2.7 Has Climate Variability, or have Climate Extremes, Changed?

2.7.1 Background

Changes in climate variability and extremes of weather and climate events have received increased attention in the last few years. Understanding changes in climate variability and climate extremes is made difficult by interactions between the changes in the mean and variability (Meehl *et al.*, 2000). Such interactions vary from variable to variable depending on their statistical distribution. For example, the distribution of temperatures often resembles a normal distribution where non-stationarity of the distribution implies changes in the mean or variance. In such a distribution, an increase in the mean leads to new record high temperatures (Figure 2.32a), but a change in the mean does not imply any change in variability. For example, in Figure 2.32a, the range between the hottest and coldest temperatures does not change. An increase in variability without a change in the mean implies an increase in the probability of both hot and cold extremes as well as the absolute value of the extremes (Figure 2.32b). Increases in both the mean and the variability are also possible (Figure 2.32c), which affects (in this example) the probability of hot and cold extremes, with more frequent hot events with more extreme high temperatures and fewer cold events. Other combinations of changes in both mean and variability would lead to different results.

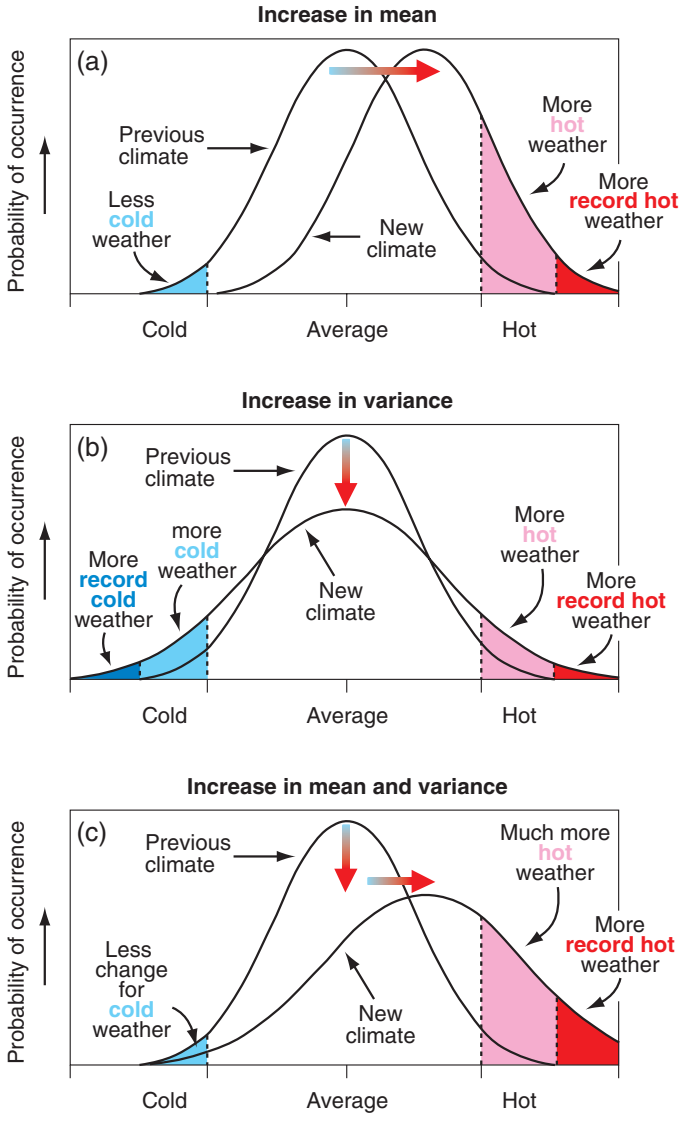

Figure 2.32: Schematic showing the effect on extreme temperatures when (a) the mean temperature increases, (b) the variance increases, and (c) when both the mean and variance increase for a normal distribution of temperature.

Consequently, even when changes in extremes can be documented, unless a specific analysis has been completed, it is often uncertain whether the changes are caused by a change in the mean, variance, or both. In addition, uncertainties in the rate of change of the mean confound interpretation of changes in variance since all variance statistics are dependent on a reference level, i.e., the mean.

For variables that are not well approximated by normal distributions, like precipitation, the situation is even more complex, especially for dry climates. For precipitation, for example, changes in the mean total precipitation can be accompanied by other changes like the frequency of precipitation or the shape of the distribution including its variability. All these changes can affect the various aspects of precipitation extremes including the intensity of precipitation (amount per unit time).

This section considers the changes in variability and extremes simultaneously for two variables, temperature and precipitation. We include new analyses and additional data compiled since the SAR which provide new insights. We also assess new information related to changes in extreme weather and climate phenomena, e.g., tropical cyclones, tornadoes, etc. In these analyses, the primary focus is on assessing the stationarity (e.g., the null hypothesis of no change) of these events, given numerous inhomogeneities in monitoring.

2.7.2 Is There Evidence for Changes in Variability or Extremes?

The issues involved in measuring and assessing changes in extremes have recently been comprehensively reviewed by Trenberth and Owen (1999), Nicholls and Murray (1999), and Folland *et al.* (1999b). Despite some progress described below, there remains a lack of accessible daily climate data sets which can be intercompared over large regions (Folland *et al.*, 2000). Extremes are a key aspect of climate change. Changes in the frequency of many extremes (increases or decreases) can be surprisingly large for seemingly modest mean changes in climate (Katz, 1999) and are often the most sensitive aspects of climate change for ecosystem and societal responses. Moreover, changes in extremes are often most sensitive to inhomogeneous climate monitoring practices, making assessment of change more difficult than assessing the change in the mean.

2.7.2.1 Temperature

Given the number of ways in which extreme climate events and variability about the mean can be defined, (e.g., extreme daily temperatures, large areas experiencing unusual temperatures, severity of heat waves, number of frosts or freezes, changes in interannual variability of large area temperatures, etc.) extreme care must be exercised in generalising results. Here we assess the evidence for changes in temperature extremes or variability, first based on global analyses and then on more detailed regional analyses.

Parker *et al*. (1994) compared the interannual variability of seasonal temperature anomalies from the 1954 to 1973 period to the 1974 to 1993 period for most of the globe. They found a small increase in variability overall with an especially large increase in central North America. By restricting the analyses to the latter half of the 20th century, Parker *et al*. (1994) minimised the potential biases due to an increasing number of observations in this period. Several other studies found a reduction in other aspects of variability over longer time periods. Jones (1999) also analysed global data and found no change in variability, but since 1951 the rise in global mean temperatures can be attributed to an increase (decrease) in areas with much above (below) normal temperatures. They also analysed the change in the aggregated total of much below and much above normal temperatures (upper and lower ten percentiles). They found little overall change, except for a reduced number of much above or below normal temperatures during the 1960s and 1970s. Michaels *et al*. (1998) examined 5° latitude × 5° longitude monthly temperature anomalies for many grid cells around the world and found an overall decrease in intra-annual variance over the past 50 to 100 years. They also examined the daily maximum and minimum temperatures from the United States, China, and the former Soviet Union and found a general decline in the intra-monthly temperature variability. As reported in the SAR, a related analysis by Karl *et al*. (1995b) found reduced day-to-day variability during the 20th century in the Northern Hemisphere, particularly in the United States and China. Recently, Collins *et al*. (2000) has identified similar trends in Australia. By analysing a long homogenised daily temperature index for four stations in Northern Europe, Moberg *et al*. (2000) also found a progressive reduction in all-seasons inter-daily variability of about 7% between 1880 and 1998. Balling (1998) found an overall decrease in the spatial variance of both satellite-based lower-tropospheric measurements from 1979 to 1996 and in near-surface air temperatures from 1897 to 1996.

