THE RECENT CLIMATE RECORD: WHAT IT CAN AND CANNOT TELL US

Thomas R. Karl,[1] J. Dan Tarpley,[2] Robert G. Quayle,[1] Henry F. Diaz,[3] David A. Robinson,[4] and Raymond S. Bradley[5]

Abstract. While a great deal of climate data have been gathered over the past hundred years, there remains a number of problems limiting our ability to fully utilize these data in reconstructing the climate of the past century. This is particularly true for research demanding high precision and/or detailed local or regional-scale climate analyses. In this review we consider our ability to quantify climate change with respect to near-surface air temperature (measured 1.25–2 m above ground), sea surface temperature, precipitation, snow cover, sea ice, and vegetation measured from space and the Earth's surface. Among the data issues we discuss are calibration, observing practices, urbanization, station changes, data representativeness, data access, and areal coverage. The diversity of measurements over the past century and the new monitoring system being introduced via space-based and surface-based platforms offer an unparalleled opportunity for global monitoring; but to quantify climate change, we must tackle such issues as changing retrieval algorithms, relatively short periods of record, satellite Earth location precision, incompatibility with previous conventional historical observations, calibration, and potentially overwhelming data volumes. A new specialty within the climate field is beginning to emerge to address these problems. Despite the litany of problems the instrumented climate record can tell us a great deal about the spatial distribution and secular trends in temperature and precipitation over many areas of the world. In the future a blend of many data types and observing systems will be necessary to better quantify climate change. These large data sets will have to be made accessible to scientists in such a way that allows them an opportunity to check the veracity of their hypotheses and predictions regarding climate change.

1. INTRODUCTION

A comprehensive understanding of the Earth's climate includes consideration of surface, volcanic, tectonic, oceanic, atmospheric, and astronomical forcings and feedbacks. No area can be neglected. In this paper, however, we focus our interest on the surface climate record, both land and sea. This is where we live, work, fish, and grow our food. The spatial and temporal changes of the climate described by temperature, precipitation, and snow and ice cover and their impact and feedback with the vegetation of the surface are not only of scientific interest; rather, it can be argued that the origin and evolution of many of our socioeconomic and biophysical systems are closely linked to the surface climate.

At any location the surface climate is described by a variety of time averages and fluctuations about these averages. The instantaneous measure of these fluctuations is generally considered "weather." Over the past several decades, climatologists have developed and used numerous statistics to describe and predict the variations about these time averages. Commonly used time averages include 1 day, 1 month, 1 season, 1 year, and 30 years. Variations about these means have been described in terms of the diurnal and annual cycle, time-averaged day-to-day changes of the weather's monthly, seasonal, and annual anomalies. Anomalies are often expressed in a form such as 50% of seasonal normal precipitation or seasonal mean temperatures 2°C below normal. A recent example of these anomalies is the 1988 heat wave and drought which swept the North American continent.

In the past, most climatologists had little reason to believe that large changes in the climate were imminent. This implied that they could often use statistical sampling theory to predict important parameters of the climate over the next several decades. Over the past few decades, however, considerable evidence has been presented to suggest that the climate can change rather quickly. *Lorenz* [1963] showed that the climate system is a nonlinear chaotic system. In such a system, classical statistical sampling theory can be misleading. Significant "climate changes" can occur in relatively short periods (a decade or so) and persist for perhaps as long as half a century or more [*Lorenz*, 1986; *Hansen et al.*, 1988]. Hence the traditional 30-year normals often fail to adequately describe the climate. During the 1970s and 1980s,

EDITOR'S NOTE: The affiliations of the authors may be found on the last page of this paper.

Reviews of Geophysics, 27, 3 / *August 1989*
pages 405–430

8755-1209/89/89RG-01133 *$05.00*

Paper number 89RG01133

evidence mounted that man's use of fossil fuels was changing the chemical composition of the Earth's atmosphere to such an extent that global climate change seemed to be a likely consequence of increases of atmospheric greenhouse gases. General circulation climate models (GCMs) with doubled concentrations of CO_2 now predict significant changes of surface temperature, precipitation, and snow and ice cover over the next several decades [*Mitchell*, 1989]. In the near term, many climatologists are trying to determine whether the observational climate record is consistent with these predictions. As such, the climate record is now being used not only to identify anomalies but also to determine whether there are trends or changes in these anomalies. The primary difficulty in this exercise is that the changes or trends are considerably smaller than the natural variability of the climate system (as depicted by the seasonal and annual temperature anomalies), and biases and measurement errors in some instances can be as large or larger than the observed changes in the climate record. Thus we pose the question, Just what can the modern climate record tell us?

We focus on the uncertainties in our ability to quantitatively describe changes in the climate record. In this sense we distinguish our article from the comprehensive review of *Ellsaesser et al.* [1986] which brought together a wide variety of analyses of the modern climate record primarily for the purpose of evaluating the evidence for changes in the climate.

The ensemble of the daily surface observations that describe our weather is the essence of the climate record. Until 1960 the Earth's weather was measured solely by surface-based observations, including balloons. Since then, space-based observations have complemented these traditional data sources. These two observational systems form the basis of our knowledge of the contemporary climate. The robustness of the climate record that can be derived from these measurements is dependent upon a number of factors which are common to all climatological data sets. These factors include (1) the accuracy (including bias) and precision of the instruments and procedures, (2) the environment or area which the observations represent, (3) the spatial and temporal variability of observed climate elements, (4) the data reduction techniques and the quality control procedures used to convert raw observations to meaningful climatic data bases, and (5) accessibility of the data for diverse research applications.

A desire to forecast the weather, not the climate, has been the major reason for taking most meteorological measurements. As a result, the priority and treatment of each of the five factors listed above has been largely dictated by these needs. Another important goal recognized early on was the need to develop climatological information for the support of agriculture, commerce, transportation, and other economic activities. Observing systems designed for this application, however, generally implicitly assumed that climate was stationary, and the focus was on defining the mean state. Over recent decades, however, the success of the daily weather forecasts has been used as the primary justification for the resources necessary to make weather/climate measurements.

The climate elements addressed include observations of temperature, liquid and frozen precipitation, snow cover and sea ice, and vegetation. Each element and observational system is considered in context with the five factors listed above. In the following sections, both ground-based and spaced-based observations are considered. Since space-based observations have some unique characteristics, some preliminary discussion associated with these observation systems is the topic of the next section. Section 3 focuses on temperature; section 4 on precipitation; section 5 on snow cover and sea ice; and section 6 on vegetation. Finally, section 7 contains conclusions and recommendations.

2. SPACE-BASED OBSERVATIONS

2.1. Background

Operational environmental satellites have become an integral part of national weather observation and forecast systems. The present full complement of spacecraft consists of two Sun-synchronous polar orbiters (United States) that provide twice daily global coverage and, under normal circumstances, five geostationary satellites (two from the United States) (one of which is now inoperative and one each from Japan, India, and the European community) that provide hourly or better observations of that portion of the Earth that is continuously scanned from a geostationary orbit. There are also special military meteorological satellites. The Polar-Orbiting Operational Environmental Satellites are referred to as POES; likewise, we will refer to all Geostationary Operational Environmental Satellites as GOES. The primary purpose of the geostationary satellites is to deliver frequent images for weather analysis and warnings. Quantitative data from geostationary spacecraft are used for estimating cloud drift wind vectors, precipitation, snow cover, insolation, and atmospheric soundings. The polar orbiters are configured to provide both images and quantitative measures of atmospheric and surface properties such as atmospheric soundings, sea surface temperature, ozone profiles, vegetation index, and snow cover. Because they have become central to weather forecasts, operation of both geostationary and polar-orbiting spacecraft will likely continue, and the spacecraft will probably be configured to provide, at a minimum, the current operational products. They are also likely to have an expanding role in nonmeteorological environmental remote sensing, such as monitoring vegetation conditions, amounts of trace gases (ozone being the most important), aerosols, and sea state.

Digital data and derived products from the operational spacecraft are archived routinely at National Climate Centers. In addition, special data sets from experiments and research projects are becoming available to climate researchers. Some special data sets are also available from research satellites, but the operational environmental satellites (such as the National Oceanic and Atmospheric Administration (NOAA) satellites) are likely to be the primary source of long-term data for monitoring climate change. The operational satellite data record is now long enough to consider the statistical evaluation of changes of various climate variables. It is worthwhile therefore to consider the properties of satellite data that affect the data's value as a contribution to the climate record.

Generic characteristics of satellite observations that must be considered when using them for climatological studies include coverage, uniformity of observations, extent of horizontal variations, navigation/Earth location, calibration and biases of instruments, variations in algorithms, wavelengths used, and effects of intermittent observation. The latter three issues are discussed in subsequent sections in context with the climate elements of interest.

2.2. Orbits/Coverage

Compared to ground-based data, the most striking characteristic of satellite data is its comprehensive geographic coverage. Weather forecast models require global data delivered daily. Orbits of POES are chosen to provide global observations while the coverage from GOES is determined by the geometry of geostationary orbit. Geostationary spacecraft observe the Earth from 36,000 km altitude above the equator at fixed longitude. At this altitude the effective coverage for quantitative products is about 60 geocentric degrees from the satellite nadir (subpoint on Earth directly below the satellite). Under normal circumstances, five geostationary satellites provide coverage for about 85% of the Earth's surface (Figure 1). Irregularities in the Earth's gravitational field cause the GOES orbit to drift away from being exactly geostationary, so the satellites have motors for station-keeping maneuvers. The orbits are adjusted about every 2 weeks. The geostationary satellites make routine observations every 30 min and are capable of scanning limited latitude bands at shorter intervals.

The POES have orbits (altitudes of approximately 850 km) and instrument scan patterns designed to provide daily near-global coverage at relatively fixed local times [*Kidwell*, 1986]. The local times are chosen to accommo-

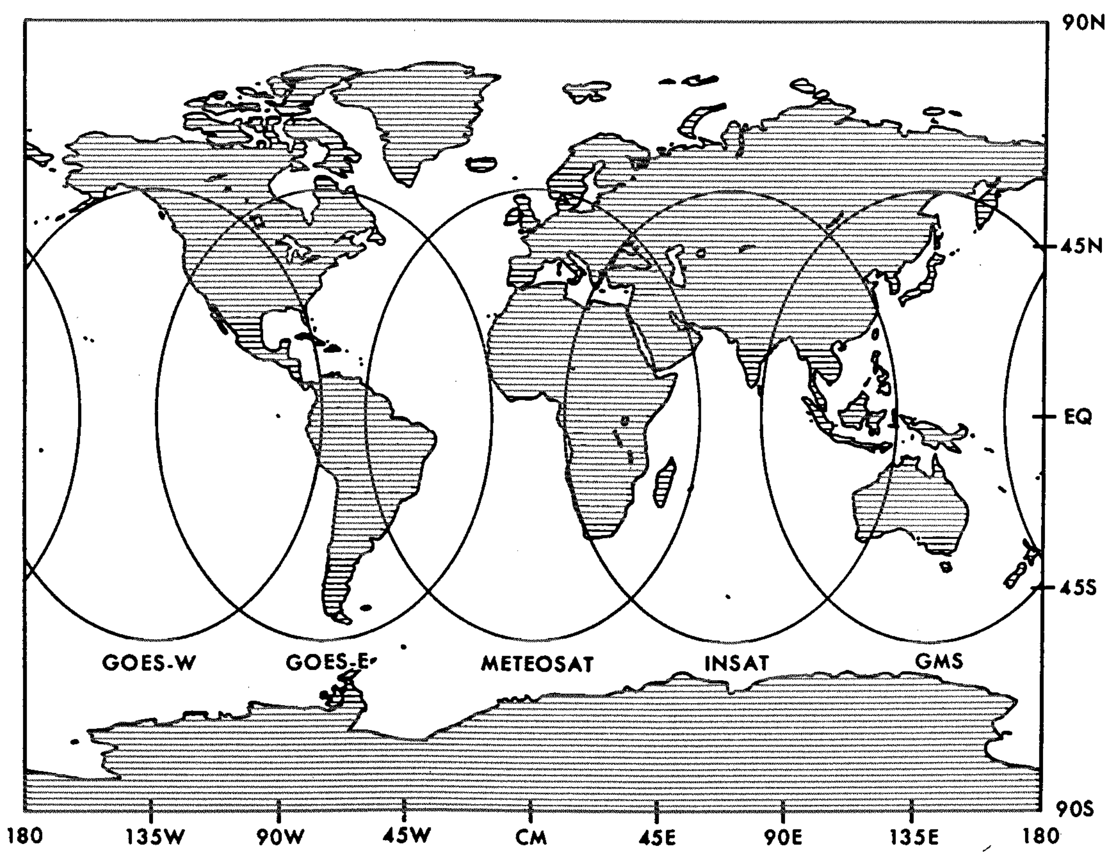


Figure 1. Global coverage of the geostationary satellites under normal operating conditions GOES (United States), METEOSAT (Europe), INSAT (India), and GMS (Japan)).

date deadlines for ingesting satellite information into weather forecast models. These deadlines have changed from time to time and likely will again in the future. Observations are made at relatively fixed local times by placing the POES in Sun-synchronous orbits, that is, orbits with orbital planes that precess through 360° in 365.25 days, maintaining a fixed orientation in space with respect to the Sun. Satellite precession is a function of orbital inclination and altitude. Errors in orbital insertion and atmospheric drag cause the orbit to depart from being exactly Sun-synchronous. These effects cause the equator-crossing time to drift slowly during the lifetime of the spacecraft.

Because the number of orbits per day is not an integer number, the orbital track on the surface does not repeat from day to day, although the local solar time for crossing any latitude is almost constant. The viewing geometry of a given spot on the surface is cyclic with a period equal to the repeat frequency of the satellite. For example, NOAA 9 is a 9-day repeater, so a given Earth location moves from the eastern to the western side of a daytime orbital swath during the 9-day cycle. This causes a location to be viewed in the antisolar direction on day 1 (or the eastern side of the swath) and progress to the solar side by day 9. Figure 2 illustrates the effects of shifting orbital track on the viewing time and solar zenith angle of a site near Manhattan, Kansas.

Both daily and yearly changes in viewing geometry and observation time must be accounted for in climatological interpretation of satellite data. Observation of quantities such as land surface temperature and precipitation that have pronounced diurnal variation require correction for the varying observation times. For the NOAA 9 case illustrated here, the local time variation is as much as 1.6 hours within the 9-day cycle, which is short enough that simple averaging over the repeat cycle may suffice. However, when the 9-day cycle is superimposed on the long-term drift of the orbital plane, the local times of observation will vary up to 4 hours over the life of a single satellite. This is a significant problem for diurnally varying quantities.

