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Global Trends of Measured Surface Air Temperature

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We analyze surface air temperature data from available meteorological stations with principal focus on the period 1880–1985. The temperature changes at mid- and high latitude stations separated by less than 1000 km are shown to be highly correlated; at low latitudes the correlation falls off more rapidly with distance for nearby stations. We combine the station data in a way which is designed to provide accurate long-term variations. Error estimates are based in part on studies of how accurately the actual station distributions are able to reproduce temperature change in a global data set produced by a three-dimensional general circulation model with realistic variability. We find that meaningful global temperature change can be obtained for the past century, despite the fact that the meteorological stations are confined mainly to continental and island locations. The results indicate a global warming of about 0.5°–0.7°C in the past century, with warming of similar magnitude in both hemispheres; the northern hemisphere result is similar to that found by several other investigators. A strong warming trend between 1965 and 1980 raised the global mean temperature in 1980 and 1981 to the highest level in the period of instrumental records. The warm period in recent years differs qualitatively from the earlier warm period centered about 1940; the earlier warming was focused at high northern latitudes, while the recent warming is more global. We present selected graphs and maps of the temperature change in each of the eight latitude zones. A computer tape of the derived regional and global temperature changes is available from the authors.

1. INTRODUCTION

Surface air temperature has been measured at a large number of meteorological stations for the past century, mainly at northern hemisphere land locations. These station data have been used by a number of investigators [e.g., *Willett,* 1950; *Mitchell,* 1961; *Budyko,* 1969; *Vinnikov et al.,* 1980; *Yamamoto and Hoshiai,* 1980; *Jones et al.,* 1982, 1986*a*; *Jones and Kelly,* 1983; *Bradley et al.,* 1985] to estimate temperature change, with appropriate caveats concerning restrictions of spatial coverage (cf. review by *Wigley et al.* [1986]). Analysis of ocean surface temperature change has also been made [*Paltridge and Woodruff,* 1981; *Barnett,* 1984; *Folland et al.,* 1984] on the basis of ship data. Because the land and ocean data sets each have their own problems concerning data quality and uniformity over long periods (see previously cited references above, especially *Barnett* [1984] and *Jones et al.* [1986*a*]), it seems better to analyze the two data sets separately, rather than lumping them together prior to analysis. Another valuable source of global temperature data is provided by the radiosonde stations [*Angell and Korshover,* 1983]. This source includes data through the troposphere and lower stratosphere but is restricted to the period from 1958 to the present.

Although it is safer to restrict temperature analyses to regions with dense station coverage, there is a great incentive for trying to obtain estimates of long term global temperature change. Such global data would provide the most appropriate comparisons for global climate models and would enhance our ability to detect possible effects of global climate forcings, such as increasing atmospheric CO_2. In this paper we use the temperature records of meteorological stations to obtain an estimate of global surface air temperature change, and we estimate the errors due to incomplete spatial coverage.

Jones et al. [1986*c*] recently published an estimate of global near-surface temperature change obtained by combining the surface air temperature measurements of meteorological stations with marine surface air and surface water temperature measurements. We compare their results with ours at the end of this paper; our global mean and hemispheric mean results are generally in good agreement with theirs.

In section 2 we define the surface air temperature data set we employ, including illustration of the global distribution of stations, and we estimate the area over which the temperature change obtained from a given station is meaningful. In section 3 we describe the method we use to combine the records of different stations, which is designed to retain temperature change information while minimizing effects of incomplete spatial and temporal coverage. In section 4 we present detailed graphs of our results for global, hemispheric, zonal and regional temperature change. In section 5 we make several checks of the significance of the inferred trends, for example, by using an artificial global temperature history generated by a three-dimensional general circulation model to obtain a measure of the error due to incomplete spatial coverage, by reanalyzing the northern hemisphere temperature trend using a station distribution comparable to that available in the southern hemisphere, and by omitting urban stations to test for possible anthropogenic heat island effects. In section 6 we compare the derived hemispheric and global temperature change with the recent results of *Jones et al.* [1986*c*] and *Angell and Korshover* [1983; private communication, 1987].

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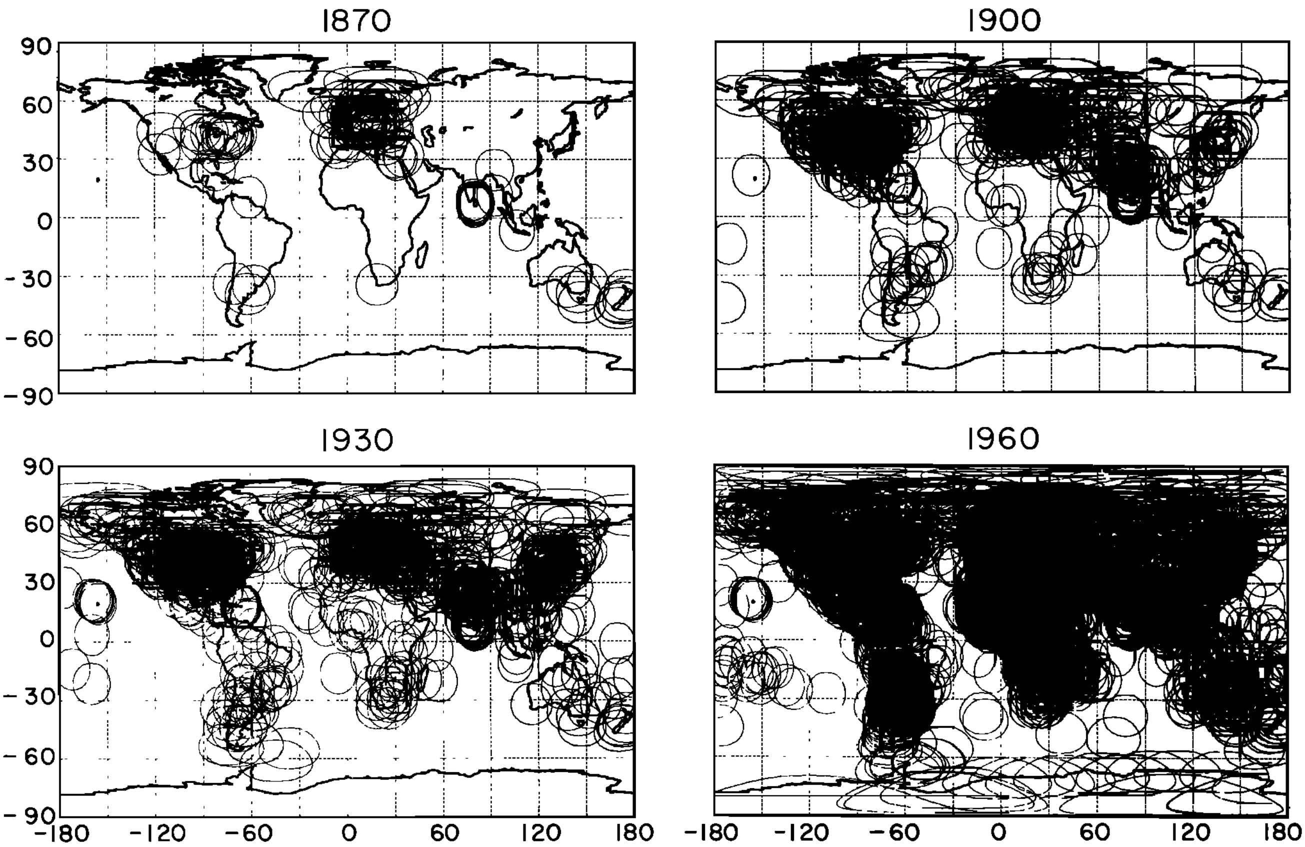


Fig. 1. Global distribution of meteorological stations with surface air temperature records for the four indicated dates. A circle of 1200-km radius is drawn around each station.

The method of temperature analysis described here was previously used by *Hansen et al.* [1981], who presented global, northern latitude, southern latitude, and low latitude temperature change for the period 1880–1978. The present paper represents a more complete documentation of the method of analysis, includes additional stations in the basic data set, and includes a more comprehensive presentation of results. The temperature changes obtained in the two studies are in close agreement.

There are several features of our surface air temperature study which we believe justify its publication, despite the existence of the other studies mentioned previously. Our method of analysis is designed to utilize fully information from stations with incomplete spatial and temporal coverage. We obtain a quantitative estimate of errors due to incomplete station coverage. We show that meaningful global temperature change can be obtained from only the meteorological station data; thus we avoid the ambiguity inherent in combining sea surface temperatures with surface air station data as well as the difficulties encountered with any marine (surface air or sea surface) temperatures due to temporal changes in the nature of ships. Our presentation also includes some novel results, for example, long-term changes in the seasonal cycle.

2. Station Temperature Records

The principal data sources for surface air temperature at meteorological stations are the World Weather Records (WWR), published by the Smithsonian Institution and their continuation, Monthly Climatic Data of the World (MCDW), published by The National Oceanic and Atmospheric Administration (NOAA). The full data set is continuously updated and is available in digital form from the National Center for Atmospheric Research (NCAR), as described by *Jenne* [1975] and *Spangler and Jenne* [1980].

The data set available from NCAR changes with time as late station reports are obtained, additional stations are added, and errors in existing station records are found and corrected. Our present analysis is based on the NCAR data set as of June 1984 to which we added data for 1984 and 1985 obtained from MCDW which is prepared by the National Climatic Data Center of NOAA in cooperation with the World Meteorological Organization. However, we emphasize that we have worked with several versions of the NCAR data set in the past 7 years; none of the general conclusions which we draw in this paper have varied as station data were added or corrected.

The principal limitation of this data set for global or hemispheric analysis is the incomplete spatial coverage, illustrated in Figure 1 for four dates. Although the number and geographical extent of recording stations on land areas increased strongly between 1870 and 1900, there were still large areas in Africa and South America, and all of Antarctica, without coverage in 1900. Substantial station data for Antarctica begins in the 1950s. Large ocean areas remain without fixed meteorological stations at all times.

Another indication of station coverage is provided by Figure 2, which divides the global surface into 80 equal area

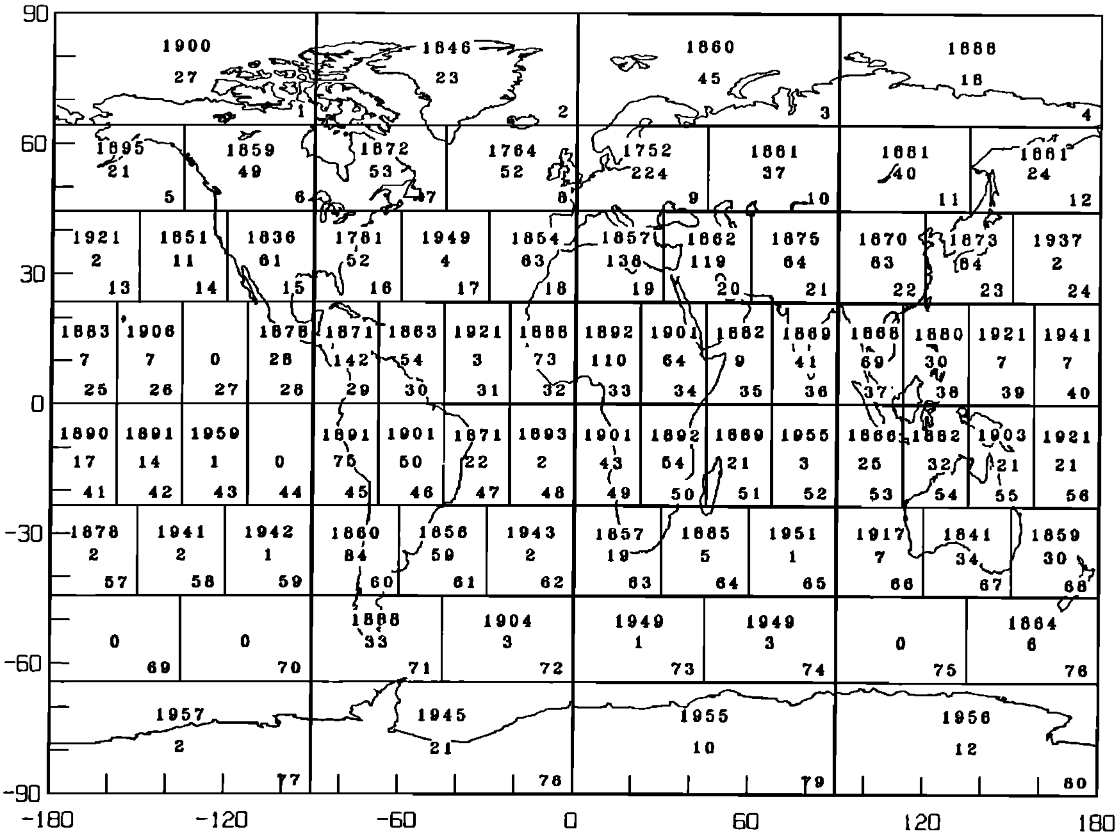


Fig. 2. Total number of stations in each of 80 regions of equal area, and the date when continuous coverage began for each region. A box identification number is given in the lower right-hand corner of each box.

"boxes," the full dimension of a box side being about 2500 km. The total number of stations within each box and the date at which continuous station coverage began for that box is given in Figure 2. Most ocean boxes contain at least a few island stations, but five of the 80 boxes have no stations. Note that the fraction of the hemispheric area within each of the four latitude zones, starting at the pole, is 10, 20, 30 and 40%, respectively. Thus the Antarctic latitude band, which had practically no temperature records until the second half of the twentieth century, represents 5% percent of the global area. The neighboring latitude band, which also has poor station coverage, represents an additional 10% of the global area.

Before defining a procedure for extracting large-area temperature change from measurements, it is important to have a quantitative measure of the size of the surrounding area for which a given station's data may provide significant information on temperature change. For this purpose we computed the correlation coefficient between the annual mean temperature variations for pairs of stations selected at random from among the station pairs with at least 50 common years in their records. The distribution of correlation coefficients as a function of station separation is shown in Figure 3 for the same latitude zones as in Figure 2. At middle and high latitudes the correlations approach unity as the station separation becomes small; the correlations fall below 0.5 at a station separation of about 1200 km, on the average. At low latitudes the mean correlation is only 0.5 at small station separation. The distance over which strong correlations are maintained at high latitudes probably reflects the dominance of mixing by large-scale eddies. At low latitudes the most active atmospheric dynamical scales are smaller, but apparently there are also substantial coherent temperature variations on very large scales (for example, due to the quasi-biennial oscillation, Southern Oscillation, and El Niño phenomena), which account for the slight tendency toward positive correlations at large station separations.

We examined the dependence of the correlations on the direction of the line connecting the two stations. For the regions for which this check was performed, the United States and Europe, no substantial dependence on direction was found. For example, in these regions the average correlation coefficient for 1000-km separation was found to be within the range 0.5–0.6 for each of the directions defined by 45° intervals. We did not investigate whether the correlations are more dependent on direction at low latitudes.

The number of stations as a function of time is shown in Figure 4, as is the percent of the global surface that has a station located within 1200 km. The 1200-km limit is the distance at which the average correlation coefficient of temperature variations falls to 0.5 at middle and high latitudes and 0.33 at low latitudes. Note that the global coverage defined in this way does not reach 50% until about 1900; the northern hemisphere obtains 50% coverage in about 1880 and the southern hemisphere in about 1940. Although the number of stations doubled in about 1950, this increased the area coverage by only about 10%, because the principal deficiency is ocean areas which remain uncovered even with

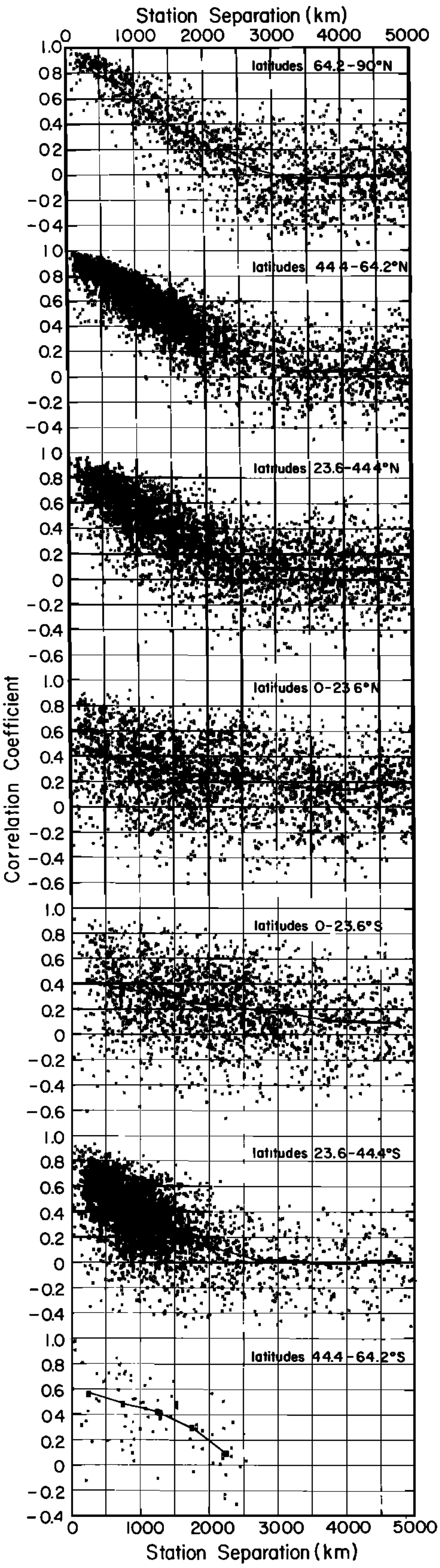


Fig. 3. Correlation coefficients between annual mean temperature changes for pairs of randomly selected stations having at least 50 common years in their records. Each dot represents one station pair. The latitude zones are the same as those of the boxes in Figure 2.

the greater number of stations. For the same reason, the decrease in the number of stations in the early 1960s, (due to the shift from Smithsonian to Weather Bureau records), does not decrease the area coverage very much. If the 1200-km limit described above, which is somewhat arbitrary, is reduced to 800 km, the global area coverage by the stations in recent decades is reduced from about 80% to about 65%.

In addition to the limitations imposed by the incomplete spatial coverage, there are temporal inconsistencies in certain station records, which are caused, for example, by changes in instrumentation, station location, observation time, or environmental factors such as urban heat island effects, as discussed in detail by *Jones et al.* [1986*a*]. We screened the data only to eliminate gross errors; the screening involved examination of the space and time variability of the temperature deviations from their long-term mean. Specifically, we (1) used the time history at each station to identify instances when the temperature deviation was more than five standard deviations from the long-term mean, and (2) examined color maps of temperature change, as illustrated later, to identify any station with a trend greatly inconsistent with its surroundings. These cases were individually examined and usually led to the discovery of a misplaced decimal or incorrect sign for the temperature. In cases where obviously bad data was discovered this was reported to NCAR so that the original data set could be corrected. Undoubtedly some bad data with small errors escaped this screening, but the very large number of stations reduces the large-scale impact of such errors. Later, we also test the importance of urban heat island effects by selectively eliminating city stations from the analysis, and we estimate the uncertainty in the global trends. Perhaps the best indication that these problems do not have a dominant effect on the results is provided by examination of the physical nature of the geographic and temporal patterns of the derived temperature change.

3. Spatial Averaging: Bias Method

Our principal objective is to estimate the temperature change of large regions. We would like to incorporate the information from all of the relevant available station records. The essence of the method which we use is shown schematically in Figure 5 for two nearby stations, for which we want the best estimate of the temperature change in their mutual locale. We calculate the mean of both records for the period in common, and adjust the entire second record (T_2) by the difference (bias) δT. The mean of the resulting temperature records is the estimated temperature change as a function of time. The zero point of the temperature scale is arbitrary.

