trends in Sweden. On the other hand, Barros and Camilloni (1994) note that the urbanisation effect in Buenos Aires relative to the surrounding rural environment has decreased since the 1950s. Remote sensing techniques hold promise for the eventual worldwide estimation of urban temperature bias (Johnson *et al.*, 1994).

Concerns about a possible link between climate change and desertification indicate the need for monitoring of arid region temperatures. An analysis of the Jones (1994a) gridded temperature anomalies for dryland areas of the world (UNEP, 1992) yielded a significantly greater trend for 1901–1993 (0.62°C) than for the land areas as a whole (0.44°C). Trends for dry lands were greatest in Central and North America (nearly 0.8°C) and least in South America (a little over 0.3°C). They were also significantly greater in the least arid subclass (nearly 0.8°C) than in the most arid subclass (around 0.3°C). The total arid area is only about 14% of the land surface. Even if all the greater warming in these areas was due to desertification, this would only have contributed a few hundredths of a degree to the observed global warming.

3.2.2.2 *Sea surface temperature*

A combined physical-empirical method (Folland and Parker, 1995) has been used to estimate improved adjustments to ships' sea surface temperature (SST) data obtained up to 1941, to compensate for heat losses from uninsulated (mainly canvas) or partly-insulated (mainly wooden) buckets. The time-series of global SST anomalies is very similar to that in IPCC (1992) (Figure 3.2). The differences compared with IPCC (1992) mainly result from an improved formulation of the heat transfers affecting wooden buckets and an improved climatology in the Southern Ocean. This climatology incorporates, for 1982 onwards, satellite-based data, using a Laplacian blending technique (Reynolds, 1988) to remove overall biases relative to the in situ data (Parker *et al.*, 1995). In addition, following Folland and Parker (1995), slightly fewer wooden buckets are assumed than was the case in IPCC (1992), and the SST data in the analysis of Jones and Briffa (1992) are no longer incorporated. The data used to construct the night-time marine air temperature (NMAT) series in Figure 3.2 largely avoid daytime heating of ships' decks and were corrected independently of SST from the mid-1890s onwards (Bottomley *et al.*, 1990; Folland and Parker, 1995). The NMAT data confirm the trends in SST.

Many historical in situ data remain to be digitised and incorporated into the data base, to improve coverage and reduce the uncertainties in our estimates of marine climatic variations. Annual hemispheric and global SST anomalies since 1950 appear to be insensitive to the spatial averaging technique used, to within about 0.02°C (Parker, 1994a).

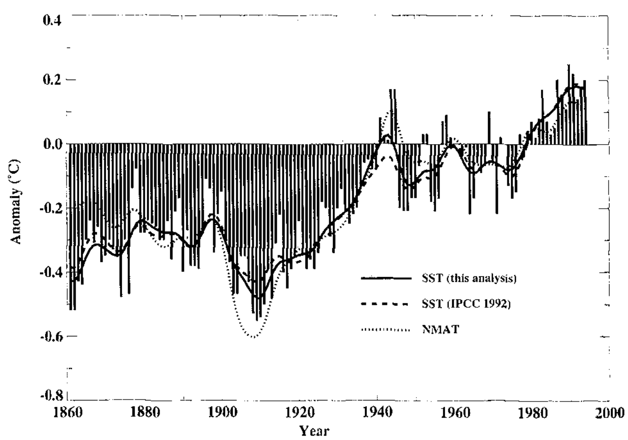


Figure 3.2: Annual global sea surface temperature anomalies (SST, bars and solid curve) and night marine air temperature (NMAT, dotted curve), 1861 to 1994, relative to 1961 to 1990 (°C). The smoothed curves were created using a 21-point binomial filter. The dashed curve is sea surface temperature from IPCC (1992), adjusted to be relative to 1961 to 1990.

But hemispheric and global trends of SSTs calculated over a decade or so are subject to large biases and sampling errors owing to incomplete data coverage, especially in the 19th century and during the period of the World Wars (Karl *et al.*, 1994). The spatial coherence and temporal persistence of seasonal 5° area SST anomalies have been used to estimate the random and sampling errors of decadal SST anomalies (Parker *et al.*, 1994). At the beginning of the century, the estimated combined random and sampling standard errors were generally less than 0.1°C *in those 5° areas with sufficient data to perform an analysis* (about 60% of the world's oceans).

3.2.2.3 Land and sea combined

Comparisons of island air temperatures with SSTs (e.g., Folland and Salinger, 1996) have demonstrated that the two independent fields exhibit similar decadal- and century-scale variations. Figures 3.3a to c show annual time-series of anomalies of combined land-surface air temperature and SST for the hemispheres and globe since 1861. These series, shown as bars and solid curves, differ slightly from those presented by IPCC (1992) which are summarised by the dashed curves, because of the above-mentioned improvements in both land and sea temperatures. Thus, the new curves are typically up to 0.05°C warmer before 1900, but differences are smaller thereafter.

In accord with IPCC (1990), global average land-surface air temperature anomalies exceeded SSTs by around 0.1°C in the 1920s and up to 0.2°C in recent years, but were up to 0.3°C lower in the 1880s (Figure 3.3d). Real atmospheric circulation changes, as well as some instrumental uncertainties, are likely to be the cause of this variation (Parker *et al.*, 1994).

A variety of tests (Parker *et al.*, 1994) suggests that the sampling uncertainty on the smoothed curves in Figure 3.3 is possibly within 0.05°C since the 1880s. However, these findings take no account of unsampled regions so a trend uncertainty of 0.1°C/century may be more realistic (Karl *et al.*, 1994). The instrumental bias uncertainty is assessed by Parker *et al.* (1994) as less than 0.1°C for land, around 0.1°C for SST, and less than 0.15°C for the combination, since the 1880s, consistent with preliminary estimates in IPCC (1992). In addition, an urbanisation uncertainty of less than 0.05°C is estimated (Section 3.2.2.1). The overall uncertainty remains about 0.15°C and leads to an estimate of 0.3 to 0.6°C for global near-surface warming since the late 19th century, unchanged from the estimates of IPCC (1990, 1992).

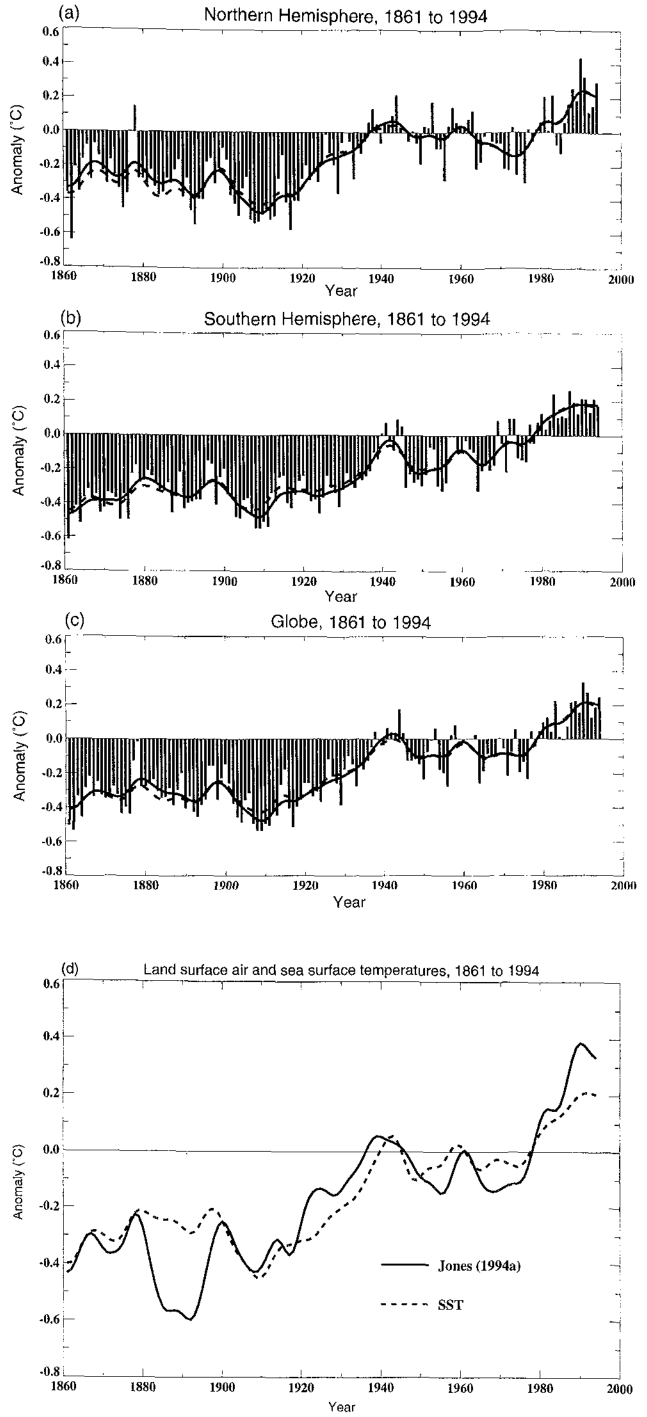


Figure 3.3: Combined annual land-surface air and sea surface temperature anomalies (°C) 1861 to 1994, relative to 1961 to 1990 (bars and solid smoothed curves): (a) Northern Hemisphere; (b) Southern Hemisphere; (c) Globe. The dashed smoothed curves are corresponding results from IPCC (1992), adjusted to be relative to 1961 to 1990. (d) Global land-surface air temperature (solid line) and SST (broken line).

Figure 3.4 shows the change of surface temperature, for the four seasons as well as for the annual averages, from the period 1955–1974 to the period 1975–1994. This second period has seen unusual ENSO activity (Section 3.4.2). Note, in accord with the results in IPCC (1990) and IPCC (1992), the recent warming over the mid-latitude Northern Hemisphere continents in winter and spring, and year-round cooling in the north-west North Atlantic and mid-latitudes over the North Pacific.

Zonal mean anomalies of combined land-surface air temperature (from Jones, 1994a) and SST (from Parker *et al.*, 1995), shown in Figure 3.5, confirm that the recent warmth is greatest in mid-latitudes of the Northern Hemisphere. This can be compared with the warm period of the mid-20th century, where the greatest warmth was in the higher latitudes of the Northern Hemisphere. The recent warm period also exhibits higher temperatures in the Southern Hemisphere. It should be noted that the anomalies in Figure 3.5 are less reliable in data sparse areas and periods, e.g., before 1900, during the World Wars, and in the Southern Ocean.

Figure 3.4 shows that maximum recent warming has been in winter over the high mid-latitudes of the Northern Hemisphere continents. Tropospheric data show no statistically significant Arctic-wide temperature trends for the 1958–86 period or during the 1950-90 period over the Arctic Ocean (Kahl *et al.*, 1993a,b). Significant warming since the 1950s along the west coast of the Antarctic Peninsula is not representative of continental Antarctica (Raper *et al.*, 1984; King, 1994), where weaker warming has been observed. However, expeditionary records (Jones, 1990) and ice temperature profiles (Nicholls and Paren, 1993) suggest 20th century warming for various parts of Antarctica, and Jones (1995a) reported an Antarctic warming trend from 1957 to 1994, although temperatures were low in 1993 and 1994. All of this warming occurred before the early 1970s.

3.2.2.4 Changes in the diurnal temperature range

An analysis of worldwide quality-selected station monthly average maximum (day) and minimum (night) temperatures (Horton, 1995) now covers about 41% of land areas. It confirms the report of IPCC (1992) and the findings of Karl *et al.* (1993a) that worldwide increases in minimum land-surface air temperature since 1950 have been about twice those in the maximum (Figure 3.6).

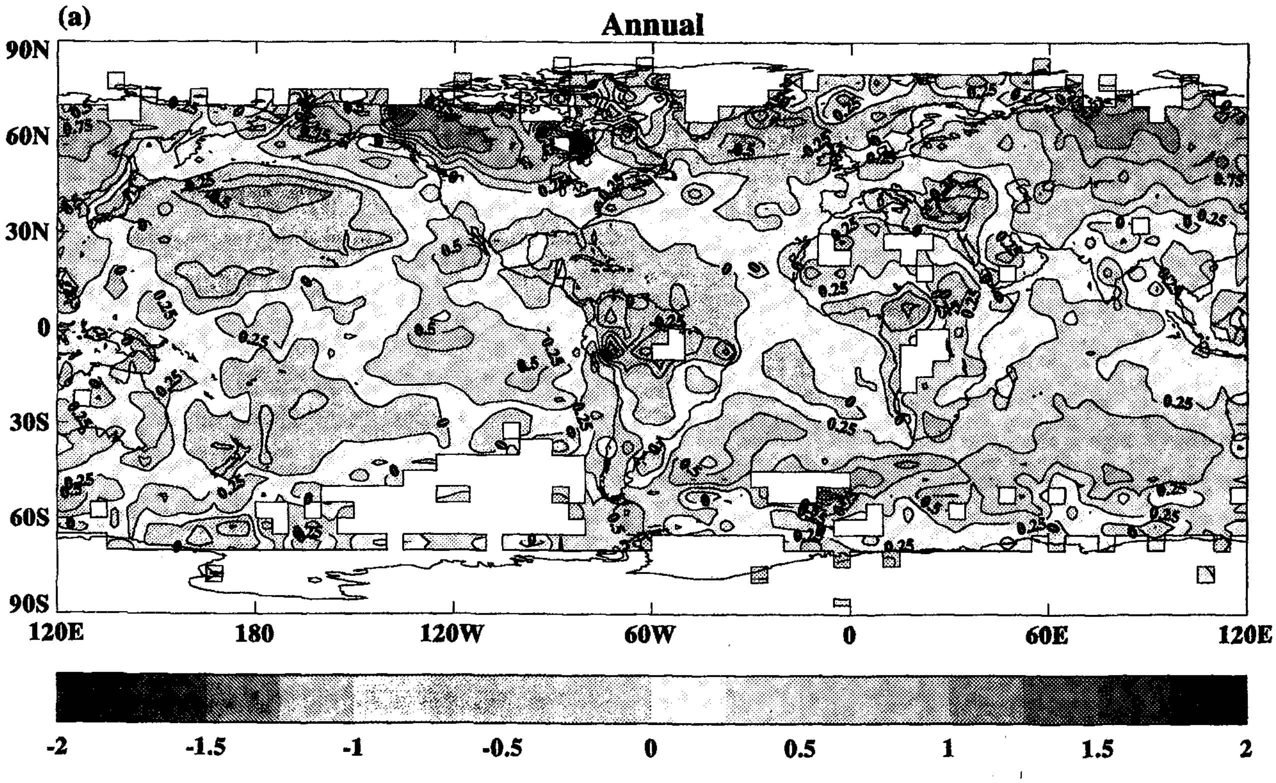


Figure 3.4: Change in surface temperature (°C), from 1955–1974 to 1975–1994: (a) annual; (b) December to February; (c) March to May; (d) June to August; (e) September to November. Sea surface temperatures are from Parker *et al.* (1995) and land-surface air temperatures are from Jones (1994a).

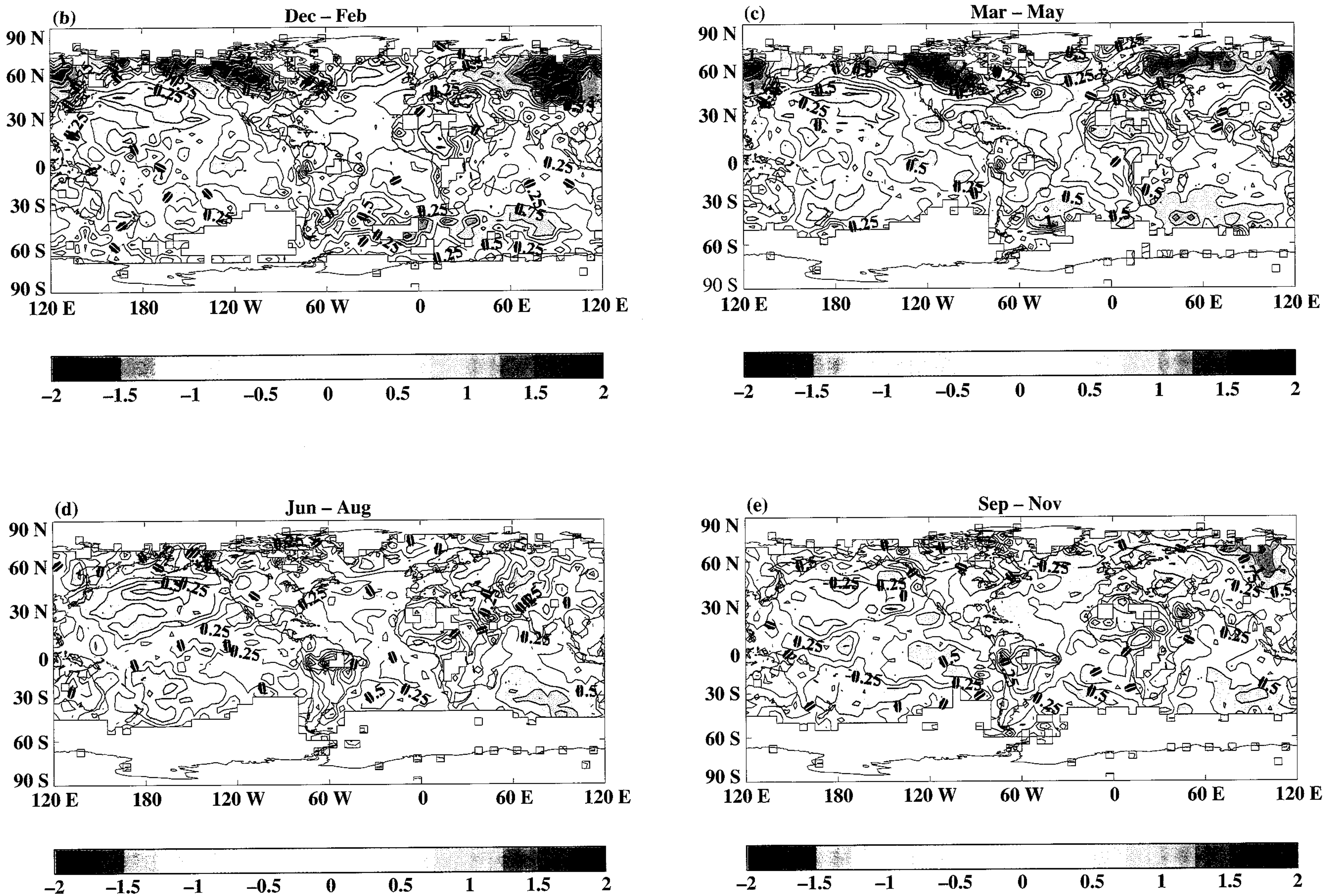


Figure 3.4: *cont.*

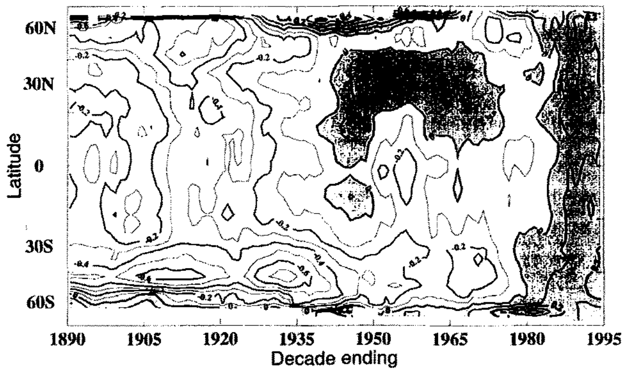


Figure 3.5: Zonal mean combined land-surface air and sea surface temperature anomalies (°C), 1881 to 1994, relative to 1961 to 1990. Values are 10-year running means. Data are updates of Parker *et al.* (1995) for SST and Jones (1994a) for land.

Additional areas with decreasing diurnal temperature range (DTR) have been identified (e.g., Jones, 1995b). The decrease of the DTR in several areas has been most pronounced in the Northern Hemisphere autumn (Karl *et al.*, 1993a; Kukla and Karl, 1993; Horton, 1995). The observed decreases in the DTR have been found to relate to increases of cloud cover (Plantico *et al.*, 1990; Henderson-Sellers, 1992; Dessens and Bücher, 1995; Jones, 1995b; Kaas and Frich, 1995; Plummer *et al.*, 1995; Salinger *et al.*, 1995b). The decrease of the DTR has mostly but not always been due to the faster rise of the night temperatures. The general increases in minimum (overnight) temperature occurred in rural areas as well as cities, and could not therefore simply reflect an increasing urban heat island effect. In the south-western part of the former Soviet Union, DTR has decreased because of depressed daily maxima (Razuvaev *et al.*, 1995).

Some coastal and island areas (Horton, 1995; Salinger *et al.*, 1993, 1995b), India (Rupa Kumar *et al.*, 1994), and alpine stations (Weber *et al.*, 1994) have shown no long-term decrease in annual average DTR. No systematic changes of minima or maxima and no general warming has been observed in the Arctic over the last 50 years or so (Kahl *et al.*, 1993a,b; Michaels *et al.*, 1995; Ye *et al.*, 1995), though regions with reduced DTR in recent decades do include Alaska and central Siberia (Figure 3.6).

3.2.3 *Tropospheric and Lower Stratospheric Temperatures*

Climate monitoring has focused on measurements at the Earth's surface; only in the past few decades has the atmosphere above the surface been regularly measured. Regular upper-air measurements by balloon ascents in scattered locations began in the 1940s and observations from satellites generally only began in the 1970s.

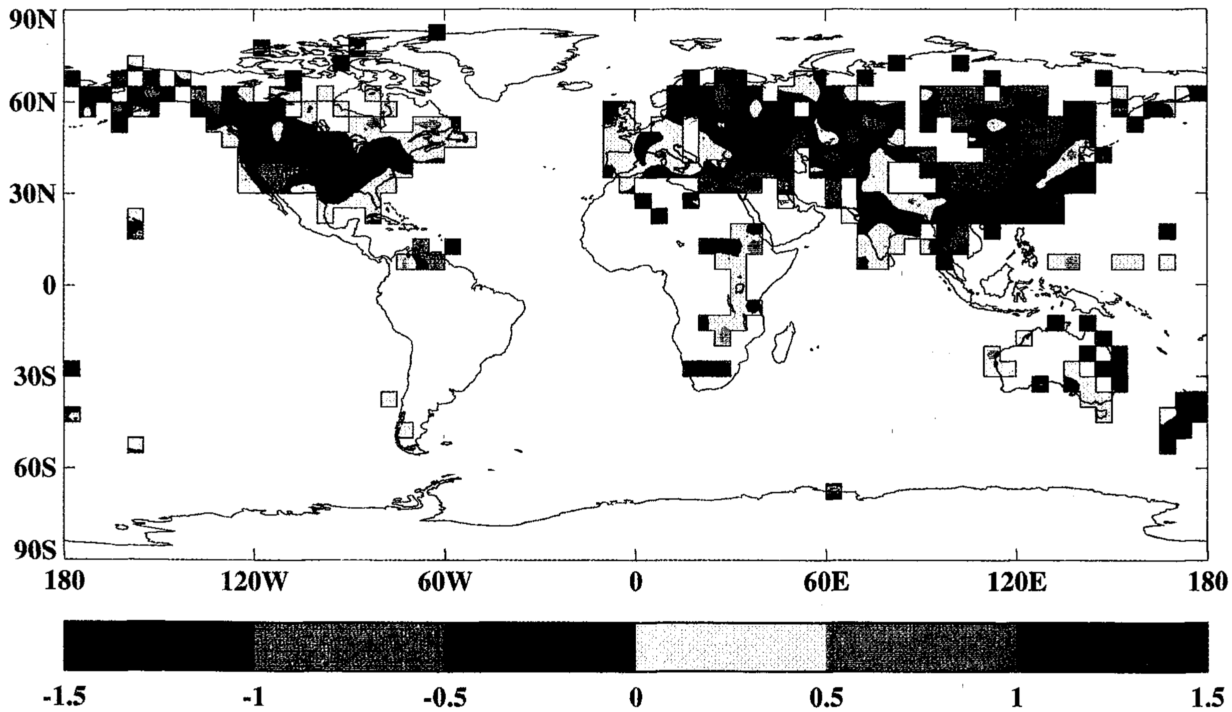


Figure 3.6: Diurnal temperature range 1981 to 1990 relative to 1951 to 1980 (°C).

