GISS analysis of surface temperature change

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Abstract. We describe the current GISS analysis of surface temperature change for the period 1880-1999 based primarily on meteorological station measurements. The global surface temperature in 1998 was the warmest in the period of instrumental data. The rate of temperature change was higher in the past 25 years than at any previous time in the period of instrumental data. The warmth of 1998 was too large and pervasive to be fully accounted for by the recent El Nino. Despite cooling in the first half of 1999, we suggest that the mean global temperature, averaged over 2-3 years, has moved to a higher level, analogous to the increase that occurred in the late 1970s. Warming in the United States over the past 50 years has been smaller than in most of the world, and over that period there was a slight cooling trend in the eastern United States and the neighboring Atlantic Ocean. The spatial and temporal patterns of the temperature change suggest that more than one mechanism was involved in this regional cooling. The cooling trend in the United States, which began after the 1930s and is associated with ocean temperature change patterns, began to reverse after 1979. We suggest that further warming in the United States to a level rivaling the 1930s is likely in the next decade, but reliable prediction requires better understanding of decadal oscillations of ocean temperature.

1. Introduction

Surface air temperature change is a primary measure of global climate change. Studies of temperature change over land areas based on measurements of the meteorological station network are routinely made by groups at the University of East Anglia (UEA) [*Jones et al.*, 1982; *Jones*, 1995], the Goddard Institute for Space Studies (GISS) [*Hansen et al.*, 1981; *Hansen and Lebedeff*, 1987], and the National Climatic Data Center (NCDC) [*Peterson et al.*, 1998b; *Quayle et al.*, 1999]. These studies are updated frequently because of current interest in global warming and the possibility of human influence on climate [*Intergovernmental Panel on Climate Change (IPCC)*, 1996]. Analysis by several independent groups provides a useful check, because of their different ways of handling data problems such as incomplete spatial and temporal coverage, urban influences on the station environment, and other factors affecting data quality [*Karl et al.*, 1989].

Our purpose is to update and document the current GISS analysis, which has evolved substantially since the previous documentation by *Hansen and Lebedeff* [1987], hereinafter abbreviated as HL87. Our analysis concerns primarily meteorological station measurements over land areas, as was the case with HL87. However, we also illustrate results for a global surface temperature index formed by combining our land analysis with sea surface temperature data of *Reynolds and Smith* [1994] and *Smith et al.* [1996], as described by *Hansen et al.* [1996]. It is useful to estimate global temperature change from both the meteorological station data alone, and the combined analysis, because the land and ocean data have their own measurement characteristics and uncertainties.

We first describe the source of our raw data, our data quality controls, and an optional adjustment for estimating urban effects on local data. We describe the method for combining station records to obtain regional and near-global temperature change, illustrate the resulting near-global temperature change of the past century, and compare this with the temperature change in the United States. Finally, we present examples of data products that are available from our web site (www.giss.nasa.gov).

2. Source Data

The source of monthly mean station temperatures for our present analysis is the Global Historical Climatology Network (GHCN) version 2 of *Peterson and Vose* [1997]. This is a compilation of 31 data sets, which include data from more than 7200 independent stations. One of the 31 data sets, the Monthly Climatic Data of the World (MCDW) with about 2200 stations, was the data source used in the analysis of *Hansen and Lebedeff* [1987]. The GHCN version 2 data set has many merits for research applications, including provision of useful metadata such as population and ready availability to researchers, as described by *Peterson and Vose* [1997] and *Peterson et al.* [1998c]. When we apply our "data-cleaning" programs to this GHCN data set, we find it to be unusually free of obvious problems, as discussed in section 3 below. We use the version of the GHCN without homogeneity adjustment, as we carry out our own adjustment described below.

Measurements at many meteorological stations are included in more than one of the 31 GHCN data sets, with the recorded temperatures in some cases differing in value or record length. Our first step was thus to estimate a single time series of temperature change for each location, as described in section 4. The cumulative distribution of the resulting station record lengths is given in Figure 1a, and the number of stations at a given time is shown in Figure 1b.

Analyses of global temperature change based on instrumental measurements are limited prior to the twentieth century by the sparse global distribution of measurements. The area represented by observations is addressed in Figure 1c. It was shown by HL87 that monthly temperature anomalies (the deviation from climatology, which is the long-term mean) at a given station are highly correlated with anomalies of neighboring stations to distances as great as about 1200 km, with the correlations for nearby stations being better at middle and high latitudes than in the tropics. Using 1200 km as the distance to which a station is representative, Figure 1c shows that 50% area coverage in the Northern Hemisphere was obtained by about 1880 and at the same time, coverage in the Southern Hemisphere jumped from less than 10% to more than 20%. The coverage subsequent to 1880 is sufficient to yield useful estimates of annual global temperature (with an error of the order of 0.1°C), as shown by quantitative tests of the error due to incomplete spatial sampling using either climate models or empirical data to specify spatial-temporal variability [*HL87*; *Karl et al.*, 1994; *Jones et al.*, 1997a]. The error bars that we include in our global temperature curve below account (only) for this incomplete spatial sampling.

Note the recent decline of the number of stations and area covered by the stations (Figure 1). First, there has been a real reduction since the 1960s in the number of stations making and reporting measurements. Second, updates of the GHCN data covering the most recent several years include only three component data sets [*Peterson and Vose*, 1997]: (1) up to about 1500 of the global MCDW stations that report monthly data over the Global Telecommunications System or mail reports to NCDC, (2) up to about 1200 United States Historical Climatology Network stations, which are mostly rural; (3) up to about 370 U.S. First Order stations, which are mostly airport stations in the United States and U.S. territories in the Pacific Ocean. Third, the update for the final (current) year is based mainly on MCDW stations. Sampling studies discussed below indicate that the decline in number of stations is unimportant in regions of dense coverage, although the estimated global temperature change can be affected by a few hundredths of a degree. The effect of poor coverage on estimated regional and zonal temperatures can be large in specific areas, such as high latitudes in the Southern Hemisphere, as illustrated in section 4.

We limit our study primarily to the period since 1880, because of the poor spatial coverage of stations prior to that time and the reduced possibility of checking records against those of nearby neighbors. Meteorological station data provide a useful indication of temperature change in the Northern Hemisphere extratropics for a few decades prior to 1880, and there are a small number of station records that extend back to previous centuries. However, we believe that analyses for the earlier years need to be carried out on a station by station basis with an attempt to discern the method and reliability of measurements at each station, a task beyond the scope of our present analysis. Global studies of the earlier times depend upon incorporation of proxy measures of temperature change. We refer the reader to studies of *Mann et al*. [1998, 1999], *Hughes and Diaz* [1994], *Bradley and Jones* [1993] and *Jones and Bradley* [1992] and references therein.

When we combine surface air temperatures over land with sea surface temperatures (SSTs) to form a global temperature index [*Hansen et al*., 1996] we normally use SST data of *Reynolds and Smith* [1994] and *Smith et al*. [1996]. However, for the sake of obtaining an indication of uncertainties, we also test the effect of instead employing the GISST (global ice and sea surface temperature) data [*Parker et al*., 1995; *Rayner et al*., 1996] for the SST component of the temperature index.

3. Data Quality Control

Data collected and recorded by thousands of individuals with equipment and procedures subject to change over time inevitably contains many errors and inconsistencies, some of which will be impossible to identify and correct. The issue is whether the errors are so large that their effect on the temperature analysis is comparable to the climate change that we are attempting to measure. It turns out, as the global maps of temperature change illustrate, that the analyzed temperature changes generally have a clear physical basis associated with large-scale climatological patterns, and the greatest changes occur in remote locations where effects of local human influence are minimal. This suggests that the influence of errors is not dominant, perhaps because many of the errors in recording temperature are random in nature. Nevertheless, it is important to examine data quality to try to minimize local errors and to obtain an indication of the nature and magnitude of any artificial sources of temperature change.

The GHCN data have undergone extensive quality control, as described by *Peterson et al*. [1998c]. In their data cleaning procedure they nominally exclude individual station months (i.e., monthly mean temperatures at a given station) that differ by more than five standard deviations (5σ) from the long-term mean for that station month. This procedure may exclude valid data points, but the number is so small in a physically plausible distribution that such deletions have little effect on the average long-term global change. They also examine those station months that differ from the long-term mean by between 2.5σ and 5σ, retaining those that are consistent with nearest neighbor stations, and they perform several other quality checks that are described by *Peterson et al.* [1998c].

Our analysis programs that ingest GHCN data include data quality checks that were developed for our earlier analysis of MCDW data. Retention of our own quality control checks is useful to guard against inadvertent errors in data transfer and processing, verification of any added near-real-time data, and testing of that portion of the GHCN data (specifically the United States Historical Climatology Network data) that was not screened by *Peterson et al*. [1998c].

A first quality check was to flag all monthly data that differed more than five standard deviations (5σ) from the long-term mean for that month, unless one of the nearest five neighboring stations had an anomaly of the same sign for the same month that was at least half as large. Data were also flagged if the record had a jump discontinuity, specifically if the means for two 10 year periods differed by more than 3σ. A third flag was designed to catch clumps of bad data that occasionally occur, usually at the beginning of a record; specifically, a station record was flagged if it contained 10 or more months within a 20 year period that differed from the long-term mean by more than 3σ.

All flagged data were graphically displayed along with neighboring stations that contained data during the period in question, and a subjective decision was made as to whether the apparent discontinuity was flawed data or a potentially real climate anomaly. The philosophy was that if the data were not quite obviously flawed, it was retained. Only a very small portion of the original data was deleted: approximately 20 station records were deleted entirely, in approximately 90 cases the early part of the record was deleted, in five cases a segment of 2-10 years was deleted from the record, and approximately 20 individual station months were deleted.

We also modified the records of two stations that had obvious discontinuities. These stations, St. Helena in the tropical Atlantic Ocean and Lihue, Kauai, in Hawaii are both located on islands with few if any neighbors, so they have a noticeable influence on analyzed regional temperature change. The St. Helena station, based on metadata provided with MCDW records, was moved from 604 m to 436 m elevation between August 1976 and September 1976. Therefore assuming a lapse rate of about 6°C/km, we added 1°C to the St. Helena temperatures before September 1976. Lihue had an apparent discontinuity in its temperature record around 1950. On the basis of minimization of the discrepancy with its few neighboring stations, we added 0.8°C to Lihue temperatures prior to 1950.

The impact of our data deletions and alterations is small compared with the climate changes discussed in this paper. The largest effects are those due to the changes on St. Helena and to a lesser extent Hawaii. Nevertheless, we wish to continue to clean and improve the basic station data, if problems or improvements can be identified. In section 10 we describe easy access to all of our station data via the world wide web. We would welcome feedback from users on any specific data in this record.

4. Combination of Station Records

4.1. Records at Same Location

We first describe how multiple records for the same location are combined to form a single time series. This procedure is analogous to that used by HL87 to combine multiple-station records, but because the records are all for the same location, no distance weighting factor is needed.

Two records are combined as shown in Figure 2, if they have a period of overlap. The mean difference or bias between the two records during their period of overlap (ΔT) is used to adjust one record before the two are averaged, leading to identification of this way for combining records as the "bias" method (HL87) or, alternatively, as the "reference station" method [*Peterson et al.,* 1998b]. The adjustment is useful even with records for nominally the same location, as indicated by the latitude and longitude, because they may differ in the height or surroundings of the thermometer, in their method of calculating daily mean temperature, or in other ways that influence monthly mean temperature. Although the two records to be combined are shown as being distinct in Figure 2, in the majority of cases the overlapping portions of the two records are identical, representing the same measurements that have made their way into more than one data set.

A third record for the same location, if it exists, is then combined with the mean of the first two records in the same way, with all records present for a given year contributing equally to the mean temperature for that year (HL87). This process is continued until all stations with overlap at a given location are employed. If there are additional stations without overlap, these are also combined, without adjustment, provided that the gap between records is no more than 10 years and the mean temperatures for the nearest five year periods of the two records differ by less than one standard deviation. Stations with larger gaps are treated as separate records.

The single record that we obtain for a given location is used in our analyses of regional and global temperature change. This single record is not necessarily appropriate for local studies, and we recommend that users interested in a local analysis return to the raw GHCN data and examine all of the individual records for that location, if more than one is available. Our rationale for combining the records at a given location is principally that it yields longer records. Long records are particularly effective in our “reference station” analysis of regional and global temperature change, which employs a weighted combination of all stations located with 1200 km as described below.

The use of a single record at each location for analysis of regional and global temperature change is one characteristic of our approach that distinguishes it from the first difference method [*Peterson et al.*, 1998b]. The first difference method has the advantage that it avoids errors due to discontinuities in measurement procedures at a given location, if the data are successfully split into pieces each of which has constant measurement procedures. The reference station method has longer records and the convenience of a single record at each station location. The reference station method also naturally avoids giving too much weight to multiple measurements at the same location but this problem can be avoided in the first difference method with appropriate weighting of records. It is not obvious which of these and other methods yields the most accurate estimate of long-term global temperature change. The hope is that the differences among the methods is much smaller than the actual global change, a result that tends to be borne out in comparisons of the results [*Peterson et al.*, 1998b], as discussed below.

4.2. Regional and Global Temperature

After the records for the same location are combined into a single time series, the resulting data set is used to estimate regional temperature change on a grid with 2°×2° resolution. Stations located within 1200 km of the grid point are employed with a weight that decreases linearly to zero at the distance 1200 km (HL87). We employ all stations for which the length of the combined records is at least 20 years; there is no requirement that an individual contributing station have any data within our 1951-1980 reference period. As a final step, after all station records within 1200 km of a given grid point have been averaged, we subtract the 1951-1980 mean temperature for the grid point to obtain the estimated temperature anomaly time series of that grid point. Although an anomaly is defined only for grid points with a defined 1951-1980 mean, because of the smoothing over 1200 km, most places with data have a defined 1951-1980 mean.

In principle, the ability to use records that do not include the reference period is an advantage of our (reference station) method and the first difference method of *Peterson et al.* [1998b] over the climate anomaly method of *Jones et al.* [1982, 1985, 1997a], but Jones et al. employ methods of data interpolation that mitigate this disadvantage. The reference station and first difference methods also can make use of stations with arbitrarily short records, but with either method, a very short record can do more harm than good. For example, a 2 year record added to the middle of a 100 year record can shift the second half of the record relative to the first half, because of the (meteorological and measurement error) noise in the short record, thus yielding a less accurate estimate of the long-term change than would be provided by the single 100 year record by itself. For this reason we employ only station locations for which the net record length is at least 20 years. This reduces the number of stations employed from about 7300 to 6000 but has negligible impact on the area coverage of stations. Specifically, the change to Figure 1c is imperceptible, when the 6000 stations are employed, rather than 7300 stations.

The global distribution of our resulting temperature data is shown in Plate 1 for six specific years in the past 120 years. This illustrates the station coverage that is summarized for all years in Figure 1c. Note that the coverage with the approximately 6000 GHCN stations that we employ is only slightly greater than for the MCDW network of about 2000 stations employed by HL87.

Because we allow a given station to influence the estimated temperature change to distances of 1200 km from the station, our maps, based on only meteorological stations yield results at remote locations, including much of the ocean. This is useful for improving our estimate of global temperature change, as discussed in section 7. However, these remote temperature change estimates are only expected to be valid in an average sense; that is, they are unlikely to yield locally accurate measures of change at a substantial distance from stations. Thus we also employ a temperature index in which we combine our analysis of surface air temperature change for land with analyses of SST change for ocean regions (section 7).

Our estimate of global temperature change uses the grid box temperature anomalies to first estimate temperature time series for three large zonal blocks of the Earth (90°N-23.6°N, 23.6°N-23.6°S, 23.6°S-90°S), as described in section 6. This method of averaging over the world was introduced by *Hansen et al.* (1981) in an attempt to minimize the error due to very incomplete spatial sampling. A quantitative estimate of the sampling error is included below with our calculated global temperature.

4.3. Periods Analyzed

We use the above method to obtain a time series of temperature change for each month. A seasonal mean temperature anomaly is then defined as the mean of the available monthly anomalies, provided that data are available for at least two of the three months in that season. Similarly, an annual mean anomaly is defined as the mean of the available seasonal anomalies, provided that data are available for at least three of the four seasons.

This approach leads naturally to the use of an annual mean based on the meteorological year, December through November. Use of whole seasons, without splitting of the December-January-February season, is convenient for studies of interannual change of seasonal climate, including comparison with climate model simulations. However, for the sake of comparison with analyses based on the calendar year, we also calculate annual means for January through December.

In addition, we use the monthly mean anomalies to compute “warm season” and “cool season” temperature anomalies. Specifically, we calculate the anomalies for November-April (Northern Hemisphere cool season, Southern Hemisphere warm season) and May-October, as discussed in section 8. We suggest that for some climate change studies these warm and cool seasons provide a sufficient description of the climate change, and they allow examination of the change in a small number of maps. Use of 6 month periods, instead of 3 months, reduces the impact of weather noise, and the average of the two seasons provides an annual temperature anomaly. We show in section 9.1 that the annual temperature anomalies based on warm season plus cool season, the meteorological year, and the calendar year are all very similar.

We generally restrict our analyses to the period from 1880 to the present, because of the poor spatial coverage of stations prior to 1880 and uncertainties about the quality of the earlier measurements. The one exception is a map of estimated temperature change over the period 1870-1900 in section 8. In that case, the topic of interest is the large-scale patterns of temperature change at northern middle latitudes, and the station coverage is probably sufficient for that purpose.