Consequently, there is now little evidence to suggest that the interannual variability of global temperatures has increased over the past few decades, but there is some evidence to suggest that the variability of intra-annual temperatures has actually quite widely decreased. Several analyses find a decrease in spatial and temporal variability of temperatures on these shorter time-scales.

There have been a number of new regional studies related to changes in extreme temperature events during the 20th century. Gruza *et al.* (1999) found statistically significant increases in the number of days with extreme high temperatures across Russia using data back to 1961 and on a monthly basis back to 1900. Frich *et al*. (2001) analysed data spanning the last half of the 20th century across most of the Northern Hemisphere mid- and high latitudes and found a statistically significant increase (5 to >15%) in the growing season length in many regions. Heino *et al*. (1999) also found that there has been a reduction in the number of days with frost (the number of days with minimum temperature ≤0°C) in northern and central Europe. Thus, some stations now have as many as 50 fewer days of frost per year compared with earlier in the 20th century. Easterling *et al*. (2000) found there has been a significant decrease in the number of days below freezing over the central United States (about seven per year). For Canada, Bonsal *et al*. (2001) also found fewer days with extreme low temperatures during winter, spring and summer, and more days with extreme high temperatures during winter and spring. This has led to a significant increase in the frost-free period. Decreasing numbers of days with freezing temperatures have been found in Australia and New Zealand over recent decades (Plummer *et al*., 1999; Collins *et al*., 2000). In addition, while increases in the frequency of warm days have been observed, decreases in the number of cool nights have been stronger. Frich *et al*. (2001) show a reduced number of days with frost across much of the globe (Figure 2.33) while Michaels *et al*. (2000) find that much of the warming during the 20th century has been during the cold season in the mid- to high latitudes, consistent with the reduction of extremely low temperatures. Frich *et al*. (2001) have also found a statistically significant reduction in the difference between the annual extremes of daily maximum and minimum temperatures during the latter half of the 20th century. In China, strong increases in the absolute minimum temperature have been observed, with decreases in the 1-day seasonal extreme maximum temperature (Zhai *et al*., 1999a) since the 1950s. Wang and Gaffen (2001), however, for a similar period, found an increase in "hot" days in China. Hot days were defined as those days above the 85th percentile during July and August based on an "apparent temperature" index related to human discomfort in China (Steadman, 1984). The number of extremely cold days has also been shown to be decreasing in China (Zhai *et al.*, 1999a). Manton *et al*. (2001) found significant increases in hot days and warm nights, and decreases in cool days and cold nights since 1961 across the Southeast Asia and South Pacific Region. Jones *et al*. (1999c) have analysed the 230-year-long daily central England data set that has been adjusted for observing inhomogeneities. They found that the increase in temperature observed in central England corresponds mainly to a reduction in the frequency of much below normal daily temperatures. An increase of the frequency of much above normal temperatures was less apparent.

Analyses of 20th century trends in the United States of short-duration episodes (a few days) of extreme hot or cold weather did not show any significant changes in frequency or intensity (Kunkel *et al.*, 1996, 1999; Karl and Knight, 1997). For Australia, Collins *et al*. (2000) found higher frequencies of multi-day warm nights and days, and decreases in the frequency of cool days and nights. In an extensive assessment of the change in frequency of heat waves during the latter half of the 20th century, Frich *et al*. (2001) find some evidence for an increase in heat-wave frequency, but several regions have opposite trends (Figure 2.33c). The extreme heat in the United States during several years in the 1930s dominates the time-series of heat waves in that region. On the other hand, trends in the frequency of extreme apparent tempera-