3.2.3.1 Data reliability

IPCC (1992) presented radiosonde data since 1964, whereas here data from 1958 are presented. There are doubts, however, about the earlier data. Although the radiosonde coverage was adequate from 1958 in the Northern Hemisphere, it has only been adequate in the Southern Hemisphere since 1964. "Global" values from radiosondes from before 1964 are, therefore, somewhat suspect, because of the reduced geographical coverage.

Compilations for monitoring long-term changes of temperature aloft using radiosondes have been made by Angell (1988 and updates) and by Oort and Liu (1993). However, the sensors which measure temperature and humidity in radiosondes have undergone many changes in the past 40 years, and these changes have had significant effects on estimates of long-term trends (Gaffen, 1994; Parker and Cox, 1995). Humidity is important both on its own account (Section 3.3.7) and because it affects air density, which is often used as a surrogate for temperature. Elliott *et al.* (1994) calculate that spurious "drying" of the mid-troposphere (850-300 hPa) due to improved radiosonde sensors has led to a spurious cooling since 1958 of 0.05 to 0.1°C/decade. This spurious cooling is primarily related to sensor changes in the 1970s. An additional aspect of uncertainty is related to the non-uniform geographic distribution of stations since vast areas over the oceans, particularly in the Southern Hemisphere, are not monitored at all (Trenberth and Olson 1991), and coverage has declined over the oceans and parts of the tropics (Parker and Cox, 1995).

While information on changes in radiosonde sensors is rarely complete, Gaffen (1994) reported on the effects of documented changes in the temperature sensors and found that at least 43% of the stations used by Angell have clear heterogeneities. Oort and Liu's data will also have been affected. The net effect of these heterogeneities was to impose a spurious cooling trend (in addition to that from the humidity sensors noted above) on the time-series since 1958. The magnitude of the tropospheric impact appears to be small. However, the lower stratospheric time-series was found to have been significantly affected, particularly in the tropics and Southern Hemisphere, so as to bias the trend calculation to be cooler than actual. In addition Parker and Cox (1995) suggest that early radiosonde balloons were more likely to burst in cold conditions, biasing the incomplete data towards warmth, and giving a spurious cooling trend in the lower stratosphere as balloons were strengthened. Angell's global lower-stratospheric radiosonde time-series cooled since 1979 at about 0.6°C/decade relative to global satellite (Microwave Sounding Units (MSUs) on polar orbiting satellites) data. The relative cooling is less if only MSU data collocated with the radiosondes (rather than global MSU data) are used in the comparison, and trends in the Oort and Liu data (using more stations than Angell, but available only up to 1989) are more similar to those in the MSU, so the greater cooling in Angell's data appears to be due to undersampling of the global atmosphere (Christy, 1995), as well as to radiosonde inhomogeneities.

The MSU data, available since 1979, have exhibited high precision and global coverage for the temperature of deep layers in the troposphere and stratosphere (Spencer and Christy, 1992b, 1993). Biases because of water vapour and cloud changes have been shown to be minimal (Spencer *et al.*, 1990), although some uncertainty remains (Prabhakara et al., 1995). In addition, Spencer and Christy (1992a,b; 1993), Christy and Drouilhet (1994), and Christy and Goodridge (1995) used comparisons between satellites and with radiosondes to show that instrumental drift was insignificant until late 1991.

There has, however, been a spurious warming of 0.04°C/yr in NOAA 11[1] tropospheric data since 1990, owing to a drift in orbit times. An estimate of this bias, along with biases affecting the dynamic range of NOAA 12 MSU temperatures, has been removed from results shown here (Christy *et al.*, 1995).

3.2.3.2 Tropospheric trends

Figure 3.7a shows time-series of tropospheric temperature anomalies calculated from MSU data and radiosondes, and the global surface temperature for comparison. The global MSU tropospheric trend from 1979 to May 1995 was –0.06°C/decade, and that for the seasonal radiosonde data for the same period was –0.07°C/decade. However, if the transient effects of volcanoes and the El Niño-Southern Oscillation (which can bias trends calculated from short periods of data) are removed from the various time-series, positive trends become evident (e.g., 0.09°C/decade for MSU), in closer accord with surface data (Christy and McNider, 1994). Jones (1994b) calculated residual global trends (after removal of volcanic and ENSO transients) for the 1979–93 period of 0.09°C/decade from MSU data, 0.10°C from 850-300 hPa radiosonde temperature updated from Angell (1988), and 0.17°C from combined land-surface air temperature and SST data. The differences between these trends were about half the differences between trends in the raw data (i.e., without the removal of the transient El Niño-Southern Oscillation and volcanic

[1] NOAA 11 and NOAA 12 are USA weather satellites, launched in September 1988 and May 1991 respectively.

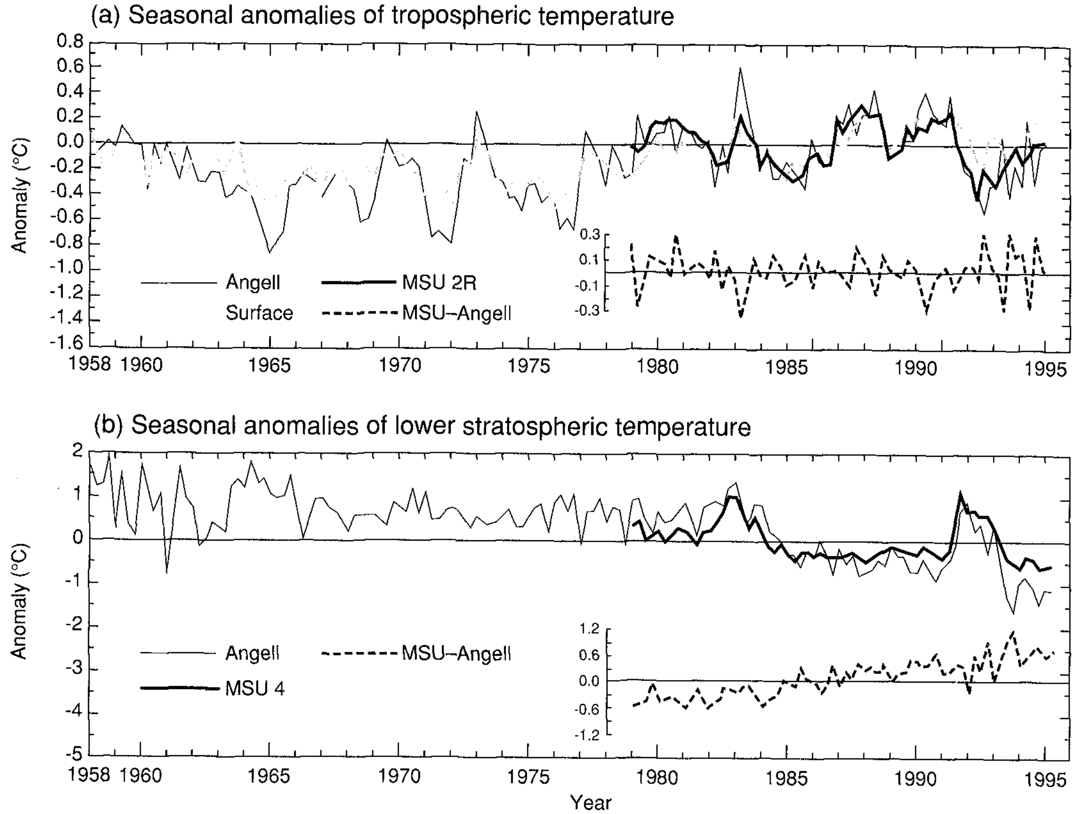


Figure 3.7: (a) Seasonal global temperature anomalies (°C), relative to 1979–1994 average, for the 850-300 hPa layer from radiosondes (Angell, 1988 and updates, light solid line) and for the troposphere from MSU 2R (Spencer and Christy, 1992b and updates, heavy solid line). Dashed line (inset) is MSU 2R minus radiosondes. Surface temperatures (shaded line) have been added for comparison with the tropospheric temperatures. (b) As in (a), but for the 100–50 hPa layer from radiosondes (Angell, 1988 and updates, light solid line) and for the lower stratosphere from MSU 4 (Spencer and Christy, 1993 and updates, heavy solid line). Dashed line (inset) is MSU 4 minus radiosonde. (Note: MSU 2R and MSU 4 are channels of the MSU instrument designed to sample the lower troposphere and stratosphere respectively.)

effects). So, apparent differences between surface and tropospheric trends for 1979–1993 appear to be partly a result of the greater influence of volcanic eruptions and ENSO on tropospheric temperatures. Hansen *et al.* (1995) also demonstrate that natural variability can account for some of the apparent differences between surface and lower tropospheric data.

For the longer period 1958 to 1993, Jones (1994b) found that the unadjusted and adjusted global trends from radiosonde and surface data were all between 0.08°C and 0.11°C/decade, reflecting the fact that longer-term trends are less likely to be biased by transient volcanic and ENSO influences. The unadjusted radiosonde trend to May 1995 was 0.09°C/decade. The similarity of the trends since the late 1950s in the tropospheric and surface temperatures is evident in Figure 3.7a.

3.2.3.3 Lower stratospheric trends

Lower stratospheric temperatures (17–22 km or 100–50 hPa) have demonstrated marked changes over the past few decades (Figure 3.7b). Sudden warmings were caused by infrared-absorbing aerosols from volcanoes (Nyamuragira 1981 with El Chichon 1982, and Mt. Pinatubo 1991). From 1979 through May 1995, the MSU global trend was –0.34°C/decade. The greater cooling in the radiosonde data is at least partly due to changes in the radiosondes and undersampling of the global atmosphere, for the reasons outlined in Section 3.2.3.1. A similar rate of cooling (–0.36°C/decade) has probably occurred since 1964, based on radiosonde data (Christy, 1995). Labitzke and van Loon (1994) examined daily historical analyses of the Northern Hemisphere lower stratosphere and concluded that the cooling was greatest at a height of 18–20 km at all latitudes in summer, and in the polar regions also in early winter.

Lower stratospheric trends are discussed in more detail in IPCC (1994) and the 1994 Ozone Assessment (WMO, 1994). The current (1994) global stratospheric temperatures are the coolest since the start of the instrumental record in both the satellite and radiosonde data.

3.2.4 Subsurface Ocean Temperatures

The deep ocean has a much lower noise level of temperature variability than at the surface, and hence long-term changes are more readily identified. Recent studies (e.g., Bindoff and Church, 1992; Bindoff and McDougall, 1994) have demonstrated that changes in water mass properties (salinity/temperature relationships) are even easier to detect.

Studies are beginning to indicate large-scale and coherent changes in subsurface conditions that appear to be related to changes, at the surface, in the formation regions of the relevant water masses. These lead to large, coherent regions of overlying layers of warming and cooling in the water column. The geographical variations in recent surface temperature changes (Figure 3.4) are linked to the subsurface changes. The surface changes can mix and advect downward with a strong component moving along surfaces of constant density.

In the Southern Hemisphere, Salinger *et al.* (1995b) report a basin-wide, depth-averaged warming of 0.3°C between 100 m and 800 m over the entire width of the Indian Ocean at 30°S over the past 20 years. Below this there was a depth-averaged cooling of up to 0.1°C. Bindoff and Church (1992) found warming in the upper 800 m at 43°S in the south-west Pacific between 1967 and 1989. Bindoff and McDougall (1994) inferred that the change between 300 m and 700 m resulted from warming at the surface where the water masses were formed during contact with the atmosphere. It appears that the upper ocean warming of these two basins is a reflection of the surface warming at the surface at latitudes of 40–50°S. The cooling at greater depth in the Indian Ocean appears to be a reflection of surface cooling at higher latitudes where there is poor surface coverage.

Recent transocean sections in the North Pacific are also beginning to reveal changes in subsurface temperatures reflecting surface temperature changes. Off California (a region of surface warming), subsurface temperatures have increased uniformly by 0.8°C in the upper 100 m in the past 42 years, and have risen significantly down to 300 m. Cooling of the surface of the central and western North Pacific is seen to depths of several hundred metres (Antonov, 1993).

In the North Atlantic, warming has occurred at 24°N in the subtropical gyre, with warming of up to 0.15°C between 800 m and 2500 m between 1957 and 1981 (Roemmich and Wunsch, 1984). A similar warming ensued between 1981 and 1992 (Parrilla *et al.,* 1994). The overall warming between 1957 and 1992 was very uniform across the Atlantic, averaging just over 0.3°C at 1100 m. Warming of 0.2°C has been observed since the late 1950s in the subtropical gyre at 1750 m near Bermuda (Levitus *et al.*, 1995).

Strong cooling at the surface of the subpolar North Atlantic connects with the subsurface ocean in the Labrador Sea, where a 0.9°C cooling of Labrador Sea Water has occurred between 1970 and 1995. This water mass is currently colder, fresher, and larger than ever before recorded, in observations extending back to the 1930s (Read and Gould, 1992; Lazier, 1995; Rhines and Lazier, 1995).

These subsurface variations are consistent with circulation and surface temperature variations.

3.2.5 Indirect Measures

A variety of indirect measures can provide supporting evidence of changes and variations in temperature. In general, however, these measures are affected by other factors as well as temperature, so care needs to be taken in determining the extent to which they provide supporting evidence of changes deduced from direct measurements of temperature.

3.2.5.1 Retreat of glaciers

Mountain glaciers provide integrated climatic evidence which is complementary to instrumental meteorological measurements (Haeberli, 1995). Measurements of glacier length extend back to the 19th century in many regions, and even to 1600 AD in Europe. Length reduction of mountain glaciers provides easily detectable evidence from cold regions that fast and worldwide climatic change has taken place over the past century (Haeberli *et al.,* 1989). The factors affecting glaciers, and a description of observed changes over the past century, are discussed in Chapter 7. The 20th century glacier retreat is consistent with a warming in alpine regions of 0.6–1.0°C (Schwitter and Raymond, 1993; Oerlemans, 1994).

3.2.5.2 Borehole temperatures

Underground temperatures, from boreholes in otherwise undisturbed locations, have been used to derive ground surface temperature (GST) histories which are found to be in accord with instrumental or proxy surface air temperature data. Low-frequency surface temperature variations occurring in the past 300 years can be detected in a borehole over 600 metres deep.

Warming has been observed in most boreholes in New England (Pollack and Chapman, 1993) and Canada (Beltrami and Mareschal, 1992; Wang *et al.*, 1992; Wang *et al.*, 1994), and the increase in GST suggested for the last century is very similar to the observed change in regional air temperatures during the same period (e.g., Beltrami and Mareschal, 1991). In temperate western North America (up to 62°N in the Yukon), however, the GST has remained relatively constant over the last century (e.g., Lewis and Wang, 1993) even though most glaciers have retreated. Further north, GSTs have increased over the last century on the Alaskan north slope (Judge *et al.*, 1983; Lachenbruch and Marshall, 1986) and in Canada's north-eastern Arctic Islands (Taylor, 1991), and there has been a retreat of the permafrost (Kwong and Gan, 1994). There are indications of increasing GSTs in the northern USA prairies (Gosnold *et al.*, 1992) and the Canadian prairies (Majorowicz, 1993). Cermak *et al.* (1992) have reported climatic warming in Cuba of 2-3°C over the last 200–300 years. Some borehole sites have indicated no recent change or cooling, e.g., in Utah (Chapman *et al.*, 1992). Deming (1995) assessed all the North American studies and concluded that all averages inferred from groups of boreholes revealed warming (ranging between 0.3 and 4.0°C) since the 19th century. The warming appears to have started in the middle of the 19th century in the eastern half of North America, whereas the warming in the west appears to have started near the beginning of the 20th century or even later.

In France, Mareschal and Vasseur (1992) made independent analyses of two boreholes and derived similar GST histories with peak warmth around 1000 AD, cooling to a minimum at 1700 AD, and warming starting at 1800 AD (see Section 3.6.2). Borehole temperatures also indicate increasing GST over the last century or two in Australia (Hyndman *et al.*, 1969) and the Ukrainian Shield (Diment, 1965), but an influence of deforestation was suspected. Where no ice was present in western Siberia, analyses indicate the most recent warming started 400 years ago in the south, and much earlier in the north (Duchkov and Devyatkin, 1992). Borehole measurements in New Zealand (Whiteford, 1993; Whiteford *et al.*, 1994) indicate cooling to a minimum around 1800 AD, followed by warming averaging 0.9°C over the past century.

Borehole temperature studies have also been conducted on ice sheets, and, especially those in Arctic regions, clearly show a warming since a cool period in the 1800s (e.g., Cuffey *et al.*, 1994).

3.2.5.3 Sea ice extent and mass

Neither hemisphere has exhibited significant trends in seaice extent since 1973 when satellite measurements began

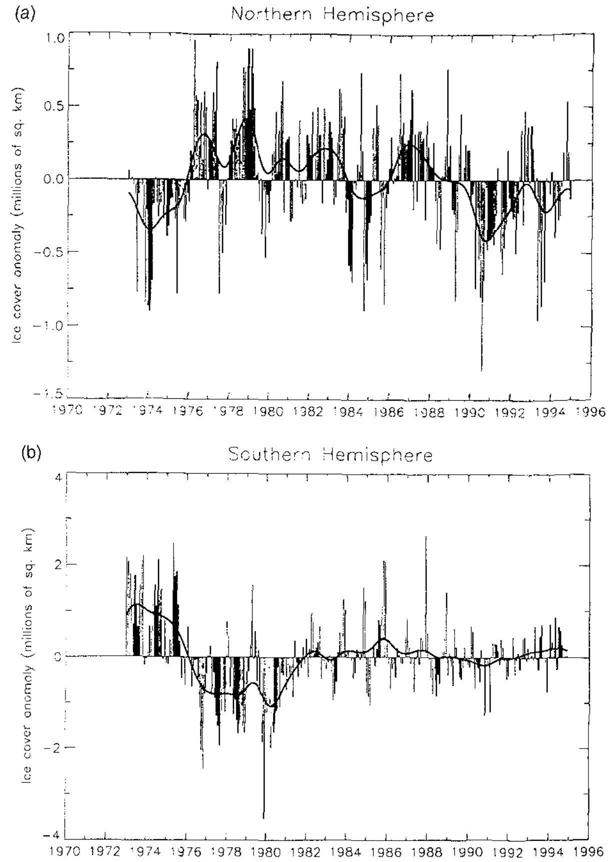


Figure 3.8: Sea ice extent anomalies relative to 1973–1994 for (a) the Northern Hemisphere and (b) the Southern Hemisphere. Data from NOAA (USA). Smooth lines generated from a 128-point binomial filter applied to the monthly anomalies. Heavy bars represent December–February in the Northern Hemisphere or June–August in the Southern Hemisphere.

(Figure 3.8). There has been below average extent in the Northern Hemisphere in the early 1990s, except for the second half of 1992 when the atmosphere was cooler. Coverage in the Southern Hemisphere has remained close to average. Jones (1995a) noted that the lack of sea ice variations around Antarctica seems unconnected to regional temperatures. For instance, sea ice did not increase during 1993 and 1994, despite low temperatures.

Sea ice total mass may be a more sensitive indicator of climate change than extent alone. Limited data on Arctic ice thickness, from upward sonar profiling from submarines and from moored subsurface sonar instruments, show large interannual variability but no trends from 1979 to 1990 (McLaren *et al.*, 1992).

3.2.5.4 Coral bleaching

Bleaching of coral reefs may result from high temperatures or from other environmental stresses, e.g., pollution episodes. IPCC (1992) found the increased incidence of bleaching to be consistent with oceanic warming. Goreau and Hayes (1994) have shown that coral bleaching events since 1979 have been closely associated with warm-season sea surface temperature anomalies of 1°C or more. Bleaching events were, as a consequence, more prevalent in 1983, 1987 and 1991 in association with El Niño warming events, and scarce in 1992 following the eruption of Mt. Pinatubo and the subsequent cooling. Published records of coral reef bleaching from 1870 to the present suggest that the scale of bleaching since 1979 has not been observed previously (Glynn, 1993).

3.2.6 Mt. Pinatubo in the Temperature Record

Following the eruption of Mt. Pinatubo in June 1991, clear-sky solar radiation incident at the Earth's surface was reduced by about 3% for several months because of aerosol scattering (Dutton and Christy, 1992). Global tropospheric temperature anomalies cooled until August 1992 and then warmed in an irregular fashion (Figure 3.7a; see also Section 5.3.1.2). In the 16-year MSU lower troposphere time-series the coolest seasonal anomalies of the entire record occurred for the Northern Hemisphere in summer 1992 and for the Southern Hemisphere in summer 1992–3. Temperatures have increased since then, to levels similar to those prior to the eruption.

Seasonal series of land-surface air temperatures indicate that the cooling in 1992, which probably resulted from the Mt. Pinatubo eruption, was particularly marked in summer and autumn in the Northern Hemisphere. Robock and Mao (1995) found that this maximum cooling pattern, in the Northern Hemisphere summer of the year after the eruption, agrees with that after the five other largest volcanic eruptions since 1883. The winter warming pattern over the Northern Hemisphere continents in 1991–92 appears to be an indirect, dynamical response to the tropical stratospheric warming after the eruption (Graf *et al.*, 1993).

The rapid fall of globally averaged lower stratospheric temperature, as the aerosols dispersed, from the Mt. Pinatubo-induced peak in September 1991 to the minimum in late November 1993, represents a temperature change of about 2°C in just 28 months, with a 1.5°C cooling of seasonal averages (Figure 3.7b).