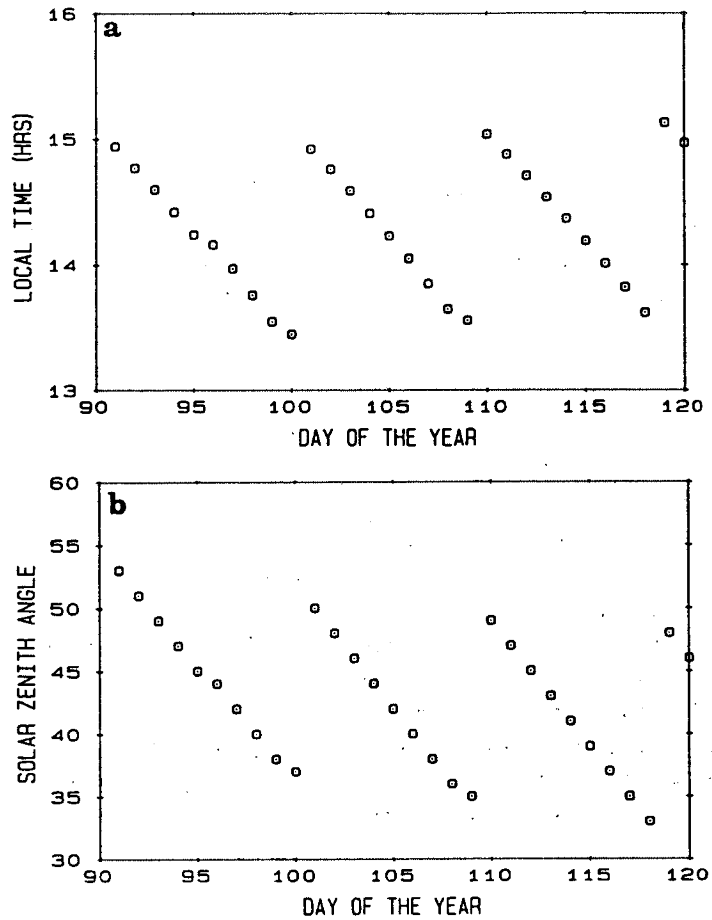


Figure 2. (*a*) Daily changes in local times of observation by a NOAA polar-orbiting satellite (NOAA 9). Observations are at Manhattan, Kansas. (*b*) Corresponding changes in local solar zenith angles are also shown.

2.3. Earth Location of Satellite Data

Knowledge of a satellite's orbital elements, its orientation in space (attitude), and the orientation of the instrument telescope or antenna with respect to the spacecraft are all required to Earth locate the data. There are difficult technical problems involved in determining, tracking, and predicting the orbit and attitude of spacecraft, and operational costs increase with increasing navigation accuracy. Systems to navigate the operational satellites and Earth locate the data have been designed to meet the minimum accuracies required by weather analysis and forecasting. For past and current NOAA spacecraft the Earth location accuracy is around 10 km. Archived data and derived products have appended Earth location information with errors in this range. The next generation of GOES and POES (1990s) are planned for navigation errors of about 2 km.

2.4. Biases and Calibration

Satellite-derived quantities of interest for climate studies are usually retrieved quantities, not the basic measured radiances at various wavelengths. The retrieved quantities range from standard geophysical parameters, such as temperature and moisture, to simple indices, such as vegetation index and percent ice cover, or yes/no quantities like snow cover. The algorithms for deriving these quantities vary in complexity from very simple, manual photointerpretation to complex mathematical schemes requiring many thousands of lines of computer code. Even

The earliest and most frequently used instruments to measure surface temperature were liquid-in-glass thermometers. In recent years, automated and semiautomated stations have been making increased use of resistance-type sensors. Calibration errors are serious problems with early temperature records, some dating back to the seventeenth and eighteenth century. Early thermometers consisted of a U tube with one open end and required pressure corrections. Varying temperature measurement scales and instrument shelters were used. Readings from these instruments are often difficult to interpret. Temperature measurements over the last 100–140 years have been refined so that the accuracy and the precision of the measurements is at least 0.5°C. Automated instruments of recent decades often have a precision close to 0.1°C and respond more rapidly to short-term temperature changes. This can lead to higher and lower extreme values, when compared to liquid-in-glass thermometers. Although the automated instruments are usually more precise than their liquid-in-glass counterparts, they are prone to electromechanical problems which can be quite serious. Instrument housings also vary, and differences in radiation and ventilation of the housings can introduce biases. Often, these types of problems can be rectified by field maintenance and data adjustments.

Of particular interest with respect to detecting changes of surface temperature are the space and sampling periods which the measurements represent. The history of temperature measurements throughout the world is such that the lcoation of the measurements rarely remains constant over a long period of time (100 years), and even if it does, the local environment around the station is often modified by natural processes or by man. This makes it difficult to separate local changes in climate from regional or large-scale changes. Figure 3 provides an example of

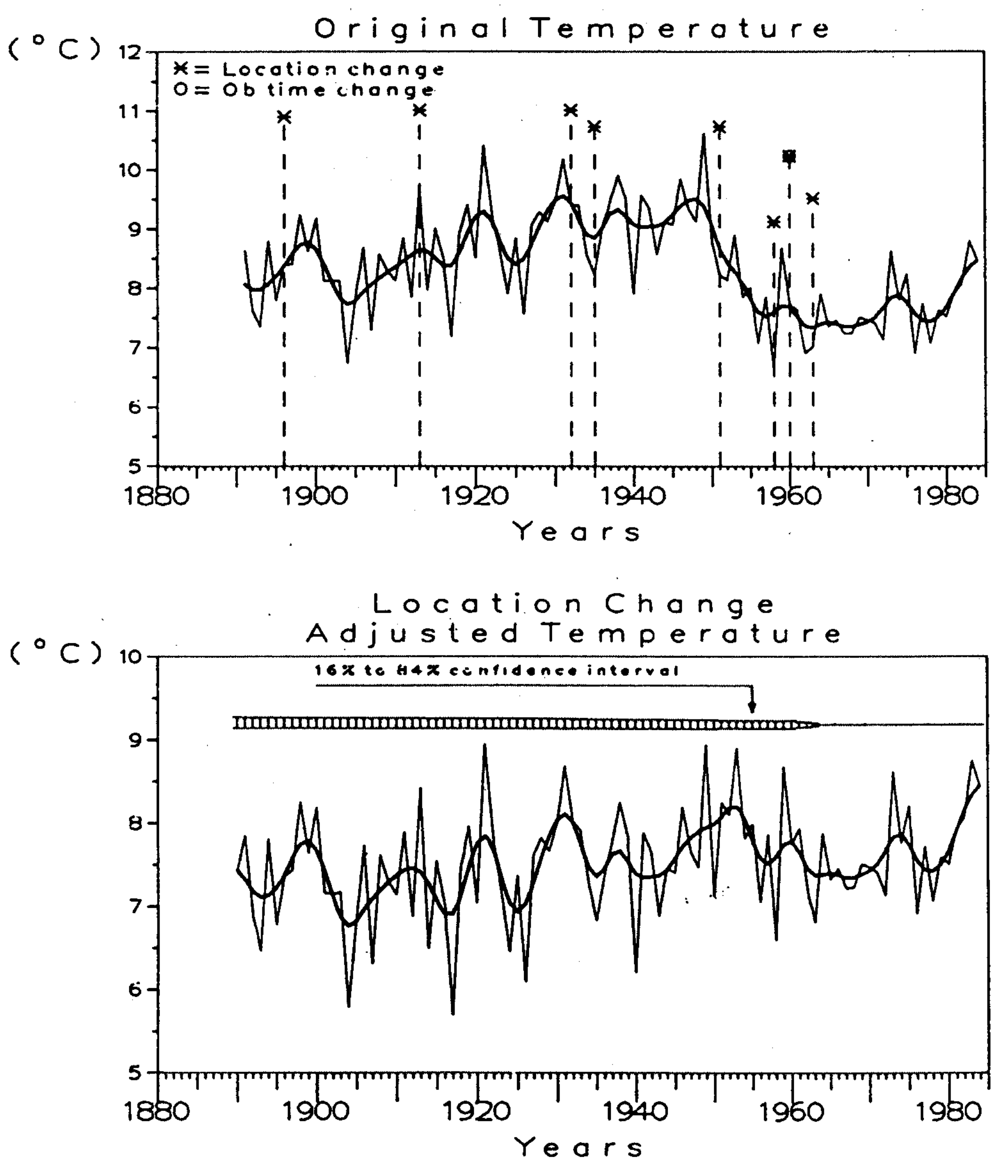


Figure 3. Time series for Binghamton, New York, of the original and adjusted surface temperature. Estimate of the confidence interval of the corrections is also given. "Ob" refers to observations. Location changes were often accompanied by changes in instrumentation and/or the height of the instrument above the ground [from *Karl and Williams*, 1987].

the most carefully designed algorithms can introduce biases in the product, and ongoing changes and improvements to algorithms that occur in any operation can affect the nature or magnitude of biases. If the retrieved quantity is equivalent or nearly so to conventional measurements of the same thing, then the retrieval algorithm can be tuned to conventional measures.

Climate studies using long-term time series of satellite data must take into account instrument calibration and stability. The prelaunch procedure for calibrating spacecraft radiometers is to measure the instrument signal when it is observing a known radiation source that is traceable to the National Bureau of Standards. In the case of visible and near-infrared sensors the calibration source is an integrating sphere (a hollow internally illuminated sphere that serves as a radiation source), while for infrared and microwave radiometers the calibration is against precision blackbody targets. The prelaunch calibrations determine characteristics of the instrument, including linearity, signal to noise ratios, and gain. Other results from the prelaunch calibration pertain to the thermistors that measure temperatures of the on-board internal blackbodies and determination of the effects of instrument temperature on calibration [*Rao*, 1987; *Price*, 1987*a*, *b*; *Planet*, 1988].

To maintain calibration, the instruments should be monitored and evaluated periodically after launch. Ideally, this is done using a stable on-board source with well-defined characteristics. The infrared channels on board the POES and GOES have an internal blackbody source that allows routine recalibration of the sensors. Recalibration of the infrared is done frequently because the instrument response is a function of instrument temperature which changes throughout the orbit. The visible channels on the POES and GOES have the most difficult calibration problem. There is no on board visible calibration target on either, so recalibration after launch is difficult. Currently, no effort is made by satellite operating agencies to provide systematic postlaunch calibration and stability-monitoring data to users of visible data. Each user must provide his own calibration, and most use technqiues involving observations of stable surface targets (deserts, mostly) and modeling atmospheric effects to obtain a calibration [*Frouin and Gautier*, 1987; *Paris and Justus*, 1988].

Biases can also arise because of unexpected changes in atmospheric composition. This includes regional effects from undetected clouds, water vapor changes, or large-scale changes such as those that occur during the following major volcanic eruptions. For these reasons a continuous appraisal of biases with respect to reliable surface-based measurements is most desirable, but it is often difficult to implement reliable corrections on a routine basis because effects are regional and change with time.

3. TEMPERATURE

3.1. Land

3.1.1. Surface-Based Observations The building blocks of the surface thermometric climate record consist of the daily and synoptic weather observations collected by national weather services worldwide. Near-surface temperature observations (recommended height above ground 1.25–2.00 m) are routinely taken by World Meteorological Organization (WMO) member countries and transmitted across the Global Telecommunications System (GTS) every 3–6 hours. The primary purpose of these observations is operational weather forecasting, analysis, and assessment. As such, the location, design, and changes made to these observing stations are not motivated by the needs of those interested in detecting climate change. This can have deleterious consequences regarding the ability of climate change researchers to provide accurate information on climate change.

At the end of each month, climate summary messages known as climatological or CLIMAT reports are sent via the GTS, or in hard copy format, to the U.S. National Weather Service in Washington, D. C., and the U.S. National Environmental Satellite Data and Information Service's National Climatic Data Center (NCDC) in Asheville, North Carolina. All of these data are then transferred to computer-readable format and published in the *Monthly Climatic Data for the World* (MCDW). Ten-year compilations of the data are published in several volumes of *World Weather Records* (WWR). These data span the world, but the lag time is several months for MCDW and up to a decade or more for WWR. This long delay often stems from late receipts of data from WMO member countries. These two publications often form the nucleus of the thermometric data used by climatologists to determine global temperature changes. These publications are distributed by NCDC, and the computer-readable data sets (magnetic tape) are available from both the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, and NCDC. The only thermometric observation available from these data are mean monthly temperatures. Important information, such as the maximum and minimum temperature (or daytime and nighttime temperatures), are not included.

The quality control of these data has varied over the years. Early publications of WWR, which were compiled by the Smithsonian Institution, underwent quality control for both gross errors and biases. Recent publications of WWR and MCDW have had progressively less quality control and virtually no checks for biases. This is unfortunate because it requires every researcher to correct and adjust for the same errors and biases, often without important station history information.

what can happen when a station changes its location. In 1951 the Binghamton, New York, station moved from the city to the airport, about 15 km north-northwest of the city location; as a result its elevation changed from 255 m to 493 m above sea level, and the height of the thermometer above ground was reduced from 17 to 1.2 m. This resulted in an exaggerated cool epoch in the climate record. Station relocations, new instrumentation, and other changes in the site and sampling period often introduce inhomogeneities (or biases) into the climate records. Hence apparent changes in climate may be an artifact of some artificial or local effect. Given these inhomogeneities, it is a complex and time-consuming process to take weather observations and transform them into climatological time series which can be used to ascertain changes of temperature of the order of several tenths a degree Celsius over a 100-year period. Yet, it is precisely this magnitude of change which we are most interested in quantifying. Many regional (as well as hemispheric and global) changes in the thermometric record appear to be of this magnitude [*Karl et al.*, 1988; *Jones et al.*, 1986*a*, *b*; *Hansen and Lebedeff*, 1987].

Inhomogeneities in surface weather records can and have produced a number of serious biases in the climate record. Three of the most serious biases that have been introduced into the land-based surface temperature records are as follows:

1. Changes in observing schedules and practices have been shown to produce biases in the mean temperature of up to 1.0°C [*Bigelow*, 1909; *Schaal and Dale*, 1977; *Karl et al.*, 1986]. Even today, there is not an international standard for the calculation of the mean daily temperature, and archived data often include averages based on different formulae for calculating monthly means.

2. Rapid increases in urbanization can lead to biases in the annual mean temperature at urban locations of over 1.0°C [*Karl et al.*, 1988; *Karl and Jones*, 1989].

3. Changes in station location, instruments, instrument shelters, and the height of the instruments above the ground have lead to biases of 1.0°C or more at many stations [*Karl and Williams*, 1987].

Additional uncertainties in the determination of surface temperature trends arise because of the temporal changes in the spatial coverage and mix of stations. For example, the number of stations which have temperature data in readily usable computer-readable form (magnetic tapes, diskettes, CD ROM, etc.) has significantly changed over the years. *Hansen and Lebedeff* [1987] summarize the number of stations available to them for their global temperature data sets over the past century. Figure 4 depicts a large increase in stations from the late nineteenth century to the 1960s and the subsequent decline since the 1960s. This decline is related to two factors: fewer observing stations and decreased participation in data exchange.

In order to make use of as much data as possible, most researchers [*Jones et al.*, 1986*a*, *b*; *Hansen and Lebedeff*, 1987] have had to convert monthly, seasonal, and annual mean temperatures from an observing station into a series of anomalies or departures from some base mean value. These anomalies are often calculated over a region with boundaries defined by geography or self-imposed latitude/longitude delimiters, for example, grid boxes. There is a good reason for the use of anomalies instead of actual mean temperatures. When a station changes (opens, closes, moves, changes instruments, etc.), the mean temperature at the "new" station may change. For example, when valley stations are replaced by stations located on a plateau or mountain, the mean temperature will usually decrease without a change in climate. Use of departures helps eliminate this bias.