5. Homogeneity Adjustment

Homogeneity adjustments are made to local time series of temperature with the aim of removing nonclimatic variations in the temperature record [*Jones et al.*, 1985; *Karl and Williams*, 1987; *Easterling et al.*, 1996; *Peterson et al.*, 1998a]. The nonclimatic factors include changes of the environment of the station, the instrument or its location, observing practices, and the method used to calculate the mean temperature. Quantitative knowledge of these factors is not available in most cases, so it is impossible to fully correct for them. Fortunately, the random component of such errors tends to average out in large area averages and in calculations of temperature change over long periods.

The nonrandom inhomogeneity of most concern is anthropogenic influence on the air sampled by the thermometers. Urban heat can produce a large local bias toward warming [*Mitchell*, 1953; *Landsberg*, 1981] as cities are built up and energy use increases. Anthropogenic effects can also cause a nonclimatic cooling, for example, as a result of irrigation and planting of vegetation, but these effects are usually outweighed by urban warming.

We take advantage of the metadata accompanying the GHCN records, which includes classification of each station as rural (population less than 10,000), small town (10,000 to 50,000), and urban (more than 50,000), to calculate a bilinear adjustment for urban stations. The adjustment is based on the assumption that human effects are smaller in rural locations. We retain the unadjusted record and make available results for both adjusted and unadjusted time series (section 10). The homogeneity adjustment for a given city is defined to change linearly with time between 1950 and the final year of data and to change linearly with a possibly different slope between 1950 and the beginning of the record. The slopes of the two straight line segments are chosen to minimize the weighted-mean root-mean-square difference of the urban station time series with the time series of nearby rural stations. An adjusted urban record is defined only if there are at least three rural neighbors for at least two thirds of the period being adjusted. All rural stations within 1000 km are used to calculate the adjustment, with a weight that decreases linearly to zero at distance 1000 km. The function of the urban adjustment is to allow the local urban measurements to define short-term variations of the adjusted temperature while rural neighbors define the long-term change. The break in the adjustment line at 1950 allows some time dependence in the rate of growth of the urban influence.

The measured and adjusted temperature records for Tokyo, Japan, and for Phoenix, Arizona, are shown in Figure 3. These are among the most extreme examples of urban warming, but they illustrate a human influence that can be expected to exist to some degree in all population centers. Tokyo warmed relative to its rural neighbors in both the first and the second halves of the century. The true nonclimatic warming in Tokyo may be even somewhat larger than suggested by Figure 3, because some "urban" effect is known to occur even in small towns and rural locations [*Mitchell*, 1953; *Landsburg*, 1981]. The urban effect in Phoenix occurs mainly in the second half of the century. The urban-adjusted Phoenix record shows little long-term temperature change.

Examination of this urban adjustment at many locations, which can be done readily via our web site (section 10), shows that the adjustment is quite variable from place to place and can be of either sign. In some cases the adjustment is probably more an effect of small-scale natural variability of temperature (or errors) at the rural neighbors, rather than a true urban effect. Also, the actual nonclimatic component of the urban temperature change can encompass many factors with irregular time dependence, such as station relocations and changes of the thermometer's environment, which will not be represented well by our linear adjustment. Such false local adjustments will be of both signs, and thus the effects may tend to average out in global temperature analyses, but it is difficult to have confidence in the use of urban records for estimating climate change. We recommend that the adjusted data be used with great caution, especially for local studies.

These examples illustrate that urban effects on temperature in specific cases can dominate over real climate trends. Fortunately, there are far more rural stations than urban stations, so it is not essential to employ the urban data in analyses of global temperature change. We include adjusted urban station data in our standard analysis primarily for the sake of the last few years of the record, especially the final year. The fraction of reporting stations that are urban jumps from about one quarter to one third in the mid-1990s and to about one half in the final year of the record when the available reports are mainly from MCDW stations. We show in section 6.2 that the urban stations have little influence on the global temperature change. Examples of the regional influence are included in the appendix.

6. Temperatures from Meteorological Stations

6.1. Global Temperature

The near-global temperature, based on the meteorological station data, is shown in Figure 4. This result is based on rural, small-town, and homogeneity-adjusted urban stations. However, we show below that the effect of deleting urban stations, or deleting both urban and small town stations, is negligible in comparison with the measured temperature change of the past century, consistent with the conclusion of [*Peterson et al.,* 1999]. Examples of the global distribution of data from which the global mean estimates were obtained are shown in Plate 1 for six specific years. A given station is assumed to provide a useful estimate of monthly and annual temperature anomalies to a distance of 1200 km based on observed correlations of station records (HL87).

Our estimate of global temperature change is obtained by dividing the world into broad latitude zones, estimating temperature anomaly time series for each zone, and then weighting these zones by their area. The zones, northern latitudes (90°N-23.6°N), low latitudes (23.6°N-23.6°S), and southern latitudes (23.6°S-90°S), cover 30%, 40% and 30% of the Earth's surface. On the basis of tests with model-generated globally complete data sets, HL87 found this method of global averaging to yield a better approximation than other tested alternatives, such as simple area weighting of all regions with data (this gave too much weight to the Northern Hemisphere) or use of narrower latitude zones as soon as they had one or two stations (this allowed noise at the one or two stations to have excessive impact on the global mean). The physical basis for choosing these specific zones is discussed in section 6.3.

Although this estimate of global temperature change is derived from what are nominally "land only" measurements, it is a better estimate of global change than what might be expected given that land covers only 30% of the world. Estimates of the uncertainty in the annual-mean and 5 year running-mean global mean temper-atures at different times are indicated by error bars in Figure 4. These error estimates, which account only for the incomplete spatial sampling of the data, were obtained by HL87 from sampling studies with 100 year climate simulations using a global climate model that had a realistic magnitude of spatial-temporal variability of surface air temperature.

We describe the global temperature change of the past century, as summarized by Figure 4, as follows. In the period 1880-1910 the world was about 0.3°C colder than in the base period 1951-1980 and exhibited no obvious trend. Over the three decades 1910-1940 the temperature increased 0.3°C, i.e., about 0.1°C/decade. Between the 1930s or the 1940s and the 1970s there was little global mean temperature change, perhaps a slight cooling. Between the mid-1970s and the late 1990s global temperature increased by about 0.5°C, i.e., about 0.2°C/decade, about twice the rate of warming that occurred early in the century.

A global temperature curve more-or-less similar to Figure 4 has been published and discussed many times, especially by the UEA and GISS groups but also by NCDC and other groups and individuals. Nevertheless, it may be worth noting key features of this curve.

First, the rate of warming in the past 25 years is the highest in the period of instrumental data. Indeed, proxy measures of temperature change over the past six centuries do not reveal clearly any comparable burst of warming [*Mann et al.*, 1998]. Comparisons over longer periods are difficult, because data for earlier times have less accuracy, coverage, and temporal resolution, but it is clear that the global temperature change of the past 25 years is at least highly unusual.

Second, the global temperature in 1998 was easily the warmest in the period of instrumental data, being well outside the range of uncertainty caused by incomplete spatial sampling. The warmth of 1998 must have been in part associated with a strong El Nino that occurred in 1997-1998 [*McPhaden*, 1999]. However, strong El Ninos have occurred in previous years without engendering such unusual global warmth, and the global maps below indicate that the warmth of 1998 was too pervasive to be accounted for solely by the El Nino.

Third, the addition of the 1990s data to the global temperature curve, especially with the point for 1998 included, represents a sufficiently large qualitative change to the appearance of the record that it undercuts some of the time-honored cliches in the global warming discussion. For example, "most of the global warming occurred before 1940" is clearly shown to be invalid. Even the most shopworn summary, that global warming in the industrial era is "about 0.5°C," is probably no longer valid.

Quantitative assessment of the magnitude of global warming since the late 1800s requires consideration of (1) the effect of including ocean regions more completely and accurately, but we estimate below (section 7) that this has little impact on the long-term global temperature change; (2) the effect of imperfect homogeneity adjustment, for example, residual urban warming, but we estimate below (section 6.2) that this effect is small; (3) the unrepresentativeness of the 1998 temperature, which was enhanced by a strong El Nino [*McPhaden*, 1999], but we argue below that the global mean "background" temperature has reached a level approximately 0.5°C above the 1951-1980 mean. Thus it is probably better to say now that global warming since the late 1800s is "about 3/4°C." Indeed, if the typical year reaches a level only slightly above the 1998 temperature, it would become appropriate to describe the warming as "about 1°C."

Finally, we comment on the last 25 years of the record. This period can be described simply as a time of strong warming, modulated by brief coolings in the early 1980s and 1990s (the coolings, coincidentally or not, being associated with large volcanos and solar minima). Alternatively, the global temperature can be described as having a jump in the late 1970s, relatively little warming between 1980 and the mid-1990s and another jump in the late 1990s. Description of the global temperature change during recent decades is reconsidered in section 7, after inclusion of ocean temperature changes.

6.2. Urban Effects on Global Temperature

We test for anthropogenic influence on our global temperature as follows: We use the method for calculating global temperature described above but with the source data being (1) only rural stations, (2) rural and small-town stations, (3) all stations, with no homogeneity correction; and (4) all stations, with urban stations adjusted using nearby rural neighbors as described in section 5. We use the definition of *Peterson et al.* [1997] for these categories; that is, rural areas have a recent population less than 10,000, small towns between 10,000 and 50,000 and urban areas more than 50,000. These populations refer to approximately 1980.

The global temperature curves for these population categories are shown in Plate 2a. The urban influence on global temperature estimated in this way is small. Furthermore, most of the influence suggested in Plate 2a is only apparent, much of the variation being caused by the fact that the areas sampled by the several data sets are not the same. This latter factor is easily investigated by calculating the global temperature change using only the common area where all of the data sets have a defined temperature, with results shown in Plate 2b. *Peterson et al.* [1999] previously compared estimated global temperature change for all stations with that for rural plus small-town stations; our result is consistent with theirs.

Why does the urban influence on our global analysis seem to be so small, in view of the large urban warming that we find at certain locations (section 5)? Part of the reason is that urban stations are a small proportion of the total number of stations. Specifically, 55-60% of the stations are rural, about 20% are small town, and 20-25% are urban, with some temporal variation. In addition, local inhomogeneities are variable; some urban stations show little or no warming, or even a slight cooling, relative to rural neighbors. Such results can be a real systematic effect, e.g., cooling by planted vegetation or the movement of a thermometer away from the urban center, or a random effect of unforced regional variability and measurement errors. Another consideration is that even rural locations may contain some anthropogenic influence [*Mitchell*, 1953; *Landsburg*, 1981]. However, it is clear that the average urban influence on the meteorological station record is far smaller than the extreme urban effect found in certain urban centers.

Regional urban effects in our analyzed record may exceed substantially the small global effects suggested by Plate 2, and the small differences among the curves in Plate 2 may understate the true urban effect on global temperature. If categorization of warming by station population were the only test of the reality of global warming, conclusions would be quite constrained. However, the dominance of real climate change over analysis error due to urban effects is affirmed by the spatial patterns of the global warming, which show that the warming has occurred primarily in remote continental and oceanic areas (section 8) and by independent evidence of global warming mentioned in section 11.

We conclude, as already reported by *Jones et al.* [1990] and *Peterson et al.* [1999], that the urban effect on global temperature change analyses is small compared with the magnitude of global warming. Our estimate is that the anthropogenic urban contribution to our global temperature curve for the past century (Figure 4) does not exceed approximately 0.1°C.

We choose as our standard analysis the results based on rural, small-town, and adjusted urban stations. The adjusted urban stations increase the spatial coverage in the early part of the record, mainly between 1880 and 1900. For example, if at least three rural neighbors exist for two thirds of the period 1880-1950, we use the adjusted urban record for the full period. Such urban records reduce the sampling error at the time in the record when incomplete spatial coverage is probably the greatest source of error.

6.3. Temperature in Broad Zonal Bands

The global temperature change of the past century can be contrasted with the temperature change in broad zonal bands. It is common to examine the Northern and Southern Hemispheres separately (our web page includes hemispheric means, for people addicted to that presentation), but we prefer instead to divide the world in three broad zonal bands: northern latitudes (90°N-23.6°N), tropical latitudes (23.6°N-23.6°S), and southern latitudes (23.6°S-90°S), which cover 30%, 40%, and 30% of the Earth's surface. It is reasonable to expect that climate changes may differ among these three zones. The northern latitudes are mainly land (as well as the zone of industrial activity). The other two zones are mainly ocean, but the tropical latitudes differ from the other zones in having a relatively shallow ocean-mixed layer.

When we introduced the method of weighting station records to distances of 1200 km [*Hansen et al.*, 1981], one of our contentions was that this allowed a good estimate of global temperature change for the past century. In addition, the division into broad zones revealed significant differences among the global and the zonal temperature changes, for example, the presence of long-term global warming despite rapid cooling at northern latitudes for several decades (1940-1975). The longer record that is now available permits more definitive comparisons among these broad latitude zones.

Figure 5 illustrates that the global cooling after 1940 was confined mainly to the northern latitudes, which cooled strongly, by about 0.5°C, between 1940 and the early 1970s. Since the early 1970s the northern latitudes have warmed rapidly, by about 0.8°C in 25 years. It was not until the late 1980s that the (5 year mean) temperature of northern latitudes exceeded the level of 1940, but the temperature is now well above that level. Despite the rapidity of northern latitude warming in the past 25 years, this warming rate was nearly matched by an earlier rise of about 0.6°C between 1920 and 1940.

Tropical latitudes, after warming about 0.2C in the 1920s, showed little temperature change for the next half century until a sudden leap of temperature by about 0.25°C in the late 1970s. For the next two decades the tropics only warmed moderately prior to an intense warming in the late 1990s that was associated with a strong El Nino [*McPhaden*, 1999].

Southern latitudes have warmed more steadily over the past century (Figure 5c). Most of the decadal temperature swings have limited significance because of the poor spatial sampling in much of the century. However, the southern latitude cooling in the 1990s is larger than the sampling uncertainty. Although our objective here is not to present interpretations of the observed temperature change, and decadal variations in earlier periods were common, it may be noted that a negative climate forcing occurred in the first half of the 1990s due to the volcano of the century [*Sato et al*., 1993; *Russell et al*., 1996; *Hansen et al.*, 1997], and any cooling effect might be anticipated to have a more lasting effect in the southern latitudes because of the ocean thermal inertia there. A lesser negative climate forcing (cooling tendency) at southern latitudes in the 1980s and 1990s was caused by ozone depletion, which peaked over Antarctica [*Hollandsworth et al.*, 1995; *Hansen et al.,* 1997].

6.4. U.S. Mean Temperature

Temperature change in the United States (Figure 6) and in the global mean (Figure 4) have some similarity, but they are not congruent. In particular, evidence for long-term warming this century is less convincing for the United States than it is for the globe. Of course, year-to-year variability is much larger for the United States, which represents only about 2% of the area of the world.

The U.S. temperature increased by about 0.8°C between the 1880s and the 1930s, but it then fell by about 0.7°C between 1930 and the 1970s and regained only about 0.3°C of this between the 1970s and the 1990s. The year 1998 was the warmest year of recent decades in the United States, but in general, U.S. temperatures have not recovered even to the level that existed in the 1930s. This contrasts with global temperatures, which have climbed far above the levels of the first half of this century.

The mean temperature change for the United States hides considerable geographical variation of the change, particularly cooling in the Southeast and warming in the West during the past half century. Practical socioeconomic impacts of climate change depend upon the regional climate changes, which we illustrate in section 8.

There is no requirement that regional temperatures should correspond in magnitude to global temperature change, or even that they be qualitatively similar. Yet, other things being equal, the expectation has been that a middle-latitude land area would warm more than the global average in response to a global forcing such as greenhouse gases [*Manabe and Wetherald*, 1975; *Hansen et al.*, 1988]. The United States over the past 2-3 decades has reverted to a warming trend (Figure 6), but prediction of whether the United States temperature will climb to levels consistent with global warming requires an understanding of the mechanisms behind the cooling that began in the 1930s (Figure 6).

Some indications of possible reasons for different behaviors of the United States and global average temperatures can be obtained from examining aspects of the temperature change such as its geographical and seasonal behavior. However, before doing this it is useful to examine land and ocean temperature change together.

7. Global Temperature Index

7.1. Global Annual-Mean Temperature Index

Temperature measurements over the oceans increase global coverage of data but add other uncertainties to the global temperature record [*Folland et al*., 1992; *Parker et al.*, 1994, 1995; *Rayner* *et al.*, 1996]. Surface air measurements would be the most appropriate data, but ship heights and speeds have changed in the past century and measurements on ships probably have been even less uniform than screened measurements at meteorological stations. An alternative is to use sea surface temperature (SST) measurements. Methods of measuring SST also have changed with time, most notably from bucket water to engine intake water, and anomalies in SST need not track precisely anomalies in surface air temperature. However, SSTs have the advantage of being measurable from satellite, and thus near-global coverage is available for recent decades, and the satellite data are routinely updated. For this reason we choose to combine SST anomalies of ocean areas with the surface air data over land, describing the result as a global temperature index [*Hansen et al.*, 1996].

