NOTES AND CORRESPONDENCE

Hemispheric Surface Air Temperature Variations: A Reanalysis and an Update to 1993

P. D. JONES

Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, United Kingdom

10 August 1993 and 12 December 1993

ABSTRACT

Land-based compilations of gridded monthly surface air temperature anomalies, averaged into hemispheric values for the last 140 years, have been available for climatological analyses for the last 10 years or so. The analysis techniques used in their construction, particularly the need for a common reference period, mean that it is difficult to include, retrospectively, any of the new temperature datasets now available for some countries. So, despite data availability improvements in some areas, the number of stations used has fallen since 1970, both in the hemispheric averages and in their constituent grid-box datasets.

The present study is a reanalysis of both the existing and the newly available temperature datasets to produce a grid-box dataset of 5° × 5° temperature anomalies. The reanalysis not only uses over 1000 more stations (2961 in total), principally covering the period from the 1920s to about 1990, but also arrests the decline of stations incorporated in real time for the latest years. Two hundred and fifty-two more stations are used in this analysis for the 1991–1993 period, compared with earlier analyses. The purpose of the reanalysis, however, is not just to calculate hemispheric averages. The improvements in station numbers used mean that the grid-box dataset should better estimate time series for small subcontinental scales.

Despite the dramatic improvements in the numbers of stations used, the results change little from earlier analyses for the Northern Hemisphere average, indicating the robustness of the earlier time series. Similar results could have been achieved with as few as 109 stations. Over the Southern Hemisphere, comparisons of the results indicate larger (but still relatively small) differences with earlier analyses, particularly over continental-scale regions.

1. Introduction

Three groups, the Climatic Research Unit (Jones et al. 1986a; Jones et al. 1986b; Jones 1988, henceforth Jones), Goddard Institute for Space Studies (Hansen and Lebedeff 1987, 1988, henceforth HL), and the former Soviet Hydrometeorological Institute [Vinnikov et al. 1990, henceforth V) have monitored surface air temperatures over the terrestrial regions of the earth. Although the analysis techniques differ as do the exact number of stations used, the fact that much of the data are in common means that the results in terms of hemispheric averages are in excellent agreement (Folland et al. 1990; Folland et al. 1992). Many other reviews of the data have been undertaken (see for example Elsaesser et al. 1986; Jones and Briffa 1992; Jones 1994).

The purpose of this paper is to reanalyze, improve, and update the *gridded* land-based temperature database of Jones. There are three reasons why such an analysis is being undertaken at the current time. The first two reasons concern data availability. The original Jones analysis required not only that station temperature time series be homogeneous (Jones et al. 1985; Jones et al. 1986c), but also that each time series be available for a reference period (1951–70) common to all stations. Although some stations without this period of data had reference periods estimated by the use of neighboring data, a number of regions began recording only during the 1950s (e.g., parts of the Middle East, the Russian Arctic, some interior parts of South America and Africa, and the whole of Antarctica). A procedure for incorporating Antarctic data was used (Jones et al. 1986b), but the 1951–70 reference period was not strictly adhered to.

The first reason for the reanalysis is therefore to include, explicitly, station data for these regions using a new and longer reference period (1961–90) common to all stations. The second reason is to include many more station records collected from some countries during the course of other projects. The major source of such additional station data has come from the attempts to develop station temperature series of both maximum and minimum temperatures (Karl et al. 1993). The rationale for collecting this data is to unravel the causes of climate change over the twentieth

Corresponding author address: Dr. Phil D. Jones, Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, United Kingdom.

century. Evidence presented in Karl et al. shows that minimum temperatures are rising faster than maximum temperatures. Ideally, this present reanalysis should be two separate analyses for the two temperature extremes. Unfortunately, the spatial coverage of stations with monthly mean maximum and minimum temperatures collected so far is limited not only in space to 37% of the land area of the earth but also in time. Only for a few countries do such data exist prior to the 1930s. Average monthly temperature is still the most widely available indicator of the thermal climate, although efforts by individuals and the World Meteorological Organization are under way to improve the situation.

The third reason concerns the uses to which the data might be put. The original Jones data (gridded on a 5° latitude by 10° longitude grid) were combined with marine 5° × 5° grid-box data (sea surface temperatures) in anomaly form to produce 5° × 5° box values for as much of the world as possible (Jones et al. 1991; Jones and Briffa 1992). The resulting grid-box values were expressed as anomalies from 1950 to 1979, the reference period for the marine data. The land data were adjusted to this period by the addition, by month, of the difference between the grid-box values for 1950–79 and 1951–70. This grid manipulation of the land data is fine for large-scale averages and studies but can lead to slight distortions at the local grid-box level. The aim of this study will be therefore to create grid-box values at 5° resolution for later simple incorporation with marine information. One additional need for both a finer resolution and a grid-box format is that regional series developed from the gridded data will improve and comparison with the results of general circulation model experiments will be facilitated.

In summary, therefore, the aim of this paper is a reanalysis of station monthly mean air temperature series, with over 1000 more stations than previously used and employing a 5° box resolution with a 1961–90 reference period.

2. Data and gridding method

In Jones, the original number of stations used was 1873 (1584 in the Northern Hemisphere and 289 in the Southern Hemisphere). All these stations had sufficient data to calculate, or in a few cases accurately estimate from neighboring stations, reference period values for 1951–70. In addition to this, data from 16 stations in Antarctica were included, which were referenced to 1957–75 (Raper et al. 1984).