A principal advantage of this method is that it uses the full period of common record in calculating the bias δT between the two stations. Determination of δT is the essence of the problem of estimating the area-average temperature change from data at local stations. A second advantage of this method is that it allows the information from all nearby stations to be used, provided only that each station have a period of record in common with another of the stations. An alternative method commonly used to combine station records is to define δT by specifying the mean temperature of each station as zero for a specific period which had a large number of stations, for example,

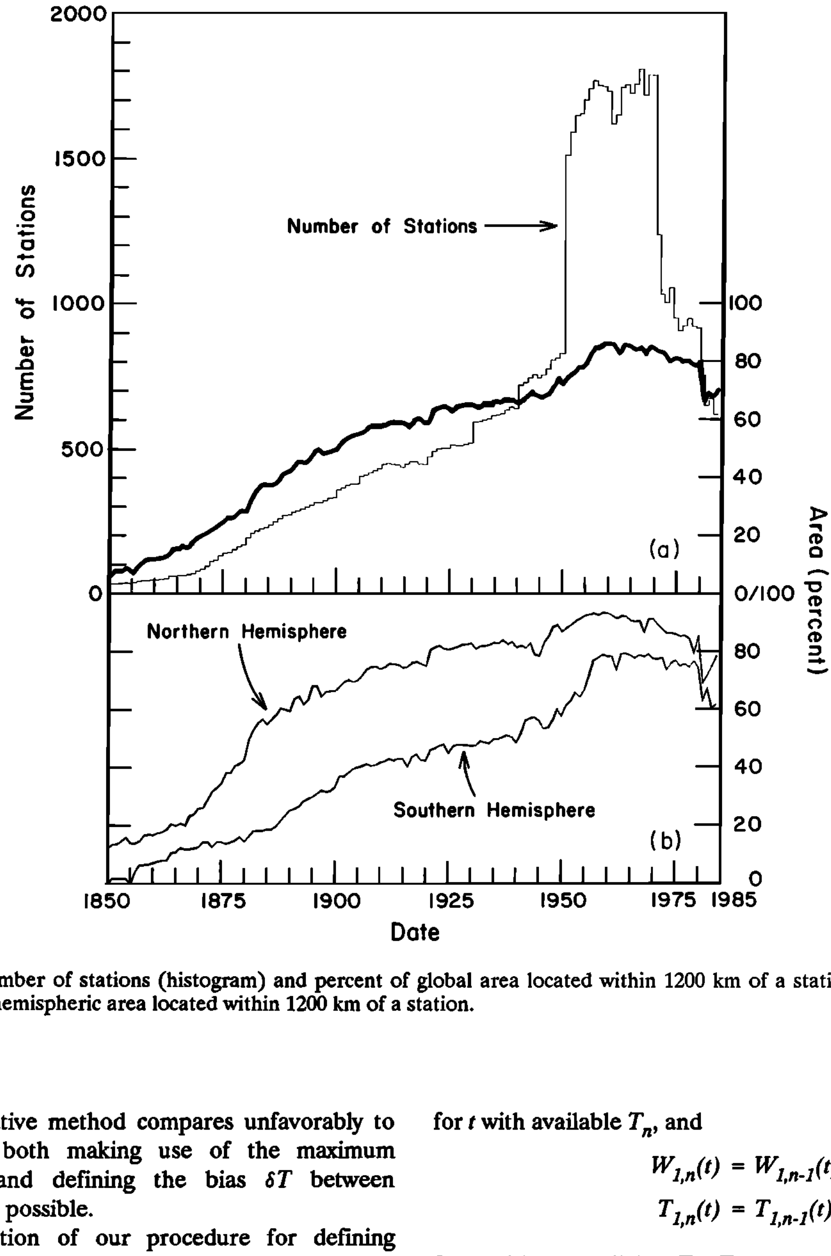


Fig. 4. (a) Number of stations (histogram) and percent of global area located within 1200 km of a station (heavy line). (b) Percent of hemispheric area located within 1200 km of a station.

1950–1980; this alternative method compares unfavorably to ours with regard to both making use of the maximum number of stations and defining the bias δT between stations as accurately as possible.

A complete description of our procedure for defining large-area temperature change is as follows. We divide each of the 80 equal-area boxes of Figure 2 into a 10 by 10 array of 100 equal-area subboxes. (The east-west and north-south dimensions of a subbox are about 200 km; in the polar boxes the equal area requirement for the subboxes causes the polemost subboxes to be noticeably elongated in the north-south direction.) For each subbox we use all stations located within 1200 km of the subbox center to define the temperature change of that subbox. The N stations within 1200 km are ordered from the one with the greatest number of years of temperature record to the one with the least number. The temperature changes for the first two stations are combined, then the third with the first two, and so on, using

$$\delta T_n = \bar{T}_n - \bar{T}_{1,n-1} \quad (1)$$

$$W_n = (D - d_n)/D \quad (2)$$

$$W_{1,n}(t) = W_{1,n-1}(t) + W_n \quad (3a)$$

$$T_{1,n}(t) = [W_{1,n-1}T_{1,n-1} + W_n(T_n\text{-}\delta T_n)]/W_{1,n} \quad (3b)$$

for t with available T_n, and

$$W_{1,n}(t) = W_{1,n-1}(t) \quad (3c)$$

$$T_{1,n}(t) = T_{1,n-1}(t) \quad (3d)$$

for t without available T_n. T represents temperature change, t is time, and n identifies the station. $T_{1,n}(t)$ is an intermediate estimate of the temperature change based on stations 1 through n; these equations are applied repeatedly until $T_{1,N}(t)$ is obtained, where N is the total number of stations within 1200 km of the subbox center. Here d_n is the distance of the nth station from the subbox center, and d_n is used to calculate the weight W_n by which the nth station temperature change is weighted. W_n decreases linearly from 1 at the subbox center to 0 at a distance D, where we have taken $D=1200$ km as a representative direction-independent distance over which the temperature changes exhibit strong correlation.

The temperature changes of the 100 subboxes are then combined to find the temperature change for a box, in the manner indicated by Figure 5 and (1)–(3). However, the subboxes are weighted equally, i.e., by area, except that subboxes which have no station within 1200 km are excluded. The zonal mean temperature change for a latitude band is obtained by combining the temperature changes of

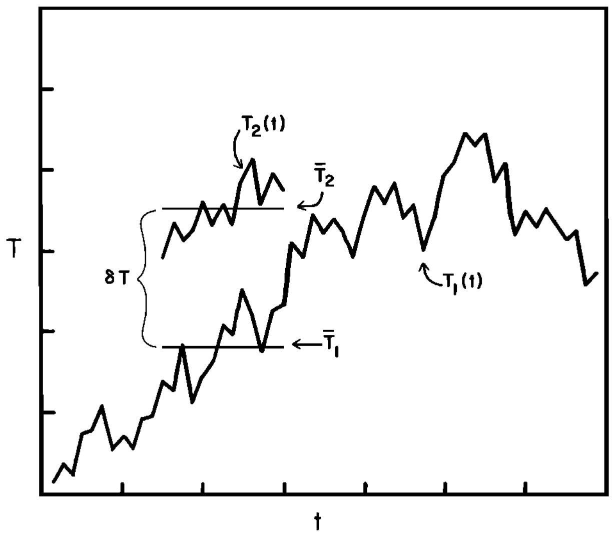


Fig. 5. Illustration of how the temperature records of two stations are combined. The value δT is computed from the averages of $T_1(t)$ and $T_2(t)$ over the common years of record. The entire curve $T_2(t)$ is then moved downward by the amount δT, and T_1(t) and $T_2(t)$ are averaged. In general, $T_1(t)$ and $T_2(t)$ may contain gaps, as may the common period used to compute δT.

the boxes in this same way, with each box weighted by the fraction of its subboxes which have a defined temperature change, i.e., the fraction of the box which has a station within 1200 km. Finally, the zonal temperature changes are combined in the same way to obtain hemispheric and global temperature change, with each latitude band weighted by the area with a defined temperature change.

One potential disadvantage of the method we have described for combining station records is that the results, in principle, depend on the ordering of the station records. However, we have tested the effect of other choices for station ordering, for example, by beginning with the station closest to the subbox center, rather than the station of longest record. The differences between the results for alternative choices were found to be very small, about 2 orders of magnitude less than the typical long-term temperature trend.

We have also tested alternatives to these procedures and compared the error estimates for the alternatives, the error estimates being obtained as described in Section 5. For example, we tried weighting each box by the box area and each zone by the zone area, rather then weighting by the area with a defined temperature change. Overall temperature changes were similar with the different procedures, but the procedure as we defined it previously was found to yield the smallest errors of the alternatives which were tested. We also tried alternatives to the 1200-km limit defined earlier; although the effects were noticeable on geographical maps of temperature trends, there was no significant effect on zonal, hemispheric, or global temperature changes.

The time unit is the monthly mean in the station records which we obtain from NCAR. We obtain monthly temperature changes for a given subbox by applying the previously described procedure individually to each of the 12 months, with the zero point for each month being its 1951–1980 mean. We tried two methods for obtaining annual trends: (1) averaging the station records to obtain annual mean data, then applying the described procedure, and (2) averaging the temperature changes obtained with this procedure for the individual months. The differences in the results from the two methods were small, of the order of 10%, but we chose the latter method because it incorporates all available data, i.e., it uses the records for years in which data are missing for 1 or more months.

If our data are employed at their highest (monthly) resolution, it should be noted that, although the seasonal cycle has been removed to first order, the effect of changes in the seasonal cycle are still present. Long-term changes of the seasonal cycle are not unexpected and, indeed, we illustrate later that some have occurred in the past century. Thus a spectral analysis of the long-term temperature changes at monthly resolution should be expected to yield a peak at 12 months.

One issue with the bias method is how many years of record overlap should be required for a station record to be combined with that of its neighbors. For example, it would seem inappropriate to combine the record of a station which had only 1 year in common with its nearby (within 1200 km) neighbors, because local interannual fluctuations are often as large as the long-term changes which we seek to define. For the results we present, we used only station records which had an overlap of 20 years or more with the combination of other stations within 1200 km. We tested other choices for this overlap period and found little effect on the global and zonal results. Some effect could be seen on global maps of derived temperature change; a limit of 5 years or less caused several unrealistic local hot spots or cold spots to appear, while a limit greater than 20 years caused a significant reduction in the global area with station coverage.

We stress that our procedure for defining temperature change is designed for obtaining the results for large regions, from the 1000 km scale to the global scale. For some local studies it is better to start with the raw station data, if a local station exists, rather than to start with the temperature change we have obtained for the local subbox (which is influenced by station data up to 1200 km away). However, we include the subbox temperature change on the data tape which we make available, and we anticipate that it will be useful for many purposes. For example, it provides an estimate of the small-scale temperature change where local stations do not exist (provided there is at least one station within 1200 km). Also, because of the variability which exists on scales of a few hundred kilometers or more (see Figure 3), if a user is interested in area-average temperature change over scales of at least a few hundred kilometers, it is probably better to use our subbox results rather than a local station. Finally, provision of the subbox results allows the user the possibility of averaging over large regions other than those which we have chosen.

4. DERIVED TEMPERATURE CHANGES

We summarize here some of the derived temperature change characteristics which are significant, based on the error analysis in the following section. The global and hemispheric annual-mean temperature changes for the period since 1880 are shown in Figure 6 and Table 1. Figure 6 also includes the 5-year smoothed temperature change and the estimated error (95% confidence limits, approximately $\pm 2\sigma$) at

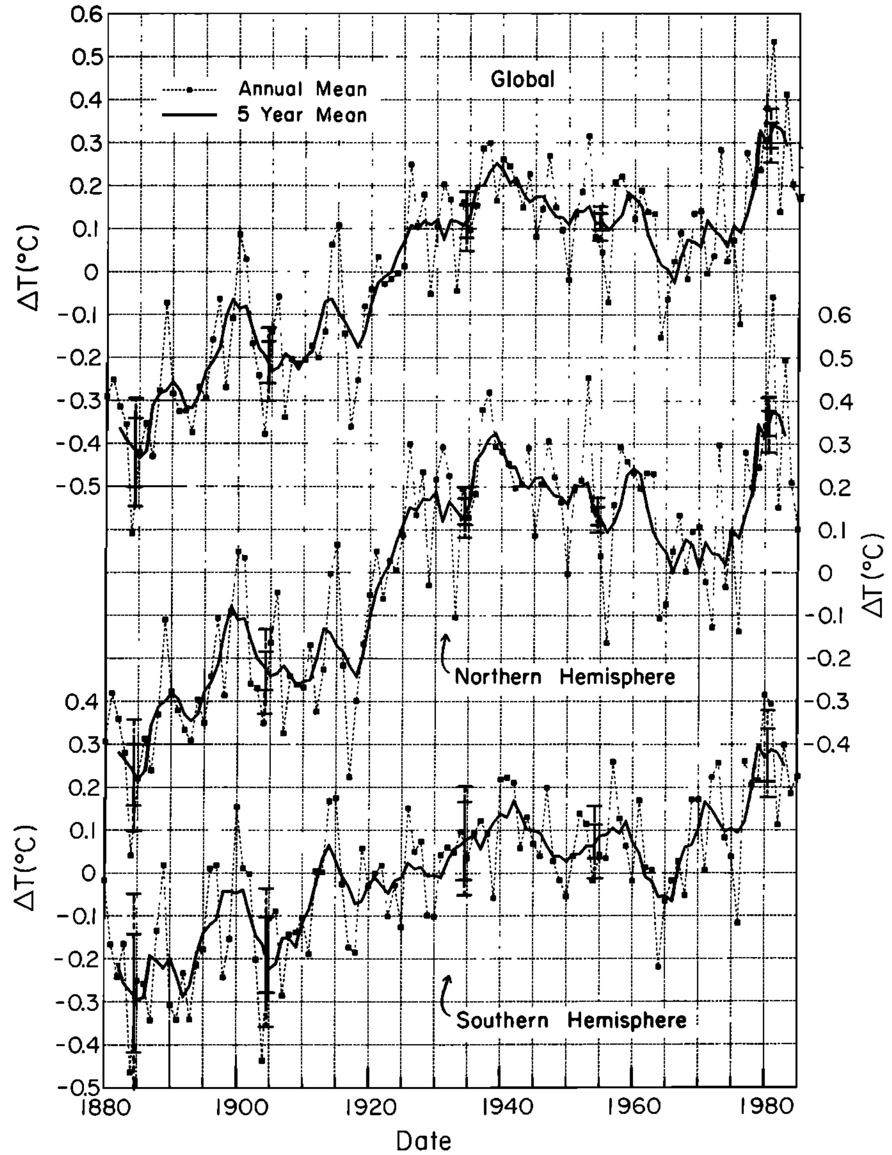


Fig. 6. Global and hemispheric surface air temperature change estimated from meteorological station records. The northern hemisphere scale is on the right. The 5-year running mean is the linear average for the 5 years centered on the plotted year. The uncertainty bars (95% confidence limits) are based on the error analysis in section 5; the inner bars refer to the 5-year mean and the outer bars to the annual mean.

several dates based on the error analysis in the following section. The smaller bar refers to the uncertainty in the 5-year mean and the larger bar refers to the uncertainty in the annual mean temperature. Note that the station distributions for 1900, 1930 and 1960 are given in Figure 1.

The smoothed global temperature increases by about 0.5°C between 1880 and 1940, decreases by about 0.2°C between 1940 and 1965, and increases by about 0.3°C between 1965 and 1980. The northern hemisphere temperature change is rather similar to the global change, increasing by 0.6°C between 1880 and 1940, decreasing by 0.3°C between 1940 and 1970, and increasing by 0.3°C between 1970 and 1980. The southern hemisphere temperature change is noisier, but, especially if averaged over a 10-year interval or longer, it shows a more steady increase in temperature, with a warming of about 0.6°C between 1880 and 1980. The largest rate of warming is between 1965 and 1980.

We include the 5-year running mean in a number of our graphs because it provides a simple smoothing which helps clarify long-term change. However, we emphasize that the resulting curve is not appropriate for study of "cycles," such as those appearing in the southern hemisphere record in Figure 6. For studies of periodicities one may employ the unsmoothed data with appropriate filtering techniques [*Mitchell et al.*, 1966].

The global surface air temperature in 1981 reached a warmer level than obtained in any previous time in the period of instrumental record. The 1981 maximum exceeded the maximum of 1940 by about 0.2°C, which is larger than the estimated error. In the northern hemisphere 1981 is also the warmest year on record, as already noted by *Jones et al.* [1982]. The 1981 peak in the northern hemisphere is 0.1°C greater than any previous year in the record, but the 5-year smoothed temperature in 1981 is only about the same

TABLE 1. Surface Air Temperature Change for the Globe and Specified Regions.