3.2.7 Possible Shift of Phase of the Annual Temperature Cycle

An analysis of monthly mean Central England Temperatures (CET) over the period 1659–1990 by Thomson (1995) indicated that there has been an observable phase shift in the mean annual cycle, implying, for example, a shift of peak summer temperature from about 20 July to about 25 July. In addition, the rate of this phase shift appeared to have increased after 1940. Thomson also found such a shift in some, but not all, Northern Hemisphere stations with long records. Emslie and Christy (1995), however, could not confirm the apparent change in the phase trend in the CET. In addition, Karl *et al.* (1995b) concluded that the vagaries of weather could produce the phase shifts found by Thomson (1995) over century-scale periods.

3.2.8 Summary of Section 3.2

Global surface temperatures have warmed by 0.3–0.6°C since the late 19th century, with the greatest warming over the continents between 40°N and 70°N. A general, but not global, tendency to reduced diurnal range has been confirmed. Minimum temperatures have, in general, increased faster than maximum temperatures. As predicted in IPCC (1992) relatively cool surface and tropospheric temperatures, and a relatively warmer lower stratosphere, were observed in 1992 and 1993, following the 1991 eruption of Mt. Pinatubo. Warmer temperatures reappeared in 1994, with the global surface temperature for the year being in the warmest 5% of years since 1860, about 0.27°C higher than the 1961–90 mean.

Long-term variations in tropospheric temperatures, measured by radiosondes, have been similar to those in the surface record since the 1950s. More work has been done in comparing recent radiosonde and Microwave Sounding Unit observations of tropospheric temperature with surface temperatures, since IPCC (1992). Radiosonde and Microwave Sounding Unit observations of tropospheric temperature show slight overall cooling since 1979, whereas global surface temperature has warmed slightly over this period. After adjustment for the transient effects of volcanic activity and ENSO (which can bias trends calculated from short periods of record), both tropospheric and surface data show slight warming since 1979.

Indirect measures of temperature, such as borehole temperatures and glacier data, are in substantial agreement with the direct indicators of recent warmth. Sea ice extent does not show noticeable trends over the 22 years of available satellite data, although Northern Hemisphere sea ice has been below average in the early 1990s. Subsurface ocean measurements appear to be consistent with the geographical pattern of surface temperature changes.

3.3 Has the Climate Become Wetter?

3.3.1 Background

An enhanced greenhouse effect may lead to changes in the hydrologic cycle such as increased evaporation, drought, and precipitation. Unfortunately, our ability to determine the current state of the global hydrological cycle, let alone changes in it, is hampered by inadequate spatial coverage, inhomogeneities in climate records, poor data quality, and short record lengths. Nonetheless, some new aspects of changes and variations of the hydrological cycle have begun to emerge.

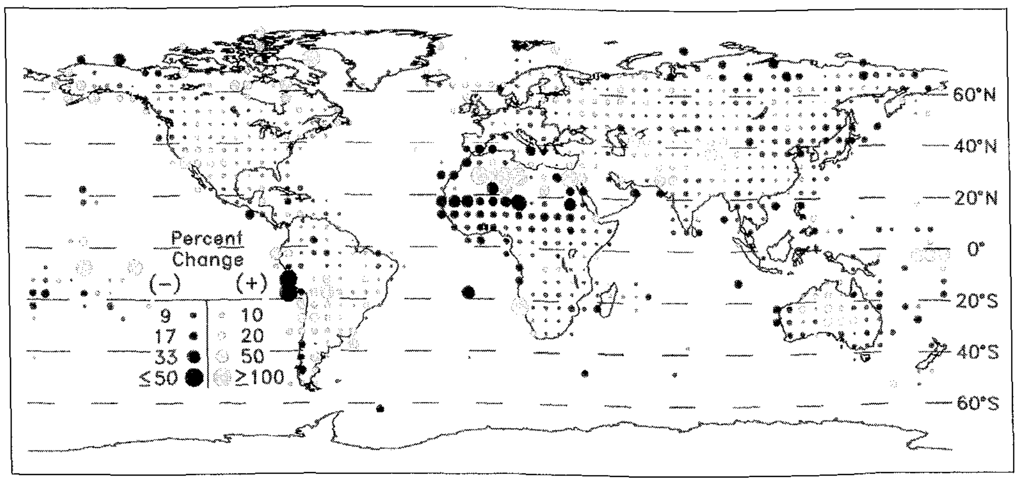
3.3.2 Precipitation

3.3.2.1 Land

IPCC (1990) concluded that precipitation over land was generally increasing in the extra-tropical areas, with a tendency for rainfall declines in the subtropics. It was noted in IPCC (1992) that precipitation over land is generally underestimated, typically by 10 to 15%, and that progressive improvements in instrumentation have introduced artificial, systematic increases in estimates of precipitation, particularly where snow is common. Nonetheless, the most reliable and useful measurements of multi-decadal precipitation variations are still these station data.

Figure 3.9a shows the change in precipitation from 1955–1974 to 1975–1994, expressed as a percentage of the 1955 to 1974 precipitation. The recent low rainfall in the Sahel is evident. Longer term trends in precipitation are

(a)



(b)

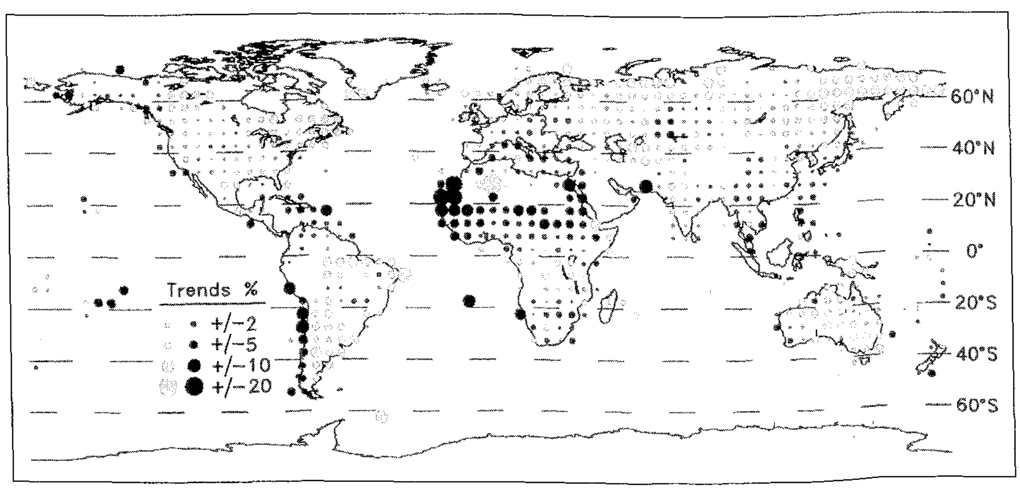


Figure 3.9: Precipitation changes based on the mean change from two data sets: "Hulme" (Hulme 1991; Hulme *et al.*, 1994) and the "Global Historical Climate Network-GHCN" (Vose *et al.*, 1992; Eischeid *et al.*, 1995). (a) Change in precipitation over land from 1955–1974 to 1975–1994, for 5° latitude by 5° longitude grid cells. Change expressed as percentage of 1955 to 1974 mean. (b) Trend in precipitation over land from 1900 to 1994. Average of trends from Hulme *et al.* (1994) and Eischeid *et al.* (1991) data sets. Trend (%/decade) expressed as percentage of the 1961 to 1990 mean from Hulme and 1951 to 1980 mean from GHCN. Magnitudes of the trends are depicted by the areas of the circles; shaded circles show increases; solid circles show decreases.

shown in Figure 3.9b. The 20th century rise in precipitation at high latitudes is clear, along with the decreases over the northern tropics of Africa. These trends are supported by regional and country studies, some of which have taken into account time-varying biases of precipitation measurements.

Groisman *et al.* (1991) evaluated information on the history of gauges and observational procedures over the former Soviet Union. Using this information they adjusted the measured precipitation for changes in instrumentation. Their adjusted data still show substantial increases of annual precipitation (~10%/100yr). The increase has been larger during winter than in summer. Much of the increase has been due to increases in the first half of the 20th century with a tendency for reduced precipitation in some areas since the middle of the century.

In North America annual precipitation has increased (Karl *et al.*, 1993b; Groisman and Easterling, 1994). The increase in the contiguous USA is most apparent after 1950 and is in large part due to increases during the autumn (September to November). Positive trends are apparent throughout much of northern Canada and Alaska during the past 40 years (Groisman and Easterling, 1994). Twentieth century station data over southern Canada and the northern USA (45–55°N) indicate increases of precipitation of 10–15%, with increases of about 5% averaged across the contiguous USA. Increases are more prevalent in the eastern two-thirds of North America (Findlay *et al.*, 1994; Lettenmaier *et al.*, 1994).

Precipitation changes in Europe (not including the former Soviet Union European countries) during the past century are latitudinally dependent. Time-varying measurement biases have been addressed in several countries (Hanssen-Bauer and Førland, 1994), where they are likely to be most serious (Karl *et al.*, 1993b). Overall, the data suggest an increase of precipitation in northern Europe and a decrease in southern Europe during the 20th century. In northern Europe (north of 55°N) Hanssen-Bauer *et al.* (1990) and Jónsson (1994) report an increase of precipitation since the 1960s for the Norwegian Arctic islands and Iceland while increasing precipitation has also been observed over the Faroe Islands (Frich, 1994). Denmark has had similar changes (Brázdil, 1992). West of the Scandinavian mountains increases have been reported (Frich, 1994; Hanssen-Bauer and Førland, 1994), but not in Finland (Heino, 1994). There is strong seasonality associated with the increases as they are in large part due to the changes during the autumn. In central Europe no significant positive trends have been observed over the past century (Brázdil, 1992). In southern Europe decreases tend to dominate (e.g., Palmieri *et al.*, 1991; Dahlström, 1994), but with some evidence for increased autumn precipitation over the maritime portions of south-western Europe (Mendes, 1994).

A long (1757–1992) record of areal average precipitation over Scotland has been analysed (Smith, 1995). This data set is believed to be consistent back to at least 1869. Annual precipitation has increased significantly, especially since the late 1970s, although summer rainfall has decreased. The recent increased precipitation is the largest sustained anomaly in the record.

Time-varying precipitation biases in the tropics and subtropics are not as severe as those in the mid- and high latitudes where higher wind speeds, smaller droplet size, and frozen precipitation all contribute to higher biases. The 20th century increase in precipitation in high latitudes is not matched by increases through the continental tropical and subtropical climates. Precipitation decreases, especially since mid-century, dominate large regions of the tropics and subtropics from North Africa east to Southeast Asia and Indonesia (Figures 3.9 and 3.10). Many of these areas with recent decreases are areas where droughts usually accompany El Niño episodes. So the decreases probably reflect the influence of the recent relatively frequent El Niño episodes (Section 3.4.2).

Consistent continental-scale trends of precipitation are not apparent through Central and South America. In part, this is due to the ENSO phenomenon, the influence of which varies across the continent. The relatively frequent El Niño episodes during the past few decades has led to decadal-scale precipitation variations in some areas. For example, precipitation has decreased over the western slopes of Central America, where the influence of ENSO is clearly evident, but March-May rainfall in the Parana-Paraguay River Basin of south-central South America has increased.

Australian and New Zealand precipitation is also heavily influenced by ENSO, and is characterised by large inter-annual fluctuations. There is evidence of an increase of summer rainfall (Nicholls and Lavery, 1992) in much of eastern Australia after the 1940s (with clusters of wet years in the 1950s and 1970s), although the north-east has suffered from frequent droughts in the last decade, associated with the relatively frequent El Niño events. The last four decades have seen a decrease in eastern Australian annual rainfall. There has been a long-term sustained decrease of winter rainfall in the far south-west, which has been linked to regional circulation changes (Allan and Haylock, 1993; see Section 3.4.4) and perhaps exacerbated by local changes in vegetation (Lyons *et al.*, 1993). Many

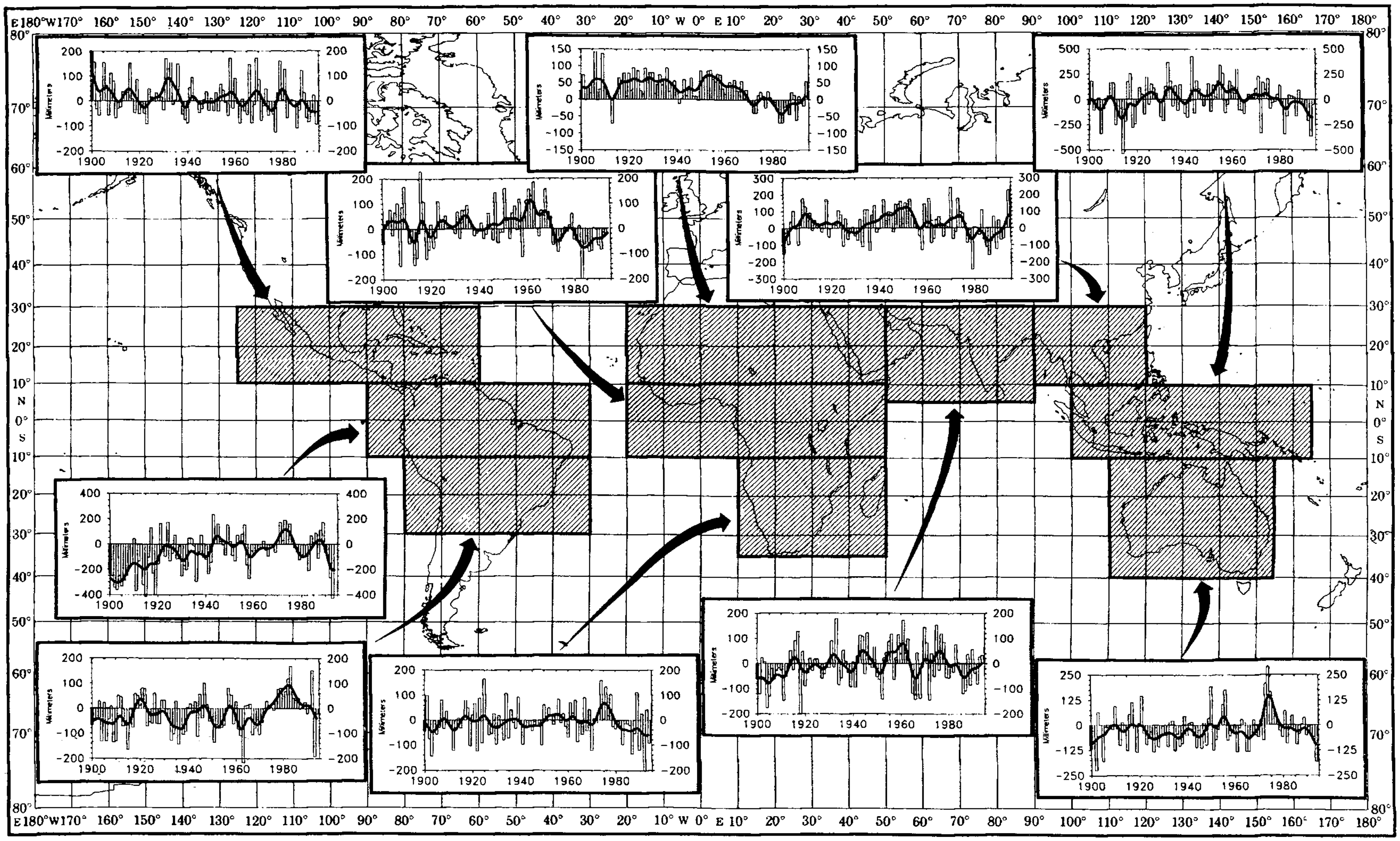


Figure 3.10: Variations of tropical and subtropical land-surface precipitation anomalies based on the average of the anomalies relative to 1961–90 from Hulme and GHCN. Smooth curves generated from nine-point binomial filters of the annual anomalies.

areas in the north and east of New Zealand have been drier since the mid-1970s, with areas in the south and west wetter (Salinger *et al.*, 1992).

One of the most complex and important precipitation systems in the Northern Hemisphere is the Asian summer monsoon. There has been a notable absence of very heavy monsoon onset (May–June) rains along the Yangtze River Valley of China ([†]Chen *et al.*, 1992) since about 1970, although total warm season rainfall has changed little. Indian summer monsoon rainfall reveals high interannual and decadal variability (Sontakke *et al.*, 1992, 1993; Parthasarathy *et al.*, 1992, 1994). The data indicate two wet periods of about 30 years (~1871–1900 and 1931–60) and two drier 30-year periods (1901–30 and 1961–90). Figure 3.10 indicates low rainfall through much of south and south-east Asia in the last few decades. At least some of this decrease reflects the influence of the recent frequent/intense El Niño episodes.

Throughout Africa marked variations in rainfall are evident (Figures 3.9 and 3.10). Rainfall in Sahelian West Africa from the late 1960s to 1993 was well below the amounts received earlier in the century, and over the last few decades has been about half that of the wet 1950s. Similar dry periods occurred during the historical and recent geologic past (Nicholson, 1994a,b; see Section 3.6.2). The recent period exhibits some differences in character from previous dry periods, namely a tendency towards continental-scale dryness (Nicholson, 1995). In recent years precipitation in eastern Northern Africa and the Arabian Peninsula has returned to levels more typical of the first-half of the century. Sahel rainfall in 1994 was greater than in any year since the 1960s.

Concerns about a possible link between climate change and desertification indicate the need for monitoring of arid region precipitation. The only large arid region with a strong trend to lower rainfall during the 20th century is Northern Africa, where rainfall has been low over the last few decades (Figure 3.10).

There have been several attempts to construct long-term instrumental worldwide precipitation time-series for hemispheric and global land areas (Bradley *et al.*, 1987; Diaz, et al., 1989; Eischeid *et al.*, 1991; Hulme, 1991; Hulme *et al.*, 1994). Figure 3.11 shows zonal average annual precipitation over land, in large latitudinal bands. There has been a substantial decrease of precipitation over the Northern Hemisphere subtropics primarily over the last three decades. Increases have occurred in the mid- and high latitudes. Since bias corrections have not yet been applied to the North American data in either the Eischeid *et al.* (1995) or the Hulme (1991) data sets these trends are likely

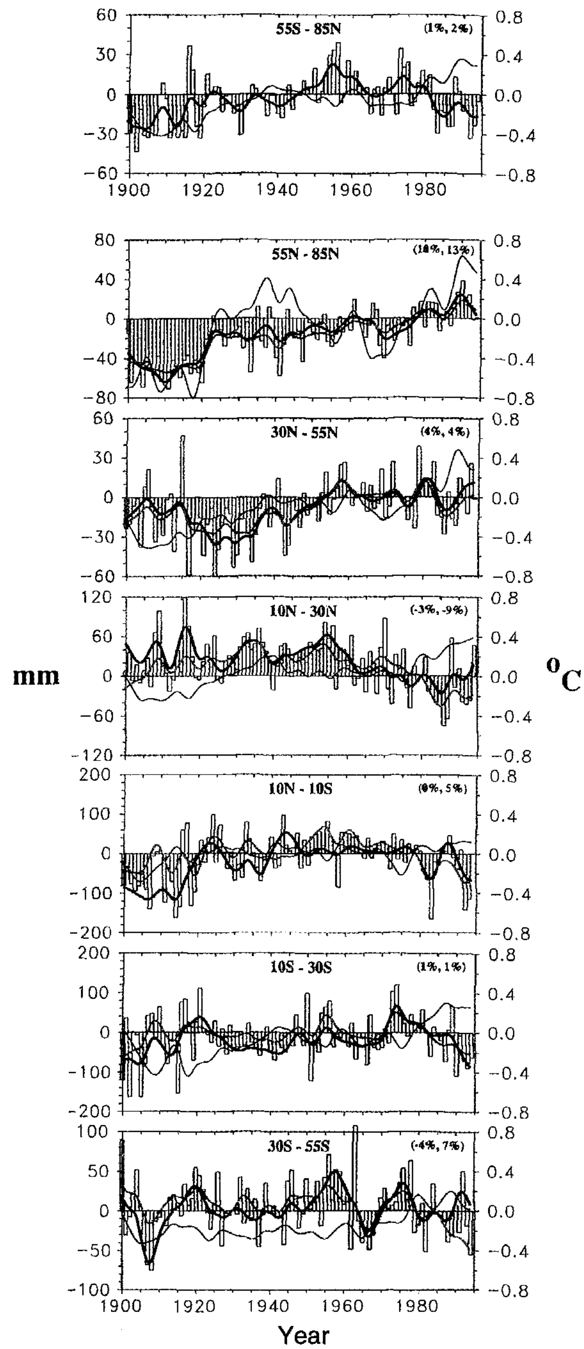


Figure 3.11: Annual and smoothed precipitation anomalies and smoothed temperature anomalies from 1961 to 1990 mean. Smooth curves were created using nine-point binomial filters of annual precipitation (blue – Hulme; black – GHCN; the green line in the top panel is the average of Hulme and GHCN), and temperature (red – Jones, 1994a). Annual bars are the average of Hulme and GHCN. Top panel is for the band 55°S to 85°N. Values in parentheses in upper right corner of each panel are the trend (%/century) of precipitation for GHCN (based on 1951 to 1980 means) and Hulme (1961 to 1990 means), respectively.

to be exaggerated. Based on the regional and country-wide studies where adjustments have been made however, the sign of the mid- to high latitude trend is not in doubt. Precipitation trends over land in the tropics and Southern Hemisphere are not statistically significant, although they indicate decreased precipitation in recent years.

In summary, the best evidence available suggests there has been a small positive (1%) global trend in precipitation over land during the 20th century, although precipitation has been relatively low since the late 1970s (Figure 3.11).

3.3.2.2 Ocean

Measurement of changes of precipitation over the oceans presents extreme difficulties (IPCC, 1990, 1992). Multi-decadal surface-based observations from gauges are limited to very small atolls. Space-based observations, although providing more or less continuous coverage, have several limitations, not least of which is that measurements to directly estimate precipitation are not available until 1979, with the operation of the Micro-Wave Sounding Unit (MSU) aboard NOAA polar orbiting satellites. As a result, researchers have had to resort to the use of data such as real-time cloud imaging, atmospheric temperature profiling, etc. to infer changes of precipitation.

Three methods (Garcia, 1981; Arkin and Ardanuy, 1989; Spencer, 1993) have been used to infer decadal variability of precipitation over the oceans from space-based instruments. These are: identifying Highly Reflective Clouds (HRC); measuring cloud top temperatures from Outgoing Long-wave Radiation (OLR); and the use of the Microwave Sounding Unit (MSU). The HRC data is limited by poor resolution of the diurnal cycle, the subjective nature of the technique, variations from satellite to satellite, and spatial sampling primarily confined to the tropics and subtropics. The OLR data are limited to those areas where precipitation is dominated by cold cloud top temperatures, again principally the tropics and subtropics. Additionally, they are based on observations from a number of instruments on successive satellites, and temporal inhomogeneities associated with satellite drift and instrument calibrations have affected the data set. Therefore, any estimate of precipitation change based on the HRC and OLR data sets is embedded with internal inhomogeneities. Being a more direct measure of rainfall, the MSU data avoid some of the limitations of the HRC and OLR. Nonetheless, these measurements are spatially limited, restricted to unfrozen ocean areas, liquid precipitation, and suffer from the low spatial resolution of the instrument, as well as diurnal sampling inadequacies (Negri *et al.*, 1994).