In this new analysis, data for 1088 extra stations are included, for which reference period values could be calculated for 1961–90, as well as some additional data for the 1873 original stations used by Jones. Some of these data had been collected as a result of a number of projects (e.g., Karl et al. 1993) and included both newly acquired stations and also data updates of some of the 1873 station series that were not routinely updated through the WMO's CLIMAT network and/or *Monthly Climatic Data for the World.* In addition, there were entirely new stations, from the routine sources, that began recording in the late 1950s and so now had enough data to create a 1961–90 reference period average. These include Antarctic stations. None of these additional stations were previously rejected as nonhomogeneous in the earlier analysis (Jones et al. 1985; Jones et al. 1986c).

The use of a reference period is essential for interpolation because of differing station elevations and different national methods for calculating monthly mean temperatures (Jones et al. 1982; Jones et al. 1985; Jones et al. 1986a; Jones et al. 1986b; Jones et al. 1986c). For a station to be included, it required data for 21 years (for each month) out of the 30. Not all the original 1873 station series fulfilled this requirement for 1961–90. One of the purposes of undertaking this analysis was to try to improve coverage during the 1980s. By the end of this decade (1990), however, only 974 stations in the original Jones series (52%) were being updated routinely. By 1992, this number had fallen to about 700.

Therefore, to not lose some of the original 1873 stations, the 1961–90 reference period values were partially estimated. The estimate is only a partial one, as all 1873 stations have data for at least 1961–70. The number requiring partial reference period estimation is not as serious as might be assumed from (1873–974) as many of the series were updated from the additional sources (see above). The partial estimation was made, if required, using the combined land and marine datasets (Jones et al. 1991; Jones and Briffa 1992) described earlier. Monthly fields were calculated on the 5° grid resolution from the weighted difference between the 1971–90 (20 years) and 1951–60 (10 years) periods. For all stations that required estimation in any 5° box, the appropriate monthly adjustment was added to the 1951–70 station average from Jones. For a few stations, where this could not be achieved, adjustments from neighboring boxes were used.

Apart from calculating monthly reference period values for 1961–90, for all 2961 stations, monthly station standard deviation values for the 1941–90 period were calculated. Despite all attempts to exclude suspect data, such as transcription and submission errors and data included for the wrong month, erroneous outliers enter the station dataset. All values in excess of six standard deviations from the mean were flagged. The reference period means and standard deviations were recalculated without these values and the process was repeated once again.

The gridding method used is essentially the same as that used by Jones, although no allowance for a station's position in the box is made. A grid-box temperature anomaly is the average of all available station anomalies in the 5° × 5° box. The values retained are the average

TABLE 1. Comparison of the new and original method.

Station configuration	Stations used	Boxes	Percent of land area of globe
This analysis	2961	779	35
Original	1873	680	31
New stations	1088	99	4
During 1991-93	1226	636	29

temperature anomaly and the number of contributing stations. The standard deviation field has been used to eliminate erroneous outliers over the 1941-90 period. For the years 1851-1940, the few outliers in excess of six standard deviations from the 1961-90 mean were also excluded. Since the beginning of 1991, the outliers are also flagged, and a manual attempt to correct the values is made using neighboring stations. If correction is not possible, the suspect value is omitted.

How good are the improvements to the spatial coverage compared to the original Jones method? Table 1 gives a basic comparison. In this, the original analysis refers to the 1873 stations with the number of boxes and percentage area calculated using the new method of analysis to 5° boxes. The improvements are best shown as maps of the world. Figure 1 shows the location of 779 boxes with data for at least 21 years for each month of the 1961-90 period. The improvement over the original Jones analysis is shown in Fig. 2 (99 new boxes that would never have had data before). The improvements have come in five main regions, parts of the former Union of Soviet Socialist Republics (mainly Russia), Mongolia, parts of Australia, South America, and a few boxes in the Middle East. Antarctica is not actually an improvement since data were incorporated in the Southern Hemisphere average (Jones et al. 1986b) by assuming that the Antarctic (65°-90°S) temperature anomaly (with respect to 1957-75) from Raper et al. (1984) could be weighted by area represented with the Southern Hemisphere anomaly (with respect to 1951-70) for 0°-60°S.

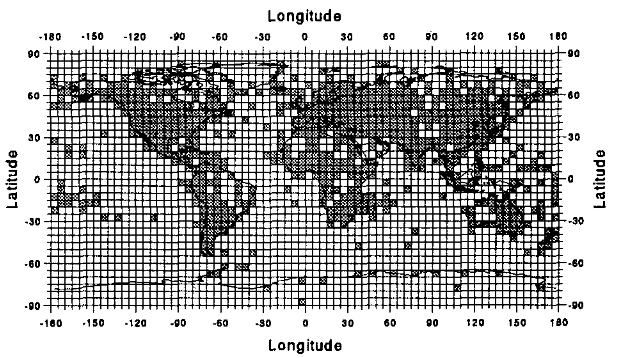

FIG. 1. The locations of the 779 boxes with data for most of the 1961-90 period. The station for the South Pole contributes to the box 85°-90°S, 5°W-0°.