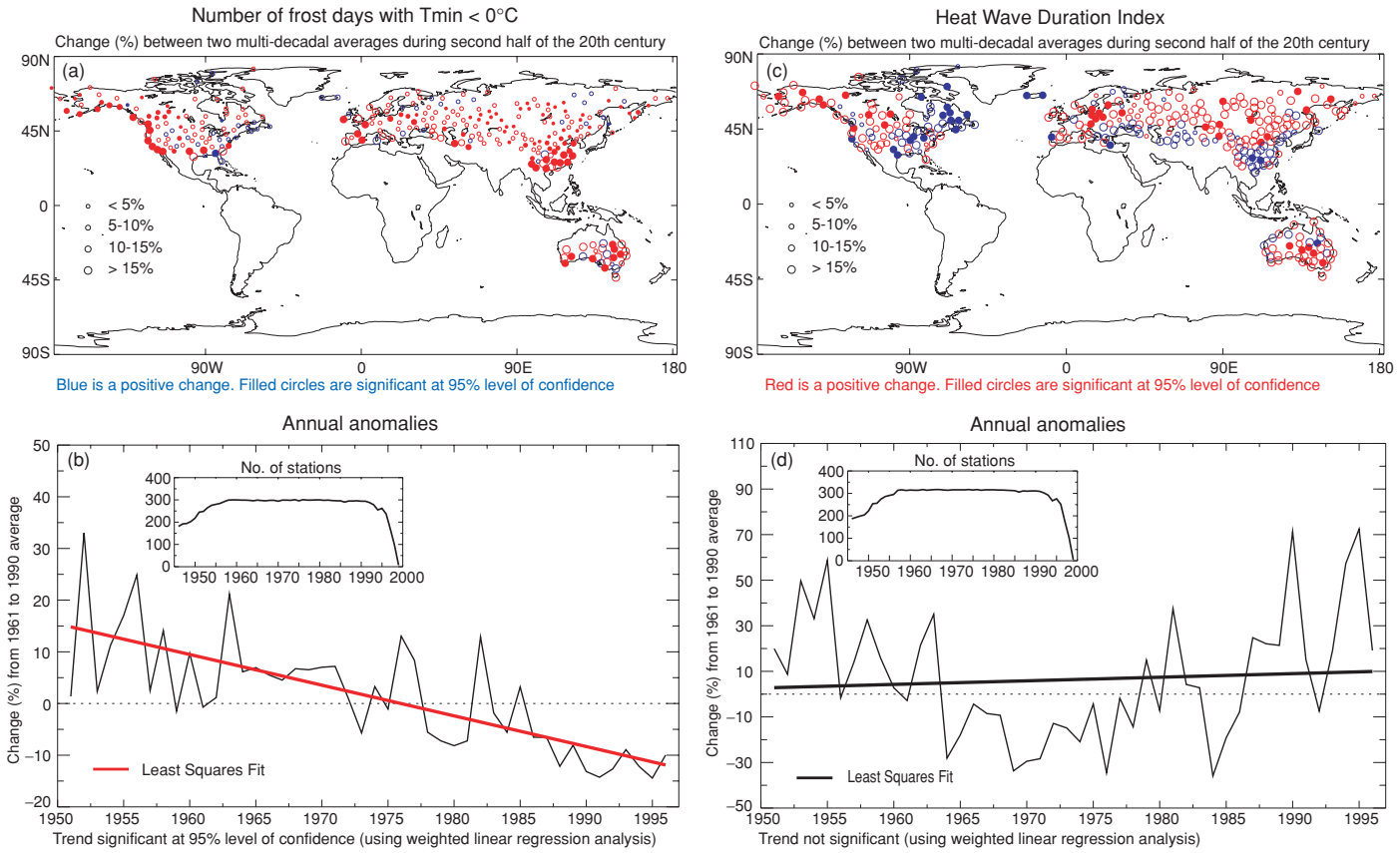

Figure 2.33: Changes in the number of frost days (a, b) and in heat-wave duration (c, d) from Frich *et al.* (2001). Panel (a) shows the percent changes in the total number of days with a minimum temperature of less than 0°C between the first and last half of the period, approximately 1946 to 1999. The red circles indicate negative changes and the blue circles indicate positive changes. Panel (c) shows percentage changes in the maximum number of consecutive days (for periods with >5 such days) with maximum temperatures >5°C above the 1961 to 1990 daily normal. The changes are for the first and second half of the period, approximately 1946 to 1999. The red circles indicate positive changes and the blue circles indicate negative changes. In both panels, the size of each circle reflects the size of the change and solid circles represent statistically significant changes. Panels (b) and (d) show the average annual values of these quantities expressed as percentage differences from their 1961 to 1990 average values. The trend shown in panel (b) is statistically significant at the 5% level.

tures are significantly larger for 1949 to 1995 during summer over most of the USA (Gaffen and Ross, 1998). Warm humid nights more than doubled in number over 1949 to 1995 at some locations. Trends in nocturnal apparent temperature in the USA, however, are likely to be associated, in part, with increased urbanisation. Nevertheless, using methods and data sets to minimise urban heat island effects and instrument changes, Easterling *et al.* (2000) arrived at conclusions similar to those of Gaffen and Ross (1998).

During the 1997/98 El Niño event, global temperature records were broken for sixteen consecutive months from May 1997 through to August 1998. Karl *et al.* (2000) describe this as an unusual event and such a monthly sequence is unprecedented in the observational record. More recently, Wigley (2000) argues that if it were not for the eruption of Mt. Pinatubo, an approximately equal number of record-breaking temperatures would have been set during the El Niño of 1990/91. As temperatures continue to warm, more events like these are likely, especially when enhanced by other factors, such as El Niño.

2.7.2.2 Precipitation

A better understanding of the relationship between changes in total precipitation and intense precipitation events has been achieved since the SAR. Although many areas of the globe have not been analysed, and considerable data remain inaccessible, enough data have been analysed to confirm some basic properties of the changes in extreme precipitation. Groisman *et al.* (1999) developed a simple statistical model of the frequency of daily precipitation based on the gamma distribution. They applied this model to a variety of regions around the world (40% of the global land area) during the season of greatest precipitation. Although Wilks (1999) shows that the gamma distribution under some circumstances can underestimate the probability of the highest rainfall amounts, Groisman *et al.* (1999) applied the distribution to the upper 5 and 10 percentiles of the distribution which are less subject to underestimation. Their analysis period varied from region to region, but within each region it generally spanned at least the last several decades, and for some regions much of the 20th century (Australia, United States, Norway, and South

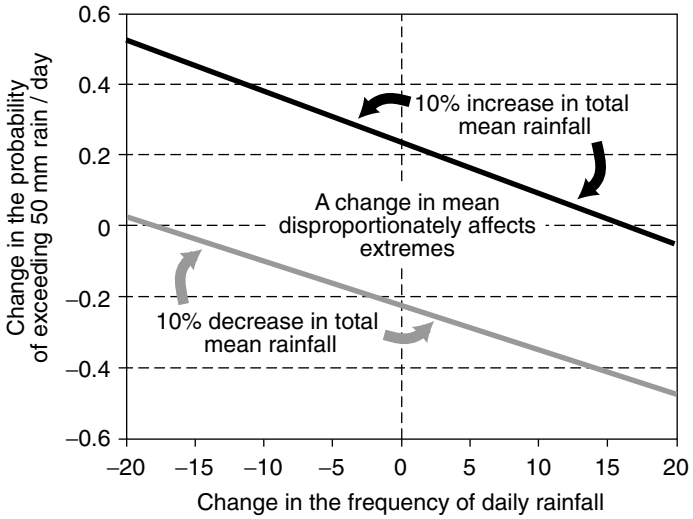

Figure 2.34: An example (from Groisman *et al*., 1999) of the sensitivity of the frequency of heavy daily rainfall to a shift in the mean total rainfall, based on station data from Guangzhou, China. This example uses a threshold of 50 mm of precipitation per day. It shows the effects of a 10% increase and a 10% decrease in mean total summer rainfall, based on a gamma distribution of the rainfall with a constant shape parameter.

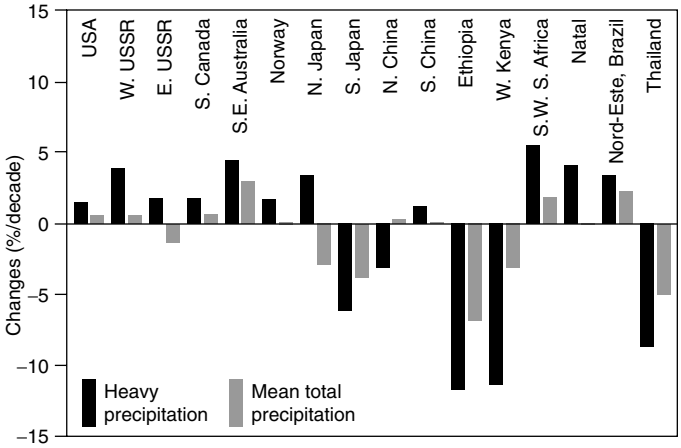

Figure 2.35: Linear trends (%/decade) of heavy precipitation (above the 90th percentile) and total precipitation during the rainy season over various regions of the globe. Seasons for each region usually span at least 50 years. Note that the magnitudes of the changes in heavy precipitation frequencies are always higher than changes in mean precipitation totals (Easterling *et al*., 2000).

Africa). In the model used by Groisman *et al*. (1999), the mean total precipitation is also proportional to the shape and scale parameters of the gamma distribution as well as to the probability of precipitation on any given day. The shape parameter of the gamma distribution tends to be relatively stable across a wide range of precipitation regimes, in contrast to the scale parameter. Given the conservative nature of the shape parameter, it is possible to illustrate the relationships between changes in the mean total precipitation, the probability of precipitation (which is proportional to the number of days with precipitation), and changes in heavy precipitation (Figure 2.34). Given no change in the frequency (number of days) of precipitation, a 10% change in the mean total precipitation is amplified to a larger percentage change in heavy precipitation rates compared to the change in the mean. Using the statistical theory of extremes, Katz (1999) obtained results consistent with those of Groisman *et al*. (1999). For many regions of the world it appears that the changes in the frequency or probability of precipitation events are either small enough, or well enough expressed in the high rainfall rates (Karl and Knight, 1998; Gruza *et al.*, 1999; Haylock and Nicholls, 2000) that an increase in the mean total precipitation is disproportionately reflected in increased heavy precipitation rates (Figure 2.35).