				Zone								Box					
Year	Globe	NH	SH	1	2	3	4	5	6	7	8	6	7	9	10	15	16
1880	-0.40	-0.52	-0.10	-1.06	-0.72	-0.32	-0.53	-0.13	-0.08	0.23	···	-1.69	-0.75	-0.41	-0.97	-0.92	0.36
1881	-0.37	-0.41	-0.25	-1.19	-0.69	-0.13	-0.29	-0.19	-0.26	0.07	···	-0.77	-0.47	-1.20	-0.74	-0.34	0.25
1882	-0.43	-0.47	-0.33	-1.71	-0.39	-0.32	-0.39	-0.35	-0.28	-0.11	···	-0.56	-1.30	0.37	-0.85	-0.42	0.20
1883	-0.47	-0.55	-0.25	-0.26	-0.86	-0.49	-0.43	-0.18	-0.30	0.17	···	-1.77	-1.92	-0.29	-0.81	-0.78	-0.20
1884	-0.72	-0.78	-0.55	-1.35	-0.90	-0.68	-0.65	-0.33	-0.54	-0.77	···	-1.51	-2.09	-0.23	-1.03	-0.86	-0.06
1885	-0.54	-0.61	-0.34	-1.83	-0.74	-0.50	-0.17	-0.14	-0.35	-0.41	···	-0.27	-1.44	-0.36	-1.06	-0.48	-0.70
1886	-0.47	-0.51	-0.34	-1.55	-0.53	-0.45	-0.25	-0.20	-0.34	-0.38	···	-0.79	-0.95	-0.18	-1.07	-0.75	-0.68
1887	-0.54	-0.59	-0.43	-1.88	-0.60	-0.31	-0.53	-0.53	-0.35	-0.10	···	-1.74	-1.44	-0.27	0.21	-0.46	-0.29
1888	-0.39	-0.46	-0.22	-1.50	-0.69	-0.28	-0.15	0.09	-0.18	-0.65	···	-0.43	-1.24	-1.28	-0.10	-0.51	-0.80
1889	-0.19	-0.24	-0.07	-0.84	-0.29	-0.25	0.00	0.30	-0.18	-0.22	···	0.86	-0.11	-0.46	-1.03	-0.17	-0.12
1890	-0.40	-0.40	-0.39	-1.18	-0.47	-0.17	-0.43	-0.60	-0.28	0.08	···	-0.48	-0.93	-0.04	-0.94	-0.17	0.04
1891	-0.44	-0.45	-0.43	-1.27	-0.48	-0.40	-0.26	-0.55	-0.30	-0.17	···	-0.10	-0.38	-0.34	-1.27	-0.78	-0.35
1892	-0.44	-0.49	-0.32	-1.22	-0.66	-0.35	-0.32	-0.30	-0.35	0.03	···	-0.49	-0.14	-0.54	-0.85	-0.84	-0.84
1893	-0.49	-0.52	-0.43	-0.65	-0.46	-0.56	-0.49	-0.65	-0.32	0.41	···	-1.51	-0.77	-0.80	0.00	-0.74	-0.77
1894	-0.38	-0.42	-0.30	-0.79	-0.43	-0.37	-0.38	-0.46	-0.22	0.39	···	0.03	-0.89	0.01	-0.75	-0.51	-0.01
1895	-0.41	-0.48	-0.26	-0.71	-0.69	-0.46	-0.25	-0.30	-0.23	0.08	···	-0.39	-0.14	-0.44	-0.67	-0.96	-0.57
1896	-0.27	-0.37	-0.08	-1.04	-0.66	-0.25	-0.06	-0.22	0.15	0.12	···	-0.68	-0.92	-0.30	-0.83	-0.07	-0.15
1897	-0.18	-0.23	-0.07	-0.37	-0.45	-0.31	0.06	0.04	-0.02	-0.29	···	-0.27	-0.85	0.12	-0.85	-0.48	-0.01
1898	-0.38	-0.41	-0.33	-1.36	-0.49	-0.22	-0.29	-0.23	-0.32	-0.40	···	0.05	-0.45	0.18	-0.99	-0.71	0.08
1899	-0.22	-0.22	-0.24	-0.97	-0.20	-0.09	-0.18	-0.32	-0.03	-0.24	···	-0.83	-0.57	-0.09	0.49	-0.77	-0.22
1900	-0.03	-0.08	0.07	-0.69	-0.11	-0.05	0.09	0.14	0.19	-0.27	···	0.58	0.01	-0.15	-0.44	0.13	0.12
1901	-0.09	-0.09	-0.07	-0.58	0.10	-0.22	0.00	-0.06	-0.05	0.10	···	0.45	0.12	0.00	-0.15	-0.22	-0.66
1902	-0.28	-0.39	-0.09	-1.67	-0.49	-0.25	-0.07	0.08	-0.03	-0.68	···	0.05	0.05	-1.20	-0.95	-0.44	-0.41
1903	-0.36	-0.40	-0.29	-0.44	-0.28	-0.59	-0.30	-0.17	-0.29	-0.46	···	-0.25	-0.75	0.36	-0.41	-0.84	-0.56
1904	-0.49	-0.48	-0.52	-0.47	-0.43	-0.47	-0.55	-0.63	-0.24	-0.41	···	-0.35	-1.36	-0.31	0.18	-0.40	-1.07
1905	-0.25	-0.29	-0.19	-0.06	-0.06	-0.59	-0.27	-0.01	-0.28	-0.40	···	0.58	-0.76	0.04	-0.19	-0.75	-0.56
1906	-0.17	-0.17	-0.17	-0.28	0.03	-0.39	-0.12	-0.07	-0.11	-0.41	···	0.63	-0.44	0.35	0.14	-0.46	-0.18
1907	-0.45	-0.50	-0.37	-0.41	-0.71	-0.54	-0.34	-0.37	-0.28	-0.25	···	-0.64	-1.55	-0.68	-1.10	-0.32	-0.56
1908	-0.32	-0.37	-0.23	-0.28	-0.41	-0.42	-0.33	-0.25	-0.25	0.07	···	0.39	-0.17	-0.67	-1.36	-0.31	0.02
1909	-0.33	-0.39	-0.22	-0.77	-0.45	-0.38	-0.25	-0.20	-0.21	-0.06	···	-1.02	0.06	-0.49	0.13	-0.67	-0.33
1910	-0.32	-0.40	-0.19	-0.79	-0.15	-0.45	-0.43	-0.25	-0.13	0.09	···	0.42	0.02	0.46	-0.39	-0.03	-0.53
1911	-0.29	-0.30	-0.28	-0.21	-0.27	-0.41	-0.25	-0.29	-0.23	-0.09	···	-0.63	-0.43	0.17	-0.56	-0.30	0.08
1912	-0.32	-0.45	-0.08	-0.86	-0.66	-0.50	-0.13	0.09	-0.07	-0.39	···	0.08	-1.03	-0.60	-1.01	-1.17	-0.58
1913	-0.25	-0.35	-0.08	-0.69	-0.27	-0.45	-0.24	-0.03	0.06	-0.32	···	-0.13	-0.57	0.31	0.19	-0.73	0.07
1914	-0.05	-0.13	0.08	-0.74	-0.03	-0.18	0.02	0.12	0.16	0.01	···	0.32	-1.35	0.27	0.16	-0.25	-0.62
1915	-0.01	-0.06	0.09	-0.97	-0.10	-0.07	0.24	0.28	0.11	-0.29	···	0.85	0.21	-0.54	0.49	-0.62	-0.32
1916	-0.26	-0.34	-0.11	-0.73	-0.43	-0.26	-0.25	-0.06	-0.04	-0.08	···	-1.05	-0.12	0.16	-0.44	-0.65	-0.48
1917	-0.48	-0.60	-0.26	-1.53	-0.54	-0.58	-0.39	-0.38	-0.28	0.55	···	-1.00	-0.99	-0.57	0.11	-0.89	-1.27
1918	-0.37	-0.43	-0.27	-1.25	-0.29	-0.37	-0.33	-0.34	-0.13	-0.07	···	0.35	-1.29	0.12	-0.52	-0.30	-0.39
1919	-0.20	-0.29	-0.03	-0.86	-0.53	-0.24	0.00	0.00	0.01	0.01	···	-0.25	-0.43	-0.70	-0.92	-0.64	-0.03
1920	-0.15	-0.18	-0.11	0.07	-0.12	-0.30	-0.21	-0.04	-0.04	-0.29	···	0.01	-0.56	0.52	-0.31	-0.67	-0.62
1921	-0.08	-0.08	-0.09	-0.16	0.17	-0.05	-0.25	-0.03	0.00	-0.22	···	0.44	-0.33	0.49	0.72	0.54	0.55
1922	-0.14	-0.19	-0.07	-0.15	-0.35	-0.08	-0.18	-0.02	-0.07	0.05	···	-0.11	-0.71	-0.48	0.69	-0.21	0.04
1923	-0.13	-0.10	-0.19	0.44	0.06	-0.22	-0.24	-0.11	-0.12	-0.42	···	0.58	-0.77	0.05	0.89	-0.41	-0.36
1924	-0.12	-0.12	-0.11	0.20	-0.13	-0.25	-0.09	0.05	-0.26	-0.10	···	-0.23	-0.45	-0.22	0.50	-0.76	-0.71
1925	-0.10	-0.04	-0.21	-0.17	0.41	-0.14	-0.22	-0.11	-0.18	-0.42	···	0.34	-0.54	0.47	1.16	0.05	0.03
1926	0.13	0.17	0.06	0.52	0.46	-0.11	0.12	0.20	0.12	-0.39	···	0.87	-0.91	0.15	0.04	-0.05	-0.55
1927	-0.01	0.01	-0.04	0.01	-0.05	-0.01	0.05	0.09	0.10	-0.61	···	-0.67	0.00	-0.06	-0.22	0.02	0.20
1928	0.06	0.11	-0.01	0.77	0.07	-0.12	0.12	0.14	0.08	-0.42	···	0.86	-0.02	-0.14	-0.51	-0.12	-0.20
1929	-0.17	-0.16	-0.18	0.40	-0.29	-0.31	-0.11	-0.12	-0.09	-0.33	···	-0.39	-0.54	-0.64	-0.92	-0.65	-0.15
1930	-0.01	0.09	-0.19	0.66	0.19	-0.04	-0.04	-0.11	0.07	-0.72	···	0.55	0.29	0.79	-0.12	-0.12	0.13
1931	0.09	0.16	-0.04	0.70	0.01	0.05	0.19	0.12	-0.12	-0.26	···	1.61	1.01	-0.39	-0.29	0.57	0.63
1932	0.05	0.10	-0.03	0.51	0.27	-0.05	-0.03	0.04	0.09	-0.27	···	-0.19	0.19	0.41	0.84	-0.32	0.37
1933	-0.16	-0.23	-0.04	-0.07	-0.47	-0.25	-0.12	0.03	0.03	-0.11	···	-0.60	-0.56	-0.58	-1.12	0.38	0.49
1934	0.05	0.07	0.01	0.87	0.36	-0.08	-0.25	0.04	0.07	0.07	···	0.98	-0.77	1.16	-0.32	1.12	-0.09
1935	-0.02	0.00	-0.05	0.51	0.08	-0.10	-0.13	0.11	-0.03	-0.51	···	-0.32	-0.44	0.31	0.03	-0.03	-0.23
1936	0.04	0.06	0.01	0.47	0.19	-0.13	0.00	0.08	-0.01	-0.02	···	-0.59	-0.27	0.74	0.46	0.12	-0.03
1937	0.17	0.25	0.04	1.40	0.21	0.13	0.04	0.14	-0.02	-0.14	···	0.04	0.47	0.84	-0.38	-0.22	0.14
1938	0.19	0.29	0.01	1.49	0.52	0.17	-0.12	0.05	0.13	-0.14	···	1.10	0.12	1.10	0.30	0.47	0.51
1939	0.05	0.17	0.14	0.91	0.32	0.14	-0.14	0.00	-0.03	-0.75	···	0.57	-0.37	0.52	0.44	0.59	0.32
1940	0.15	0.16	0.13	0.90	0.15	-0.01	0.06	0.20	0.09	0.16	···	0.95	0.18	-0.96	0.09	0.13	-0.74
1941	0.13	0.13	0.14	0.06	-0.13	0.21	0.24	0.31	0.05	-0.11	···	1.10	0.28	-1.20	-0.97	0.25	0.24
1942	0.09	0.07	0.12	0.41	0.01	0.04	0.03	0.24	0.14	-0.07	···	0.63	0.36	-1.09	-0.35	0.02	0.10

TABLE 1. (continued)

				Zone								Box					
Year	Globe	NH	SH	1	2	3	4	5	6	7	8	6	7	9	10	15	16
1943	0.04	0.08	-0.03	1.13	0.37	-0.05	-0.32	-0.05	-0.05	0.37	···	0.49	-0.58	0.71	0.31	0.30	-0.21
1944	0.11	0.16	0.04	1.07	0.47	-0.11	-0.14	0.07	0.15	-0.04	···	1.12	0.22	0.46	0.98	-0.13	0.12
1945	-0.03	-0.04	-0.02	0.49	-0.05	-0.13	-0.13	0.10	0.14	-0.45	···	-0.17	0.00	0.04	-0.92	0.00	0.09
1946	0.03	0.08	-0.05	0.08	-0.03	0.21	0.03	0.05	-0.02	-0.32	···	0.16	-0.04	0.31	-0.04	0.53	0.52
1947	0.15	0.18	0.11	0.93	-0.03	0.15	0.11	0.22	0.05	0.05	···	0.30	0.61	0.12	-0.11	0.06	0.07
1948	0.04	0.10	-0.06	0.27	0.32	0.04	-0.05	0.10	0.01	-0.44	···	-0.12	0.04	0.58	0.75	-0.11	0.24
1949	-0.02	0.04	-0.10	0.40	0.15	0.02	-0.12	0.08	0.01	-0.49	···	-0.12	0.01	0.88	-0.12	-0.06	0.83
1950	-0.13	-0.13	-0.14	0.45	-0.22	-0.09	-0.28	-0.10	0.08	-0.44	···	-1.33	-0.54	0.43	-0.38	0.13	-0.03
1951	0.02	0.07	-0.05	0.14	0.08	0.07	0.03	0.05	-0.16	0.04	···	-1.07	0.47	0.45	0.31	-0.23	0.19
1952	0.07	0.09	0.05	0.22	-0.08	0.16	0.09	0.20	-0.04	0.00	···	0.53	1.06	-0.08	-0.61	0.15	0.48
1953	0.20	0.33	0.03	1.01	0.44	0.22	0.14	0.15	0.06	-0.08	···	1.05	0.91	0.41	0.23	0.64	0.81
1954	-0.03	0.02	-0.10	0.81	-0.22	0.02	-0.07	-0.04	-0.02	-0.20	···	0.16	0.25	-0.25	-0.93	0.84	0.43
1955	-0.07	-0.09	-0.04	-0.31	-0.05	0.14	-0.22	-0.16	-0.14	0.22	···	-0.81	0.90	-0.29	0.25	-0.13	0.20
1956	-0.19	-0.29	-0.05	-0.07	-0.57	-0.23	-0.25	-0.24	-0.13	0.39	···	-0.43	-0.30	-1.28	-0.68	0.27	0.06
1957	0.09	0.03	0.17	0.09	0.26	-0.12	0.01	0.14	0.10	0.22	0.43	0.05	0.00	0.61	0.35	0.12	0.35
1958	0.11	0.16	0.04	-0.16	0.20	0.17	0.24	0.24	0.09	-0.22	-0.53	0.99	0.57	-0.09	-0.31	0.18	-0.42
1959	0.06	0.13	-0.02	0.55	0.17	0.05	0.06	0.15	0.06	-0.41	-0.46	-0.11	-0.09	0.53	-0.32	0.13	0.30
1960	0.01	0.11	-0.10	0.39	0.04	0.11	0.07	-0.03	0.06	-0.07	-0.89	0.30	0.74	0.30	-0.88	-0.18	-0.14
1961	0.08	0.07	0.08	-0.12	0.37	0.16	-0.12	0.01	0.20	-0.06	0.27	0.31	0.33	0.86	0.84	-0.11	0.00
1962	0.02	0.10	-0.07	0.45	0.31	0.05	-0.07	-0.08	0.03	0.20	-0.69	0.08	-0.37	-0.22	1.46	0.13	-0.22
1963	0.02	0.10	-0.08	-0.11	0.32	0.08	0.06	-0.03	-0.05	-0.35	-0.01	0.64	-0.29	-0.60	0.68	0.33	-0.35
1964	-0.27	-0.24	-0.31	-0.47	-0.32	-0.20	-0.14	-0.17	-0.27	-0.47	-0.73	-0.35	-0.44	-0.13	-0.33	-0.22	0.00
1965	-0.18	-0.20	-0.15	-0.31	-0.31	-0.15	-0.15	-0.12	-0.12	-0.21	-0.31	-0.52	-0.55	-0.65	0.28	-0.06	-0.22
1966	-0.09	-0.08	-0.10	-0.90	-0.23	0.10	0.11	0.00	-0.27	-0.29	0.06	-0.51	0.60	0.21	-0.44	-0.26	-0.31
1967	-0.02	0.01	-0.06	0.39	0.28	-0.15	-0.15	-0.14	0.00	-0.08	0.11	0.01	-0.47	0.53	0.98	-0.04	-0.37
1968	-0.13	-0.12	-0.14	-0.44	-0.01	-0.13	-0.09	-0.26	-0.16	0.22	-0.13	0.07	0.16	-0.11	-0.68	-0.40	-0.39
1969	0.02	-0.03	0.09	0.00	-0.53	-0.10	0.32	0.19	0.01	-0.22	0.20	-0.09	0.47	-0.74	-1.89	-0.09	-0.22
1970	0.03	-0.02	0.09	-0.25	-0.10	0.01	0.07	0.02	0.09	0.03	0.36	-0.18	-0.25	-0.17	-0.02	-0.20	-0.14
1971	-0.12	-0.15	-0.08	-0.05	-0.04	-0.10	-0.29	-0.24	-0.07	0.15	0.22	-0.22	-0.10	0.21	0.49	-0.28	0.04
1972	-0.08	-0.26	0.14	-0.34	-0.65	-0.28	0.03	0.14	0.07	-0.12	0.63	-1.22	-2.08	0.33	-0.65	-0.16	-0.28
1973	0.17	0.17	0.17	0.13	0.30	0.06	0.19	0.25	0.15	-0.01	0.13	0.43	0.51	0.19	0.66	-0.10	0.43
1974	-0.09	-0.16	0.00	-0.20	-0.19	-0.10	-0.18	-0.28	-0.02	0.31	0.70	-0.17	-0.91	0.72	-0.13	0.15	0.14
1975	-0.04	-0.03	-0.05	0.09	0.31	-0.05	-0.28	-0.22	0.02	0.09	0.28	-0.34	-0.14	1.10	1.16	-0.44	0.39
1976	-0.24	-0.27	-0.20	-0.11	-0.38	-0.27	-0.24	-0.22	-0.21	-0.16	-0.21	0.49	-0.74	-0.54	-0.76	-0.28	-0.39
1977	0.16	0.15	0.17	0.14	0.27	0.12	0.11	0.16	0.13	0.19	0.29	0.78	0.64	0.14	0.41	0.36	0.02
1978	0.09	0.07	0.12	-0.12	0.14	0.04	0.11	0.06	0.12	0.31	0.08	-0.18	-0.93	-0.63	0.32	-0.16	-0.36
1979	0.12	0.12	0.13	-0.64	0.14	0.22	0.26	0.21	0.15	0.24	-0.40	-0.25	0.18	-0.14	0.22	-0.46	-0.06
1980	0.27	0.21	0.33	0.21	0.08	0.12	0.36	0.27	0.32	0.33	0.59	0.59	-0.12	-0.67	-0.04	0.52	0.03
1981	0.42	0.51	0.31	1.26	0.93	0.25	0.21	0.02	0.24	0.54	1.63	1.79	1.18	0.23	1.63	0.76	0.13
1982	0.02	0.02	0.03	-0.26	0.08	-0.08	0.15	0.03	0.14	0.22	-0.55	-0.82	-0.88	0.40	0.84	-0.13	0.11
1983	0.30	0.37	0.21	0.13	0.74	0.10	0.40	0.38	0.09	0.15	-0.09	0.52	-0.15	0.84	1.96	0.10	0.18
1984	0.09	0.08	0.10	0.26	0.04	-0.05	0.14	0.03	-0.05	0.18	0.85	0.44	-0.18	0.19	-0.30	0.04	0.11
1985	0.05	-0.03	0.14	0.21	-0.26	-0.04	0.03	0.02	0.20	0.40	0.71	-0.37	-0.14	-0.96	-0.29	-0.29	0.04

as in 1940. In the southern hemisphere, 1980 is warmer than any previous year in the record. We have included provisional results for 1985 in Figure 6, based on a limited number of stations.

