JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. D15, PAGES 20,101–20,114, AUGUST 16, 2000

Observed climate variability and change of relevance to the biosphere

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Abstract. In this paper we review the current instrumental evidence regarding climate variations and change during the 20th century emphasizing those changes that are likely to have direct interactions with the biosphere. Three basic questions are addressed: (1) Is the climate getting warmer, (2) is the hydrologic cycle changing, and (3) is the climate becoming more extreme. Based on global near-surface temperature measurements for the 20th century, it is clear that a warming of ~0.5°C has occurred. More importantly for biospheric systems, however, are the observed asymmetric changes in daily maximum and minimum temperature, with the minimum temperatures increasing at a rate approximately twice that of the maximum temperature. Other temperature-sensitive measures, such as glacial and snow cover extent, reinforce the observed temperature trends. Examination of the hydrologic cycle indicates that changes also appear to be occurring, although less confidence can be placed on these analyses than those for temperature. Recent studies suggest that precipitation has increased in higher latitudes, particularly in the Northern Hemisphere. Increases in cloudiness, atmospheric water vapor, and changes in stream flow also suggest that changes to a more vigorous hydrologic cycle are taking place. The final question regarding climate extremes is much more difficult to assess due to a lack of high temporal resolution climate databases. Of the few studies that have been performed, however, there is evidence that precipitation extremes, particularly heavy rainfall events, are increasing in the United States and Australia, also suggesting an enhanced hydrologic cycle as the planet warms.

1. Introduction

The instrumental climate record reveals a rich spectrum of climate variability and change. Over the past decade, considerable progress has been made in assembling databases, removing systematic biases from these data, and analyzing records for interannual variability and decadal changes in the mean for large sampling times (monthly to annual) and spatial extent. Although quite important, there is a dearth of analyses regarding changes in extremes. Also, new climate fields have been generated through a number of climate model simulations that also offer opportunity for studying climate variability and biospheric interactions. This paper reviews our base of knowledge about climate variability and change during the instrumental record with a view toward better understanding of biospheric-atmospheric interannual to decadal scale interactions. Here we examine several basic questions about interannual to century-scale variations and changes of climate, including the following:

Is the planet getting warmer?

Is the hydrologic cycle changing?

Is the weather and climate becoming more extreme or variable?

Each of these apparently simple questions is quite complex because of the multivariate aspects of each question and because the spatial and temporal sampling required to adequately address each question must be considered on a global scale. A brief review of our ability to answer these questions reveals many successes but points to some glaring inadequacies that must be addressed in any attempt to understand, predict, or assess issues related to interannual climate variability or change.

2. Is the Planet Getting Warmer?

There is little doubt that measurements show that near-surface air temperatures are increasing. Figure 1 shows the globally averaged mean annual temperature time series, including both land and ocean for 1880–1998 constructed using a method developed by *Quayle et al*. [1999] to include both land and ocean data. Although the overall trend of this time series is about 0.6°C/century, it shows a number of distinct periods with different trends. The characteristics of the time series, as calculated objectively by *Karl et al*. [2000], shows a cooling of −0.38°C/century from 1880 to 1910, then warming of 1.2°C/

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Paper number 2000JD900166.
0148-0227/00/2000JD900166$09.00

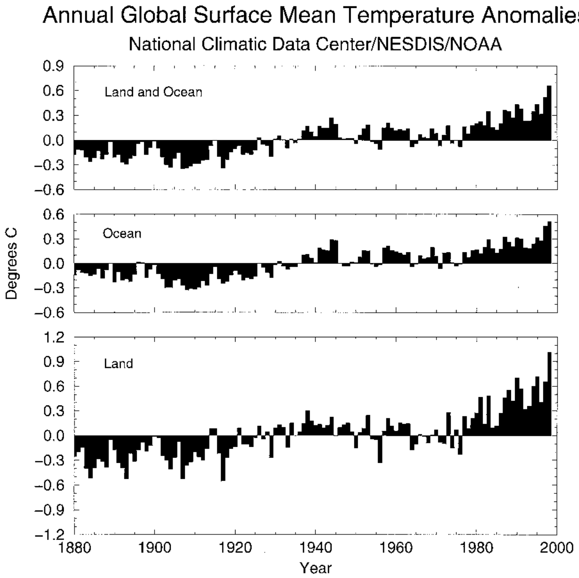

Figure 1. Global near-surface temperatures for land, ocean, and combined land and ocean.

century from 1911 to 1945, a period of no change to 1975, then strong warming of 1.96°C/century since the 1970s. The period since the late 1970s has seen stronger and more frequent El Niños, which have been shown empirically [*Jones*, 1989, 1994] to add to any warming present due to other factors. One other feature about the time series is the large positive anomaly for 1998 making this the warmest year in the instrumental record due, in part, to the exceptionally strong 1997–1998 El Niño.

Nonetheless, many questions have arisen regarding the adequacy of overall 20th century warming estimate of 0.6°C. For example, Figure 2 shows differences in the rate of change and interannual variability of global land temperatures due mainly to the use of two different methods to calculate global temperature changes. One method used by *Hansen and Lebedeff* [1987] starts by defining a set of 5° × 10° latitude-longitude grid boxes over the globe, designating the longest station time series within each grid box as the primary time series, then adjusting each additional station time series to that primary station based on a period of overlap. The second method is called the first difference technique and is implemented by creating a time series of year-to-year temperature (first) differences for each station within a grid box and developing the grid box time series by aggregating the first difference series from each station [*Peterson et al.*, 1998]. Global time series for each method are created by aggregating all the grid box time series weighted by the cosine of the latitude. Although both time series show the same general shape, there are small differences in the two trends. Furthermore, small trend differences also arise due to the methodology used to calculate the linear trend [*Peterson et al.*, 1998].

In addition, a variety of factors, such as instrumentation changes, station relocations, urbanization, and changes in measurement techniques add to uncertainty as to the temperature change. The Global Historical Climatology Network (GHCN) [*Vose et al.*, 1992; *Peterson and Vose*, 1997] data set has been developed to provide the most comprehensive land-based observed temperature, precipitation, and air pressure data set for observed climate change studies. It consists of monthly values of temperature and total precipitation for many thousands of stations around the world covering the 20th century and extending back into the 19th century and in some cases even earlier. Part of the processing of this data set has included the development of a homogeneity-adjusted data set to attempt to minimize the effects of such factors as instrument changes [*Easterling and Peterson*, 1995]. Homogeneity adjustments also can affect trend estimation, however this effect is very small on a global scale [*Easterling et al.*, 1996]. Thus factors that can lead to small differences in calculated trends, such as those discussed above, have lead the Intergovernmental Panel on Climate Change (IPCC) to suggest a range of temperature change since the late 19th century of between 0.3° and 0.6°C [*IPCC*, 1995].

The rate and direction of temperature change has not been spatially uniform, as shown in Figure 3. The data in this figure are taken from sea surface temperature records adjusted for changes in measurement methods over the ocean [*Parker et al.*, 1995] and from land surface data from the *Jones et al.* [1991] data set that, like the GHCN, have been adjusted for obvious inhomogeneities due to station moves or instrument changes and updated through 1998. These two data sets are used to portray spatial variations since they have been gridded and analyzed for spatial consistency across land/ocean boundaries. Although much of the globe is warming, portions of the southern United States, the North Atlantic Ocean, the Middle East, and China have actually cooled since the turn of the century. Some of the strongest warming is over the middle to high latitudes of the Northern Hemisphere, and it is also noteworthy that the magnitude of the warming on regional space scales is often much larger than the global mean.

