Prospects for Future Climate

A Special US/USSR Report on Climate and Climate Change

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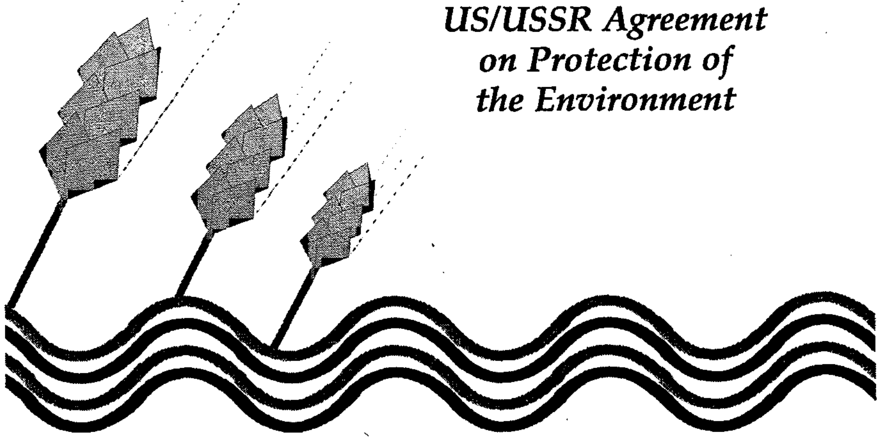
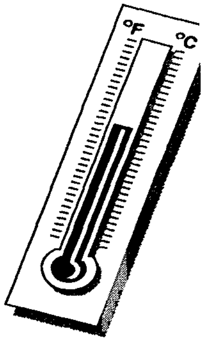


CHAPTER 3. RECENT GLOBAL CLIMATIC TRENDS



3.1. INTRODUCTION

This chapter describes climate changes that have occurred over about the last 100 years. This is the time interval for which sufficient instrumental measurements are available to allow estimation of global changes in the records of near-surface temperature and continental precipitation. Analyses of these records can provide important information about natural climate variability and about the initial response of the climate to recent changes in atmospheric composition.

Because the mean global surface air temperature is sensitive to many components of the Sun-Earth energy balance, it can be difficult to identify the specific causes of observed fluctuations of temperature. For larger and persistent changes in surface temperature, however, the most important factor on the time scale of centuries is atmospheric composition, especially the concentrations of greenhouse gases and, over few-year periods, injections of volcanic aerosols. The most important of the greenhouse gases is water vapor, which is controlled by natural climatic processes and without which our planet would be frozen. Changes in the amount of atmospheric water vapor affect the ability of the atmosphere to absorb solar energy and the radiative heat emitted from the Earth's surface, thereby affecting the vertical temperature profile and the surface temperature. Seasonal and long-term variations in the extent and characteristics of cloudiness and snow and ice cover can also change the net amount of solar energy that is absorbed. Variations in cloudiness and snow and ice cover can occur as a result of changes in temperature; thus, a feedback effect is produced whereby either more or less energy is reflected back to space.

Society's activities are leading to the emission of trace gases into the atmosphere and to the altering of atmospheric composition. The enhanced greenhouse effect that is occurring is of particular interest because it may significantly perturb the climate of the next century. The trace gases contributing to an enhancing of the greenhouse effect include carbon dioxide, (CO_2) methane, chlorofluorocarbons, ozone, and nitrous oxide (see Chapter 4). The presence of these trace gases causes changes in the atmospheric radiative fluxes, which then result in an increase in surface temperature. This change of temperature then affects the snow and ice cover, the amount of water vapor in the atmosphere, and the amount and characteristics of clouds. Such changes can then amplify or mitigate the initial response of the Earth-atmosphere system This

Another mode of natural climate variability that has received considerable attention over the past several years is the El Niño/Southern Oscillation (ENSO), which occurs irregularly about every 3 to 7 years and persists for 1 to 2 years. Typically, an area of anomalously warm surface water expands westward to the dateline from the equatorial waters of the eastern Pacific off the coast of South America. Simultaneously, above-normal sea-level pressure occurring in the western Pacific weakens or reverses the easterlies in the eastern equatorial Pacific. The induced changes in atmospheric and oceanic circulations affect the circulation in many other portions of the globe. Conditions with opposite characteristics (anti El Niño/Southern Oscillation events) have also been observed between ENSO events. They also last for a period of a year or two. Empirical analyses have shown that these events can introduce considerable short-term climate variability into the global thermometric records. Jones and Kelly (1988) estimate that as much as 25 to 30% of the year-to-year variability of the climate record may be due to the ENSO phenomena.

The concept of climatic chaos (Lorenz, 1986) may be of importance with respect to the interpretation of interannual to decadal climate fluctuations. The term "chaos" refers to the random and erratic behavior of a deterministic or nearly deterministic system. Such variations can arise without any external changes to the system and make it more difficult to identify the initial stages of climatic perturbations.

3.3. CHANGES IN MEAN SURFACE AIR TEMPERATURE

3.3.1. Land-Based Analyses

The first attempt to estimate changes in the mean global surface air temperature was made at the end of the last century (Köppen, 1883). However, Köppen's work for the period 1731 to 1871, which was supplemented by Humphreys (1929) up to 1920, is now purely of historical interest. Several tens of studies made later have gradually improved the methodological basis and have further developed the information data base (Ellsaesser et al., 1986).

Modern ideas about the recent changes in global temperature based on land observations have developed from initial studies conducted by Mitchell (1961; 1963), Budyko (1969), Borzenkova et al. (1976), Vinnikov et al. (1980), Hansen et al. (1981), and Jones et al. (1982). The time series of global estimates of temperature obtained in these papers (and later updates) have been widely used and cited by other authors. The results of some of these investigations were summarized at the 1981 Leningrad meeting of US and USSR scientists on the effects of the increasing atmospheric concentration of carbon dioxide on climate (US-USSR, 1982). The participants at that meeting noted the good agreement between the estimates of changes in the Northern Hemisphere surface air temperature that were obtained by Soviet and American scientists using different

Over the past few years, additional work has reduced the uncertainties in the data record and improved the analysis techniques used to compile estimates of the changes in the mean global surface air temperature. Independent research teams located at the University of East Anglia (Jones et al., 1986a, 1986b; Jones, 1988), the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (Hansen and Lebedeff, 1987, 1988), and the State Hydrological Institute (Vinnikov et al., 1987, 1990) have recently produced new estimates of land-based temperature change. The primary sources of data for all of these studies were the magnetic-tape archives of climatic information based on publications from the World Meteorological Organization (WMO) and other national climate publications, including the *World Weather Records* and *Monthly Climatic Data for the World* prepared by the US National Climatic Data Center.

Although each of the research teams used the same basic data sources, each used quite different methods. Except for large random errors (which they exclude), Hansen and Lebedeff (1987, 1988) implicitly assume that if there are any inhomogeneities in the data, they are not systematic and will sum to near-zero over large areas. They test for (but do not remove) the impact of locally generated, urban heat islands. Area-averages of temperature are derived by Hansen and Lebedeff (1987) using a procedure in which each station is assumed to be representative of changes over a large area (i.e., out to an influence radius of 1000 km).

Jones et al. (1986a, 1986b) attempt to adjust for all forms of biases in the data, including urban heat island effects and random errors. They use a procedure to area-weight temperatures so that stations can contribute to only one grid box of 5° latitude by 10° longitude. Jones et al. (1985) provide an estimate of the quality of the station data they use, as well as recommendations for their corrections. Both Jones et al. (1986a, 1986b) and Hansen and Lebedeff (1987, 1988) base their results on observations from about 2000 stations.

Compilations by Vinnikov et al. (1987, 1990) differ in that they are based on fewer stations (301 in the Northern Hemisphere and 265 in the Southern Hemisphere) and apply a statistically optimum method for spatial averaging of meteorological fields. The fundamentals of this technique have been described by Gandin and Kagan (1976) and Kagan (1979). These methods enable the Soviet researchers to use a smaller number of stations than the other groups when the spatial correlation function is isotropic and time is invariant. Vinnikov et al. (1987, 1990) have corrected their data for obvious inhomogeneities in the temperature records as well as for the presence of random errors. They considered the effects of urban heat islands on the climate record to be insignificant if the population of the city in which a station is located was less than 1 million (Groisman and Koknayeva, 1989).

Although the approaches used by each of the research teams vary, the hemispheric and global estimates of the change in mean surface air coupling of radiative fluxes to surface climate makes the globally averaged, mean annual surface air temperature a very sensitive measure of the climate in that it is closely linked to changes in the hydrologic cycle, atmospheric circulation (and cloudiness), ocean circulation, sea ice, and snow cover.

Twentieth-century variations in the surface air temperature are better documented and understood than are changes in any of the other climate elements. This chapter first discusses the natural factors influencing the natural variability, which serves as the background with which the enhanced greenhouse effect must compete. The chapter then analyzes changes in the thermometric record of surface temperature and, because of their great practical significance, evidence of modern-day changes in precipitation and sea level.

3.2. NATURAL CLIMATE VARIABILITY

Over the past 100 years, the global average surface temperature is believed to have been affected by a number of natural factors that can induce changes in the climate. These factors can be divided into two categories: (1) those that are best thought of as external to the climate system, and (2) those that are considered to be internal. External forcing factors are those that produce changes within the climate system, but originate outside the ocean/atmosphere system. Among the external factors that may have affected the modern temperature record are (1) volcanic activity and (2) changes in the solar irradiance. Major volcanic eruptions inject gaseous sulfur dioxide into the atmosphere that often reaches the stratosphere and is rather quickly converted to sulfuric acid aerosols. If present in sufficient quantities in the stratosphere where their removal rate is slow (the average lifetime of aerosol particles in the stratosphere is about 1 year), these aerosols can significantly affect the Earth's net radiation balance. Two internal factors that have led to climatic variations of the atmosphere/ocean system are the El Niño/Southern Oscillation (an ocean-atmosphere oscillation centered in the equatorial Pacific Ocean) and the chaotic behavior that can arise as a result of the highly complex, nonlinear behavior of and interactions between the atmosphere and ocean. It is quite possible that these external and internal factors have contributed to the natural variations in the modern temperature record in addition to any impact that man has had as a result of the enhanced greenhouse effect.