Other investigators studying temperature change with the meteorological station data have limited their analyses to the northern hemisphere (an exception, the analysis recently published by *Jones et al.* [1986*b*, *c*], is discussed in the final section 6). Our results for that region are in general agreement with most other studies, for example, *Willett* [1950], *Mitchell* [1961], *Budyko* [1969], *Vinnikov et al.* [1980], and *Jones et al.* [1982]. All of these studies found a hemispheric warming of the order of 0.5°C between 1880 and 1930–1940, and a subsequent cooling of a few tenths of a degree; the more recent of these studies also found a warming during the past decade. The only exception to the general agreement is *Yamamoto and Hoshiai* [1980], who obtained a hemispheric temperature change with a shape similar to that found in the other studies but with the magnitude of temperature variations only about half as large as in the other studies. Yamamoto and Hoshiai used the *Gandin* [1963] method of analysis, which, in effect, assumes that areas without station coverage had no temperature change. The other studies, in effect, assume that the areas without station coverage had the same change as the area with stations. It would be difficult to prove a priori which of these assumptions is better, especially since there is a high correlation of data-rich areas with the continents and

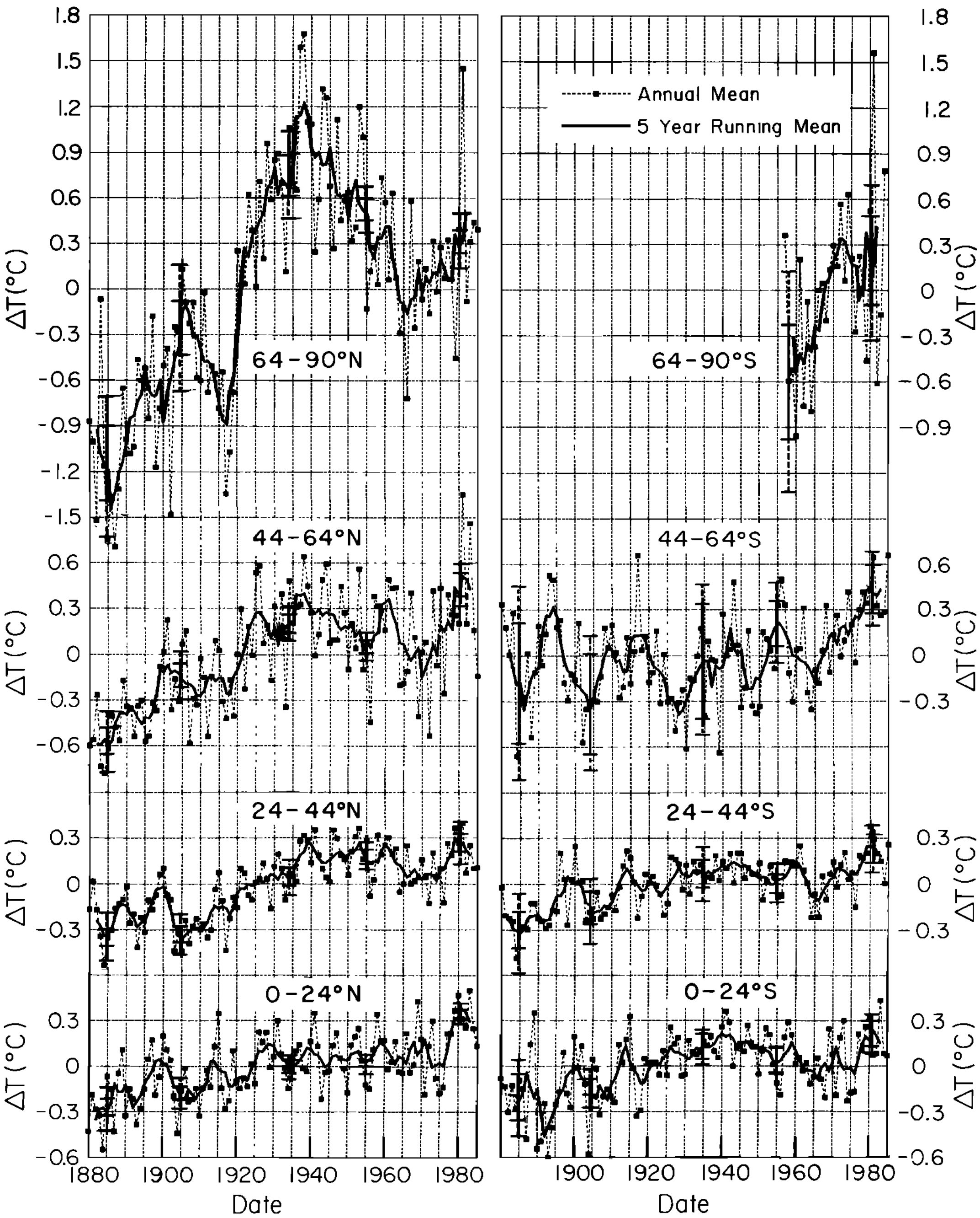


Fig. 7. Surface air temperature change for the eight latitude zones of Figure 2. Graphical details as in Figure 6.

data-free areas with the oceans. However, based on the error estimates which we obtain for our own results in section 5, we conclude that the Gandin method yields a less realistic trend.

Temperature changes for the eight latitude zones are shown in Figure 7. One aspect which they demonstrate, especially in the northern hemisphere, is high-latitude enhancement of long term change. The magnitude of the 1880–1940 warming is progressively less from the north polar region to the equatorial regions; this warming is significant in all zones except Zone 7 (44°–64°S) and Zone 8 (64°–90°S), where observations are inadequate for that period. The 1940–1965 cooling is only clearly apparent for the high northern latitude zones. For most zones it is more accurate to say that there was little trend for the period 1940–1970. There is significant warming in most zones during the past 15 years.

The zonal temperature change is shown more compactly and with higher latitudinal resolution by the color presentation in Plate 1. Annual mean results are shown in Plate 1a and the 5 year smoothed temperature change in Plate 1b. Blues and greens represent negative ΔTs for a given latitude, while yellows and reds are positive, where ΔT = 0 is the 1951–1980 mean. Plate 1 strikingly portrays the high-latitude enhancement of temperature changes and the warming maxima of 1940 and 1980. Note that the

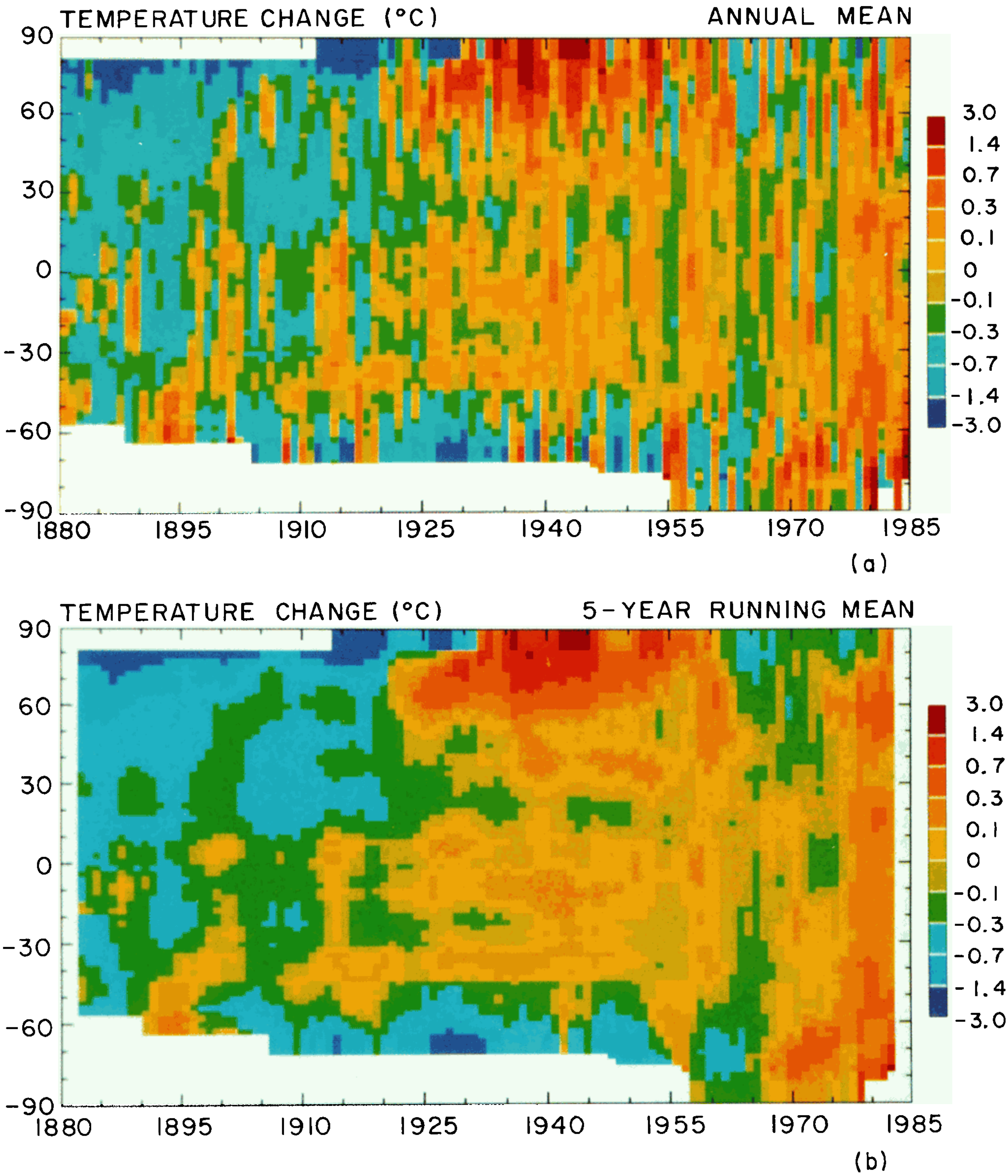
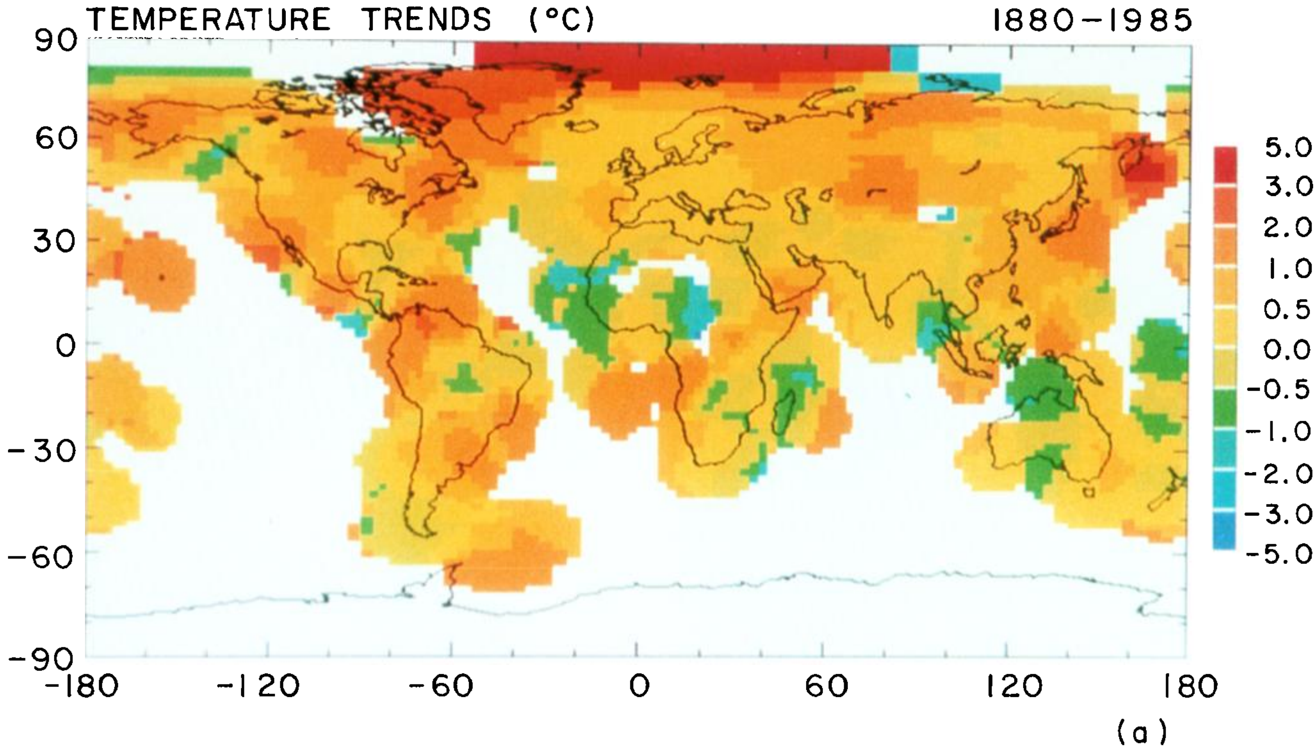


Plate 1. (a) Annual and (b) 5 year smoothed zonal mean surface air temperature change in the past century. At each latitude the temperature zero point is defined as the 1951–1980 mean. Blues and greens represent negative values and yellows and reds are positive values. A nonlinear temperature scale is used so that there are comparable areas for each color. Regions without data are white.



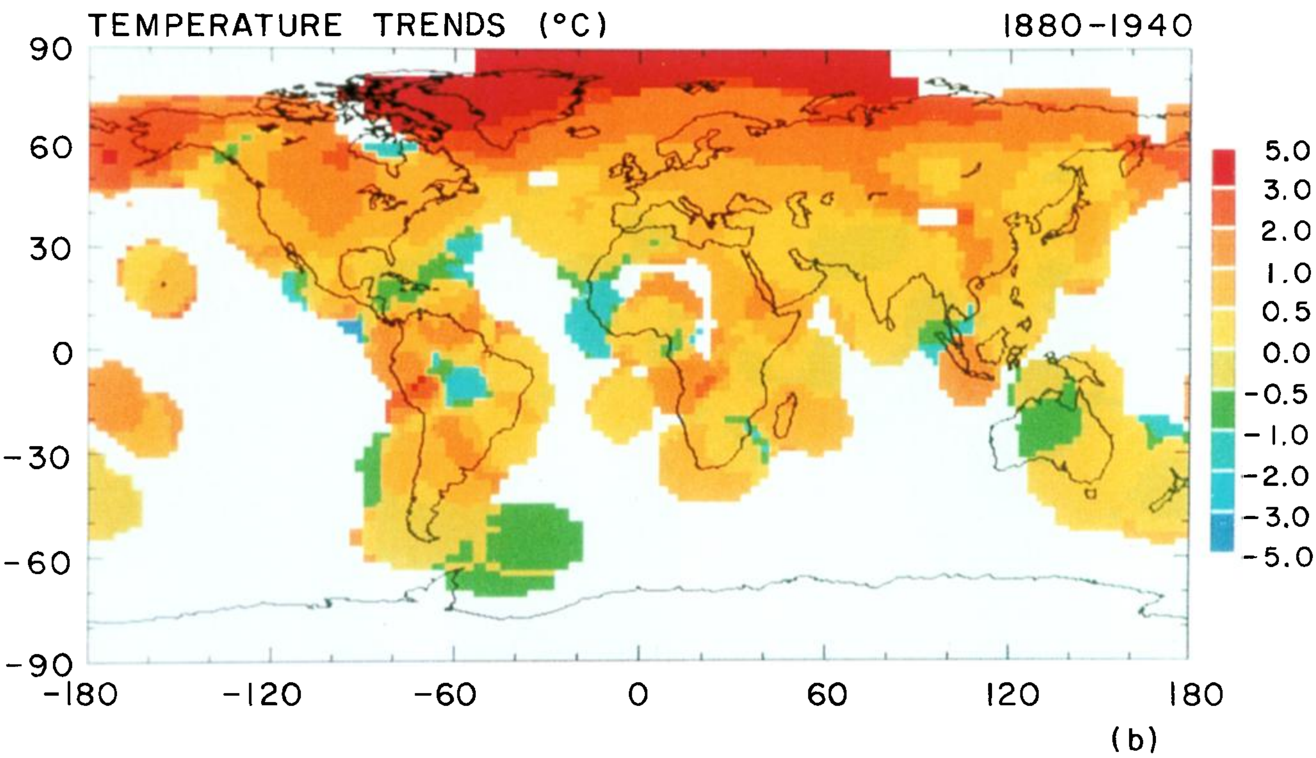
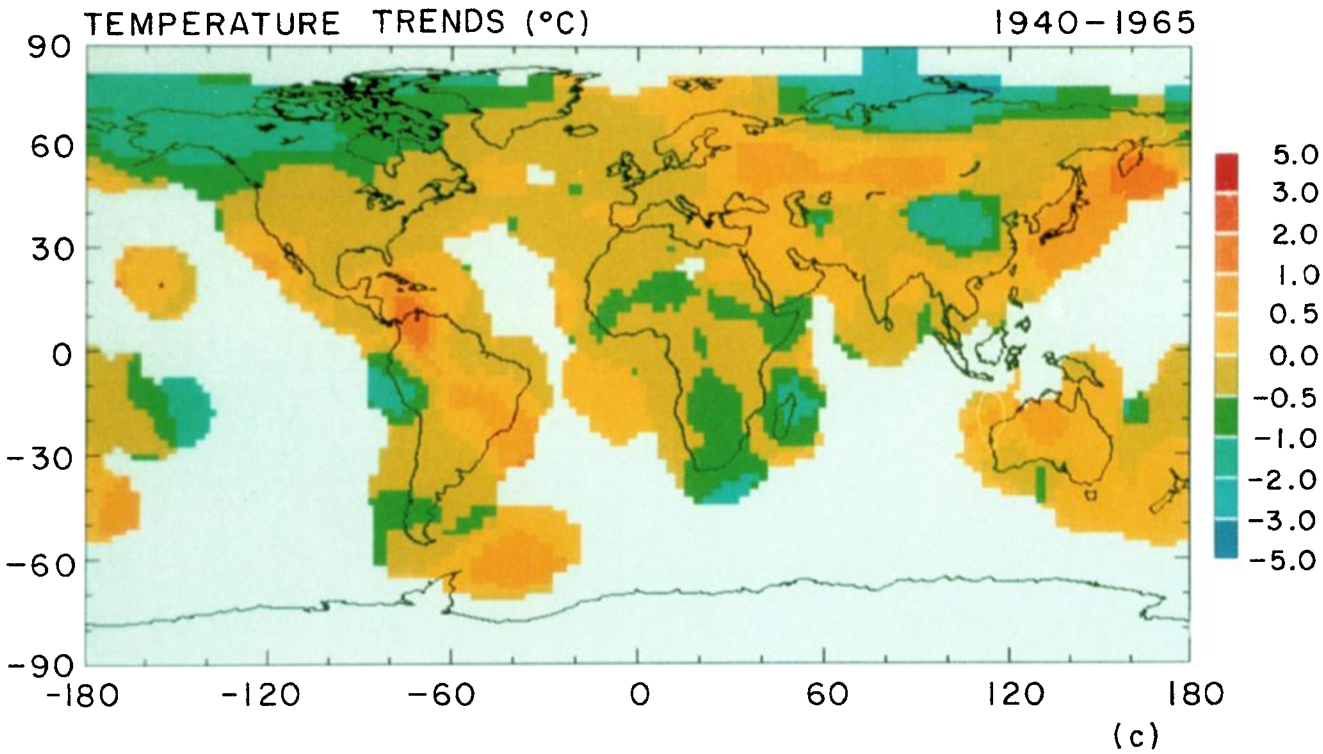


Plate 2. Temperature trends inferred for the four time intervals (a) 1880–1985, (b) 1880–1940, (c) 1940–1965, and (d) 1965–1985, from the linear best fit to all available temperatures for each interval. The indicated temperature trend is the product of the derived slope and the indicated time interval. In Plate 2a, results are shown only for those subboxes which had a defined temperature by 1925 or earlier; in 2b, 2c and 2d, the minimum record lengths for a subbox are 25, 20, and 15 years, respectively.