Changes in the mean temperature are perhaps less significant from a biophysical impact standpoint than changes in the mean daily maximum and minimum temperatures. Figure 4 shows asymmetric changes in the maximum and minimum temperature over the past several decades from *Easterling et al.* [1997]. The rate of temperature increase of the maximum temperature has been about one-half the rate of increase of the minimum temperature. It is also noteworthy that the time series in Figure 4a also show a shift upward starting in the late 1970s similar to Figure 1. The map in Figure 4b shows that as a result of the asymmetric changes of the maximum and minimum temperature, the diurnal temperature range is decreasing over much of the global landmass. One other feature about this analysis is that the possibility of urban contamination of the time series was specifically addressed. This was done by

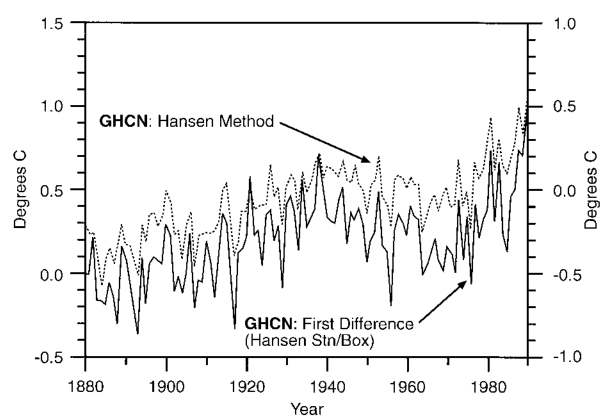

Figure 2. Worldwide near-surface land temperatures based on the method used by *Hansen and Lebedeff* [1987] and the first difference technique [*Peterson et al.*, 1998].

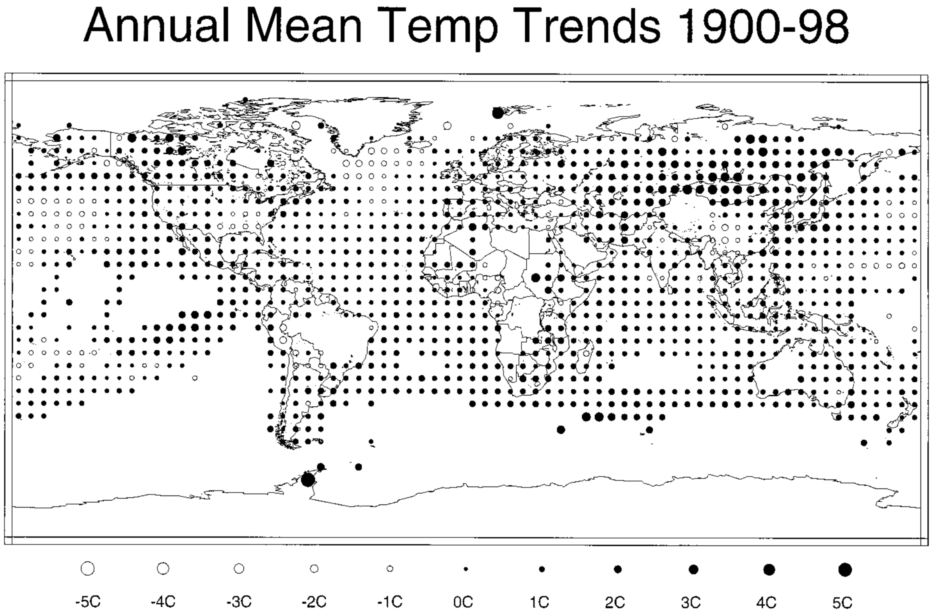

Figure 3. Map showing trends of temperature change for 1900–1998 in annual average temperature. Magnitude of the trends are reflected by the area of the circles; solid circles reflect increases and open circles decreases.

excluding observing stations in larger urban areas (>50,000 population), and comparing with the analysis with the full data set, with the effect being only a very slight reduction in the temperature trends when urban areas are excluded.

Although there have been clear changes over the 20th century in direct air surface temperature measures, consideration of other temperature-sensitive variables are necessary before we be confident that the planet surface has indeed warmed. These other variables include snow cover, glaciers, sea level, and even some proxy non-real-time measurements such as ground temperatures from boreholes. Additional evidence is needed because the measurements we rely upon to calculate global changes of temperature have been collected primarily to aid in navigation, agriculture, commerce, and in recent decades for weather forecasting, and not for monitoring global and regional temperatures.

The surface temperature warming has been greatest during the boreal winter and spring seasons and least during the autumn. This is true in both global mean temperatures and in trends in maximum and minimum temperatures [*Easterling et al.*, 1997]. Part of this seasonal disparity is related to the snow cover feedback effect as noted by *Groisman et al.* [1994] in an

Figure 4. (a) Time series of maximum and minimum temperature and DTR change. The thick line is smoothed using an 11-point binomial filter. (b) Trends of diurnal temperature range (DTR) change are reflected by the magnitude of the circles; open reflects increases and closed decreases [*Easterling et al.*, 1997].

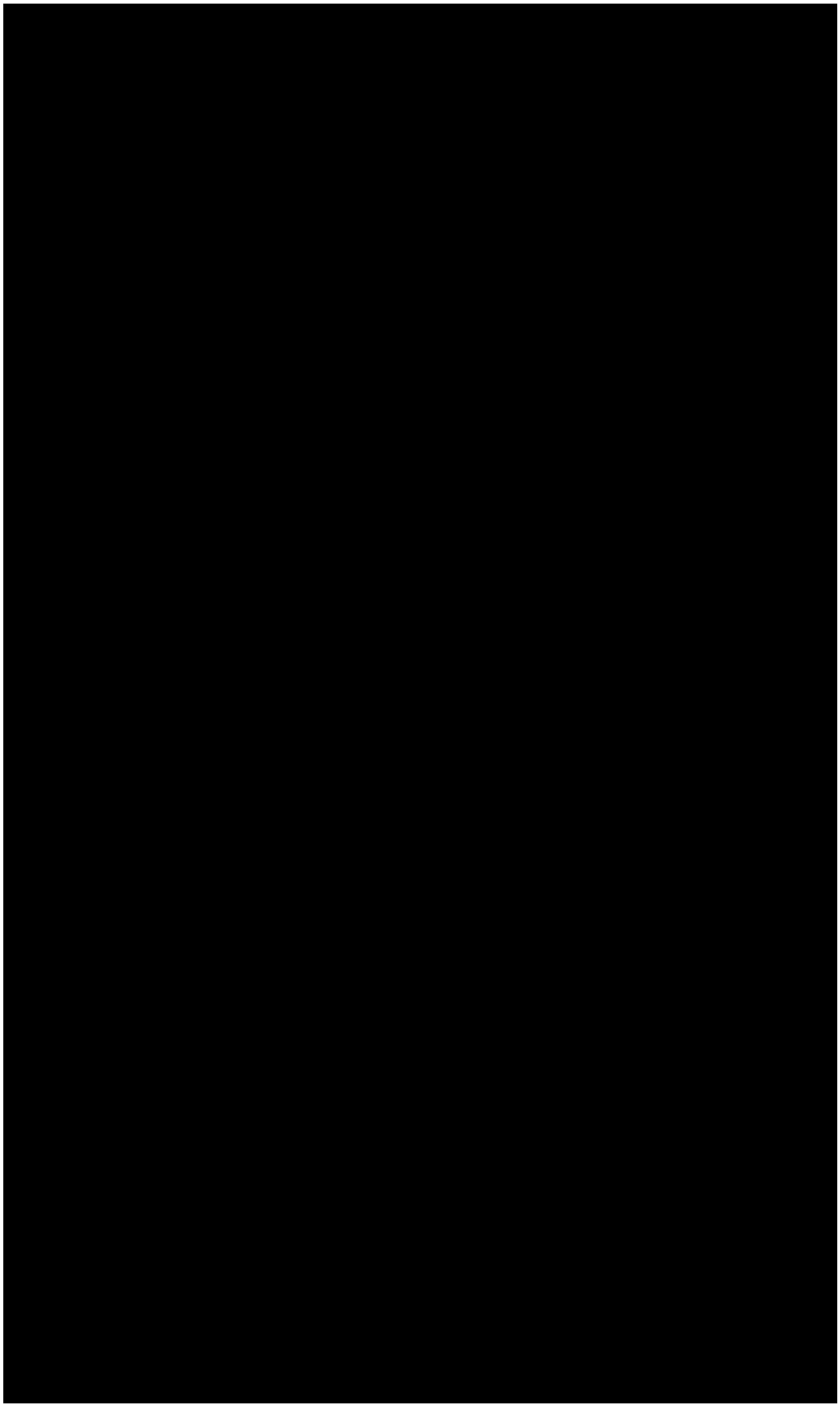

Figure 4. (continued)

analysis of the ablation of spring snow cover in recent decades. In this feedback, snow cover is melted revealing the ground surface, which absorbs more solar radiation than a snow surface, thereby warming more. NOAA weekly snow charts are the most accurate and appropriate data for assessing the variability of snow cover on a continental scale [*Wiesnet et al*., 1987] and can be used to provide support to the temperature analyses indicating the planet has warmed. These charts are derived by hand analysis of visible satellite imagery by trained observers. An analysis of the NOAA charts show that mean annual Northern Hemisphere snow cover extent is 25.3 million square kilometers, with 14.7 million km^2 over Eurasia and 10.6 million km^2 over North America (including Greenland). Monthly anomalies of greater than 4 million km^2 have been observed on occasion throughout the past two and a half decades, although anomalies are generally less than 3 million km^2.