Volcanic eruptions produce aerosols that are in a constant state of evolution. Because the size distribution of these particles is very important in determining whether their influence will tend to warm or cool the surface (Toon and Pollack, 1980), estimates of their effect on the surface climate are strongly dependent on assumptions made about the number and size distribution of the aerosols. A number of empirical studies have been carried out to identify and estimate the effect of volcanic eruptions on surface temperatures over the last 100 years or more (Angell and Korshover, 1985; Sear et al., 1987; Bradley, 1988; Mass and Portman, 1989). Generally, these studies have concluded that major volcanic events, of which there were only about five during the past 100 years, may cause cooling. The evidence is not overly convincing, however, and the cooling caused by these major eruptions has probably been only a few tenths of a degree for a 1- to 2-year period after the event. This would imply that volcanic eruptions have not been a primary factor contributing to decadal and multi-decadal climate variability over the last 100 to 150 years. Unless a change in the character or frequency of explosive eruptions occurs in the future, it is unlikely that volcanic aerosols will be a factor that could substantially counterbalance the greenhouse effect. However, studies summarized by Budyko (1974), Vinnikov (1986) and Khmelevtsov (1986) indicate that atmospheric transparency fluctuations in the Northern Hemisphere derived from station measurements of direct solar radiation can induce not only drastic short-term changes, but also interdecadal trends of mean surface air temperature able to obscure trends caused by the anthropogenic increase in trace gases. Moreover, Robock (1979) and others suggest that increasing volcanic activity was the most probable cause of the temperature reduction during the Little Ice Age that made the seventeenth and eighteenth centuries anomalously cold.

Variations in the amount of solar energy received by the Earth also can affect the surface temperature. Direct measurements of solar irradiance began in 1967 using balloons and rockets. However, these measurements are inherently less reliable than those available since 1978, when satellite measurements of the solar irradiance were begun. These satellite measurements have demonstrated that solar luminosity variations of 0.1% are occurring in association with solar activity. Overall, data since 1967 suggest that there has been a regular variation of solar irradiance with an amplitude of about ±0.4% that is coincident with the magnetic variation of the Sun (Frohlich, 1988). Because of missing data between 1971 and 1976 and limitations in the quality of early balloon data, it is not possible to be certain whether this is a 22- or an 11-year variation.

The lack of any direct measurements of solar irradiance prior to 1967 has led to use of proxy measurements of solar output (e.g., sunspots, the size of the solar disk, ^{14}C measurements, etc.). Attempts have been made to relate these proxy measurements to the thermometric record, but their impact has been difficult to substantiate. This may be partly attributed to the large buffering of the short-term fluctuations, such as the 11- or 22-year solar periodicity, that occurs as a result of the large thermal inertia of the oceans (Wigley, 1988). Longer periodicities of approximately 80 years appear in the proxy record. The relationship of such periodicities to changes in solar irradiance and the climate record is, however, still subject to considerable uncertainty; reviews by Khromov (1973) and Pittock (1978, 1983) suggest that these periodicities may not be present or related.

temperature over the past 100 years are all in close agreement. Figures 3.1 through 3.3 show changes in mean annual surface air temperature derived by the three independent research teams. The estimates are presented for the 1881 to 1987 (or 1988) period. Before the second half of this century, there were no observational data from the Antarctic regions; therefore, the estimates for the Southern Hemisphere cover only the zone 0° to 60°S and for the globe the zone 90°N to 60°S. The data presented in these figures represent the land-based thermometric record. The figures demonstrate the considerable agreement among the three independent studies. It should be noted that the reference periods (i.e., the interval of years over which the average departure is assumed to be zero) are different for the three studies; as a result, only the changes from year to year are directly comparable in that the zero departure lines have different offsets.

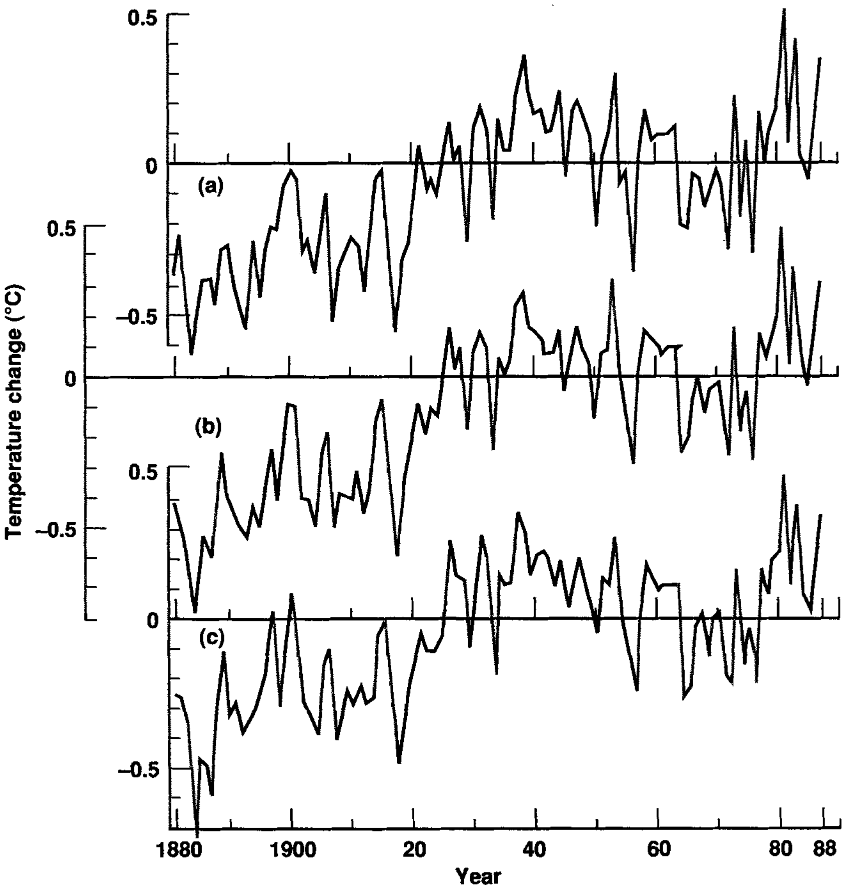


Figure 3.1. Estimates of present-day changes in mean annual surface air temperature in the Northern Hemisphere. (Note that reference periods are different.) Data are from (a) Jones et al. (1986a) and later updates, (b) Hansen and Lebedeff (1987), and (c) Vinnikov et al. (1990).

Correlation coefficients between the estimates of mean annual surface air temperature for the Northern Hemisphere range from 0.95 to 0.97; for the Southern Hemisphere from 0.93 to 0.95; and for the globe (90°N to 60°S) from 0.97 to 0.98.

Table 3.1 gives standard deviations and linear trends of the mean air temperature over the period 1881 to 1987 for the records of various research groups. Differences appear to be insignificant. A linear trend line fit through these observations indicates an increase in globally averaged surface air temperature of about 0.4 to 0.5°C over this 100-year time period for each of the three series. The rate of warming has not been continuous in time or space. For example, Fig. 3.4a indicates that the warming trend decreases and nearly vanishes for the period from the 1930s to 1987. Likewise, the rate of temperature increase is significantly lower over the full period of record compared to the years 1881 to the 1940s (Fig. 3.4b). These results serve to illustrate the difficulty in interpreting the observed increase of temperature over the past 100 years or so as a simple monotonic increase.

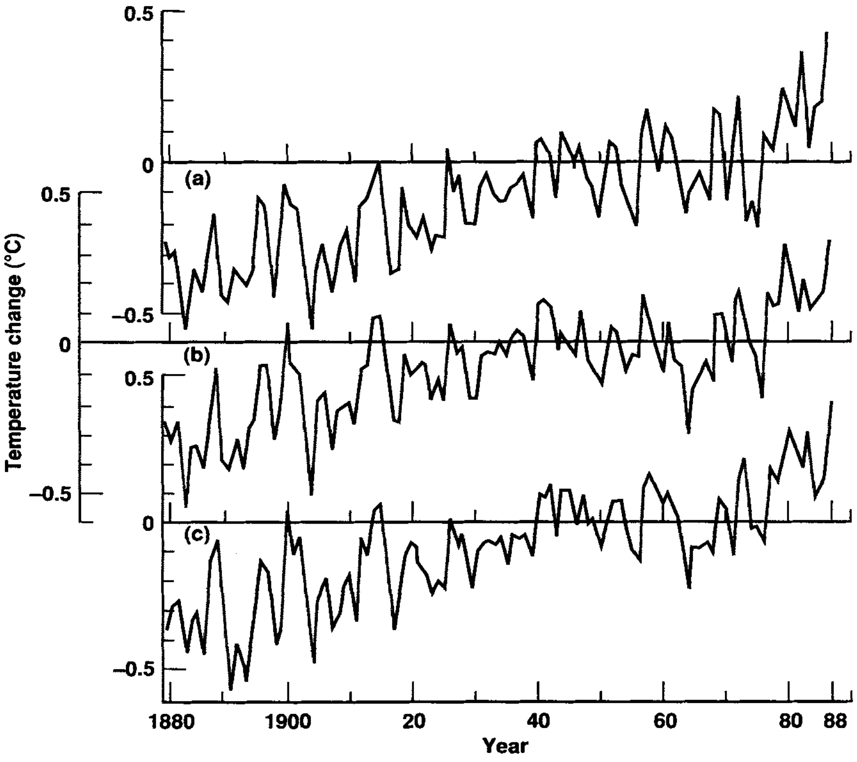


Figure 3.2. Estimates of present-day changes in mean annual surface air temperature of the Southern Hemisphere (0° to 60°S). (Note that reference periods are different.) Data are from (a) Jones et al. (1986b) and later updates, (b) Hansen and Lebedeff (1987), and (c) Vinnikov et al. (1990).