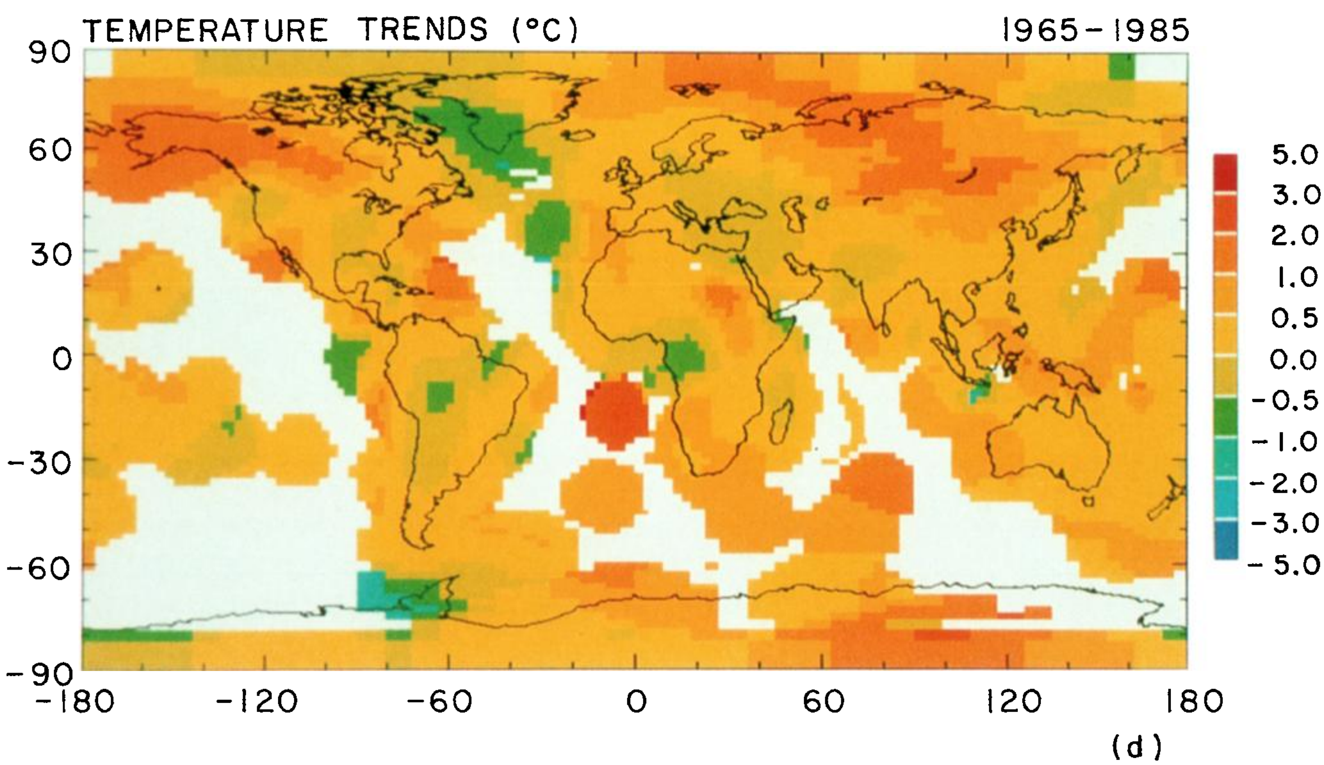


Plate 2. (continued)

warming centered in 1940 was most intense in high northern latitudes, while the recent warming is more global in extent. The geographical distribution of temperature trends in the past century is illustrated in Plate 2a. The results shown in Plate 2 (and Plate 3a) are the linear trends multiplied by the indicated time interval. Stations employed in constructing Plate 2a were restricted to those with records which extend at least as far back as 1925. The estimated temperature trends can be unreliable in fringe areas where only one or two stations contribute to the trend, as shown in section 5; such regions with potentially anomalous results include central Africa, Mongolia, and many ocean locations.

It is apparent that the warming of the past century is by no means globally uniform. The greatest warming occurs in the Arctic, but note that the area of that region is exaggerated by the map projection. Areas of greater than average warming occur at lower latitudes in west and central Asia, central and eastern Canada, Greenland, Alaska, and parts of South America.

In Plates 2b, 2c, and 2d we have broken up the past century into the periods of warming and cooling suggested by the global mean temperature change in Figure 6: the 1880–1940 warming period, the 1940–1965 cooling period, and the 1965–1985 warming period. In 1880–1940 there is a strong warming trend at high northern latitudes, especially Alaska, central Canada, Greenland, the northern coastline of Asia, and that portion of the Arctic Ocean where a temperature trend could be inferred. At lower latitudes there is warming of more than 0.5°C in most of the United States and China and in parts of South America and Africa. The few local areas where it appears that cooling may have occurred are mainly in the southern hemisphere, but the station coverage there is poor during that period.

The period 1940–1965 (Plate 2c) is marked by strong cooling at high northern latitudes, especially Alaska, northern Canada, northwestern Greenland, and the northern coastline of Asia. At lower latitudes there is strong cooling in China and Africa. A substantial area of warming stretches from western Europe across central Asia almost to Lake Baykal at latitudes about 40°–60°N.

The period 1965–1985 (Plate 2d) is marked by rapid warming over Alaska, northwest Canada, and the northern half of Asia. Substantial cooling occurs in the southern Greenland region. In comparing Plates 2d and 2b, note that the recent period is only one-third as long as the earlier period; if the temperature trends were graphed as a rate the results for the recent period would appear more pronounced.

Note in Plate 2 that the geographical patterns of the warming and the locations of the areas of greater than average warming are not of the nature that would be expected for anthropogenic heat island effects. We present additional evidence in section 5 indicating that the global warming trend of the past century is not due to anthropogenic heat island effects.

Examination of Plate 2 reveals several places where the 1880–1985 temperature trend is not the sum of the trends for the three subperiods. This is because the results in Plate 2 (and Plate 3a) are the linear trends for the indicated intervals. One characteristic of the linear trends is that a strong change at the end of a long record, such as the warming in the early 1980s, is not reflected as fully as it would be if the temperature change were obtained by differencing the initial and final temperatures.

Finally, with regard to Plate 2, we note that *Jones and Kelly* [1983] presented maps of linear temperature trends for several intervals within the period 1917–1980. Their results for periods similar to those which we chose, specifically, their results for 1940–1964 and 1965–1980, are in good general agreement with our results.

We present examples of the data at monthly resolution in Plate 3a, which illustrates that the surface air warming in the past century has been greatest in the winter months, especially at high latitudes. Plate 3b, which presents the standard deviation about the 5-year smoothed temperature change, shows that the natural variability on short time scales has a qualitatively similar geographical and seasonal pattern, the variability increasing with increasing latitude and from summer to winter. Plate 3c shows the confidence limits [*Ostle,* 1963], for the trends in Plate 3a. It is apparent that the trends are highly significant in most cases, especially at low and middle latitudes. The lesser significance at high latitudes is a result of the greater variability there, the reduced area for a given increment of latitude, and shorter records in the southern hemisphere high latitudes.

Plates 3a–3c suggest that there has been a measurable change in the seasonal cycle of temperature during the past century, in addition to a general warming. We explicitly illustrate this in Plate 3d, which shows the difference between the winter and summer temperature changes, as a function of latitude and time. On the basis of error estimates obtained in section 5, it is apparent that there has been a significant reduction in the amplitude of the seasonal cycle in the past century, but little net change between 1940 and 1985.

Finally, Figure 8 and Tables 1 and 2 provide examples of temperature change and variability at higher temporal and spatial resolution. Figure 8 shows seasonal mean temperature change for the globe, box 9 (most of Europe) and box 15 (west-central United States and northern Mexico), the latter regions being defined in Figure 2. The variability (standard deviation) of the seasonal mean temperature (average for the four seasons) is 0.2°C for the globe, 1.0°C for box 9, and 0.6°C for box 15. The temperature in these regions has little trend during the period 1950–1985, though the 5-year running mean global temperature in the 1980s is about one standard deviation above the mean. Although the area of a box is more than 6 million square kilometers, interseasonal variations at the box resolution are as much as several degrees Celsius. At high latitudes, such as box 9, the extreme variations are mostly in the winter, as can be seen in Figure 8 since the winter points fall on the lines separating successive years. Table 1 includes the annual temperature change for six individual boxes (6, 7, 9, 10, 15, and 16) and Table 2 gives seasonal temperature change for three regions (boxes 6 and 7, Canada; boxes 9 and 10, Europe and western Asia; boxes 15 and 16, United States and northern Mexico).

We have presented only a few examples from our data set for surface air temperature change. Clearly, more information could be extracted from analyses of the data's temporal and spatial characteristics, but such analyses are beyond the scope of this paper. A documented computer tape of the derived temperature changes, which we intend to keep updated in the future, is available from the authors or Roy Jenne at NCAR. The tape contains annual, seasonal, and

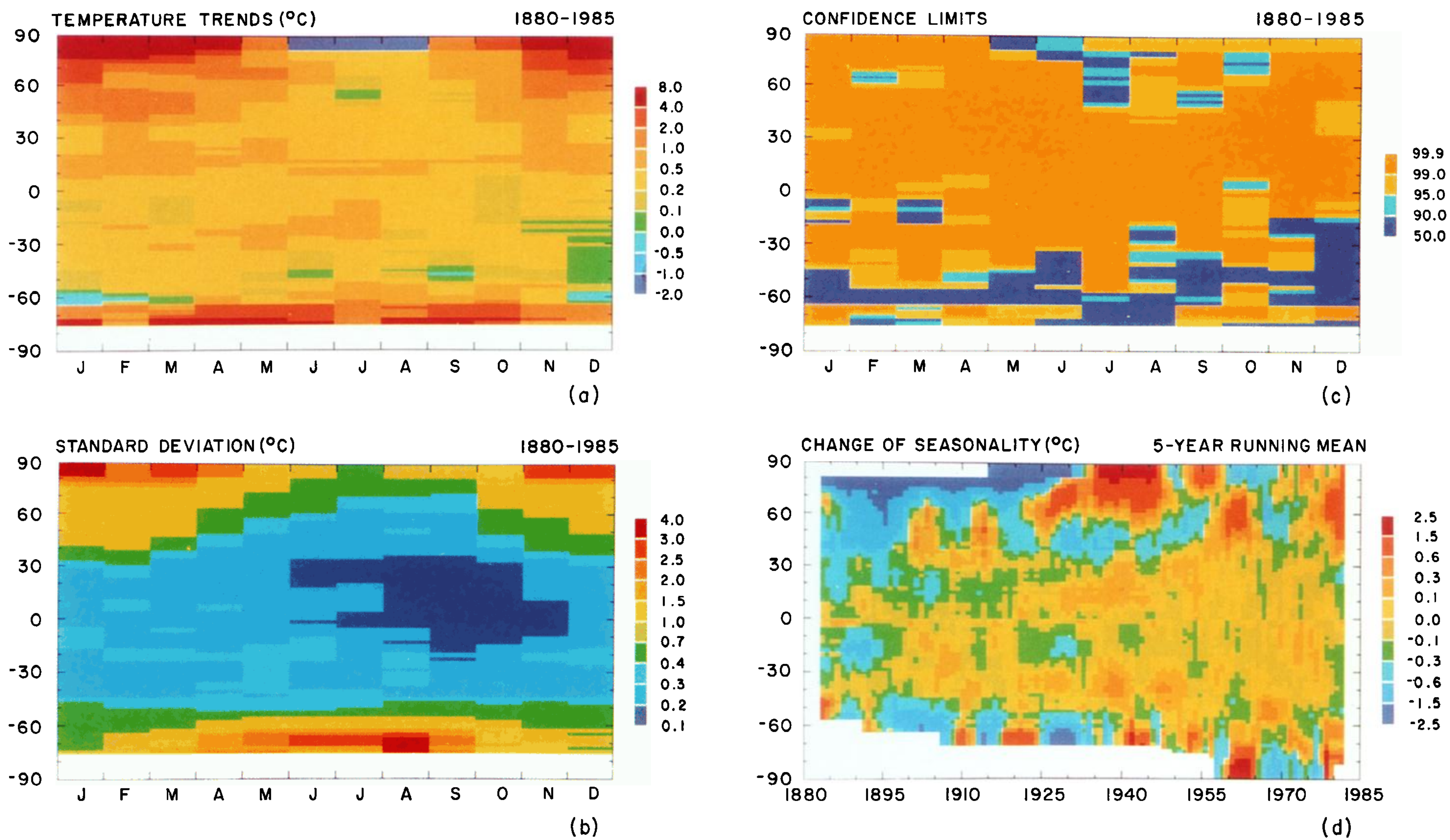


Plate 3. (a) Zonal mean temperature trend for the period 1880–1985 for each of the 12 months, inferred from the linear best fit to the temperatures for that interval. (b) Standard deviation of the monthly zonal temperature about the five-point running mean. (c) Significance level of the trends in Plate 3a. (d) Difference between winter temperature change and summer temperature change of the past century. Winter is defined as December–February in the northern hemisphere and June–August in the southern hemisphere. The temperature trends are the linear least square fits to the surface air temperature change of the seven latitude zones with long records (Figure 2). The estimated error is largest at high latitudes partly because of the reduced area there.

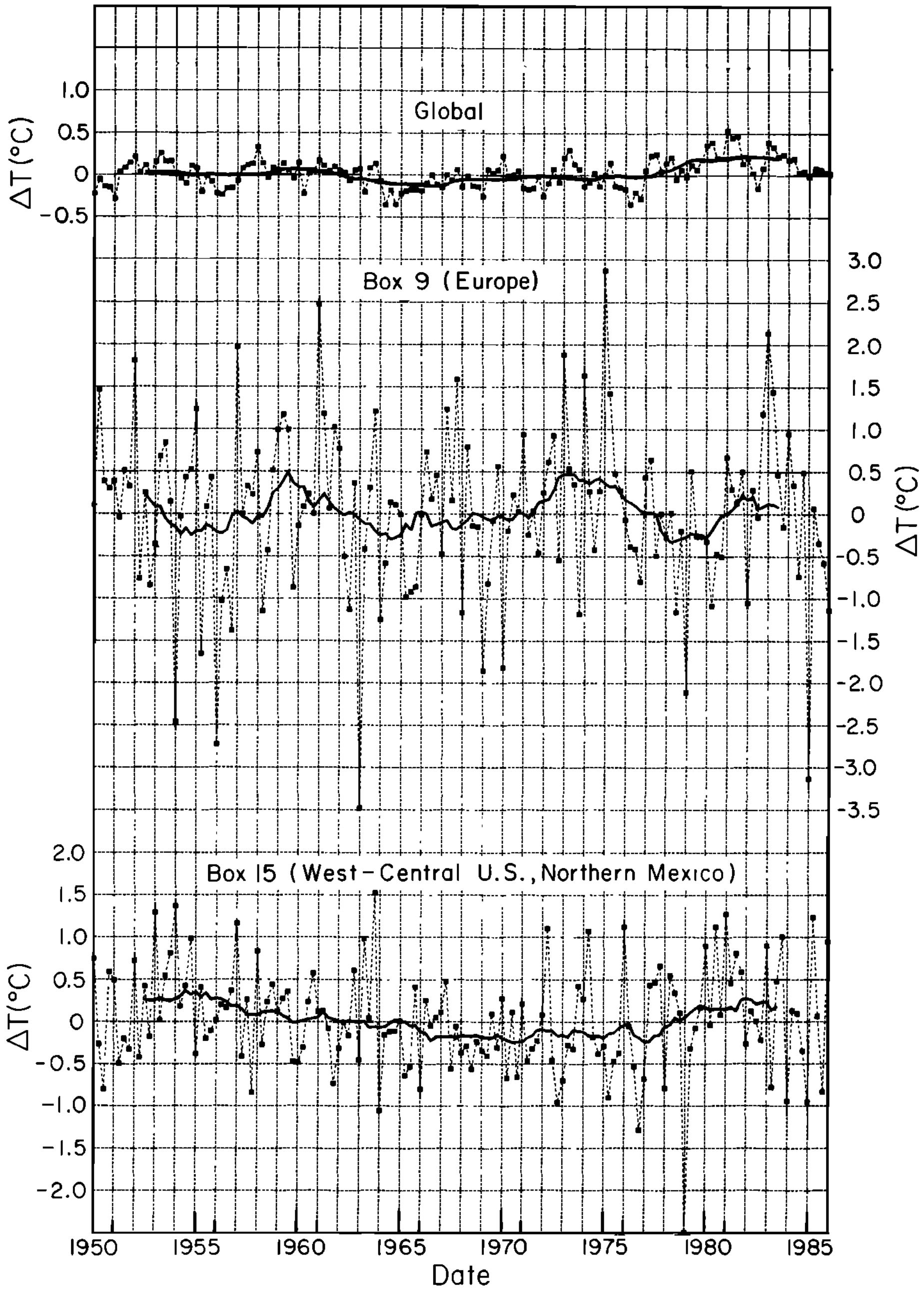


Fig. 8. Temperature change at seasonal resolution; the solid curve is the 21 point (approximately 5-year) running mean. Box 9 contains most of Europe and Box 15 contains west-central United States and northern Mexico (see Figure 2). Each season is 3 calendar months, for example from December 1 through February 28 or 29, computed as the simple mean of the ΔTs for the 3 months.

monthly temperature deviations from the long-term means at global, hemispheric zonal, box, and subbox spatial resolutions. The tape includes a small program to interpolate results to a 1° by 1° (latitude by longitude) grid; for most regions such a resolution is higher than the data meaningfully provides, but the high resolution allows the user to construct readily the results at arbitrary coarser resolutions. The user should be aware of basic limitations and probable errors in the data set, which are partially clarified in the following section.

5. Error Estimates

The greatest source of error or uncertainty in the derived temperature changes is due to the incomplete spatial and temporal coverage provided by the finite number of meteorological stations. Indeed, the coverage in the southern hemisphere is sufficiently sparse (Figure 1) that the data from that hemisphere have been dismissed in most previous studies of the station data. Thus prior to our earlier paper [*Hansen et al.*, 1981], there were no published southern hemisphere or global surface air temperature changes. More recently *Folland et al.* [1984] have analyzed marine temperature changes in both hemispheres and *Jones et al.* [1986*b*, *c*] have studied southern hemisphere and global temperature changes based on land-based stations and marine data.

We obtain a quantitative estimate of the error due to imperfect spatial and temporal coverage with the help of a 100-year run of a general circulation model (GCM). The

TABLE 2. Seasonal Surface Air Temperature Change for Specified Regions.