In IPCC (1990) evidence was presented to suggest that the OLR data analysed by Nitta and Yamada (1989) indicated an increase of tropical precipitation. A re-examination of the biases inherent in these data led Chelliah and Arkin (1992) and IPCC (1992) to conclude that a substantial portion of the increase of precipitation since 1974 was not climate-induced because of OLR biases due to changes in equatorial crossing time and uncertainties in sensor calibration (Gadgil *et al.*, 1992). However, new analyses by Graham (1995) using satellite data, a coarse Tropical Pacific Ocean island data set, and model-derived moisture flux convergence based on observed SSTs suggest an increase of tropical Pacific precipitation between two six-year periods before and after 1976, the time of the commencement of a decadal-scale fluctuation in the atmospheric circulation over the Pacific Ocean (Trenberth and Hurrell, 1994; see Section 3.4.3). Salinger *et al.* (1995a) analysed trends of precipitation from tropical Pacific atolls and islands. Central and eastern equatorial Pacific rainfall increased in the mid-1970s, concomitant with the change to increased frequency of El Niño episodes and the observed decreased precipitation in the south-west Pacific and in some land areas affected by ENSO (Figure 3.10).

3.3.3 Concomitant Changes of Precipitation and Temperature

Strong low-frequency relationships exist between temperature and land-based precipitation, on regional space-scales. Figure 3.11 indicates that the relationship between multi-decadal fluctuations of precipitation and temperature is latitudinally dependent. For the mid- to high latitudes of the Northern Hemisphere simultaneous increases of temperature and precipitation have been observed, but for the tropics, subtropics, and mid-latitudes of the Southern Hemisphere warmer temperatures have been associated with decreases of precipitation. This latter characteristic is a dominant feature of the recent increase of global temperature beginning in the mid-1970s.

3.3.4 Snow Cover, Snowfall, and Snow Depth

The lack of long-term homogeneous data is the major obstacle to evaluation of decadal-scale changes in land-surface cryospheric variables. Recent analyses however, have made some progress toward improving our understanding of changes in these variables.

Northern Hemisphere land-surface snow cover extent has decreased in recent years (1988–1994) of the 21-year period-of-record of satellite data (Robinson *et al.*, 1993; Groisman *et al.*, 1994a). The deficit of snow has been particularly apparent in spring (Figure 3.12). The snow cover of summer and autumn of these recent years has also been low, while winter snow cover exhibits less apparent decadal changes. The annual mean extent of snow cover has decreased by about 10% during the past 21 years over the Northern Hemisphere. Percentage decreases have been similar over North America and Asia (Groisman *et al.*, 1994b). The decrease in snow cover extent is closely coupled to an increase in temperature (Figure 3.12). The warming has been strong in spring over the northern land areas (Chapman and Walsh, 1993; Parker *et al.*, 1994). This is also reflected in earlier lake ice melting as reported by Skinner (1993), earlier snowmelt related floods on rivers in west-central Canada (Burn, 1994) and California (Dettinger and Cayan, 1995), and reduced duration of river ice over the former Soviet Union (Ginsburg, *et al.* 1992; Soldatova, 1993). Groisman *et al.* (1994a,b) have shown that snow-radiation feedback can account for up to 50% of the springtime April-May warming over the Northern Hemisphere land areas since the early 1970s. These results help explain why the increase of surface air temperatures over the Northern Hemisphere land areas has been more significant in spring than in other seasons.

While satellite remote sensing is being explored as a source of data on snow depth water equivalent, station data provide the only information on snowfall and snow depth over periods longer than about two decades. Station measurements indicate that annual snowfall has increased over the period 1950–90 by ~20% over northern Canada (north of 55°N) and by ~11% over Alaska (Groisman and Easterling, 1994). Total precipitation has increased in all these regions (Section 3.3.2.1); in southern Canada and the northern USA however, the increase of precipitation has been accompanied by higher ratios of liquid to solid precipitation as the temperatures have also increased. A small decrease of snowfall has been observed in the 45–55°N latitudinal belt. Decadal summaries of snowfall measurements in China have been compiled by Li (1987), who found a decrease of snowfall over China during the 1950s followed by an increase during the 1960s and 1970s.

There have been several analyses of changes in snow depth over Europe and Asia. Snow depth responds to both changes of precipitation and temperature. A synthesis of 20th century station snow depth measurements for the former Soviet Union (Meshcherskaya *et al.*, 1995) indicates decreases (~14%) of snow depth during February over the European portion of the former Soviet Union with a smaller decrease over the Asian sectors of the former Soviet Union where snow depth has actually increased since the 1960s.

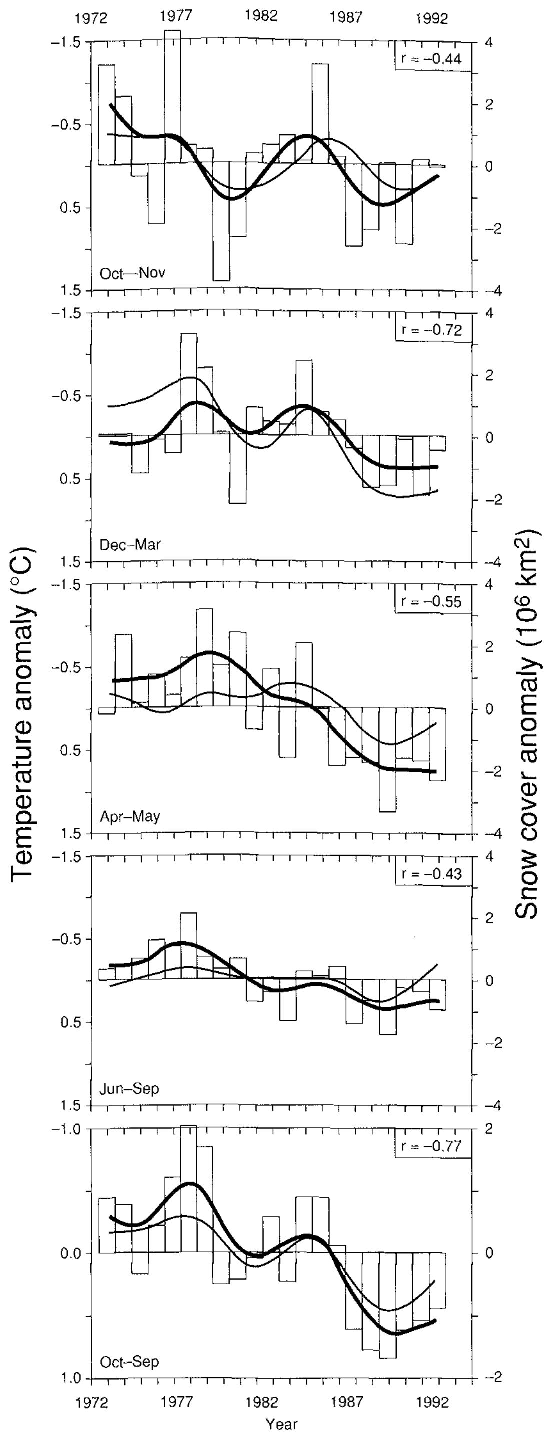


Figure 3.12: Seasonal and annual variations of Northern Hemisphere land-surface snow cover extent (Greenland excluded) and the surface temperature over regions of transient snow cover. Yearly anomalies (shown as bars) are given for snow cover extent. Smooth curves were created using nine-point binomial filters for yearly snow cover (thick) or temperature anomalies (thin) with scale reversed. "r" indicates correlation between annual values. Note bottom panel is for "snow year" (October–September).

3.3.5 Land-surface and Subsurface Water

Changes of precipitation and/or evaporation may lead to changes in runoff or soil moisture storage. Thus changes in streamflow, lake levels, levels of inland seas, and soil moisture may provide information about changes in the hydrological cycle. Data on many of these aspects of the hydrological cycle are suspect because of human influences, such as building of dams to regulate streamflow, so it is important to develop an internally consistent scenario of change.

3.3.5.1 Streamflow

Historical records of 142 rivers throughout the world with more than 50 years of historical data and drainage areas larger than 1000 km^2 were analysed for trends by Chiew and McMahon (1993, 1995). Although statistically significant trends and changes in means were detected at several locations, they were not always consistent within regions. No clear evidence of wide-spread change in the annual streamflow and peak discharges of rivers in the world was found.

Analyses from a number of streamflow gauging stations on major drainage basins across South America do not reveal general increases or decreases of streamflow. There are however, a number of drainage basins that depict important decadal-scale climate variations (Marengo, 1995). Reduced streamflow beginning in the 1970s in Colombia is consistent with similar behaviour in Pacific Central America. The Chicama and Chira River Basins in north-west Peru also reflect large interdecadal variations. Streamflow of the Rio Negro at Manaus is closely related to rainfall in north-west Amazonia (Marengo, 1992, 1995). Consistent trends are absent from the record, although there appears to be a recent (since 1973) minor short-term

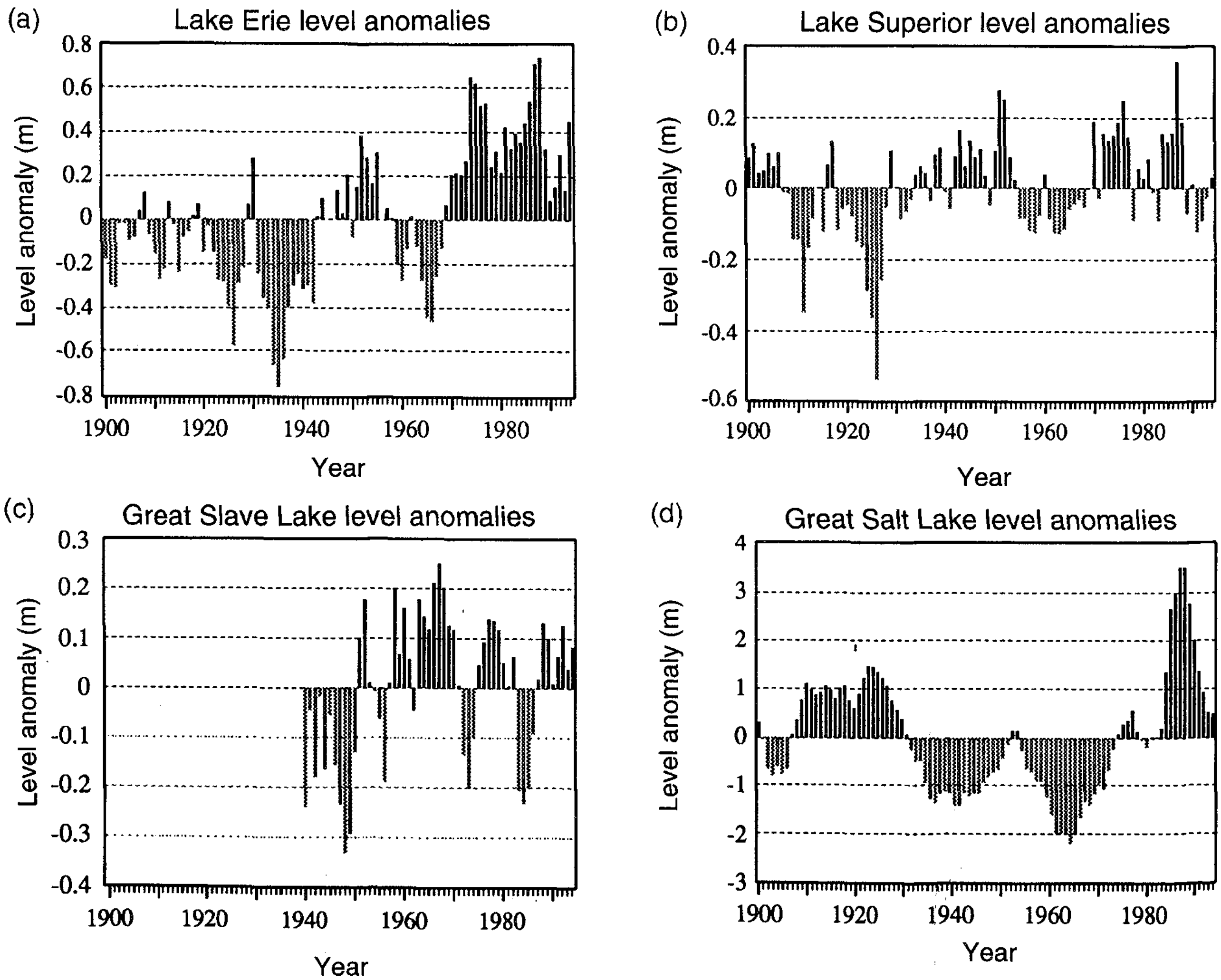


Figure 3.13: Variations in lake level for some major lakes across North America.

increase of streamflow, probably related to an increase in rainfall associated with increased convection over Amazonia as reported by Chu *et al.*, (1994) who also found little change in convective activity over areas of deforestation in south-western Amazonia. Generally, for South America, no clear unidirectional trend of streamflow is evident for the records analysed to date. A strong signal of the El Niño-Southern Oscillation is evident in several regions. These variations often dominate decadal-scale variability of streamflow. The lack of an overall trend is consistent with the precipitation variations.

In North America, the autumn increase of precipitation in the contiguous USA is also reflected in an increase in streamflow. Lins and Michaels (1994) found statistically significant increases in natural streamflow during the autumn and winter in nearly all regions of the contiguous USA (1948-88). The most significant (statistically) increases were generally found from the Rocky Mountains eastward to the Atlantic.

3.3.5.2 Lake levels

Large lakes and inland seas can serve as useful indicators of climate variability and change. With large surface areas and limited outflow capacity, these natural reservoirs filter out short-term variability and respond to longer term variations in the hydrologic cycle. However, local effects often confound the use of lake levels to monitor climate variations.

The historically small variations of levels of the North American Great Lakes are mainly due to natural changes in lake levels (Magnuson *et al.*, 1995). The lakes have been in a regime of high water levels since the late 1960s culminating in record high levels in 1986 (Changnon, 1987). A major drop occurred in response to an intense drought in 1988, but lake levels continue to remain above the long-term mean for Lakes Michigan, Huron, and Erie. Lake Superior has been slightly below its long-term average since 1988 (Figure 3.13). Levels of the Great Salt Lake in Utah are somewhat similar to those in the Great Lakes, but the Lake has recently been regulated with the introduction of pumps to relieve the historic peak water levels of 1986–87. The Great Slave Lake, located in the Northwest Territories of Canada has also continued to be at above average levels for the past several years compared to the relatively low levels observed during the 1940s. Although there has been regulation on one of the rivers flowing into the Great Slave Lake since 1968, comparison of the water levels of the Great Slave and Great Bear Lakes suggests it has had limited influence on annual or decadal fluctuations.

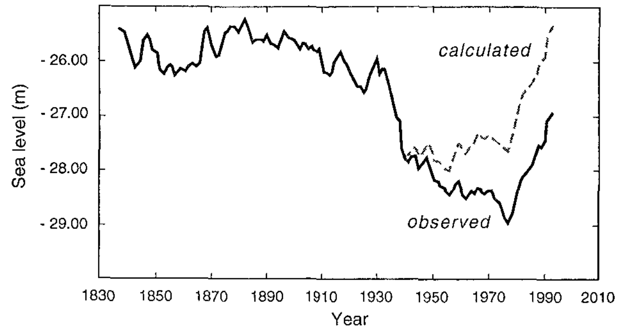


Figure 3.14: Annual mean sea level of the Caspian Sea as observed (solid line) and as calculated without local anthropogenic changes in land-use (dashed line) (updated after Shiklomanov, 1976).

The Caspian Sea is the largest closed water body in the world. Its sea level has been measured since 1837 (Figure 3.14) and has fluctuated by nearly 4 m. Sea level was quite stable until the 1930s when it fell 1.6 m in six years. The level abruptly began to rise in 1977, from record low values, perhaps the lowest values since the 14th century. The main contribution to the rapid decrease of sea level in the 1930s was reduced runoff into the Sea, but the most recent increase is attributed to a combination of reduced evaporation (Section 3.3.6.1; Figure 3.15), increases in runoff, and an engineered blockage of sea water into the Kara Bogaz Gol (which has since been reopened; Golitsyn *et al.*, 1990; Golitsyn, 1995).

Since 1965 lake levels in Northern Hemisphere Africa have declined sharply (Grove, 1995). The early 1960s were relatively wet, but the low Sahel/Sudan precipitation since then (Figure 3.10) led to Lake Chad shrinking from its highest level and extent in the 1960s to about one tenth of the area by the 1980s. This decline was due to decreased rainfall, and not the result of excessive extraction of water for irrigation.

3.3.5.3 Soil moisture

There are few long-term data sets of soil moisture measurements. One example is the so-called "water-balance" network within the former Soviet Union, at some places for more than 30 years (Robock *et al.*, 1995; Vinnikov *et al.*, 1995). In this network, total soil moisture measurements have been made over natural vegetation soil using a thermostat-weighing technique (Vinnikov and Yeserkepova, 1991). The data from the European part of the former Soviet Union exhibit a general increase in soil moisture from the 1970s to the 1980s, consistent with the increase of precipitation observed over the European portion of the former Soviet Union, and a reduction of evaporation (Section 3.3.6.1).

3.3.6 Evaporation

Systematic long-term measurements of surface evaporation have been carried out over many continental areas, but few analyses of their trends have been completed. Changes in evaporation over the ocean have proven to be particularly difficult to monitor, and are prone to time-varying biases.

3.3.6.1 Land

Estimates of evaporation over land have been obtained from pan evaporimeters. Although these measurements can neither be considered as evaporation from lakes or reservoirs, nor as evaporation from ground, they can be used as a composite index that characterises the annual and seasonal water and heat balance between the water surface of the evaporimeter and the atmosphere. Trends in such an evaporation index from the former Soviet Union have recently been analysed (Golubev and Zmeikova, 1991) for a network of 190 stations. Although some measurements date back to the late 19th century, changes in instrumentation, observational procedures, and data management practices make the data inhomogeneous prior to 1951. The analysis indicates a reduction of evaporation since 1951 during the warm season (the freeze-free period) over the European and Siberian (north of 55°N) portions of the former Soviet Union (Figure 3.15), with little change in central Asia and Kazakhstan. The rapid decrease in evaporation in the European sector in 1976 corresponds with the timing of the decrease in the diurnal temperature range (Section 3.2.2.4 and Karl *et al.*, 1993a; Peterson *et al.*, 1995) over the former Soviet Union. In the USA, where

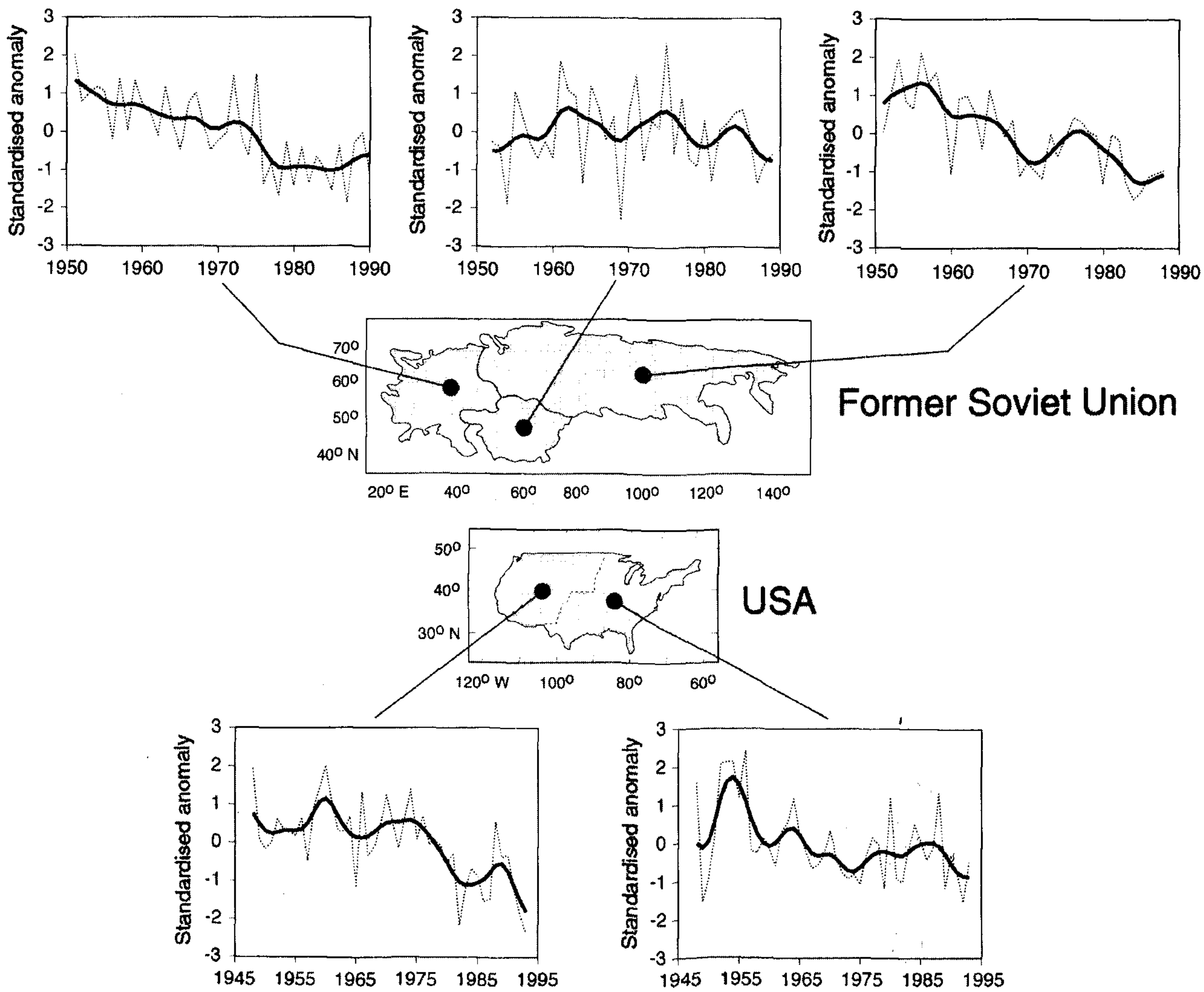


Figure 3.15: Area-averaged standardised anomalies of evaporation derived from pan evaporimeters for sectors in the former Soviet Union in the warm period of the year (updated from Golubev and Zmeikova, 1991), and for the USA (Peterson *et al.*, 1995). The dashed lines represent interannual variations and the smoothed curves suppress variations on time-scales of a decade or less.

data from a network of over 300 stations are available but have yet to be thoroughly inspected for inhomogeneities, an overall decrease in evaporation is also observed (Figure 3.15; Peterson *et al.*, 1995) that closely resembles the decrease in the diurnal temperature range.