Both the variability in the trend and the sensitivity of the calculation to the specified starting and ending years cannot be over-emphasized. For example, if instead of calculating the 100-year Northern Hemisphere trend over the years 1881 to 1987, the trend were calculated over the period 1901 to 1987 (87 years), the trend would be reduced to a rate of 0.4°C/100 yr. Obviously, great caution must be taken in interpreting linear trend estimates. This is especially true with respect to trends of temperature calculated starting in the 1880s, because this was probably one of the coldest decades of the second half of the nineteenth century (Jones et al., 1986a). On hemispheric space scales, warming in the Northern Hemisphere was interrupted between the early 1940s and the mid-1960s by weak cooling. Concurrently, a small decrease in the positive trend of temperature occurred in the Southern Hemisphere. Since the early 1970s, however, the warming has resumed in both hemispheres such that the global average temperature for the 1980s was about 0.25°C higher than that in the 1970s.

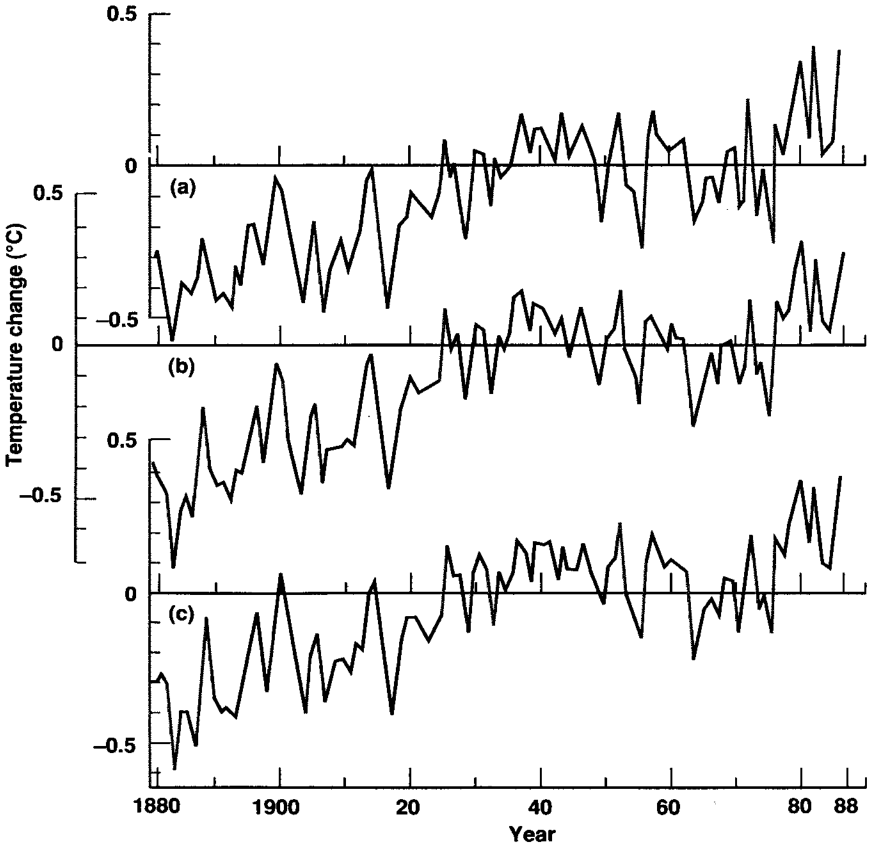


Figure 3.3. Estimates of present-day changes in mean global annual surface air temperature (90°N to 60°S). (Note that reference periods are different.) Data are from (a) Jones et al. (1986c) and later updates, (b) Hansen and Lebedeff (1987), and (c) Vinnikov et al. (1990).

Table 3.1. Standard deviations and linear trends of the mean annual surface air temperature for the period 1881 to 1987 for Northern Hemisphere (NH, 0° to 90°N), Southern Hemisphere (SH, 0° to 60°S), and the global (90°N to 60°S) domains based on data from the three compilations cited.

	Standard deviation (°C)		
Compilers of data set	NH	SH	Global
Jones et al. (1986a, 1986b, 1988)	0.24	0.20	0.21
Hansen and Lebedeff (1987,1988)	0.26	0.18	0.22
Vinnikov et al. (1987, 1990)	0.23	0.19	0.20
	Linear trend (°C/100 yr)		
	NH	SH	Global
Jones et al. (1986a, 1986b, 1988)	0.50	0.50	0.50
Hansen and Lebedeff (1987,1988)	0.61	0.41	0.51
Vinnikov et al. (1987, 1990)	0.48	0.49	0.48

Figure 3.5 displays the changes in the mean annual surface air temperature for the six latitudinal zones 60° to 90°N, 30°to 60°N, 0° to 30°N, 0° to 30°S, 30° to 60°S and 60° to 90°S. The data are from Vinnikov et al. (1990). These graphs show that the trends in the mean zonal surface air temperature increase with increasing latitude. In the zone 60° to 90°N, the mean warming rate has been approximately 1°C/100 yr (1881 to 1987), which is about twice as large as the global mean. Because the year-to-year variability of temperature in the high latitudes is several times larger than that observed in other areas, however, the statistical significance of the warming is actually greater in the lower latitudes.

As for the global domain, the rates of change in the different latitudinal zones do not show a simple monotonic or constant increase in temperature. Not only are there latitudinal variations in the trends, but there are seasonal variations as well. Figure 3.6 shows the estimated trends for the mean monthly air temperature for each hemisphere based on the results from Jones et al. (1986a, 1986b), Jones (1988), and Vinnikov et al. (1987, 1990). Although there are small differences in the estimates due to random errors in data and sampling variability, the general features are quite consistent. The warming takes place in all months of the year in both hemispheres, but it is most pronounced in winter months. Part of the reason for the smaller amplitude of seasonal

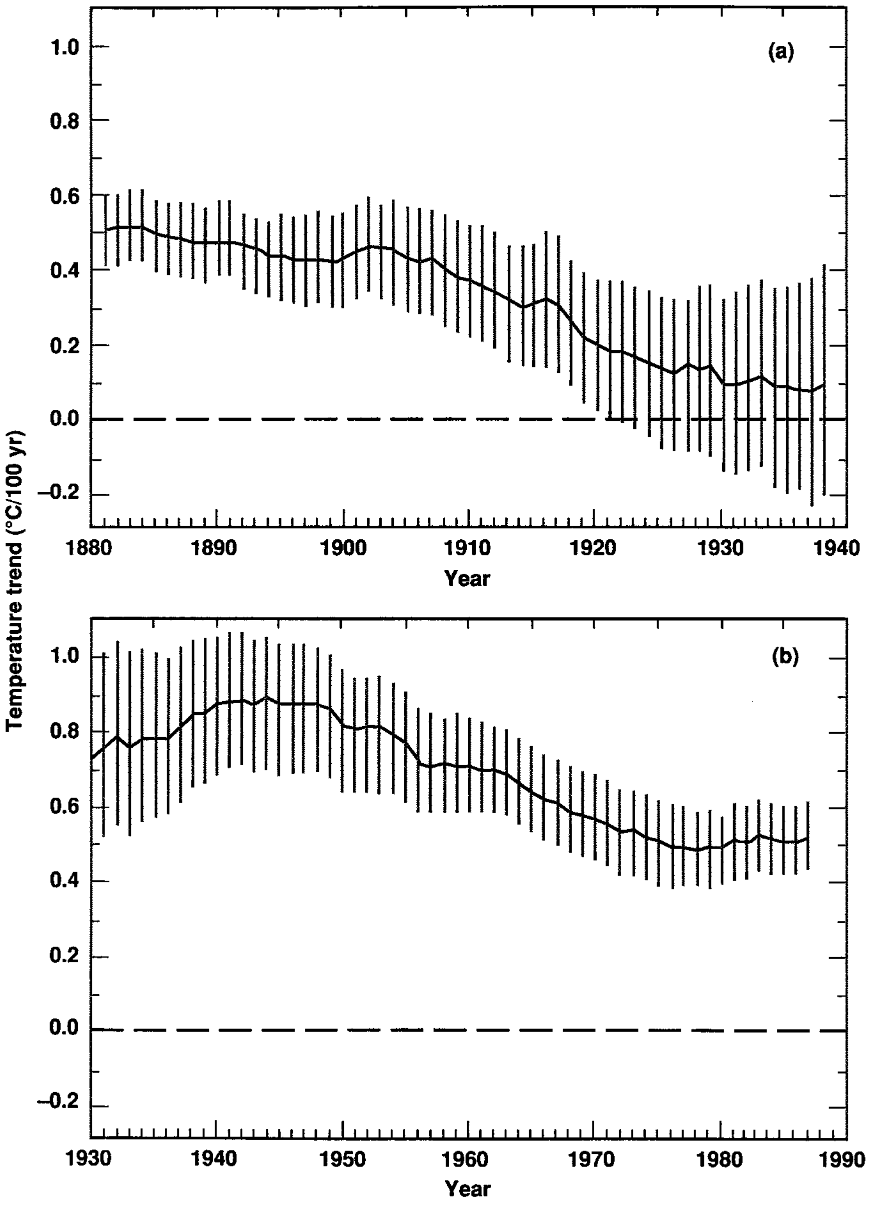


Figure 3.4. Linear trends of Northern and Southern Hemisphere land temperatures (from Jones, 1988) and their associated 95% confidence intervals expressed as rates of change over 100 years: (a) ending year for all trends is 1987, and the beginning year is given on the x-axis; and (b) ending year for all trends is given along the x-axis, and the beginning year is 1881. Trends reflect changes due to changes in both atmospheric composition and to other factors.