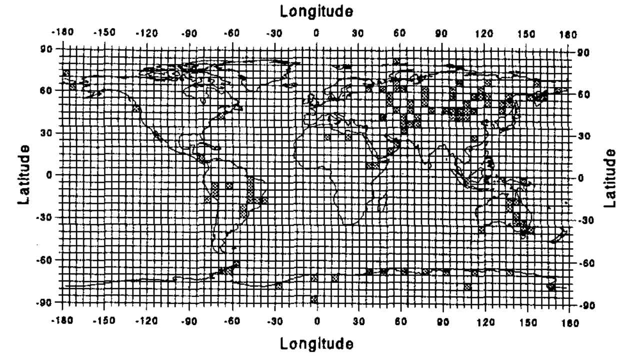

FIG. 2. The locations of the additional 99 boxes incorporated in this dataset compared to Jones (1986a), Jones et al. (1986b), and Jones (1988).

Finally, in this section, Fig. 3 shows the 143 boxes with data during 1961-90 and without data during the 1991-93 period. Much of this is explained by station data available to the late 1980s but not reported internationally from developed countries [e.g., the United States (particularly Alaska), Canada, Russia, China, Australia, and some Pacific and Atlantic islands]. Only over parts of Africa and Southeast Asia can the problem be blamed on inadequate reporting from the operational network. The closing down of the majority of ocean weather ships causes some of the boxes to be filled in the North Atlantic and North Pacific. Despite the loss of 6% (35-29) of the area during the early 1990s, 252 more stations (i.e., 1226 minus 974) are being used now than in the earlier Jones analysis. In reality, because up to 200 of the 974 stations stopped reporting during the 1980s, the percentage improvement is higher.

3. Results

Figures 4 and 5 show seasonal and annual average temperature series for the Northern and Southern Hemispheres. In most respects, the new analyses are

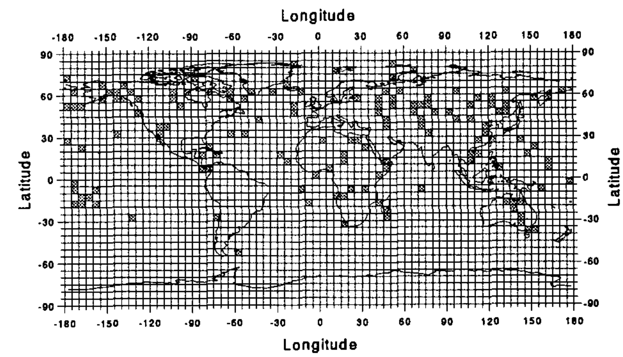

FIG. 3. The locations of the 143 boxes that do not have data for the 1991-93 period.

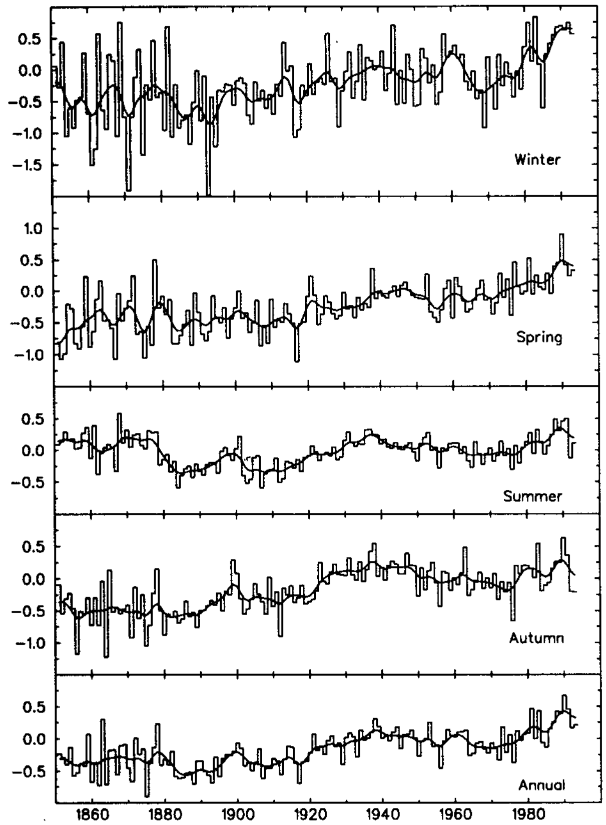

FIG. 4. Northern Hemisphere surface air temperatures for land areas by season, 1851–1993. Standard meteorological seasons are used: winter is December to February, dated by the year of the January. Data are expressed as anomalies from the period 1961–90. Time series in this and subsequent plots have been smoothed with a 10-year Gaussian filter.

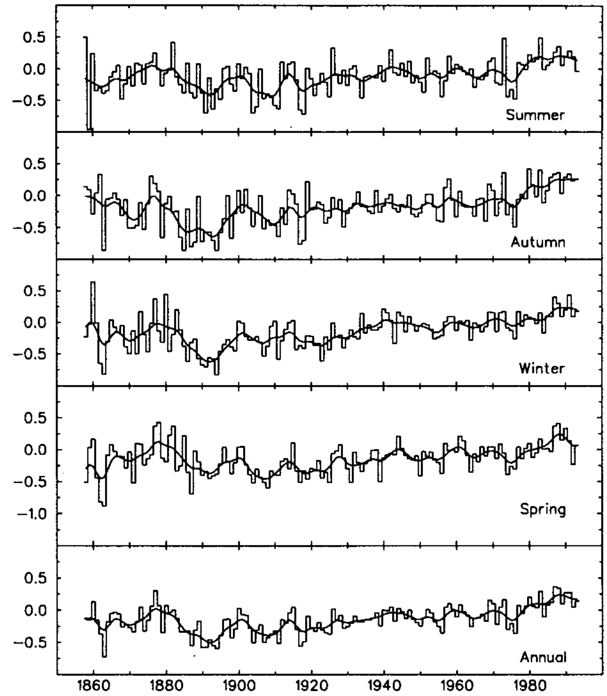

FIG. 5. Southern Hemisphere surface air temperatures for land areas by season, 1858–1993. Standard meteorological seasons are used: summer is December to February, dated by the year of the January. Data are expressed as anomalies from the period 1961–90.