Given the patterns of mean total precipitation changes (Section 2.5.2) during the 20th century, it could be anticipated that, in general, for those areas with increased mean total precipitation, the percentage increase in heavy precipitation rates should be significantly larger, and *vice versa* for total precipitation decreases. Regional analyses of annual precipitation in the United States (Karl and Knight, 1998; Trenberth, 1998a; Kunkel *et al*., 1999); Canada (Stone *et al*., 1999); Switzerland (Frei and Schär, 2001); Japan (Iwashima and Yamamoto, 1993; Yamamoto and Sakurai, 1999); wintertime precipitation in the UK (Osborn *et al*., 2000); and rainy season precipitation in Norway, South Africa, the Nord Este of Brazil, and the former USSR (Groisman *et al*., 1999; Gruza *et al*., 1999; Easterling *et al*., 2000) confirm this characteristic of an amplified response for the heavy and extreme events.

Increases in heavy precipitation have also been documented even when mean total precipitation decreases (for example, see Northern Japan in Figure 2.35, or Manton *et al*., 2001). This can occur when the probability of precipitation (the number of events) decreases, or if the shape of the precipitation distribution changes, but this latter situation is less likely (Buffoni *et al*., 1999; Groisman *et al*., 1999; Brunetti *et al*., 2000a,b). For example, in Siberia for the summer season during the years 1936 to 1994 there was a statistically significant decrease in total precipitation of 1.3%/decade, but the number of days with precipitation also decreased. This resulted in an increase (1.9%/decade) in the frequency of heavy rainfall above 25 mm. The opposite can also occur when the number of rainfall events increases; thus Førland *et al*. (1998) found no trends in 1-day annual maximum precipitation in the Nordic countries, even when mean total precipitation increased.

There has also been a 10 to 45% increase in heavy rainfall, as defined by the 99th percentile of daily totals, over many regions of Australia from 1910 to 1995, but few individual trends were statistically significant (Hennessy *et al*., 1999). In south-west Australia, however, a 15% decrease has been observed in winter rainfall on very wet days (Hennessy *et al*., 1999; Haylock and Nicholls, 2000).

In Niger, a recent analysis of hourly rainfall data (Shinoda *et al*., 1999) reveals that the droughts in the 1970s and 1980s were characterised primarily by a reduced frequency of heavy rainfall events (those exceeding 30 mm/day) rather than by a reduction in rainfall amount within heavy events. Such a result is still consistent with the model of Groisman *et al*. (1999), as a decrease in the

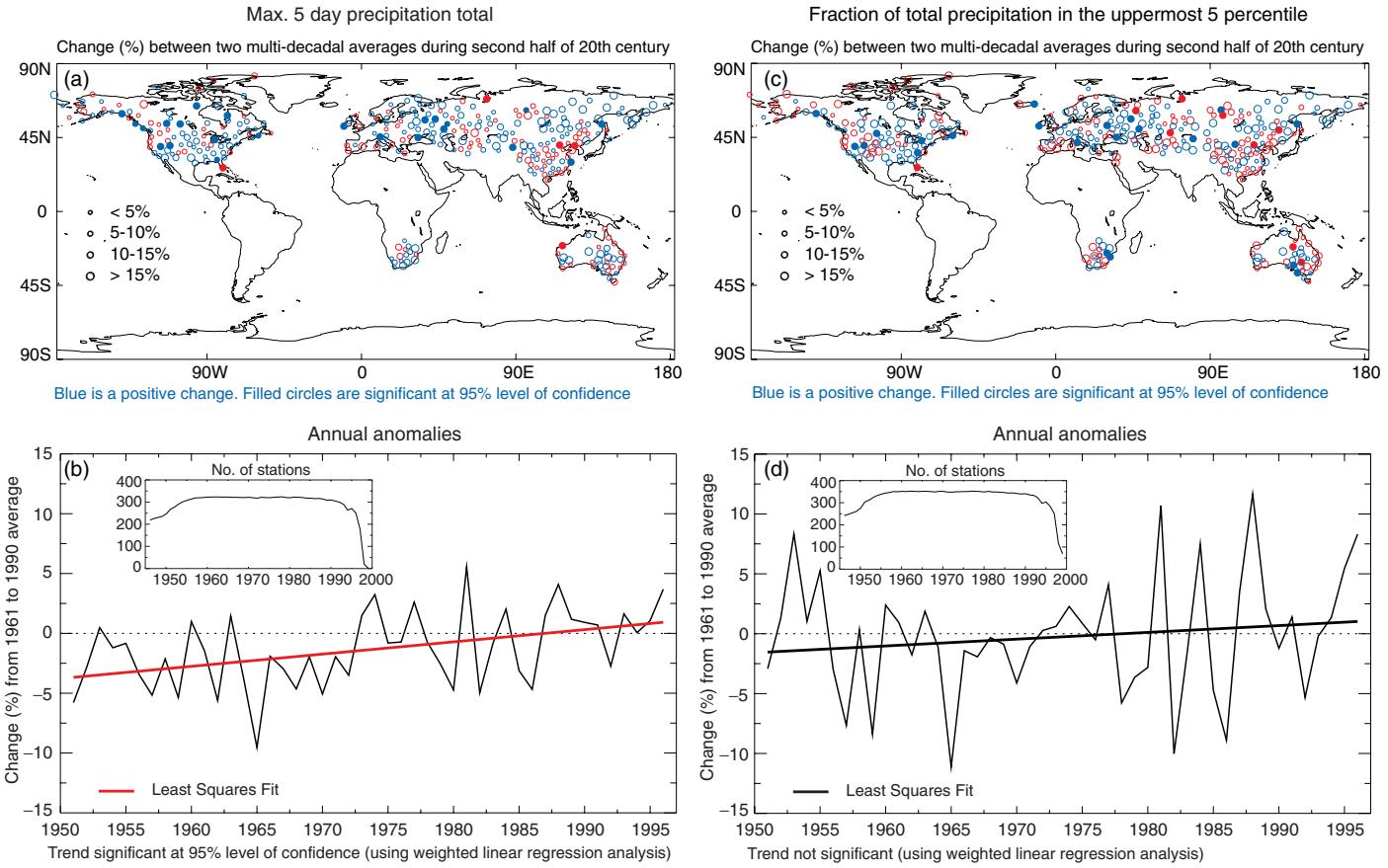

Figure 2.36: Changes in the maximum annual 5-day precipitation total (a, b) and in the proportion of annual precipitation occurring on days on which the 95th percentile of daily precipitation, defined over the period 1961 to 1990, was exceeded (c, d). The analysis shown is from Frich *et al.* (2001). Panels (a) and (c) show percentage changes in these quantities between the first and last half of the period, approximately 1946 to 1999. In both panels, the red circles indicate negative changes and the blue circles indicate positive changes. The size of each circle reflects the size of the change and solid circles represent statistically significant changes. Panels (b) and (d) show the average annual values of the quantities expressed as percentage differences from their 1961 to 1990 average values. The trend shown in panel (b) is statistically significant at the 5% level.

frequency of rainfall events has been responsible for the decrease in total rainfall. In the Sahel region of Nigeria, however, there has been a decrease in the heaviest daily precipitation amounts, coincident with an overall decrease in annual rainfall. This pattern is apparent throughout the Sudano-Sahel Zone, including the Ethiopian plateau (Nicholson, 1993; Tarhule and Woo, 1998; Easterling *et al.*, 2000). Again, it is apparent that there has been an amplified response of the heaviest precipitation rates relative to the percentage change in total precipitation.