3.3.6.2 Ocean

The oceans provide a source of moisture for the atmosphere and subsequent precipitation over land. Estimating long-term changes of oceanic evaporation is very difficult, and all estimates must be viewed with considerable caution due to time varying biases in the data. Bulk aerodynamic parametrizations are the only practical means of comprehensively calculating evaporation over regions as large as ocean basins and over multi-decadal time-scales. Routine marine weather observations of wind, temperature, and humidity, among other elements, are available over broad sectors of the oceans for the past four decades. These observations allow estimation of evaporation based on the sea surface saturation specific humidity, the specific humidity of the overlying air, and the near-surface wind speed.

Marine weather observation procedures were not designed to provide long-term homogeneous climate data, and several problems exist that can obscure climate-induced changes. Marine data show an increase of wind speed (Cardone *et al.*, 1990) over the four decades since World War II, believed to be largely artificial, involving changes from Beaufort scale sea state estimates of wind speed to anemometer observations (Ramage, 1987). Posmentier *et al.* (1989) argued an increase in wind is inconsistent with observed trends in tropical sea level and sea surface temperature, which in the eastern tropical Pacific have increased rather than decreased as would be expected under an increasing trade wind regime. The notion of no global increase in wind speed is consistent with the calculations of Ward (1992, 1994) who used sea level pressure gradients to estimate changes in wind speed. Even after removing the apparent wind bias however, evaporation was estimated to have increased by more than 0.5 mm/day over the tropical oceans (10°S to 14°N) during the last four decades (Flohn *et al.*, 1992). Graham (1995) used model calculations to suggest that increases of evaporation should also have occurred in the tropical Pacific, even without any increase of wind speed.

Weare (1984) and Cayan (1992) indicate that anomalous evaporation is influenced about equally by fluctuations in wind speed and fluctuations in vertical moisture gradients. Furthermore, the calculations of evaporation trends over much of the Atlantic indicate that evaporation has increased both because of vertical moisture gradients and increases in wind speed. That is, evaporation trends would still be positive even without any change in wind speed. Increases in evaporation are found in both winter and summer.

Other areas of the oceans are known to exhibit multi-decadal changes in evaporation. For example, there was a transition from warm to cool conditions in the western and central North Pacific associated with a cluster of winters with deep Aleutian Lows beginning in the winter of 1976–77 (Douglas *et al.*, 1982; Venrick *et al.*, 1987; Trenberth, 1990; Miller *et al.*, 1994; Trenberth and Hurrell, 1994). Since such transitions involve a redistribution of the paths of storms across the Pacific basin there are large-scale changes in the wind, temperature, and humidity with concomitant changes of evaporation. The magnitude of these changes over the North Pacific basin is estimated to be between 0.2 and 0.4 mm/day, with evaporation increasing over the western North Pacific, but decreasing over the Gulf of Alaska.

3.3.7 Water Vapour

Water vapour is the most abundant greenhouse gas and makes the largest contribution to the natural greenhouse effect. Half of all the moisture in the atmosphere is between sea level and 850 hPa and less than 10% is above 500 hPa. The amount in the stratosphere is probably less than 1% of the total. Despite the small amount of water vapour in the stratosphere, changes there may lead to significant changes in the radiative forcing of climate (Oltmans and Hofmann, 1995).

Monitoring atmospheric moisture presents many difficulties. Because the residence time of water vapour in the atmosphere is short, about 10 days, its distribution is horizontally, as well as vertically, heterogeneous. Therefore observations at many places and levels are necessary for adequate representation of climatically important changes. Measurement problems also make detecting trends of water vapour difficult. Most of the information about tropospheric water vapour comes from radiosonde measurements taken for daily weather forecasts. Unfortunately, this instrumentation is not capable of accurate measurements at the low temperatures and very low moisture conditions of the upper troposphere, stratosphere, and polar regions of the planet. Another serious problem with radiosonde data stems from the changes of instruments and reporting practices that have occurred through the period of record. About a dozen different manufacturers supply radiosondes to the world's weather services, some with quite different sensor designs.

These factors make it difficult to separate climate changes from changes in measurement programs (Elliott and Gaffen, 1991). Our inability to account for these inhomogeneities limits assessments of the change in atmospheric moisture to the last 20 years, thereby making it difficult to distinguish between transient phenomena, such as ENSO, and long-term change. Nevertheless, with careful attention to these problems, some estimates of tropospheric water vapour can be obtained.

Elliott *et al.* (1995) found increases in precipitable water from 1973 to 1993 over all of North America except northern and eastern Canada, where it decreased slightly. The positive trends tended to increase with decreasing latitude, with maximum values of about 3 mm/decade. The increases as a percentage of the annual mean also tended to be greater at lower latitudes, approaching a maximum of 8%/decade. The regions of moisture increase were generally also regions with rising temperatures over the same period and the regions of moisture decrease were generally regions with decreasing temperatures. There was a strong (but not universal) tendency for the moisture increases to be accompanied by increases in relative humidity.

There have been several analyses of changes in water vapour over the tropical oceans using radiosonde data. Hense *et al.* (1988) report an upward trend of moisture in the 700–500 hPa layer in the western Pacific from 1965 to 1986, but the data prior to 1973 are not necessarily homogeneous because of a change in instrumentation in 1973 (Elliott and Gaffen, 1991). Elliott *et al.*, (1991) document a moisture increase in the equatorial Pacific from 1973-86 and Gaffen *et al.* (1991) using more stations also found an increase of specific humidity on the order of 10% from 1973 to 1986, but the scatter of data is such that this value is only a rough estimate of the order-of-magnitude of the change. Much of the change occurred during a relatively brief interval, beginning about 1977 (see Section 3.4.3). An increase in tropical western Pacific moisture was also found by Gutzler (1992) at four tropical island stations. There were increases in humidity throughout the troposphere with the largest increases near the surface. The study indicates an increase in water vapour of about 6%/decade for the period 1973–1988.

Gaffen *et al.* (1992) computed trends of water vapour for some 35 radiosonde stations. Most of these stations, especially in the western tropical Pacific, showed an increase in precipitable water during the period 1973–90. The largest and most statistically significant trends were at tropical stations, where increases as large as 13%/decade were found.

Oltmans and Hofmann (1995) analysed stratospheric and upper tropospheric water vapour measurements (10–26 km) over Boulder, Colorado during the period 1981–94. Over this short period they found positive trends of water vapour in the stratosphere, but statistically significant increases, of between 0.5 and 1%/yr, were confined to the layers between 16 and 24 km. Data from other locations must be analysed and over longer time intervals however, before these results can be generalised.

3.3.8 Clouds

In addition to providing evidence of an enhanced hydrological cycle, changes of cloud distribution can have very important climatic feedbacks. Changes in clouds modify both incoming and outgoing radiation depending on their level, amount, vertical extent, and composition.

3.3.8.1 Land

There have not been any major new analyses of large-scale changes in land-based observations of cloud cover published since the IPCC (1990) report. Henderson-Sellers (1992) has, however, summarised her analyses of changes in cloud cover over Australia, Europe, India and North America. Added confidence has been attached to these analyses because the diurnal temperature range, which is quite sensitive to changes of cloud cover (Karl *et al.*, 1993a), has decreased in many of the regions with a reported increase in cloud cover. Moreover, Karl *et al.* (1995e) report a step-like increase in cloud amount over the former Soviet Union around 1976 consistent with the step-like decreases of evaporation (in the European sector of the former Soviet Union, Figure 3.15) and of the diurnal temperature range. In addition, analyses by Environment Canada (1995) generally support an increase in cloud amount throughout Canada since 1953, in particular over the lower Great Lakes region during autumn. There have been increases of cloud cover over Australia and the USA since at least the mid-20th century. In at least some areas (e.g., Australia), however, cloud cover over land may have decreased since about 1980 (Henderson-Sellers, 1992).

3.3.8.2 Ocean

Marine weather observations of clouds have been analysed. Satellite observations have also been used, but owing to instrumental changes and the shortness of their record, cannot be used with any degree of confidence to assess multi-year trends or changes.

Fifty million routine weather observations from ships were analysed by Warren *et al.* (1988), who computed average total cloud cover and the amounts of six cloud types for each of the four seasons for the 30 year period 1952 to 1981. During the 1952 to 1981 period London *et* *al.* (1991) reported a global ocean average increase of cloud cover of 0.7%. This increase was concentrated at low latitudes (20°N–20°S), and the cloud types contributing most to the increase were cumulonimbus and cirrus. The increase in cumulonimbus was nearly 3% and in cirrus about 1%, at the expense of cumulus clouds which decreased by about 1%. This data set has recently been updated through 1991, and indicates that cloud cover over the oceans has continued to increase.

Interannual variations of marine stratus and stratocumulus in the subtropics and mid-latitudes are inversely correlated with SST (Norris and Leovy, 1994). The 30-year trends of marine stratus and stratocumulus exhibit the same geographical patterns as do SSTs (cf. Parker *et al.*, 1994): increases in cloud amount over areas with decreasing temperatures in the northern mid-latitude oceans, and decreases with warming off the west coast of North America. Analysis of changes in cloud types (Parungo *et al.*, 1994) suggests an increase in altostratus and altocumulus cloud amount centred in the Northern Hemisphere mid-latitudes (30°N–50°N). Over the 30-year period 1952 to 1981 these mid-level clouds increased in frequency from 20 to 26%. This large apparent increase requires investigation of possible time-varying biases.

3.3.9 Summary of Section 3.3.

Precipitation has increased over land in high latitudes of the Northern Hemisphere, especially during the autumn. A decrease of precipitation occurred after the 1960s over the subtropics and tropics from Africa to Indonesia, as temperatures increased. Many of the changes in precipitation over land are consistent with changes in streamflow, lake levels, and soil moisture. There is evidence to suggest increased precipitation over the equatorial Pacific Ocean (near the dateline) in recent decades, with decreases to the north and south. Based on the available data, there has been a small positive (1%) global trend in precipitation over land during the 20th century, although precipitation has been low since about 1980.

Evaporation potential has decreased (since 1951) over much of the former Soviet Union (and possibly also in the USA). Evaporation appears to have increased over the tropical oceans (although not everywhere). There is evidence suggesting an increase of atmospheric water vapour in the tropics, at least since 1973. In general, cloud amount has increased both over land (at least up to the end of the 1970s) and the ocean. Over the ocean increases in both convective and middle and high level clouds have been reported.

3.4 Has the Atmospheric/Oceanic Circulation Changed?

3.4.1 Background

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 variables are strongly related through large-scale features of the atmospheric circulation, as well as through interactions involving the land and ocean surfaces (IPCC, 1990). Two well-known examples of such large-scale features are the El Niño-Southern Oscillation and the North Atlantic Oscillation, both of which are closely related to climatic fluctuations in many areas. Evidence of associated changes or variations in the atmospheric circulation may enhance confidence in the reality of observed changes and variations in the climate variables in these areas.

Comprehensive, long-term monitoring of changes and variations in the El Niño-Southern Oscillation and North Atlantic Oscillation, and the atmospheric circulation in general, requires the analysis of meteorological and oceanic fields on a routine basis. Analyses of such fields are performed every day by national meteorological services. However, the analysis schemes, their observational basis, and even the theoretical meteorology underlying the analysis have all changed dramatically over the decades (Trenberth, 1996). Thus, these analyses are of only limited use for analysis of variations and changes in circulation over extended periods. Where such analyses are used, their results need to be confirmed by analysis based solely upon high-quality station data. The lack of homogeneity in the atmospheric analyses restricted the variety of atmospheric circulation features IPCC (1990) decided could be examined with confidence. The same problem occurred in IPCC (1992), and again here only a small number of the more reliable circulation features are examined, namely the El Niño-Southern Oscillation and the North Atlantic Oscillation. The discussion of a possible recent increase in the intensity of the winter atmospheric circulation over the extra-tropical Pacific and Atlantic (IPCC, 1990) is also updated.

Ocean circulation variations and change can also be important determinants of climate variations, so their routine monitoring is also necessary. However, little information is available, as yet, on variations and change in ocean circulation on the time-scales of relevance to this chapter.

3.4.2 El Niño-Southern Oscillation

The El Niño-Southern Oscillation (ENSO) phenomenon is the primary mode of climate variability in the 2–5 year time band. Release of latent heat associated with ENSO episodes affects global temperature (Pan and Oort, 1990; Graham, 1995), and associated changes in oceanic upwelling influence atmospheric CO_2 levels (Keeling *et al.*, 1989). It is important to assess the stability of the ENSO, i.e., to determine how long it has been operating, and whether it exhibits longer-term variations in its influence.

As instrumental records for the El Niño-Southern Oscillation extend back only to the late 19th century, it is necessary to use various proxy approaches to derive the history of El Niño-Southern Oscillation events. In addition to analyses of historical records (Quinn, 1992), corals, tree rings, tropical ice cores, and varve sediments have also been employed to derive temporal histories of ENSO variability (Diaz and Markgraf, 1992; Cole *et al.*, 1993; Diaz and Pulwarty, 1994). Whetton *et al.* (1995) demonstrate that proxy records of ENSO from different regions do not always correspond with each other. One coral record (Dunbar *et al.*, 1994) is from the Galapagos Islands, where a time-series of oxygen isotope measurements indicates significant variations in the El Niño-Southern Oscillation. Tree ring and other records also indicate temporal variations in some of the ENSO periods (Diaz and Markgraf, 1992).

Instrumental records have also been examined to search for possible changes in the El Niño-Southern Oscillation. The Southern Oscillation Index (SOI), a simple index of the El Niño-Southern Oscillation based on surface atmospheric pressures at Darwin and Tahiti, is plotted in Figure 3.16. El Niño (or warm) events are associated with large negative excursions of the SOI and warmer than normal temperatures in the central and east equatorial Pacific. La Niña episodes (or cold events, when the east equatorial Pacific is cool) are associated with positive values of the SOI. The dominance of time-scales of 2–5 years in the El Niño-Southern Oscillation is apparent in this figure. The periodicity of El Niño-Southern Oscillation has varied since 1950. Between 1950 and 1965 the phenomenon exhibited a period of about five years. Since 1965 the period has shortened somewhat, closer to four years. A similar pattern of change in frequency was evident in a central equatorial Pacific coral record of the El Niño-Southern Oscillation (Cole *et al.*, 1993). El Niño events occurred more often around the start of the 20th century than during the 1960s and 1970s (Anderson, 1992).

Allan (1993) and Karoly *et al.* (1996) have documented decadal-scale variations in the El Niño-Southern Oscillation and its teleconnections over the last century.

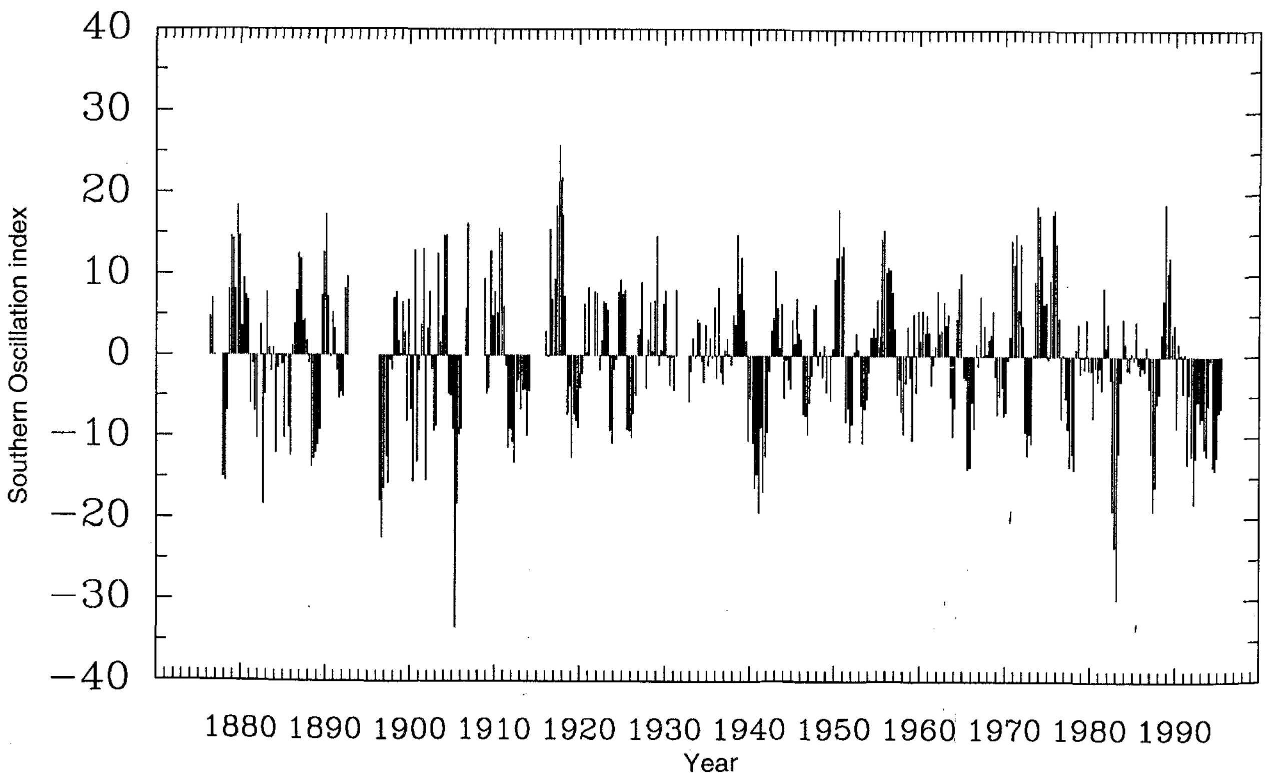


Figure 3.16: Seasonal values of the Troup Southern Oscillation Index (SOI), March–May 1876 through March–May 1995. SOI only plotted when both Darwin and Tahiti data available.

The most robust and coherent signals were evident in the late 19th century, and since the 1940s. ENSO activity was weaker and more fragmented in the intervening period. Wang (1995) found that the characteristics of the onset of the Pacific-wide warming associated with an El Niño changed after the mid-1970s.

Indeed, there appears to have been a rather distinct change in ENSO in 1976/77 (Figure 3.16). Since then, there have been relatively more frequent El Niño episodes, with only rare excursions into the other extreme (La Niña episodes) of the phenomenon (Trenberth and Hurrell, 1994), and the SOI has tended to be negative for extended periods. During this period sea surface temperatures in the central and equatorial Pacific have tended to remain anomalously high, relative to previous decades. As well, precipitation over land in many areas where dry conditions usually accompany El Niño episodes (e.g., Indonesia, north-east Australia) has been low.

The recent ENSO behaviour, and especially the consistent negative SOI since 1989, appears to be unusual in the context of the last 120 years (the instrumental record). However, some data for Tahiti is missing from before 1935, so it is difficult to compare the length of the post-1989 period of negative SOI with earlier periods. It may be, for instance, that the period of negative SOI values starting around 1911 was comparable with the recent period. Trenberth and Hoar (1996) examined the recent El Niño-Southern Oscillation behaviour using Darwin data only. The Darwin data are continuous and therefore allow a strict comparison of the post-1989 behaviour with that of earlier periods, although by themselves they may not provide a complete representation of the El Niño-Southern Oscillation. The Trenberth and Hoar analysis indicates that the post-1989 behaviour is very unusual. From the Darwin data, there has been no period in the last 120 years with such an extended period of negative SOI. Trenberth and Hoar fitted statistical models to the 1882 to 1981 Darwin data, to determine how unusual the recent behaviour has been. They concluded that the 1990 to 1995 behaviour had a probability of natural occurrence of about once in 2,000 years. Allan and D'Arrigo (1996), however, present evidence that episodes with similarly persistent ENSO characteristics have occurred prior to the period of instrumental data.

3.4.3 Northern Hemisphere Circulation

In the past few years considerable work has been done to document decadal and longer time-scale variability regionally in several parts of the globe, especially the North Pacific (IPCC, 1990; Trenberth and Hurrell, 1994; Hurrell, 1995). Substantial changes in the North Pacific atmosphere and ocean began about 1976. This is illustrated in Figure 3.17 which shows a time-series of mean sea level pressures for the five winter months November to March, averaged over most of the extra-tropical North Pacific (updated from Trenberth and Hurrell, 1994). This index is closely related to changes in the intensity of the Aleutian low pressure centre, and to a pattern of atmospheric circulation variability known as the Pacific-North American (PNA) pattern (Wallace and Gutzler, 1981). The abrupt shift in pressure after 1976 is evident. Observed significant changes in the atmospheric circulation involving the PNA teleconnection pattern were described in IPCC (1990). Associated changes occurred in surface winds. The storm tracks and associated synoptic eddy activity shifted southward. This regime appears to have ended about 1989.

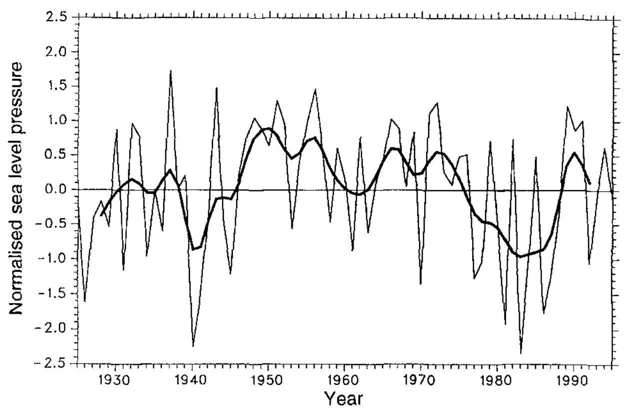


Figure 3.17: Time-series of mean North Pacific sea level pressures averaged over 30–65°N, 160°E to 140°W for the months November to March beginning in 1925 and smoothed with a low pass filter (thick line). Updated from Trenberth and Hurrell (1994).

The Pacific decadal time-scale variations have been linked to recent changes in the frequency and intensity of El Niño versus La Niña events and it has been hypothesised that the decadal variation has its origin in the tropics (Trenberth and Hurrell, 1994). While some analyses of observations (Deser and Blackmon, 1995; Zhang *et al.*, 1995) show that this link is not linear, observational studies by Kawamura (1994), and Lau and Nath (1994) have shown that the decadal variation in the extratropics of the Pacific is closely tied to tropical sea surface temperatures (SSTs) in the Pacific and Indian Oceans. Several aspects of the decadal-scale fluctuation beginning around 1976 have been simulated with atmospheric models using specified SSTs (Kitoh, 1991; +Chen *et al.*, 1992; Miller *et al.*, 1994; Kawamura *et al.*, 1995). These studies also suggest that the changes over the North Pacific are substantially controlled by the anomalous SST forcing from the tropics. Yamagata and Masumoto (1992) have suggested that the decadal time-scale variations may also involve the Asian monsoon system.