The NOAA snow cover time series for the Northern Hemisphere, shown in Figure 5, indicates that recent years have less snow cover than the earlier part of the satellite record over both Eurasia and North America. However, 12-month running means have been close to the long-term mean since the middle of 1995 (Figure 5). The reduced snow extent in the late 1980s to the late 1990s is not associated with a steady decrease of snow extent but with a step change. Between 1972 and 1985, 12-month running means of snow extent fluctuated around a mean of 25.9 million km^2. A rather abrupt transition occurred in 1986 and 1987, and since then, mean annual extent has been 24.2 million km^2. The means of these two periods are significantly different; however, it is possible that the differences are due to a change in satellites.

Of the four seasons, fluctuations of spring and summer hemispheric snow extent are responsible for the downward jump around 1987 (Figure 6). Snow cover ablation during these seasons is particularly important because of the snow albedo feedback and subsequent march of the seasons. Winter and autumn snow cover extent do not reveal any overall tendencies. Monthly observations show the past decade reductions of late season snow cover beginning in February. During 7 of the first 15 years of record, February snow extent exceeded the January value. Only once has this occurred in the past decade.

Seasonal snow cover extent varies similarly over the Eurasian and North American continents. Each continent shows the year-to-year variability seen in the hemispheric fall record, and spring cover extent is a close match on each continent, particularly in the 1990s. Perhaps the most interesting differences in the spring occurred between 1987 and 1989. Snow cover area was low over North America in the first two years, while Eurasian snow cover area was above or close to normal. The opposite situation occurred in 1989.

The robustness of the temperature record and the snow cover record can be partially assessed through a comparison of the changes of temperature over the snow-covered regions of the world. Figure 7 depicts the snow cover and temperature anomalies and indicates a high correlation between the two quantities on a yearly basis. Moreover, the decadal trends and variations are quite consistent; that is, areas with increasing temperature trends coincide directly with areas having lower snow cover extent.

Recent global-scale measurements of layer-averaged atmospheric temperatures and sea surface temperatures from instruments aboard satellites have greatly aided our ability to monitor global temperature change [*Spencer and Christy*, 1992a, b; *Reynolds*, 1988], but the situation is far from satisfactory [*Hurrell and Trenberth*, 1996, 1998]. Changes in satellite temporal sampling, for example, orbital drift, instrument calibration and change in atmospheric composition, for example, volcanic emissions, and technical difficulties related to overcoming surface emissivity variability have reduced our ability to produce highly reliable products of near-surface global temperature change. Until 1998, temperature changes in the lower half of the troposphere were thought to have decreased slightly since the late 1970s, but recent analyses by *Hurrell and Trenberth* [1998] have called into question the veracity of the satellite temperature record. The magnitude of the corrections that are required to account for intersatellite differences are so large that at this time it is uncertain as to whether the satellite record of temperature changes in the lower troposphere, as derived from the microwave sounding unit (MSU) data really reflect unbiased changes. Furthermore, as with the surface temperature record, 1998 in the satellite record was also exceptionally warm, which has now resulted in a positive trend in satellite-derived tropospheric temperatures for the 1979–1998 period (Figure 8).

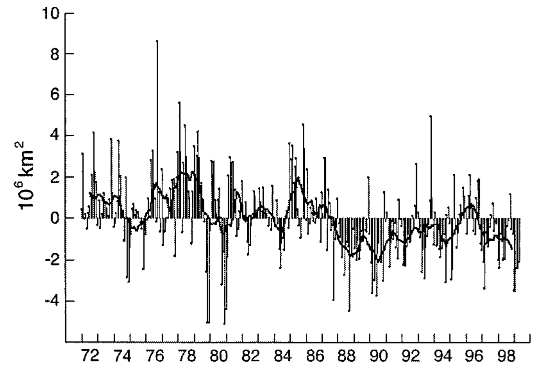

Figure 5. Anomalies of monthly snow cover extent over Northern Hemisphere lands (including Greenland) between January 1972 and March 1998. Also shown are 12-month running anomalies of hemispheric snow extent, plotted on the seventh month of a given interval. Anomalies are calculated from a mean hemispheric snow extent of 25.4 million km^2 for the full period of record. Values are determined from analyses of NOAA snow charts, which are created using visible satellite imagery.

Lastly, the *IPCC* [1995] has summarized known changes in the temperature record and assessed their confidence in these changes. They are summarized in Figure 9 (top) and reflect our best estimates of what we know and do not know about changes in temperature. In addition to the evidence discussed above, this figure also provides information about alpine glacial retreat, sea ice extent, ground temperatures, and stratospheric temperatures. For some of these factors confidence in the changes is not high; however, if the balance of evidence is considered, overall confidence in surface air temperature warming in the observed record is quite high.

3. Is the Hydrologic Cycle Changing?

Global warming would very likely lead to changes in precipitation due to changes in atmospheric circulation and a more active hydrologic cycle. This would be due, in part, to an increase in the water-holding capacity of the atmosphere with an increase in temperature. The source term for the hydrologic

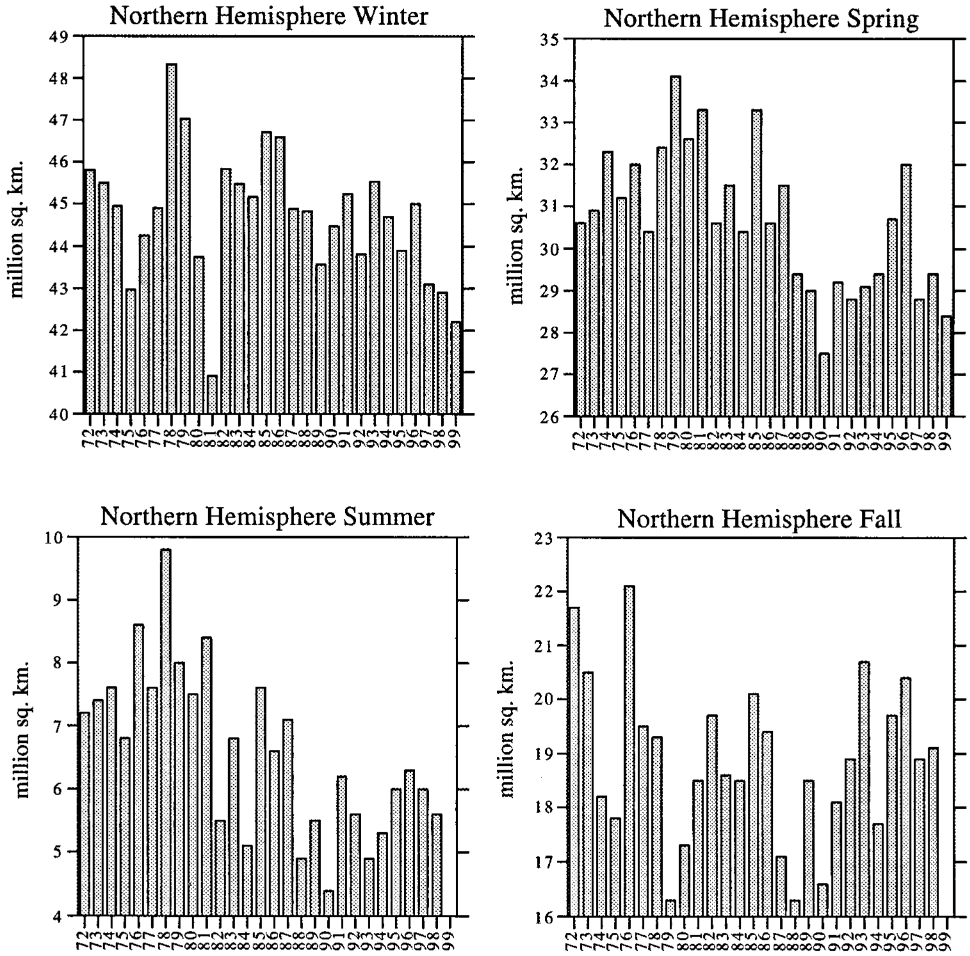

Figure 6. Seasonal snow cover over Northern Hemisphere lands between 1972 and 1998. Year of winter season (December–February) is for the year in which January falls, spring covers March–May, summer June–August, and autumn September–November.