remarkably similar to those produced by Jones. This indicates the robustness of the earlier conclusions concerning the course of surface temperature change over the land areas of the world (Jones; Folland et al. 1990; Folland et al. 1992, and many other references therein). The striking feature of the early 1990s is the dramatic cooling that took place between 1991 and 1992, particularly during the 1992 summer and autumn seasons and to a slightly lesser extent in the same seasons in 1993 in the Northern Hemisphere. Cooling in the Southern Hemisphere was less seasonally specific. The cause of the cooling is probably the dust veil caused by the eruption of Mt. Pinatubo. The lack of any cooling in the boreal winter season in the Northern Hemisphere, noticed by Robock and Mao (1992) using the Jones data for periods with other explosive volcanic eruptions, is seen here.

Figure 6 shows the effect of changing spatial coverage through time as a percentage of the area of each hemisphere with data. When compared with the earlier analysis (Jones), the percentage figures are smaller, but this is entirely due to the change of analysis from a 5° × 10° grid to a 5° × 5° box. An individual station can now represent only half (one 5° box) the area of the earlier analysis. This avoids the extrapolation of single stations to large areas in data-sparse regions. The implication of this for a new combined land–marine dataset is that the recent global warming will appear to be reduced because the warming has been greater over land than over the ocean.

For the Northern Hemisphere mean, standard deviations are greatest during the winter months and least

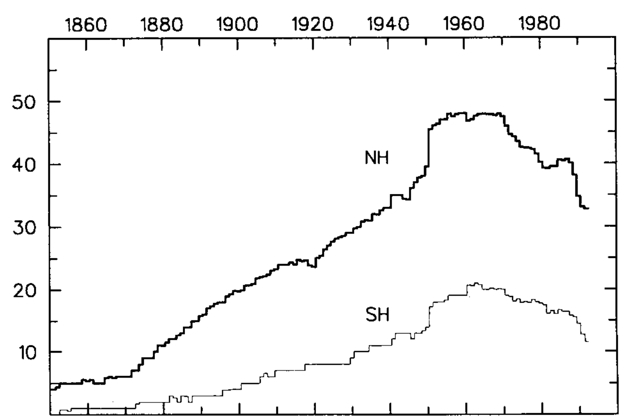

FIG. 6. The coverage of grid boxes with data for the Northern and Southern Hemispheres.

TABLE 2. Standard deviations of the new analysis and correlations with the earlier Jones analysis, 1901–90.

	Northern Hemisphere		Southern Hemisphere	
	1901–90 σ	Correlation r	1901–90 σ	Correlation r
Jan	0.55	0.98	0.28	0.87
Feb	0.61	0.98	0.30	0.90
Mar	0.48	0.96	0.28	0.88
Apr	0.36	0.97	0.27	0.89
May	0.30	0.97	0.33	0.92
Jun	0.25	0.98	0.27	0.88
Jul	0.24	0.98	0.25	0.86
Aug	0.25	0.98	0.28	0.87
Sep	0.26	0.98	0.25	0.85
Oct	0.33	0.98	0.26	0.89
Nov	0.40	0.98	0.28	0.90
Dec	0.51	0.97	0.29	0.90
Annual	0.25	0.99	0.19	0.95

during the summer (Table 2). For the Southern Hemisphere, this annual cycle of variability is also found, although the amplitude is negligible. Comparison with the earlier Jones analysis (see Jones and Briffa 1992) indicates that in the new analysis standard deviations are slightly higher although not in every month in the Southern Hemisphere. Also included in Table 2 are the correlation coefficients between hemispheric mean estimates based on the present analysis and those based on the earlier Jones analysis for the 1901–90 period. Calculation of both of these statistics over the entire length of the series (1851–1992 for the Northern Hemisphere and 1858–1992 for the Southern Hemisphere) yield very similar results. Standard deviations for the longer period are up to 25% higher, indicating the greater year-to-year variability of the nineteenth century data. In Jones et al. (1986a) and Jones et al. (1986b), it was shown by frozen grid analyses that this greater variability was due principally to the sparser availability of data during that time. Correlations, including the nineteenth century data, are very similar to those presented for 1901–90 in Table 2. It must be remembered, however, that hardly any of the additional data series included in the new analysis incorporated extra data for the nineteenth century. Differences in this period, therefore, represent the effects of both the change in the method used to calculate the grid-box values and the change of the reference period.

The greatest difference between Jones and the new analyses is evident in the correlation values for the Southern Hemisphere. As a proportion of the original data, the increase in grid boxes with data is greater (see Fig. 2), with increases coming mainly in South America and Australia and with Antarctic data treated correctly. In the Northern Hemisphere, the increases were mainly in middle to high latitude areas of Asia.