	Box 6 + Box 7				Box 9 + Box 10				Box 15 + Box 16			
Year	D-J-F	M-A-M	J-J-A	S-O-N	D-J-F	M-A-M	J-J-A	S-O-N	D-J-F	M-A-M	J-J-A	S-O-N
1880	-1.35	-1.73	-0.46	-1.67	-2.09	-0.50	0.10	-0.76	1.40	0.27	-0.36	-1.81
1881	-1.62	0.39	-0.75	-1.82	-1.09	-0.63	-0.45	-1.58	-1.32	-0.24	0.17	0.03
1882	-0.15	-1.90	-0.46	-0.80	0.86	0.08	-0.23	-1.24	1.38	-0.26	-0.41	-0.34
1883	-3.07	-1.38	-0.63	-1.75	-2.15	-0.99	-0.36	-0.14	-0.80	-0.81	-0.19	-0.53
1884	-3.24	-0.99	-0.98	-1.28	1.21	-2.02	-1.22	-0.76	-0.23	-0.58	-0.61	0.03
1885	-3.33	-0.53	-0.88	-0.46	-0.12	-0.63	-0.61	-1.10	-1.27	-0.48	-0.40	-0.60
1886	-0.93	-0.33	-0.17	-1.07	-0.64	-1.44	-0.58	-0.53	-0.79	-0.43	-0.34	-0.80
1887	-3.85	-0.62	-0.82	-1.19	0.95	-0.41	-0.20	0.34	-0.55	0.15	-0.35	-0.73
1888	-1.95	-1.36	-0.39	-0.58	-0.88	-0.22	-0.11	-0.32	-1.06	-0.88	-0.52	-0.74
1889	0.81	1.72	-0.18	-0.23	-1.76	-0.50	-0.03	-1.03	-0.12	0.32	-0.75	-1.01
1890	-2.21	-0.95	-0.25	0.19	-0.56	-0.24	0.28	-1.20	2.16	-0.46	-0.56	-0.38
1891	-0.43	-0.23	-0.61	-0.19	-2.30	-0.47	-0.28	-1.47	0.33	-1.15	-1.03	-0.60
1892	0.74	-0.56	-0.36	-0.06	-0.07	-1.30	0.32	-0.44	0.12	-1.28	-0.79	-0.65
1893	-1.90	-1.73	0.06	-0.86	-3.88	0.34	0.05	0.76	-1.28	-0.85	-0.59	-0.94
1894	-1.94	-0.25	0.38	-0.65	1.10	-0.31	-0.36	-1.10	-0.25	0.22	-0.76	-0.24
1895	-0.17	0.55	-0.55	-0.89	-2.33	-0.53	-0.05	0.53	-1.26	-0.30	-0.75	-0.51
1896	0.26	-0.98	-0.09	-2.36	-1.14	-1.21	0.18	0.15	0.18	-0.03	-0.16	-0.74
1897	-0.24	-0.69	-0.40	-0.71	-1.37	-0.18	0.37	-0.39	0.09	-0.21	-0.58	0.14
1898	-0.13	0.11	0.12	-0.87	-0.38	-2.56	-0.06	-0.15	0.24	-0.23	-0.31	-0.61
1899	-1.57	-1.52	-0.50	0.42	2.25	-0.40	-0.42	1.50	-1.51	-0.59	-0.41	0.13
1900	0.59	0.76	0.01	-0.43	-2.57	-0.69	0.21	0.22	-0.02	-0.26	-0.14	0.62
1901	0.61	0.64	-0.10	-0.03	0.15	0.76	0.40	-0.75	-0.15	-0.74	0.08	-0.46
1902	1.64	0.61	-0.88	-0.16	0.62	-1.75	-0.24	-2.25	-0.90	0.05	-0.89	0.02
1903	-0.52	-0.78	-1.06	-0.40	0.63	-0.51	-0.48	-0.55	-0.54	-0.08	-1.27	-0.76
1904	-1.74	-1.02	-0.54	0.08	0.50	-0.84	-0.35	-0.12	-1.16	-0.45	-1.19	-0.30
1905	-1.14	0.77	-0.33	-0.17	0.25	-1.36	-0.16	0.72	-1.79	0.03	-0.67	-0.25
1906	1.15	-0.20	0.28	0.07	0.15	1.32	0.38	-0.48	0.29	-0.88	-0.68	-0.32
1907	-2.34	-2.16	-0.93	-0.09	-0.81	-0.48	-0.42	-0.94	0.56	-0.79	-1.06	-0.59
1908	1.34	-0.55	-0.17	0.59	-1.01	-1.57	-0.47	-1.33	0.28	0.38	-0.81	-0.34
1909	-1.48	-0.58	0.09	0.10	-0.86	-1.33	-0.23	0.95	0.79	-0.88	-0.58	-0.18
1910	-0.67	1.64	-0.11	-0.26	1.49	0.09	-0.22	-1.19	-1.51	0.74	-0.76	-0.20
1911	-1.47	0.22	0.01	-1.18	-0.43	-0.69	0.25	0.22	0.19	-0.05	-0.44	-0.53
1912	-0.31	-0.59	-0.93	-0.11	-0.23	-0.59	-0.66	-1.73	-1.20	-0.83	-1.14	-0.41
1913	-0.77	-0.56	-0.40	-0.04	0.16	0.05	-0.58	0.45	0.07	-0.47	-0.56	-0.29
1914	-0.15	-0.06	-0.56	0.26	2.95	0.14	-0.36	-1.18	0.04	-0.52	-0.49	0.03
1915	0.03	1.30	-0.76	0.15	1.37	-0.08	0.22	-1.01	-0.58	-1.06	-1.19	0.26
1916	-1.03	-0.14	0.08	-0.27	1.07	-0.59	-0.62	-0.27	0.07	-0.40	-0.76	-0.83
1917	-1.81	-1.06	-0.10	-0.12	-1.24	-0.91	0.00	1.20	-0.77	-1.56	-0.70	-0.95
1918	-2.42	-0.37	-0.89	-0.03	0.43	-0.88	-0.30	0.43	-1.65	0.24	-0.37	-0.54
1919	1.53	-0.11	0.02	-1.59	-1.53	-1.15	-0.54	-0.53	0.27	-0.32	-0.47	-0.18
1920	-1.32	-0.98	-0.01	0.03	0.09	2.16	0.49	-1.68	-0.73	-1.02	-0.98	-0.32
1921	0.79	0.12	0.23	-0.62	0.06	1.45	0.72	-0.51	0.93	0.66	-0.28	0.54
1922	-1.36	0.43	-0.18	0.28	-1.04	0.84	0.32	-0.48	0.04	-0.07	-0.36	0.13
1923	-1.56	-1.33	-0.34	1.22	0.65	-0.62	0.29	1.85	0.36	-0.86	-0.76	-0.57
1924	1.05	0.13	-0.54	0.15	-0.47	-0.12	0.05	0.96	0.18	-1.24	-0.47	-0.30
1925	-1.85	0.53	-0.11	-0.96	2.86	0.07	0.25	0.30	0.07	0.62	-0.17	-0.75
1926	2.11	0.00	-0.41	-0.89	0.70	-0.15	-0.64	0.79	0.26	-0.83	-0.48	-0.16
1927	0.11	-0.17	-0.32	-0.30	-0.50	-0.32	0.92	0.30	0.88	0.15	-1.06	0.73
1928	-0.06	0.11	-0.22	0.06	-0.70	-1.63	-0.38	0.52	-0.02	-0.33	-0.57	-0.24
1929	-0.11	-0.12	-0.12	-0.13	-3.29	-0.92	0.49	1.24	-0.74	0.30	-0.51	-0.66
1930	-0.96	0.47	0.66	0.17	-0.40	0.45	0.47	0.54	0.59	0.00	-0.06	-0.17
1931	3.21	0.64	0.77	0.99	-2.07	-0.54	0.78	0.00	0.61	-0.55	0.29	1.27
1932	0.44	0.16	0.51	-0.27	0.68	-0.12	0.43	0.97	1.84	-0.52	0.02	-0.49
1933	-0.37	-0.10	0.31	-0.97	-1.20	-0.64	0.08	-0.04	0.43	-0.02	0.12	0.50
1934	-1.41	0.32	-0.19	0.38	0.04	-0.19	-0.21	0.78	0.81	0.68	0.49	0.63
1935	-0.75	-0.73	0.24	-0.97	0.97	-0.26	0.25	0.19	0.39	-0.14	-0.07	-0.26
1936	-1.63	0.39	0.70	-0.64	0.13	-0.51	0.71	0.70	-1.59	0.59	0.59	-0.16
1937	-1.18	0.96	0.84	0.29	1.26	-0.36	0.63	1.03	0.33	-0.34	0.38	-0.21
1938	-0.16	0.45	0.58	0.89	0.17	0.97	0.70	1.58	0.78	0.61	0.05	0.28
1939	0.00	-0.54	0.10	0.02	-0.11	0.04	0.75	-0.43	0.61	0.37	0.11	0.40
1940	2.32	0.72	0.00	0.17	-1.99	-0.17	0.73	0.40	-0.46	-0.35	-0.14	-0.21
1941	1.61	1.18	0.33	-0.34	-1.17	-1.22	-0.23	-1.28	0.70	-0.14	-0.19	0.61
1942	1.31	1.43	0.00	0.09	-2.81	-1.73	0.10	0.49	0.21	0.28	-0.01	0.28
1943	-0.72	-1.25	-0.37	1.15	0.11	1.21	0.35	0.28	0.51	-0.14	0.40	-0.43

TABLE 2. (continued)

	Box 6 + Box 7				Box 9 + Box 10				Box 15 + Box 16			
Year	D-J-F	M-A-M	J-J-A	S-O-N	D-J-F	M-A-M	J-J-A	S-O-N	D-J-F	M-A-M	J-J-A	S-O-N
1944	1.68	0.20	0.12	0.85	2.46	1.02	-0.04	0.26	0.34	-0.25	0.02	0.02
1945	0.99	0.18	-0.44	-0.60	-1.59	-0.21	0.40	-0.07	-0.07	0.59	-0.44	0.28
1946	-0.58	1.18	-0.27	-0.26	0.77	0.14	0.08	-0.32	-0.09	1.11	-0.31	0.31
1947	0.60	-0.42	-0.01	0.91	-2.58	0.80	0.05	0.99	0.64	-0.38	-0.07	0.61
1948	0.12	-1.34	0.45	1.32	1.30	0.68	0.24	0.65	-0.53	0.25	0.02	0.21
1949	-1.49	0.51	0.20	0.51	1.60	-0.04	-0.08	0.07	0.49	0.37	0.27	0.43
1950	-2.48	-0.91	-0.52	-0.51	-1.30	1.08	-0.04	-0.12	1.40	-0.56	-0.62	0.23
1951	0.43	0.40	-0.14	-0.65	-0.95	0.78	0.52	0.20	0.37	-0.24	-0.07	-0.24
1952	-0.72	1.16	0.30	0.54	2.33	-1.39	0.50	-1.22	1.10	-0.18	0.65	-0.23
1953	2.20	0.95	0.14	1.36	-0.32	0.93	0.82	-0.91	1.35	0.34	0.43	0.65
1954	0.42	-0.85	0.12	0.82	-2.45	-0.89	0.48	0.81	1.43	0.12	0.35	0.66
1955	1.19	-0.24	0.69	-0.40	0.93	-1.11	0.37	0.63	-0.12	0.61	0.06	-0.09
1956	-0.03	-0.90	-0.33	-0.17	-2.87	-0.89	-0.28	-0.90	0.03	-0.21	-0.01	0.10
1957	-1.72	0.45	-0.19	0.46	1.18	-0.45	0.41	0.41	1.29	-0.05	0.13	-0.44
1958	2.27	1.56	-0.04	0.18	1.80	-1.59	-0.43	0.14	0.19	-0.22	0.00	0.35
1959	-0.84	-0.11	0.09	-0.82	0.90	0.64	0.47	-1.08	-0.23	0.29	0.30	-0.09
1960	2.26	-0.39	0.38	0.49	-0.36	-1.29	-0.18	-0.75	0.16	-0.59	0.11	0.53
1961	0.64	-0.12	0.78	0.03	2.38	1.40	0.07	0.17	-0.26	-0.20	-0.15	-0.03
1962	-1.05	0.05	-0.40	0.66	2.11	0.97	-0.42	0.24	-0.03	0.03	-0.24	0.14
1963	0.23	-0.15	0.02	1.09	-0.77	-0.44	0.10	1.35	-0.94	0.63	-0.04	1.00
1964	1.01	-1.18	-0.45	-0.44	-0.74	-1.27	0.07	0.11	-0.99	0.10	-0.24	-0.18
1965	-1.41	-0.36	-0.54	-0.94	0.53	-0.29	-0.31	-0.62	0.04	-0.46	-0.57	0.11
1966	0.15	0.18	0.12	-0.26	0.20	0.34	0.27	0.26	-0.40	-0.15	-0.03	-0.12
1967	-0.17	-1.86	0.43	0.50	-1.49	1.83	0.12	1.38	0.10	-0.09	-0.49	-0.45
1968	0.45	0.61	-0.86	0.84	-0.04	1.09	-0.47	-1.06	-0.60	-0.18	-0.32	-0.08
1969	0.11	-0.21	-0.22	-0.10	-4.36	-1.47	-0.38	0.55	-0.36	-0.39	0.12	-0.31
1970	0.88	-0.37	0.46	-0.11	-0.53	0.03	-0.34	0.15	-0.49	-0.30	0.12	-0.19
1971	-1.02	0.24	-0.01	0.14	0.27	-0.68	-0.18	0.96	0.00	-0.69	-0.27	0.28
1972	-2.85	-0.94	-0.66	-1.65	-0.42	0.02	0.32	-0.35	0.51	0.31	-0.57	-0.73
1973	-1.20	1.03	0.50	-0.03	1.31	0.86	0.09	-0.56	-0.20	0.05	0.07	0.55
1974	-0.75	-1.34	0.03	-0.52	0.49	0.59	-0.06	0.26	0.66	0.70	-0.23	-0.55
1975	0.12	-0.62	0.41	0.05	2.45	1.72	0.34	0.10	0.59	-0.55	-0.15	0.02
1976	-0.17	0.17	0.00	-0.33	0.35	-0.32	-0.12	-1.73	0.75	0.20	-0.41	-1.43
1977	0.70	1.84	-0.15	0.34	-1.16	1.48	0.05	0.47	-1.36	0.86	0.32	0.43
1978	-0.25	-0.47	-0.47	-1.34	0.44	0.16	-1.01	0.50	-1.29	0.08	0.27	0.16
1979	-1.79	0.35	0.11	0.27	-1.41	-0.03	-0.26	0.27	-1.73	0.06	-0.05	0.22
1980	1.30	1.14	-0.10	-0.03	-0.24	-0.74	-0.57	0.22	0.44	0.12	0.92	-0.05
1981	1.93	1.56	0.26	0.87	2.24	0.16	0.82	0.73	0.38	0.46	0.76	0.10
1982	-0.96	-0.94	-0.51	-0.46	0.45	0.51	-0.08	0.99	-0.42	0.16	-0.18	0.01
1983	0.87	-0.03	0.53	0.54	3.82	1.12	0.50	0.31	1.09	-0.58	0.57	0.71
1984	-0.24	0.59	0.55	-0.80	1.80	0.21	-0.14	-0.22	-0.51	-0.30	0.10	-0.24
1985	-0.57	0.36	-0.13	-1.45	-2.69	-0.44	-0.28	-0.22	-0.48	0.99	-0.06	0.09

GCM is model II, described by *Hansen et al.* [1983]. In the 100-year run the ocean temperature was computed, but horizontal ocean heat transports were fixed (varying geographically and seasonally, but identical from year to year) as described by *Hansen et al.* [1984]. The ocean mixed layer depth also varied geographically and seasonally, and no heat exchange occurred between the mixed layer and the deeper ocean. This 100-year run will be described in more detail elsewhere, since it serves as the control run for several transient CO_2/trace gas climate experiments.

We note that *Oort* [1978] previously used output from a GCM to estimate errors in meteorological variables due to spatial gaps in observing stations, specifically the errors in atmospheric winds and temperatures for the rawinsonde station distribution. He found rms errors of about 0.5° to 1°C for the temperature distribution in the free atmosphere, for the rawinsonde stations. Our problem is somewhat different, since we are seeking the error in the long-term surface air temperature change due to spatial gaps in meteorological stations, and we are mainly interested in the error in large-area average results, such as the global surface air temperature change.

Our procedure is to use the surface air temperature at all grid points in the 100-year run to define a "perfect" temperature data set, i.e., one with complete geographical and temporal coverage. We then sample that data set at only the points where stations existed at a given time, and examine how well a given station distribution can reproduce the full 100-year temperature variation. In order for this test to provide an accurate measure of the error, the model's spatial and temporal variability must be similar to that in the real world. Therefore we first examine the

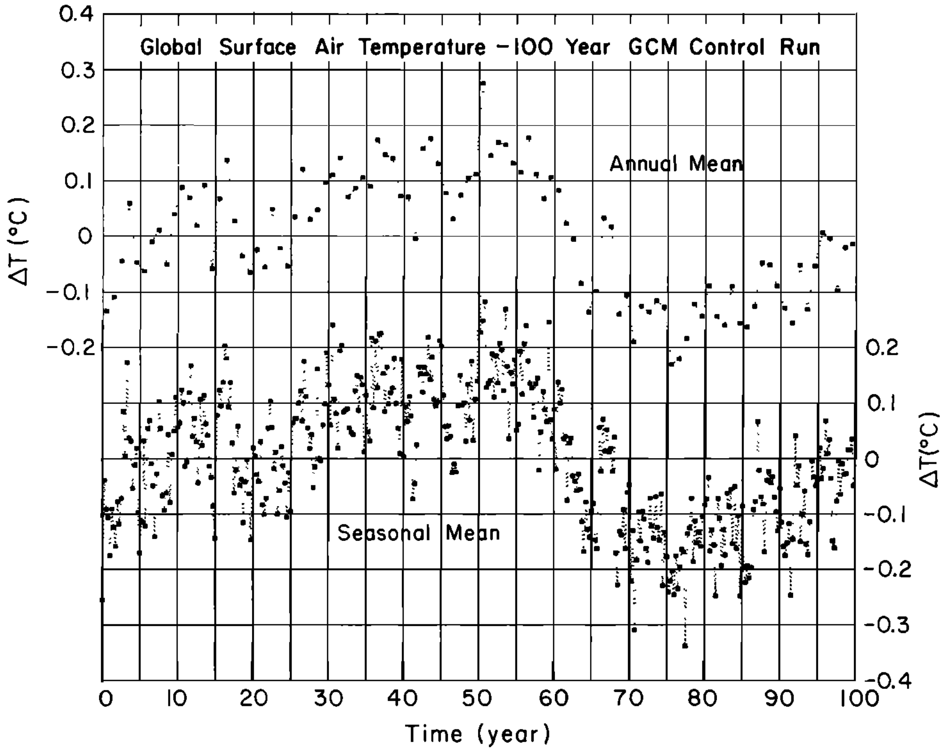


Fig. 9. Global annual mean (left scale) and seasonal mean (right scale) surface air temperature change in a 100-year GCM run with fixed climate forcing. The "seasonal" ΔT is computed as the simple mean of the three ΔTs for the relevant months (e.g., December–January–February). The ΔT for a given month is the difference between that month's temperature and the 100-year mean temperature for that month.

model's variability and compare it to available estimates for the real world, the latter, of course, only being well known in areas of dense station coverage.

The global annual-mean and seasonal-mean surface air temperature changes in the 100-year GCM run are shown in Figure 9. Evidently the interannual variability and the longer term fluctuations are of the same order of magnitude as in the estimate from observations (Figure 6), but the GCM has somewhat less global variability. A smaller variability in the model is not surprising since the ocean heat transports are specified to be identical each year, thus excluding phenomena such as El Niño, and since atmospheric trace gas composition, aerosols, solar irradiance and other external forcing are fixed, thus excluding any long-term trend in the GCM temperature. It is relevant to note that the model exhibits unforced temperature changes on decadal scales as well as on shorter time scales. Examination of the mechanisms of the model's internal variability is beyond the scope of this paper; a discussion of this subject is given by *Lorenz* [1985].

A crucial model variability, for the purpose of examining the error due to incomplete spatial coverage of stations, is the geographical distribution of interannual variability. The standard deviation of the annual mean surface air temperature is shown in Plate 4 for both observations and the GCM. Plate 4a shows the observed standard deviation for 1950–1980, a period with good station coverage over the continents, and Plate 4b shows the standard deviation about the 100-year mean for the GCM. We also computed the GCM's variability as the mean standard deviation about the 30-year running mean, with a result very similar to that illustrated in Plate 4b.

Plate 4 suggests that the model's variability of annual mean temperature is realistic to first order. The standard deviation of annual mean temperature is typically 0.25°–0.5°C at low latitudes, increasing to about 1°C in polar latitudes. At mid-latitudes the variability is greater in midcontinents than in coastal regions.

The interannual variability of seasonal mean temperature is illustrated in Plate 5 for the model and for observations. The magnitude and global distribution of the model's variability are fairly realistic, for example as regards the change in variability from low latitudes to high latitudes, from ocean to continent, and from summer to winter. There are discrepancies in the locations of some of the centers of high variability in northern hemisphere winter. The largest discrepancy in the model is the overestimate of variability in continental areas during summer, with the model yielding a variability about twice as large as in the observations. However, the nature of this discrepancy is such as to make it more difficult for a given station distribution to reproduce the model's variability, i.e., this model characteristic should tend to cause us to overestimate the error due to incomplete station coverage.