cycle, precipitation, has been measured for over two centuries in some locations, but even today, it is acknowledged that in many parts of the world we still cannot reliably measure true precipitation [*Sevruk*, 1982; *IPCC*, 1995]. For example, annual undercatch biases of more than 50% are not uncommon in cold climates due to wind-induced turbulence over the gage [*Karl et al*., 1995], and even for more moderate climates, precipitation is believed to be underestimated by 10 to 15% [*IPCC*, 1992]. Progressive improvements in instrumentation, such as installation of wind shields, have also introduced time-varying biases [*Karl et al*., 1995]. Satellite-derived measurements of precipitation have provided the only large-scale ocean coverage of precipitation. This includes data sets from the Global Precipitation Climatology Project [*Xie and Arkin*, 1996] and the work of *Spencer* [1993] on the MSU satellite data. Although these data sets provide comprehensive estimates of large-scale spatial precipitation variability over the oceans, where few measurements exist, problems inherent in developing precipitation estimates hinder our ability to have much confidence in global-scale decadal changes. For example, even the recent landmark work of *Spencer* [1993] in estimating worldwide ocean precipitation has several limitations. The observations are limited to ocean coverage and hindered by the requirement of an unfrozen ocean. Furthermore, they do not adequately measure solid precipitation, have low spatial resolution, and are affected by the diurnal sampling inadequacies associated with polar orbiters, e.g., generally limited to two overpasses per day for a given location.

Information about past changes in land-surface precipitation, similar to temperature, has been compared with other hydrologic data, such as changes in stream flow, to ascertain the robustness of the documented changes and variations of precipitation. These comparisons have led to more confidence in the in situ precipitation data, which show a worldwide precipitation increase of about 1%. This increase is statistically significant but is not spatially uniform. Figure 8 reflects changes in precipitation for a variety of zones using the GHCN data set [*Vose et al*., 1992]. Other data sets from *Hulme et al.* [1994], have also been used in IPCC assessments and are considered reliable and show the same general patterns of change. As is apparent in Figure 10, which shows precipitation time series averaged for a number of latitude bands, and in map form in Figure 11, changes in precipitation have not been uniform by any means. There is an increase in the middle- to high-latitude precipitation and a notable decrease in subtropical precipitation. Some of the largest tropical decreases have occurred in the Sahel region in Africa due to long-term drought conditions from the 1960s to the mid-1990s. This region, however, has seen an increase in precipitation in the most recent years to a level approximately that of the 20th century average. There is also evidence to suggest that much of the increase of precipitation in middle to high latitudes arises from increased autumn and early winter precipitation in much of North America [*Groisman and Easterling*, 1994] and Europe [*IPCC*, 1995]. Furthermore, large-scale coherent patterns of change in precipitation during the 20th century are shown in Figure 11, which provides added confidence in the results. This figure shows the sometimes large but spatially consistent patterns of decrease across the tropical and subtropical regions and increases in most other areas. One other point about Figure 11 is that there are some large areas where we currently do not have reliable enough data to calculate long-term trends. These areas include parts of high-latitude North America and Russia as well as western China and the Sahara.

Other changes related to the hydrologic cycle are summarized in Figure 9 (bottom). In many instances the confidence is low for the changes, and this is particularly disconcerting considering the important role of clouds and water vapor in biospheric processes. Long-term observations of cloud amount have been made by surface-based human observations and shorter-term observations by satellite. However, the human observations are now being replaced by automated measurements in the United States and other parts of the world. Furthermore, neither surface-based nor spaced-based data sets have proven to be entirely satisfactory for detecting changes in clouds. For polar orbiting satellites there is an enormous difficulty to overcome related to sampling problems and satellite drift discussed earlier with regard to the MSU [*Rossow and Cairns*, 1995]. For human observers, changes in observer schedules, observing biases, and incomplete sampling have created major problems in data interpretations, now compounded by a change to new automated measurements at many stations. Nonetheless, there is still some confidence (albeit not very high) that global cloud amounts have tended to increase. On a regional basis this is supported by a number of interesting comparisons. First, cloud variations and changes are well related to the changes in the diurnal temperature range. Increased cloud amount reduces incoming solar radiation during the day and retards outgoing long-wave radiation at night. This can lead to a reduction in maximum (daytime) temperatures but would also lead to warmer minimum (nighttime) temperatures with the result being a decrease in the diurnal temperature range (DTR = maximum-minimum). Figures 12, 13, and 14 reflect coherent relationships among cloud amount, precipitation, diurnal temperature range, and potential evaporation. As shown in Figure 12, there is generally moderate to very strong negative correlation between the DTR and the cloud amount, showing that as cloud amount has increased, the DTR has decreased in each country. The same is true for Figure 13, showing precipitation and DTR, although correlation is not so strong. Pan evaporation in Figure 14 also shows a coherent relationship between decreased DTR and decreased pan evaporation. A scenario of increased cloud cover and greater soil moisture due to increased precipitation and reduced evaporation would lead to a reduction in the diurnal temperature range. Soil moisture data from the former U.S.S.R. show increases over the past few decades [*IPCC*, 1995], which is consistent with the increased cloud cover and reduced evaporation potential as calculated from pan evaporimeters. It is clear, however, that in some regions, like China, cloud amount and

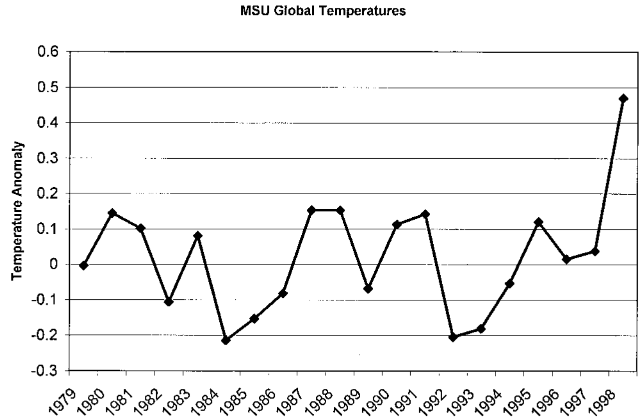

Figure 8. Annual midtropospheric air temperatures for 1979–1998 derived from the microwave sounding unit (MSU) satellite instrument.

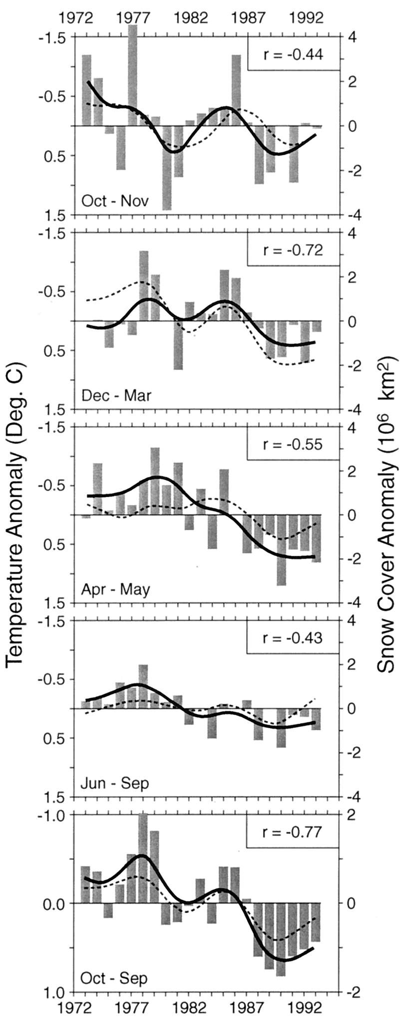

Figure 7. Seasonal and annual variations of Northern Hemisphere land-surface snow cover extent (Greenland excluded) and the surface temperature over regions of transient snow cover. Yearly anomalies (shown as bars) are given for snow cover extent. Smooth curves were created using nine-point binomial filters for yearly snow cover (thick) or temperature anomalies (thin) with scale reversed. The "*r*" indicates correlation between annual values. Note bottom panel is for "snow year" (October–September).