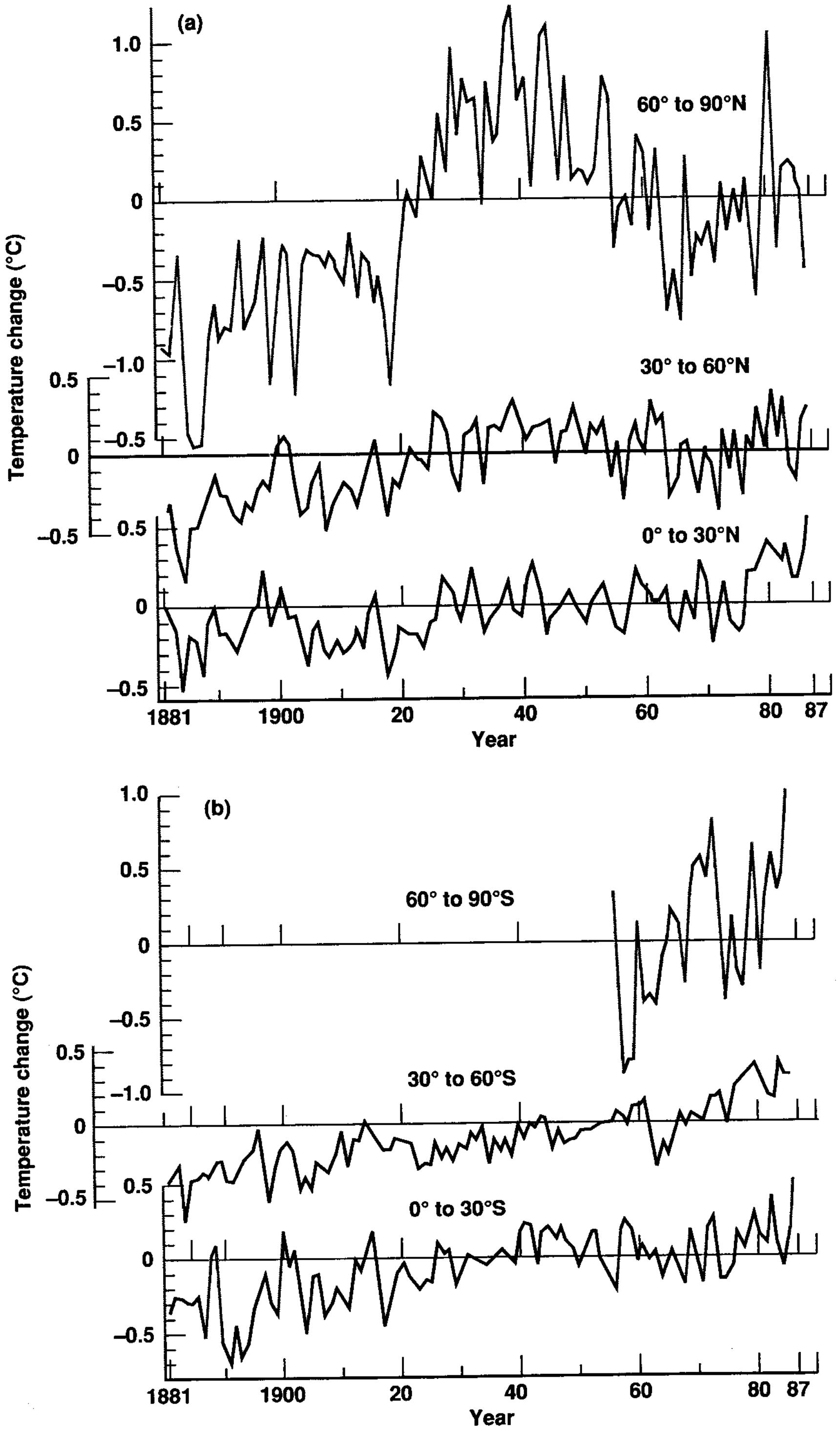


Figure 3.5. Mean annual surface air temperature of three latitudinal belts in (a) the

variations in trends in the Southern Hemisphere as compared to the Northern Hemisphere can be attributed to a lack of data for the zone 60° to 90°S. Figure 3.7 shows the changes of seasonal surface air temperature over land areas from the data of Jones et al. (1986a, 1986b). Since 1880, when the station-data coverage first became minimally acceptable for global calculations, there has been an upward trend of surface air temperatures in all seasons.

3.3.2. Uncertainties in the Land-Based Observations

Although there is a general consistency among the results of the three analyses, questions about the certainty of the estimates of global, hemispheric, and regional trends of temperature have been raised by a number of authors (e.g., Callendar, 1961; Mitchell, 1963; Bradley et al., 1985; Ellsaesser et al., 1986; Karl and Quayle, 1988; Karl et al., 1989; Karl and Jones, 1989; Parker, 1989; Wood, 1990). Questions of data reliability focus on three aspects:

(1) Insufficient and changing spatial coverage of the station network.
(2) Rapid increases in urbanization around many of the observing stations, which might produce a spurious warming in the climate record.
(3) Inhomogeneity of the time series due to varying types of instrument shelters, to station relocation, and to changes in the methods of observation, measurement, and processing of thermometric data.

The changing density of observations over the land has been addressed by sensitivity studies using so-called "frozen" networks (Jones et al., 1986a, 1986b). The results of these studies indicate that changes in station density since about 1900 seem to have had little effect on the estimates of hemispheric temperature trends. However, between 1880 and 1900, the decadal uncertainty of global average temperature anomalies could be as large as 0.1 to 0.2°C.

A considerable amount of work has been focused on estimating the effects of increased urbanization on the thermometric record. Recent work by Jones et al. (1989) estimates that perhaps as much as 0.1°C of the 0.5°C warming over the past 100 years may be due to urbanization. Hansen and Lebedeff (1987) also addressed this problem by recalculating their estimates of global average temperatures after omitting all stations in cities with populations in excess of 100,000. This reduced their estimate of the global trend by about 0.1°C/100 yr, down to 0.4°C/100 yr. They hypothesized that perhaps as much as another 0.1°C/100 yr of urban-induced warming may remain in their data due to urban warming effects at stations with populations below 100,000. This would produce a global warming trend of about 0.3°C/100 yr.

In another recent study, Karl et al. (1988) showed that urban biases of annual average temperatures as large as 0.1°C can be detected at stations in towns with population as small as 10,000. This result was

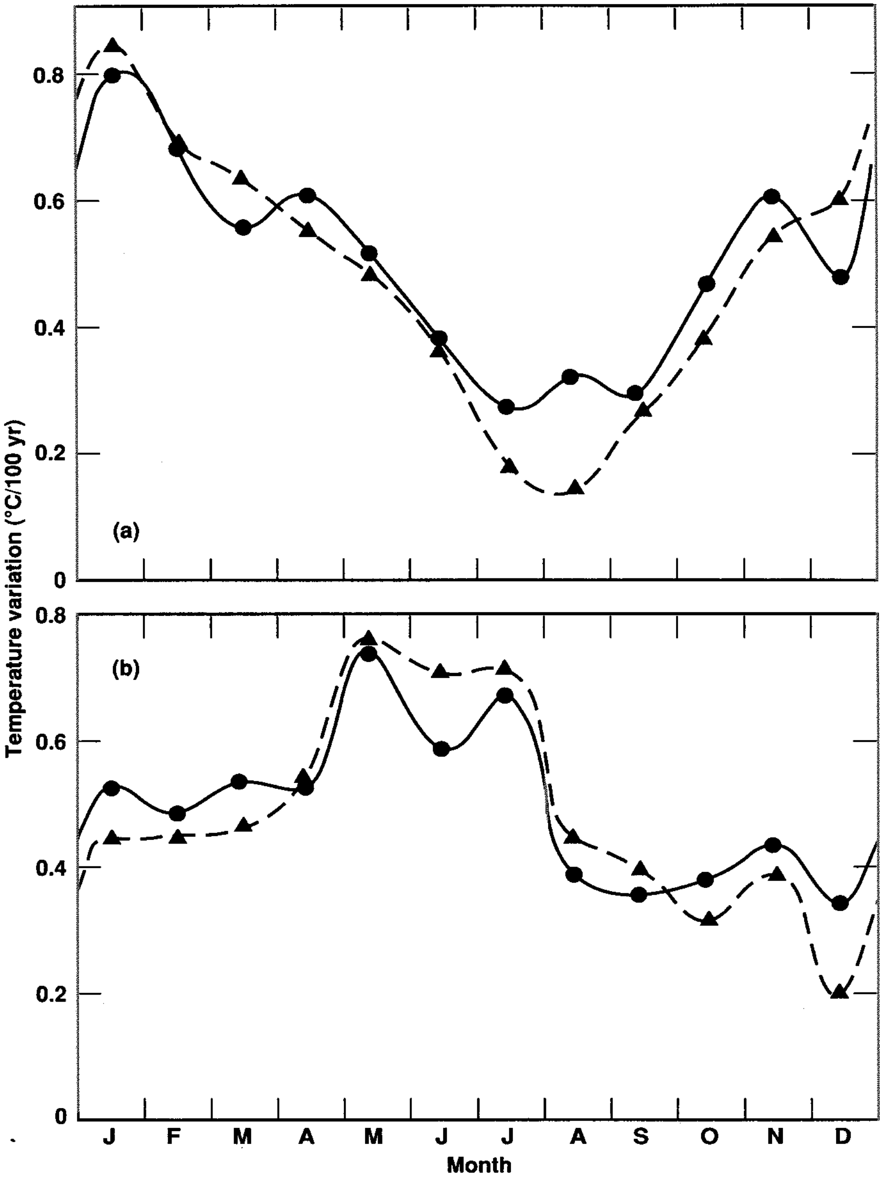


Figure 3.6. Annual variations in estimates of linear trends of mean monthly surface air temperatures for the (a) Northern (0° to 90°N) and (b) Southern (0° to 60°S) Hemispheres from 1881 to 1987. The solid curve is based on Jones et al. (1986a, 1986b), and the dashed curve is based on Vinnikov et al. (1990).

based on a comprehensive network of mostly rural stations in the US Historical Climate Network (HCN), data which have been corrected to the extent possible for other station inhomogeneities (Karl et al., 1986; Karl and Williams, 1987; Quinlan et al., 1987). Groisman and Koknayeva (1989) compared the United States area-average temperature trends derived from this network to estimates from Vinnikov et al. (1990) for the continental United States. The differences in the trends between the two data sets were quite small (about 0.05°C/100 yr), despite the fact that many of the stations used by Vinnikov et al. (1990) were located in and around major metropolitan areas that have experienced rapid growth over the past century. The other two global land-based thermometric data sets were also compared for the contiguous United States with the HCN data. Both the Jones et al. (1986a, 1986b) and the Hansen and Lebedeff (1987) data were found to warm at a faster rate than the HCN by about 0.1 to 0.2°C/100 yr (Hansen et al., 1988; Karl and Jones, 1989; Karl and Jones, 1990). Comparison of mean air temperature trend estimates from a network of rural stations in the USSR (Vinnikov et al., 1987, 1990) show no noticeable urban bias (Groisman and Koknayeva, 1989).