The North Atlantic Oscillation (NAO) is of interest because of its relationship to regional precipitation and temperature variations. The NAO is a large-scale alternation of atmospheric pressure between the North Atlantic regions of subtropical high pressure (centred near the Azores) and subpolar low surface pressure (extending south and east of Greenland). The state of the NAO determines the strength and orientation of the poleward pressure gradient over the North Atlantic, and hence the speed and direction of the mid-latitude westerlies across that ocean. These, in turn, affect the tracks of European-sector low-pressure storm systems (Lamb and Peppler, 1991). One extreme of the NAO coincides with strong westerlies across the North Atlantic, cold winters in western Greenland and warm ones in northern Europe, while the other NAO extreme is associated with the opposite pattern. In addition, precipitation over Europe is related to the NAO (Hurrell, 1995). The recent decade-long winter dry conditions over southern Europe and the Mediterranean, and the wet anomalies from Iceland eastward to Scandinavia, are related to the recent persistent positive phase of the NAO (Hurrell, 1995).

IPCC (1990) used the smoothed standardised difference of December-February atmospheric pressure between Ponta Delgada, Azores, and Stykkisholmur, Iceland, to describe the variations in the westerly flow in the North Atlantic, and thus the NAO. Figure 3.18 updates IPCC (1990) and reveals strong westerlies since 1989. It also highlights an apparent near century time-scale variation in the westerly flow with peaks around 1910 and at the present. The amplitude of this variation is as large as one standard deviation of the interannual variations. Flohn *et al.* (1992), using meteorological analyses, reported a deepening of quasi-stationary cyclones in the Northern Atlantic and in the Northern Pacific leading to an intensification of the extra-tropical circulation, most pronounced during winter, supporting the suggestions of intensification in Figures 3.17 and 3.18.

In the North Atlantic, decadal period fluctuations are superposed on a longer time-scale variation (Deser and Blackmon, 1993; Kushnir, 1994; Schlesinger and Ramankutty, 1994), which is reflected in the global mean temperature variations. The short-period mode, i.e., irregular fluctuations averaging about 9 years in length before about 1945 and about 12 years thereafter, is

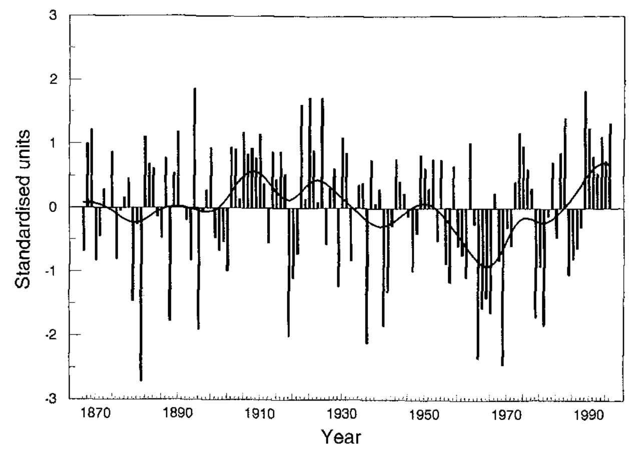


Figure 3.18: Standardised difference of December to February atmospheric pressure between Ponta Delgada, Azores, and Stykkisholmur, Iceland, 1867 to 1995. Smooth curve was created using a 21-point binomial filter. Updated from IPCC (1990).

characterised by a dipole pattern in SSTs and surface air temperatures, with anomalies of opposite polarity east of Newfoundland and off the south-east coast of the USA. Distinctive sea level pressure and wind patterns have been identified with this short-period mode and it seems that the SSTs result largely from the winds, with cooler-than-normal SSTs accompanied by stronger-than-normal winds.

The lower frequency mode is identified as a temperature fluctuation with largest amplitude in the North Atlantic and surrounding continents where the period appears to vary regionally from 50 to 88 years. Relative to the record from 1850 on, it corresponds to a much colder period from the late 1800s to about 1920, much warmer than normal from about 1930 to 1960, and another cooler period in the 1970s and 1980s (Kushnir, 1994; Schlesinger and Ramankutty, 1994). The sea level pressures and surface winds associated with this pattern have been explored by Deser and Blackmon (1993) and Kushnir (1994) who find an anomalous cyclonic circulation during the warmer years and anticyclonic during the cooler years, centred in the mid-Atlantic near 40°N.

It seems likely that relationships among the atmosphere and ocean variables include the patterns of dynamical coupling between the atmosphere and ocean, which may extend outside the Atlantic domain. It is likely that there are changes in the ocean thermohaline circulation such as those seen in models with time-scales of roughly 50 years (Delworth *et al.*, 1993). The thermohaline circulation is greatly influenced by density fluctuations at high latitudes which apparently arise mainly in the fresh water availability which alters salinity, and originates from changes in precipitation, runoff, and evaporation. These kinds of fluctuations may also be related to the abrupt climate changes seen in recent Greenland ice core analyses (Section 3.6.3).

Some reported variations in temperature and precipitation have been related to observed regional variations in atmospheric circulation. Analysis of trends in 700 hPa heights (O'Lenic, 1995) provides some evidence linking the regional circulation anomalies to the trends in surface temperature over the past 40 years, e.g., negative trend in the North Pacific and positive over western Canada. Ward (1992, 1994) demonstrated that the recent low rainfalls in the Sahel are also related to circulation anomalies. IPCC (1990) pointed out that changes in SSTs on a global scale played a major role in the reduction of Sahel precipitation. Lare and Nicholson (1994) have again reiterated the potential role of land-surface changes in the prolonged dry period in the Sahel, but Shinoda and Kawamura (1994a) suggest that changes in the SSTs of the Indian Ocean and the tropical North and South Atlantic modulate different aspects of the Sahel rainfall. Specifically, the contrasting anomalies of North and South Atlantic SSTs play a major role in the year-to-year latitudinal displacement of the rainbelt and the strong warming trend of the SSTs in the Indian Ocean (Figure 3.4) is associated with large-scale subsidence over the rainbelt. A new analysis of the interannual and decadal variations of the summer rains over the Sahel (Shinoda and Kawamura, 1994b) however, suggests that the decreased rainfall from the 1950s to the 1980s primarily resulted from weakened convection over the entire monsoonal rainbelt, rather than a systematic displacement of its central position.

One aspect of atmospheric circulation variations considered recently is the possible impact of volcanic eruptions. The eruption of Mt. Pinatubo (Section 3.2.6) led to studies which suggested, based on geographical variations in temperature after major eruptions, that heating of the tropical stratosphere resulting from volcanic aerosols drives an enhanced zonal wind (Groisman, 1992; Robock and Mao, 1992; Graf *et al.*, 1993). This stronger wind advects warmer maritime air over the continents, leading to warming, in the Northern Hemisphere winter, in higher latitudes. Such variations are limited to a year or two after a major eruption. So, only a protracted change in the level of volcanic activity could be expected to lead to a long-term atmospheric circulation change.

3.4.4 Southern Hemisphere Circulation

Over the Southern Hemisphere, analysis of decadal variability is difficult because of the paucity of data. Nevertheless careful analysis of station data together with the available analyses has revealed real decadal-scale climate changes (van Loon *et al.*, 1993; Hurrell and van Loon, 1994). A change in the atmospheric circulation is evident in the late 1970s with sea level pressures in the circumpolar trough generally lower in the 1980s than in the 1970s and with the changes most pronounced in the second half of the year, so that the tropospheric polar vortex remained strong into November. This was associated with a delayed breakdown in the stratospheric polar vortex and the ozone deficit in the Antarctic spring.

A near-global atmospheric pressure data set (Allan, 1993) and other data have been used to examine longer term variations in circulation in the Indian Ocean, since late last century (Allan *et al.*, 1995; Salinger *et al.*, 1995b). Circulation patterns in the periods 1870 to 1900 and 1950 to 1990 were more similar to each other than to those in the 1900 to 1950 period. These variations were most apparent in the mid- to high latitudes of the Southern Hemisphere. A more meridional long-wave pattern occurred in the early and late periods, and a more zonal flow regime occurred in the 1900 to 1950 period. This research suggests that the vigour of the atmospheric circulation has increased since the 1950s, particularly around the anticyclones in the southern Indian Ocean during summer, and Australia in winter. These high pressure features were found to wax and wane, but show no distinct displacements in the latitude of central pressure.

Coherent changes in the amplitude of the long-wave troughs to the south-west of Australia and in the Tasman Sea/New Zealand region have occurred during spring and summer (Salinger *et al.*, 1995b). On a decadal time-scale the troughs in the two regions have varied out of phase during winter. Most of the longer term trends are associated with the Tasman Sea/New Zealand trough during summer and autumn. Pressure in the south-west Australian winter trough has increased since the 1960s, and this has led to a decrease in the winter rainfall in the far south-west (Nicholls and Lavery, 1992; Allan and Haylock, 1993).

3.4.5 Summary of Section 3.4

Evidence that the El Niño-Southern Oscillation has varied in period, recurrence interval, and area and strength of impact is found in historical instrumental data and in palaeoclimatic data. The cause of these variations is not known. The rather abrupt change in the El Niño-Southern Oscillation, and atmospheric circulation, around 1976/77, noted in IPCC (1990), has continued. Since then, there have been relatively more frequent El Niño episodes, with only rare excursions into the other extreme (La Niña episodes) of the phenomenon. This ENSO behaviour, and especially its behaviour since 1989, is unusual in the context of the last 120 years (the instrumental record). At least some of the recent fluctuations in rainfall in the tropics and subtropics (Figure 3.10) appear to be related to this unusual ENSO behaviour.

Anomalous atmospheric circulation regimes persisted over the North Pacific from 1976 to about 1988, and in the North Atlantic since 1989. Many long-lived temperature and precipitation anomalies are now known to be associated with regional anomalous atmospheric circulation features.

There remain problems with the monitoring of changes and variations in atmospheric circulation, because of doubts about the long-term consistency of analysis techniques, observations, and even the meteorological theories underlying analysis techniques. Such doubts restrict the number of fields which can be examined confidently for evidence of real change and variation.

3.5 Has the Climate Become More Variable or Extreme?

3.5.1 Background

Concerns are often expressed that the climate may be more variable (i.e., more droughts and extended wet periods) or extreme (i.e., more frequent severe weather events) now than in the past. A possible source of confusion in any discussion of variability is that variability of the climate can be defined and calculated in several ways. Apparently contradictory conclusions may be reached from the different definitions. For instance, using the standard deviation or a similar measure to determine variability will, in certain circumstances, result in different conclusions from the use of interperiod differences (e.g., first differences of annual means) as a measure of variability. Care needs to be taken in the comparison of variabilities calculated and defined in different ways. Analysis of how the frequency and intensity of extreme weather events (e.g., tornadoes) have varied over time is also difficult, because of inhomogeneities in the data. Comparisons over longer periods, such as comparing late 20th century extremes with those of the late 19th century, are especially problematic because of changes in instrumentation and analysis methods, as well as site and exposure changes.

3.5.2 Climate Variability

3.5.2.1 Temperature

Parker *et al.* (1992) show plots of the low-pass filtered variances of the daily central England temperature series since the mid-18th century. There is no clear evidence of trends in the variance over this very long record. Although there are interdecadal differences in variability, no tendency to higher variance is evident in recent decades.

Karl *et al.* (1995c) searched for evidence of changes in temperature variability in the USA, the former Soviet Union, China and Australia. They defined temperature variability as the absolute difference in temperature between two adjacent periods of time (1-day to annual). In the Northern Hemisphere their results indicate a tendency towards decreased temperature variability on intraseasonal (1-day to 5-day) time-scales. The decrease is strongest in the USA and China. The decreased variability at short time-scales could reflect a decrease in baroclinicity or the frequency of air mass change, suggesting that the Northern Hemisphere circulation may have become less variable through the 20th century. The interannual variability changes showed no consistent pattern across the three Northern Hemisphere areas. There was little consistency in patterns of change in temperature variability for Australia since 1961, apart from statistically significant decreases in interannual variability in September-November, for minimum, maximum, and average temperature, especially in temperate regions.

Parker *et al.* (1994) calculated the interannual variability of seasonal surface temperature anomalies for the 20-year period 1974 to 1993 for each calendar season separately, and compared it with the period 1954 to 1973. There was evidence of only a small global increase of variability in the later period. The spatially averaged ratios of the variances between the two 20-year periods, for the four seasons, were between 1.04 and 1.11. This suggests surface temperature variability increased slightly over the period of analysis. The analysis did reveal regions with strongly enhanced variability in the later period. Variance was enhanced over central North America between December and August. The El Niño events of 1982/3, 1986/7, and 1991/2 produced enhanced variance in the eastern tropical Pacific in 1978 to 1992 relative to 1951 to 1980.

In summary, temperature shows no consistent, global pattern of change in variability. Regional changes have occurred, but even these differ with the time-scale considered.

3.5.2.2 Precipitation and related moisture indices

Means and standard deviations of Indian summer monsoon rainfall, calculated using a 31-year moving window, over the period 1871 to 1993, were examined by Sontakke *et al.* (1992). No trend was apparent in variability over the entire period. However, higher variability is generally associated with drier periods, such as that observed since about 1970. Droughts have increased in frequency in Sub-Saharan Africa over the past few decades. This partly reflects the downward trend in mean rainfall (Section 3.3.2.1), but there were also changes in variability. Hulme (1992) examined changes in relative variability over Africa between 1931 to 1960 and 1961 to 1990 and found that areas of increased variability outweighed areas of reduced variability. The Sahel showed increased rainfall variability, especially in the east where increases were over 5% and in some places over 15%.

Changes in variability of the diurnal temperature range may provide some suggestive information regarding changes of variability of precipitation or cloudiness, since increased cloud cover can lead to warmer overnight temperatures, and lower daytime temperatures, in some regions. Karl *et al.* (1995c) examined changes in the variability of the diurnal range of temperature in the USA, the former Soviet Union, and China. They found decreases in the variability of the diurnal range, especially in the former Soviet Union. Since the diurnal range of temperature is related to cloud cover and humidity, decadal decreases in the variability of the diurnal range may reflect a decrease in variability of cloud cover, soil moisture, humidity, or wind.

Droughts have been relatively frequent since the late 1970s in some of the areas where drought usually accompanies El Niño events (e.g., north-east Australia). This presumably reflects the relatively frequent El Niño events during this period (see Section 3.4.2). Few analyses of the frequency of floods have been conducted. A study of floods in Sweden (Lindström, 1993) found no convincing evidence of trends through the 20th century, although the 1980s had larger floods than usual and the 1970s had few high floods. Wigley and Jones (1987) reported a higher than usual frequency of extreme dry summers and wet springs over England and Wales in 1976 to 1985. Gregory *et al.* (1991) updated the Wigley and Jones data to 1989 and found no evidence of a continuation of this tendency.

3.5.2.3 Atmospheric circulation

Born (1995) and Born and Flohn (1995) investigated atmospheric circulation variability using interdiurnal (i.e., day-to day) changes of surface pressure and geopotential in the Atlantic sector. Since 1970 there appears to have been a trend to increased variability on this time-scale. They also investigated maritime winds in the Atlantic between 60°N and 30°S, by examining trends in constancy (the resultant wind speed as a percentage of scalar wind speed). The trend at most latitudes from 1949 to 1989 was negative, indicating increasing variability. A trend towards lower variability (increasing constancy) was found only in winter between 45°N and 60°N. Doubts remain about the long-term consistency of the analyses from which these results were derived. Trenberth (1996) notes some of the changes in the systems used to analyse atmospheric circulation.

The results of Karl *et al.* (1995c) suggest that these findings cannot be extrapolated to infer increases in atmospheric circulation variability over the USA or much of Asia. Karl *et al.* found evidence of decreased variability of temperature at the interdiurnal time-scale in the USA, former Soviet Union and China. Since the variability of the atmospheric circulation provides the dominant forcing of interdiurnal temperatures in these regions, it seems unlikely that the interdiurnal variability of atmospheric circulation has increased there.

Changes in the mean atmospheric circulation over the North Pacific (Section 3.4.3) in the late 1970s were accompanied by a southward shift in storm tracks and the associated synoptic eddy activity (Trenberth and Hurrell, 1994). The incidence of cold outbreaks increased across the plains of North America at this time. Such shifts could be interpreted as changes in atmospheric circulation variability, at least on a regional scale.

The variability of the El Niño-Southern Oscillation has been examined by Wang and Ropelewski (1995) who noted a general rise in the level of variability from the earliest records to the 1910s, followed by a period of 20 to 40 years of no change, with a suggestion of increased variability over recent decades. ENSO variability was greater when the sea surface temperature was generally higher. However, the results were sensitive to the sea surface temperature analysis technique. Nonetheless, their conclusion was consistent with that of Rasmusson *et al.* (1994), who found a relative minimum in surface pressure variance and precipitation variability during the periods of relatively low mean sea surface temperature.

3.5.3 Extreme Weather Events

3.5.3.1 Tropical cyclones

Atlantic hurricane (tropical cyclone) activity over the period 1970 to 1987 was less than half that in the period 1947 to 1969 (Gray, 1990). A similar quiet period occurred at the same time in the western North Pacific, suggestive of a decrease in the number of very intense tropical cyclones. Bouchard (1990) and Black (1992), however, demonstrated that this apparent change in intensity in the western North Pacific was an artefact, due to a change around 1970 in the method used to derive wind estimates from pressure estimates. When a consistent method for determining wind estimates was used throughout the period of record, the pre-1970 data were statistically indistinguishable from the post-1970 data. Landsea (1993) suggested that the Atlantic hurricane intensity record was probably also biased. Winds were 5 kt higher before 1970, compared with hurricanes with the same minimum pressure after 1970. After adjusting for this bias a substantial downward trend in intense hurricane activity is still apparent. There remains a possibility that not all the bias in the Atlantic records has been removed, because of the remarkable drop in apparent intensity from 1970, the same year the artificial drop in frequency of intense typhoons appeared in the north-west Pacific. However, this step decrease was also observed in the frequency of storms hitting the USA. These storms were categorised by using minimum sea level pressure recorded at landfall. Such observations should not be as suspect as observations over the ocean. Also, the decrease in hurricanes appears to reflect a relationship between hurricane activity and Sahel rainfall (Landsea and Gray, 1992; Goldenberg and Shapiro, 1996). Finally, hurricane activity is also weaker during El Niño episodes. The relatively more frequent El Niño episodes since the mid-1970s (see Section 3.4.2) would, therefore, have led to a tendency for weak hurricane activity. There are strong grounds, therefore, for concluding that the decrease in Atlantic intense hurricane activity is real (Landsea *et al.*, 1996). However, Karl *et al.* (1995d) found no trend in the numbers of hurricanes crossing the USA coast since 1900, although numbers were higher during the middle decades of the century. The 1995 Atlantic hurricane season was more active than recent years.

In the north-east and south-west Pacific the number of cyclones appears to have increased (Thompson *et al.*, 1992; Landsea and Gray, 1995), although doubts must be expressed about the consistency of the observation systems over this period. In the south-east Pacific, where tropical cyclone activity is usually associated with El Niño events, the frequency of occurrence appears to have increased in recent decades. Again, the quality of the long-term cyclone data base in this region is suspect. In the Australian region much of the apparent long-term variations in cyclone activity appear to be the result of changes in observing systems or analysis techniques (Nicholls, 1992). Raper (1993) noted that little confidence could be placed in apparent long-term trends (except perhaps in the North Atlantic) because of doubts about the consistency of the data.

Doubts about the quality and consistency of the data on maximum wind speeds in most cyclone basins preclude convincing analysis of how peak cyclone intensity might have changed in recent decades. Only in the Atlantic do the

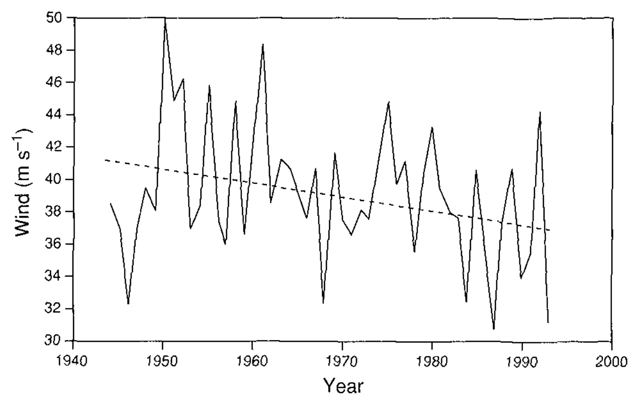


Figure 3.19: Time-series of mean annual maximum sustained wind speed attained in Atlantic hurricanes (Landsea *et al.*, 1996). Linear trend shown as dashed line.

data seem of sufficient quality to allow such an analysis. Figure 3.19 shows the mean maximum sustained wind speed attained each year in Atlantic hurricanes (Landsea *et al.*, 1996). Mean maximum wind speed appears to have decreased. However, the peak intensity reached by the strongest hurricane each year has shown no trend in the five-decade period.

3.5.3.2 *Extra-tropical storminess*

There is some evidence of recent increased storminess around the North Atlantic, although there are doubts about the consistency of the meteorological analyses from which this increase has been derived. Hand-drawn analyses of Atlantic surface pressure patterns, produced since 1956 by Seewetteramt, Hamburg, have been used to analyse the annual occurrence of extra-tropical cyclones (also known as low pressure systems or depressions) with minimum pressures below 950 hPa (Dronia, 1991). Little trend was found, except for an abrupt increase in frequency since 1988. Stein and Hense (1994), using daily grid-point pressure data, deduced that the North Atlantic winters since 1988/89 had been affected by a higher frequency of extreme low pressure systems than at any time since 1880. Schinke (1993) used once-daily analyses (USA analyses 1939 to 1964; thereafter German analyses) to count the number of storms with pressures below certain thresholds. This study revealed a substantial increase in the number of severe storms in the North Atlantic area, in the early 1970s. The mean central pressure showed a decreasing trend. Stein and Hense (1994) also deduced an increase in the numbers of extreme lows in the early 1970s, but concluded that this increase does not appear to be significant, when considered in the context of the observed interannual variability.

Schmidt and von Storch (1993) suggest that local studies with homogenous data bases may provide more definite answers, at least for specific regions, than the use of analyses with time-varying biases (Section 3.4.1). They used daily air pressure observations at three stations in the south-east North Sea to calculate the annual distributions of daily geostrophic wind speeds and concluded that the frequency of extreme storms in this area has not changed in the past 100 years. Von Storch *et al.* (1993) analysed a long time-series of "severe storm days" on Iceland, based on local wind observations, and found little trend in the number of severe storm days, (apart from an artificial change in storm frequency around 1949, because of changes in observing practices). Numbers of storms were quite low during the 1980s. Von Storch *et al.* (1993) also examined high water levels at Hoek van Holland, after removing the effects of tides and sea level changes. The resultant time-series should reveal storm-related surge heights. No trend was found in the frequency of extreme surge heights.