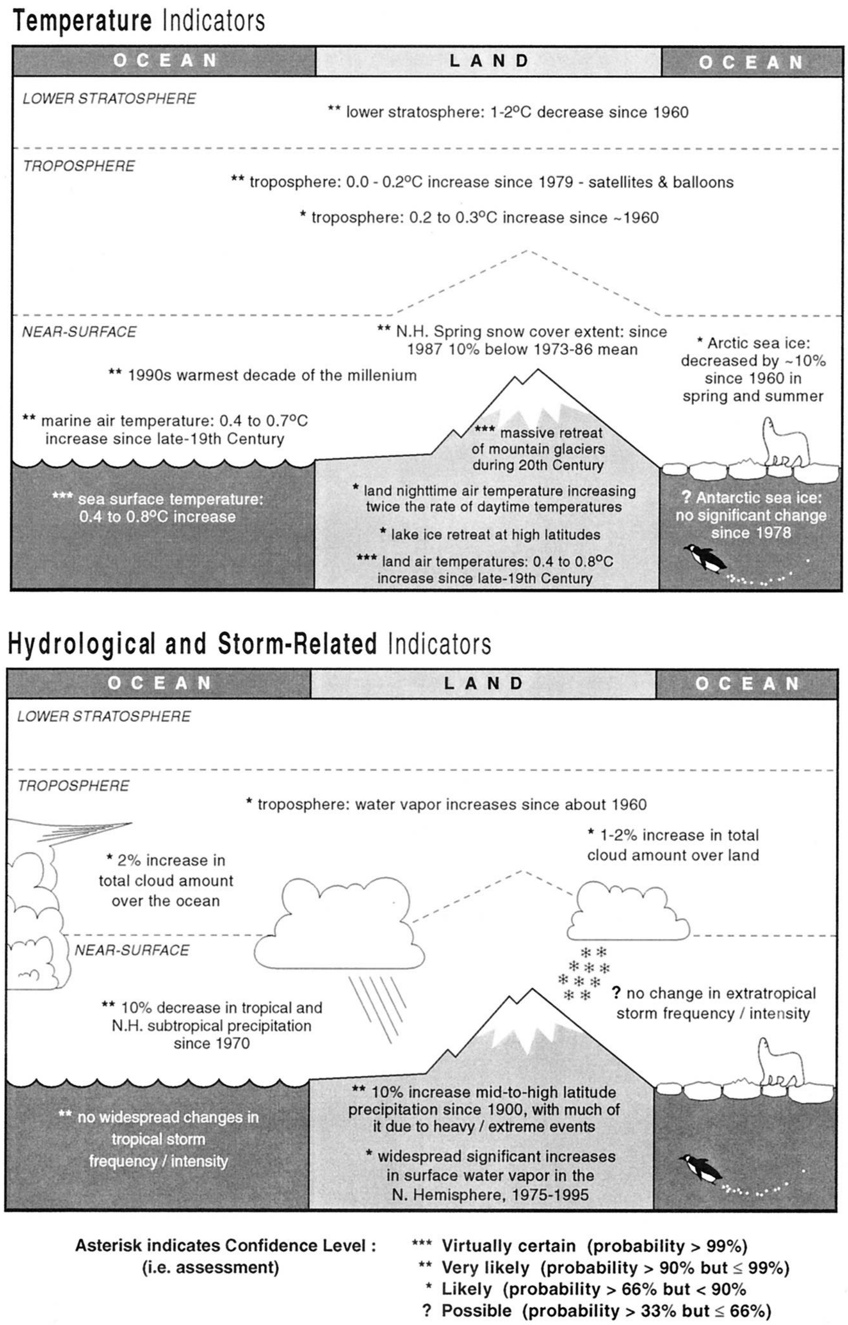

Figure 9. Schematic of observed variations of selected indicators regarding (top) temperature and (bottom) the hydrologic cycle (based on *IPCC* [1995]).

precipitation do not readily explain the decrease in the diurnal temperature range. In this region, sulfur dioxide emissions have increased several-fold since the early 1970s, and it is likely that this has helped to reduce daytime temperatures contributing to the decrease in the diurnal temperature range.

Changes in water vapor are very important for understanding climate change as water vapor is the most important greenhouse gas in the atmosphere. The measurement of changes in atmospheric water vapor is hampered by both data processing and instrumental difficulties for both weather balloon and satellite retrievals. The latter also suffers from discontinuities among successive satellites and errors introduced by changes in orbits and calibrations. Despite these problems, an increase in water vapor has been documented over much of North America and in the tropics [*IPCC*, 1995]. It is noteworthy that this increase over North America occurs at a time of increasing precipitation and precipitation intensity.

New data have emerged since *IPCC* [1995] which are of relevance to atmospheric biospheric interactions, including data from several reanalyses. These data are derived by using observed boundary conditions to simulate climate using a numerical weather prediction model, and they are now providing additional information on difficult to measure climate variables, many of which are directly relevant to biospheric processes. There have been several reanalysis efforts from a variety of national meteorological centers. The National Oceanic

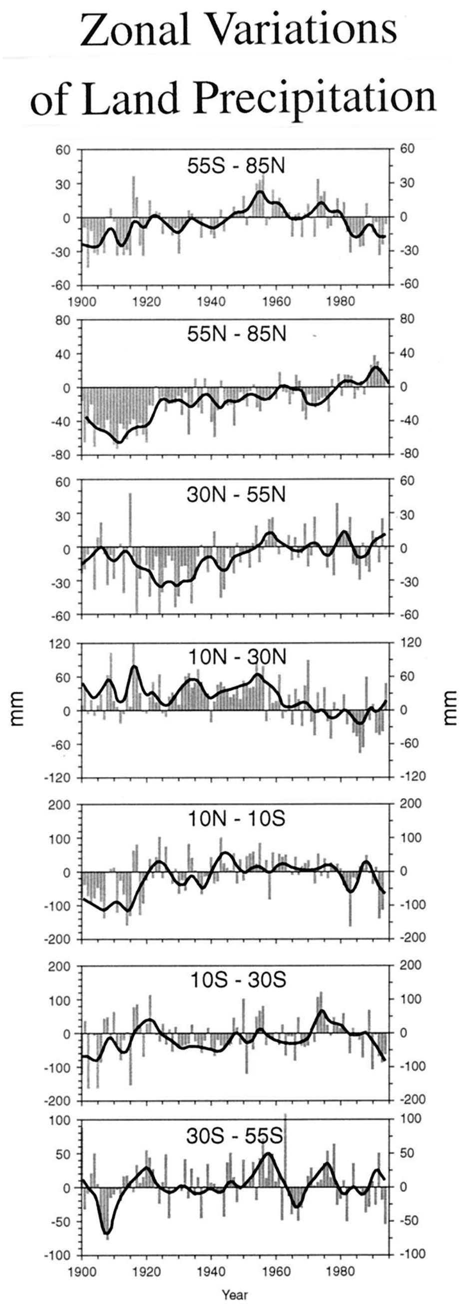

Figure 10. Zonally averaged annual precipitation anomalies (using 1961–1990 as base). Smooth curves were created using a nine-point binomial filter. Anomalies are based on the Global Historical Climate Network data set.

and Atmospheric Administration (NOAA) has recently conducted the longest reanalysis effort, and it is worth examining some examples from this effort here, particularly since many of these reanalysis fields are being used to examine climate variability on longer timescales and are directly relevant to biospheric processes.

Trenberth and Guillemot [1996, 1997] carried out an evaluation of the moisture fields, the precipitation (P), and evaporation (E), and the moisture transport and divergence in the atmosphere from the global atmospheric National Centers for Environmental Prediction (NCEP) reanalyses produced with four-dimensional data assimilation. This is a methodology used to take observations of a variety of meteorological data, such as temperature, moisture, and pressure, from different observing platforms (e.g., satellites, rawinsondes, in situ weather observing stations), and blend them into physically consistent gridded spatial fields through time for use in initializing numerical weather forecast models. The moisture fields were summarized by the precipitable water which was compared with analyzed fields from the NASA Water Vapor Project (NVAP) based primarily on Special Sensor Microwave Imager (SSM/I) over the oceans and rawinsonde (weather balloon) measurements over land, plus TIROS Operational Vertical Sounder (TOVS). The moisture budgets have been evaluated through computation of the freshwater flux at the surface (E-P) from the divergence of the total moisture transport, and this was compared with the reanalysis (E-P). The (P) field is evaluated using Xie-Arkin Global Precipitation Climatology Project (GPCP) estimates, and although it contains considerable uncertainties, the patterns are probably good enough to show that there are substantial biases in the NCEP precipitation fields. The Xie-Arkin climatology is based on precipitation gage estimates over the land and satellite measurements over the oceans.