We use the SST data of *Reynolds and Smith* [1994] for the period 1982 to present. This is their "blended" analysis product, based on satellite measurements calibrated with the help of thousands of ship and buoy measurements. For the period 1950-1981 we use the SST data of *Smith et al.* [1996], which are based on fitting ship measurements to empirical orthogonal functions (EOFs) developed for the period of satellite data. For comparison, we also calculate the global temperature index using our land data combined with the SSTs of the GISST analysis [*Parker et al.*, 1995; *Rayner et al.*, 1996]. With either SST data set we use the SSTs wherever they are defined and use our meteorological station analysis to fill in as much of the rest of the world as possible. Thus because the Reynolds and Smith SSTs are not defined south of 45°S, we use the analysis based on meteorological stations to cover that latitude range as well as possible.

We compare the global annual temperature index obtained using the two different data sources for SST with our analysis based on only meteorological stations in Plate 3a, and we compare the 5 year means of the same data in Plate 3b. GISST yields slightly more rapid global warming in the past two decades than does the Reynolds and Smith data. This difference, discussed at a workshop on November 2-4, 1998, at Lamont-Doherty Earth Observatory [*WMO*, 1999], occurs mainly at high latitudes and may be caused in part by inadequate ship calibration of the satellite SST data and the treatment of sea ice. The apparent difference between the GISST and the Reynolds/Smith curves is minimized by the fact that they are both forced to have a zero mean for the interval 1951-1980. Also, the index using Reynolds/Smith data employs the GISS meteorological station data at latitudes south of 45°S and their positive trend partially compensates for the weaker trend in the Reynolds/Smith data at other latitudes.

One result illustrated by Plate 3 is how closely the analysis of meteorological station data alone approximates the global land-ocean temperature index. The method of analyzing the meteorological station data was designed to yield an estimate of global temperature change at a time when globally analyzed SST data were not readily available [*Hansen et al.*, 1981]. Island stations and ocean areas up to 1200 km from the coast lines are included in the global integration in a way intended to capture as much of the ocean's effect on global temperature as permitted by the correlation distance of temperature anomalies.

The standard deviation of the global temperature based on only meteorological station data also closely approximates the standard deviation of the complete land-ocean global temperature curves. Specifically, the standard deviations about the 11 year running means are 0.105°, 0.116°, and 0.125°C for the annual-mean global temperatures based on GISST, Reynolds and Smith, and only meteorological stations. The standard deviations about the mean for the entire period (1950-1998) for these three data sets are 0.17°, 0.19° and 0.20°C. These are similar to the standard deviations used by *Hansen et al.* [1981], 0.1°C for 10 years and 0.2°C for 100 years, to estimate that global warming due to greenhouse gases should exceed natural variability in the 1990s.

7.2. Seasonal-Mean Temperature Index

The seasonal (three month) mean is a useful frequency for studying large area temperature change. It is long enough to average out most weather noise but short enough to define features that have irregular periods of a year or so, such as El Ninos. The seasonal mean of the land-ocean temperature index for the last half of the twentieth century is shown in Figure 7 averaged over the globe and over the tropics. The dates of major volcanos are marked for reference, as are the occurrences of El Ninos and La Ninas. The timing of El Ninos and La Ninas is based on the temperature maps of section 9.1 below but corresponds closely with Southern Oscillation indices [*Rasmusson*, 1985].

El Ninos and La Ninas show up prominently in the low-latitude temperature. Their impact also can be seen in the global temperature but only in approximate accord with the portion of the global area (40%) represented by the low latitudes. In general, an El Nino or La Nina causes the global temperature to deviate from its mean trend line by at most 0.2°C. In only two instances in this half century were there somewhat larger deviations of temperature, in 1964 and 1992, both cases occurring after a large volcano.

The data in Figure 7 provide only weak support for the contention of *Hunt* [1999] that the frequency of La Ninas has decreased in concert with the global warming of the past two decades; nor does the data in Figure 7 suggest that the strongest El Ninos of the last two decades, in 1983 and 1997-1998, had an unusual impact on tropical temperature compared with earlier large El Ninos. However, the maps of temperature anomalies in section 9.1 reveal that the La Ninas of recent decades have been unusually weak. The maps also show that the El Ninos of 1983 and 1997-1998 were unusually strong within the Pacific Ocean region, and that the El Ninos that stand out in Figure 7 are those (including the 1997-1998 El Nino) which were accompanied by warm conditions in the Atlantic and/or the Indian Oceans.

A simple description of the long-term temperature change in this half century (1950-1999) is that there was no trend of either tropical or global temperature in the first half of the period but then a rather strong warming in the second half of the period. A more detailed description is that there was no trend in the first 25 years, a sharp increase of temperature (by about 0.2°C) in the late 1970s, followed by a weak warming trend for about two decades, and then possibly another jump in the late 1990s.

The final three seasons in Figure 7, through mid-1999, suggest that the cooling due to the current La Nina may already be achieving its maximum effect. If that is correct, and if the seasonal temperature begins to rebound from the strong decline of the past year, then it appears that global temperature indeed has moved to a significantly higher level, perhaps to an average of about 0.5°C above the 1951-1980 mean. There is a precedent in this record, from mid-1973 to mid-1976, when prolonged La Nina cooling helped drag down global temperature for an extended period (Figure 7 and section 9.1). However, rebounds of tropical mean temperature have occurred after all La Ninas in this half century, in most cases accompanied by a rebound in global mean temperature. Thus, as discussed in section 9.2, we anticipate confirmation within the next several seasons, after the current La Nina dissipates, that global temperature has moved to a higher level.

7.3. Monthly Mean Temperatures

Monthly mean global temperatures are shown in Figure 8 for the present decade. These monthly data are affected more by weather noise than the seasonal mean (Figure 7), but longer term features such as the cooling after the Mount Pinatubo eruption of 1991 and the 1998 El Nino are still apparent. Figure 8 also shows that the meteorological stations, despite their limited geographical coverage, do a good job of reproducing the more truly global land-ocean temperature index. Figure 8 is updated each month on our web site (www.giss.nasa.gov/data/update/gistemp/graphs/).

The global temperature in mid 1999 has fallen to a level typical of 1997. However, despite the appearance of this graph, we suggest in section 9.2 that the underlying global temperature, i.e., the average over two or three years, moved to a significantly higher level in 1998. Simple comparison of the mid 1997 and mid 1999 temperatures may be misleading regarding long-term change, because the planet at those 2 times is in different phases of the tropical El Nino cycle. Also, simulations with a global climate model using current SSTs as a boundary condition [*Hansen et al.*, 1999] indicate that the planet with mid-1999 ocean temperatures is out of radiation balance, with net energy inflow to the planet. We infer that the mid-1999 temperature is a floor from which global temperature will soon rise.

8. Decade-Century Regional Temperature Change

8.1. Global Maps of Temperature Change

Global patterns of surface temperature change provide invaluable clues about the mechanisms, both natural fluctuations and anthropogenic influence, which may be involved in decade-to-century climate change. We focus especially on the past half century, which is the time with the most complete climate observations, an unusually large rate of climate change, and the largest and best measured anthropogenic climate forcings. For these reasons we believe that successful description of this period is the sine qua non of any claimed interpretive and predictive capabilities for decade-to-century climate change.

The principal features in temperature change of the past 50 years (Plate 4) are (1) a strong warming trend in northern Asia and northwest North America, (2) cooling in the North Atlantic and Greenland region, centered on Baffin Bay, and (3) nearly ubiquitous tropical warming. We comment here only briefly about climate mechanisms that might be involved in this climate change. The data invite interpretation, which can be pursued with or without the help of climate models.

The map of temperature change in Plate 4 reveals detail associated with the earlier observation (Figure 6) [see also *Hanson et al.*, 1989] that the United States has not warmed as much as the rest of the world this century. Indeed, the eastern half of the United States has cooled in the past half century. At first glance, the cooling in the United States seems to be associated with the large area of cooling centered in Baffin Bay and covering much of the North Atlantic Ocean. Such cooling might be associated with an unusually strong cool phase of the North Atlantic Oscillation [*Hurrell*, 1995], a reduction in ocean heat transports which has been found in climate model simulations with increasing greenhouse gases [*Manabe and Stouffer*, 1995; *G. Russell*, private communication, 1999] and suggested earlier by Broecker, et al. (1985), or a tropospheric response to greenhouse gas induced stratospheric cooling [*Shindell et al.*, 1999].

Examination of the observed temperature change suggests that more than one mechanism probably is involved in this climate change. For one thing, the cooling in the United States is spatially separated from the North Atlantic cooling by an area that is not cooling, as revealed more clearly in the seasonal temperature change shown in the bottom part of Plate 4. Secondly, the cooling in the United States is greatest in the summer, while the North Atlantic phenomenon associated with all of the above explanations is primarily a winter effect. Finally, the cooling in the United States occurred mainly in the period 1930-1970, while the cooling in the North Atlantic was greatest after 1960.

One candidate mechanism for summer cooling is anthropogenic tropospheric aerosols; indeed, the spatial distribution of increasing anthropogenic sulfate aerosols in the period 1950-1998 [*D. Koch*, private communication, 1999] coincides closely with the region of summer cooling. *Karl et al.* [1995] have shown empirical evidence for cooling in several regions around the world with heavy aerosol loadings. However, we suggest caution toward attributing a dominant role to aerosols for the United States cooling. The strong SST anomalies off the west coast of North America and in the North Atlantic Ocean during the warm season (Plate 4) suggest that accompanying atmospheric circulation anomalies play an important role. Although aerosols might be involved in causing SST anomalies, other forcings and unforced variability are also viable candidates.

Another reason to be cautious in interpreting these decadal climate variations is provided by Plate 5, which shows surface temperature change during several multidecadal periods. Perhaps the most relevant feature in Plate 5 is the cooling in the Baffin Bay region during the 1870-1900 period, which seems to be at least as strong as the cooling in recent decades. Presumably, there was little anthropogenic climate forcing in that era, indicating that such regional cooling can occur naturally.

Such observed multidecadal variability of temperature has been described and analyzed by *Mann and Park* [1994, 1996], *Kushnir* [1994], *Schlesinger and Ramankutty* [1994], and *Hurrell* [1995], and the association of variability in the North Atlantic Ocean with climate in Europe and the United States has long been recognized [*Walker*, 1932; *van Loon and Rogers*, 1978]. *Rodwell et al.* [1999] have shown that climate models driven by observed SST variations can simulate some observed variations of the atmospheric circulation, and *Delworth et al.* [1993, 1997] have shown that an unforced coupled atmosphere-ocean model can generate irregular multidecadal oscillations in the North Atlantic resembling those observed.

Systematic climate model experiments that examine different forcing mechanisms one by one should be helpful for understanding these past climate changes and thus for anticipating future change. Experiments driven by observed SSTs for 1951-1997 [*Hansen et al.,* 1999] indicate that the SST patterns alone, without any explicit radiative forcings, cause a cooling in the United States comparable to that observed. Full analysis will require experiments with more fully interactive ocean-atmosphere coupling, but it should be easy to quantify the contributions of different ocean regions via additional experiments with specified geographically limited SST anomalies.

As cooling in the United States seems to be partly associated with cooling in the North Atlantic, and evidence from the past few years suggests a warming trend in the North Atlantic (section 9), it is tempting to suggest that temperatures in the United States are likely to rise in the next decade. Figure 6 also suggests that United States temperatures, after bottoming out in 1979, are now into a warming trend. Continuation of that trend would make United States temperatures more consistent with observed global warming and with the expectation from climate models that an increasing greenhouse effect will warm middle-latitude land areas strongly. Possible complications in transient regional climate change, including changes in ocean circulation, dictate caution in such data interpretation, especially in the absence of a demonstrated ability to simulate and understand past regional climate changes. We conclude only that it is likely that the U.S. temperatures will increase in the next decade, which will make the mean temperature at least rival that of the 1930s.

Additional perspectives on regional temperature change can be obtained from maps of temperature anomalies and trends for arbitrary periods. Such maps are available from our web site (section 10).

8.2. Zonal Mean Temperature Change

A concise perspective on global temperature change in the past century is provided by the zonal-mean surface air temperature anomaly as a function of time (Plate 6). This presentation emphasizes the contrasting natures of the current global warmth and the warm period that peaked in 1940. The earlier warmth occurred predominately at high latitudes in the Northern Hemisphere, peaking at the North Pole. The recent warming encompasses essentially all latitudes, including the tropics.

The one exception to the strong warmth in the 1990s occurs in high southern latitudes. We speculated in section 6.3 about the possible influence there of transient negative radiative forcings, specifically volcanic aerosols and ozone depletion. However, because of the large unforced variability of polar temperatures, an emphasis on deterministic descriptions of temperature fluctuations there may be inappropriate.

Plate 7 provides higher temporal resolution for the zonal-mean surface temperature index. The El Ninos of the past two decades are especially apparent. The 1983 and 1997-1998 El Ninos had intense cores of warmth just south of the equator. However, beginning with the El Nino of 1986-1987, warmth has been pervasive at all tropical latitudes, even during a time (1995-1996) when there was no El Nino in the usual sense with a positive anomaly of SST in the eastern equatorial Pacific Ocean.

The change of surface temperature as a function of season and latitude is illustrated by Plate 8. In the tropics the warming occurs throughout the year. At higher latitudes the warming is largest in the winter and, especially at northern latitudes, in the spring.

There is a narrow band of latitudes in the Northern Hemisphere, approximately 30°N-40°N, for which the zonal mean surface temperature exhibits practically no warming throughout the year. It is apparent from Plate 4 that this is a combination of warming at some longitudes and cooling at others. Cooling occurs in the North Pacific Ocean, the eastern United States, and the Middle East, and there is little temperature change in Northern India and China.

9. Year-to-Year Regional Temperature Anomalies

9.1. Cool Season and Warm Season Anomalies

We define the (Northern Hemisphere) cool season as the six months November-April and the warm season as May-October. We see several merits to the use of these 6 month periods in climate analyses. First, the use of six months, as opposed to shorter intervals, minimizes the effect of weather noise in the climate anomalies. Second, the use of only two seasons per year makes it practical to compare simultaneously many years, even decades, of climate data, as shown by Plates 9a and 9b.

The Northern Hemisphere cool season anomalies (Plate 9a) illustrate interannual and decadal changes of temperature in the North Atlantic region discussed by *Kushnir* [1994] as well as the larger scale Arctic Oscillation discussed by *Thompson and Wallace* [1998]. Note that in the Northern Hemisphere cool season for the past 3 years, Central Asia has continued to have warm anomalies despite relative warmth in the North Atlantic and Baffin Bay regions. It will be interesting to see if the pattern of the past few years continues, because it does not match well with the usual tendency of the Arctic Oscillation by itself; it may, however, be consistent with a combination of the Arctic Oscillation and a global warming trend that is strongest in Asia.

The cool season and warm season surface temperature anomaly maps also define the occurrence and duration of El Ninos (1951, 1953, 1957-1958, 1963, 1965-1966, 1969, 1972-1973, 1976-1977, 1979-1980, 1982-1983, 1987-1988, 1991-1992, 1997-1998) and La Ninas (1950, 1954-1956, 1961-1962, 1964, 1967-1968, 1970-1971, 1973-1974, 1975-1976, 1978, 1984-1985, 1988-1989, 1995-1996, 1998-1999). Specification of an El Nino or La Nina occurrence is somewhat arbitrary, as the surface temperature anomalies in the tropical Pacific Ocean cover a continuous range, but for most applications, this choice is probably made best on the basis of such temperature anomaly maps.

The temperature anomaly maps in Plates 9a and 9b show that the La Ninas in the past two decades have been unusually weak and illustrate the well-known fact that the El Ninos of 1983 and 1997-1998 were very strong in the eastern and central Pacific Ocean. These maps also reveal that some El Ninos, particularly those of 1957-1958, 1969, 1972-1973, 1987-1988, and 1997-1998, were accompanied by unusually high temperatures in the Atlantic and/or Indian Oceans, which accounts for the magnitude of the tropical zonal-mean warmth for those years in Figure 7.

Another possible use of such maps is to heuristically compare anomalies in one region with anomalies in other regions. Possible relationships can be investigated statistically with the full data set and mechanistically by comparing the observed temperatures with ensembles of global climate simulations for different atmospheric and surface forcings.

Finally, we note that the cool and warm seasons can be averaged to yield an annual (November-October) temperature anomaly that probably serves just as well for annual mean analyses as either the meteorological year (December-November) or the calendar year (January-December). Figure 9 shows that the global mean temperature anomaly has little dependence on this choice.

9.2. The 1998 and 1999 Temperatures

A global map of the surface temperature anomaly for 1998 is shown in Plate 10. The strong El Nino of 1997-1998 [*McPhaden*, 1999] contributes to the record global temperature, but the global warmth is too strong to be accounted for solely by the El Nino. Figure 7 and previous analyses [*Jones*, 1989; *Angell*, 1990] indicate that El Ninos typically increase global mean temperature by only about 0.2°C, the amount by which the 1998 temperature exceeded the previous high temperature in the past century. Thus the 1998 global temperature would have been at or near a record value for the period of instrumental measurements even without the El Nino.

The global warmth of 1998 was also too pervasive geographically to be solely the result of an El Nino (Plate 10). The surface temperature was unusually high throughout the Atlantic Ocean and the Indian Ocean and over all of the continents except Antarctica. The Arctic north of North America was about 3°C above the 1951-1980 mean. The temperature just south of Greenland and in Baffin Bay was well above normal, consistent with indications from the previous two years (Plates 9a and 9b) that the long extended cold phase of the North Atlantic Oscillation [*Kushnir*, 1994; *Hurrell*, 1995] has drawn to a close.