Bardin (1994) reported an abrupt increase in the frequency of extra-tropical depressions in the central North Pacific, in the late 1970s. For the Northern Hemisphere as a whole, Bardin found a decrease in cyclone frequency beginning in the second half of the 1980s, after a period of about a decade with higher numbers of cyclones. The size and intensity of cyclones were approximately constant until 1980, and had increased since then. Serreze *et al.* (1993) found increasing numbers of cyclones and anticyclones over the Arctic between 1952 and 1989.

Agee (1991) combined data from three previous studies of cyclone and anticyclone frequency around North America to examine trends. He found evidence of increases in extra-tropical cyclone numbers between 1905 and 1940 and decreasing numbers of both cyclones and anticyclones between about 1950 and 1980. Agee found some evidence of an increase in cyclone numbers between 1980 and 1985, but his data did not extend into more recent years. Temporal variations in winter storm disasters (Changnon and Changnon, 1992) closely matched the trends in cyclone numbers for North America. Davis and Dolan (1993) found a similar variation in the occurrences of mid-latitude cyclones over eastern North America. Cyclones were less frequent between the mid-1960s and the mid-1970s, relative to the period from 1942. Since the mid-1970s the yearly number has increased but has not consistently reached pre-1965 levels. The prevalence of the most destructive storms has been erratic, but has increased overall. Seven of the eight most intense storms that have developed in the past 50 years occurred in the last 25 years.

One Southern Hemisphere region where atmospheric depressions appear to have increased in number in recent decades is along the east coast of Australia. Hopkins and Holland (1995) determined the numbers of east coast cyclones with an objective method of specification based on a consistent set of observing stations spread along the coast. They found an upward trend in the numbers of cyclones between 1958 and 1992.

In summary, the evidence on changes in extra-tropical synoptic systems is inconclusive. There is no clear evidence of any uniform increase. Evidence from some areas suggests no change during the 20th century; in some other areas there is some evidence of change.

3.5.3.3 Intense rainfalls

Long-term rainfall observing sites can be used to examine changes in the frequency of intense 24-hour rainfall totals. Iwashima and Yamamoto (1993) did this, for 55 stations in Japan and for 14 stations in the contiguous USA, by determining the decades in which the three highest daily rainfall totals were recorded. A trend towards higher frequencies of extreme rainfalls in recent decades was evident. Such a trend was also found by Karl *et al.* (1995c) who analysed the trends in the percentage of total seasonal and annual precipitation occurring in heavy daily rainfall events (days with rainfalls exceeding 50.8 mm) over the USA (1911 to 1992), the former Soviet Union (1935 to 1989), and China (1952 to 1989). A significant trend to increased percentages of rainfall falling in heavy events is evident in the USA, largely due to a strong increase in extreme rainfall events during the warm season. A similar trend is also apparent in heavy rainfall events calculated from 3-day total rainfalls. Trends to more extreme rainfall events were not apparent in the other regions. A trend to increased annual rainfall around the periphery of the North Atlantic, since early this century, also appears to reflect an increase in the number of heavy rainfall events (Frich, 1994).

Rakhecha and Soman (1994) examined annual extreme rainfalls in the time-scale of 1–3 days at 316 stations well-distributed across India, for the period 1901 to 1980. Most annual extreme rainfall records were free of trend or autocorrelation. The extreme rainfall series over the west coast north of 12°N and at some stations to the east of the Western Ghats over the central parts of the Peninsula showed a statistically significant increasing trend. Stations over the southern Peninsula and over the lower Ganga valley exhibited a decreasing trend.

In Australia, the relationship between trends in mean rainfall and trends in intensity of rain events is complex (e.g., Nicholls and Kariko, 1993; Yu and Neil, 1991, 1993), except in the tropical regions (Lough, 1993; Suppiah and Hennessey, 1996). Lough (1993) found no evidence of a trend to more intense rainfall, or for greater numbers of heavy rain days between 1921 and 1987, in general over north-east Australia. Suppiah and Hennessey (1995), however, reported an increase in the frequency of extreme rainfall events at a majority of stations in northern Australian summers since 1910. Few of the increases were statistically significant.

Few studies have reported changes in occurrence of hail. Dessens (1994) reported a substantial increase in hail fall severity in France during summer. This increase was related to an increase in the summer mean minimum temperature which is significantly correlated with hail occurrence in France.

3.5.3.4 Extreme temperatures

One extreme that might be anticipated to change in frequency if mean temperatures increased is the frequency of frosts or freezes. Decreases over the past few decades in the frequency of extreme low minimum temperatures or the length of the frost season have been reported for several widely separated locations (Salinger *et al.*, 1990; Karl *et al.*, 1991; Watkins, 1991; Bootsma, 1994; Palecki, 1994; Cooter and LeDuc, 1995; Stone *et al.*, 1996). Cooter and LeDuc, for instance found that the frost-free season in the north-eastern USA now begins 11 days earlier than 30 years ago. However, not all the stations and regions examined in these studies exhibited a decrease in frost occurrence.

Changes in frequency of extreme maximum (daytime) temperatures were less consistent than was the case for minimum temperatures. Across the USA a spatially complicated pattern of variations in extreme maximum temperatures is evident, with no evidence of a country-wide increase in extremes (Karl *et al.*, 1991; Balling and Idso, 1990; DeGaetano *et al.*, 1994; Henderson *et al.*, 1994). Karl *et al.* found evidence of increases in extreme seasonal minimum temperatures in the contiguous USA and the former Soviet Union, but little or no change in extreme seasonal maximum temperatures. Plummer (1996) found that, in Australia, extreme minimum temperatures have been increasing at a similar rate to average temperatures but that trends in the extreme maximum temperatures were smaller.

In some areas there is evidence of decadal variations in the frequency of occurrence of regional cold outbreaks. For instance, changes in Pacific Ocean storm tracks since about 1976 (Trenberth and Hurrell, 1994) have been implicated in higher incidences of regional cold outbreaks, from the late 1970s to the mid-1980s, across the plains of North America, ultimately leading to an increased frequency of major freezes affecting Florida (Rogers and Rohli, 1991; Downton and Miller, 1993).

3.5.3.5 Tornadoes, thunderstorms, dust storms, and fire weather

The final type of extreme weather event considered here consists of events normally subject to visual reports. Identification of trends in such data is likely to be problematic, because of doubts about consistency of observer behaviour. There is little or no evidence of consistent increases in such events. For example, Ostby (1993) found no evidence of increased occurrence of strong or violent tornadoes in the USA, although the numbers of reports of less severe tornadoes appears to have increased, perhaps due to increased population, eagerness in reporting, or improved reporting procedures. Grazulis (1993) reported a drop in damaging tornadoes in the 1980s over the USA.

There is some evidence of an increase in thunderstorms in the global tropics, from observations of trends in cloudiness (London *et al.*, 1991). The amount of cumulonimbus clouds, often associated with thunderstorms, increased over the tropical oceans between 1952 and 1981 partly at the expense of cumulus clouds (Section 3.3.8.2). This suggests an increase in thunderstorm activity in the tropics. Increases in summer extreme rainfall events in the USA reported by Karl *et al.* (1995c), and in tropical Australia during summer (Suppiah and Hennessey, 1995) also may reflect an increase in thunderstorm activity. Overall, however, land based tropical rainfall has declined in the last few decades (see Figure 3.11). A large percentage of rainfall is associated with thunderstorm activity, so the decrease in rainfall might reflect a drop in thunderstorm activity, at least over tropical land areas. Karl *et al.* (1995c) did not find increases in summer extreme rainfall events in China or the former Soviet Union.

Goudie and Middleton (1992) examined time-series of dust storms for many parts of the world. They found no global pattern of dust storm frequency trend, and concluded that, in the absence of regional-scale human activities (e.g., changes in agricultural practices), the major factor affecting numbers of dust storms is rainfall. So a change in rainfall might be expected to lead to changes in the frequency of dust storms.

Balling *et al.* (1992) examined variations in wildfire data in the Yellowstone National Park between 1895 and 1990. The area burnt is positively related to summer temperature and negatively related to summer and antecedent precipitation. Summer temperatures have been increasing in this area through the 20th century, while antecedent precipitation has been decreasing. Balling *et al.* concluded that there has been a significant trend to a set of climatic conditions favouring the outbreak of wildfires.

3.5.4 Summary of Section 3.5

There has been no consistent trend in interannual temperature variability in recent decades. In some areas variability on shorter time-scales has decreased. Few regions have been examined for evidence of changes in interannual variability of rainfall. The areas examined have not exhibited a consistent pattern. Trends in intense rainfalls are not globally consistent, although in some areas (Japan, the USA, tropical Australia) there is some evidence of increases in the intensity or frequency of extreme events. There has been a clear trend to fewer low temperatures and frosts in several widely-separated areas in recent decades. Widespread significant changes in extreme high temperature events have not been observed, even in areas where the mean temperatures have increased.

There are grounds for believing that intense tropical cyclone activity has decreased in the North Atlantic, the one tropical cyclone region with apparently consistent data over a long period. Elsewhere, apparent trends in tropical cyclone activity are most likely due to inconsistent analysis and observing systems. Doubts in the consistency of meteorological analyses also confound the estimation of trends in extra-tropical cyclones. In some regions (e.g., over the USA, the east coast of Australia, the North Atlantic) there is some evidence suggestive of recent increases. However some other highly reliable records in particular regions (e.g., the German Bight) do not exhibit any trends to increased storminess.

Overall, there is no evidence that extreme weather events, or climate variability, has increased, in a global sense, through the 20th century, although data and analyses are poor and not comprehensive. On regional scales there is clear evidence of changes in some extremes and climate variability indicators. Some of these changes have been toward greater variability; some have been toward lower variability.

3.6 Is the 20th Century Warming Unusual?

3.6.1 Background

To understand recent and future climatic change, it is necessary to document how climates have varied in the past, i.e., the space- and time-scales of natural climate variability. Such information is necessary, for instance, to determine whether the changes and variations documented earlier in this chapter are likely to reflect natural (rather than human-induced) climate variability. Some measure of this natural variability can be deduced from instrumental observations, but these are restricted, for the most part, to less than 150 years. Longer records of climate variations are required to provide a more complete picture of natural climate variability against which anthropogenic influences in the observed climate record can be assessed. Changes in the thermohaline circulation are one example of internal (natural) variability in the climate system affecting temperature trends. Evidence of such changes has been found in some ice-age records, although the evidence is more muted for fluctuations of the last 10,000 years.

IPCC (1990) provided a broad overview of the climates of the past 5,000,000 years, and a more detailed presentation of three periods suggested as possible analogues of a greenhouse-enhanced world. IPCC (1992) concentrated on the climate of the past 1000 years, a topic which this chapter also examines, because of the recent increase in data for this period, and because of its relevance to the current climate. The data from the last 1000 years are the most useful for determining the scales of natural climate variability. Rapid natural climate changes also provide information on the sensitivity/stability of the climate system of relevance in projections of climate change. Recent evidence of such changes over the last 150,000 years is also assessed here.

Climates from before the recent instrumental era must be deduced from palaeoclimatic records. These include tree rings, pollen series, faunal and floral abundances in deep-sea cores, isotope analysis from coral and ice cores, and diaries and other documentary evidence. The difficulty of determining past climates can be illustrated by the case of tropical sea surface temperatures (SSTs) around the time of the last glacial maximum (around 22,000-18,000 years ago). The lack of consensus on this topic provides an indication of the problems of using proxy data. The topic is important partly because of the possible use of glacial data in validating climate models, and relating past climates to radiative forcings (Crowley, 1994). The relationship between modern and past terrestrial and sea surface temperatures is still one of the major uncertainties involved in understanding the climate during the last ice age. Terrestrial surface temperature estimates from snow line and pollen data (e.g., Webster and Streten, 1978; Seltzer, 1992), SSTs from coral (e.g., Beck *et al.*, 1992; Aharon *et al.*, 1994; Guilderson *et al.*, 1994), and from ice cores in the Andes (Thompson *et al.*, 1995) do not concur with estimates from other sources such as oxygen isotope, planktonic foraminiferal and pollen records and the temperature dependent saturation of long-chain alkenones from algae (e.g., Ohkouchi *et al.*, 1994; Sikes and Keigwin, 1994; Thunnell *et al.*, 1994). The land-based data (and some estimates from coral) suggest that ice age SSTs in the tropics were about 5°C lower than present, while the other sources suggest about 1–2°C. These inconsistencies cause problems in the use of palaeoclimatic data to validate climate models, and need to be resolved.

3.6.2 Climate of the Past 1000 Years

Various methods based on historical, ice core, tree-ring, lake level and coral data have been used to reconstruct the climate of the last millennium (Cook, 1995). For example, a significant number of annually resolved, precisely dated temperature histories from tree rings are available. However, these records are still too sparse to provide a complete global analysis, and must, in general be interpreted in a regional context. In addition, they usually only reflect changes in warm-season (growing season) temperatures. Tree-ring records frequently represent interannual and decadal time-scale climate variability with good fidelity, as indicated by comparison with recent instrumental records. However, the extent to which multi-decadal, century, and longer time-scale variability is expressed can vary, depending on the length of individual ring-width or ring-density series that make up the chronologies, and the way in which these series have been processed to remove non-climatic trends. In addition, the possible confounding effects of carbon dioxide fertilisation needs to be taken into account when calibrating tree-ring data against climate variations. Coral records are available from regions not represented by tree rings and usually have annual resolution. However, none extends back more than a few hundred years. The interpretation of ice core records from polar ice sheets and tropical glaciers may be in some cases limited by the noise inherent to snow depositional processes, especially during this period when climate changes were rather small (by comparison, for instance, with the large rapid changes discussed in the next section). On the other hand, they can give an unambiguous record of accumulation change, on an annual basis. All these forms of data can and have been used to provide information regarding climate variations of the past 1000 years.

There are, for this last millennium, two periods which have received special attention, the Medieval Warm Period and the Little Ice Age. These have been interpreted, at times, as periods of global warmth and coolness, respectively. Recent studies have re-evaluated the interval commonly known as the Medieval Warm Period to assess the magnitude and geographical extent of any prolonged warm interval between the 9th and 14th centuries (Hughes and Diaz, 1994). The available evidence is limited (geographically) and is equivocal. A number of records do indeed show evidence for warmer conditions at some time during this interval, especially in the 11th and 12th centuries in parts of Europe, as pointed out by Lamb (1965, 1988). There are also indications of changes in precipitation patterns and associated droughts both in California and Patagonia during medieval time (Stine, 1994). However other records show no such evidence, or indicate that warmer conditions prevailed, but at different times. This rather incoherent picture may be due to an inadequate number of records or a bias in the geographical and seasonal representation in the available data (Briffa and Jones, 1993; Jones and Briffa, 1996), and a clearer picture may emerge as more and better calibrated proxy records are produced. However, at this point, it is not yet possible to say whether, on a hemispheric scale, temperatures declined from the 11–12th to the 16–17th century. Nor, therefore, is it possible to conclude that global temperatures in the Medieval Warm Period were comparable to the warm decades of the late 20th century.

The term Little Ice Age is often used to describe a 400-500 year long, globally synchronous cold interval, but studies now show that the climate of the last few centuries was more spatially and temporally complex than this simple concept implies (Jones and Bradley, 1992). It was a period of both warm and cold climatic anomalies that varied in importance geographically. For the Northern Hemisphere as a whole, the coldest intervals of summer temperature were from 1570 to 1730 (especially 1600 to 1609) and during most of the 19th century, though individual records show variations in this basic pattern. Warmer conditions were more common in the early 16th century and in most of the 18th century, though for the entire hemisphere, conditions comparable to the decades from 1920 onward (the time when instrumental records become more reliable and widely available) have not been experienced for at least several hundred years. Temperatures from boreholes (Section 3.2.5.2) also suggest that the present temperatures in parts of North America and perhaps elsewhere may be warmer than the last few hundred years. Regional temperatures do not all, of course, conform to this pattern. For instance, spring temperatures during the period 1720 to 1770 appeared to be warmer than the 20th century in parts of China (Hameed and Gong, 1994). However, despite the spatial and temporal complexity, it does appear that much of the world was cooler in the few centuries prior to the present century.

Bradley and Jones (1993, 1995) developed a Northern Hemisphere summer temperature reconstruction since 1400 from 16 palaeoclimatic records (Figure 3.20). Recent decades (the recent instrumental record is also plotted on this figure) appear to be warmer than any extended period since 1400, and the warming since the late 19th century is unprecedented in this record. Regionally, however, the recent warming is not always exceptional. For instance, in the Swedish Torneträsk tree-ring series, the 20th century warming appears as a relatively minor event (Briffa *et al.*, 1990; 1992). In this region, in both the 1400s and, especially, the 900–1100 interval, summer conditions appear to have been warmer than today. Tree-ring width series from the northern Urals (Graybill and Shiyatov, 1992) indicate that in this area 20th century summers have been somewhat warmer than average. A recent analysis, using tree-ring density data, has attempted to reproduce more of the century time-scale temperature variability in this region (Briffa *et al.*, 1995). This shows that the 20th century was clearly the warmest in the last 1000 years in this region, though shorter warmer periods occurred, for example, in the 13th and 14th centuries. The Californian Cirque Peak ring-width cool-season temperature history (Graybill and Funkhouser, 1994) indicates unusual warmth during most of the 20th century, but with recent cooling (contrary to instrumental observations in this area). The nearby Campito Mountain ring-width warm-season temperature history (LaMarche, 1974) agrees well with the Cirque Peak record, e.g., the 20th century appears to have been unusually warm, while the 17th century was generally cool. North-west Alaska has been unusually warm during the 20th century (Jacoby *et al.*, 1996).

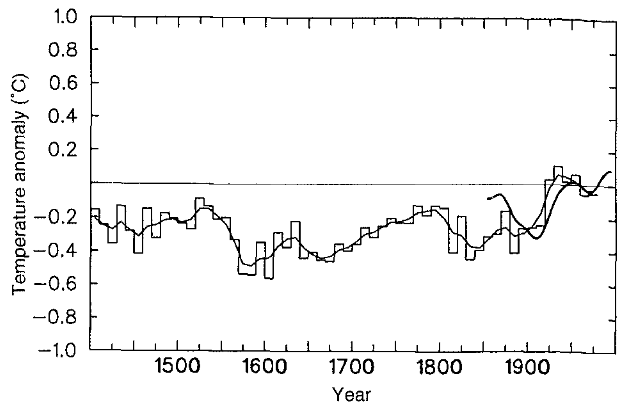


Figure 3.20: Decadal summer temperature index for the Northern Hemisphere, from Bradley and Jones (1993), up to 1970-1979. The record is based on the average of 16 proxy summer temperature records from North America, Europe and east Asia. The smooth line was created using an approximately 50-year Gaussian filter. Recent instrumental data for Northern Hemisphere summer temperature anomalies (over land and ocean) are also plotted (thick line). The instrumental record is probably biased high in the mid-19th century, because of exposures differing from current techniques (e.g., Parker, 1994b).

In the Southern Hemisphere, the records from Australasia show evidence of recent unusual warmth, especially since 1960, but some from South America do not. Thus the Northern Patagonia and Rio Alerce ring-width records from Argentina (Villalba, 1990; Boninsegna, 1992) and the Chilean Lenca ring-width temperature history (Lara and Villalba, 1993) show no clear indication of 20th century warming, in accord with local instrumental records (Villalba, 1990). Recently analysed ice cores from the north-central Andes (Thompson *et al.*, 1995) indicate that temperatures were cool in the 200–500 years before the present. Strong warming has dominated the last two centuries in this region. Temperatures in the last two centuries appear higher than for some thousands of years in this area. New Zealand tree rings reproduce the warming observed instrumentally since about 1950, although there is also a suggestion of warmer periods early in the 18th and 19th centuries (Salinger *et al.*, 1994), near a time of maximum mountain glacier ice volumes in the Southern Alps of the country. The Tasmanian Lake Johnston history (Cook *et al.*, 1991) shows recent anomalous warming, especially since 1960 (Cook *et al.*, 1992).

Temperature records derived from coral supplement the records from tree rings. A Galapagos Islands coral temperature record for 1607 to 1982 has been derived by Dunbar *et al.* (1994) who found a very high correlation with directly measured local annual SST for 1961 to 1982. Coral-estimated SSTs have fallen significantly throughout the 20th century in this location and may now be at their lowest since 1650. This is in broad agreement with the lack of recent warming in the South American tree-ring studies. However, there has not been a general cooling in the eastern tropical Pacific this century (Bottomley *et al.*, 1990), so the Galapagos cooling may be a local phenomenon. Australian Great Barrier Reef temperature histories since 1583 have been derived from corals distributed along the reef from 10–30°S (Lough *et al.*, 1996). These coral-based SSTs have been relatively warm for most of the 20th century. This warm period was preceded by below-average SSTs in the 1850 to 1900 period. An earlier warm period is indicated around 1830 to 1840, but with less certainty. The pre-1800 period was probably a time of conspicuously below-average SSTs. Similar results were obtained from the Abraham Reef record (Druffel and Griffin, 1993), on the south-western tip of the Great Barrier Reef.

Just as important as temperature are variations in the hydrological cycle during the last millennium. Global-scale records do not exist, but useful information has been derived for several continents. Especially relevant, because of the recent low rainfall in the Sahel (Section 3.3.2.1), is the evidence from Africa. From the 10th to 13th centuries the evidence suggests a much wetter climate over much of North Africa (Nicholson, 1978). After a drier regime during the 14th and 15th centuries, resembling the 20th century climate, North Africa again reverted to relatively wet conditions during the 16th to the late 18th centuries. Interspersed in this moderately wet era were extreme droughts in the Sahel in the 1680s and the 1740s to 1750s. Continental-scale dryness began in the 1790s and climaxed in a severe drought in the 1820s and 1830s. These two decades were likely drier than current conditions throughout the continent, except in the Sahel where current conditions are similar to those in the 1820 to 1830 period. The late 19th century again saw a rise in African rainfall that subsided around 1900. Rainfall increased during the 1950s and 1960s in North and Equatorial Africa, followed by a sharp decrease in the Sahel. The conditions during the last 100 years have been, for the most part, substantially drier than the rest of the last millennium. Of particular note are the dry conditions in the Sahel between 1968 and 1993. Nicholson (1989) has documented several previous dry regimes also lasting on the scale of a decade or two, particularly the 1680s, 1740s and 1750s, and 1820s and 1830s, that mirrored the recent period in the Sahel. So, the recent past has exhibited periods of comparable dryness to the last few decades.