Since large portions of the mid- and high latitude land areas have had increasing precipitation during the last half the 20th century, the question arises as to how much of this area is affected by increases in heavy and extreme precipitation rates. The Frich *et al.* (2001) analysis suggests an overall increase in the area affected by more intense daily rainfall. Figure 2.36 shows that widely distributed parts of the mid- and high latitudes have locally statistically significant increases in both the proportion of mean annual total precipitation falling into the upper five percentiles and in the annual maximum consecutive 5-day precipitation total. However, for the regions of the globe sampled taken as a whole, only the latter statistic shows a significant increase. Regional analyses in Russia (Gruza *et al.*, 1999), the United States (Karl and Knight, 1998) and elsewhere (Groisman *et al.*, 1999; Easterling *et al.*, 2000) confirm this trend. Although the trends are by no means uniform, as would be anticipated with the relatively high spatial and interannual variability of precipitation, about 10% of the stations analysed show statistically significant increases at the 5% level. This equates to about a 4% increase in the annual maximum 5-day precipitation total (Figure 2.36b). The number of stations reflecting a locally significant increase in the proportion of total annual precipitation occurring in the upper five percentiles of daily precipitation totals outweighs the number of stations with significantly decreasing trends by more than 3 to 1 (Figure 2.36c). Although not statistically significant when averaging over all stations, there is about a 1% increase in the proportion of daily precipitation events occurring in the upper five percentiles (Figure 2.36d). Overall, it is likely that there has been a 2 to 4% increase in the number of heavy precipitation events when averaged across the mid- and high latitudes.

It has been noted that an increase (or decrease) in heavy precipitation events may not necessarily translate into annual peak (or low) river levels. For example, in the United States, Lins

and Slack (1999) could not detect an increase in the upper quantiles of streamflow, despite the documented increase in heavy and extreme precipitation events. It is possible that this null result is partly due to the method of analysis, but it is also attributable to the timing of the annual peak streamflow discharge, which in the United States is usually in late winter or early spring. A reduced snow cover extent in the mountainous West changes the peak river flow, as does timing of increases in heavy and extreme precipitation reported in the United States, which is best reflected during the warm season. Groisman *et al*. (2001) and Zhang *et al*. (2000) also show reduced peak streamflow in areas with reduced spring snow cover extent. Nonetheless, in much of the United States where spring snow melt does not dominate peak or normal flow, Groisman *et al*. (2001) show increasing high streamflow related to increasing heavy precipitation.

It is noteworthy that the influence of warmer temperatures and increased water vapour in the atmosphere (Section 2.5.3) are not independent events, and are likely to be jointly related to increases in heavy and extreme precipitation events.

2.7.3 Is There Evidence for Changes in Extreme Weather or Climate Events?

In this section we assess changes in the intensity and frequency of various weather phenomena. One aspect of change that is important, but which is beyond the analysis of present records, relates to changes in the tracks of storms. Severe storms are often rare, so the analysis of large areas and long lengths of homogeneous storm records are required to assess changes. So far this combination of data is not available.

2.7.3.1 Tropical cyclones

This section updates the information provided in the SAR regarding changes in tropical cyclones across various ocean basins and those affecting the nearby continents. As reported in the SAR, a part of the multi-decadal trend of tropical cyclones occurring in the Australian region (105° to 160°E) is likely to be artificial, as the forecasters in the region no longer classify some weak (>990 hPa central pressure) systems as "cyclones" (Nicholls *et al*., 1998). By considering only the moderate and intense tropical cyclones (central pressure ≤990 hPa), this artificial trend is eliminated. The remaining moderate and strong tropical cyclones reveal a numerical decline since the late 1980s, but the trend is not statistically significant. Similarly, the trend in intense tropical cyclones (minimum central pressure below 970 hPa) is not significantly different from zero. Nicholls *et al*. (1998) attributed the decrease in moderate cyclones to more frequent occurrences of El Niño during the 1980s and 1990s. However, a weak trend in the intense tropical cyclones implies that while ENSO modulates the total frequency of cyclones in the region, other factors must be more important in regulating their intensity. For example, new work by Higgins and Shi (2000) and Maloney and Hartmann (2001) show that 30 to 80 day Madden-Julian oscillations modulate tropical cyclone activity.

As reported in the SAR, the north-east sub-tropical Pacific has experienced a significant upward trend in tropical cyclone frequency in the short period examined, but additional data since

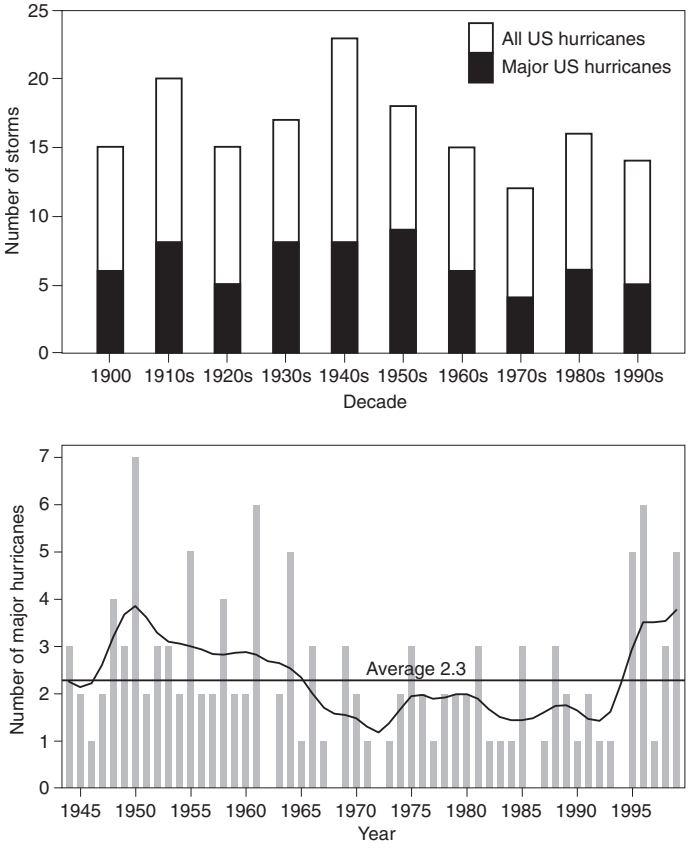

Figure 2.37: Top figure, decadal variations in hurricanes making landfall in the USA (updated from Karl *et al*., 1995). Bottom figure, interannual variability in the number of major hurricanes (Saffir-Simpson categories 3, 4, and 5) and the long-term average across the North Atlantic (from Landsea *et al*., 1999).