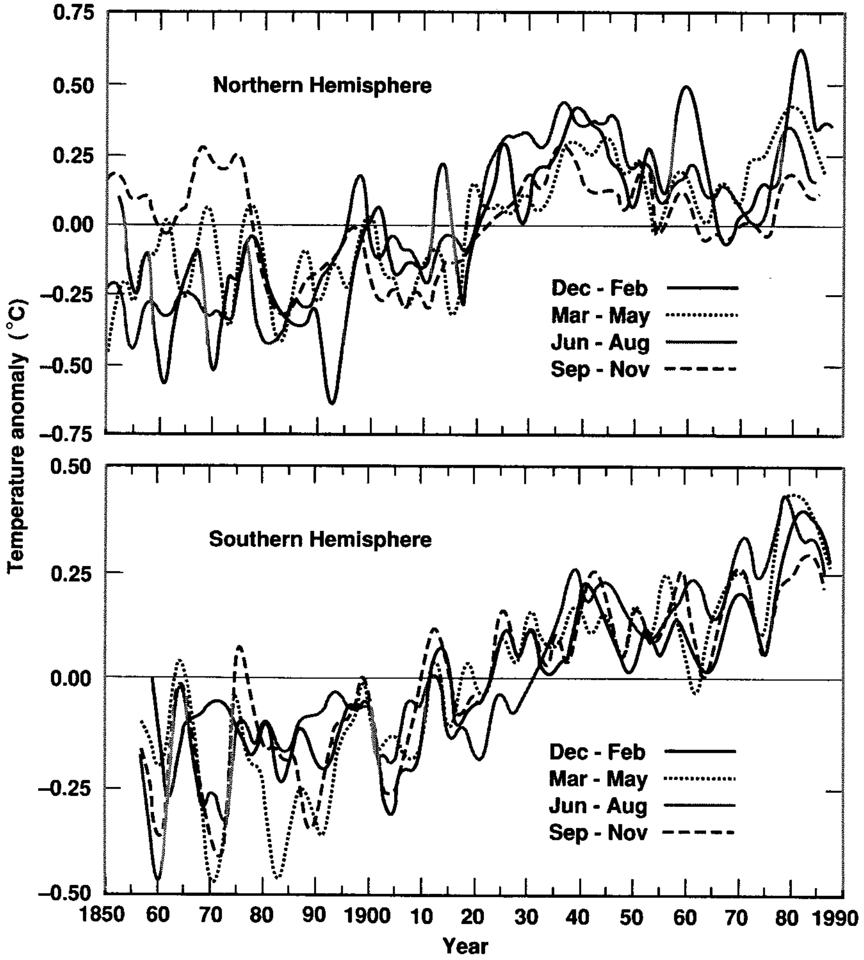


Figure 3.7. Seasonal land-surface air temperature anomalies (based on data from Jones et al., 1986a, 1986b) relative to means for 1881 to 1987. A nine-point binominal filter has been applied to the data (beginning and end segments are derived by using double weights of the last 5 years of data).

A crucial question is why the results over the United States using the rural HCN data set are so similar to the results of Vinnikov et al. (1990). A likely reason is that other inhomogeneities in the thermometric record have compensated for the urban warming bias found in the HCN analysis. Examples of such opposing systematic biases that could compensate for each other include station relocation to airports versus development of urban heat islands. Other forms of inhomogeneities in the thermometric record stem from changes in the observation times used to record the daily temperatures and from changes in instrument shelters used to house thermometers. However, changes in observation times and in instrument shelters are likely to have had a substantial effect on global or hemispheric temperature only if systematic changes occurred in large countries. Based on current information, we do not expect that these effects have introduced significant biases in the globally and hemispherically averaged changes of temperature, but caution must be exercised.

Thus, based on the close agreement of all three research groups, the global average surface temperature is estimated to have risen by between 0.4°C and 0.5°C from the late nineteenth century to the present.

3.3.3. Ocean Surface Temperatures

Data sets of ocean surface temperature are also valuable sources of information about climate changes. Systematic measurements of sea surface and marine air temperatures began in the mid-nineteenth century, and over 100 million of these observations have been transferred to computer-readable magnetic tapes. Although many observations date back to the mid-nineteenth century, over three-fourths of them have been taken since World War II. Most observations were taken by ships of opportunity (i.e., ships that just happened to be sailing in a particular location) following routes that favored preferred navigational transects across the global oceans; these routes have changed over the past century. As a result, large geographic areas of the oceans have not been adequately sampled, and even today, one-third of the global oceans are not represented in the National Oceanic and Atmospheric Administration (NOAA) Comprehensive Ocean-Atmosphere Data Set (COADS) (Slutz et al., 1985).

There are few observations from the tropical areas of the Pacific Ocean until the 1950s, and few from oceanic regions poleward of 40°S until even more recently. Even when observations are available for a given area, there may be only one or two values for a given month, and adjustments may be required to convert the resulting estimate to a mid-month or mid-area equivalent. On the other hand, the rather poor coverage of marine observations across the global oceans is compensated for to some extent by the fact that the trends of ocean temperature anomalies tend to have a substantial amount of spatial coherence; that is, warming and cooling trends tend to occur on large spatial scales in the oceans (much more so than for surface temperature anomalies over land).

For marine air temperatures, biases exist for a variety of reasons. Ships have become larger over the years, and the height of the deck above sea level has increased. As ships have become larger, their absorption of insolation has increased and caused a bias in the observations of daytime marine air temperature. For sea surface temperature measurements, biases are known to have been introduced by changes in the methods by which the temperature is measured. Only in recent decades have observations of sea surface temperatures included records of the measurement procedure used; however, the depth of the measurement, shallow for small or empty ships, deeper for large, fully laden ships, is still not documented. Oceanographic measurements of sea temperature (i.e., data from research cruises) are well-documented and precise, but far fewer in number than voluntary ship observations and very poorly distributed for long-term global studies.

In spite of these difficulties, observations of both sea surface temperature and marine air temperature have been used to construct time series (see Fig. 3.8) that show a warming trend of approximately the same magnitude as that of the land-based data. However, with so few long-term observations of temperature over the oceans, particularly in the Southern Hemisphere, and because of the differing measurement practices, global and hemispheric time series extending back into the nineteenth century should be used circumspectly. Nevertheless, the observations from both the land and marine data provide us with unequivocal evidence that the near-surface global average of temperature has increased between 0.4° and 0.5°C over the last 100 years.

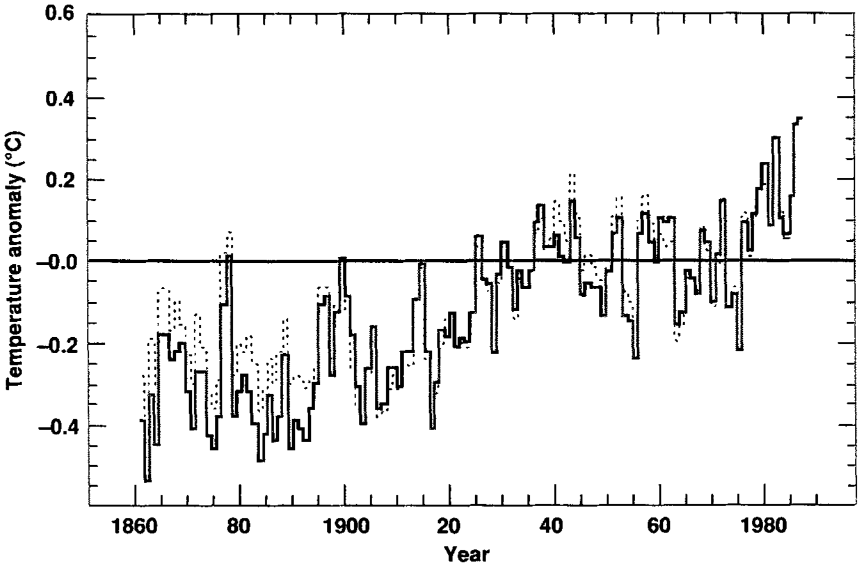


Figure 3.8. Estimates of global temperature anomalies (land and ocean) from Folland and Parker (1989) (dotted) versus Jones et al. (1986c) (solid). Updates to 1988 were provided by Folland (1989)

3.4. CHANGES IN PRECIPITATION OVER THE CONTINENTS

Along with air temperature, precipitation is the most important meteorological element characterizing the state of the natural environment and influencing the conditions of human economic activity. The world precipitation network was quite well-developed by the beginning of the twentieth century, encompassing more than 20,000 gauging stations. In some countries, the network was very dense. For example, in Germany at the start of this century, precipitation was observed at over 3000 gauging stations, in Australia at 2250, in Great Britain at 4000, in India at 2700, etc. (Vannari, 1911). At present, precipitation is measured at about 40,000 fully-equipped meteorological stations and 140,000 gauging stations. However, the regular international exchange of precipitation information comes from only about 1500 stations. Observations from only approximately 1250 stations are published at regular intervals in the international publication *Monthly Climatic Data for the World.* Thus, it is not possible at this time to use the full set of meteorological data in climatological studies even though there are a great number of operating meteorological stations and gauging sites.

3.4.1. Observed Changes in Precipitation

One of the first attempts to estimate recent trends in mean precipitation over the extratropical part of the Northern Hemisphere was by Apasova and Gruza (1982). Their work was based on maps of relative anomalies of monthly precipitation sums. They concluded that total precipitation amounts for January, for July, and for the year as a whole have increased over the last 100 years. Because the technique for constructing maps did not consider the homogeneity of the precipitation time series, however, this must be viewed as a preliminary result.