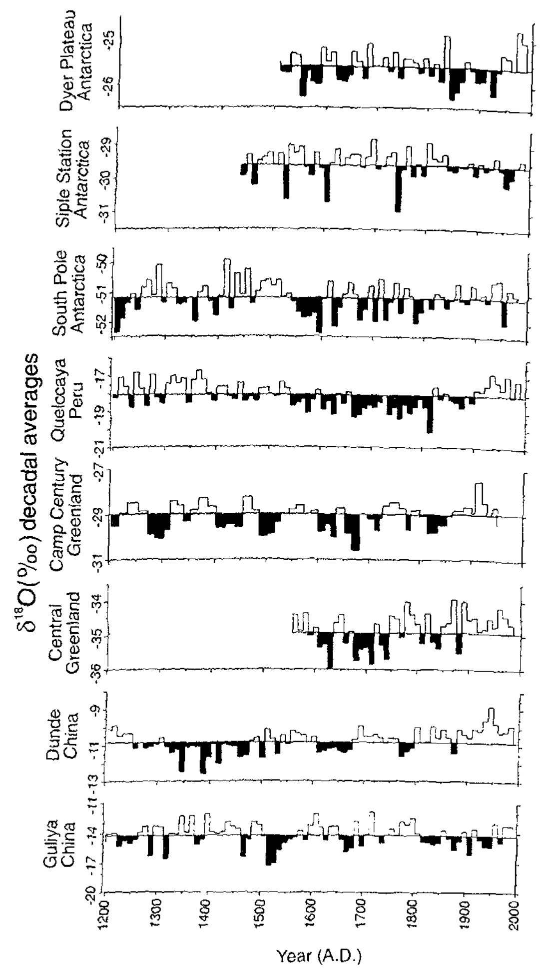


Figure 3.21: Decadal averages of the $\delta^{18}O$ records from ice cores in several widespread locations (after Thompson *et al.*, 1993). The shaded areas represent isotopically more negative (cooler) periods relative to the individual record means.

The climate of the past 1000 years provides opportunities to determine the spatial and temporal scales of natural climate variability required for detection of climate change, and the causes of the natural climate variations. A relatively small number of records from key regions could help discriminate the relative importance of different phenomena (Crowley and Kim, 1993), in the creation of decadal-century time-scale variability. For instance, volcanism would influence land more than ocean, North Atlantic thermohaline processes may have unique climate signatures, records from the equatorial Pacific could be used to monitor decadal-scale variations in that region (e.g., variations in the El Niño-Southern Oscillation – see Section 3.4.2). Some of the palaeoclimatic records already exist. Figure 3.21 (after Thompson *et al.*, 1993) shows temperature estimates from ice cores in several widespread locations. These show warming this century, but the warming appears to be more significant in some locations than others. As noted above, geographical differences also exist in the warming estimated from tree-ring chronologies. The development and combination of more high-quality records such as those in Figure 3.21 are needed, if a more complete understanding of the scales and causes of natural climate variability is to be gained. Overall, however, it appears that the 20th century has been at least as warm as any century since at least 1400 AD. In at least some areas, the recent period appears to be warmer than has been the case for a thousand or more years (e.g., Briffa *et al.*, 1995; Thompson *et al.*, 1995). Alpine glacier advance and retreat chronologies (Wigley and Kelly, 1990) suggest that in at least alpine areas, global 20th century temperatures may be warmer than any century since 1000 AD, and perhaps as warm as during any extended period (of several centuries) in the past 10,000 years. Crowley and Kim (1995) estimate the variability of global mean

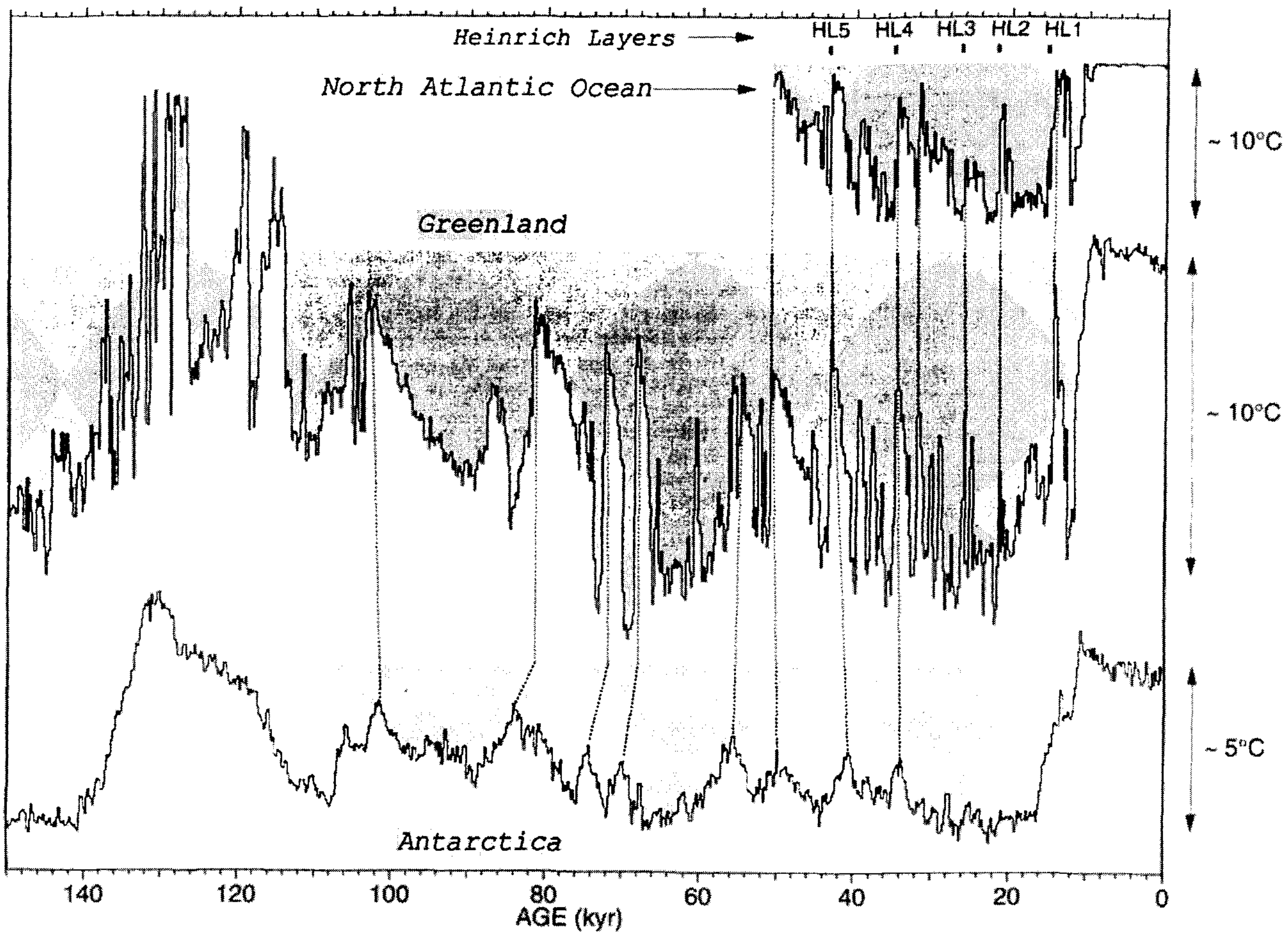


Figure 3.22: Reconstructed climate records showing rapid changes in the North Atlantic and in Greenland; the corresponding events (indicated by thin dashed vertical lines) are damped in the Antarctic record. Temperature changes are estimated from the isotopic content of ice (Greenland and Antarctica) and from faunal counts (North Atlantic). HL1 to HL5 indicate sedimentary "Heinrich" layers. Figure adapted from Jouzel et al. (1994).

temperature on century time-scales, over the past millennium, as less than ±0.5°C.

3.6.3 Rapid Cimate Changes in the Last 150,000 Years

The warming of the late 20th century appears to be rapid, when viewed in the context of the last millennium (see above, and Figures 3.20, 3.21). But have similar, rapid changes occurred in the past? That is, are such changes a part of the natural climate variability? Large and rapid climatic changes did occur during the last ice age and during the transition towards the present Holocene period which started about 10,000 years ago (Figure 3.22). Those changes may have occurred on the time-scale of a human life or less, at least in the North Atlantic where they are best documented. Many climate variables were affected: atmospheric temperature and circulation, precipitation patterns and hydrological cycle, temperature and circulation of the ocean.

Much information about rapid climatic changes has recently been obtained either from a refined interpretation of existing records or from new ice, ocean and continental records from various parts of the world. Of particular significance are those concerning the North Atlantic and adjacent continents such as the GRIP (Dansgaard *et al.*, 1993) and GISP 2 (Grootes *et al.*, 1993) central Greenland ice cores, numerous deep-sea core records from the North Atlantic, and continental records (lake sediments, pollen series, etc.) from Western Europe and North America. These records provide descriptions of the last glacial period and the following deglaciation. The observed rapid changes are often large in magnitude, and thus there is considerable confidence in their reality.

There is evidence from these records of rapid warming ~11,500 calendar years ago. Central Greenland temperatures increased by ~7°C in a few decades (Dansgaard *et al.*, 1989; Johnsen *et al.*, 1992; Grootes *et al.*, 1993). There are indications of an even more rapid change in the precipitation pattern (Alley *et al.*, 1993) and of rapid reorganisations in the atmospheric circulation (Taylor *et al.*, 1993a; Mayewski *et al.*, 1993). Changes in SST, associated with sudden changes in oceanic circulation, also occurred in a few decades, at least in the Norwegian Sea (~5°C in fewer than 40 years; Lehman and Keigwin, 1992). During the last 20,000 years surface water salinity and temperature have exhibited parallel changes that resulted in reduced oceanic convection in the North Atlantic and in reduced strength of the global conveyor belt ocean circulation (Duplessy *et al.*, 1992). There was also a hiatus in the warming in the Southern Hemisphere during the last deglaciation. The subsequent warming was much less abrupt than in the Northern Hemisphere (Jouzel *et al.*, 1995). Similar behaviour occurred in New Zealand (Suggate, 1990; Denton and Hendy, 1994; Salinger, 1994).

There is also firm evidence of rapid warm-cold oscillations during the last glacial (Dansgaard-Oeschger events) in the central Greenland records (Johnsen *et al.*, 1992). Rapid warmings of ~5–7°C in a few decades were followed by periods of slower cooling and then a generally rapid return to glacial conditions. About 20 such intervals (interstadials) lasting between 500 and 2000 years occurred during the last glacial period (Dansgaard *et al.*, 1993). Their general progression was similar to the rapid changes in North Atlantic deep-sea core records. The most prominent of these interstadials may be associated with the sedimentary "Heinrich" layers interpreted as reflecting massive iceberg discharge from Northern Hemisphere ice sheets (Bond *et al.*, 1993; Mayewski *et al.*, 1994; Bond and Lotti; 1995), see Figure 3.22. These discharges occurred at the end of the cooling cycles and were followed by abrupt shifts to warmer SSTs.

During the last glacial period, rapid changes were also felt over at least parts of the continents as suggested by recently obtained records for Western Europe, North America, and China (Grimm *et al.*, 1993; Guiot *et al.*, 1993; Porter and An, 1995). Moreover, a significant increase in methane concentration is associated with the warm interstadials (Chappellaz *et al.*, 1993) that may be due to variations in the hydrological cycle at low latitudes. This suggests that the interstadials were at least hemispheric in their extent. Moreover, Greenland interstadials lasting more than 2000 years have weaker and smoother counterparts in Antarctica (Bender *et al.*, 1994; Jouzel *et al.*, 1994). Keigwin *et al.* (1994) and McManus *et al.* (1994) found that Atlantic deep-water circulation and surface temperatures exhibited high variability through much of the last glacial, and that these variations were closely related to fluctuations in the Greenland ice cores. Keigwin *et al.* (1994) also report evidence from terrestrial palaeoclimate data suggesting that the short duration events since about 100,000 years ago were at least hemispheric, possibly global in extent.

The GRIP central Greenland ice core suggests that climate instability may also have been present during the last interglacial (Eemian). This period (~115,000–130,000 years ago) was locally warmer in Greenland than the present climate by up to 4°C but may have been interrupted by a series of changes that began extremely rapidly and lasted from decades to centuries. Questions about the validity of interpretation of the GRIP Eemian changes arise because there are significant differences between the GRIP and the GISP 2 records for the Eemian whereas the two cores, only 28 km apart, are in excellent agreement throughout the Holocene and the last glacial period. The bottom 10% of each core contains deformational features that are likely to have disturbed their stratigraphy (Taylor *et al.*, 1993b; Alley *et al.*, 1995). Comparison of the composition of entrapped air with the undisturbed Antarctic air composition record shows that mixing of ice of different origin has affected the bottom part of the GISP 2 core (Bender *et al.*, 1994). Until such an approach has been exploited for GRIP the possibility that disturbances simply change the apparent timing of events within the Eemian cannot be excluded for this core.

Evidence from other sources does little, at this stage, to determine whether or not these apparent Eemian rapid climate changes are real. Keigwin *et al.* (1994) and McManus *et al.* (1994) find little evidence of variability during the Eemian. Thouveny *et al.* (1994) and Field *et al.* (1994), however, report that pollen and rock magnetism data from western Europe show somewhat similar changes to the GRIP ice core record although the abrupt change found by Field *et al.*, may be a statistical artefact (Aaby and Tauber, 1995). Cortijo *et al.* (1992) also found rapid cooling in the ocean record during the Eemian. This may suggest that climate changes during the Eemian were fundamentally different in scale and area of influence, compared to more recent events.

These rapid events are relevant to understanding current climate because they affect on the human time-scales important climatic variables on a large geographical scale. However, at least some of these abrupt changes have been attributed to the instability of an ice sheet which does not exist in today's world. The relevance of past abrupt events to present and future climate would be more convincing if the suggested high climate variability in the Eemian was confirmed.

Abrupt regional events also occurred in the past 10,000 years (e.g., Berger and Labeyrie, 1987). These changes, however, have been smaller and smoother than those during the previous glacial period. Such events are perhaps more relevant to the estimation of the possible speed of natural climate variations in the current climate, because of the closer similarity of boundary conditions (e.g., continental positions and ice sheets) to the current situation. It seems unlikely, given the smaller regional changes, that global mean temperatures have varied by 1°C or more in a century at any time during the last 10,000 years (e.g., Wigley and Kelly, 1990).

3.6.4 Summary of 3.6

Palaeoclimatic data are needed to better estimate natural climate variability to help resolve the climate change detection issue (Chapter 8), and are useful for the evaluation of climate models (Chapter 5).

Large and rapid climatic changes occurred during the last ice age and during the transition towards the present Holocene period. Some of those changes may have occurred on time-scales of a few decades, at least in the North Atlantic where they are best documented. They affected atmospheric and oceanic circulation and temperature, and the hydrologic cycle. There are suggestions that similar rapid changes may have also occurred during the last interglacial (the Eemian) period, but this requires confirmation. The recent (20th century) warming needs to be considered in the light of evidence that rapid climatic changes can occur naturally in the climate. However, temperatures have been far less variable during the last 10,000 years (i.e., during the Holocene).

Recent studies have demonstrated that the two periods commonly known as the Medieval Warm Period and the Little Ice Age were geographically more complex than previously believed. It is not yet possible to say whether, on a hemispheric scale, temperatures declined from the 11–12th to the 16–17th century. However, it is clear that the period of instrumental record began during one of the cooler periods of the past millennium.

Two views of the temperature record of the last century are possible if this record is viewed with the longer perspective provided by the palaeoclimatic data (Figure 3.20). On the one hand, the long-term change of temperature could be interpreted as showing a gradual increase from the late 16th century, interrupted by cooler conditions in the 19th century. Alternatively, one could argue that temperatures fluctuated around a mean somewhat lower than the 1860 to 1959 average (punctuated by cooler intervals in the late 16th, 17th and 19th centuries) and then underwent pronounced, and unprecedented (since 1400) warming in the early 20th century. Whichever view is considered, mid-late 20th century surface temperatures appear to have been warmer than any similar period of at least the last 600 years (Figures 3.20, 3.21). In at least some regions 20th century temperatures have been warmer than any other century for some thousands of years.

3.7 Are the Observed Trends Internally Consistent?

Estimates of changes in some important climatic variables examined earlier in this chapter, for the instrumental period are provided in Figure 3.23. The periods over which the changes have been estimated differ for the different variables, reflecting the availability of credible data. The information in the figure is meant to provide only a gross picture of climate variations during the instrumental record. In particular, it should not be interpreted as implying that any changes in the climate during the instrumental period have been linear or even necessarily monotonic. Examination of the earlier parts of this chapter will reveal more information, including the general absence of simple, linear trends over extended periods, for all the variables included in Figure 3.23.

Not all the climatic variables exhibiting substantial variations are represented in Figure 3.23, for simplicity. For example, changes in extreme events are not indicated on the schematic. There has been a clear trend to fewer frosts and low temperatures in several widely separated areas in recent decades. One recent circulation change is well-documented: the rather abrupt change in ENSO and atmospheric circulation, around 1976/77, noted in IPCC (1990). El Niño episodes have been relatively frequent since that time, with only rare excursions into La Niña episodes (e.g., 1988/89). There have been substantial prolonged precipitation and circulation anomalies associated with this extended period.

The pattern of change represented in Figure 3.23 is internally consistent. All the forms of data used to examine climate change and variability suffer from problems of quality and consistency, so conclusions reached on the basis of just one form of data must always be somewhat suspect. However, the internal consistency shown in Figure 3.23, of a warm late-20th century world, accompanied by some changes in the hydrologic cycle, confirms the validity of the messages from the individual forms of data. So, the

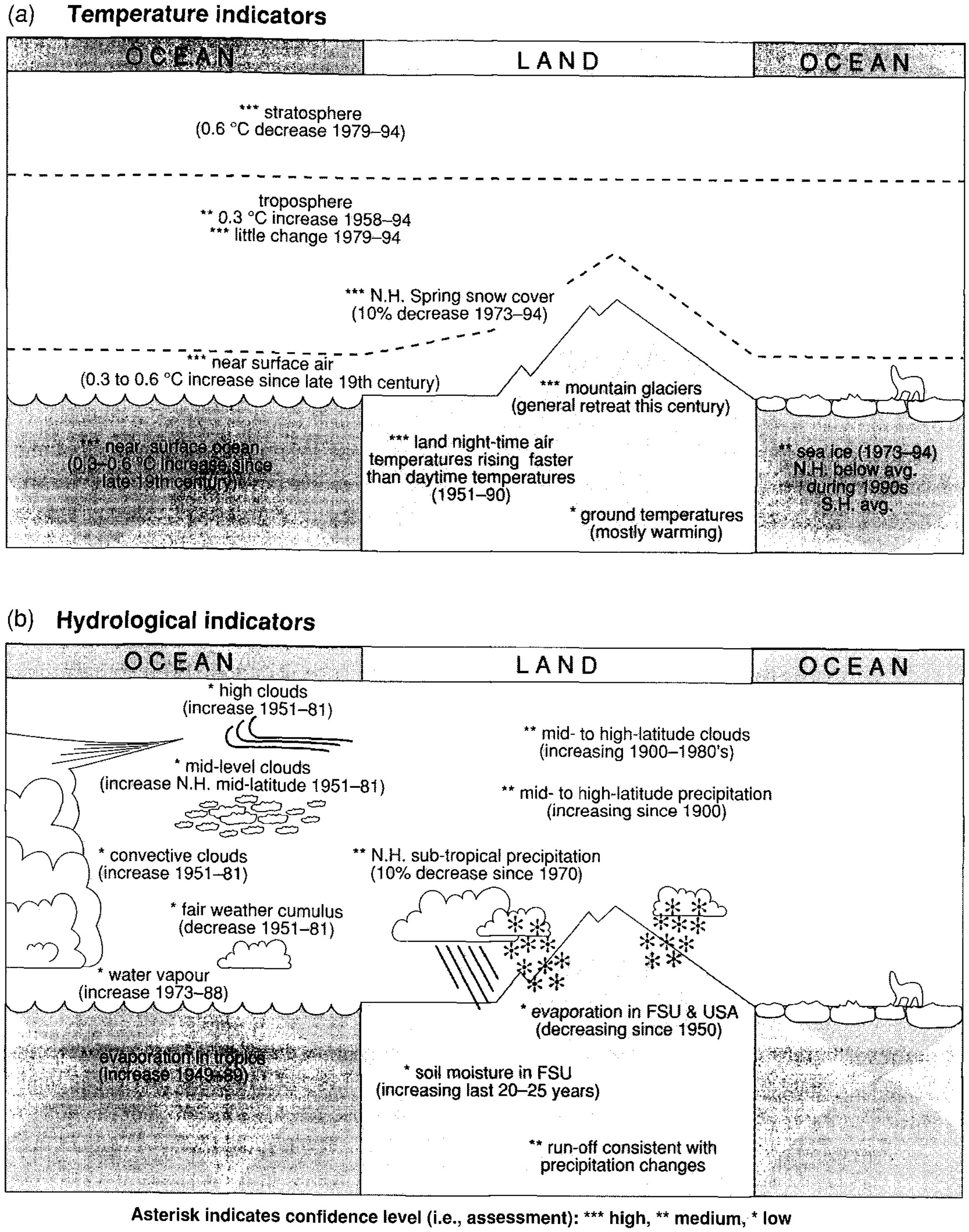


Figure 3.23: (a) Schematic of observed variations of temperature. (b) Schematic of observed variations of the hydrologic cycle.

observed warming cannot be attributed to urbanisation since it is also found in ocean temperatures and reflected in indirect temperature measurements. The increased 40–70°N precipitation is reflected in increased streamflow.

Despite this consistency, it should be clear from the earlier parts of this chapter that current data and systems are inadequate for the complete description of climate change. Virtually every monitoring system and data set requires better data quality and continuity. New monitoring systems, as well as improvements on current systems and studies to reduce quality problems from historical data, are required. Such improvements are essential, if we are to answer conclusively the questions posed in this chapter. Enormous amounts of meteorological data have been collected and archived over the past century. Even greater amounts will be collected, using new observing systems, in the future. The old and new observations will need to be combined carefully, and comprehensive efforts made to reduce the influence of time-varying biases in all the data, and to protect the integrity of long-established, high-quality observing systems and sites, if we are to obtain more accurate and complete estimates of observed climate change and variability.

Conventional meteorological data, both now and in the past, were collected for weather prediction and for the description of the current climate. They require considerable work to ensure that they are useful for monitoring climate variability and change. Studies are required to ensure that adequate corrections can be made for changes in instrumentation, exposure, etc. The reduction of such problems in the future, as well as the past, will require the protection of high-quality climate observing sites.

Probably no single climate element has been studied more than near-surface temperature over land. Unfortunately, the present rate of decline of global data acquisition and exchange across the Global Telecommunications System threatens estimates of near-surface global temperature change (Karl *et al.*, 1995a). Historical temperature data are plagued by inhomogeneities from changes in instrumentation, exposure, site-changes, and time-of-observation bias. Many of these problems can be overcome by thorough comparisons between stations and with the help of metadata (documentation regarding site and instrumentation changes etc.). Few countries, however, provide adequate support for such activities. Changes in instrumentation in recent times continue to pose problems. Karl *et al.* (1995a) note, for instance, that the introduction of a new maximum-minimum thermistor in the USA co-operative observing network has introduced a systematic bias. Oceanographic data suffer from a lack of continuity. Conclusive detection and attribution of global climate change will require an ongoing homogenous, globally representative climate record. This needs to be given high priority in the design and maintenance of meteorological and oceanographic monitoring systems.

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