that time show no appreciable trend. There is no appreciable long-term variation of the total number of tropical storm strength cyclones observed in the north Indian, south-west Indian and south-west Pacific Oceans east of 160°E. (Neumann, 1993; Lander and Guard, 1998). For the north-west sub-tropical Pacific basin, Chan and Shi (1996) found that the frequency of typhoons and the total number of tropical storms and typhoons have been more variable since about 1980. There was an increase from 1981 to 1994, which was preceded by a nearly identical magnitude of decrease from about 1960 to 1980. No analysis has been done on the frequency of intense typhoons (having winds of at least 50 m/s) due to an overestimation of the intensity of such storms in the 1950s and 1960s (Black, 1993).

There has been an extensive analysis of the North Atlantic basin for the entire basin back to 1944, and also for the United States landfall tropical storms and hurricanes back to 1899. The all-basin data, however, have been affected by a bias in the measurement of strong hurricanes. This bias has been removed in an approximate way to provide estimates of the true occurrence of intense (or major) hurricanes since 1944 in the North Atlantic (Landsea, 1993). Earlier events lack reliable data on the strong inner core of the hurricanes. The United States record of landfall frequency and intensity of hurricanes is very reliable because of

the availability of central pressure measurements at landfall (Jarrell *et al*., 1992). Both of these data sets continue to show considerable inter-decadal variability, but no significant long-term trends (Figure 2.37, from Landsea *et al*., 1999). Active years occurred from the late 1940s to the mid-1960s, quiet years occurred from the 1970s to the early 1990s, and then there was a shift again to active conditions from 1995 to 1999. Concurrent with these frequency changes, there have been periods with a strong mean intensity of the North Atlantic tropical cyclones (mid-1940s to the 1960s and 1995 to 1999) and a weak intensity (1970s to early 1990s). There has been no significant change in the peak intensity reached by the strongest hurricane each year (Landsea *et al*., 1996). As might be anticipated, there is a close correspondence between the intensity of hurricanes in the North Atlantic and those making landfall in the United States (Figure 2.37).

Using historical records, Fernandez-Partagas and Diaz (1996) estimated that overall Atlantic tropical storm and hurricane activity for the years 1851 to 1890 was 12% lower than the corresponding forty year period of 1951 to 1990, although little can be said regarding the intense hurricanes. They based this assessment upon a constant ratio of USA landfalling tropical cyclones to all-basin activity, which is likely to be valid for multi-decadal time-scales. However, this also assumes that Fernandez-Partagas and Diaz were able to uncover all USA landfalling tropical cyclones back to 1851, which may be more questionable.

2.7.3.2 Extra-tropical cyclones

Extra-tropical cyclones are baroclinic low pressure systems that occur throughout the mid-latitudes of both hemispheres. Their potential for causing property damage, particularly as winter storms, is well documented, where the main interest is in wind and wind-generated waves. In place of direct wind measurements, which suffer from lack of consistency of instrumentation, methodology and exposure, values based on SLP gradients have been derived which are more reliable for discerning long-term changes. Over the oceans, the additional measurements of wave heights and tide gauge measurements provide additional ways of indirectly evaluating changes in extra-tropical storm strength and frequency (see Chapter 11, Section 11.3.3). Global analyses of changes in extra-tropical storm frequency and intensity have not been attempted, but there have been several large-scale studies. Jones *et al*. (1999c) developed a gale index of geostrophic flow and vorticity over the UK for the period 1881 to 1997. This revealed an increase in the number of severe gale days over the UK since the 1960s, but no long-term increase when considering the century period. Serreze *et al*. (1997) found increases in cold season cyclones in the Arctic region for the period 1966 to 1993. Angel and Isard (1998) found significant increases in strong cyclones (<993 mb) in the Great Lakes region from 1900 to 1990 during the cold season. Graham and Diaz (2001) find evidence for increases in strong cyclones over the Pacific Ocean between 25 and 40°N since 1948 and link the increase to increasing sea surface temperatures in the western Tropical Pacific. Alexandersson *et al*. (1998, 2000) similarly studied extreme geostrophic wind events in the north-western European area based on homogenised observations during the period 1881 to 1998. These studies revealed an increase in the number of extreme wind events around and to the north of the North Sea. The WASA group (1998) similarly investigated the storm related sea level variations at gauge stations in the south-eastern part of the North Sea. They found no long-term trend during the last 100 years, but a clear rise since a minimum of storminess in the 1960s, which is consistent with the rise in extreme geostrophic wind found by Jones *et al*. (1999c). This increase is also consistent with changes in the NAO (Figure 2.30). Some analyses have focused on hemispheric changes in cyclone activity. Lambert (1996) analysed gridded SLP over both the North Atlantic and North Pacific Oceans for the period 1891 to 1991. He found a significant increase in intense extra-tropical storms, especially over the last two decades of his analysis, but the data were not completely homogenised. Simmonds and Keay (2000) used data from 1958 to 1997 in the Southern Hemisphere and found an increase in cyclone activity through 1972 before decreasing through 1997 with strong decreases during the 1990s.

Hourly values of water levels provide a unique record of tropical and extra-tropical storms where stations exist. Zhang *et al*. (1997a) have analysed century-long records along the East Coast of the United States. They calculated several different measures of storm severity, but did not find any long-term trends. On the other hand, they did find that the effect of sea level rise over the last century has exacerbated the beach erosion and flooding from modern storms that would have been less damaging a century ago.

Another proxy for cyclone intensity is wave height (see Chapter 11, Section 11.3.3). Several studies report increased wave height over the past three decades in the North Atlantic (approximately 2.5 cm/yr) and in coastal areas, though no longer-term trends were evident (Carter and Draper, 1988; Bacon and Carter, 1991; Bouws *et al*., 1996; Kushnir *et al*., 1997; WASA Group, 1998).

It appears that recent work points towards increases over time in extra-tropical cyclone activity during the latter half of the 20th century in the Northern Hemisphere, and decreased activity in the Southern Hemisphere. However, the mechanisms involved are not clear, and it is not certain whether the trends are multi-decadal fluctuations, or rather part of a longer-term trend. Furthermore decreased cyclone activity in higher latitudes of the Southern Hemisphere is not obviously consistent with an increase in the positive phase of the Antarctic Oscillation in the last fifteen years or so (Section 2.6.6). A more fundamental question is whether we would expect more or fewer extra-tropical cyclones with increased warming. As pointed out by Simmonds and Keay (2000), the specific humidity increases as temperatures increase, and this increased moisture should enhance extra-tropical cyclones, but Zhang and Wang (1997) suggest that cyclones transport energy more efficiently in a more moist atmosphere, therefore requiring fewer extra-tropical cyclones (see Chapters 7 and 10 for more discussion).