On the other hand, the variability of surface air temperature over the ocean may be too small in the model, because the ocean horizontal heat transports are identical each year. The modeled and observed surface air temperature variabilities over the ocean appear to be in good agreement (Plates 4 and 5), but it should be remembered that the observations

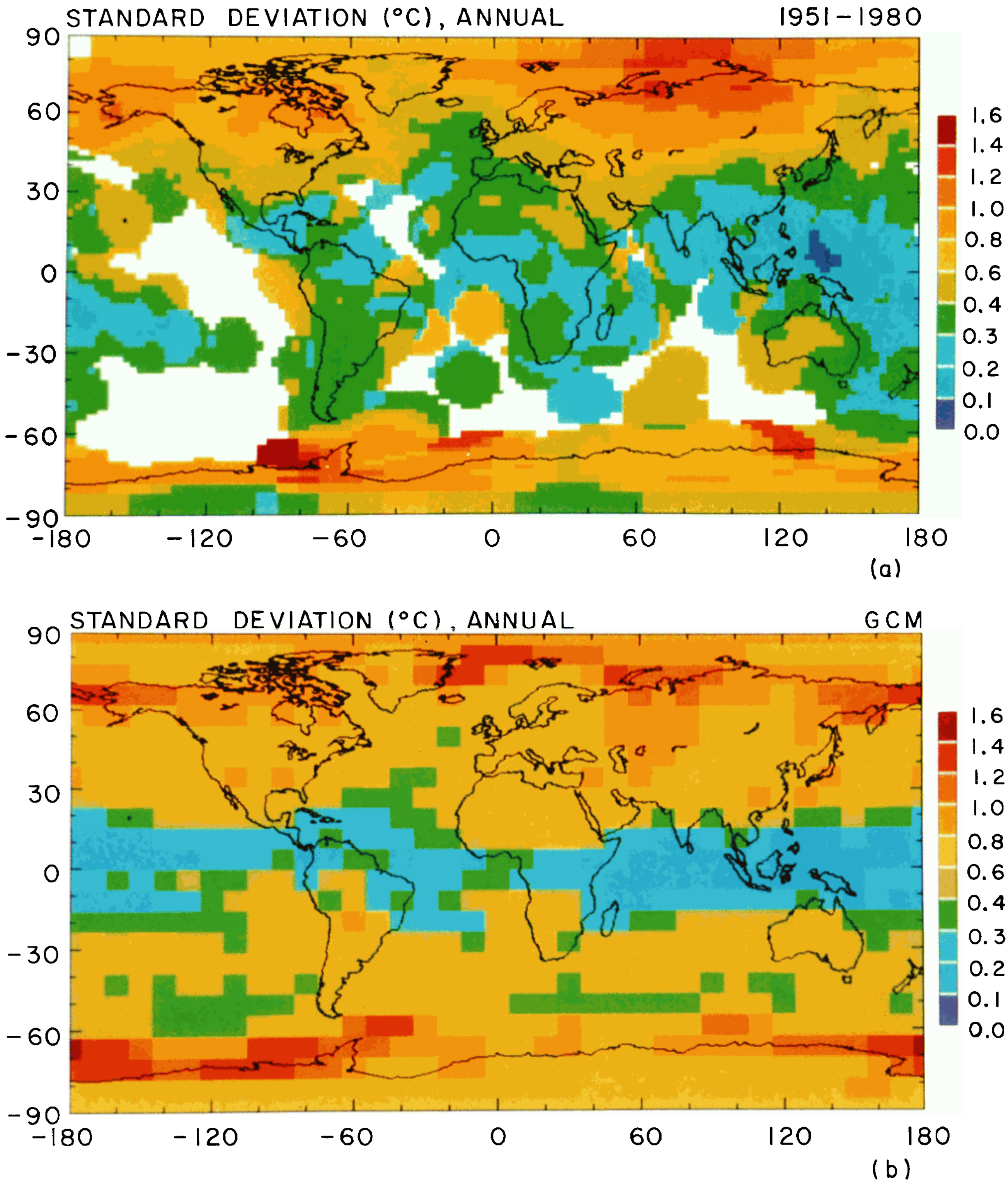


Plate 4. Interannual variability of annual mean surface air temperature, specifically the standard deviation of the annual mean surface air temperature about the long term mean. (a) Standard deviation about the 30-year mean for our analysis of observations of meteorological stations for the period January 1, 1951, through December 31, 1980. (b) Standard deviation about the mean for the 100-year run of our GCM.

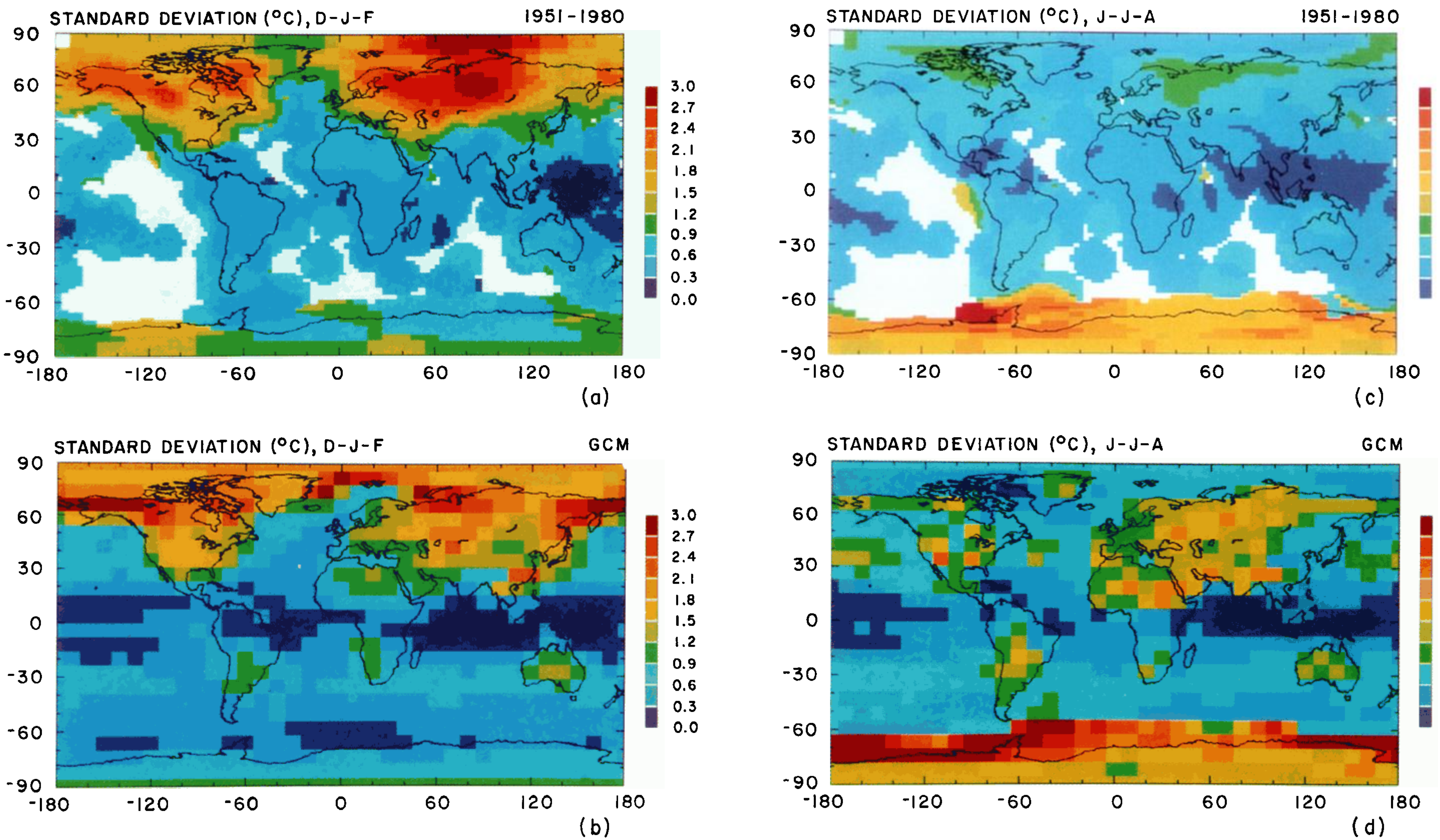


Plate 5. Interannual variability of seasonal mean surface air temperature, as defined for Plate 4. Plates 5a and 5b are for December–February and 5c and 5d are for June–August. Plates 5a and 5c are based on the observations at meteorological stations during 1951-1980, and 5b and 5d are from the GCM control run.

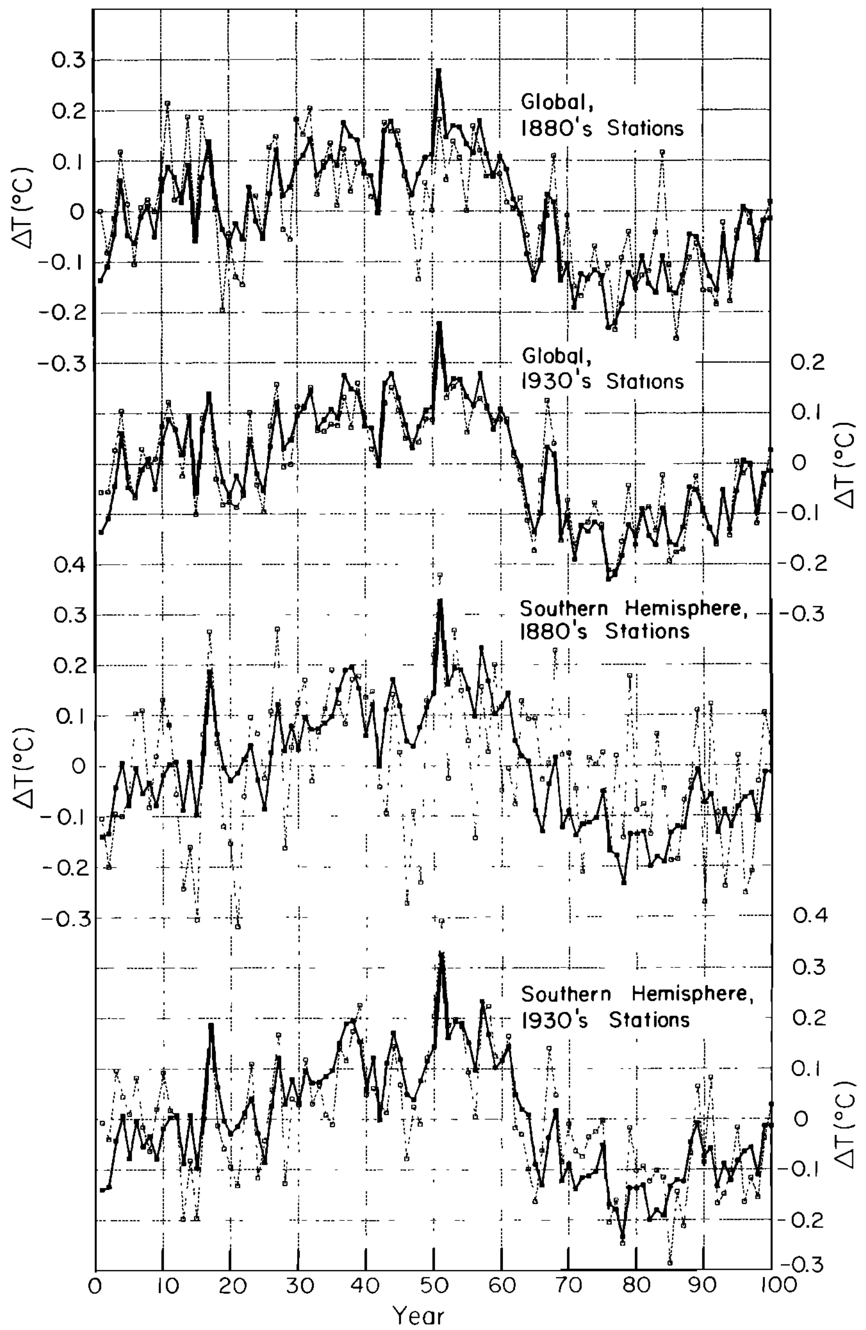


Fig. 10. Global and southern hemisphere temperature change in the 100-year GCM run based on all the model grid points (solid line) and as estimated from equations (1)–(3), using only temperatures from locations where stations existed during the indicated decade (dashed line).

are based on continent and island locations: interannual variability of surface air temperature due to variable ocean heat transports, such as the El Niño phenomenon, are probably muted in these observations and they are absent in the model. This model deficiency probably causes some underestimate of interannual temperature variability and perhaps also an underestimate of interdecadal variability.

A more comprehensive comparison of the model's space-time variability with observations is desirable and relevant to the issue of how good is the error estimate obtained from the model. Although we plan to pursue such comparisons, as an aide to development of the next version of the model, they are beyond the scope of this paper. At this time we can only say that the available comparisons suggest that the model's temperature variability on large spatial scales is comparable in magnitude to the variability in the real world.

Our first error estimate was obtained as follows. For each decade (1880s, 1890s, etc.) we determined the locations of those stations which reported temperature records for at least 5 years during the decade. We used the GCM-calculated temperatures at only the station locations for a given decade in an attempt to reproduce the entire 100-year global temperature record of the GCM. An example is shown in Figure 10 for the 1880's and 1930's stations. The

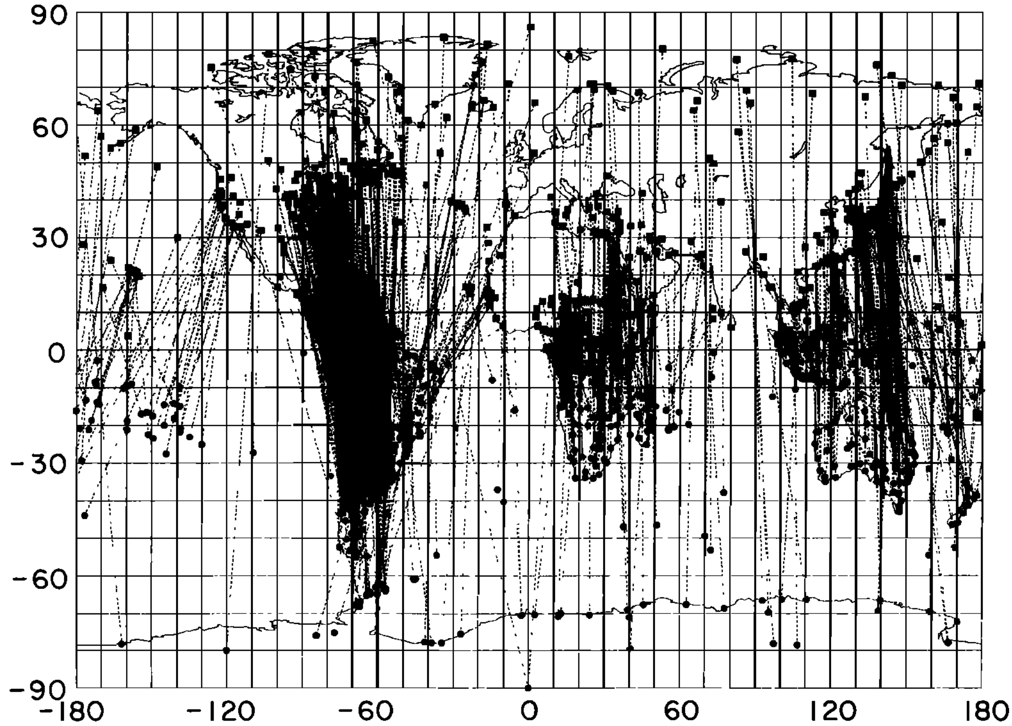


Fig. 11. Circles mark the southern hemisphere station locations. Each Southern Hemisphere station is connected to a northern hemisphere station with similar longitude, reflected latitude, and length of temperature record.

deviations in individual years from the "true" GM temperature trend (i.e., the trend based on all grid points) were found to be normally distributed. The standard deviation σ for the global mean temperature decreases from about 0.07°C in the 1880s to about 0.02°C in the 1960s and for the southern hemisphere, from about 0.13°C in the 1880s to 0.04°C in the 1960s. These error estimates are illustrated for several decades in Figures 6 and 7, where the bars are $\pm 1.96\sigma$, corresponding to 95% confidence limits, based on the GCM's variability. Since the GCM and real-world temperature variabilities are not identical and since there are other sources of error, the bars only represent a

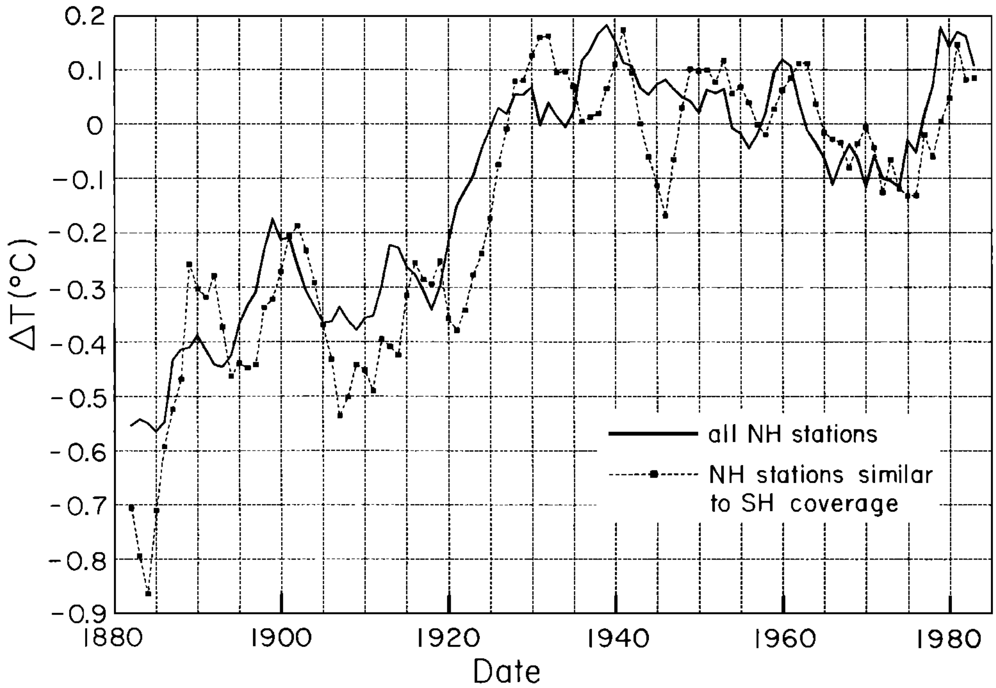


Fig. 12. Five-year running mean of the annual northern hemisphere temperature change, as estimated from all northern hemisphere stations (solid curve) and as estimated using only those stations which yield a coverage equivalent to that in the southern hemisphere (see Figure 11).