The first half of 1999 has cooled considerably from 1998 (Figures 7, 8 and Plates 9a, 9b and 10). The global temperature anomaly fell to about 0.3°C in March-May 1999 (Figure 7), with low temperatures in the equatorial Pacific Ocean (Plate 10) which can be expected to lead to low global tropospheric temperatures. However, the cool Pacific Ocean only enhances the planetary energy imbalance [*Hansen et al.*, 1997, 1999] which tends to increase surface temperature. The present cool surface temperature in the Pacific Ocean is somewhat analogous to that of the mid-1970s, which persisted about 3 years (Plates 9a, 9b), but the temperature was lower then and the radiative forcing was less. We thus anticipate that the global surface temperature will return to higher values and average at least 0.5°C relative to the 1951-1990 mean over the next 2-3 years. At this level the period beginning in 1998 would represent an increase comparable to that which occurred in the late 1970s.

Recent data for 1999 (June-July-August, Plate 10) has a few warm places over the ocean, especially at middle northern latitudes in the Atlantic, and an interesting "African El Nino" at 5°S (similar, weaker, such features occurred with the La Ninas of 1984 and 1988 (compare Plates 9a and 9b)). However, relatively cool water has spread over much of the Pacific Ocean, so that, according to climate model calculations (Hansen et al., 1999), the ocean and the planet as a whole are in a mode of soaking up heat.

10. Data Products

All of our data (except the station records) are in the form of anomalies relative to the 1951-1980 mean temperature. We work with anomalies because the monthly temperature anomaly is representative of a much larger area, to distances of the order of 1000 km or more at middle and high latitudes (HL87), than the absolute temperature. Thus area-averaged temperature anomalies can be defined more accurately than the area-averaged absolute temperature. Furthermore, since anomalies are sufficient to define climate change, for many purposes anomalies are all that is needed. Estimates of global climatologies of absolute temperature are available from *Shea* [1986], *Legates and Willmott* [1990], and *Jones et al.* [1999].

We recommend that our data only be used for applications requiring temperature change, not absolute temperature. However, for the sake of users who need an estimate of absolute global mean temperature, we point out that an approximation of time-dependent global temperature can be obtained by adding a constant to our global temperature anomaly. The value 14°C was obtained as a typical global mean surface air temperature in the GISS global climate model when it is run with observed sea surface temperatures [*Hansen et al.,* 1997]. A global mean temperature of 14°C is also obtained by *Jones et al.* [1999] when they integrate their absolute surface air temperature climatology over the globe. Although these estimates of absolute global mean temperature are not accurate to 0.1°C, for the sake of consistency between the Jones data and the GISS data, one can add 13.9°C to our temperature anomalies and 14°C to the Jones anomalies. The reason for this is that we define our anomalies relative to the base period 1951-1980, while Jones defines his relative to 1961-1990, and the mean temperature for 1961-1990 is 0.1°C warmer than for 1951-1980.

Our data are available over the web site of the NASA Goddard Institute for Space Studies (www.giss.nasa.gov/data/update/gistemp/). Data sets can be downloaded directly from the web or via ftp. In addition, the following displays of the data, which are updated regularly, are available from our web site.

10.1. Global Mean Graphs

Line graphs are provided for the global monthly mean, seasonal mean, and annual mean temperature anomalies. A tentative estimate of the seasonal anomaly is estimated when the first two months of data are available, and a tentative annual anomaly is estimated when three seasons of data are available.

10.2. Global Maps

Global maps of temperature anomalies are available for monthly, seasonal and annual periods. The user can also obtain the average of these maps over an arbitrary period. The base period for calculating anolmalies can be specified to be different than the default period, 1951-80.

A second global map provided is the temperature change over an arbitrary period, analogous to Plate 4. The local temperature change is based on the local linear trend of temperature using all years in the period of interest. The calculations, which are done on our local web server, require several seconds.

10.3. Animations

Animations of the global temperature anomalies are available on the basis of monthly temperature data. These require that the user's computer be equipped with software for displaying animations.

10.4. Station Data

The station data can be obtained by specifying a location name or pointing a cursor at a global map. In the latter case, a list of stations appears ordered by distance from the specified point. After clicking on one of these stations, a new list appears ordered by distance from the chosen station. The user can then choose to view either a single station record or the records for the primary station plus a specified number of neighbors. The station data are also available via our Common Sense Climate Index, where for the urban stations, both the homogeneity-adjusted and unadjusted records are provided.

11. Discussion

11.1. Global warming

We discuss observed global temperature change of the past century, the past 25 years and the past two years.

11.1.1. The past century: Observed global warming on the century time scale is unambiguous and unusual. We estimate that the 5 year mean global surface temperature has increased about 0.7°C since the late 1800s. The current global warmth is not only a record for the period of instrumental data but also the warmest level in at least the past few centuries [*Mann et al.*, 1998; *Jones and Bradley*, 1992]. Although it becomes increasingly difficult to reconstruct accurately the global mean temperature for earlier times, current temperatures must be at least comparable to those of the climatic optimum that occurred near 1100 AD [*Hughes and Diaz*, 1994]. Indeed, *Mann et al.* [1999] argue that the 1998 global temperature was probably higher than any earlier time in this millenium.

The issue about whether global warming might be largely a figment of nonclimatic influences on the thermometers at meteorological stations [*Ellsaesser et al.,* 1986] has been settled. The fact that warming is essentially the same for rural stations (population less than 10,000) as for all stations would not be convincing by itself, because nonclimatic human effects can exist even in small towns. However, there is extensive additional evidence. The simplest evidence is the global distribution of the warming (Plate 4). Not only does the largest warming occur in remote ocean and high-latitude regions, where local human effects are minimal, but the geographical patterns of warming represent climatic phenomena, not patterns of human development. Borehole temperature profiles from hundreds of locations around the world have been used to infer a mean warming of 0.5°-0.6°C between the 1800s and the 1980s [*Harris and Chapman*, 1997; *Pollack et al.*, 1998]. Analysis of the near-global meltback of mountain glaciers on the century time scale yields an estimated global warming rate of 0.66°C/century [*Oerlemans*, 1994]. These confirming analyses are not influenced by urban effects.

11.1.2. The past 25 years: Global surface temperature has increased at a rate of about 0.2°C/decade since the mid-1970s. Global warming of 0.5°C in 25 years is at least highly unusual in the past millennium and may be unprecedented [*Mann et al.*, 1999; *Hughes and Diaz*, 1994; *Jones and Bradley*, 1992]. The observed warming rate of 0.2°C/decade is just that calculated due to increasing greenhouse gases in global climate model experiments with greenhouse gas scenarios (slow growth, scenario B) that match observed greenhouse gas changes [*Hansen et al.*, 1998a]. The observed warming is less than the 0.3°-0.4°C/decade in IPCC "business as usual" scenarios [*IPCC*, 1995] or the 0.3°C/decade in the fast growth scenario A of *Hansen et al.* [1988], but the climate forcings in those scenarios exceed the climate forcing in the real world [*Hansen et al.,* 1998a].

The issue about global surface warming of the past two decades has been that it appears to be at odds with a slight cooling in the lower troposphere measured by satellites for the period 1979-1997 [*Christy et al.*, 1998; *Jones et al.*, 1997b; *Hurrell and Trenberth*, 1998]. We believe this apparent discrepancy arises from a combination of several factors. First of all, tropical surface temperatures increased only slowly between 1979 and 1997, as shown by Figure 7; thus we would not expect the global troposphere, driven by rising air in the tropics, to show much warming in that period. The global surface temperature increased between 1979 and 1997, but much of the surface warming in that period occurred in the cool season at high latitudes (Plate 5), where stable lapse rates cause the tropospheric response to be much reduce [*Hurrell and Trenberth*, 1996]. Another special factor in the past two decades has been ozone depletion, which cools the troposphere slightly more than it cools the surface [*Hansen et al.*, 1995, 1997].

Thus if one fixates on the period 1979-1997, a qualitative difference between the surface and the satellite temperature trends is not surprising. Both temperature trends are limited in magnitude because this period excludes the large rises in temperature that occurred in the late 1970s and in 1998. The tropospheric temperature change in 1979-1997 is limited by the small tropical surface temperature change and by ozone depletion. Given this situation, even small measurement errors can add to real differences between the surface and the tropospheric trends and have a large qualitative impact on their comparison. The satellite record is affected by the difficulty in homogenizing the record from several satellites that drift through the diurnal cycle and decay in altitude [*Christy et al.*, 1998; *Wentz and Schabel*, 1998; *Hurrell and Trenberth*, 1997, 1998; *Hansen* *et al.*, 1998b], and the surface record is affected by various measurement and sampling errors, as discussed above.

These difficulties can be minimized by extending the period of analysis. Extension of the tropospheric record back to even 1975 captures a greater temperature change. Although radiosonde measurements have their own problems [*Gaffen*, 1994], reliable extension of tropospheric temperatures certainly can be made at least back to 1975, which is sufficient to reveal a strong positive trend. Similarly, addition of data for 1998 and beyond adds to the climate change. With detailed analysis including these extensions of the record we expect that the surface and tropospheric data will be in much better qualitative agreement about the existence of long-term warming. Remaining quantitative differences, after instru-mental measurement problems are minimized, are a potentially valuable source of information on the workings of the climate system. We caution that exploitation of this potential information requires not only good temperature measurements, but also measurements of all the major climate forcings [*Hansen et al.*, 1998a].

11.1.3. The past two years: The magnitude of global warming in 1998 is noteworthy. Previous "record" global temperatures, for the period of instrumental data, were set in 1980, 1981, 1988, 1990, and 1995, but in these cases the previous record usually was broken by only a few hundredths of a degree Celsius. The global temperature of 1998 broke the previous record by almost 0.2°C.

The global temperature of 1998 was undoubtedly influenced by the strong El Nino that was present in the first half of 1998, and the influence of El Ninos on global temperature has been found to lag the El Nino by up to six months [*Pan and Oort*, 1983; *Jones*, 1994a]. Nevertheless, we argue that the recent warming probably represents a jump to a significantly higher level of global temperature. Although our estimate of global temperature in the most recent season is only about 0.3°C, we expect the global temperature to average about 0.5°C or higher, relative to 1951-1980, within the next 2 or 3 years.

Confirmation of such a high temperature level will have significance that extends beyond the question of short-term temperature records. Such a high temperature level should be sufficient to settle the contentious issue of whether global warming is occurring during the satellite era, regardless of measurement problems. More generally, maintenance of such a high global temperature over 2 or 3 years will represent a "smoking gun," providing both scientific and practical confirmation that global warming in the industrial era is unnatural. Scientifically, such continued warmth will make the present climate clearly the warmest of the millennium, with the greatest warming rate, exceeding previous epochs such as the "Medieval Climatic Optimum" [*Mann et al.*, 1999]. Practically, warming of a few tenths of a degree is probably all that is needed to begin to make global warming noticeable to the perceptive lay person [*Hansen et al.*, 1998c].

11.2. Regional temperature change.

Regional patterns of climate change have more practical impact than global mean temperature change. A principal challenge is to determine how much of observed regional climate change is a deterministic response to climate forcings and how much is unforced variability. Of course, this distinction depends upon the timescale considered and thus whether factors such as ocean temperature can be considered as forcings. Our objective is to provide data that can be used conveniently in analyses of observed climate change.

We emphasize the merits of analyzing the climate change of the past 50 years, a time when climate forcings are known best and have a rapid rate of change. Observed climate change of the past several decades includes substantial surface warming throughout the tropics. There has been even greater warming in Siberia and Alaska, especially in the winter and early spring, yet the Arctic has only recently approached the temperatures that it achieved in the 1930s. There has been a moderate cooling trend around Greenland and in the eastern United States during the past half century, but most of the cooling in the United States occurred between about 1940 and 1960. On the basis of the different seasonalities and time periods of these changes, we have argued that there is more than one phenomenon involved in this regional cooling. Changes of Pacific Ocean SSTs probably played a large role in causing the cooling trend in the United States.

We suggest that warming in the United States is likely in the next decade, making the mean temperature at least rival that of the 1930s. However, this inference is based to a large degree on the fact that the U.S. temperature has lagged the global mean temperature, contrary to expectations with global warming, and on the modest warming trend that has occurred since the 1970s. A more substantive prediction of regional climate change requires that we first demonstrate an ability to simulate and analyze regional changes of the past.

Appendix: Data Comparisons

We illustrate a few checks and comparisons for our global and United States temperature change analysis. Such comparisons do not yield a measure of absolute error, which is difficult if not impossible to specify because of inherent and common limitations of available data. However, they provide consistency checks and address questions that we asked ourselves and that others are likely to ask about our data.

A1. Comparison With Jones Data.

Plate A1 compares our data with that of *Jones et al.* [1999], with the latter labeled “Jones” in our figures. The Jones data are a combination of the land data analysis of *Jones* [1994b] and ocean data of *Parker et al.* [1995a], as described by *Jones et al.* [1999]. The ocean data in the Jones data set are MOHSST6D (Meteorological Office Historical Sea Surface Temperature, version 6D), thus both the land and the ocean portions are based on observations without filling of data voids via principal component or empirical orthogonal function analyses. For GISS data we show our analysis based on only meteorological stations and the combination of our data over land with GISST3.0 SST data [*Parker et al.*, 1995a]. The ocean data in this latter case (GISST3.0) have nominally the same source as the ocean data of Jones, but data interpolation and smoothing were necessarily employed in producing the GISST climatology, which is designed to be globally complete as suitable for climate models.

Plate A1a shows that the global mean temperature changes in these analyses are very similar. Differences among the three curves are shown on an expanded scale in Plate A1b. In the land plus ocean analyses the Jones and GISS + GISST results differ by as much as 0.1°C in only one year, 1941. It is evident from the global map of the difference for 1941 (Plate A1c) that it arises not from the land but rather from the ocean. This is presumably associated with poor data coverage or quality during World War II, although that observation by itself does not prove which ocean analysis is more accurate.

Larger differences occur between the GISS analysis based on only meteorological stations and either of the land plus ocean analyses, as expected, yet in most years, the differences are less than or of the order of 0.1°C. An instructive case is provided by 1981, which is the year with the largest difference between the GISS station analysis and the Jones land plus ocean analysis during the past half century, with the GISS land analysis 0.15°C warmer than the Jones land plus ocean result. The greatest contribution to this difference comes from the North Pacific Ocean, where a region of low temperature is entirely missed by the meteorological stations and replaced by high temperatures extrapolated from Alaska, Hawaii, and northeast Russia. It also appears that part of the larger global warmth in the GISS station analysis, perhaps 0.05°C, arises from extrapolation of warm anomalies into the Arctic and Antarctic; on the basis of meteorological patterns of the anomalies, it is possible that this portion of the higher GISS estimate may be valid. Nevertheless, the 1981 example illustrates that occasional errors exceeding 0.1°C in estimated global temperature are inherent if the input to the global analysis is restricted to land data. This is consistent with the uncertainty bars in our Figure 4.

Systematic differences in the analyses early in the twentieth century and in the late 1800s average only about 0.1°C. The spatial sampling for both land and ocean is much poorer then, which must contribute to the increased differences among the data sets. However, there are also systematic difficulties with ocean data, such as changing bucket corrections [*Parker et al.,* 1995], so it is impossible to be certain which data set more accurately represents the decadal global mean temperature change. Rather we emphasize that the different records of global temperature change are very similar overall [Plate A1a], with the century timescale temperature change being much larger than the variations among the data sets.

Finally, we compare Jones data for the 1990s with GISS plus GISST and with GISS plus *Reynolds et al.* [1994] in the lower two rows of Plate A1c to investigate the systematically positive differences in Plate A1b. The difference between Jones and GISS plus GISST occurs mainly over land, averaging only 0.02°C globally. That difference arises because the Jones data does not average exactly to zero over the base period. The reason, at least in part, is that zero means are enforced station by station for that portion of 1961-1990 with data, and some stations have data only for a relatively cool part of the period (say 1961-1980) (P. Jones, private communication, 1999). In any case, 0.02°C is small relative to the climate change matters of interest. The difference between Jones and GISS plus Reynolds for the 1990s is larger, about 0.08°C. As shown by the last row in Plate A1c much of this arises from the high-latitude ocean analyses, where there are differences in the treatment of sea ice, as discussed in section 7.1. Also, 0.02°C of the 0.08°C arises from displacement of the base period mean, as discussed above.

Overall, we conclude that the differences among the analyses are small compared with the long-term temperature change, as illustrated by Plate A1a. Given the commonality of much of the input data, the similarity of the results does not prove the validity of the long-term changes, and such is not the intent of this intercomparison. Evidence in support of the long-term change is discussed in section 11.1.

A2. Urban Adjustment and U.S. Data.

We examine here the sensitivity of our analyzed temperature change to the urban adjustment, especially for the United States. We present results for the calendar year, January-December, rather than the meteorological year as in Figure 6, thus allowing a test of the sensitivity to that choice and helping comparison with other results that employ the calendar year, such as those of *Bell et al.*

[1999].

There is a high density of stations in the United States in the GHCN network, which includes the USHCN stations, with more than 1000 stations since about 1900. For most of the twentieth century, 55-60% of the U.S. stations are rural (population less than 10,000), about 20% are small town (population less than 50,000), and 20-25% are urban. However, in the final (near-real time) year of data, before USHCN data are available, the urban proportion of stations jumps to about 50-55%.

Plate A2a shows the temperature change for the contiguous 48 states on the basis of only rural stations, rural plus small town, all stations with no urban correction, and all stations with homogeneity-correction of urban stations (section 5). The temperature curve, based on rural stations, is not affected much by addition of small-town or urban data. The exception is the 1998 temperature, which would rival the 1934 record without the urban correction. Because the proportion of urban stations jumps from 20% in 1997 to 55% in 1998, the urban correction is important.