Even with conversion to an anomaly series, poor station coverage can adversely affect the time series, as demonstrated by *Jones et al.* [1986*a*]. In one experiment they varied the number of stations for successive iterations while keeping the number of stations in each iteration constant over time. When the spatial coverage was low, they demonstrated that the variability of the time series became exaggerated. Changes in the mean temperature of 0.1°C on a decadal basis were also observed. In general, when the number of stations used to calculate area-averaged temperatures becomes too small, biases in the trends can also arise because of the inability to determine stations with homogeneous trends. Many parts of the world lack the data coverage necessary for developing regional long-term time series with a fixed network of stations.

The treatment of the three most serious biases has been addressed differently by various researchers, often depending upon the size of the area over which they average their data. As an example, it is generally accepted that more rigorous homogeneity assessments of the thermometric data are required for the estimation of climate change over small areas, such as provinces, states, or counties, compared to large-scale hemispheric and global analyses. The reason is related to the canceling effect of random errors and biases when many stations (the law of large samples) are used to construct temperature time series. Usually, larger areas have more stations compared to smaller areas.

With respect to the calculation of global and hemispheric trends of temperature, some scientists [*Hansen and Lebedeff*, 1987] have considered the urban heat island bias to be of greatest concern. The reasons for such concern are illustrated in Figure 5. The biases are all in one direction. Although this figure points out the potential data biases associated with urbanization, similar biases can be introduced by other local changes at the measurement sites. Some local environmental changes may cause temperature increases (deforestation), while

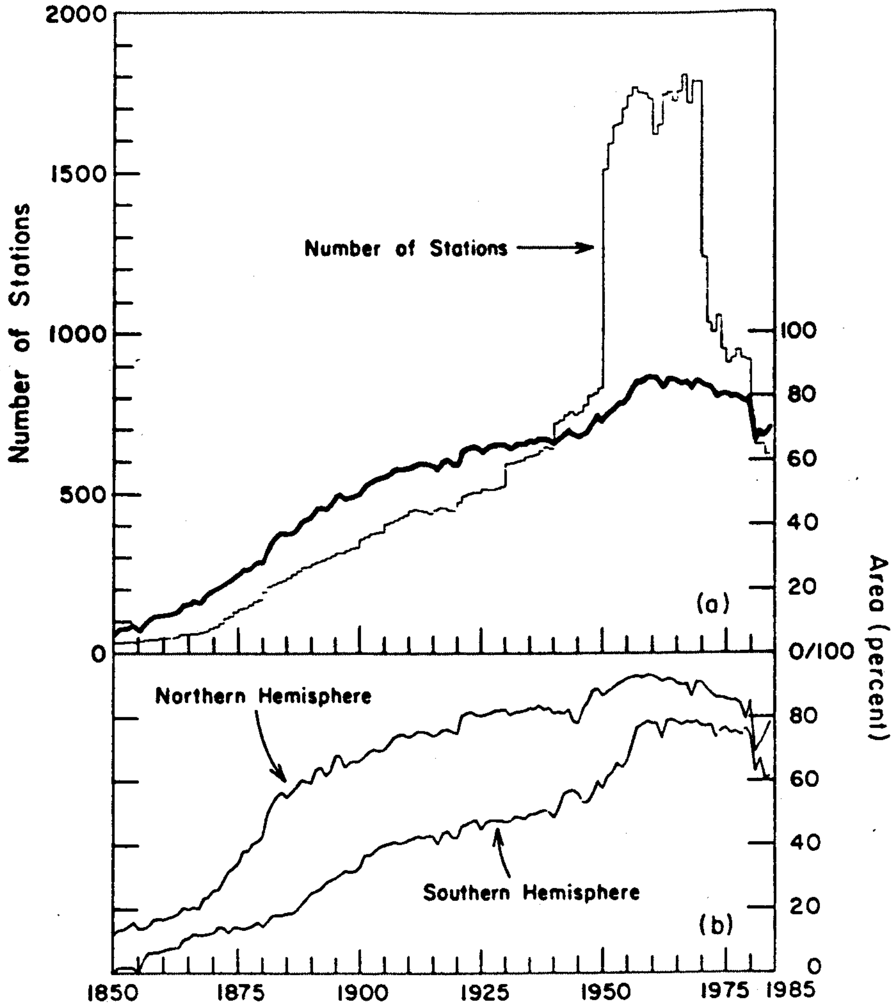


Figure 4. From the global data set of *Hansen and Lebedeff* [1987]: (*a*) the number of stations (histogram) and percent of global area located within 1200 km of a station (heavy curve) and (*b*) the percent of hemispheric area located within 1200 km of a station.

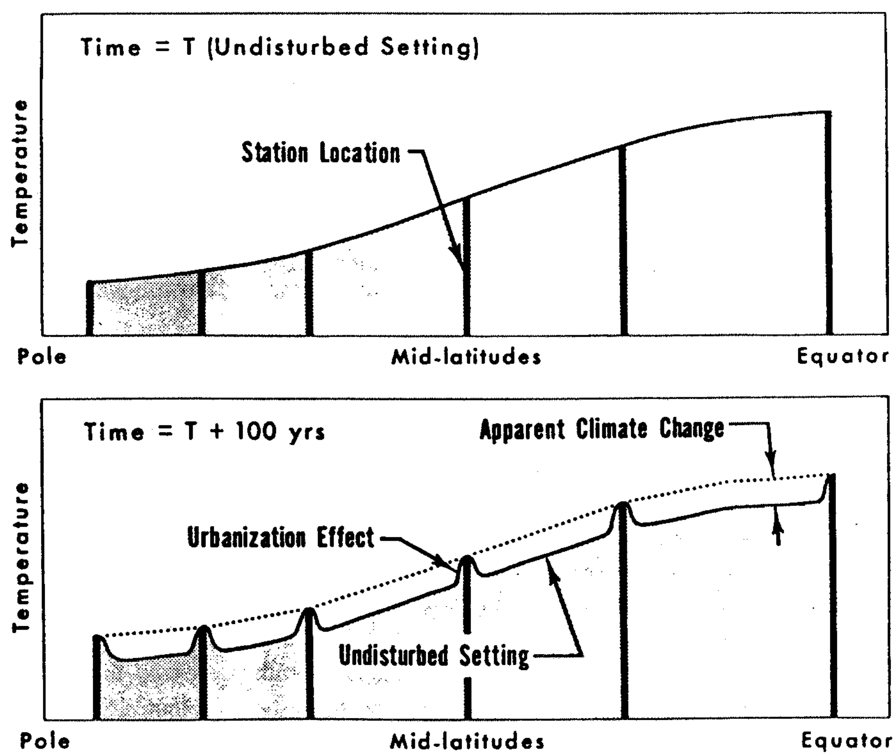


Figure 5. Apparent climate change deduced from a network of stations affected by increasing urbanization.

others may cause temperature decreases (reforestation). Thus changes in the local environment around a station can also produce apparent climate change.

Hansen and Lebedeff [1987] implicitly assume that most of the station biases associated with the changes in observing practices, station relocations, new instruments, etc. (biases 1 and 3, listed above) when averaged over the globe (or hemisphere) will tend to cancel each other. They have assessed the biases associated with increases in urbanization by performing experiments which omit stations with populations exceeding 100,000. They find a bias of 0.1°C over 100 years (Table 1) and speculate that perhaps another 0.1°C bias remains in the data for stations with populations less than 100,000.

TABLE 1. Linear Trends of Temperature Over the Period 1881–1987 for the Northern and Southern Hemisphere and the Globe as Derived From the *Hansen and Lebedeff* [1987] and *Jones et al.* [1986*a*, *b*] Data Sets

	Temperature Trend, °C/100 years		
	Jones et al.	*Hansen & Lebedeff*	*Hansen & Lebedeff, Adjusted**
Northern hemisphere	0.50	0.61	0.51
Southern hemisphere	0.48	0.39	0.29
Globe	0.49	0.54	0.43

*The *Hansen and Lebedeff* [1987] data in which stations with a 1970 population exceeding 100,000 have been removed from the network.

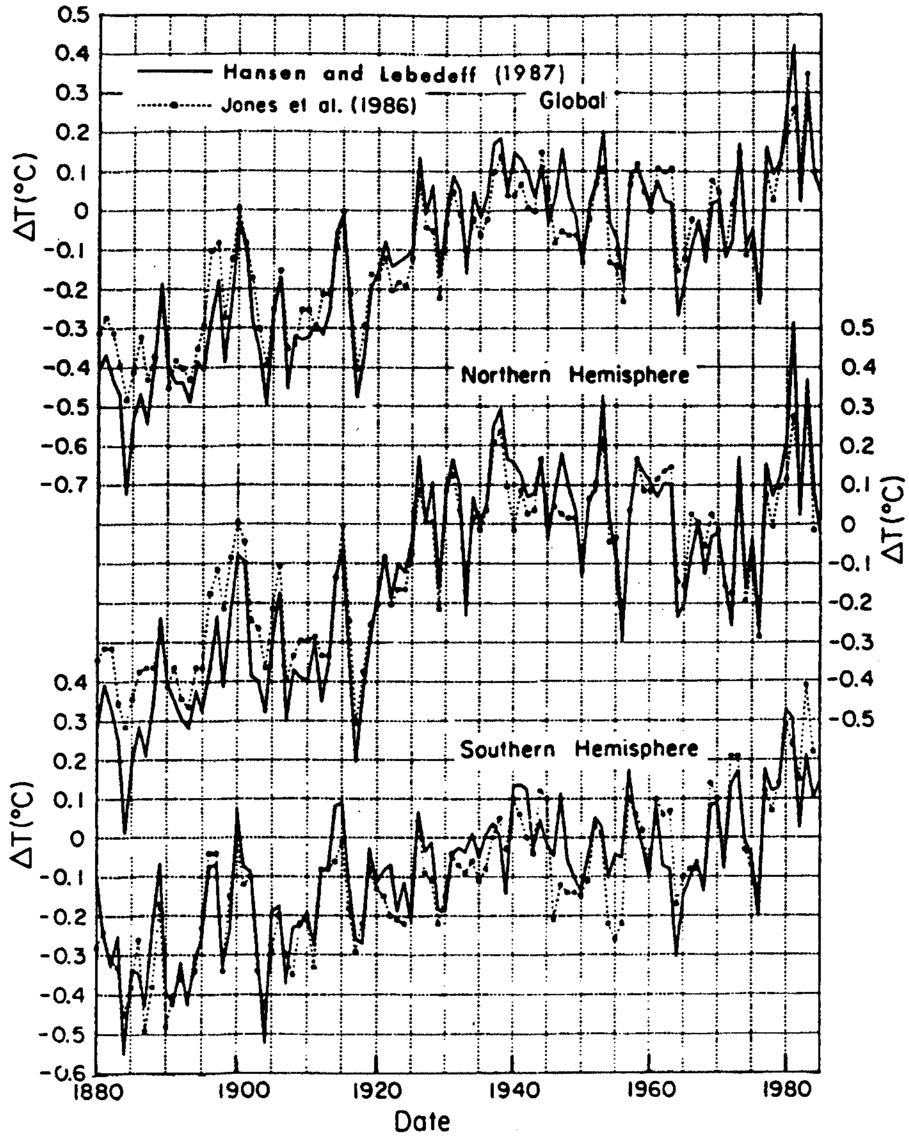
Other researchers [*Jones et al.*, 1986*a*, *b*] address biases 1 through 3 by constructing time series of temperature differences between a specific station and three or four of its nearest neighbors. These time series are visually inspected for gradual changes or discontinuities. This approach assumes that the differences in temperature between neighboring stations should be random over time so that any trend or discontinuity which manifests itself in the time series is a result of a change at one of the stations. By cross comparison of the plots, one determines whether the inhomogeneity was in the neighboring station or the candidate station being assessed. Problems can and do arise with this subjective approach when there are many inhomogeneities in the record. Also, the procedure can break down if similar biases are present at neighboring stations and/or the correlations between the neighboring stations and the station under assessment are not strong. For example, the urban heat island bias is difficult to detect if most of the neighboring stations are also affected by increasing urbanization [*Karl et al.*, 1988]. Furthermore, if there are many inhomogeneities in the climate records of the neighboring stations, as well as the candidate station, the biases and discontinuities are difficult to detect.

Another approach which has been used to remove these biases is described by *Quinlan et al.* [1987] and *Karl and Williams* [1987]. When computerized station histories are available, this information can be used to directly assess the effects of station changes. That is, comparisons of a specific station with its neighbors are made before and after a known change at the candidate station. Station histories of neighboring stations can be used to ensure that no changes occur at the neighboring stations. This method is dependent on an accurate station history. Similar to the approach adopted by *Jones et al.* [1986*a*, *b*], it is dependent upon the availability of highly correlated neighboring stations.

Despite the differences in analysis methods, many of the important details of the hemispheric and global changes in temperature are in rather close agreement, as depicted in Figure 6. The linear trends of temperatures in these data sets are given in Table 1. Perhaps it should not be surprising to find close agreement between these two data sets because much of the same data were used in each of them. It is tempting to conclude that when averaging over large areas, all the important inhomogeneities in surface temperature cancel. Such a conclusion may be premature. In a recent analysis, *Karl and Jones* [1989] compared both of these global data sets with a dense network of rural stations in the United States referred to as the Historical Climate Network (HCN). The HCN stations were explicitly adjusted for all the inhomogeneities listed in biases 1 through 3 above. These results and those of *Jones et al.* [1989] indicate that a significant urban bias still remains in the data. The exact magnitude is unknown, but perhaps as much as a 0.1°C bias still exists in these data on a global basis over the last 100 years.

Because of inadequate or inaccessible station histories, none of the analyses have directly assessed the effects of changes in the instrument shelters used to house the thermometer or the changes in methods used to calculate mean daily temperature. These problems are particularly acute when constructing records back to the nineteenth century because many thermometers were exposed to the open air on a north-facing wall as opposed to the cotton region shelter (CRS) or the Stevenson Screen so typical of the twentieth century. Thermometers in a CRS are known to average as much as 0.1°–0.2°C warmer than those with free air circulation mounted with a north facing exposure [*Flora*, 1920; *Young*, 1920]. New thermometric shelters are being introduced with automated stations. They are likely to produce another bias. Existing side-by-side comparative data are not sufficient for an adequate evaluation. The method of calculating the mean daily temperature has been derived from a variety of averaging techniques. Examples include averages based on the use of the maximum and minimum temperature observed over

Figure 6. Comparison of the annual global and hemispheric temperature change for the *Hansen and Lebedeff* [1987] data and the *Jones et al.* [1986*a*, *b*] data set [after *Hansen and Lebedeff*, 1987].



various 24-hour periods (midnight-to-midnight, 0700 Local Standard Time (LST) to 0700 LST, 1700 LST to 1700 LST, etc.), observations made at several fixed hours of the day, and 24-hourly measurements. These methods produce varying estimates of the mean daily temperature of ±1°C or more, depending on the season and climate.

3.1.2. Space-Based Observations Unfortunately, space-based observations from satellites have yet to demonstrate their capability for monitoring changes of near-surface temperature. In fact, the vertical resolution required to estimate the free air temperature 1.25–2 m above the Earth's surface does not yet (and may never) exist. Instead, land surface skin temperature has been the product produced from several satellites. Long-term changes of skin temperature can be just as much a function of changing land use as of changing climate.