2.7.3.3 Droughts and wet spells

In the SAR, an intensification of the hydrological cycle was projected to occur as the globe warms. One measure of such intensification is to examine whether the frequency of droughts and wet spells are increasing. Karl *et al*. (1995c) examined the

proportion of land areas having a severe drought and a severe moisture surplus over the United States. Dai *et al*. (1998) extended this analysis to global land areas using the water balance approach of the Palmer Drought Severity Index. Long-term global trends for 1900 to 1995 are relatively small for both severe drought and wet area statistics. However, during the last two to three decades, there have been some increases in the globally combined severe dry and wet areas, resulting from increases in either the dry area, e.g., over the Sahel, eastern Asia and southern Africa or the wet areas, e.g., over the United States and Europe. Most of the increases occurred after 1970. Except for the Sahel, however, the magnitude of dry and wet areas of the recent decades is not unprecedented during this century, but it should be noted that rainfall in the Sahel since the height of the drought has substantially increased. In related work, Frich *et al*. (2001) found that in much of the mid- and high latitudes, there has been a statistically significant increase in both the number of days with precipitation exceeding 10 mm per day and in the number of consecutive days with precipitation during the second half of the 20th century.

Recent changes in the areas experiencing severe drought or wet spells are closely related to the shift in ENSO towards more warm events since the late 1970s, and coincide with record high global mean temperatures. Dai *et al*. (1998) found that for a given value of ENSO intensity, the response in areas affected by drought or excessive wetness since the 1970s is more extreme than prior to the 1970s, also suggesting an intensification of the hydrological cycle.

2.7.3.4 Tornadoes, hail and other severe local weather

Small-scale severe weather phenomena (SCSWP) are primarily characterised by quasi-random temporal and spatial events. These events, in turn, have local and regional impacts, often with significant damage and sometimes loss of life. Tornadoes and thunderstorms and related phenomena such as lightning, hail, wind, dust, water spouts, downpours and cloudbursts belong to this group. In the light of the very strong spatial variability of SCSWP, the density of surface meteorological observing stations is too coarse to measure all such events. Moreover, areally consistent values of SCSWP are inherently elusive. Statistics of relatively rare events are not stable at single stations, observational practices can be subjective and change over time, and the metadata outlining these practices are often not readily available to researchers. For these reasons, monitoring the occurrence of local maxima and minima in smoothed SCSWP series, as well as checking for trends of the same sign for different but related SCSWP (e.g., thunderstorms, hail, cloud bursts), are important for checking inconsistencies. Because of the inherent difficulty in working with these data, there have been relatively few large-scale analyses of changes and variations in these events. Nonetheless, a few new regional analyses have been completed since the SAR.

A regional analysis by Dessens (1995) and more recent global analysis by Reeve and Toumi (1999) show that there is a significant interannual correlation between hail and lightning and mean minimum temperature and wet bulb temperatures. Using a three-year data set, Reeve and Toumi (1999) found a statistically

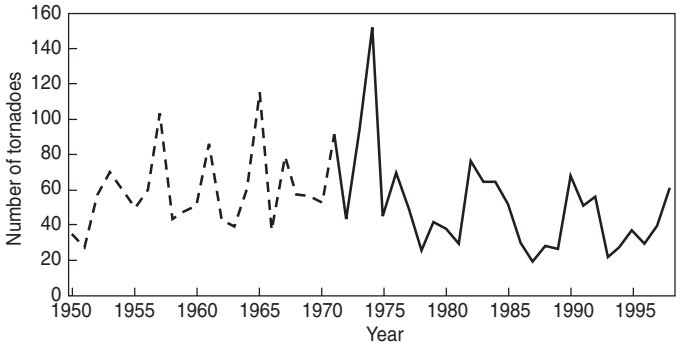

Figure 2.38: Annual total number of very strong through violent (F3-F5) tornadoes reported in the USA, which are defined as having estimated wind speeds from approximately 70 to 164 ms^{-1}. The Fujita tornado classification scale was implemented in 1971. Prior to 1971, these data are based on storm damage reports (National Climatic Data Center, NOAA).

significant relationship between lightning frequency and wet bulb temperature. They show that with a 1°C increase in global wet-bulb temperature there is a 40% increase in lightning activity, with larger increases over the Northern Hemisphere land areas (56%). Unfortunately, there are few long-term data sets that have been analysed for lightning and related phenomena such as hail or thunderstorms, to calculate multi-decadal hemispheric or global trends.

A regional analysis assessed the temporal fluctuations and trends in hail-day and thunder-day occurrences during a 100-year period, from 1896 to 1995, derived from carefully screened records of 67 stations distributed across the United States. Upward hail day trends were found in the High Plains-Rockies and the south-east, contrasting with areas with no trend in the northern Midwest and along the East Coast, and with downward trends elsewhere (Changnon and Changnon, 2000). The major regions of decrease and increase in hail activity match regions of increased and decreased thunder activity for 1901 to 1980 well (Changnon, 1985; Gabriel and Changnon, 1990) and also crop-hail insurance losses (Changnon *et al*., 1996; Changnon and Changnon, 1997). In general, hail frequency shows a general decrease for most of the United States over the last century, with increases over the High Plains, the region where most of the crop-hail damage occurs in the United States. So, despite an increase in minimum temperature of more than 1°C since 1900 and an increase in tropospheric water vapour over the United States since 1973 (when records are deemed reliable), no systematic increase in hail or thunder days was found.

In south Moravia, Czech Republic, a decreasing linear trend in the frequency of thunderstorms, hailstorms and heavy rain from 1946 to 1995 was related to a significant decrease in the occurrence of these phenomena during cyclonic situations, when 90% of these phenomena occur in that region (Brázdil and Vais, 1997). Temperatures have increased in this area since 1946.

Since 1920, the number of tornadoes reported annually in the United States has increased by an order of magnitude, but this increase reflects greater effectiveness in collecting tornado

reports (Doswell and Burgess, 1988; Grazulis, 1993; Grazulis *et al*., 1998). On the other hand, severe tornadoes are not easily overlooked. Restricting the analysis to very strong and violent tornadoes results in a much different assessment (Figure 2.38) showing little long-term change, though some years like 1974 show a very large number of tornadoes. Furthermore, consideration of the number of days with tornadoes, rather than number of tornadoes, reduces the artificial changes that result from modern, more detailed damage surveys (e.g., Doswell and Burgess, 1988). The data set of "significant" tornado days developed by Grazulis (1993) shows a slow increase in number of days with significant tornadoes from the early 1920s through the 1960s, followed by a decrease since that time.