The effect of the urban adjustment on regional temperature change over the period 1950-1998 is shown in Plate A2b. The global average effect of the urban adjustment is only 0.01°C over this period, but there are several noticeable regional changes. In general, we cannot be confident in the validity of the adjustment in any specific region, because of the possibility of errors in the rural station data and regional variability of temperature change, as discussed in section 5. We are reasonably confident in the nature of the adjustment in the United States, which increases the cooling in the Southeast and decreases the warming in the Southwest. But the fact that the adjustment is not negligible suggests the desirability of trying and comparing alternative approaches for removing urban influence. A promising approach initiated by *Gallo et al.* [1999] is to use satellite observations of land use to define the degree of human influence on each station. This will be particularly useful if it is possible to define a rate of change of the human influence around each station.

Although the influence of the urban correction is moderate, even in the United States, the implied correction to the urban records themselves is larger. Urban warming in the United States presumably accounts for the upward trend of temperature found by *Gaffen and Ross* [1998, 1999], who employ National Weather Service “first-order stations” that are predominately urban. Such a station selection is appropriate for the objective of describing conditions where most people live. It may be useful to have, in addition, similar studies for areas that are relatively undisturbed by local human influence. Station selection presumably also influences the results of *Bell et al.* [1999], who report the United States as being as warm in the 1990s as in the 1930s, but they do not characterize their station selection.

In summary, we have not found any evidence that would qualitatively alter our conclusions about global warming in the past century or cooling in the United States between the 1930s and the 1970s. However, urban effects are nonnegligible, and studies of current climate trends need to pay close attention to station selection. We encourage research aimed at improved definition and removal of urban influences.

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Figure Captions

Figure 1. (a) Number of stations with record length *n* years or longer, (b) number of stations with defined annual temperature anomaly as a function of time, and (c) percent of hemispheric area located within 1200 km of a station.

Figure 2. Illustration of how two temperature records are combined. The bias ΔT between the two records is the difference between their averages over the common period of data. The second record is shifted vertically by ΔT and T_1 and T_2 are then averaged.

Plate 1. Temperature anomalies, relative to the base period 1951-1980, for 6 years that illustrate the change of station coverage with time (compare Figure 1c).

Figure 3. (a, b) Measured time series of temperature for Tokyo, Japan, and for Phoenix, Arizona; (c, d) adjustments required for linear trends of measured temperatures to match rural neighbors for the periods before and after 1950; and (e, f) adjusted (homogenized) temperatures.

Figure 4. Global annual-mean surface air temperature change based on the meteorological station network. Uncertainty bars (95% confidence limits), shown for both the annual and the 5 year means, are based on spatial sampling analysis of HL87.

Plate 2. (a) Global 5 year running-mean surface air temperature change based on rural, rural plus small town, all stations without any homogeneity adjustment, and all stations with the urban records adjusted as described in section 5. (b) Same as Plate 2a, but with the region used to calculate global temperature restricted to the common area where the temperature is defined for all data sets.

Figure 5. Annual and 5 year running-mean surface air temperature change for three latitude bands that cover 30%, 40%, and 30% of the global area. Uncertainty bars (95% confidence limits) are based on spatial sampling analysis of HL87.

Figure 6. Annual and 5 year running-mean surface air temperature (meteorological year, December-November) for the contiguous 48 United States relative to the 1951-1980 mean.

Plate 3. (a) Global annual-mean change of land-ocean temperature index with SSTs based on *Reynolds and Smith* [1994] compared with the (near) global surface air temperature anomaly based on the meteorological station network (Figure 4), (b) 5 year mean of this land-ocean temperature index, the same index with GISST [*Parker et al.*, 1995; *Rayner et al.*, 1996] used for the SST, and the near-global temperature change based on only land meteorological stations.

Figure 7. Surface temperature index change since 1950 at seasonal resolution, for the globe and for low latitudes. Semi circles mark La Ninas, rectangles mark El Ninos, and triangles mark large volcanos.

Figure 8. Monthly mean global surface temperature derived from meteorological stations alone and the land-ocean temperature index incorporating the SSTs of *Reynolds and Smith* [1994].

Plate 4. Change of surface temperature index for the period 1950-1998 based on local linear trends using surface air temperature change over land and SST change over the ocean [*Reynolds and Smith*, 1994], with the latter measured for the period 1982-1998 and calculated on the basis of ship measurements and an EOF analysis for 1950-1981 [*Smith et al.*, 1996]. (a) Based on annual mean temperatures; (b, c) results for the (Northern Hemisphere) warm (May-October) and cool (November-April) seasons.

Plate 5. Surface air temperature change for the periods 1870-1900, 1900-1938, 1938-1970 and 1970-1998 based on local linear trends derived from only meteorological station data.

Plate 6. Five year running mean of zonal surface temperature anomaly since 1880, based on surface air temperature measurements at meteorological stations. At each latitude the zero point of temperature is the 1951-1980 mean.

Plate 7. Seasonal-mean zonal surface temperature index since 1950, based on the land-ocean temperature index. At each latitude and season the zero point of temperature is the 1951-1980 mean.

Plate 8. Zonal mean change of surface temperature index during 1950-1998 as a function of month.

Plate 9a. Surface temperature anomalies for the (Northern Hemisphere) cool season for the past five decades.

Plate 9b. Surface temperature anomalies for the (Northern Hemisphere) warm season for the past five decades.

Figure 9. Annual mean temperature anomalies for cool season plus warm season (November-October), meteorological year (December-November), and calendar year (January-December).

Plate 10. The 1998 and 1999 temperature anomalies: (a) annual, (b) six seasons.

Plate A1. (a) Jones land plus ocean temperature change analysis [*Jones et al.*, 1999], our result based on meteorological stations, and the combination of our data for land areas with GISST3.0 SST data.. In all cases the base period is 1961-1990. (b) Differences of the Jones data and the other two analyses in Plate A1. (c) Maps of the Jones and GISS plus GISST data for 1941, Jones and GISS meteorological station data for1981, Jones and GISS plus GISST for 1990-1998 mean, and Jones and GISS plus *Reynolds et al.* [1994] for 1990-1998 mean. The global mean numbers in the top right-hand corner are based on the area-weighted four-zonal-band means (section 6.3); the result for Jones - GISS refers to the common area.

Plate A2. (a) Annual and 5 year running-mean surface air temperature for the contiguous 48 United States relative to the 1951-1980 mean for several choices of station data. (b) Change of surface temperature for 1950-1998 based on local linear trends for the same four choices of station data.