Although there are many fields of interest in the NCEP reanalysis which are improvements over previous information available, the NCEP moisture fields are directly relevant to biospheric processes. These fields are shown to contain large and significant biases in the tropics. On an annual mean basis the largest evaporation of over 6 mm/d is in the subtropical Indian Ocean. The tropical structures are less well defined since values are generally smaller where they should be high and higher where they should be low. In addition, the NCEP moisture fields contain less variability from year to year. The NCEP model (P) generally reveals a pronounced double Intertropical Convergence Zone in the central Pacific and the location of the South Pacific Convergence Zone is not well captured. Rainfall amounts are lower than observed in the oceanic tropical convergence zones. The variability in the central tropical Pacific of (P) associated with El Niño-Southern Oscillation (ENSO) is underestimated in the NCEP reanalyses and, moreover, is not very well correlated with the GPCP product. A bias for too much rainfall in the model over the southeastern United States and southeast Asia is also present in northern summer. Figure 15 reveals the rather poor correlation of the NCEP precipitation field from that derived from the *Xie and Arkin* [1996] climatology. This is further highlighted by the differences in precipitation during the 1983 El Niño/Southern Oscillation event (Figure 16).

The comparison of (E-P) from moisture budget diagnostics and observed values with the model result reveals some strong systematic differences. Biases in the reanalysis fields of (E) are inferred in some places from the (E-P) differences, and they probably arise from spurious land moisture sources in some cases. Remarkably, nearly all island stations show up as bull's-eyes in the difference field calculation (Figure 17). Positive differences in Figure 17 imply that the model E is too high, the model P is too low, and/or the analyzed moisture divergence is too negative. While the moisture budget diagnostic estimates of (E-P) often produce better answers, in some places they are clearly inferior to those from the model parameterizations [*Trenberth and Guillemot*, 1996]. Both sets of estimates are affected by biases in moisture, as analyzed, and the model estimates also depend upon the parameterizations of sub-grid-scale processes, such as convection, which influence (E) and (P).

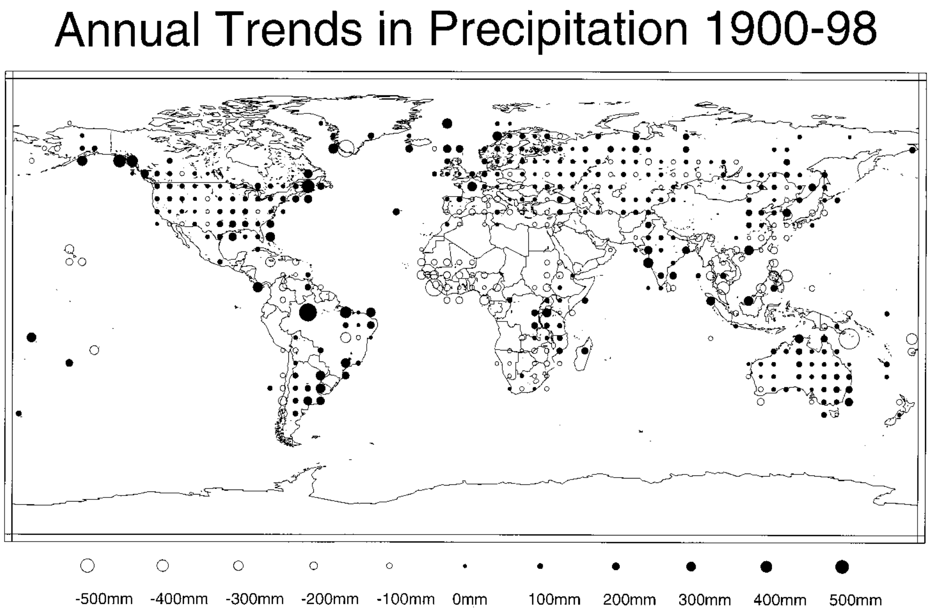

Figure 11. Precipitation trends over land 1900–1994. The trend is expressed in millimeters/century and the magnitude of the trend is represented by the area of the circle, with open circles decreasing and solid circles increasing.

4. Is the Weather and Climate Becoming More Extreme or Variable?

Perhaps one of the greatest interests in weather and climate relates to extremes of climate. Because of inadequate monitoring as well as prohibitively expensive access to weather and climate data held by the World's national weather and environmental agencies only limited reliable information is available about large-scale changes in extreme weather or climate variability. The time-varying biases that affect climate means are even more difficult to effectively eliminate from the ex-

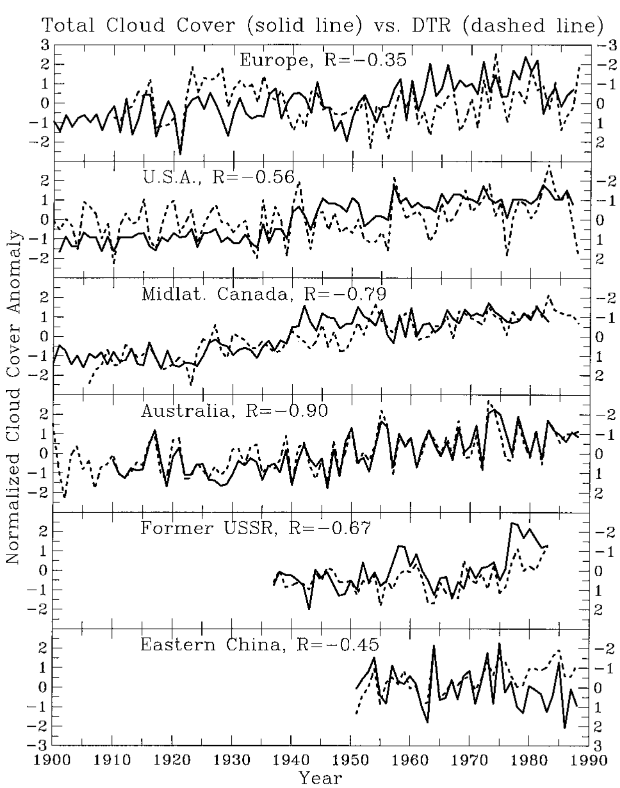

Figure 12. Time series of total cloud cover (solid curve) and the diurnal temperature range (dashed curve) for various countries. The correlation between the time series is given within each panel.

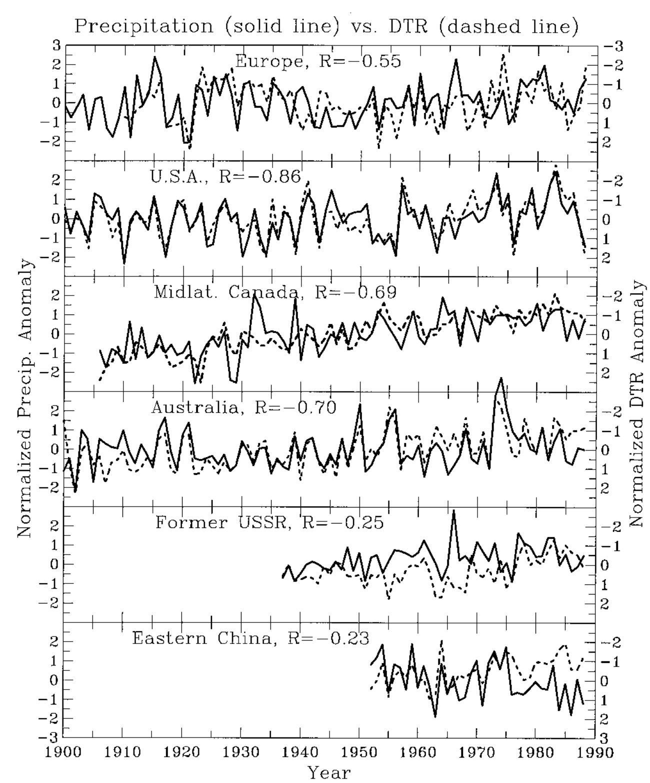

Figure 13. Same as Figure 12 except for precipitation and the diurnal temperature range.