Table 3 lists the temperature change accounted for by month when fitting a linear trend to the present analysis. Inspection of the temperature time series in Figs. 4 and 5 shows that a linear function is a poor fit and a gross oversimplification of the seasonal temperature series (see also the discussion in Folland et al. 1990; Folland et al. 1992). However, Karl et al. (1994) have shown that century timescale trends, estimated from surface data, have errors that are an order of magnitude smaller than the values (e.g., 0.5°C per century) themselves. For comparison purposes, only the results of calculations over the two periods 1861–1990 and 1901–1990 are presented. Trends are calculated both by standard techniques and by the robust trend method given in Hoaglin et al. (1983). In the robust trend calculation, the trend is estimated by a straight-line fit between the median value of the first and last third of the time series. For the Northern Hemisphere, the results are similar to those presented in early analyses (see Folland et al. 1990; Folland et al. 1992). For the Southern Hemisphere, however, the results are only similar for the 1901–90 period. The few additional stations over Australia (see later) during the nineteenth century and the change in reference period have warmed the 1870s causing the trends over the 1861–1990 period to be about 0.2°C less than earlier analyses.

4. Discussion

Although this reanalysis, with over 1088 additional stations, has improved both the extent and, in some regions, the accuracy of available grid-box temperatures by increasing the number of contributing stations, the effect on hemispheric averages is negligible. This result both confirms the robustness of the hemispheric-mean temperature series and suggests that similar results could have been achieved with fewer stations. This

TABLE 3. Comparison of the trend of surface air temperatures for land areas of both hemispheres for two periods, 1861–1990 and 1901–1990 (TR = trend coefficient × 10^2 °C yr^{-1} and RTR = robust trend coefficient × 10^2 °C yr^{-1}).

	1861–90				1901–90			
	NH		SH		NH		SH	
	TR	RTR	TR	RTR	TR	RTR	TR	RTR
Jan	0.59	0.49	0.21	0.17	0.41	0.43	0.43	0.40
Feb	0.54	0.40	0.26	0.20	0.84	0.89	0.44	0.36
Mar	0.68	0.58	0.26	0.28	0.80	0.68	0.44	0.32
Apr	0.47	0.47	0.19	0.23	0.78	0.86	0.32	0.27
May	0.43	0.45	0.46	0.60	0.70	0.64	0.64	0.78
Jun	0.17	0.15	0.38	0.46	0.50	0.36	0.37	0.37
Jul	0.08	0.09	0.34	0.34	0.36	0.27	0.44	0.43
Aug	0.20	0.25	0.28	0.23	0.37	0.23	0.59	0.69
Sep	0.30	0.35	0.16	0.09	0.38	0.18	0.40	0.44
Oct	0.63	0.56	0.22	0.27	0.37	0.30	0.50	0.53
Nov	0.80	0.71	0.22	0.14	0.52	0.32	0.58	0.47
Dec	0.71	0.42	0.15	0.17	0.74	0.61	0.52	0.58
Year	0.47	0.43	0.26	0.25	0.56	0.58	0.47	0.56

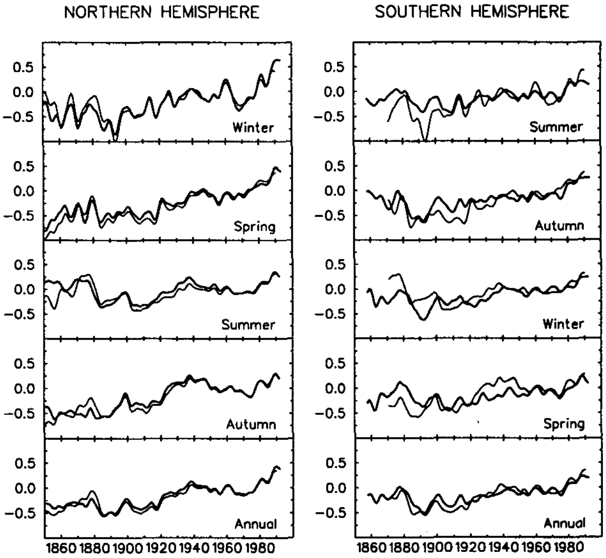

FIG. 8. Northern and Southern Hemisphere surface air-temperature series estimated from the full analysis (thick line) (Figs. 4 and 5) and the 172 (NH 109, SH 63) subset (thin line). All series have been smoothed with a 10-year Gaussian filter.

suggestion might be posed in a statistical way. Because of spatial correlation between the 2961 stations used here, what is the effective number of independent stations (or degrees of freedom) for the land areas of the world? This question is applicable only when estimating the hemispheric or some other large-scale average. If the dataset developed here is to be used for any of the numerous other purposes for which it was developed, it is essential that it be as accurate as possible for each grid box. This can be achieved only by using as many stations as possible. Because the individual grid-box accuracy will be principally dependent upon the number of contributing stations, the accuracy varies from one region to another.

What methods are available for estimating the effective number of independent stations? A common method of dimension reduction is principal components analysis. There are a number of rules (see, e.g., Preisendorfer et al. 1981) for deciding how many components contain significant information. The number retained would be the effective number, and rotation of the components might indicate where the sites might be located. Another means of estimating the effective number would be to use the correlation decay-length concept discussed by Briffa and Jones (1993). The correlation decay length l is the distance at which the correlation between one station and another falls to a value of $0.37 (l/e)$ estimated from the formula

$$r = e^{-d/l},$$

where r is the correlation and d is the distance between the stations. With l at a typical value of 1500 km for midlatitudes, a station would have to be less than 520 km away to maintain half the variance ($r = 0.71$) in common with its neighbor. The 5° resolution, in terms of latitude, gives a spacing of approximately 550 km. Although the spacing would reduce in the longitudinal direction, particularly at high latitudes, correlation decay lengths are shorter here. To correctly account for variable correlation decay length would require a grid-box size that varied not only with latitude but also with season, as decay lengths are shorter in the boreal summer season.