FIGURE 1

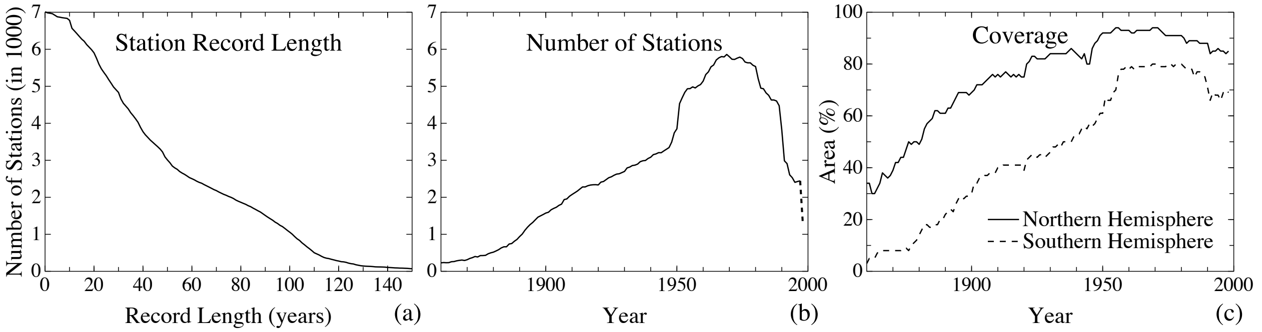


FIGURE 2

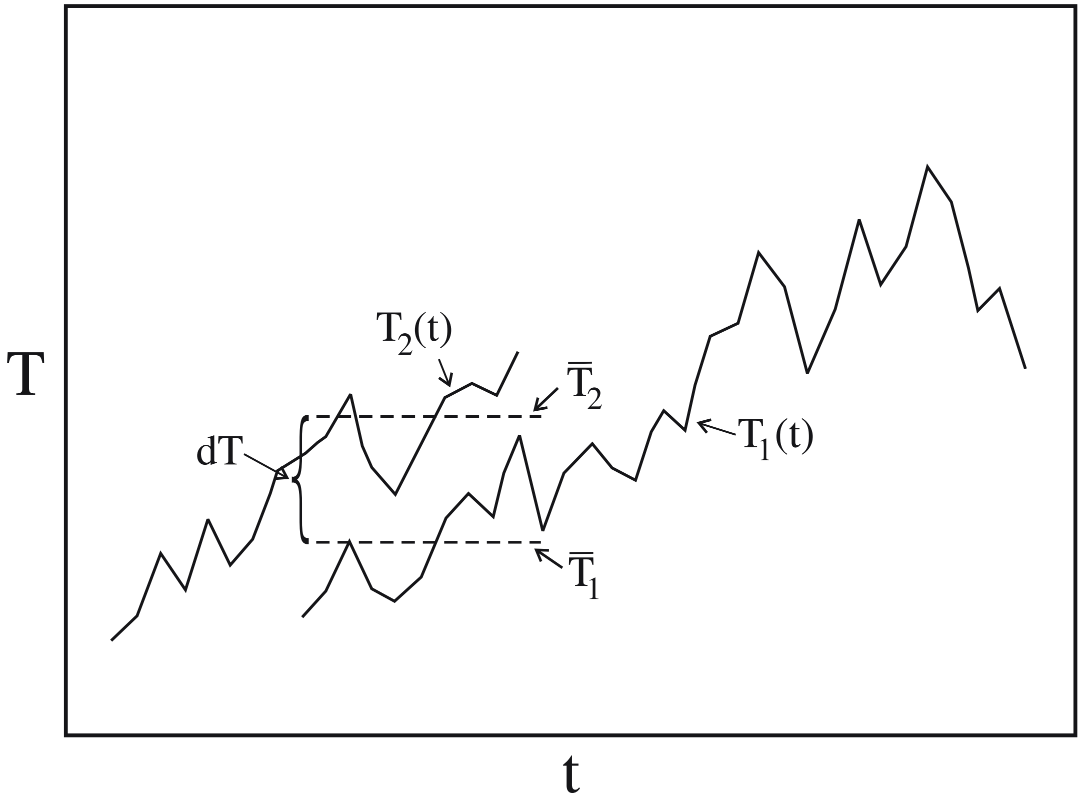


Plate 1

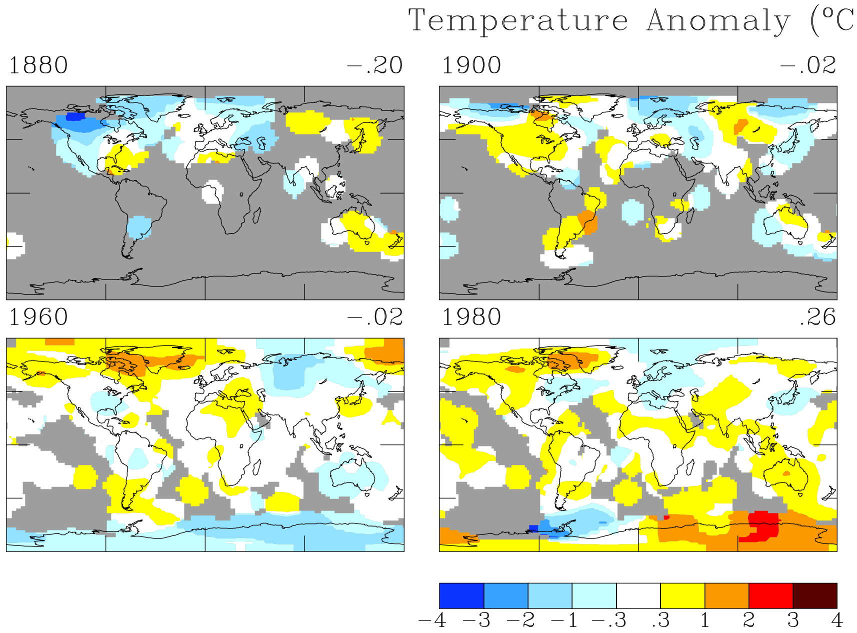


Figure 3

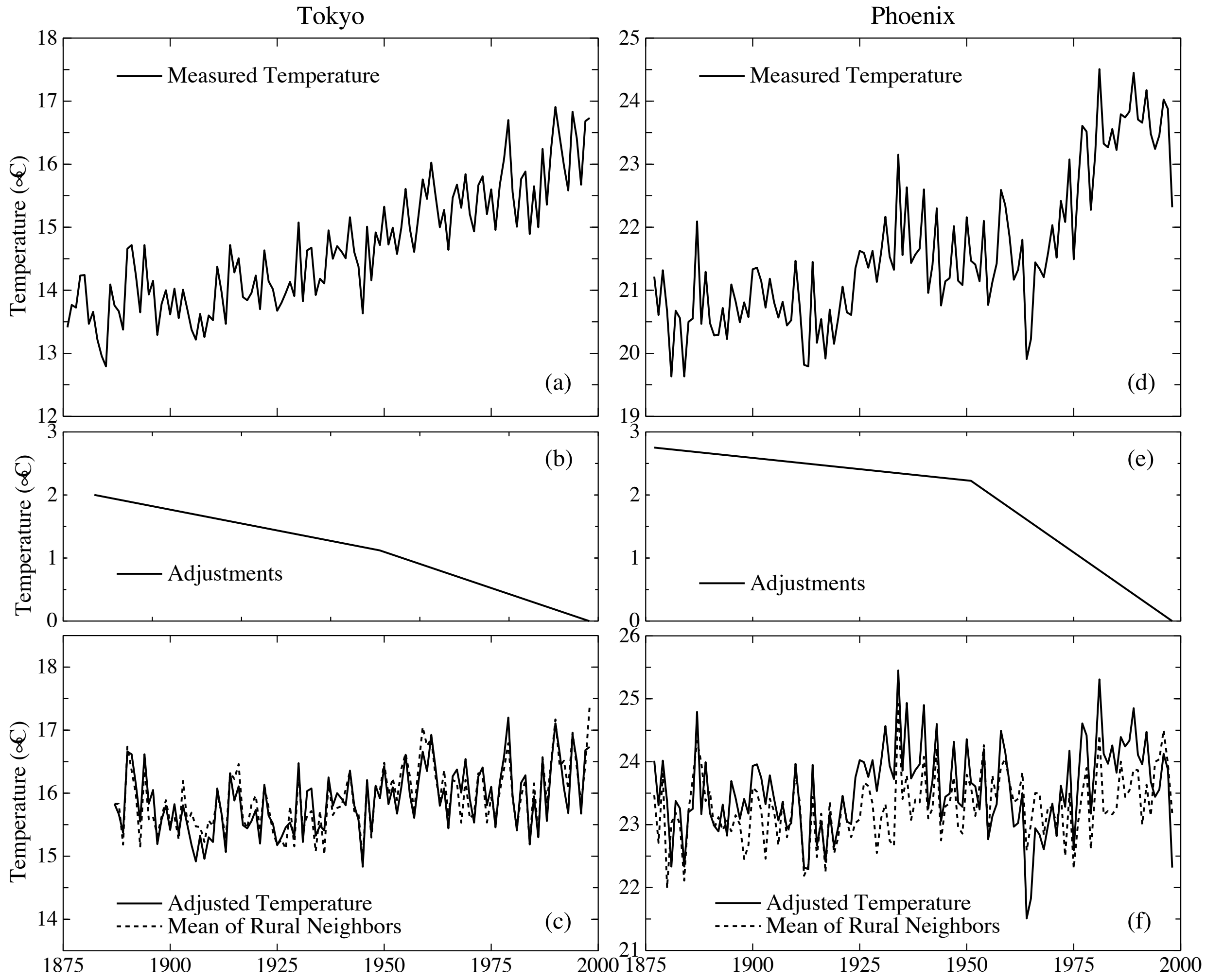


Figure 4

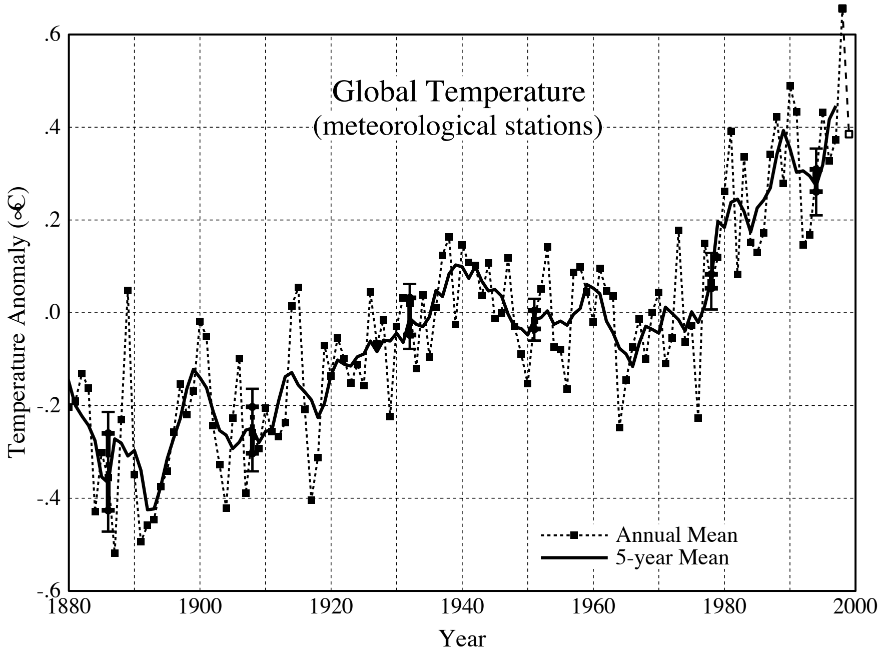


Plate 2

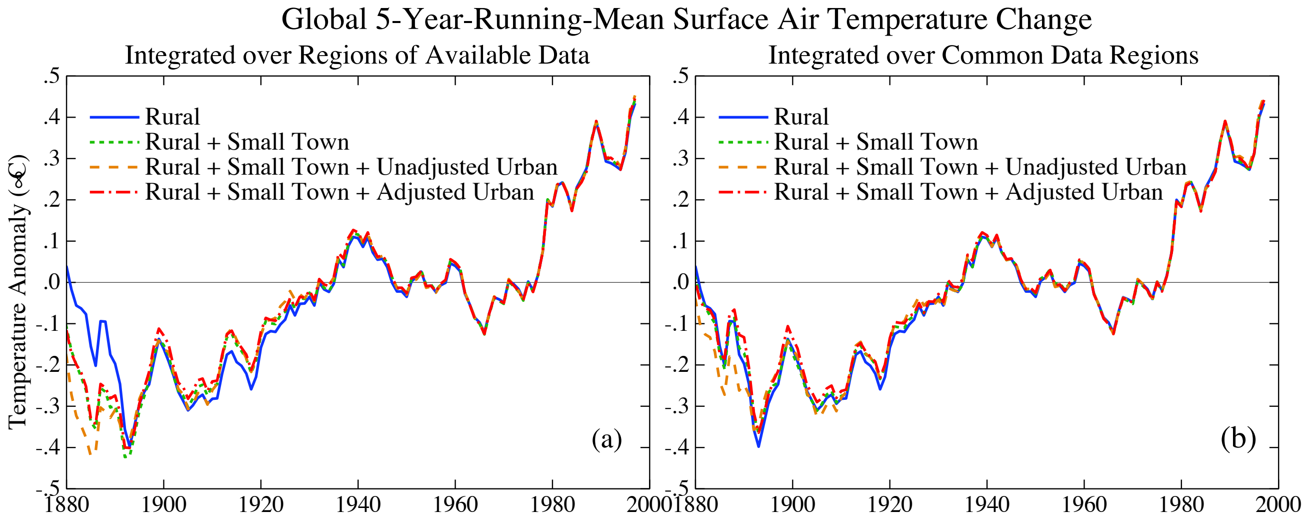


Figure 5

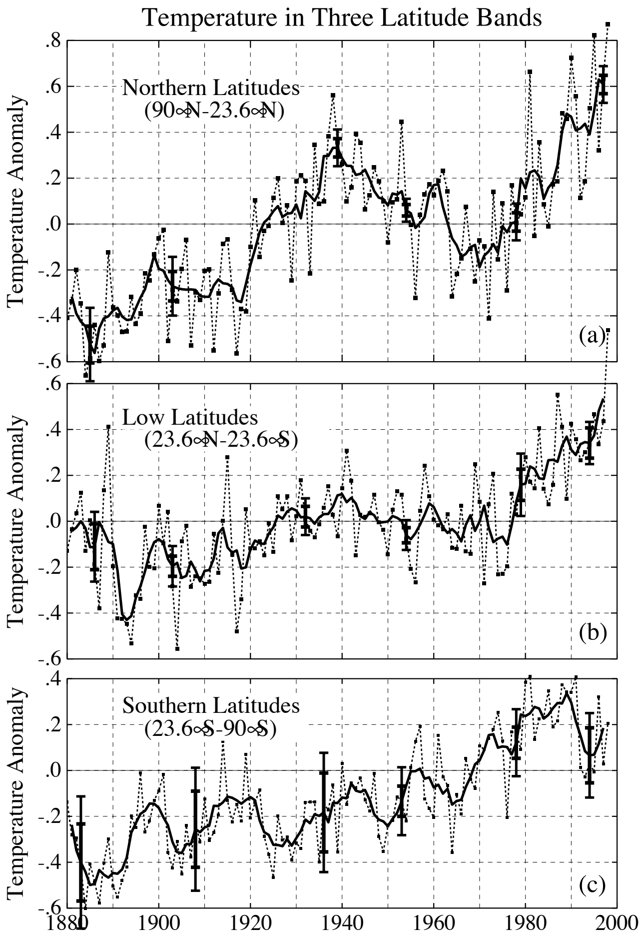


Figure 6

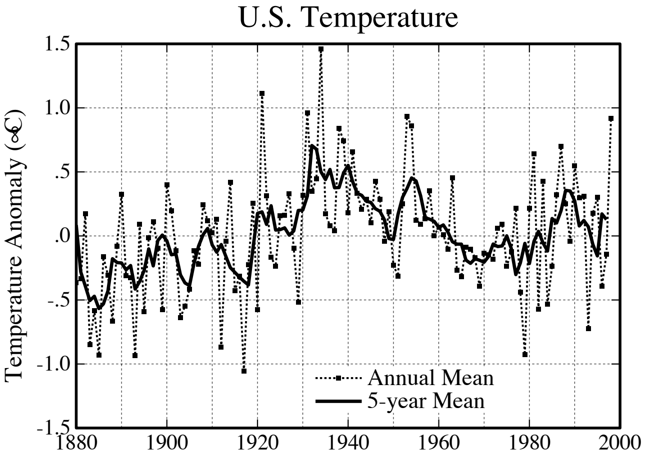


Plate 3

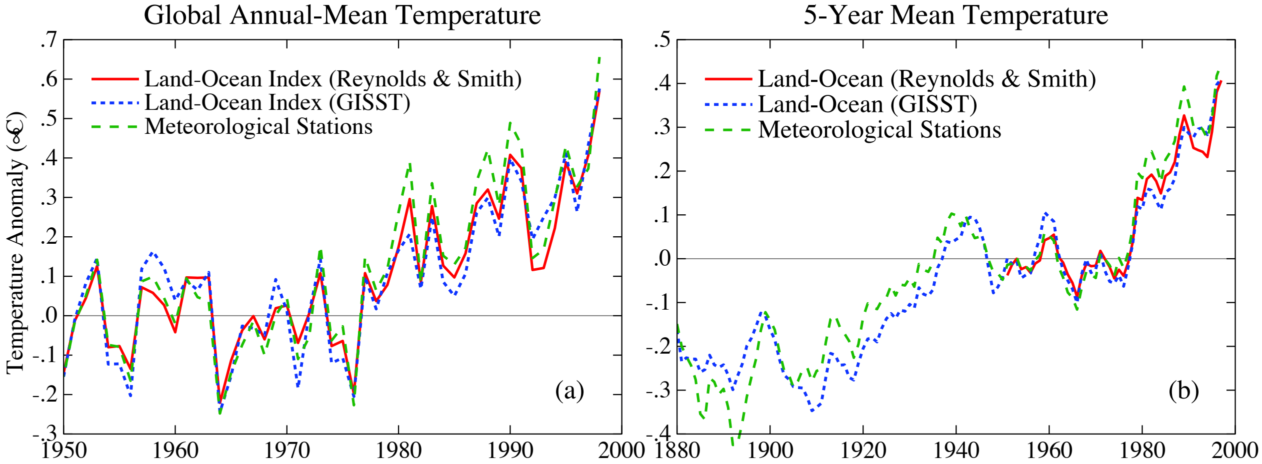


Figure 7

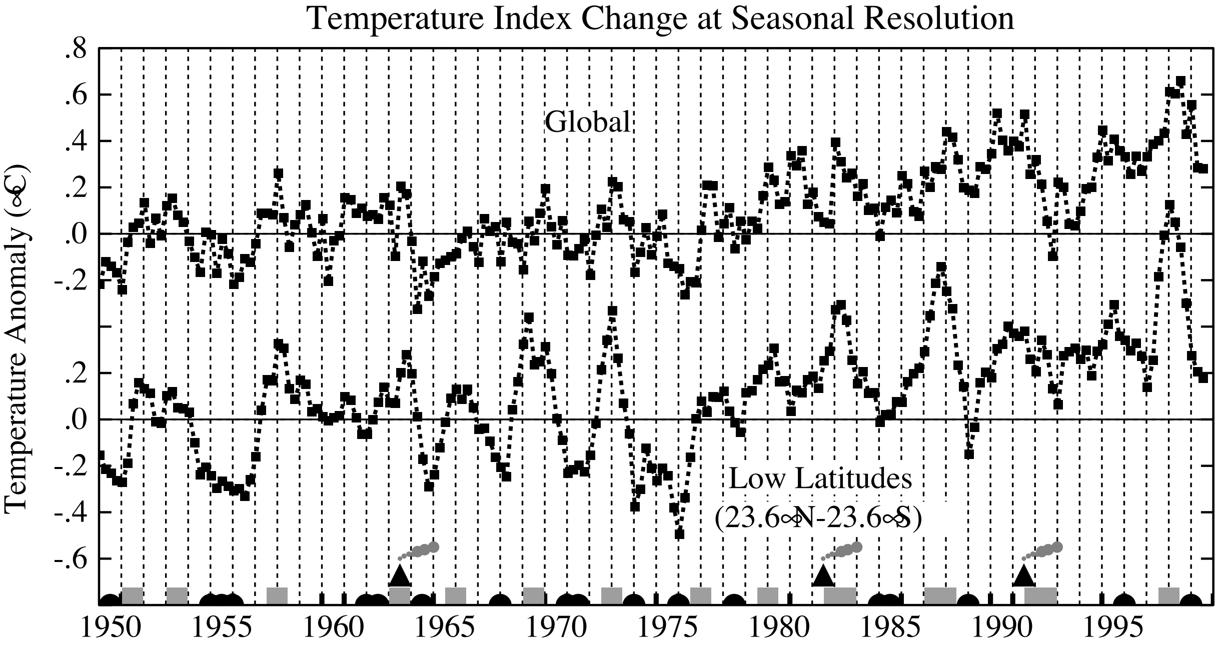


Figure 8

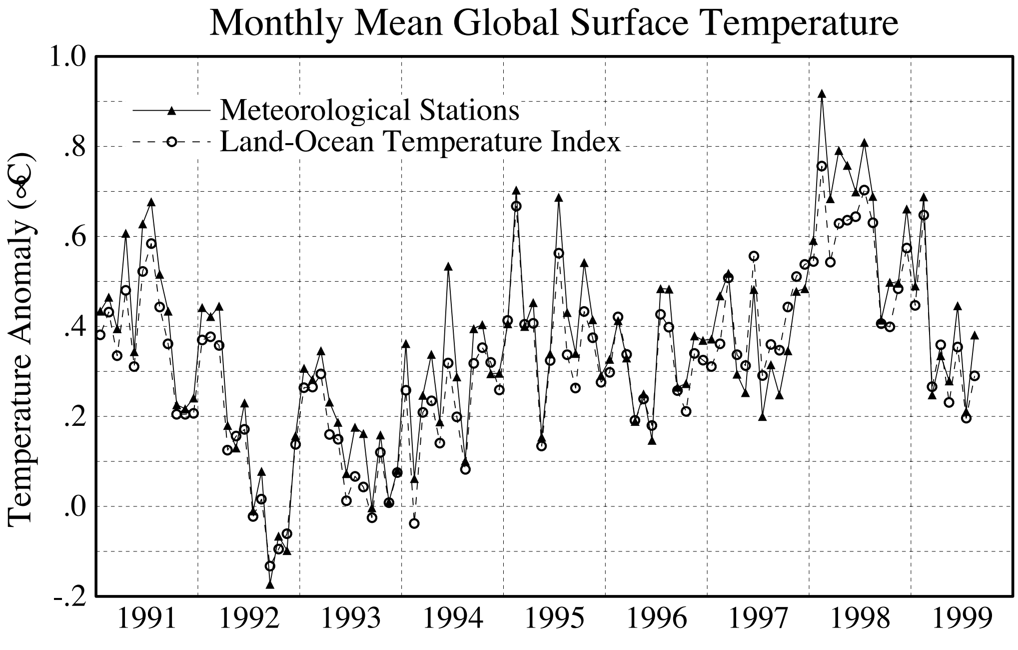
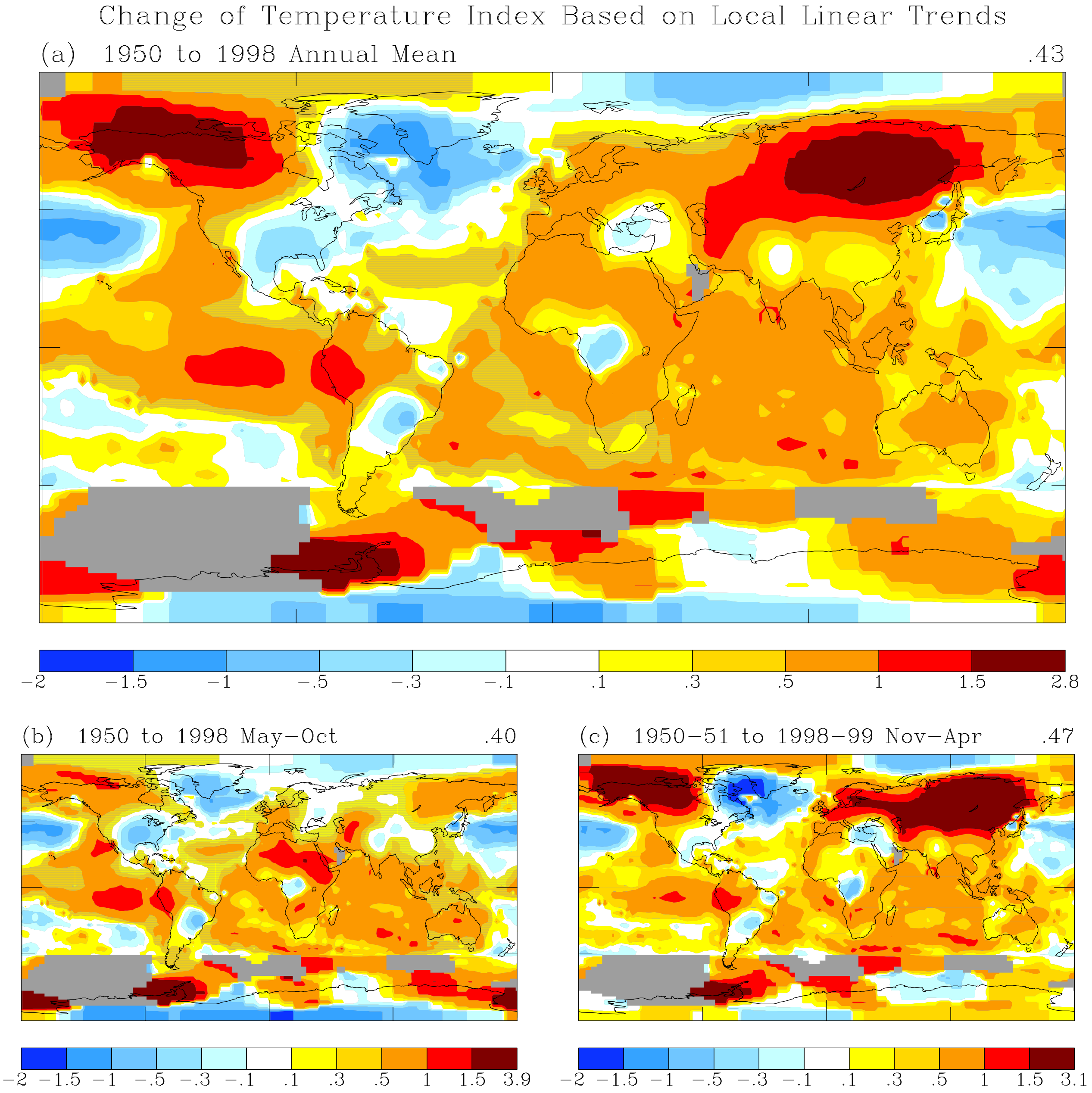