It is true that satellite observations afford continuous spatial coverage of the land surface skin temperature, but only with clear skies. This biases the data sample, and the relatively small changes of annual and seasonal temperature that have been observed over the past century make the problems with data calibration/validation particularly acute. Despite these problems, *Ohring et al.* [1987] provide some encouraging results with respect to comparisons of satellite-derived clear sky brightness temperatures to surface temperature observations, but considerable work remains.

3.2. Sea

3.2.1. Surface-Based Observations Systematic measurements of sea surface and marine air temperatures began in the midnineteenth century, and over 100 million of these observations have been transferred to computer-readable magnetic tapes. Although many observations date back to the midnineteenth century, over three fourths of them have been taken since World War II. Since most observations have been taken by ships of opportunity, their routes have favored preferred navigational transects across the global oceans which have changed over the past century (Figure 7). As a result there are large geographic areas of the oceans which have not been adequately sampled (Figure 8), and even today, only two thirds of the global oceans are sampled in NOAA's Comprehensive Ocean-Atmosphere Data Set (COADS). The tropical areas of the Pacific Ocean have few observations until the 1950s, and oceanic regions poleward of 40°S (which account for 15% of the world surface area) have few observations available until recent decades. Even when observations are available for an individual grid box, there may be only one or two values for a given month, and adjustments may be required to convert the value to a midmonth or midarea equivalent. Observations of both sea surface temperature and marine air temperature (both day and night observations) have been used to construct thermometric time series.

The rather poor coverage of marine observations across the global oceans is compensated to a significant degree by the fact that the trends of ocean temperature anomalies tend to have a substantial amount of spatial coherence, i.e., warming and cooling trends tend to occur on large spatial scales in the oceans (much more so than the land surface temperature observations). Nonetheless, the poor spatial coverage in the tropical Pacific and southern oceans adds an uncomfortable level of uncertainty regarding long-term (50–100 years) changes of ocean temperatures.

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 with respect to daytime observations of marine air temperature. During wartime, thermometers were taken indoors to record the observation to avoid using lights on deck. Use of painted versus varnished shelters and differences in instruments also introduce biases.

For sea surface temperature measurements, biases are known to be caused by changes in the vessel used to hold the seawater in which the temperature is measured. Wooden buckets, metal buckets, canvas buckets, and intake tubes for engine cooling have all been used to measure sea surface temperatures since the midnineteenth century. As sail gave way to steam and particularly around World War II, ships began switching from measuring the temperature of seawater from canvas buckets dipped into the ocean to measuring the temperature of the water in the engine intake tubes. Only in recent decades have observations of sea surface temperatures documented the type of measurement. 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.

The lack of knowledge of the exact manner in which sea surface temperatures have been measured over the years often requires indirect methods to remove biases from the record. On an annual basis the comparison of sea surface temperatures before and after 1942 with nighttime marine air temperatures indicates the switch to engine intake seawater, and insulated buckets produced a substantial bias, with the engine intake seawater several tenths of a degree Celsius warmer than that obtained from the buckets [*Folland et al.*, 1984]. Additionally, island surface air temperatures [*Jones et al.*, 1986c] as well as empirically adjusted physically based models of a canvas bucket's heat budget [*Bottomley et al.*, 1989] have been used to adjust sea surface temperature biases. The magnitude of the warm bias obtained using the modeling approach is similar to that obtained by comparison with the nighttime marine air temperatures (several tenths of a degree Celsius). Differences among types of buckets (for which the timing is uncertain) can translate into an uncorrected or uncorrectable bias of 0.1°–0.2°C in the sea surface temperatures over the past century.

Time series of unadjusted marine air temperatures also contain biases. The biases in nighttime marine air temperatures, however, are thought to be significantly smaller than biases in the sea surface temperatures and daytime air temperatures, because hull heating is not as significant at night. However, the number of nighttime marine air temperatures is less than one-half of the sea surface temperatures, making them less desirable for use in global assessments of climate change.

The importance of the marine corrections is depicted in Figures 9 and 10. The corrections applied by C. K. Folland and D. E. Parker (personal communication, 1989) are based on the physical model developed by *Bottomley et al.* [1989]. The corrections applied by P. D. Jones (personal communication, 1989) are based on comparisons of ocean sea surface temperatures with near-coastal land-based temperatures and nighttime marine air temperatures. The differences between these two sets of corrections are almost as large as the observed changes of temperature during the nineteenth century. Some of the differences may be due to the assumption used by C. K. Folland and D. E. Parker (personal communication, 1989) that canvas, rather than wooden buckets were prevalent during the latter part of the nineteenth century, but C. K. Folland and D. E. Parker (personal communication, 1989) have evidence that canvas buckets were in widespread use after circa 1875. In any case, Folland and Parker plan to test this by deducing a set of corrections for wooden

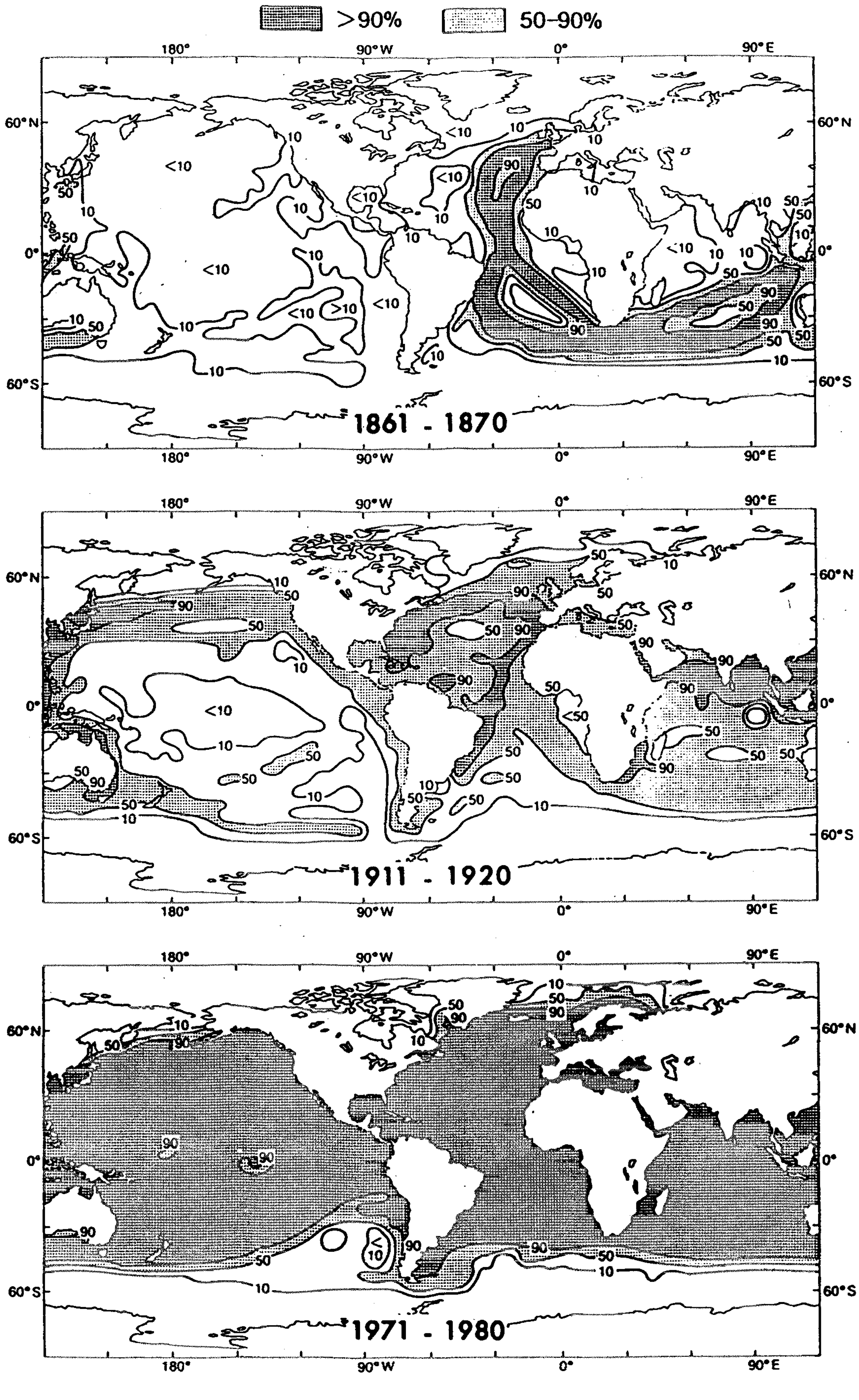


Figure 7. Percent of seasons with at least one observation on a $5^\circ \times 5^\circ$ space scale [from *Bottomley et al.*, 1989].

buckets and comparing these corrections with those for a variety of canvas buckets. In summary, with so few long-term observations of temperature over the oceans, particularly in the southern hemisphere, and the differing measurement practices, global and hemispheric time series extending into the nineteenth century should be used circumspectly.

3.2.2. Space-Based Observations Features that vary slowly in time, such as sea surface temperatures (SSTs), will not be affected by local daily variations as occurs with the land temperatures. Furthermore, sea surface temperatures are not as seriously affected by viewing geometry (relatively homogeneous terrain and surface) as may be the case with other surface features such as snow cover or vegetation. Additionally, and probably of greatest importance, the measured radiances can be more easily calibrated to surface-based measurements than to land-based skin temperatures because the skin temperature of the ocean is more uniform in time and space.

The National Environmental Satellite Data and Information service (NESDIS) SST product is tuned to a set of geographically diverse buoy measurements of ocean temperature [*Strong and McClain*, 1984]. These buoys measure the SST generally about 1.0m below the sea surface. Gross errors in buoy temperatures are detected by quality control measures, but if there is a small or gradually changing bias associated with the calibration of the buoy measurements (drifting buoys have been known to have calibration problems), this will be translated into a bias in the space-based observations. Furthermore, the radiometer aboard the satellite senses skin radiances, not subsurface radiances. Fortunately, the upper 1 m of the ocean is usually well mixed, but recent work [*Emery*, 1989] suggests calibration of SST based on in situ skin temperature, as opposed to buoys, may improve the product. Differences in excess of 1°C between skin temperature and buoy-derived temperatures are not uncommon with clear skies and calm winds.

Stated briefly, the SST processing consists of three parts: cloud detection, atmospheric correction, and analysis. The cloud detection procedures make use of cloud brightness, cloud spectral characteristics, and differences in spatial coherence between clear and cloudy scenes. Each procedure requires setting thresholds on the value of certain quantities that are used to discriminate cloud-contaminated pixels. The thresholds are determined by trial and error, and their sensitivity to changes in sensor characteristics, observation time, and sensor calibration is unknown. The atmospheric correction is made by regression against combinations of brightness temperature in three thermal infrared window channels [*McClain et al.*, 1985]. The initial coefficients in the regression are derived by simulating the channel radiances for a set of about 70 maritime atmospheric temperature and moisture profiles for which the SST is assumed to be equal to the air temperature at the lowest level of the profile. The sea surface is assumed to have an emissivity (the ratio of the emittance of a given surface at a specified wavelength and emitting temperature to the emittance of an ideal blackbody at the same wavelength and temperature) of 1. To compensate for residual errors that may have occurred, a final step, the tuning of the retrievals against buoy measurements, is done shortly after the launch of each new spacecraft. A coincident (within 25-km and 6-hour spatial and temporal sampling) data set of fixed and drifting buoy measurements of bulk ocean temperatures (bulk temperatures are those measured by conventional in situ instruments) and retrieved SST values from an advanced very high resolution radiometer (AVHRR) is used to derive a regression equation that converts the satellite SST to buoy measurements. This regression is used to remove biases due to inaccurate atmospheric transmittances, undetected cloud and aerosol effects, and the unknown and variable difference between skin temperature and subsurface bulk temperature. An ongoing routine comparison is made between satellite retrievals and buoy observations to monitor the stability of the SST product, identify sensor changes, and provide a smooth transition between satellites [*Strong and McClain*, 1984].

The globally produced satellite-based SST illustrates one of the advantages of space-based SST observations for large-scale climate monitoring. The satellite SST products are generally more spatially comprehensive than surface-based SST measurements, but there still remains some potentially serious geographic and temporal biases. For example, satellite observations of SSTs can only be made in cloud-free areas. Different infrared channels are used during the day compared to night; the presence or absence of sea ice, changes in atmospheric composition, such as those that occur because of volcanic eruptions, and undetected clouds or unanticipated water vapor can all lead to important biases. A recent example of just such a bias is the eruption of El Chichon in April 1982. C. K. Folland et al. (Comments on "Greater global warming revealed by satellite-derived sea surface temperature trends," A. E. Strong, submitted to *Nature*, 1989) provide evidence to suggest that a substantial portion of the rise in temperature detected in the SST satellite analysis of *Strong* [1989] was due to a cool bias in the early portion of the record. The presence of stratospheric aerosols effectively decreases the radiance measured in the infrared. They also argue that there are other biases of unknown origin in the operational SST data on the basis of comparisons with expendable bathythermographs, blended analyses of space-based and surface-based observations, and nighttime marine air temperatures.

One of the greatest strengths of space-based observations also poses a major problem: data volume. Current

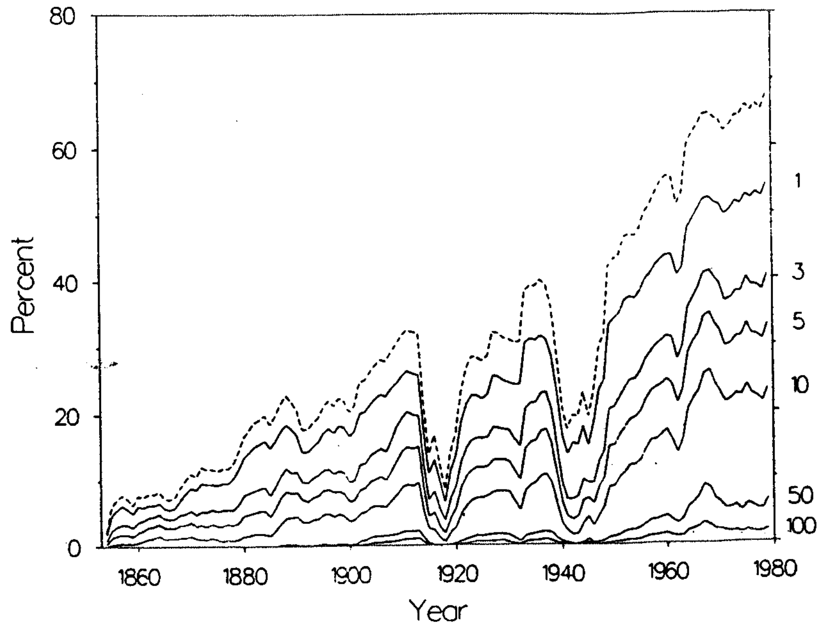


Figure 8. Global (including both land and ocean) percentage of possible year-month 2° boxes per year, containing at least 1, 3, 5, 10, 50, or 100 observations (denoted by the numerals along the right side of the figure) of sea surface temperature (solid curves). The dashed curve is the area-weighted equivalent using boxes containing at least one observation [from *Woodruff et al.*, 1987].