The correlation decay-length concept can also be used to estimate the minimum number of stations that might approximate the hemispheric average from land stations. Any analysis would only be approximate, but both the correlation decay-length approach and principal components would indicate that the effective number of independent stations would be smaller in the northern winter and larger in the northern summer in the Northern Hemisphere (NH), with little seasonal difference over the Southern Hemisphere (SH). In the above example, the number of stations required to cover the earth at a spacing of 520 km is about 594 (assuming the earth's radius is 6340 km). With the approximate land fractions of 40% (NH) and 20% (SH), this gives 119 stations for the NH and 59 in the SH. The approach is now tested by selecting a subset of stations from the 2961. The selection was done subjectively by the author, choosing stations roughly equally spaced from predominantly rural locations and with relatively long periods of record. The location of the 172 stations (109 in the NH, 63 in the SH) is shown in Fig. 7. Hemispheric averages were now computed by simply averaging the station temperature anomalies (from 1961–90) together, weighting the stations by the cosine of their latitude. Unlike the reanalysis performed earlier, no grid box "weighting" was performed. The cosine weighting, here, is an attempt to allow for the slightly greater number of mid- and high-latitude stations compared with tropical ones.

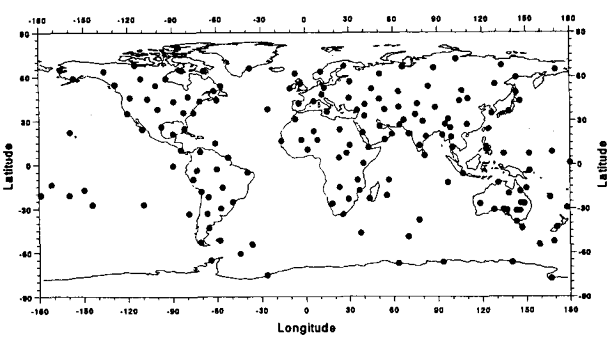

FIG. 7. Locations of the 172 selected subset of stations. Three station pairs in Australia were chosen to help long-term series over central parts of the continent. One of the pair extends from the last century to the early 1980s, while the other extends to the present from 1961.

TABLE 4. Interannual correlations (1901–90) between the present analysis and the 172 selected station subset (109 in NH, 63 in SH).

	NH	SH
Jan	0.94	0.85
Feb	0.93	0.83
Mar	0.91	0.80
Apr	0.91	0.88
May	0.90	0.90
Jun	0.94	0.78
Jul	0.92	0.77
Aug	0.91	0.84
Sep	0.93	0.89
Oct	0.93	0.85
Nov	0.91	0.84
Dec	0.93	0.84
Annual	0.96	0.89

The resulting hemispheric-average time series are compared (after the application of a 10-year Gaussian filter) in Fig. 8 with the full analysis undertaken earlier. Correlation coefficients calculated using the raw unsmoothed data over the 1901–90 period are given in Table 4. On the timescales depicted in Fig. 8 for the Northern Hemisphere, there is practically no difference between the two sets of analyses. The correlations are the same order as those that have been found between the three "independent" analyses (Jones; HL; V) discussed in the introduction (see Folland et al. 1990). Differences tend to be greater in the nineteenth century, but for this current period, the number of stations has dropped to 43 in the NH and 12 in the SH (see Fig. 9 for their locations). Interannual correlations (Table 4) are lower for the SH, and the smoothed series in Fig. 8 differ more markedly than in the north. However, even with only 12 stations, the annual curve is well replicated for the 1871–1900 period, partly due to compensating biases in the seasonal data. There are only minor differences in the overall trends in the selected station set and the full analysis over the 1901–90 period. Based on linear and robust trends (°C $yr^{-1} \times 10^2$) the selected set for annual data warms relative to the full analysis by 0.12°C in the NH and cools by 0.08°C in the SH.

One might conclude from this study that over the NH the number of selected stations could be reduced even further. Inferences from how well the 43 stations performed in the nineteenth century cannot be taken too far as some large regions are missing from the full analysis during this time. Since the 1940s though, when almost all the 109 stations have data, decadal variations in the NH average series are well approximated. For the SH, the 63 stations perform reasonably well, although never as well as in the NH. Data reduction in the SH, therefore, is considerably less (only 15%, 63 of 421) than in the NH (4.3%, 109 of 2540). This may result partly from the four distinct landmasses compared to the much larger two landmasses in the NH.

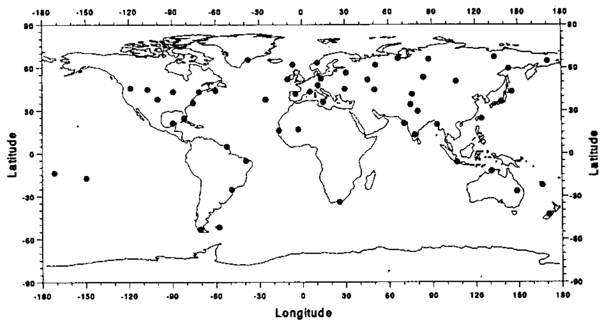

FIG. 9. Locations of the 55 stations of the subset in Fig. 7 with data series beginning in the nineteenth century.