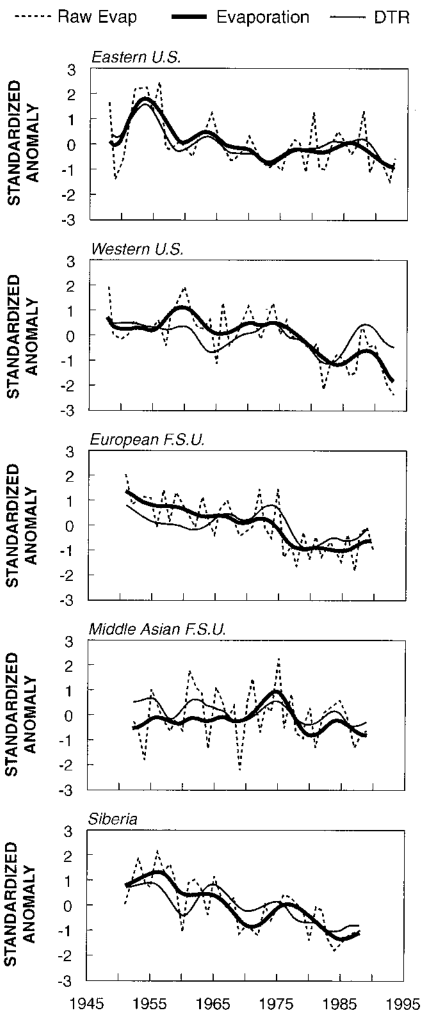

Figure 14. Area-averaged standardized anomalies of evaporation from pan evaporimeters for various sectors in the United States and the former U.S.S.R. The thick line represents the diurnal temperature range, the thin line evaporation, and the yearly anomalies are reflected by the dashed line.

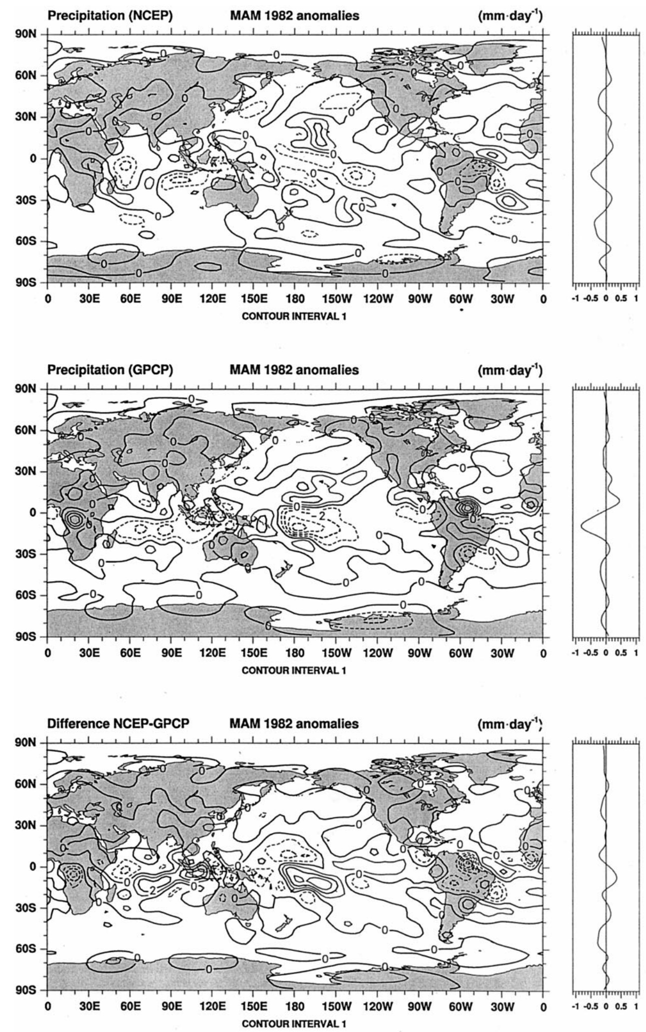

Figure 16. Precipitation for March through May 1983 based on the Xie-Arkin Global Precipitation Data Set and the NCEP reanalysis and the subsequent difference field. Panels on the far right are zonal averages for the cosine of the latitude.

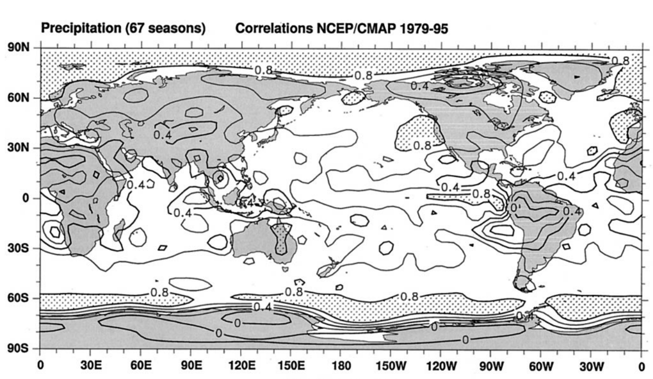

Figure 15. Correlation between the seasonal anomalies in precipitation in NCEP and Xie-Arkin GPCP analyses over the period 1979–1995 (67 seasons). Values exceeding 0.8 are stippled.

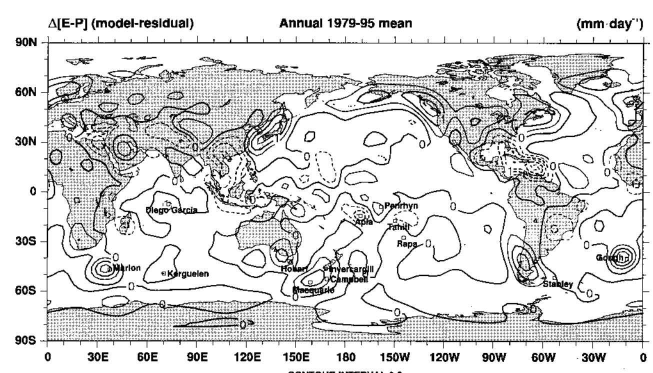

Figure 17. Map showing the location of a number of island rawinsonde stations superimposed on the annual mean E-P from NCEP minus E-P from observations and moisture budget diagnostics showing how they are located relative to bull's-eye features nearby.

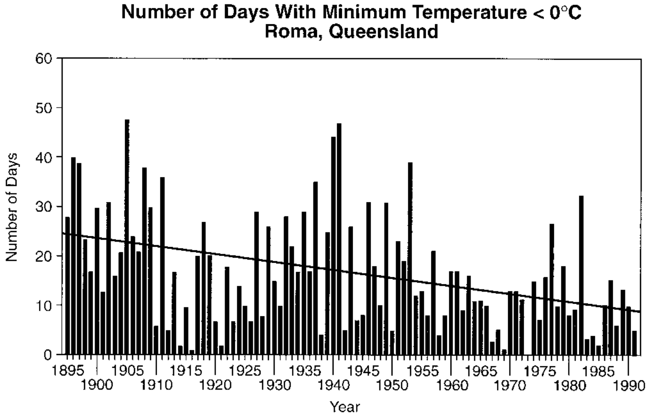

Figure 18. Number of days per year below 0°C at Roma, Queensland, in Australia.

tremes of the distributions of various weather and climate elements. There are a few regions and climate variables however, where regional and global changes in weather and climate extremes have been reasonably well documented.

Interannual temperature variability has not changed significantly over the past century. However, on shorter timescales and higher frequencies however, e.g., days to a week, there is some evidence for a decrease in temperature variability across much of the Northern Hemisphere [*Karl et al*., 1995]. Related to the decrease in high-frequency temperature variability, there has been a tendency for fewer low-temperature extremes and a reduction in the number of freezes in disparate locations such as the northeastern United States [*Cooter and LeDuc*, 1995] and Queensland, Australia (Figure 18), but widespread changes in extreme high temperatures have not been noted. In the former U.S.S.R., for example, since 1951, the annual extreme minimum averaged over the country has increased by over 3°C with little change in the extreme maximum [*Karl et al*., 1991]. Elevated minimum temperature can have significant implications on plant respiration.