2.7.4 Summary

Based on new analyses since the SAR, it is likely that there has been a widespread increase in heavy and extreme precipitation events in regions where total precipitation has increased, e.g., the mid- and high latitudes of the Northern Hemisphere. Increases in the mean have often been found to be amplified in the highest precipitation rates total. In some regions, increases in heavy rainfall have been identified where the total precipitation has decreased or remained constant, such as eastern Asia. This is attributed to a decrease in the frequency of precipitation. Fewer areas have been identified where decreases in total annual precipitation have been associated with decreases in the highest precipitation rates, but some have been found. Temperature variability has decreased on intra-seasonal and daily time-scales in limited regional studies. New record high night-time minimum temperatures are lengthening the freeze and frost season in many mid- and high latitude regions. The increase in global temperatures has resulted mainly from a significant reduction in the frequency of much below normal seasonal mean temperatures across much of the globe, with a corresponding smaller increase in the frequency of much above normal temperatures. There is little sign of long-term changes in tropical storm intensity and frequency, but inter-decadal variations are pronounced. Owing to incomplete data and relatively few analyses, we are uncertain as to whether there has been any large-scale, long-term increase in the Northern Hemisphere extra-tropical cyclone intensity and frequency though some, sometimes strong, multi-decadal variations and recent increases were identified in several regions. Limited evidence exists for a decrease in cyclone frequency in the Southern Hemisphere since the early 1970s, but there has been a paucity of analyses and data. Recent analyses of changes in severe local weather (tornadoes, thunder days, lightning and hail) in a few selected regions provide no compelling evidence for widespread systematic long-term changes.

2.8 Are the Observed Trends Internally Consistent?

It is very important to compare trends in the various indicators to see if a physically consistent picture emerges, as this will critically affect the final assessment of our confidence in any such changes. A number of qualitative consistencies among the various indicators of climate change have increased our confidence in our analyses of the historical climate record: Figure 2.39a and b summarises the changes in various temperature and hydrological indicators, respectively, and provides a measure of confidence about each change. Of particular relevance are the changes identified below:

- Temperature over the global land and oceans, with two estimates for the latter, are measured and adjusted independently, yet all three show quite consistent increasing trends (0.52 to 0.61°C/century) over the 20th century.

- The nearly worldwide decrease in mountain glacier extent and mass is consistent with 20th century global temperature increases. A few recent exceptions in maritime areas have been affected by atmospheric circulation variations and related precipitation increases.

- Though less certain, substantial proxy evidence points to the exceptional warmth of the late 20th century relative to the last 1,000 years. The 1990s are likely to have been the warmest decade of the past 1,000 years over the Northern Hemisphere as a whole.

- Satellite and balloon measurements agree that lower-tropospheric temperatures have increased only slightly since 1979, though there has been a faster rate of global surface temperature increase. Balloon measurements indicate a larger lower-tropospheric temperature increase since 1958, similar to that shown by global surface temperature measurements over the same period. Balloon and satellite measurements agree that lower-stratospheric temperatures have declined significantly since 1979.

- Since 1979, trends in worldwide land-surface air temperature derived from weather stations in the Northern Hemisphere, in regions where urbanisation is likely to have been strong, agree closely with satellite derived temperature trends in the lower troposphere above the same regions. This suggests that urban heat island biases have not significantly affected surface temperature over the period.

- The decrease in the continental diurnal temperature range since around 1950 coincides with increases in cloud amount and, at least since the mid-1970s in the Northern Hemisphere, increases in water vapour.

- Decreases in spring snow cover extent since the 1960s, and in the duration of lake and river ice over at least the last century, relate well to increases in Northern Hemispheric surface air temperatures.

- The systematic decrease in spring and summer Arctic sea-ice extent in recent decades is broadly consistent with increases of temperature over most of the adjacent land and ocean. The large reduction in the thickness of summer and early autumn Arctic sea ice over the last thirty to forty years is consistent

with this decrease in spatial extent, but we are unsure to what extent poor temporal sampling and multi-decadal variability are affecting the conclusions.

- The increases in lower-tropospheric water vapour and temperature since the mid-1970s are qualitatively consistent with an enhanced hydrological cycle. This is in turn consistent with a greater fraction of precipitation being delivered from extreme and heavy precipitation events, primarily in areas with increasing precipitation, e.g., mid- and high latitudes of the Northern Hemisphere.

- Where data are available, changes in precipitation generally correspond with consistent changes in streamflow and soil moisture.

We conclude that the variations and trends of the examined indicators consistently and very strongly support an increasing global surface temperature over at least the last century, although substantial shorter-term global and regional deviations from this warming trend are very likely to have occurred.

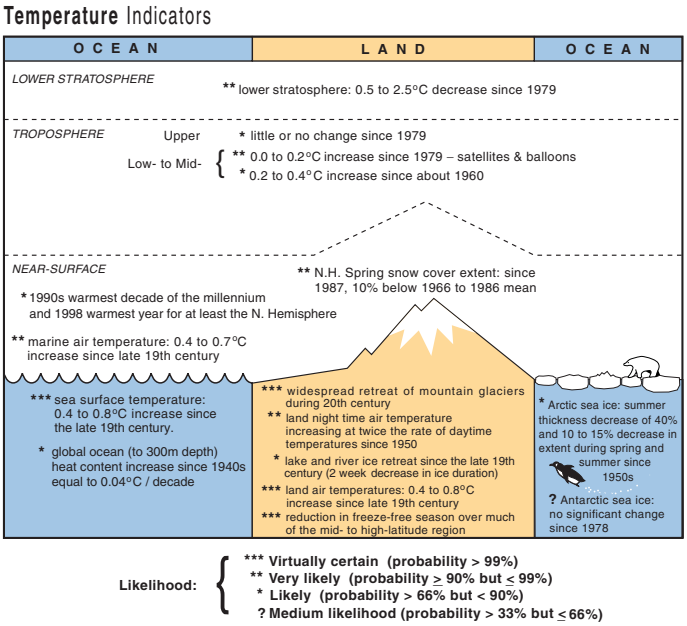

Figure 2.39a: Schematic of observed variations of various temperature indicators.

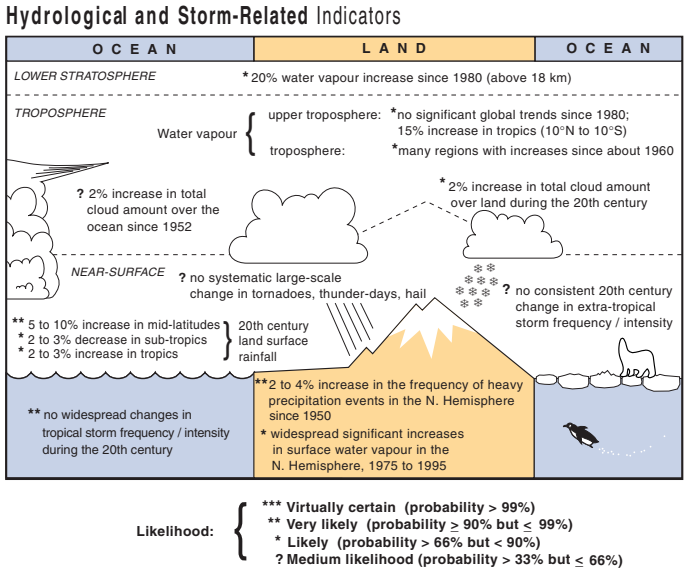

Figure 2.39b: Schematic of observed variations of various hydrological and storm-related indicators.

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