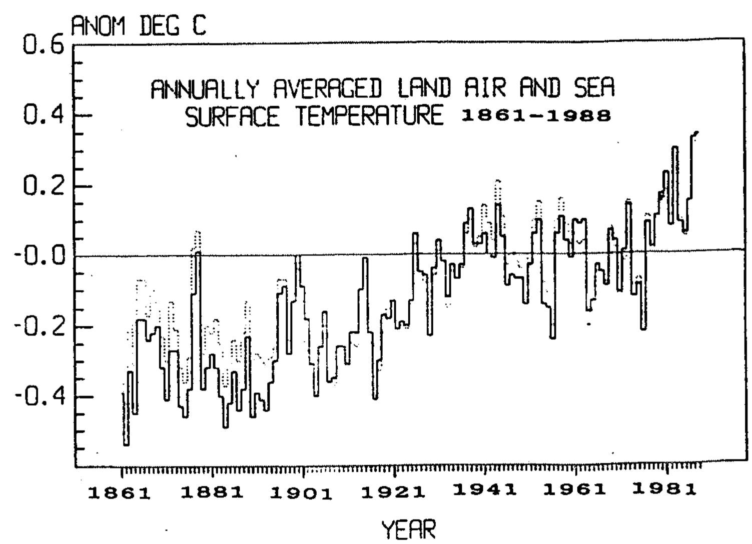


Figure 9. Global temperature estimates (land and ocean) from C. K. Folland and D. E. Parker (personal communication, 1989) (dotted curve) versus *Jones et al.* [1986c] (solid curve).

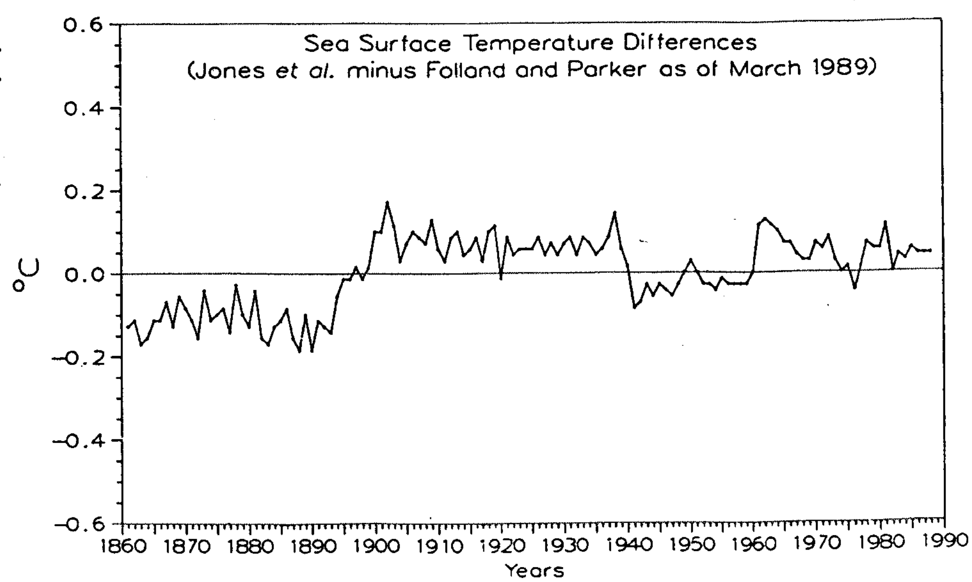


Figure 10. Differences in sea surface temperatures: the values of *Jones et al.* [1986c] minus those of C. K. Folland and D. E. Parker (personal communication, 1989). Differences are standardized to an overall mean difference of 0°C.

satellites are producers of huge quantities of data, and future satellites will produce even more. The data must be carefully compressed to avoid biases and so as not to overwhelm state-of-the-art computer capacities available to most scientists. At the present time, in order to make the most effective use of these data as related to issues of climate change, it will be necessary to merge these data with the conventional surface-based historical record and understand the biases that this merger may introduce into the record.

4. PRECIPITATION

4.1. Land

Precipitation in the form of rain, hail, sleet, snow, and other forms of frozen (or freezing) water is measured by collection in gauges deployed in exposed locations away from trees and buildings. Precipitation in the form of dew, frost, and rime ice (although locally important in some areas) is not generally recorded, except in rare experimental situations. World Meteorological Organization (WMO) guidelines recommend that gauges be at least twice the distance from the nearest building or tree as the height of those obstacles. Gauges are not uniform in design, though generally within each country, relatively few standard designs are employed. The significance of this is that gauges are not equally "efficient" at collecting precipitation. In high winds, turbulence around the gauge may introduce irregularities (usually underestimates) which could result in different readings even between closely separated catchment vessels. Additionally, an estimate of gauge wetting (i.e., precipitation that is not measured because it coats the upper inside surfaces of the gauge) is sometimes added to measured values. There is voluminous literature on these matters, and many studies have been conducted to compare the efficiencies of various gauge designs [e.g., *Rodda*, 1971; *Sevruk*, 1982, 1986, 1987; *Folland*, 1988]. Here we will simply note that gauge accuracy (i.e., the degree to which a gauge records the "true" amount of precipitation falling at a site) does vary with gauge design, with the height of the gauge above the ground, and with other local features. No universally accepted instrument or exposure height has been adopted [cf. *Houghton*, 1985, pp. 296–299]. It is difficult to assess gauge accuracy, since precipitation may vary considerably over small areas and experiments using a closely spaced network of identical gauges have revealed differences in gauged precipitation of 50% or more [*Sevruk*, 1987]. Notwithstanding these problems, precipitation data reported by each country are generally accepted as the best available estimate of precipitation amounts for that region. We should bear in mind, however, that regional trends in precipitation may be in error if new gauge designs are introduced and systematic changes occur in gauge siting (e.g., a general change from poorly exposed sites to open treeless areas would produce an apparent increase of precipitation) without provision for adjusting the new measurements to the old ones. It is known, for example, that in Canada and the Soviet Union, new gauge designs as well as changes in mesurement practices were introduced sometime after 1960 [*Bradley and England*, 1978; *Vinnikov et al.*, 1989]. In the United Kingdom, changes in exposure over the last 40 years have occurred because of the introduction of "turf wall" (a circular embankment of soil around the gauge to reduce wind deformation) gauges in exposed areas.

Precipitation in the form of snow is particularly problematical [*Goodison*, 1981]. In the United States the guidelines for measuring snow water equivalent amounts (i.e., the melted catch) stipulate that the snow be either weighed (to determine its mass) or melted and then measured as water. If this is impractical, a general rule is applied to convert snow depth to water equivalent by using a ratio of 10 to 1. This is an average figure, however, since snow density does vary significantly from dry, cold snowfall events (density of less than 0.1) to warm, wet snowfalls (density of greater than 0.1). In the past, observers may have used a combination of methods, based on their experience and the snowfall event in question. In parts of the western United States and some other mountainous regions of the world, snow course data (standard networks of snow depth and snow density measurements) are used in place of conventional precipitation gauge data. In rare cases (generally experimental watersheds), snow pillows (weighing platforms) provide additional cumulative snowfall data. Compared to nonsnowy land areas, there is far less certainty about precipitation in those regions of the world where snowfall is an important component of annual totals. The problem is compounded in snow-covered regions by blowing snow. Measured snowfall amounts may, in part, reflect previously deposited snow, creating further uncertainty. In Europe and the Soviet Union, various types of shields have been used with precipitation gauges. Without appropriate adjustments, such changes can lead to inaccurate assessments of actual trends. Studies of Canadian precipitation and river runoff data clearly demonstrate that in northern regions, where snowfall is important, measured precipitation amounts are underestimated, since runoff is higher than would be expected from recorded data [*Hare and Hay*, 1971]. Another problem that has been noted in Arctic precipitation measurements concerns the recording of trace amounts (i.e., amounts too small to measure). Trace amounts are often recorded several times a day during synoptic observing periods, with the daily total also recorded as a trace. The sum of several trace amounts of precipitation in the Arctic can still be a trace amount. However, where trace amounts are very common, studies indicate that this procedure may result in underestimates of annual precipitation amounts by as much as 26% [*Jackson*, 1960; *Bradley and England*, 1978].

A calendar month is normally used as the minimum sampling interval for climate studies. Data can then be aggregated into seasonal and annual totals. Daily and hourly precipitation rates can also be of interest in terms of "event size" frequency analysis. It is conceivable that climate change could affect the climatology of these events with or without an appreciable impact on the total precipitation [*May and Hitch*, 1989]. Rainfall rate data (e.g., millimeters per hour) derived from automatic-recording gauges (tipping bucket systems coupled to a digital or analog event recorder) are not generally available on a global basis. For some applications, however, continuous gauging of precipitation, for instance, over critical watersheds for purposes of flood monitoring or water supply forecasting, is of critical importance.

The question of how many stations are sufficient to serve as a monitoring network for studying climatic change has been grappled with for many decades [*Gandin*, 1970; *WMO*, 1985]. There is no universally applicable solution to this problem, since topographic variations and climatological processes both play a role. Operational factors must also be taken into account, as well as the historical record for the area in question. Because precipitation is characteristically more spatially variable than temperature, a denser network of recording stations is required to obtain representative regional estimates. Most investigators have based their analysis of long-term variations in precipitation on averages from as many stations as possible [*Bradley*, 1976; *Nicholson*, 1981, 1986; *Diaz and Quayle*, 1980; *Barnett*, 1985; *Diaz*, 1986; *Bradley et al.*, 1987; *Diaz et al.*, 1989]. The objective in most of these studies has been to obtain estimates which maximize the signal (low frequency) to noise (high frequency) in the record of each region [cf. *Wigley and Jones*, 1981].

The need for a compilation of worldwide weather data was recognized earlier this century and led to compilations of data by the Smithsonian Institution. The first of these summaries, containing many nineteenth century records from the United States and other countries, was published in 1927, with subsequent updates occurring in 1934 and 1947. Since then, periodic updates to precipitation, temperature, and pressure data have been published in decadal increments in WWR as noted in the discussion on temperature. These data and additional station records are retained in computer form as the World Monthly Surface Station Climatology (WMSSC) data set.

Similar to the thermometric data, the individual station records that make up this precipitation data collection may not be homogeneous. Techniques have been developed to assess the homogeneity of precipitation data [*Kohler*, 1949; *Mitchell*, 1961]. They rely on the basic assumption that precipitation at one location maintains a constant ratio to a composite index of precipitation at a network of nearby stations [cf. *Bradley*, 1976, p. 29]. Typically, however, global precipitation networks are not sufficiently dense to allow one to assess the reliability of a particular record by comparison with adjacent station records. And even where there are relatively dense long-term networks (as in the United States), there is rarely a sufficiently dense amount of digitized records available to conduct homogeneity tests for large areas. This problem is particularly acute in those areas where the spatial variability of precipitation is high. One alternative would be to study precipitation trends at only a few "benchmark" climatological stations [cf. *Karl and Quayle*, 1988], which have been selected as being relatively free of biases which produce inhomogeneities in their records. However, because there are few such stations, one then has to deal with problems associated with data representativeness. At the present time, very few comprehensive large-scale assessments of precipitation data homogeneity have been carried out, the general approach being to average a large number of station records for a given region and assume that data inhomogeneity problems at individual stations are randomly distributed in time and are not cumulative. This may be a reasonable assumption for many causes of inhomogeneity, but it is perhaps less justifiable where systematic changes in instrumentation were introduced over wide areas at the same time, or where urbanization changes might have affected a large number of stations in a region. In spite of these potential problems the WMSSC data set represents the world's primary source of historical temperature and precipitation information at the monthly, as well as at longer, time scales [e.g., *Kraus*, 11955; *Barnett*, 1985; *Bradley et al.*, 1987; *Diaz et al.*, 1989].

While about 9000 monthly station precipitation summaries are compiled for the United States alone, only about 1250 stations worldwide are designated as GTS international exchange stations for monthly data [*Ropelewski et al.*, 1985]. The criteria generally used in the selection of these stations for global climate monitoring are (1) the availability of GTS transmission capability, (2) consistent data reliability from past experience, and (3) the availability of sufficiently long records (>30 years) to provide reasonable statistics that would permit expressing the "real-time" data in the form of anomalies. Unfortunately, the density of these stations is not equally distributed over the global land masses; for example, no stations are found in Mexico, Nigeria, Indonesia, etc. (see Figure 11). Notwithstanding this bias, this network provides a quasi-global view of precipitation and temperature data for the land areas of the world (about 60 stations are island locations or quasi-stationary ocean weather

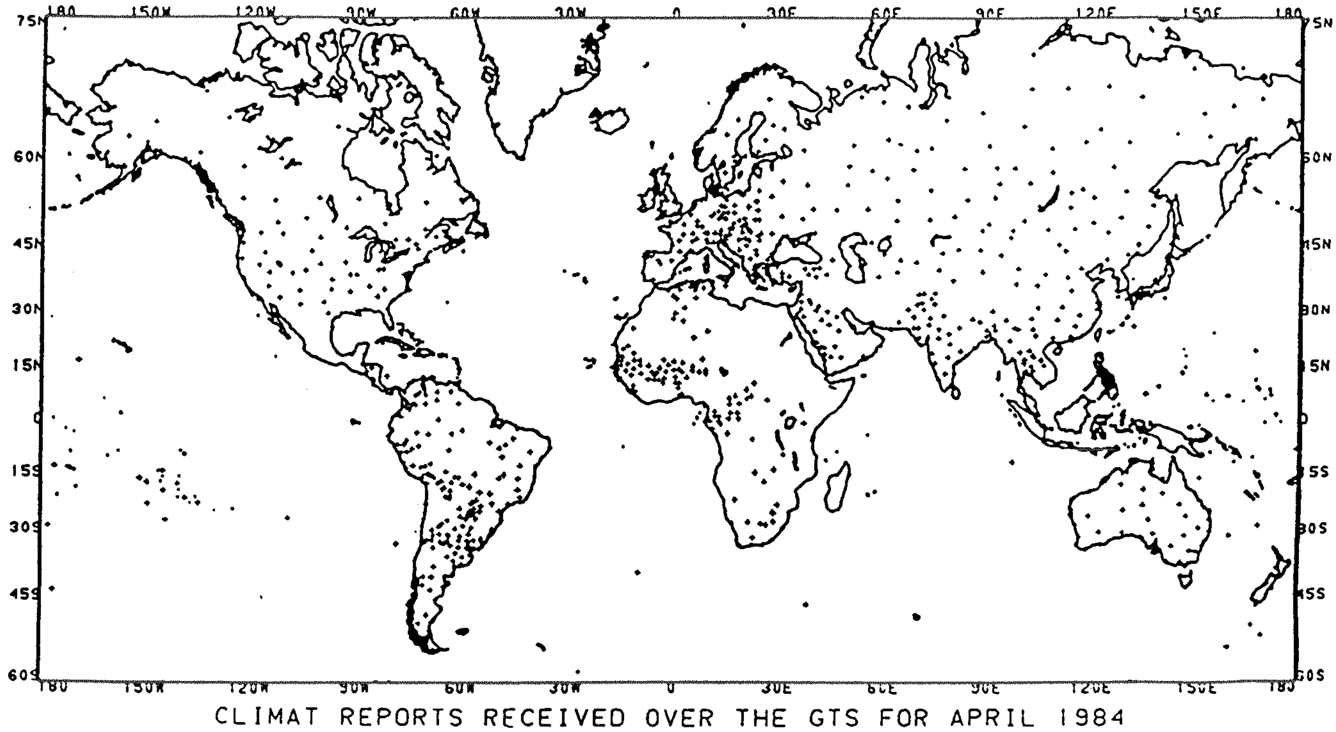


Figure 11. Locations of stations which exchange monthly climate summary messages (CLIMAT reports) on a routine basis based on April 1984 reports [from *Ropelewski et al.*, 1985].

ships) within about 1 week after the end of each month. However, in practice, only about two thirds of the monthly climate summaries (CLIMAT reports) from these 1250 stations are received at the U.S. National Meteorological Center within a few weeks following the end of each month (C. Ropelewski, personal communication, 1989). Delays in obtaining data from some areas (principally tropical regions) are not uncommon. Corrections and amendments to the original transmissions may occur sporadically over subsequent months.