Trends in intense rainfall events have been examined for a variety of countries [*Karl et al*., 1996; *Nicholls and Lurey*, 1992; *Suppiah and Hennesy*, 1996]. There is some evidence for an increase in intense rainfall events (United States, tropical Australia, Japan, and Mexico), but analyses are far from complete and subject to many discontinuities in the record. The strongest increases in extreme precipitation are documented in the United States and in Australia. Figure 19 shows annual trends in the highest 1-day precipitation total for the United States and trends in median 1-day precipitation amounts. Results from this figure show that the extreme precipitation amounts are increasing, in some areas by as much as 12%. However, for many areas this is being offset by decreases in more moderate events, and in other areas of the country (e.g., the Northwest, Southeast, and Northeast) both amounts are increasing. Such an increase, at least in the United States, has been supported by an observed increase in water vapor [*Ross and Elliott*, 1997] and total precipitation.

There are grounds for believing that intense tropical cyclone activity has decreased in the North Atlantic, the one basin with reasonably consistent tropical cyclone data over the 20th century, but even here data prior to World War II is difficult to assess regarding tropical cyclone strength [*IPCC*, 1995]. Elsewhere, tropical cyclone data do not reveal any long-term trends, or if they do, they are most likely a result of inconsistent analyses. Changes in meteorological assimilation schemes have introduced very difficult problems in interpreting changes in extratropical cyclone frequency. In some regions however, such as the North Atlantic, a clear trend to increased storm activity has been noted [*Kushnir et al*., 1997]. This is also reflected in an increase of significant wave heights in the northern half of the North Atlantic. In contrast, decreases in storm frequency and wave heights have been noted in the south half of the North Atlantic over the past few decades.

Changes have not been detected in the year-to-year or season-to-season variability of snow extent during the satellite era. Whether the recent variability is indicative of that which occurred over earlier portions of the century remains uncertain, however. A regional study over the U.S. Great Plains suggests that the variability of seasonal snow extent has actually increased since the 1970s [*Hughes and Robinson*, 1996]. This is in comparison to conditions dating back to 1910, at which time station observations became sufficiently abundant to permit a regional assessment.

Although initially used for monitoring the seasonal progression of vegetation "green-up" and "green-down", increased interest and the use of vegetation indices have demonstrated their usefulness for determination of the amount of area irrigated for agricultural production, monitoring of crop phenology, and monitoring extreme drought. The most commonly used satellite-derived vegetation index is the normalized difference vegetation index (NDVI) which has been used to infer changes in a number of variables that have a direct impact on biospheric processes. The NDVI has been used primarily in studies of interannual variability. For example, *Kerr et al*. [1989] observed that seasonally cumulated values of NDVI were a good estimator of seasonal rainfall and evapotranspiration (ET) in Senegal. Examples of the ability of the NDVI to capture the relative intensity of major droughts has been demonstrated in the Sahel and Brazil [*Tucker*, 1989] and during the 1988 extreme drought in the United States. *Teng* [1990] monitored the 1988 drought in the U.S. Corn Belt with NDVI

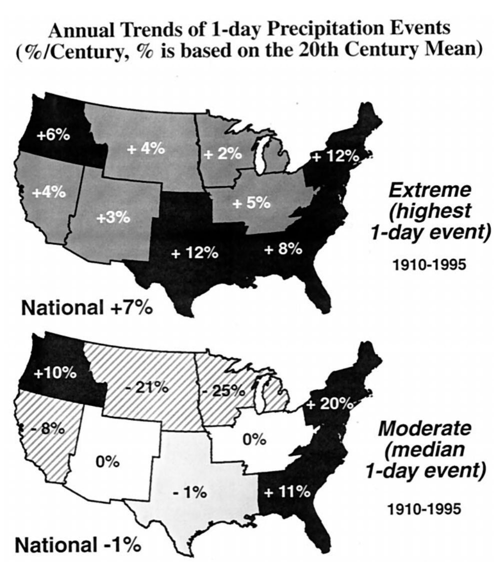

Figure 19. Trends in the highest 1-day extreme precipitation and the median 1-day precipitation amount. Trends are expressed as a percentage of the average precipitation for the respective precipitation quantile.

values compared to observed 1987 values. *Kogan* [1995] has developed a vegetation condition index based on the NDVI and has used this index to successfully identify regions of the United States which have experienced drought, including the 1988 Midwest drought. *Lozano-Garcia et al*. [1995] linked the NDVI observed during drought and nondrought growing seasons to the precipitation and soil characteristics. The combined use of vegetation indices, and other satellite products, has been the current focus of several research efforts related to hydrological applications of remotely sensed data. *Carlson et al*. [1990, 1994] and *Gillies and Carlson* [1995] have combined NDVI and surface temperature to estimate fractional vegetation cover and surface soil moisture availability. Current research efforts continue on refinement of the use of vegetation indices (and ancillary variables) to monitor, both timely and accurately, soil moisture availability on interannual timescales.

5. Summary and Conclusions

The suite of available climate data can be used to assemble a coherent, if yet still incomplete, quantitative description of variations and changes during the instrumental climate record. These data indicate that the planet has warmed by ~0.5°C during the past century, and this temperature increase has been strongest at night and over the middle- to high-latitude continental areas. The warming has tended to occur in jumps rather than in a continuous fashion with the most recent jump(s) occurring in the late 1970s and perhaps around 1990 (subsequent data will affirm or contradict this recent jump). Global data are available from these analyses but are largely based on monthly means which are often unsatisfactory in capturing extreme climate and weather events, critical to understanding biosphere-atmosphere interactions. Exceptions to this occur primarily on a national basis; that is, high-resolution daily temperatures are available on a country-by-country basis but have not been assembled into a consistent long-term database. Time-varying biases are particularly difficult to correct for at this resolution. Nonetheless, a number of national data sets are available and have been analyzed to some extent in order to identify changes in extremes. These analyses reveal an increase in the extreme minimum in both the United States and the former Soviet Union but with little change in the extreme maximum temperature.

Snow cover extent has been compiled on a weekly basis, and the data have been considered to be reliable since the early 1970s. The snow cover extent and temperature data covary inversely thereby providing additional confidence in each data set. Snow cover extent decreased rather abruptly in the late 1980s and with the exception of one year remain low.

Nighttime temperatures have been increasing at twice the rate of daytime temperatures over the past several decades and appear to be related to an increase in cloud cover and precipitation (wetter soils) and decreased potential evaporation (based on pan evaporimeters). Cloud cover and cloud type data are available from surface-based observations back to the 1950s and much earlier on a national basis. The latter data are subject to some significant biases and must be used with caution. Space-based data from the International Satellite Cloud Climatology Project (ISCCP) provide the best large-scale coverage and very good information about interannual climate variability but is not yet reliable enough to deduce multidecadal changes of cloud amount.

Precipitation has increased in the middle to high latitudes and has tended to decrease in the subtropics. A major issue related to precipitation measurement relates to the biases associated with solid precipitation measurement. Nonetheless, comparisons with stream flow data suggest that the data are robust with respect to multidecadal trends. High-resolution daily precipitation data are also available for a few countries and have been analyzed for changes in extremes. Significant increases in extreme precipitation rates are apparent in the United States and Australia, the two areas most closely studied.

Decreases in pan evaporation closely track the observed decrease, the diurnal temperature range over the United States, and the former U.S.S.R. (where data are available and have been analyzed). In addition, multidecadal measurements of soil moisture over portions of the western former U.S.S.R. reflect increasingly moist soils during this same time period. Moreover, variations of precipitation also track variations in the diurnal temperature range over much of the world.

A considerable amount of additional model data is available for analysis from the reanalysis efforts at various national meteorological centers. A thorough analysis of the evaporation and precipitation fields of the NCEP reanalysis indicates that many of the generated quantities must be used with caution. This includes precipitation and estimates of evaporation minus precipitation. Nonetheless, there are many fields, such as precipitable water, which offer an excellent opportunity for better understanding of atmospheric-biospheric interactions.

There is enormous potential to better understand atmospheric-biospheric interactions with existing data sets, both observed and modeled, but extreme caution must be exercised in using any of these data sets. All data sets have some systematic biases and uncertainties, whether they are useful depends on the specific application.

Acknowledgments. David Easterling, Tom Karl, and Kevin Gallo work is supported by the NOAA Climate and Global Change Program Climate Change Data and Detection and the U.S. Department of Energy. David Robinson's work is supported by NSF grants ATM-9314721 and SBR-9320786 and NASA grant NAGW-3568. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

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(Received July 19, 1999; revised December 21, 1999;
accepted February 28, 2000.)