The recent work by Bradley et al. (1987) and Diaz et al. (1989) has been the most comprehensive, in terms of the quantity of data used and the size of the territory analyzed. In these studies, measurements were used from about 1500 stations. However, it was not the absolute amounts of precipitation or their anomalies that were averaged, but a precipitation index based on percentiles of the statistical distribution. These indices vary in the range of 0 to 1 and represent the probabilities of receiving a specified amount of precipitation. It is important to understand that this time series of mean indices does not give a measure of the total integrated water accumulating over a region. However, the index used by Bradley et al. (1987) is a useful measure of the areal extent that receives either more (≥0.5) or less (≤0.5) than normal precipitation. If total precipitation is of interest, then it is most meaningful to compute the precipitation indices for areas of relatively uniform precipitation characteristics. For such areas, the indices are approximately proportional to changes in mean precipitation amount (Bradley et al., 1987).

Examples of the differences between area-averages of total precipitation and an index of precipitation are shown in Figs. 3.9 and 3.10. This particular index of precipitation has been derived by standardizing the precipitation anomalies using the gamma distribution over various portions of the United States that have similar rainfall characteristics. Although there are important year-to-year differences, the overall trend, or lack thereof, is similar for both treatments of the data. The overall trend is positive, but not statistically significant. The data in Fig. 3.9 are derived from a fine-scale national network of 5000 stations in the United States (Karl, 1988), and the data in Fig. 3.10 are extracted from Bradley et al. (1987) and a denser set of Soviet stations (Bradley and Groisman, 1989). Further studies of precipitation indices and actual precipitation anomalies for different regions of the world confirm that both approaches provide similar estimates of year-to-year changes in precipitation and in long-term trends (Bradley and Groisman, 1989).

Spatial averages of the percentile values from the work of Bradley et al. (1987) are shown in Fig. 3.11 for annual precipitation indices in three latitudinal zones: 35° to 70°N, 5° to 35°N, and 0° to 5°N. As can be seen, the precipitation index at continental stations in the extratropical part of the Northern Hemisphere has increased over the last 100 years, particularly over the last 30 to 40 years. In lower latitudes (5° to 35°N), there is no systematic trend in the precipitation index before the early 1950s, but thereafter the precipitation index begins to decrease. In the subequatorial belt from 0° to 5°N, there is no obvious trend in the annual index.

Similar changes have been observed by other studies using mean total precipitation data (not indices) for the continents of the Northern Hemisphere in the band 35° to 70°N (Groisman, 1990; Vinnikov, et al., 1990). In their study, the anomalies of mean annual precipitation and mean precipitation for the warm period of each year (May to September) have been calculated. The records of mean annual precipitation for the Soviet Union, for western Europe, for North America in the 35° to 55°N zone, and for all continents in the 35° to 70°N belt (excluding Canada north of 55° and China) are shown in Fig. 3.12. Sloping lines correspond to estimates of linear trends. The estimates are based on data from about 300 stations in North America and western Europe, and from more than 600 stations in the USSR.

Table 3.2 presents statistical parameters and estimates of the linear trend for these regions (Groisman, 1990; Vinnikov et al., 1990). An upward tendency is apparent in all regions except western Europe. For the USSR and North America (35° to 55°N), the mean annual precipitation rates have increased at about 9%/100 yr and 7%/100 yr, respectively. However, the increase of precipitation in North America (35° to 55°N) is not well represented by a linear trend because precipitation was high at

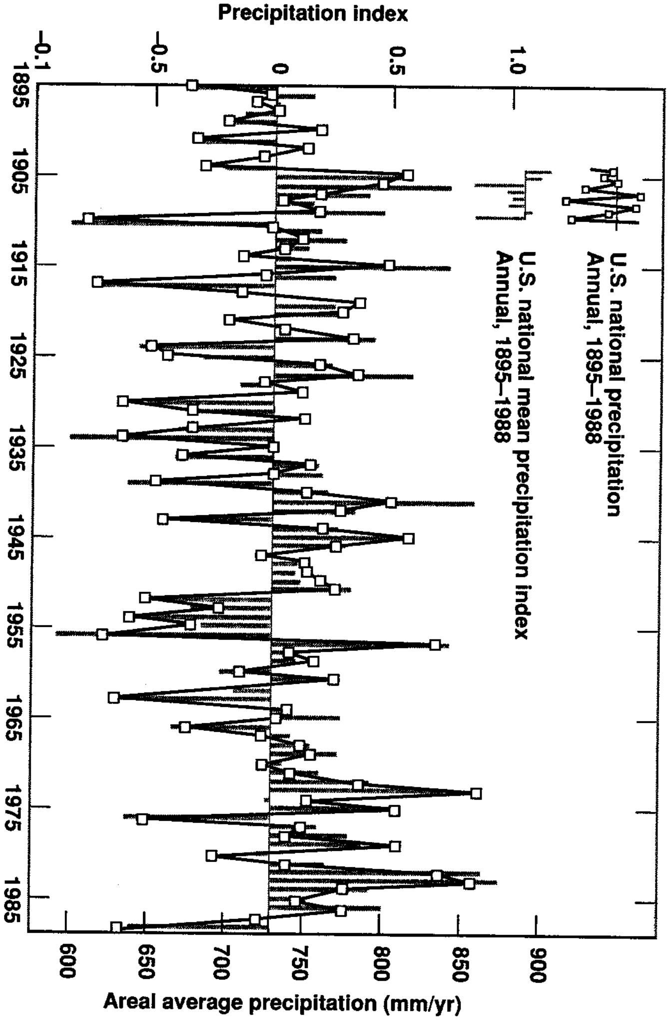


Figure 3.9. Changes in mean annual precipitation based on areal averages of total precipitation (solid lines) and an index of precipitation (shaded bars) for the contiguous United States.

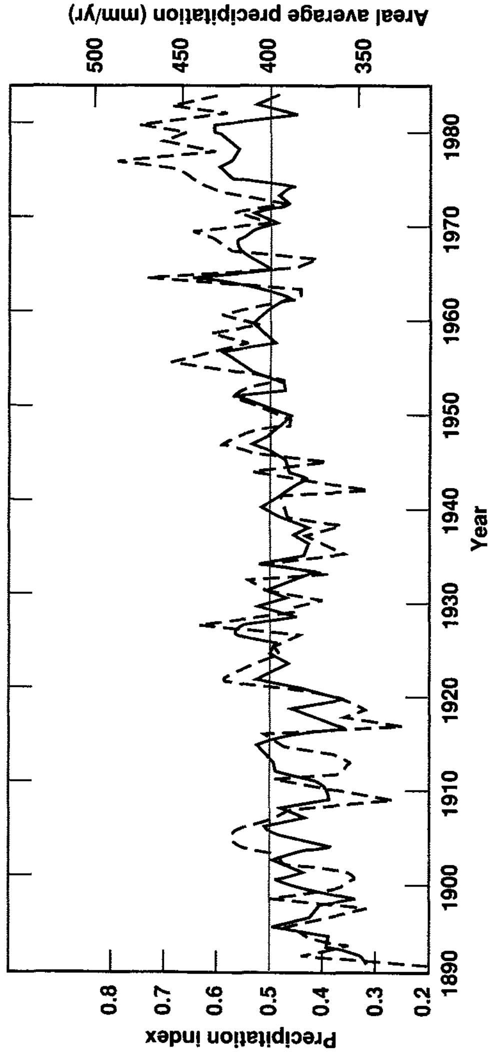


Figure 3.10. Changes in annual precipitation based on areal averages of total precipitation (solid lines) and an index of precipitation (dashed lines) for the USSR.

the beginning of the twentieth century, and the trend is heavily influenced by the multi-year wet period during the early 1980s. Karl (1988) points out the importance of multi-year climate fluctuations and the difficulty of ascribing physical significance to general trends in the data when these multi-year fluctuations are embedded in the climate record.

Based on the work of Groisman (1990) and Vinnikov et al. (1990), estimates for precipitation changes for the warm part of the year, when snow cover is absent almost everywhere, are similar to the estimated trends for annual precipitation, except for the area of the contiguous United States where little or no trend is apparent (2% increase over 100 years). On the average, for the entire continental region in the 35° to 70°N zone, the annual precipitation increase over the past 100 years was approximately 6% and 4% for the warm part of the year.

3.4.2. Uncertainties in the Precipitation Record

Although the abundance of measurements would seem to make estimates of precipitation trends a relatively easy task, a great deal of

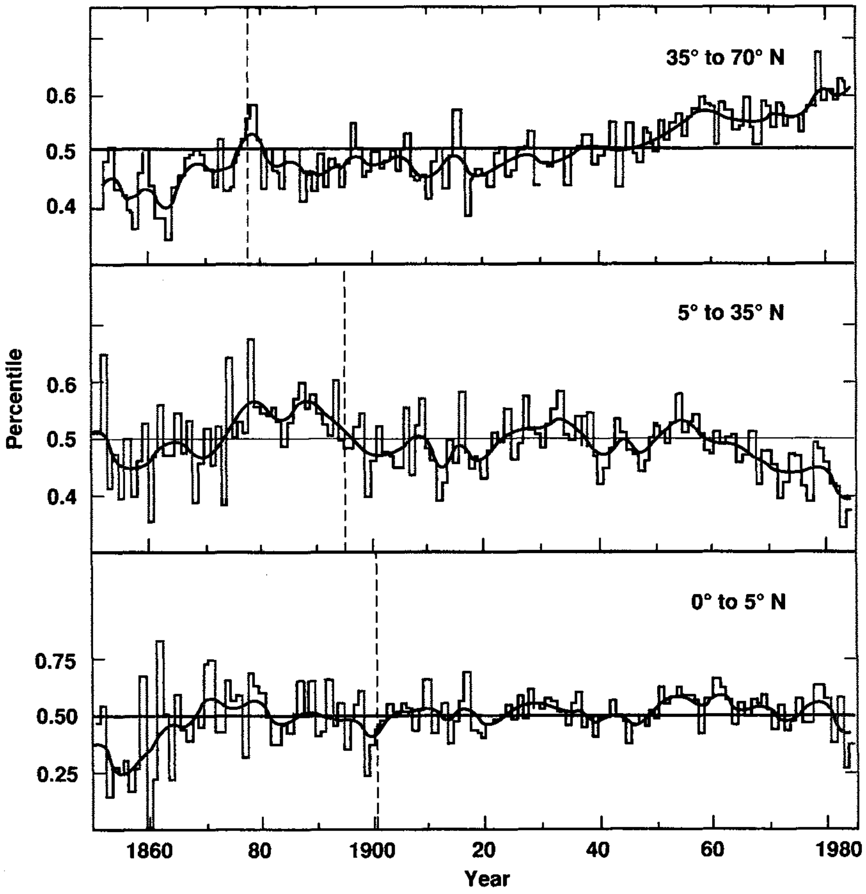


Figure 3.11. Precipitation indices for zones 35° to 70°N, 5° to 35°N, and 0° to 5°N