Most of the reports in the MCDW publication are the same as those received via the GTS. However, as many as 20% additional unique monthly summaries may be received by mail. CLIMAT data are relatively "untouched," in the sense that only a minimum of quality control is performed on them. This involves simple checking for gross errors (e.g., unrepresentative departures from average) during data processing. It is assumed that data quality control is performed prior to data transmission from each country, but this may not always be the case.

WWR was last produced for all countries for the decade 1961–1970. An update for the 1970s has been completed for only two world regions; for the rest of the world, this important publication remains to be updated. Some indication of the problems of obtaining reliable up-to-date precipitation data is given by the available data coverage for different regions of the world reported by *Bradley et al.* [1987] and *Diaz et al.* [1989] (Figure 12). Similar to the thermometric data, precipitation data coverage has declined markedly in the last 2 decades. Since a dense network is particularly important for detecting changes in precipitation, delays and data gaps raise important questions about our ability to place contemporary climatic conditions in a reliable long-term framework.

The use of monthly totals as the minimum unit eliminates some of the synoptic scale variability resulting from individual events. Data from individual stations may be used to derive precipitation statistics for larger areas or may form the basis of an index of water availability. For the United States, NCDC routinely produces divisional statistics for large watershed areas as well as statewide and larger regional averages. The state and regional means are derived from area-weighted averages of divisional data that are in turn the simple arithmetic average of all the reporting stations within that division [*Diaz and Quayle*, 1980]. Provided the network has remained approximately constant, these regional statistics can yield a relative measure of interannual and interseasonal changes in precipitation. Figure 13 shows such a record for the contiguous United States.

Radar estimating techniques have improved tremendously over the past 20 years, but they are useful only at ranges of about 150 km and may vary significantly from gauged values [*Browning and Collier*, this issue].

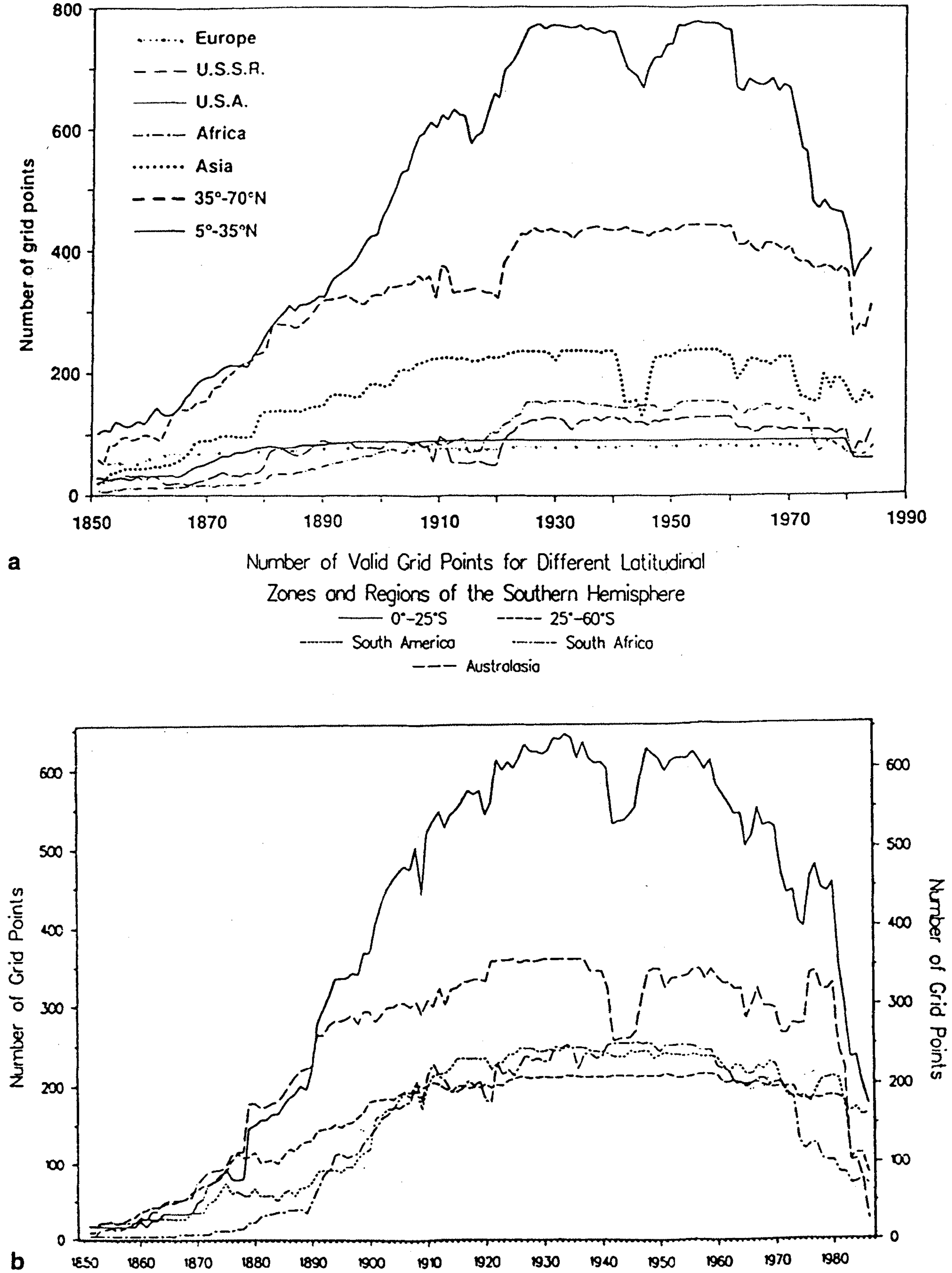


Figure 12. The changes in the areal coverage of grid points with data (400 × 400 km) available for various regions of the globe. A maximum of about 1600 grid points could be computed for each hemisphere.

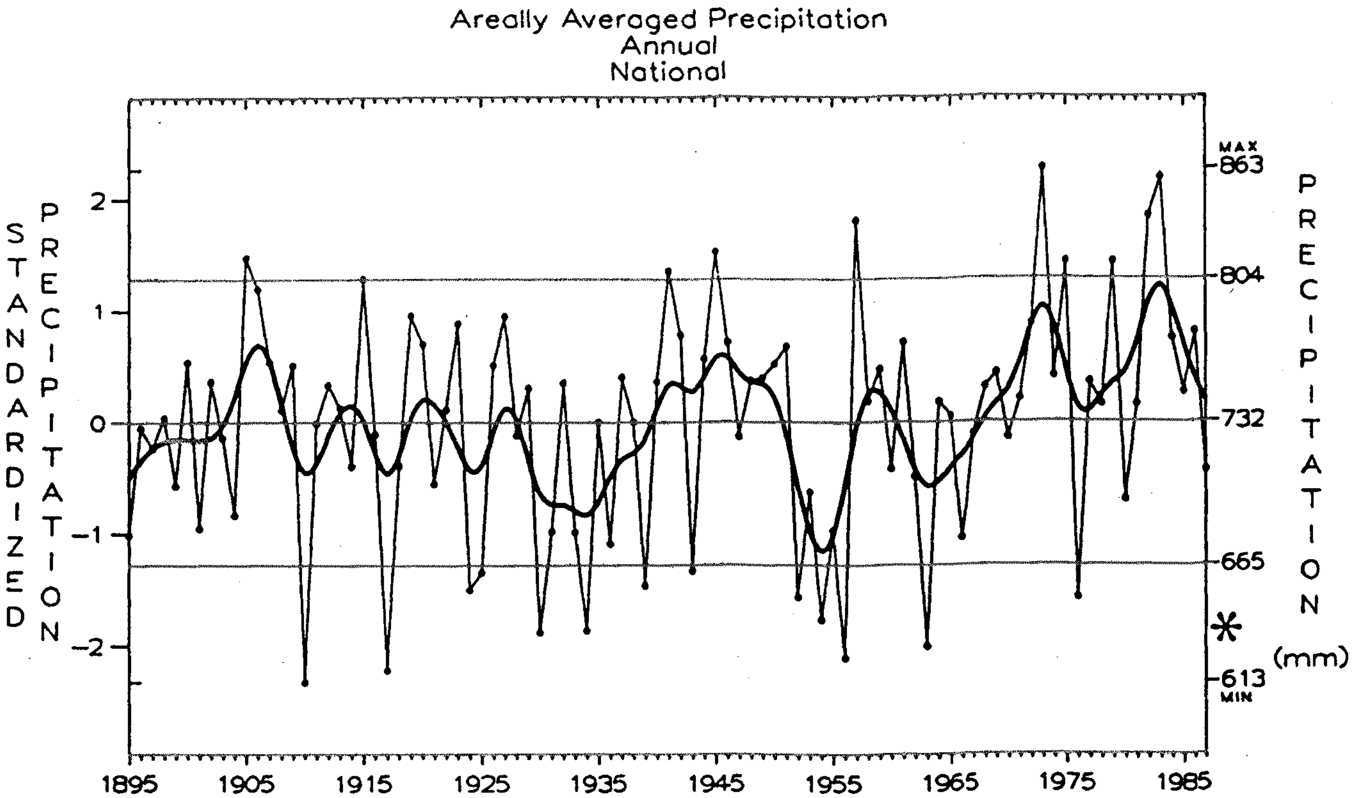


Figure 13. Precipitation in the United States since 1895. Data are based on area averages using arithmetic averages of precipitation within each state's climate division (an area of relatively homogeneous climate anomalies). The asterisk represents the preliminary value for 1988. The smoothed curve is a nine-point binomial filter with overlapping endpoints. Standardized values are based on the gamma distribution. Solid horizontal lines represent -1.28, 0.00, and +1.28 standardized departures (or the 10th, 50th, and 90th percentiles of the gamma distribution).

Well-calibrated, very dense radar networks would be too expensive for the purpose of providing global precipitation coverage.

4.2. Sea

4.2.1. Surface-Based Observations As our understanding of the climate system has improved, the need has grown for the development of more comprehensive real-time observational systems for measuring global precipitation. Surface-based precipitation measurements over the ocean are not recorded operationally, but some studies have used the present weather synoptic weather code to estimate open ocean rainfall [cf. *Jaeger*, 1983; *Elliot and Reed*, 1984]. The only real prospect for eventually achieving a global precipitation monitoring network is via careful interpretation of satellite-derived data, assisted by the ongoing development of buoy-based sensors.

4.2.2. Space-Based Observations Over the past decade or so, efforts at estimating precipitation amounts by remote sensing techniques have had some degree of success [*Kilonsky and Ramage*, 1976; *Adler and Negri*, 1987; *Griffith et al.*, 1978; *Hudlow*, 1979; *Krueger and Gruber*, 1984]. One of the most promising measuring platforms to observe precipitation on very large scales is the proposed Tropical Rainfall Measuring Mission (TRMM) satellite, which is planned for an operational life of at least 3 years, starting in the mid-1990s. The major scientific goal for this mission is to determine the monthly average distribution and variability of precipitation and latent heat release over areas of about 10^5 km^2 spatial resolution for use in improving short-term climate models and global circulation models and in understanding the hydrological cycle, particularly as it is affected by tropical oceanic rainfall [*Simpson et al.*, 1988; *Rasmusson and Arkin*, 1985].

While satellite remote sensing procedures offer a great deal of promise for the future, they have until now been hampered by a number of factors, including problems with calibration against ground data and other difficulties related to sampling frequency. The biggest problems regarding the interpretation of the satellite imagery are found outside the tropics, where different types of clouds, with differing brightness temperatures and underlying surfaces, can affect the results. For example, passive and even active microwave measurements will continue to be instantaneous measurements for the foreseeable future, whereas rainfall is a continuous process. A major sampling problem will be inherent in the use of the data to monitor climate [*Wilheit*, 1987].

In the context of present planning the TRMM satellite program is expected to have strong international cooperation and close connections with the tropical Ocean-Global Atmosphere (TOGA) program, providing critical information for the design and implementation of the Global Energy and Water Cycle Experiment (GEWEX) that is planned for around the turn of the century [*Simpson et al.*, 1988]. The World Climate Program has established a Global Precipitation Climatology Project (GPCP) for the purpose of developing an adequate climatology of global precipitation [*WMO*, 1986]. Begun in 1987, it is expected to integrate precipitation data from GOES, POES, radar, the operational network of rain gauges over land areas, and any available "ground truth" measurements over the oceans. The organizational structure for implementation of these various observational and data management programs is presently evolving. The reader is referred to *WMO* [1986] for an introduction to the issues, organizations, and scientists currently involved. Much of the scientific basis for this program has been developed in a paper relating satellite-derived cloud top temperatures to tropical rainfall [*Arkin and Meisner*, 1987].

Remote sensing techniques may offer significant improvements over those of the conventional observational network for both the temporal and the spatial resolution of precipitation measurements. However, this remains to be established; in any case, programs such as TRMM are still several years in the future, and they will need to operate for many years or even decades to provide an adequate background climatology. This type of long-term satellite operation is unlikely. For now the maintenance and upgrading of the present system of global observations, coupled with improvements in access and communication capabilities among WMO member countries, offer an interim solution to the problem of monitoring and detecting change in precipitation.

5. SNOW COVER AND SEA ICE

5.1. Background

Snow and ice are highly variable on scales of days to years. These fluctuations, along with the unique physical characteristics of these cryospheric elements, make them critical components of the climate system [*Barry*, 1985]. The extent, concentration, thickness, and surface albedo of sea ice regulate the exchange of heat, moisture, and momentum between the ocean and the atmosphere, influencing circulations within both systems [*Walsh*, 1983; *Crane*, 1983; *National Research Council*, 1984]. The low heat conductivity, high thermal emissivity, low vapor pressure, and high shortwave albedo of snow differ greatly from snow-free land. Accurate and complete information on the spatial extent and physical state of snow and ice is necessary to gain an improved understanding of cryosphere-climate interactions and of the role snow and sea ice may play in any regional and global climate change. The data bases of snow and ice conditions and their quality and longevity are of particular interest here.