Plate 4



Change of Temperature Index Based on Local Linear Trends

(a) 1950 to 1998 Annual Mean .43

(b) 1950 to 1998 May−Oct .40

(c) 1950−51 to 1998−99 Nov−Apr .47

Plate 5

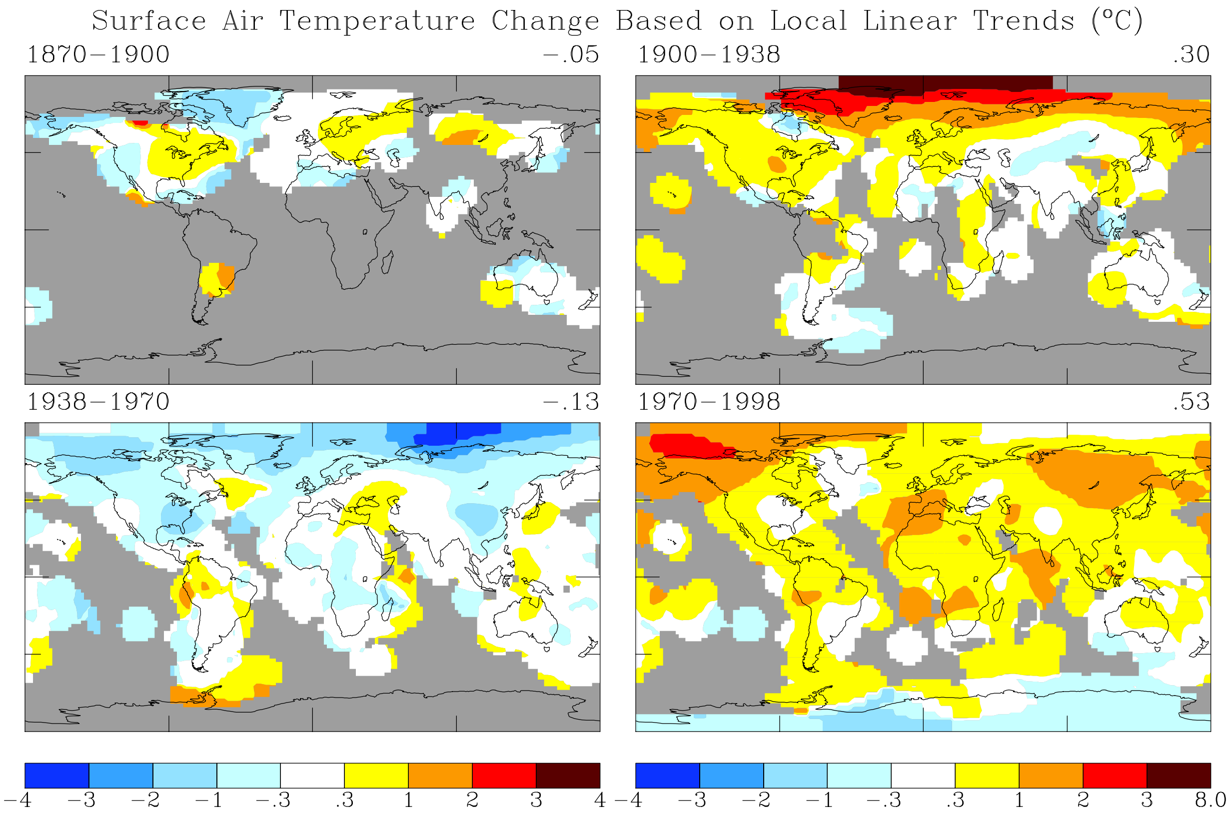


Plate 6

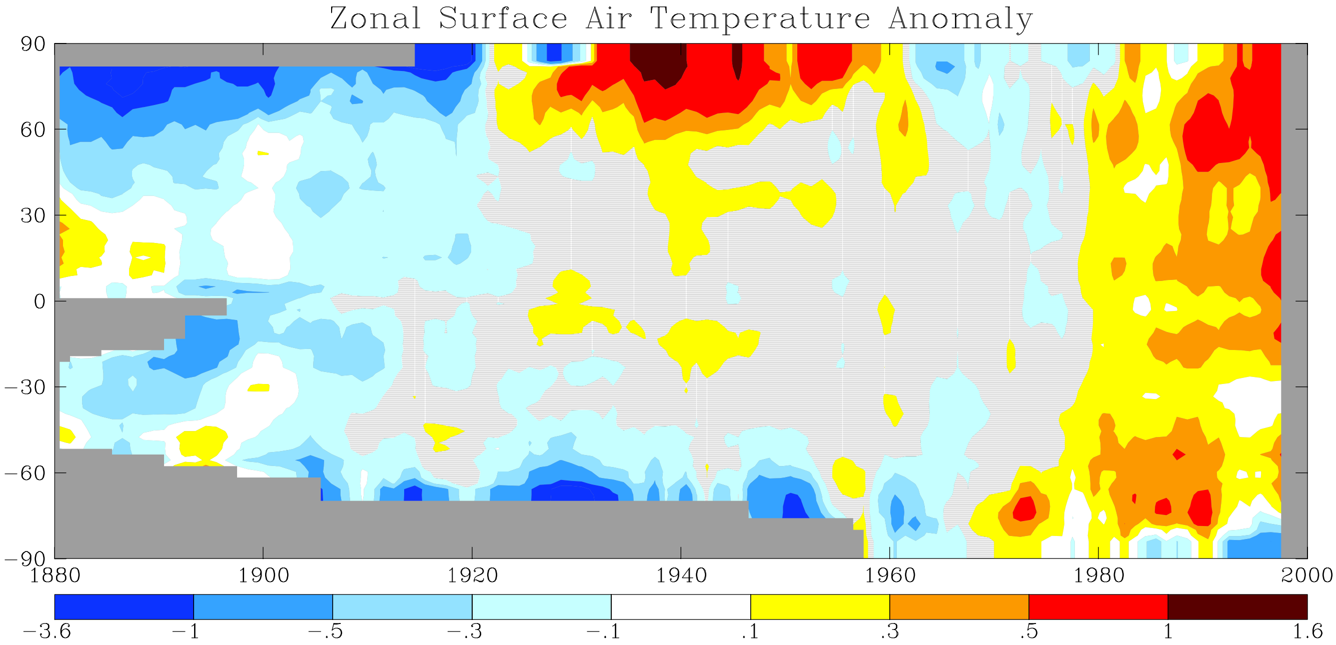


Plate 7

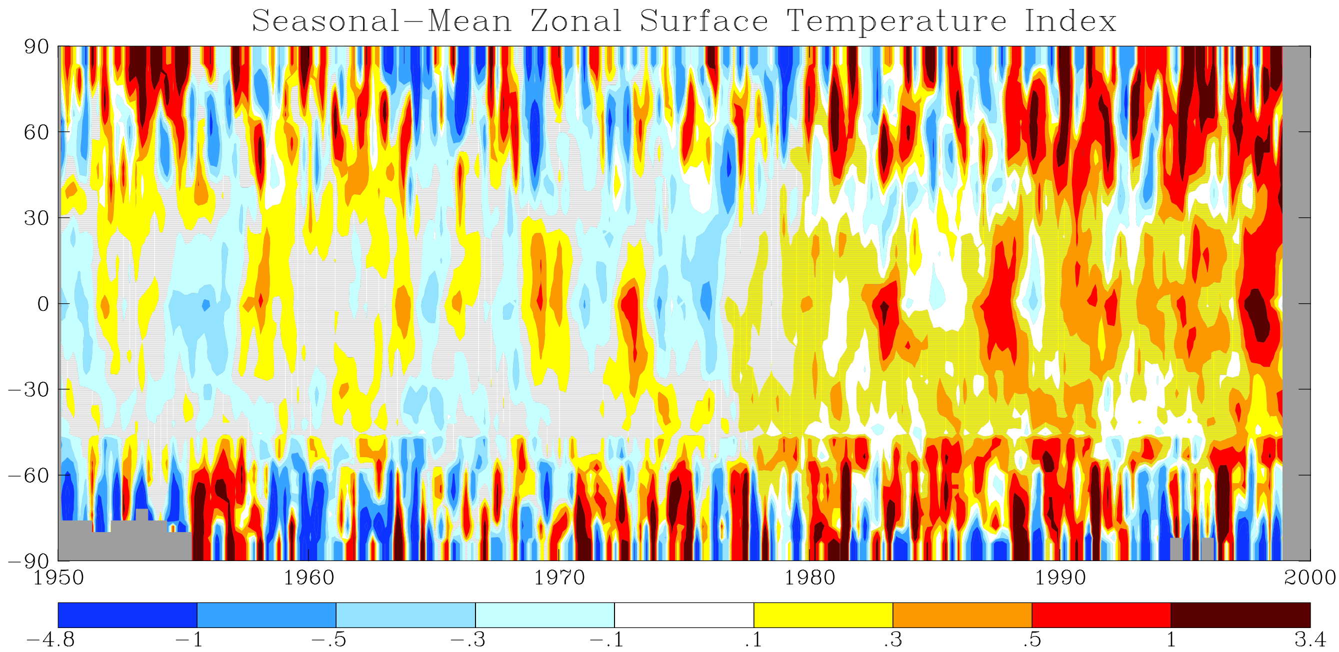
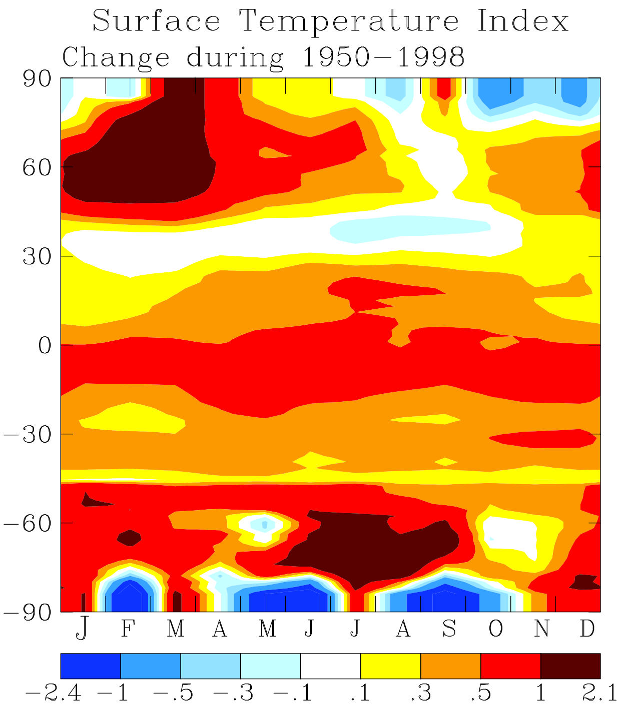
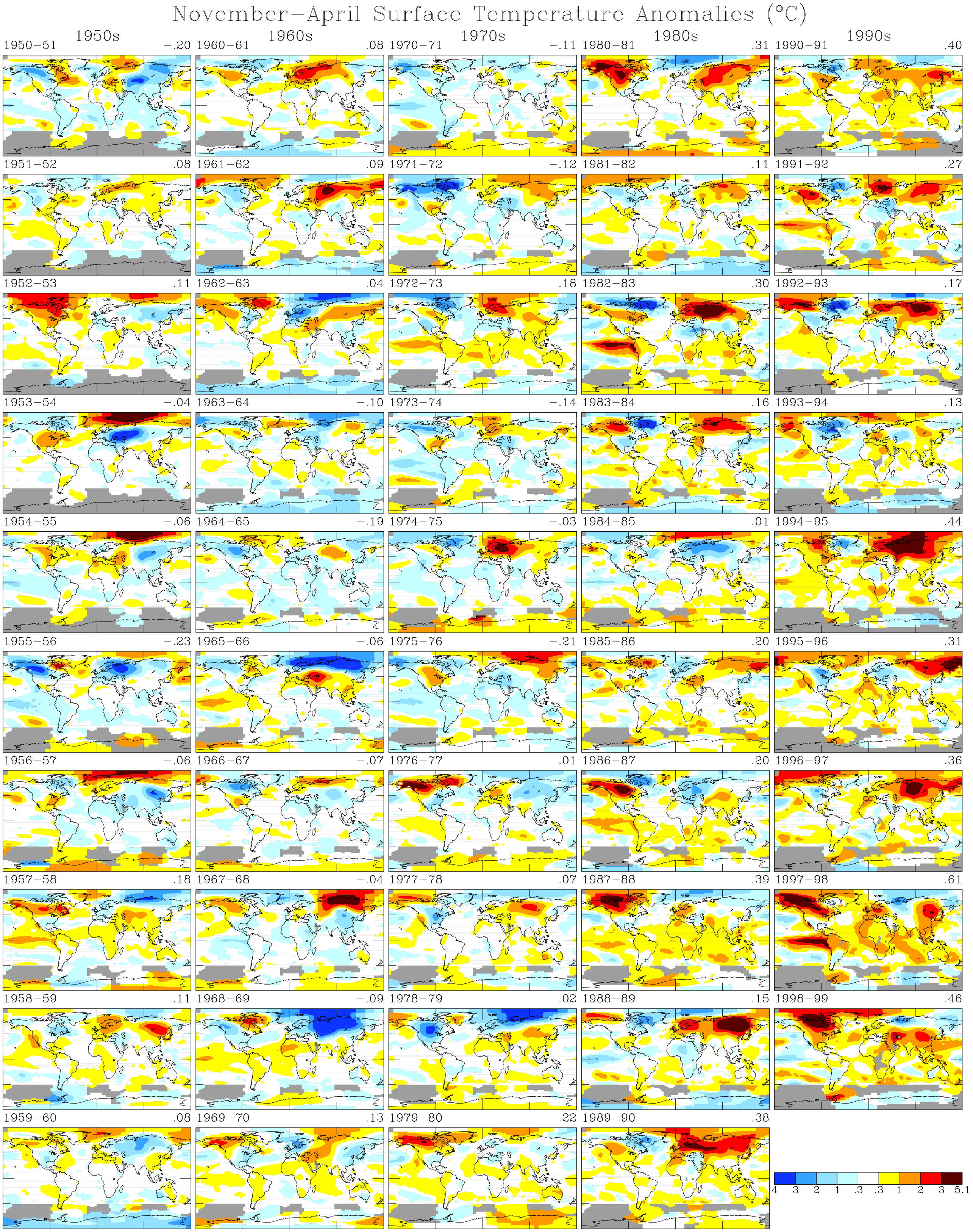
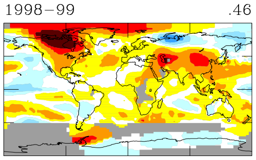


Plate 8




November–April Surface Temperature Anomalies (°C)



May–October Surface Temperature Anomalies (°C)