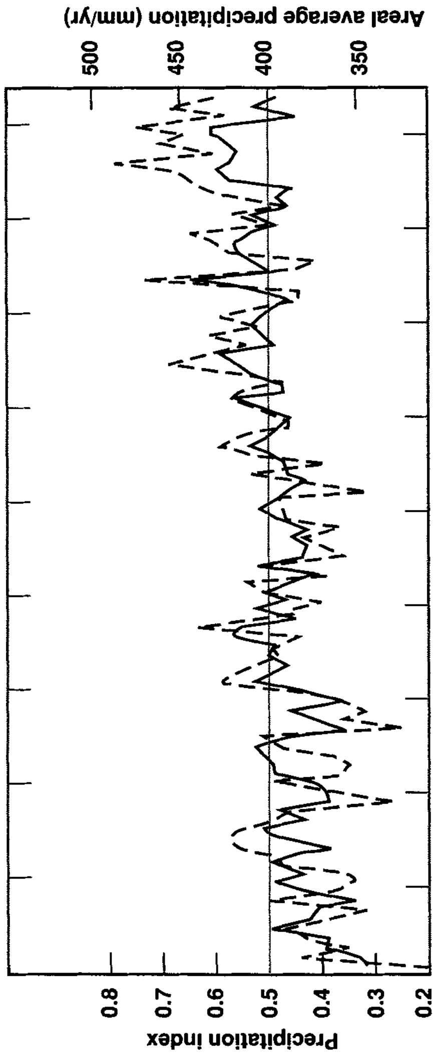


Figure 3.10. Changes in annual precipitation based on areal averages of total precipitation (solid lines) and an index of precipitation (dashed lines) for the USSR.

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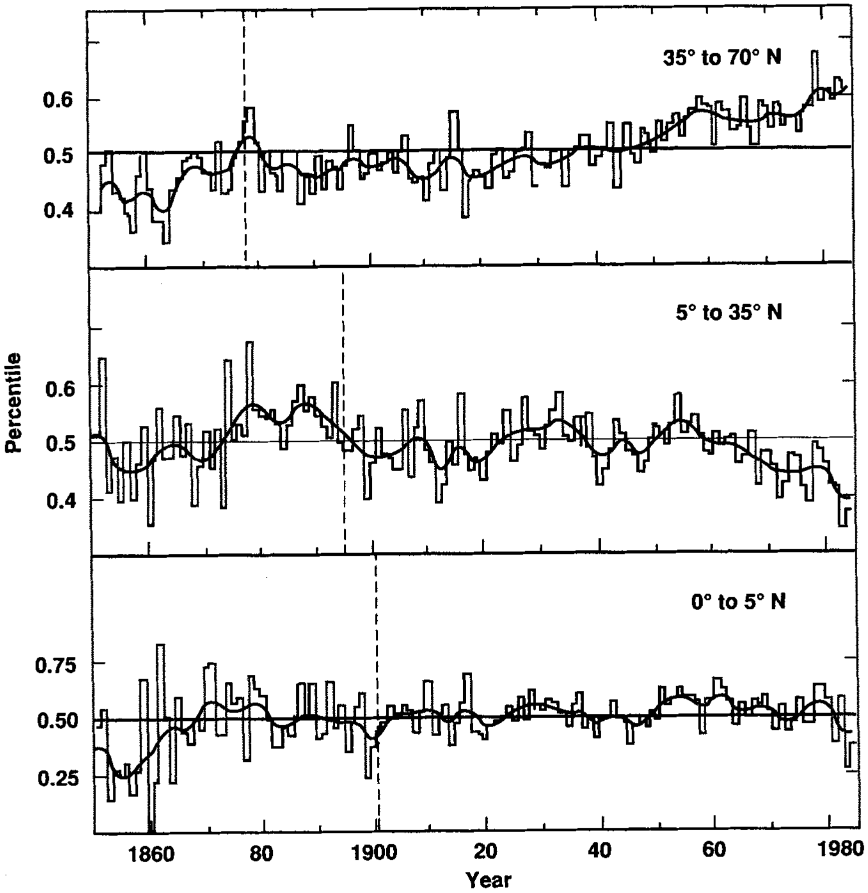

Figure 3.11. Precipitation indices for zones 35° to 70°N, 5° to 35°N, and 0° to 5°N

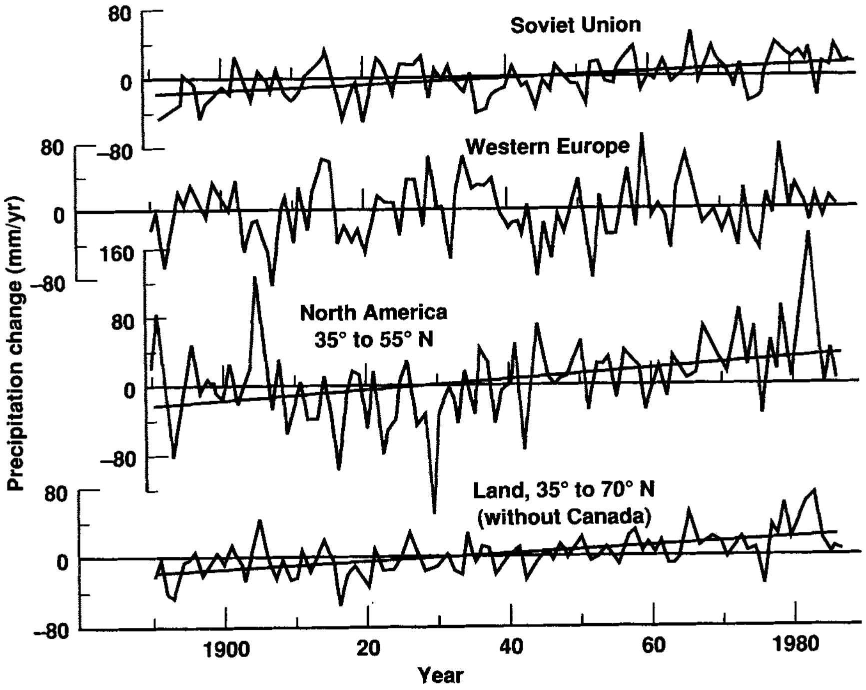

Figure 3.12. Changes in mean annual precipitation on the continents of the extratropical part of the Northern Hemisphere. The inclined lines correspond to estimated linear trends (Vinnikov et al., 1990).

information obtained in the past remains unavailable for computer-based analysis. In addition, there are other difficulties in detecting global precipitation trends related to their specific temporal and spatial statistical structure:

(1) Monthly and annual precipitation amounts vary significantly over small spatial scales. The spatial correlation declines markedly as the distance increases up to several hundred kilometers.

(2) The statistical distribution of mean monthly and annual precipitation for many regions of the Earth is significantly different from normal.

(3) Precipitation-gauge measurements are biased estimates of the actual amounts of precipitation falling over a particular area (Sevruk, 1989). Throughout the time of record, new techniques have been developed that allow collection of an ever-increasing portion of the actual precipitation falling. This is particularly important in recording solid precipitation (e.g., snow, hail). As a result, the series of measurements at individual stations probably contains instrumental trends not corresponding to real changes in precipitation.

Table 3.2. Estimates of trends and other statistical parameters of precipitation on the continents of the Northern Hemisphere (Groisman, 1990; Vinnikov et al., 1990).

Territory	Normal (mm/yr)	Standard deviation (mm/yr)	Trend (mm/100 yr)	Trend (% of normal /100 yr)	Fraction of variance accounted for by the trend
Annual precipitation:					
USSR	400	19	35	9	26
Western Europe	760	36	6	1	0
North America (35° to 55°N)	720	45	53	7	9
Continents in the zone 35° to 70°N (excluding Canada north of 55°N, and China)	570	20	34	6	22
May through September precipitation:					
USSR	240	11	9	4	4
Western Europe	300	20	0	0	0
North America (35° to 55°N)	320	28	23	7	4
Continents in the zone 35° to 70°N (excluding Canada north of 55°N, and China)	280	12	12	4	7

To decrease the influence of noise and random errors in measurements, the values measured are averaged over space and time, using as many station records as can be assembled for a given region. In this way, it is assumed that nonsystematic errors will tend to cancel out. Where systematic errors are known to be present in the data, adjustments can be made. For example, Vinnikov et al. (1990) removed inhomogeneities from the USSR precipitation record. Because methods for correcting Soviet

Table 3.4. Estimates of sea level rise from various analyses.

Rate (cm/100 yr)			
Uncorrected	Corrected[a]	Comments	References
11 ± 8		Many stations, 1907 to 1939	Gutenbert (1941)[b]
12 to 14		Combined methods	Kuenen (1950)[b]
11 ± 4		Six stations, 1807 to 1943	Lisitzin (1958)[b]
12		Cryologic estimate	Wexler (1961)[b]
12		Selected stations, 1900 to 1950	Fairbridge and Krebs (1962)
30		Many stations, 1935 to 1975	Emery (1980)
12		Many stations, grouped into regions, 1880 to 1980	Gornitz et al. (1982)
	10	Many stations, grouped into regions	Gornitz et al. (1982)
15 ± 1.5		Selected stations, 1903 to 1969	Barnett (1983)
14 ± 1.4		Many stations, grouped into regions, 1881 to 1980	Barnett (1984)
23 ± 2.3		Many stations, grouped into regions, 1930 to 1980	Barnett (1984)
	10 ± 1	Mean of regional means, 1880 to 1982	Gornitz and Lebedeff (1987)
	12 ± 3	Arithmetic mean, 1880 to 1982	Gornitz and Lebedeff (1987)
	11	East coast only	Peltier (1986)
	24 ± 9	40 stations, 1920 to 1970	Peltier and Tushingham (1989)

[a] Correction attempted for crustal and/or glacial isostatic motion.