The World Data Center A (WDCA) for Glaciology is the recommended place to begin a search for regional or global snow and ice products. The center is colocated with the U.S. National Snow and Ice Data Center at the University of Colorado, Boulder. Much of the data, particularly the older products, are in hard copy format. However, global products, such as the NOAA snow charts, Navy/NOAA ice charts, and NASA ice and snow charts, are available digitally. In addition, the Colorado Center also serves as the archive for U.S. Defense Meteorological Satellite Program hard copy imagery from the mid-1970s to present (daily imagery which is quite useful for charting snow and ice) and has recently begun archiving microwave sea ice products from the Special Sensor Microwave/Imager which was launched in 1987 [*Weaver et al.*, 1987]. Along with the WDCA the World Data Centers for Glaciology at the Scott Polar Research Institute (WDCC), Cambridge, England; at Moscow, USSR (WDCB); and at Lanzhou, China (WDCD) are excellent sources for published references on snow and ice. Various national climate archives have raw station data and some summarized processed products, although much of the data are unverified. In most cases, data are on paper or microfiche, some of which is also digitized and available on computer tapes, diskettes, and CD ROM.

5.2. Snow Cover

5.2.1. Surface-Based Observations Surface-based observations of snow cover are of a sufficient density for climatological study in the lower elevations of the middle latitudes. Elsewhere, data are spotty at best. There is no hemispheric snow cover product based entirely on station reports. The U.S. Air Force global snow depth product relies primarily on surface-based observations as input into a numerical model which creates daily charts with global coverage [*Hall*, 1986]. Disadvantages include having to rely on extrapolations and climatology in data-sparse regions [*McGuffie and Robinson*, 1988]. The utility of these charts in climatological studies is severely limited because the analyst does not know where actual data and estimated data are used. On a regional scale, NOAA daily weather charts and *Weekly Weather and Crop Bulletin* (WWCB) snow cover charts are produced for the United States, but neither of these products is of a particularly high resolution.

There have been a number of regional snow cover products over the years which are based on station data. Of greatest longevity are the WWCB U.S. charts which cover the conterminous United States and have been produced since 1935. Unfortunately, since December 1983, no attempt has been made to estimate the position of the snow line. Only point data for those stations reporting snow cover are given. This is a major limitation, as the charts give no indication as to where the snow-free stations are located.

Observations used in the preparation of WWCB and other regional charts are generally from primary stations supplemented with secondary or cooperative station reports. While they are among the most complete and accurate over the long term, the consistency of primary station observations suffers from the numerous station relocations from cities to airports in the middle part of this century (particularly in the United States). Potential influences of urbanization on the depth and duration of snow on the ground also must be considered. To date, no comprehensive study has been done on either of these subjects.

In a number of countries there are numerous secondary stations with relatively complete records of snow extending back 50 years or more. Most data, however, remain unverified and disorganized [*Robinson*, 1989]. As a result, few studies have dealt with long-term trends or low-frequency fluctuations of snow over even small regions [*Arakawa*, 1957; *Manley*, 1969; *Jackson*, 1978; *Pfister*, 1985; *Robinson*, 1987].

5.2.2. Space-Based Observations Data recorded in the visible, near-infrared, and microwave wavelengths on GOES and POES are used to produce several snow cover products [cf. *Hall and Martinec*, 1985]. The visible and near-infrared data provide continental coverage with a relatively high spatial resolution. Snow is identified by recognizing characteristic textured surface features and brightnesses. Information on surface albedo and percent snow coverage (patchiness) may also be gleaned from the data. Shortcomings include the inability to detect snow cover when solar illumination is low or when skies are cloudy and the lack of all but the most general information on snow depth [*Kukla and Robinson*, 1981; *Dewey and Heim*, 1982; *Dewey*, 1987].

At present, NOAA produces the only hemispheric (northern) snow chart. Weekly charts are constructed by a manual analysis of satellite imagery. They portray the extent of relatively complete snow cover and areas of patchy cover. Chart accuracy is poorest in the autumn, when clouds are spatially and temporally ubiquitous [*Wiesnet et al.*, 1987]. The NOAA weekly snow charts have been produced since 1966. Unfortunately, the quality of the charts has not remained constant throughout this period, and the inaccuracies imposed by cloudiness have persisted [*Kukla and Gavin*, 1984; *Matson et al.*, 1986]. The NOAA charts should not be used to establish climatological means in the autumn or summer and must be used with caution when investigating trends, cycles, or low-frequency events.

Clouds and low solar illumination are not problems when using microwave data to chart snow cover. The recognition of snow results from differences in the emissivity of snow-covered and snow-free surfaces. There is some indication that information on depth and liquid water content can be obtained, although the accuracy of such output remains uncertain. It is difficult to identify shallow or wet snow using microwaves, and no direct information on surface albedo can be obtained. NASA has recently completed a 10-year data set of midmonth global snow cover which includes estimates of snow depth. The snow cover data should be of use in climate change studies, particularly when used in conjunction with the NOAA snow product. The reliability of the snow depth information remains unclear.

The high variability of snow (and sea ice) make long-term data sets a necessity when investigating means, trends, low-frequency events, or interactions of snow and ice with other climatic elements. Unfortunately, consistent decades-long data sets of snow and ice are scarce [*Barry and Armstrong*, 1987]. Satellite-derived snow and ice charts are only available from the late 1960s on. Thus only regional information from station and aircraft data is available for a period exceeding approximately 20 years. In all cases, limitations in the gathering, quality controlling, archiving, and synthesizing of cryospheric data must be considered before applying the data in long-term climatological investigations.

5.3. Sea Ice

Observations of sea ice are made from shore stations, ships, aircraft, and satellites. The former three are quite limited in scope, particularly outside of the North Atlantic and subpolar seas. Satellite analyses of sea ice provide much more extensive coverage. Visible and near-infrared data are interpreted manually, with ice recognized by its characteristic textured surface features and brightness. However, clouds often obscure the surface, and distinguishing ice cover from clouds is frequently difficult. The age and concentration of the ice and the distribution of snow cover atop the ice may also be estimated from analyses of visible imagery by trained observers. Low solar illumination in the polar regions during winter limits the utility of the data. Infrared data provide information on ice extent and concentration. Clouds are a problem in the infrared, but low illumination is not.

Radar (active monitoring systems) provides detailed information on ice pack extent and physical characteristics, regardless of the weather or solar illumination. This is due to the different backscattering characteristics of water and various types of ice. Studies to date have used aircraft platforms, with satellite observations to follow in the future [*Hall and Martinec*, 1985].

Passive microwave sensors on board polar orbiting satellites provide information on ice extent and concentration regardless of cloud conditions or illumination. Information on ice age can be derived for most of the year in the Arctic as a result of different emissivities of the first year and multiyear ice, but not in the southern ocean where emissivities vary little with ice age [*Zwally et al.*, 1983; *Cavalieri et al.*, 1984]. The relatively low resolution (several tens of kilometers) of the passive sensors makes studies of ice movement and the structure of climatically important leads (ice-free gapsor fractures) difficult [*Hall and Martinec*, 1985].

There is only one global ice product produced on a regular basis. The U.S. Navy/NOAA Joint Ice Center compiles weekly ice charts for the Arctic and Antarctic. While shore, ship, and aerial reports provide spot data for the charts (mostly in the northern hemisphere), the bulk of the input is provided by satellite data [*Godin*, 1981]. This includes manually interpreted visible and infrared imagery and microwave-derived ice products. These charts report ice extent, concentration, and age with a sufficient accuracy for climate studies [*Kukla and Robinson*, 1981]. Reflectivity is not reported, nor is any information given on the thickness and state of the snow on the ice.

Navy/NOAA hemispheric sea ice charts have been providing data of a sufficient accuracy for large regional and global climate studies since 1972. Data quality has been rather consistent throughout this period, although the charting of concentration switched from a system of eighths to tenths in 1980.

Long-term regional charting efforts in the northern hemisphere include those of the British, Danish, Canadians, and Soviets [*Crane*, 1979]. Danish charts for a number of Arctic areas extend back to the turn of the century, and Soviet charts of the eastern Arctic Basin began in 1937. Before using any of these products in long-term studies, detailed information of charting methodology and consistency through time must be considered. Compilations of northern hemisphere ice data from various international sources include those of *Kelly* [1979] covering 1901–1956 and those of *Walsh* [1978] which include the years 1953–1976. Antarctic ice information prior to 1973 can only be obtained from scattered expeditions and whaling parties and is of limited use in quantitative climate studies.

6. VEGETATION

Increasingly, climatologists are giving more attention to the interaction between the biota and the climate. Not only does the plant community respond to climate, but also, changes in plant transpiration and albedo have feedback effects which are important properties of the climate system. In this context a relatively new satellite-derived product has been developed to monitor the extent, density, and vigor of land vegetation. The satellite-derived product has been called the vegetation index (VI).

It is illustrative to consider in some detail how such a product is produced. The VI is derived from the AVHRR and is a very simple measure of scene "greenness." It has been the subject of considerable study over the past few years [cf. *Malingreau*, 1986; *Justice*, 1986]. The most common VI is the normalized difference (NDVI) which is calculated from the equation NDVI = (CH2 - CH1)/(CH2 + CH1), where CH1 and CH2 are the AVHRR channel 1 (0.58–0.68 μm) and channel 2 (0.70–1.10 μm) reflectivity, respectively. Vegetation reflectance is higher in the near-infrared than in the visible band, and the differential reflectance in the two bands is a measure of the vigor and density of green vegetation. Clouds, water, and snow have a higher reflectance in the visible than in the near infrared, so for these surfaces NDVI is negative. Soil and rock have reflectances that are similar in both bands and result in small NDVI values. The NDVI is an index that reduces the contribution of viewing geometry, terrain features, and illumination condition to the variance of the differential reflectance.

Typically, the VI is processed into a mapped data base that has a significantly lower resolution than the original AVHRR data. Each location on the map represents an area on the Earth that contains several (usually 10–40) pixels of AVHRR data. The mapping procedure requires selection of a value of the VI that is representative of that area. An additional complicating factor is the presence of clouds in the observed scene. Most VI processing systems have methods for detecting and eliminating cloud-contaminated pixels from the data. Each method introduces a different bias into the final VI product.

Clouds in an AVHRR pixel reduce the value of NDVI below its clear value. This property of clouds often is used to detect and eliminate cloud-contaminated pixels by maximum greenness compositing. If this procedure is applied in the daily mapping process, that is, if the greenest pixel is the one mapped to a given map cell, then for partly cloudy scenes the map will be constructed from the clearest pixels. This process effectively screens clouds and produces a daily vegetation map with the minimum cloud contamination. On clear days, however, maximum greenness compositing selects out the pixel with the greenest vegetation to represent the whole area in the daily map. In mixed scenes the greenest pixel may not be representative. Irrigated land will be selected over surrounding arid land; forested pixels will be selected over croplands; and agricultural areas will be selected over fallow land. There is a substantial apparent greening of the Earth when this cloud-screening method is used.

The current NESDIS operational VI is not cloud-screened in the daily mapping process. Each map cell contains a single pixel value that is selected in a nearly random way from the pixels that map to the cell. The method used is to retain in each map cell the last pixel that maps to that cell. If the Earth location of the data were perfect, then the final mapped pixel would be in the corner of the cell that is seen last as the AVHRR scans the scene. In fact, the jitter in the navigation causes the last mapped pixel to move from day to day over an area equivalent to the uncertainty in the Earth location. Cloud screening is done with 7-day maximum VI composites from the daily maps. For each 7-day compositing period, only the largest VI is retained at each map location. This eliminates clouds from the composite except at locations that were cloud-covered for all 7 days. It is not quite a random sampling of the data because if several days are clear, then the compositing selects the greenest area out of the several sampled. A longer compositing period increases the bias while at the same time decreasing cloud contamination.

Other cloud-screening methods bias the result in different ways. Selection based on temperature (map the warmest) biases in favor of less vegetated scenes because during the day, vegetation is cooler than the surrounding bare soil. Saving the pixels corresponding to the darkest channel 1 value biases in favor of the pixels containing the most water (lakes, rivers).

Any climatological study making use of quantities, such as VI, derived from the visible and infrared channels must take into account the postlaunch stability of the instrument. Sensor drift may be as large as 10–20% over the lifetime of a spacecraft.

The VI and NDVI data are currently being saved on magnetic tape at the NCDC. Several years of data have now been retained. Presently, these data cannot be used to determine changes in climate because the record is too short, and the calibration problems are unresolved. But, as this data base continues to grow, it may provide a useful integrated proxy of climate change. Today, the data are particularly useful in understanding the annual variations of vegetative changes and their feedback to the climate system.

7. CONCLUSIONS AND RECOMMENDATIONS

Reliable observational data are essential for analyzing the climate record and verifying the predictions of our complex mathematical climate models. In recent years, heightened awareness regarding climate change and variability has challenged our ability to construct meaningful data sets of various climate elements. New technology has provided us with the means to access and distribute much of this data, but the science required to integrate data from various sources and measurement techniques is still in the process of maturing. With careful analysis the recent climate record, as it now exists over the past century, can tell us the general trend of global, hemispheric, or zonal near-surface air temperature. It can also reveal the general distribution and the sign of the trend of precipitation over land. For some areas of the world it can also yield valuable information on local and regional climate. It cannot yet tell us the precise magnitude of these trends or changes.

Robust model data analyses will require an improved climatic data base to determine the appropriate sensitivity of the model predictions. To this end, weather-observing programs must become more cognizant of the requirements for monitoring climate change. Ongoing observational programs need to be continued to assure long-term homogeneous records well into the twenty-first century. In addition, global scale data rescue efforts will be required to retrieve and digitize historical records before they self-destruct via acid-induced decomposition [*Committee on Preservation of Historical Records*, 1986]. Improved analytical tools will be needed to remove biases, including globally coordinated urbanization studies and improved benchmarking of marine data. The marriage of space-based satellite observations with traditional surface-based observations offers the potential to significantly reduce our uncertainties in the climate record.

Data of critical importance must be stored and retrieved in such a way that it is accessible to many scientists. This is particularly important for high-volume data generators such as satellites. In the absence of invariant climate laws the robustness of research results is derived partly from the many and varied applications of the data. Readily accessible sources of climatic data are required to achieve consensus among many scientists analyzing the data in various ways.

ACKNOWLEDGMENTS. This work was supported by the National Oceanic and Atmospheric Administration, the U.S. Department of Carbon Dioxide Research Division's grant DE-FG0285ER60372, and the National Science Foundation Atmospheric science grants ATM 89-96113, ATM 89-96114, and ATM87-19865. We also thank our reviewers who helped us clarify a number of issues.

Ann Henderson-Sellers was the editor responsible for this paper. She thanks Roger Barry, Roy Jenne, and an anonymous reviewer for their assistance.

REFERENCES

Adler, R. F., and A. J. Negri, A satellite infrared technique to estimate tropical convective and stratiform rainform, *J. Clim. Appl. Meteorol.*, *26*, 1553–1564, 1987.

Arakawa, H., Climatic change as revealed by the data from the Far East, *Weather*, *12*, 46–51, 1957.

Arkin, P. A., and B. N. Meisner, The relationship between large-scale convective rainfall and cold cloud over the western hemisphere during 1982–84, *Mon. Weather Rev.*, *115*, 51–74, 1987.