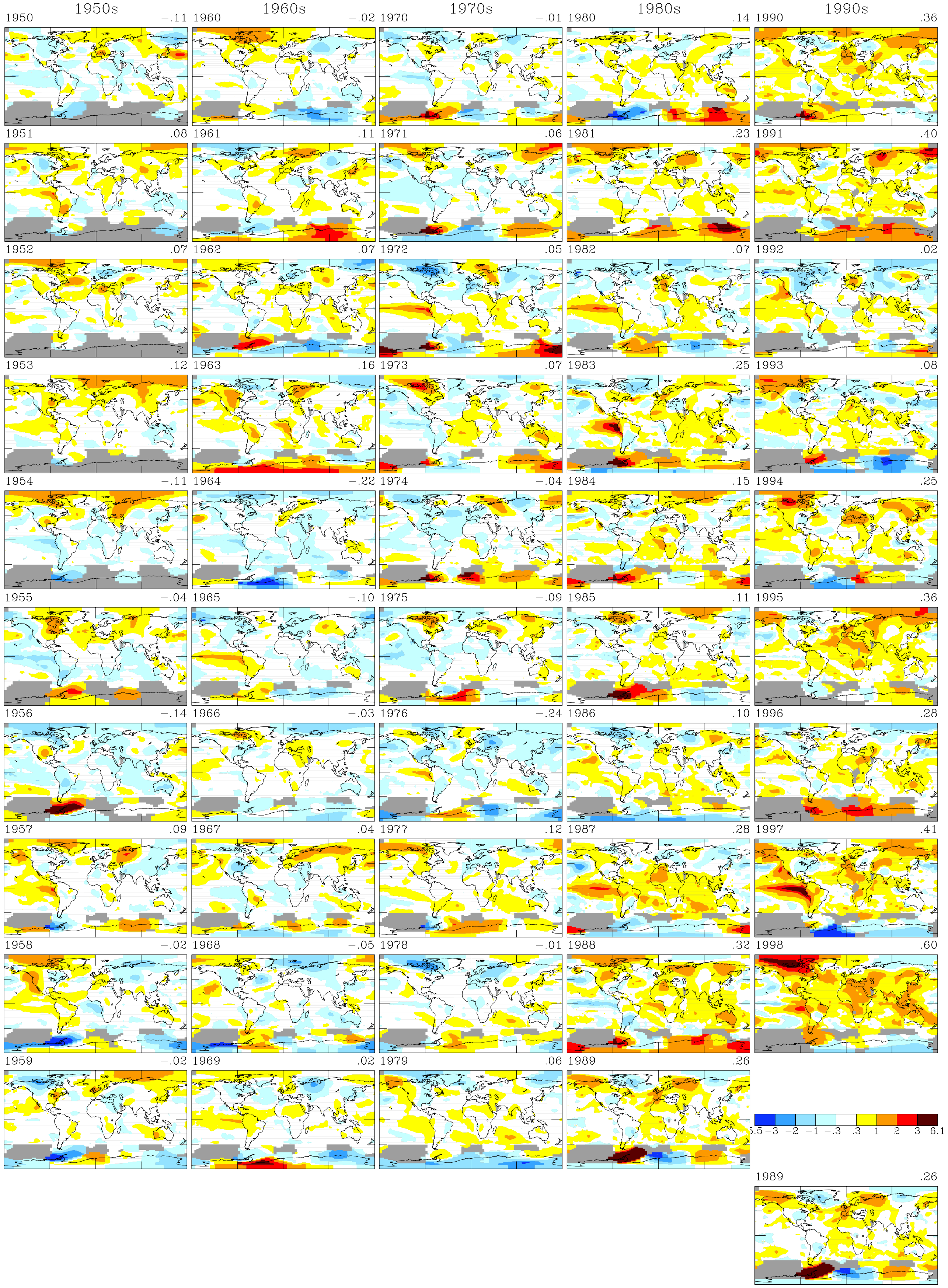


Figure 9

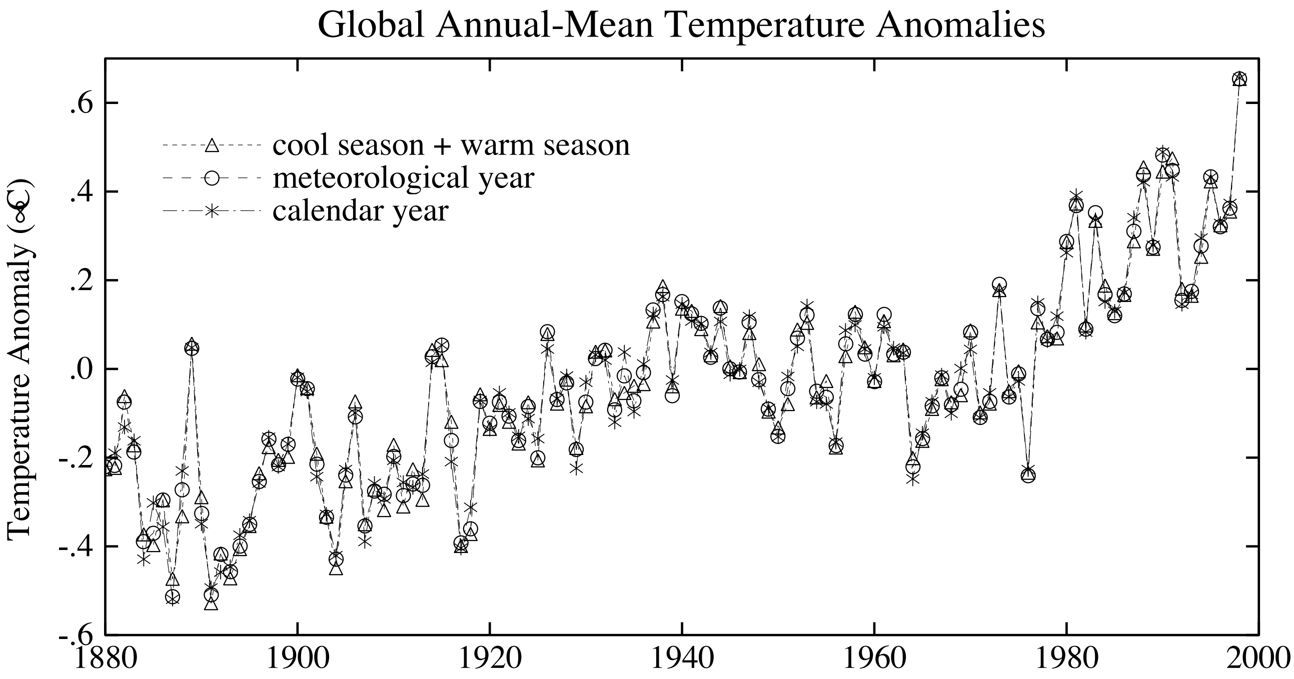
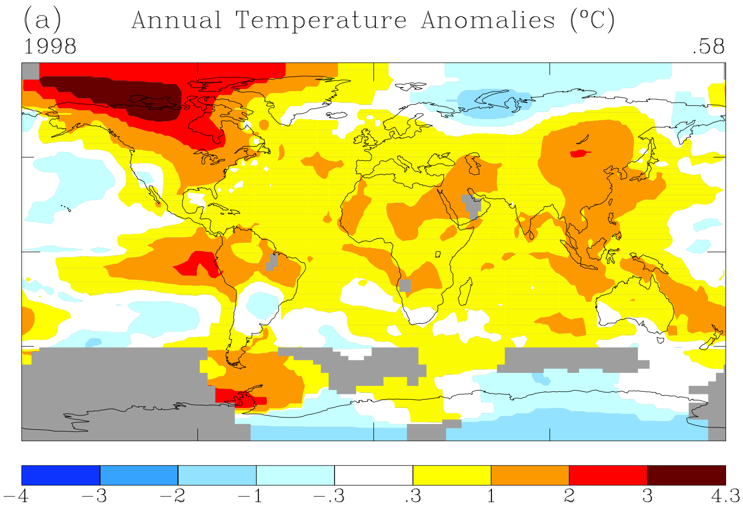

Global Annual-Mean Temperature Anomalies
cool season + warm season
meteorological year
calendar year
Temperature Anomaly (∞C)
.6
.4
.2
.0
-.2
-.4
-.6
1880
1900
1920
1940
1960
1980
2000

Plate 10


(a)
Annual Temperature Anomalies (°C)
1998
.58
−4
−3
−2
−1
−.3
.3
1
2
3
4.3

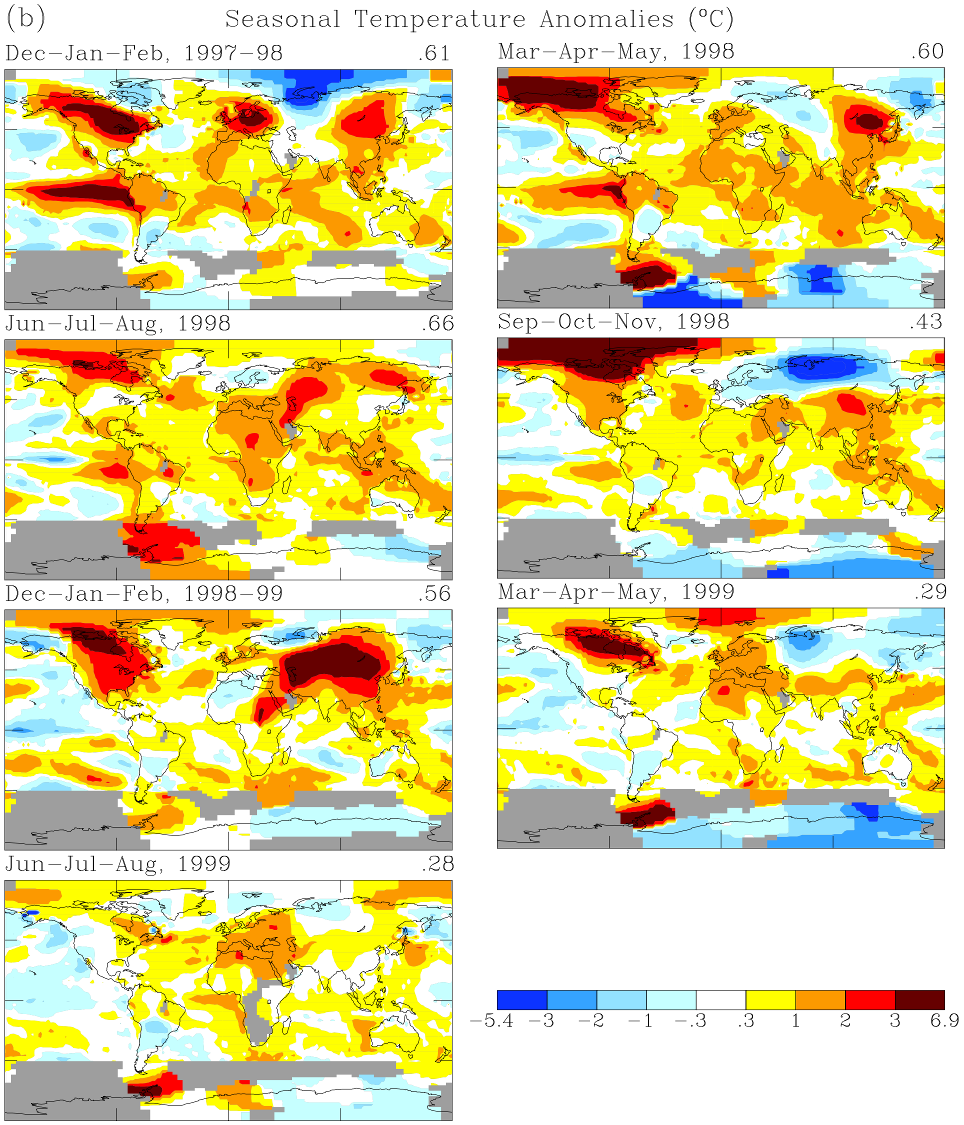

(b)
Seasonal Temperature Anomalies (°C)
Dec−Jan−Feb, 1997−98
.61
Mar−Apr−May, 1998
.60
Jun−Jul−Aug, 1998
.66
Sep−Oct−Nov, 1998
.43
Dec−Jan−Feb, 1998−99
.56
Mar−Apr−May, 1999
.29
Jun−Jul−Aug, 1999
.28
−5.4
−3
−2
−1
−.3
.3
1
2
3
6.9

Plate A1

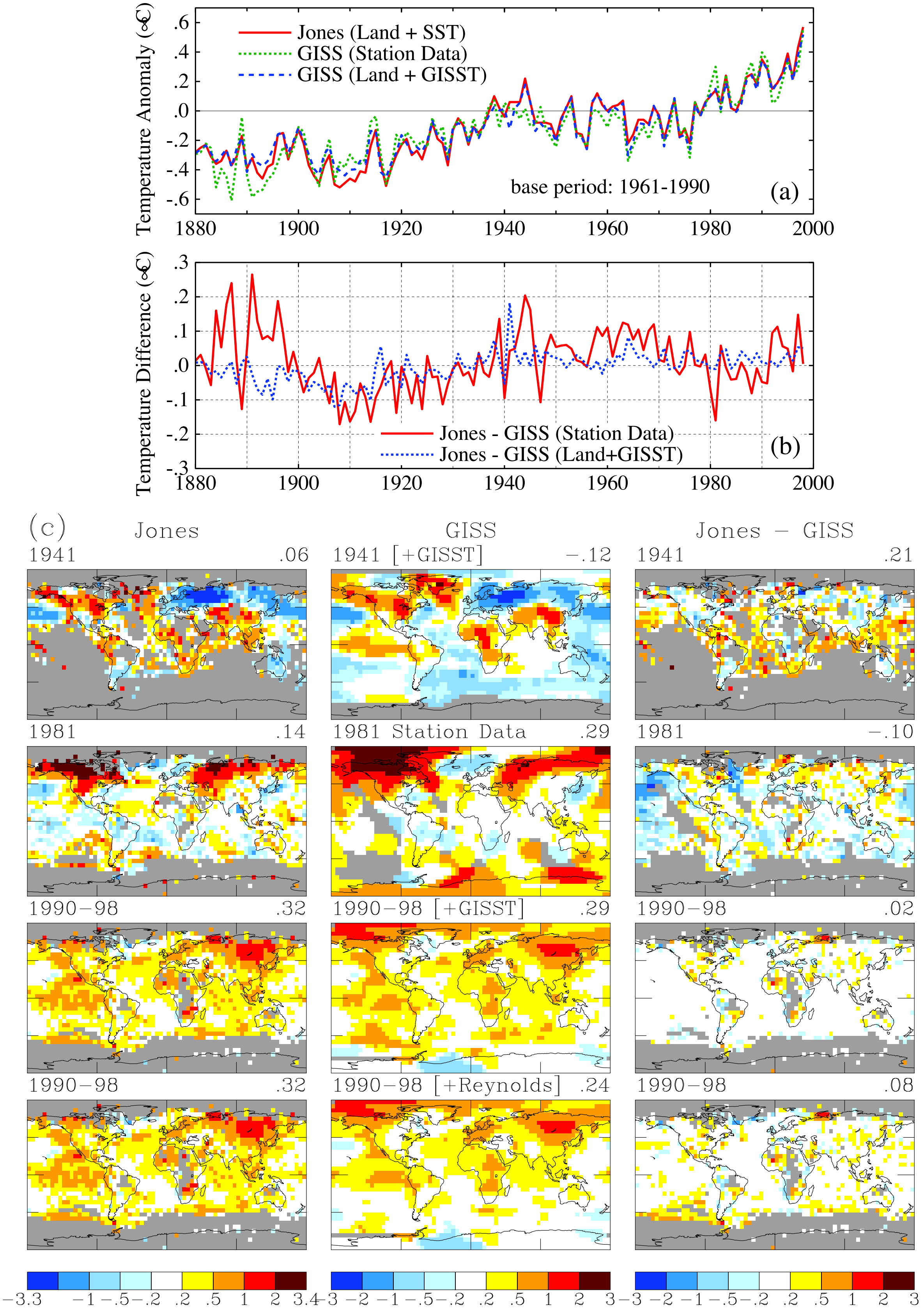
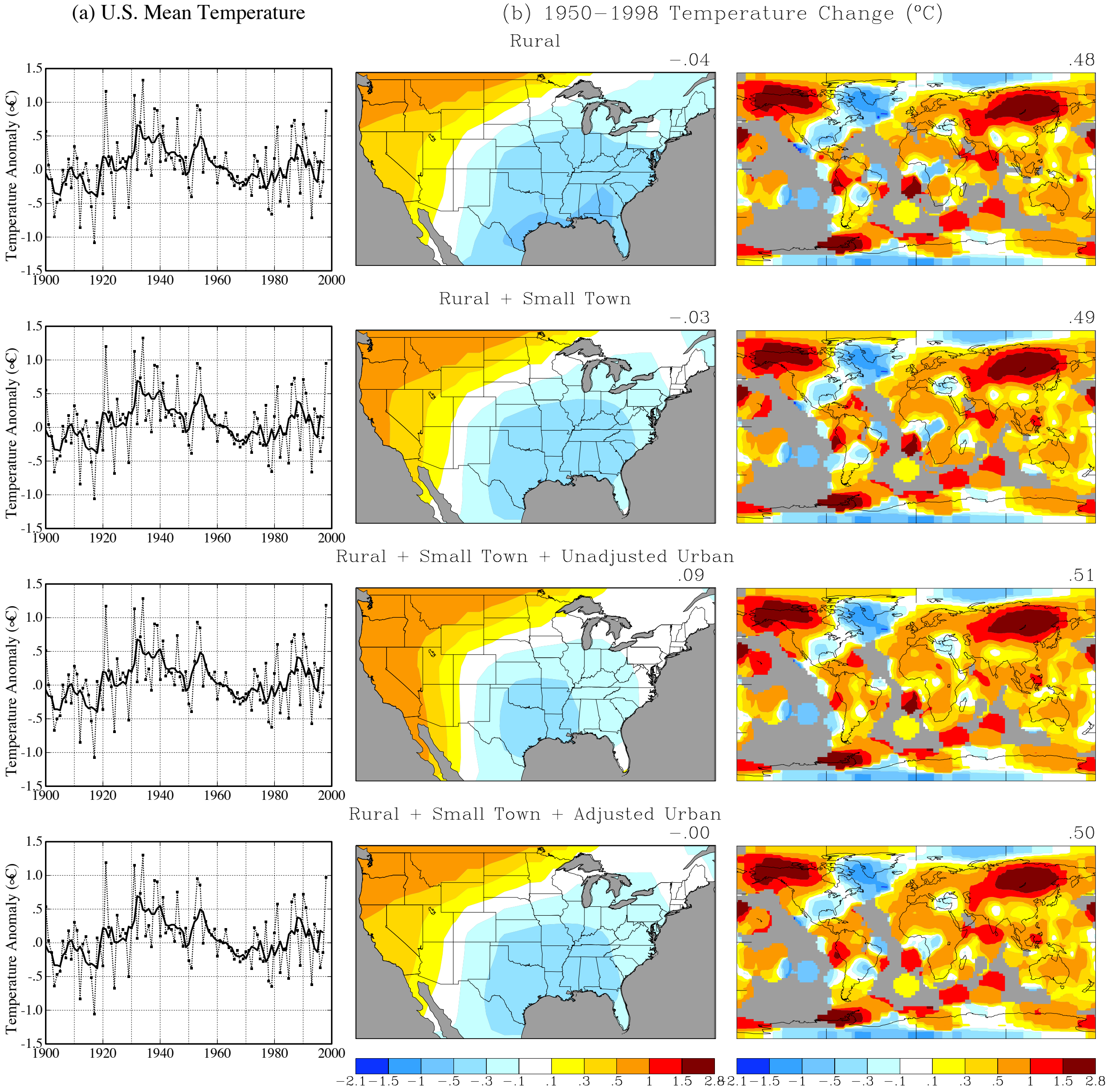

Temperature Anomaly (°C)
Jones (Land + SST)
GISS (Station Data)
GISS (Land + GISST)
base period: 1961-1990
(a)
.6
.4
.2
.0
-.2
-.4
-.6
1880
1900
1920
1940
1960
1980
2000
Temperature Difference (°C)
Jones - GISS (Station Data)
Jones - GISS (Land+GISST)
(b)
.3
.2
.1
.0
-.1
-.2
-.3
(c)
Jones
GISS
Jones − GISS
1941 .06
1941 [+GISST] −.12
1941 .21
1981 .14
1981 Station Data .29
1981 −.10
1990−98 .32
1990−98 [+GISST] .29
1990−98 .02
1990−98 .32
1990−98 [+Reynolds] .24
1990−98 .08
−3.3 −1 −.5 −.2 .2 .5 1 2 3.4
−3 −2 −1 −.5 −.2 .2 .5 1 2 3
−3 −2 −1 −.5 −.2 .2 .5 1 2 3

Plate A2


(a) U.S. Mean Temperature
(b) 1950–1998 Temperature Change (°C)
Rural
−.04
.48
Rural + Small Town
−.03
.49
Rural + Small Town + Unadjusted Urban
.09
.51
Rural + Small Town + Adjusted Urban
−.00
.50
Temperature Anomaly (°C)
1.5
1.0
.5
.0
-.5
-1.0
-1.5
1900
1920
1940
1960
1980
2000
−2.1 −1.5 −1 −.5 −.3 −.1 .1 .3 .5 1 1.5 2.8