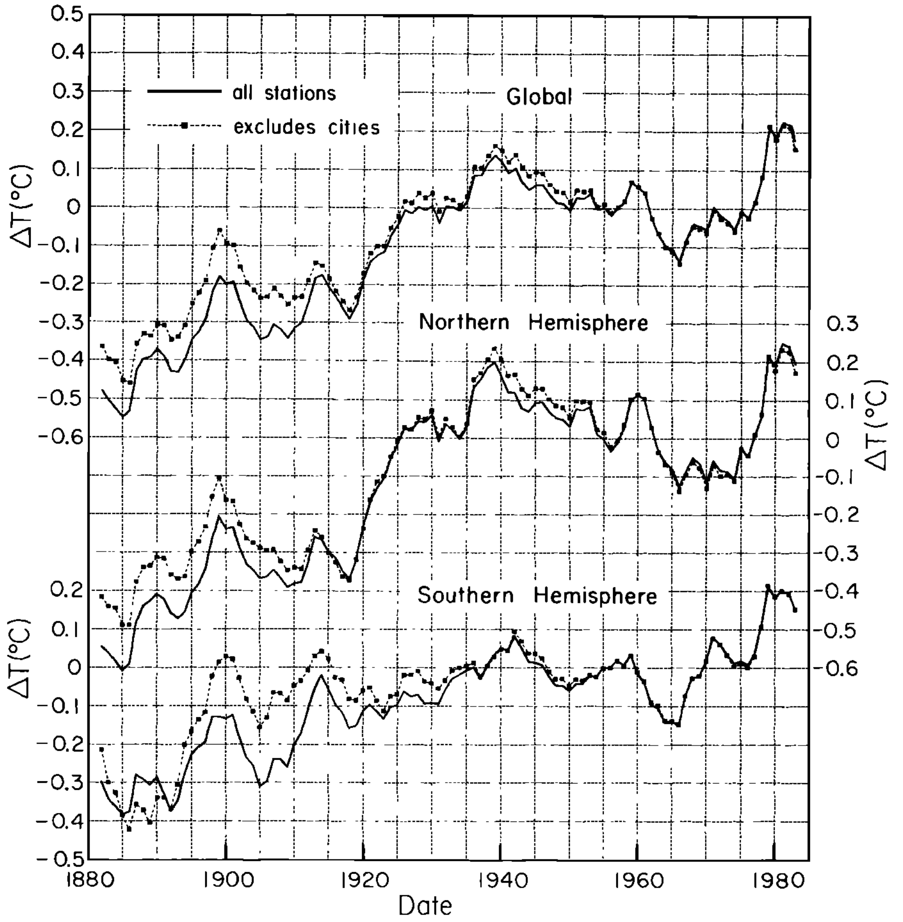


Fig. 13. Comparison of 5-year running mean temperature change derived with and without urban stations included.

nominal measure of the expected error in the temperature change.

One potential difficulty with basing an error estimate on the GCM's 100 year control run is that, unlike the observations for the period 1880–1985, the GCM temperatures had no long-term trend. Thus we performed the same calculations using the temperatures from the transient CO_2/trace gas climate experiment (Scenario A) of *Hansen et al.* [1986, 1987]. The resulting error estimates were practically the same as those obtained from the 100-year control run.

We obtained an independent estimate of the error in the southern hemisphere temperature change by estimating the northern hemisphere temperature change using only a subset of the northern hemisphere stations, specifically a subset having spatial and temporal coverage in the northern hemisphere equivalent to the coverage by all the southern hemisphere stations. The northern hemisphere stations were chosen by reflecting the locations of each southern hemisphere station about the equator and finding the nearest available station with similar record length. As shown in Figure 11, it was possible to preserve the clustering of station locations to closely mimic the southern hemisphere station distribution. The northern hemisphere temperature change obtained with this subset of stations is compared with the temperature change based on all of the stations in Figure 12. The standard deviation between the two curves in Figure 12 is about σ = 0.1°C, somewhat larger than the southern hemisphere error estimate obtained in the GCM studies described earlier. This result is not surprising, because the southern hemisphere station distribution should be less adequate in the northern hemisphere, which has greater variability; also no northern hemisphere analog could be found for several of the southern hemisphere stations. We infer that the error estimate from the second method is roughly consistent with the value obtained from the GCM. The "error bars" which we display in our figures are $\pm 1.96\sigma$, based on the GCM σ; although formally a "95% confidence" limit, we only regard it as an approximate measure of the uncertainty.

We conclude that the principal features in the global and hemispheric temperature changes are real, in the sense that they are not artifacts due to poor spatial coverage of stations. The long-term global trends illustrated in Figure 6, i.e., the 1880–1940 warming, 1940–1965 cooling, and 1965–1985 warming, are much larger than the estimated errors. Also, shorter-term features such as the 1961–1964 cooling and 1981–1984 cooling are much greater than the error, as are many of the single-year changes. It is not clear, though, whether 1980, 1981, or 1983 was the warmest year in the global record.

We also conclude that the uncertainty in the southern hemisphere temperatures is large in the period 1880–1900, and the southern hemisphere temperature trend up to about 1930 is too small to be meaningful. However, the results

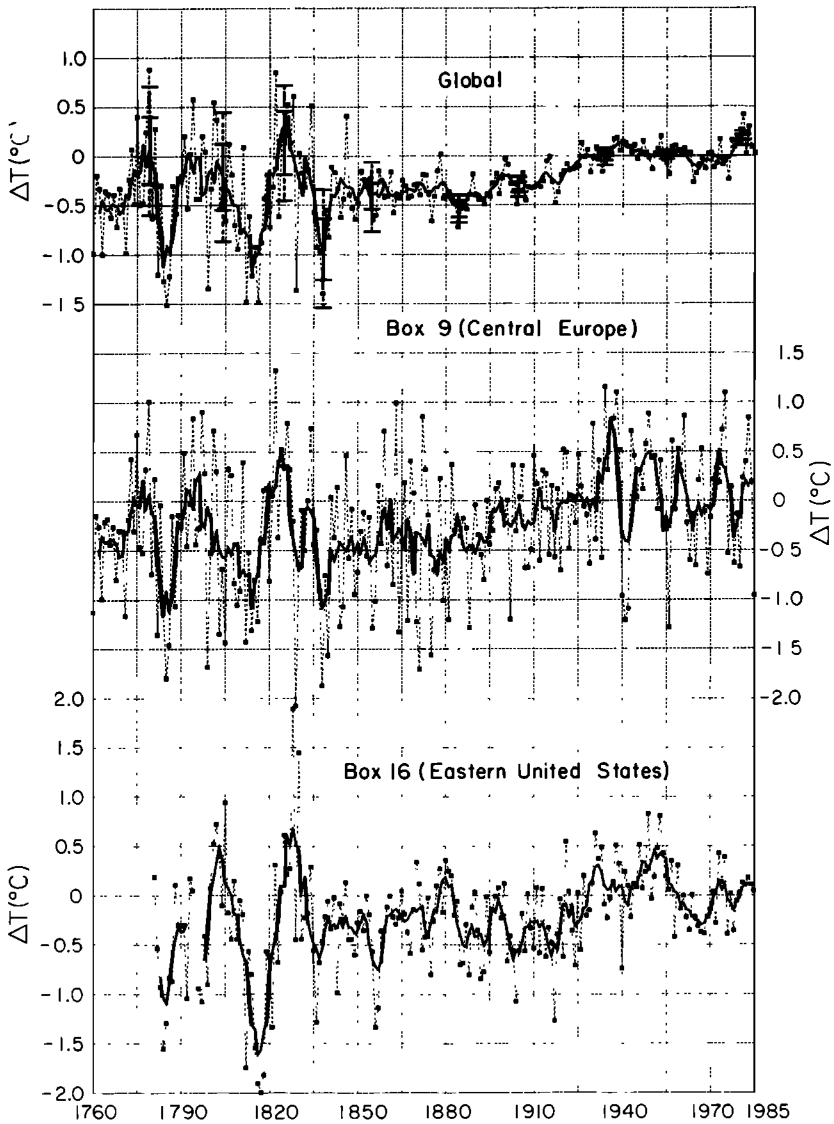


Fig. 14. Estimated temperature change in the period 1760–1985 for the globe, box 9, and box 16 (see Figure 2). The error bars on the global temperature change are 95% confidence limits derived as described in the discussion of Figures 6 and 10.

show that there was a real warming trend in the southern hemisphere during the past century, and the sharp warming trend which has occurred since 1965 is much larger than the uncertainty.

An additonal issue or uncertainty about the derived global temperature change is the following: How much of the change is a result of the growth of urban heat island effects? There is abundant evidence that the growth or development of urban areas is a significant contributor to local temperature trends [*Mitchell*, 1953; *Landsberg*, 1981; *Cayan and Douglas*, 1984; *Karl*, 1985; *Kukla et al.*, 1986]. We obtained an estimate of the magnitude of urban influence on the global temperature change of the past century by eliminating from the data set all stations associated with population centers which had more than 100,000 people in 1970. The usefulness of the test is based on the assumption that even though the urban heat island effect exists for all city sizes, the effect generally increases with population; this assumption is supported by empirical studies, e.g., *Mitchell* [1953]. We used Table E of *Davis* [1969] to identify population centers exceeding 100,000 people. Elimination of all stations within these population centers reduced the number of stations by about one third.

Removal of the city data reduced the magnitude of the global and hemispheric warmings, as illustrated in Figure 13. For example, the global temperature change in the past century was reduced from 0.7° to 0.6°C, where these numbers represent the difference between the mean 1980–1985 temperature and the mean 1880–1885 temperature. We subjectively estimate that complete correction for urban heat island effects should not reduce the global warming in the past century, defined as the temperature difference between 1980–1985 and 1880–1885, to less than about 0.5°C.

As mentioned already, the nature of the observed temperature trends, especially the geographical distribution of the warming, also provides strong evidence that the global

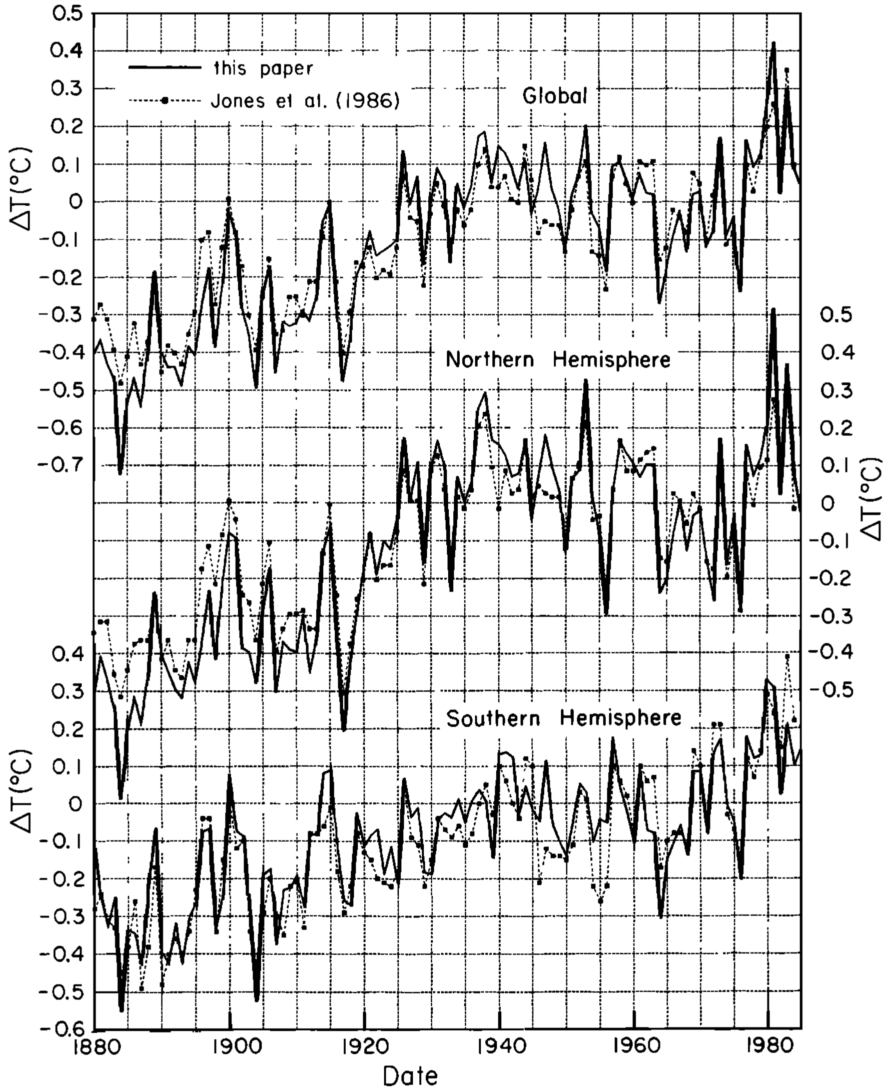


Fig. 15. Comparison of our results for annual global and hemispheric temperature change with the results reported by *Jones et al.* [1986c].

temperature change is not a figment due to urban heat island effects. This evidence and the quantitative test just described lead us to conclude that the global warming of the past century is a real climate trend, even though it does contain a significant contribution due to urban heat island effects. More detailed and comprehensive studies of urban influence are warranted; perhaps the data set we have developed, including the seasonal variation of trends, can contribute to such studies.

Finally, we consider the contention of *Ellsaesser et al.* [1986] that much of the warming of the past century is an artifact due to most analyses beginning near a minimum in the temperature record. Specifically, they suggest that 25-50% of the approximate 0.5°C temperature rise in the past century is due to the fact that several analyses began in 1880 or 1881 "near the apparent temperature minimum of 1883."

Our estimated "global" temperature change for the period 1760-1985 is shown in Figure 14, along with the temperature change of the two regions (Europe and the United States) where the records extend over two centuries. Although our procedure for estimating global temperature change is designed to obtain maximum trend information from sparse data, it is apparent from the magnitude of the uncertainty bars that the global change prior to 1880 is not very meaningful. What we can say is that the data provide no evidence that 1880 was unusually cold, and thus no evidence that much of the subsequent warming represents a return to levels prevailing a few years earlier. The data do suggest that the 1884 temperature is lower than that in 1880-1881, an effect that some have associated with expected cooling from a large volcanic eruption (Krakatoa) in 1883. However, the 1984 temperature is lower than that in 1980-1981, and there was a large volcanic eruption (El Chichon) in 1982. Thus we also do not find evidence of prejudice in the comparison of the 1880-1885 mean with the 1980-1985 mean.

We conclude that the evidence from the meteorological station records supports the estimate of a global warming of approximately 0.5°C in the past century, an estimate which has been used in many studies of climate sensitivity. The reason for beginning temperature analyses in 1880 is apparent from Figure 4, especially the curve for the station coverage in the northern hemisphere, and also from the error bars in Figure 14.

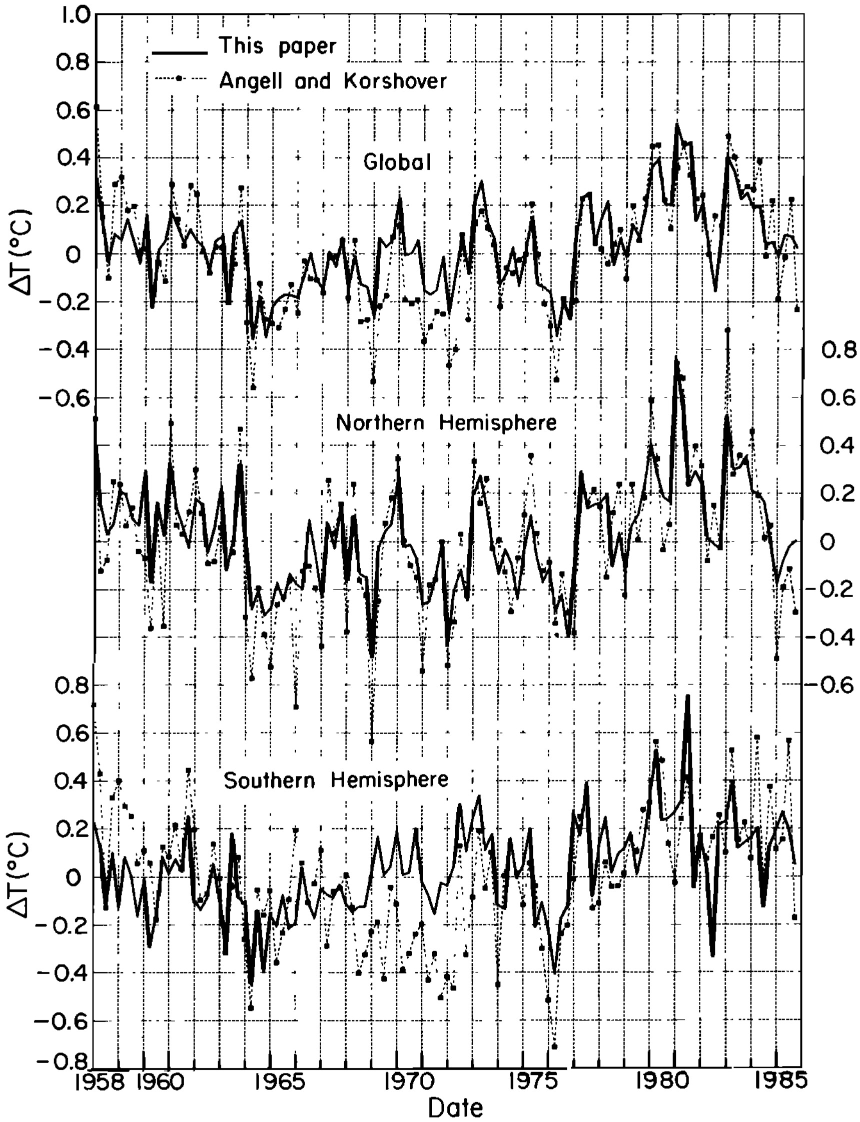


Fig. 16. Comparison of our results for seasonal surface air temperature change with results provided by Angell and Korshover. The arbitrary zero-point is set as the 1951–1980 mean for our data; we set the zero-point for Angell and Korshover's data by making the mean the same as for our data for the period of record in common (1958–1985).

6. Comparisons With Other Data Sets

We have shown that the network of meteorological stations which measure surface air temperature is sufficient to yield reliable temperature change for both the northern and southern hemispheres, despite the fact that most stations are located on the continents. The estimated errors are sufficiently small to imply that long-term, decadal and interannual temperature changes obtained from the station data are meaningful.

Jones et al. [1986c] have recently estimated global near-surface temperature change by combining meteorological station data with marine data. The marine data contain a number of systematic errors, for which Jones et al. developed an empirical correction using nearby meteorological station data. Their global and hemispheric results are generally in good agreement with ours, as shown in Figure 15. One difference is that they describe their results for the global temperature change as being flat from 1940 to 1970, while we note a temperature decline in the period 1940-1965. This is partly a matter of perception, although the temperature change they find is slightly flatter than that which we find for that period. The fact that these two analyses of surface air temperature change, which differ substantially in their methods, are in good overall agreement lends additional credibility to the gross conclusions.

J. K. Angell [private communication, 1987] kindly provided us with updated temperatures based on analysis of radiosonde data as described by *Angell and Korshover* [1983]. Their analysis is based on 63 radiosonde stations (38 in the northern hemisphere and 25 in the southern hemisphere) which have wide geographical distribution. The great advantage of their data is that it includes records of temperature change in the upper air, through the troposphere and lower stratosphere. Thus it is free of any significant influence of the urban heat island effect, and more importantly, it provides information on the altitude dependence of any observed temperature change.

Our global and hemispheric seasonal mean surface air temperature changes are compared with those of Angell and Korshover in Figure 16. The standard deviation between the two results is 0.09°, 0.09°, and 0.17°C for the globe, northern hemisphere, and southern hemisphere, respectively. The corresponding 1-σ error estimates are 0.06°, 0.07° and 0.09°C for the radiosonde stations and 0.03°, 0.03°, and 0.05°C for the (1970s) distribution of meteorological stations used in our analysis, where the error estimates were obtained as described in section 5 and refer only to the error due to incomplete spatial coverage by the stations. These results suggest that most of the difference between the two temperature records is due to the incomplete spatial coverage of stations. The error in surface air temperature change is only about twice as large for the radiosonde stations as for the meteorological stations, even though these are more than an order of magnitude more of the meteorological stations (Figure 4). Of course the main advantage of the radiosonde stations is the information they provide on changes in the upper air.

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