[b] In Lisitzin (1974), after Barnett (1983).

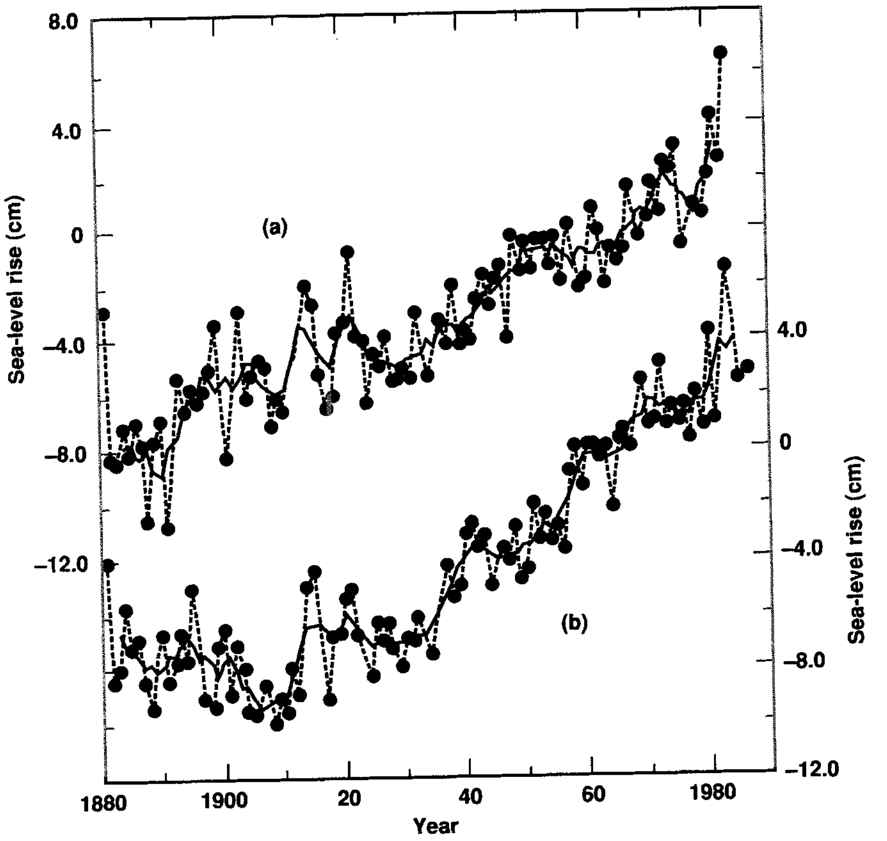

Figure 3.13. Global mean sea level rise over the last century. The baseline is obtained by setting the average for the period 1951 to 1970 equal to zero. The dashed line represents the annual mean; the solid line represents the 5-year running mean. Data are from (a) Gornitz and Lebedeff (1987) and (b) Barnett (1988).

snow accumulation in polar regions increases markedly. Warming of the ocean waters could add as much as 25 cm to sea level by the year 2050, depend-ing on the intensity of vertical mixing and changes in the ocean circulation (see Chapter 5). Taken together, such changes, (which are quite uncertain) could raise sea level to heights not experienced in historical times and start to cause inundation in low-lying areas and along coastlines subject to storm surges.

3.6. LESSONS AND OPPORTUNITIES FOR THE FUTURE

Climates of the past 100 years provide context for considering climate change over the next 100 years.

(1) *What have we learned about how the climate has varied over the past 100 years?*

Measurements of surface air temperature, which is the best availnot used by Bradley et al. (1987), this could have affected their results to some extent. However, the estimated trend is similar in sign in both studies. For the US national data (Fig. 3.9), only small differences were found between the national network of 5000 stations and a fixed network of 900 HCN stations that had been adjusted for station inhomogeneities (Karl and Williams, 1987).

3.4.3. Sensitivity of Precipitation to Changes of Temperature

The sensitivity of mean precipitation to global warming is very important. In the zone 0° to 35°N, there is a nonsignificant, inverse relationship between temperature anomalies and precipitation indices, temperatures having increased overall while precipitation has decreased (see Figs 3.5 and 3.11). For the Northern Hemisphere as a whole and for the zone 35° to 90°N, temperatures and precipitation have both increased over the past 100 years; however, their increase has not been consistent in time. Moreover, the relationship between these two elements is weak (Table 3.3). Note that the 1920s were warm and dry, while the 1960s were cool and wet. Nonetheless, there appears to have been a 0.4°C increase in the mean temperature of the Northern Hemisphere and an increase in precipitation of about 6% over the continents in the 35° to 70°N zone from 1891 to 1986.

Model results described in Chapter 5 also indicate that an increase in global precipitation will be associated with CO_2-induced global warming, although the regional pattern of the precipitation changes are complex. It is interesting that precipitation increases have been observed in instrumental data over the last century when global temperatures have also increased. However, it would be unwise to extrapolate this (or, for that matter, any) empirically estimated climate trend for purposes of predicting future precipitation. Further research on the relationship between temperature and precipitation for various regions is warranted in view of the importance of these parameters for many aspects of human activity.

Table 3.3. Correlation coefficients of annual anomalies of temperature and precipitation indices for continental land areas. Italicized values are statistically significant at the $\alpha = 0.05$ level.

Interval	0° to 35°N	35° to 90°N	0° to 90°N
1891 to 1920	–0.21	0.18	0.13
1921 to 1950	–0.31	0.01	–0.15
1951 to 1980	–0.05	0.05	*0.32*
1981 to 1986	–0.09	*0.26*	*0.26*

3.5. CHANGES IN SEA LEVEL

Global mean sea level has long been considered an indicator of climate change. For example, sea level has varied over a range of about 100 m during past glacial-interglacial cycles, being depressed as ice built up on the continental areas during the very cold glacial periods. Climate warming, either natural or anthropogenic, can logically be expected to cause a rise in global sea level as a consequence of thermal expansion of ocean waters and of the melting of continental ice sheets in polar regions and mountain glaciers in temperate regions. However, the problem of detecting climate-induced sea level change is complicated by the large number of factors to which sea level responds and by the limitations of the technology that has been used to measure it.

Tide-gauge records are the traditional source of data used to analyze long-term changes in sea level. These records show variations on various time scales due to tides, storm surges, ocean-atmosphere effects such as the ENSO, and vertical land movement (including such effects as mountain uplift, volcanism, and glacial rebound). Other effects, such as either changes in the prevailing winds, tides, and ocean currents or the subsidence of land due to the withdrawal of water, oil, or natural gas, are less easily identified. Thus, changes in sea level recorded by tide gauges may reflect either real changes in the level of the oceans, or simply changes in the elevation of the land on local or regional scales.

The importance of sea level rise as an indicator of global climate change was noted by Etkins and Epstein (1982), among others. Prospective increases in sea level may have serious consequences for coastal communities all over the world, yet all quantitative estimates of future sea level rise as a consequence of the projected global warming have very important limitations.

Over the last half century, various researchers have estimated the rate of change of global mean sea level. Their estimates generally fall within the range of 10 to 30 cm/100 yr, as shown in Table 3.4. The results of studies by Gornitz and Lebedeff (1987) and by Barnett (1988) are shown in Fig. 3.13. These increases appear to be in excess of trends over the past 1000 years, which are believed to have been quite small. A recent study by Peltier and Tushingham (1989), utilizing both linear regression and empirical orthogonal function analyses of tide gauge records corrected for glaciostatic land motion, indicates a global rate of rise of 24 ± 9 cm/100 yr for the period 1920 to 1970.

Accelerated warming and consequent melting of the existent mountain glaciers may lead to a further increase of 5 to 15 cm to sea level over the next 60 years, and deterioration of the ice shelves emerging from the polar ice caps in Greenland and Antarctica may either add or subtract up to about 20 to 30 cm to sea level over this period, depending on whether the rate of increase of snow accumulation is greater than the rate of increase of melting (Polar Research Board, 1985; Meier, 1990). There is however, the potential for modest reduction in sea level if the rate of been occurring in both the Northern and Southern Hemispheres, but that it has been more uniform in time and space in the Southern Hemisphere. The increase in the global mean surface air temperature is estimated to have been about 0.4 to 0.5°C over the past 100 years.

(2) *What have we learned about the seasonal and latitudinal pattern of the changing climate?*

The warming has generally been largest in the winter and concentrated in high latitudes. The warming has not, however, been spatially uniform, with some regions experiencing little change while other areas have experienced warming or even cooling.

(3) *What have we learned about changes in precipitation?*

Although the record is much more variable, analyses of rain-gauge measurements suggest a tendency for a considerable increase in precipitation in many midlatitude regions on the Northern Hemisphere's continents. However, because multi-year fluctuations have been large, it is still difficult to interpret the meaning of these trends.

(4) *What have we learned about other recent changes in the climate system?*

The global mean sea level responds to changes in the amount of glacial ice and the temperature of the ocean. Over the past 100 years, sea level has risen by 10 to 20 cm, which is consistent with indications that warming is occurring.

There remain a number of critical gaps in our understanding of the climate variations of the past 100 years. To accelerate the rate at which these gaps are closed, the following actions are recommended:

(1) Quantify the impact of urban warming in the temperature record and develop a strategy to prevent its impact on future climate monitoring.
(2) Make better use of the extensive operational networks of precipitation measurements, placing emphasis on ensuring data homogeneity and on reducing the uncertainties introduced into spatial averages of precipitation by temporal changes in the spatial density of stations.
(3) Expand research on the relationship between change in global and regional temperature and precipitation using both modeling and empirical studies.
(4) Continue monitoring the solar irradiance to better understand the fluctuations in climate caused by variations in solar energy; also, continue analyses of data from dendroclimatology and other proxy measures of past solar behavior.
(5) Conduct much better statistical analyses of the changes of temperature and precipitation over the past 100 years to analyze the causes and mechanisms of global and regional climate change, including the role of chaotic climatic behavior and other natural fluctuations.
(6) Expand the collection and monitoring of data to include additional variables (e.g., soil moisture) that are expected to change or that are of importance in impact analyses.