Barnett, T. P., Long-term changes in precipitation patterns, Detecting the Climatic Effects of Increasing Carbon Dioxide, edited by M. C. MacCracken and F. M. Luther, *Rep. DOE/ER-0235*, pp. 149–162, U.S. Dep. of Energy, Washington, D. C., 1985.

Barry, R. G., The cyrosphere and climate change, Detecting the Climatic Effects of Increasing Carbon Dioxide, edited by M. C. MacCracken and F. M. Luther, *Rep. DOE/ER-0235*, pp. 109–148, U.S. Dep. of Energy, Washington, D. C., 1985.

Barry, R. G., and R. L. Armstrong, Snow cover data management: The role of WDC-A for glaciology, *Hydrol. Sci. J.*, *32*, 281–296, 1987.

Bigelow, F. H., Report on the temperature and vapor tension of the United States reduced to a homogeneous system of 24-hourly observations for the 33-year period, 1873–1905, *U.S. Weather Bur. Bull. S*, Washington, D. C., 1909.

Bottomley, M., C. K. Folland, J. Hsiung, R. E. Newell, and D. E. Parker, *Global Ocean Surface Temperature Atlas (GOSTA)*, British Meteorological Office, Bracknell, England, in press, 1989.

Bradley, R. S., *Precipitation History of the Rocky Mountain States*, 334 pp., Westview Press, Boulder, Colo., 1976.

Bradley, R. S., and J. England, Recent climatic fluctuations of the Canadian High Arctic and their significance for glaciology, *Arct. Alp. Res.*, *10*, 715–731, 1978.

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

Browning, K. A., and C. G. Collier, Nowcasting of precipitating systems, *Rev. Geophys.*, this issue.

Cavalieri, D. J., P. Gloersen, and W. J. Campbell, Determination of sea ice parameters with the Nimbus 7 SMMR, *J. Geophys. Res.*, *89*, 5355–5369, 1984.

Committee on Preservation of Historical Records, *Preservation of Historical Records*, 128 pp., National Academy Press, Washington, D. C., 1986.

Crane, R. G., Inventory of snow cover and sea ice data. *Glaciol. Data Rep. GD-7*, 171 pp., World Data Cent. A for Glaciol., Univ. of Colo., Boulder, 1979.

Crane, R. G., Atmosphere-sea ice interactions in the Beaufort/ Chukchi Sea and in the European sector of the Arctic, *J. Geophys. Res.*, *88*, 4505–4523, 1983.

Dewey, K. F., Satellite-derived maps of snow cover frequency for the northern hemisphere, *J. Clim. Appl. Meteorol.*, *26*, 1210–1229, 1987.

Dewey, K. F., and R. Heim, Jr., A digital archive of northern hemisphere snow cover, November 1966 through December 1980, *Bull. . Meteorol. Soc.*, *63*, 1132–1141, 1982.

Diaz, H. F., An analysis of twentieth century climate fluctuations in northern North America, *J. Clim. Appl. Meteorol.*, *25*, 1625–1657, 1986.

Diaz, H. F., and R. G. Quayle, The climate of the United States since 1895: Spatial and temporal changes, *Mon. Weather Rev.*, *108*, 249–266, 1980.

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

Elliot, W. P., and R. K. Reed, A climatological estimate of precipitation for the world ocean, *J. Clim. Appl. Meteorol.*, *23*, 434–439, 1984.

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

Emery, W. J., Global differences between skin temperature and bulk sea surface temperatures, *Eos Trans. AGU*, *70*, 210–211, 1989.

Flora, S. D., Shading instrument shelters, *Mon. Weather Rev.*, *48*, 271–273, 1920.

Folland, C. K., Numerical models of the raingauge exposure problem, field experiments and an improved collector design, *Q. J. R. Meteorol. Soc.*, *114*, 1485–1516, 1988.

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

Frouin, R., and C. Gautier, Calibration of NOAA-7 AVHRR, GOES-5, and GOES-6 VISSR/VAS solar channels, *Remote Sens. Environ.*, *22*, 73–101, 1987.

Gandin, L. S., The planning of meteorological station networks, *Rep. 265, Tech. Pap. 149*, World Meteorol. Organ. Geneva, 1970.

Godin, R. H., Sea ice charts of the Navy/NOAA Joint Ice Center, Snow Watch 1980, *Glaciol. Data Rep. GD-11*, pp. 71–77, World Data Cent. l., Univ. of Colo., Boulder, 1981.

Goodison, B. E., Compatibility of Canadian snowfall and snow cover data, *Water Resour. Res.*, *17*, 893–900, 1981.

Griffith, C. G., W. L. Woodley, P. G. Grube, D. W. Martin, J. Stout, and D. N. Sikdar, Rain estimation from geosynchronous satellite imagery—Visible and infrared studies, *Mon. Weather Rev.*, *106*, 1151–1171, 1978.

Hall, D. K., and J. Martinec, *Remote Sensing of Ice and Snow*, 189 pp., Chapman and Hall, London, 1985.

Hall, S. J., AFGWC snow analysis model, *Rep. AFGWC/TN-86/001*, 24 pp., Offutt Air Force Base, Nebr., 1986.

Hansen, J., and S. Lebedeff, Global trends of measured surface air temperature, *J. Geophys. Res.*, *92*, 13,345–13,372, 1987.

Hansen, J., I. Fung, A. Lacis, D. Rind, S. Lebedeff, R. Ruedy, G. Russell, and P. Stone, Global climate change as forecast by Goddard Institute for Space Studies three-dimensional model, *J. Geophys. Res.*, *93*, 9341–9364, 1988.

Hare, F. K., and J. E. Hay, Anomalies in the large-scale annual water balance over northern North America, *Can. Geogr.*, *15*, 79–94, 1971.

Houghton, D. D., *Handbook of Applied Meteorology*, 1461 pp., John Wiley, New York, 1985.

Hudlow, M., Mean rainfall patterns for the three phases of GATE, *J. Appl. Meteorol.*, *18*, 1656–1669, 1979.

Jackson, C. I., Snowfall measurements in northern Canada, *Quart. J. R. Meteorol. Soc.*, *86*, 273–275, 1960.

Jackson, M. C., Snow cover in Great Britain, *Weather*, *33*, 298–309, 1978.

Jaeger, L., Monthly and areal patterns of mean global precipitation, in, *Variations in the Global Water Budget*, edited by A. Street-Penot et al., pp. 129–140, D. Reidel, Hingham, Mass., 1983.

Jones, P. D., S. C. B. Raper, R. S. Bradley, H. F. Diaz, P. M. Kelly, and T. M. L. Wigley, Northern hemisphere surface air temperature variations: 1851–1984, *J. Clim. Appl. Meteorol.*, *25*, 1986*a*.

Jones, P. D., S. C. B. Raper, and T. M. L. Wigley, Southern hemisphere surface air temperature variations, 1851–1984, *J.Clim. Appl. Meteorol.*, *25*, 1213–1230, 1986*b*.

Jones, P. D., T. M. L. Wigley, and P. Wright, Global temperature variations between 1861 and 1984, *Nature*, *322*, 340–434, 1986*c*.

Jones, P. D., P. M. Kelly, C. M. Goodess, and T. R. Karl, The effect of urban warming on the northern hemisphere temperature average, *J. Clim.*, *2*, 285–290, 1989.

Justice, G. O. (Ed.), Monitoring the Grasslands of Semi-Arid Africa Using NOAA-AVHRR Data, *Int. J. Remote Sens.*, *7*(11), 1986.

Karl, T. R., and P. D. Jones, Urban bias in area-averaged surface air temperature trends, *Bull. Am. Meteorol. Soc.*, *70*, 265–270, 1989.

Karl, T. R., and R. G. Quayle, Climate change in fact and in theory: Are we collecting the facts?, *Clim. Change*, *13*, 5–17, 1988.

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

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

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

Kelly, P. M., An arctic sea ice data set, 1901–56, *Geol. Data Rep. G D-5,* pp. 101–106, World Data Cent. A for Glaciol., Univ. of Colo., Boulder, 1979.

Kidwell, K. B. (Ed.), *NOAA Polar Orbiter Data Users Guide,* National Oceanic and Atmospheric Administration/National Climatic Data Center/Satellite Services Division, U.S. Department of Commerce, Washington, D. C., 1986.

Kilonsky, B. J., and C. S. Ramage, A technique for estimating tropical open-ocean rainfall from satellite observations, *J. Appl. Meteorol., 15,* 972–975, 1976.

Kohler, M. A., On the use of double mass analysis for testing the consistency of meteorological records and for making required adjustments, *Bull. Am. Meteorol. Soc., 30,* 188–189, 1949.

Kraus, E. B., Secular changes of tropical precipitation, *Q. J. R. Meteorol. Soc., 81,* 198–210, 1955.

Krueger, A. F., and A. Gruber, The status of NOAA outgoing longwave radiation data set, *Bull. Am. Meteorol. Soc., 65,* 958–962, 1984.

Kukla, G., and J. Gavin, Recent fluctuations of northern hemisphere snow cover in autumn, in *Proceedings of the Eighth Annual NOAA Climate Diagnostics Workshop,* pp. 189–196, National Oceanic and Atmospheric Administration, Washington, D. C., 1984.

Kukla, G., and D. Robinson, Climatic value of operational snow and ice charts, *Glaciol. Data Rep. GD-11,* pp. 103–119, or Glaciol., Univ. of Colo., Boulder, 1981.

Lorenz, E. N., The mechanics of vacillation, *J. Atmos. Sci., 20,* 448–464, 1963.

Lorenz, E. N., The index cycle is alive and well, in *Namias Symposium,* pp. 188–196, Scripps Institution of Oceanography, La Jolla, Calif., 1986.

Malingreau, J. P., Global vegetation dynamics: Satellite observations over Asia, *Int. J. Remote Sens., 7,* 1121–1146, 1986.

Manley, G., Snowfall in Britain over the past 300 years, *Weather, 24,* 428–437, 1969.

Matson, M., C. F. Ropelewski, and M. S. Varnadore, *An Atlas of Satellite-Derived Northern Hemispheric Snow Cover Frequency,* 75 pp., National Oceanic and Atmospheric Administration, Washington, D.C., 1986.

May, B. R., and T. J. Hitch, Periodic variations in extreme rainfalls in the United Kingdom, *Meteorol. Mag., 118,* 45–50, 1989.

McClain, E. P., W. G. Pichel, and C. C. Walton, Comparative performance of AVHRR-based multichannel sea surface temperatures, *J. Geophys. Res., 90,* 11,587–11,601, 1985.

McGuffie, K., and D. A. Robinson, Examination of USAF nephanalysis performance in the marginal cryosphere region, *J. Clim., 1,* 1124–1137, 1988.

Mitchell, J. F. B., The "greenhouse" effect and climate change, *Rev. Geophys., 27,* 115–139, 1989.

Mitchell, J. M., Jr., The measurement of secular temperature change in the eastern United States, *Res. Pap. 43,* 70 pp., U.S. Weather Bur., Washington, D. C., 1961.

National Research Council, *The Polar Regions and Climatic Change,* edited by Committee on the Role of the Polar Regions in Climatic change, Polar Research Board, Commission on Physical Sciences, Mathematics, and Resources, 59 pp., National Academy Press, Washington, D. C., 1984.

Nicholson, S. E., Rainfall and atmospheric circulation during drought periods and wetter years in West Africa, *Mon. Weather Rev., 109,* 2191–2208, 1981.

Nicholson, S. E., The nature of rainfall variability in Africa south of the equator, *J. Climtol., 6,* 515–530, 1986.

Ohring, G., A. Thomasell, L. Stowe, P. Pellegrino, and C. Long, Monitoring global surface temperature variations using cloud data sets, *Adv. Space Res., 7,* 191–194, 1987.

Paris, M. V., and C. G. Justus, A cloudy-sky radiative transfer model suitable for calibration of satellite sensors, *Remote Sens. Environ., 24,* 269–285, 1988.

Pfister, C., Snow cover, snow lines and glaciers in central Europe since the 16th century, in *The Climate Scene,* pp. 154–174, George Allen and Unwin, London, 1985.

Planet, W. G., (Ed.), Data extraction and calibration of TIROS-N/NOAA radiometers, *Tech. Memo. NESS-107-REV.1,* Natl. Oceanic and Atmos. Admin., Washington, D. C., 1988.

Price, J. C., Calibration of satellite radiometers and the comparison of vegetation index, *Remote Sens. Environ., 21,* 15–27, 1987*a*.

Price, J. C., Radiometric calibration of satellite sensors in the visible and near infrared: History and outlook, *Remote Sens. Environ., 22,* 3–11, 1987*b*.

Quinlan, F. T., T. R. Karl, and C. N. Williams, Jr., United States Historical Climatology Network (HCN) serial temperature and precipitation data, *Rep. NDP-010,* 33 pp. plus appendices, Carbon Dioxide Inf. and Anal. Cent., Oak Ridge Nat. Lab., Oak Ridge, Tenn., 1987.

Rao, C. N. Prelaunch calibration of channels 1 and 2 of the advanced very high resolution radiometer, *Tech. Rep. NESDIS36,* 62 pp., Natl. Oceanic and Atmos. Admin., Washington, D. C., 1987.

Rasmusson, E. M., and P. A. Arkin, Interannual climate variability associated with the El-Nino southern oscillation, in *Coupled Ocean-Atmosphere Models,* edited by J. C. J. Nihoul, pp. 958–962, Elsevier, New York, 1985.

Robinson, D. A., Snow cover as an indicator of climate change, Large-Scale Effects of Seasonal Snow Cover, *IAHS Publ., 166,* 315–327, 1987.

Robinson, D. A., Construction of a United States historical snow data base, in *Proceedings of the 45th Eastern Snow Conference, Lake Placid, NY,* edited by J. Lewis, pp. 50–59, Eastern Snow Conference, Canada, 1989.

Rodda, J. C., The precipitation measurement paradox—The instrument accuracy problem, *Publ. 316,* World Meteorol. Organ., Geneva, 1971.

Ropelewski, C. F., J. E. Janowiak, and M. S. Halpert, The analysis and display of real time surface climate data, *Mon. Weather Rev., 113,* 1101–1106, 1985.

Schaal, L. A., and R. F. Dale, Time of observation temperature bias and "climatic change," *J. Clim. Appl. Meteorol., 16,* 215–222, 1977.

Sevruk, B., Methods of correction for systematic error in point precipitation measurement for operational use, *Oper. Hydrol. Rep. 21, Publ. 589,* 91 pp., World Meteorol. Organ., Geneva, 1982.

Sevruk, B., Correction of precipitation measurements, Proceedings of the Zurich Workshop on the Correction of Precipitation Measurements, *Zurcher Geogr. Schr. 23,* pp. 13–23, Eidenöss. Tech. Hochsch., Zurich, 1986.

Sevruk, B., Point precipitation measurements: Why are they not corrected?, Water for the Future: Hydrology in Perspective, *IAHS Publ., 164,* 477–486, 1987.

Simpson, J., R. F. Adler, and G. R. North, A proposed Tropical Rainfall Measuring mission (TRMM) satellite, *Bull. Am. Meteorol. Soc., 69,* 278–295, 1988.

Strong, A. E., Greater global warming revealed by satellite derived sea-surface-temperature trends, *Nature, 338,* 642–645, 1989.