The greater differences between the full reanalysis and Jones, in terms of hemispheric analyses, have occurred over the SH. Differences are also greater over the SH in the subset selection analysis (Figs. 8 and 9 and Table 4). In this section, we will compare the reanalysis and the original Jones analysis for the continents of Australia and South America. Monthly continental temperature anomalies were calculated from both analyses, areally weighting the grid boxes or grid points in the two regions (South America, 5°–55°S, 30°–80°W; Australia, 10°–50°S, 110°–160°E). Comparisons of the two sets of time series are shown in Fig. 10 (using 10-year Gaussian-filtered data). No attempt has been made to correct for the two reference periods used, 1961–90 and 1951–70. Interannual correlation coefficients over the 1901–90 period are given in Table 5.

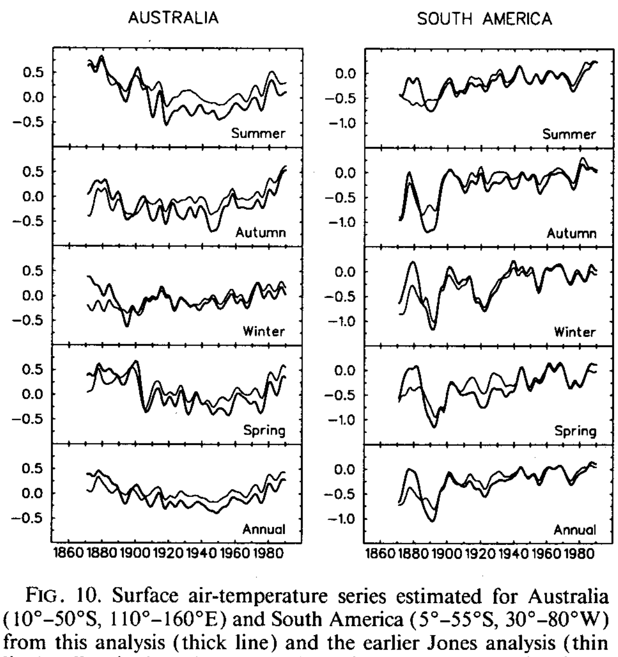

FIG. 10. Surface air-temperature series estimated for Australia (10°–50°S, 110°–160°E) and South America (5°–55°S, 30°–80°W) from this analysis (thick line) and the earlier Jones analysis (thin line). All series have been smoothed with a 10-year Gaussian filter.

TABLE 5. Interannual correlations (1901–90) between the present analysis and that of Jones over Australia (10°–50°S, 110°–160°E) and South America (5°–55°S, 30°–50°W).

	Australia	South America
Jan	0.85	0.93
Feb	0.89	0.94
Mar	0.89	0.95
Apr	0.92	0.94
May	0.94	0.96
Jun	0.96	0.97
Jul	0.95	0.97
Aug	0.95	0.96
Sep	0.95	0.90
Oct	0.90	0.94
Nov	0.89	0.92
Dec	0.89	0.92
Annual	0.89	0.91

For South America, the two analyses are in excellent agreement since 1940, and agreement does not become poor until the nineteenth century for some seasons. There is little difference in reference period values for South America as a whole, the 1970s being cooler and the 1980s warmer than the 1951–70 average. For Australia, however, there is a clear difference in the reference periods, 1961–90 being on average about 0.15°C warmer than 1951–70. This difference causes the original analysis to be plotted higher than the new analysis. The difference has a seasonal bias, being greatest in summer and least in winter. The bias also diminishes and even changes sign during the nineteenth century. Long-term warming trends (°C $yr^{-1} \times 10^2$) estimated for 1901–90 from the original analysis will be considerably greater than the new analysis (0.38 for original of 0.24 for the new). The figures would be even greater for longer periods. Thus, much of the difference between the new and original analysis, noted in Table 3 for the SH, is coming from the Australian sector.

The results of these two analyses could lead to somewhat paradoxical conclusions being drawn. While reliable estimates of NH average temperatures could be obtained from about 100 stations, estimates for continental-scale regions are reliable only since the 1940s when trend estimates were similar. Reducing the scale still further to local regional series, estimated from the average of a few boxes, will probably also result in similar, or even greater, problems as in the examples shown in Fig. 10, except probably where station numbers per grid box are high (>5) over parts of North America and Eurasia. The only inference that can be drawn about the construction of a 5° × 5° grid-box dataset is that as many stations as possible should be used in order to produce a dataset that is the best possible for a multitude of uses. Although it might be possible to estimate accurately hemispheric temperatures from as few as 170 stations, such an analysis only has this one use. Only through analyzing all available station time series can we be confident about the accuracy of the subset analysis.

5. Conclusions

An improved and revised analysis of land-based temperature data has been presented that incorporates over 1000 more stations than previously included. Comparisons with earlier analyses indicate that the results differ most over the Southern Hemisphere. Here, improvements to the data availability represent a greater proportion of the hemisphere than in the north. Improvements here have come from additional data, principally over Australia but also over South America. The change of the reference period to 1961–90 means that Antarctic data can be incorporated easily. The robustness of this and the earlier analyses for the Northern Hemisphere is confirmed by the fact that the additional 800+ stations has only a negligible effect on the results. Indeed, reasonable hemispheric estimates can be made from as few as 109 stations. We can be confident of this, however, only by analyzing all available data. As expected, estimation errors are larger for smaller regions up to continental in scale.

Of greatest concern is the dramatic reduction in real-time reporting from stations in some countries during the late 1980s and early 1990s. Improvements to the network are being planned by the World Meteorological Organization to report monthly mean maximum and minimum temperatures. To make use of this, historical time series of these variables will be required to place the new information in context. Work by Karl et al. (1993) is an important first step in this regard. Sadly, however, there are no plans to improve the density of stations reporting mean temperature.

Acknowledgments. The author acknowledges the assistance of many individuals and institutions in improving the availability of station temperature data, particularly Mike Hulme of the Climatic Research Unit; Tom Karl of the National Climatic Data Center in Asheville, North Carolina; and David Parker of the Hadley Centre, U.K. Meteorological Office, Bracknell. The new temperature datasets (both the 5° grid-box dataset and the hemispheric temperature anomalies) are available through the Carbon Dioxide Information Analysis Center in Oak Ridge, Tennessee. This work was supported by the U.S. Department of Energy, Atmospheric and Climate Research Division under Grant DE-FG02-86ER60397.

REFERENCES

Briffa, K. R., and Jones, P. D., 1993: Global surface air temperature variation over the twentieth century. Part 2: Implications for large-scale palaeoclimatic studies of the Holocene. *Holocene,* **3,** 77–88.

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

Folland, C. K., T. R. Karl, and K. Ya. Vinnikov, 1990: Observed climate variations and change. *Climate Change: The IPCC Scientific Assessment,* J. T. Houghton, G. J. Jenkins, and J. J. Ephraums, Eds., Cambridge University Press, 195–238.

——, ——, N. Nicholls, B. S. Nyenzi, D. E. Parker, and K. Ya. Vinnikov, 1992: Observed climate variability and change. *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment,* J. T. Houghton, B. A. Callander, and S. K. Varney, Eds., Cambridge University Press, 135–170.

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

——, and ——, 1988: Global surface temperatures: Update through 1987. *Geophys. Res. Lett.,* **15,** 323–326.

Hoaglin, D. C., F. Mosteller, and J. W. Tukey, 1983: *Understanding Robust and Exploratory Data Analysis.* Wiley and Sons, 447 pp.

Jones, P. D., 1988: Hemispheric surface air temperature variations: Recent trends and an update to 1987. *J. Climate,* **1,** 654–660.

——, 1994: Observations from the surface—Projections from traditional meteorological observations. *Future Climates of the World,* A. Henderson-Sellers, Ed., Elsevier, in press.

——, and Briffa, K. R., 1992: Global surface air temperature variations over the twentieth century. Part 1: Spatial, temporal and seasonal details. *Holocene,* **2,** 174–188.

——, T. M. L. Wigley, and P. M. Kelly, 1982: Variations in surface air temperatures. Part 1: Northern Hemisphere 1881–1980. *Mon. Wea. Rev.,* **110,** 59–70.

——, S. C. B. Raper, B. D. Santer, B. S. G. Cherry, C. M. Goodess, P. M. Kelly, T. M. L. Wigley, R. S. Bradley, and H. F. Diaz, 1985: A grid point surface air temperature data set for the Northern Hemisphere. U.S. Dept. of Energy, Carbon Dioxide Research Division, Tech. Rep. TR022, 251 pp.

——, ——, R. S. Bradley, H. F. Diaz, P. M. Kelly, and T. M. L. Wigley, 1986a: Northern Hemisphere surface air temperature variations: 1851–1984. *J. Climate Appl. Meteor.,* **25,** 161–179.

——, ——, and T. M. L. Wigley, 1986b: Southern Hemisphere surface air temperature variations: 1851–1984. *J. Climate Appl. Meteor.,* **25,** 1213–1230.

——, ——, B. S. G. Cherry, C. M. Goodess, and T. M. L. Wigley, 1986c: A grid point surface air temperature data set for the Southern Hemisphere. U.S. Dept. of Energy, Carbon Dioxide Research Division, Tech. Rep. TR027, 73 pp.

——, T. M. L. Wigley, and G. Farmer, 1991: Marine and Land temperature data sets: A comparison and a look at recent trends. *Greenhouse-Gas-Induced Climatic Change: A Critical Appraisal of Simulations and Observations,* M. E. Schlesinger, Ed., Elsevier Scientific Publishers, 153–172.

Karl, T. R., P. D. Jones, R. W. Knight, G. Kukla, N. Plummer, V. Razuvayev, K. P. Gallo, J. Lindesay, R. J. Charlson, and T. C. Peterson, 1993: Asymmetric trends of daily maximum and minimum temperature. *Bull. Amer. Meteor. Soc.,* **74,** 1007–1023.

——, R. W. Knight, and J. R. Christy, 1994: Global and hemispheric temperature trends: Uncertainties related to inadequate spatial sampling. *J. Climate,* **7,** 1144–1163.

Preisendorfer, R. W., F. W. Zwiers, and T. P. Barnett, 1981: Foundations of principal component selection rules. *Scripps Institution of Oceanography Reference Series 81-4,* 192 pp.

Raper, S. C. B., T. M. L. Wigley, P. R. Mayes, P. D. Jones, and M. J. Salinger, 1984: Variations in surface air temperature. Part 3: The Antarctic, 1957–82. *Mon. Wea. Rev.,* **112,** 1341–1353.

Robock, A., and J. Mao, 1992: Winter warming from large volcanic eruptions. *Geophys. Res. Lett.,* **19,** 2405–2408.

Vinnikov, K. Ya., P. Ya. Groisman, and K. M. Lugina, 1990: The empirical data on modern global climate changes (temperature and precipitation). *J. Climate,* **3,** 662–677.