July 1985

Prepared for:
United States Department of Energy

Office of Energy Research
Office of Basic Energy Sciences
Carbon Dioxide Research Division
Washington, D.C. 20545

DOE/EV/10098-2
Dist. Category UC-11

TR022

A Grid Point Surface Air Temperature Data Set for the Northern Hemisphere

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Under Contract No. DE-AC02-79EV10098

ABSTRACT

A compilation of 2666 station records of monthly surface air temperature has been assembled for the Northern Hemisphere. In order to use these data to form a gridded data set for the Northern Hemisphere we have assessed, where possible, the homogeneity of each of these records. The results of this assessment are presented and stations are classed as immediately usable, corrected or uncorrectable. Full details of how this has been achieved for each station are presented in tabular form.

Of the 2666 station records, 1584 were used to produce the gridded temperature data set. Temperature anomalies were calculated with respect to the appropriate monthly mean for the reference period 1951-70 using the homogenized data. Anomalies at each point of a 5° latitude by 10° longitude grid were interpolated from the station data for each month for the period 1851 to 1984.

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ACKNOWLEDGEMENTS

The work described in this Technical Report was funded by the U.S. Department of Energy under Contracts: DE-AC02-79EV10098 and DE-AC02-81EV10739.

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INTRODUCTION

Most studies of "global" or "hemispheric" temperature fluctuations have relied on the compilations of station data in World Weather Records (WWR), published by the Smithsonian Institution (1927, 1934, 1947) and the United States Weather Bureau (1959-82). These data have formed the basis of many attempts to grid surface air temperature onto a regular spatial network and/or to form large area average surface air temperature series. Comprehensive reviews of these studies, from the early analyses of Willett (1950) and Mitchell (1961, 1963) to the recent work of Jones et al. (1982), are given by Chen (1982) and Ellsaesser et al. (1985).

Bradley et al. (1985) have added considerably to the WWR data using material available in published and manuscript form in meteorological archives, particularly those of the U.K. Meteorological Office. The additions made to the air temperature data base for the Northern Hemisphere prior to 1900 allow much more representative values of hemispheric mean air temperature to be calculated back to 1851. Full details of these improvements in station coverage are given in Bradley et al. (1985). The most important improvements in coverage occur over parts of the Soviet Union and northern Europe, particularly before 1881. The lack of readily available data for the Soviet Union has constrained all previous studies of hemispheric mean temperatures to start about 1880 or later. Further improvements in coverage have also been made for the twentieth century, particularly over northern Africa before 1940 and over the Peoples Republic of China (PRC). In the latter region, some 30 station records have been assembled with data back to the 1920s with another 20 station records covering northern and western China for 1951-84. No other source of data for the 1951-60 decade is known outside the PRC.

In this technical note, we document the use of this extended data bank to construct a reliable gridded surface air temperature data set for the Northern Hemisphere for the years 1851-1984. In order to achieve this, it has been necessary to examine each individual station temperature series for possible inhomogeneities (errors of non-climatic origin). The full results of this examination are described here and the derivation of the gridded data set is presented. Details of each of the 2666 stations in the data bank are documented in Appendices using the formats described in Goodess et al. (1985)

and Bradley et al. (1985).

STATION HOMOGENEITY ASSESSMENT

Reasons for Station Inhomogeneities

The four main factors affecting station homogeneity are (Mitchell, 1953; see also the summary by Bradley and Jones, 1985):

(i) changes in instrumentation, exposure and measurement techniques;

(ii) changes in station location (altitude or position);

(iii) changes in observation times and the methods used to calculate monthly means; and

(iv) changes in the environment around the station, particularly with respect to urban growth.

The effects of these four major factors have been discussed at length in Bradley et al. (1985), Bradley and Jones (1985) and Jones et al. (1985).

Effects of Station Inhomogeneities

Change in station location could be an important factor in determining station homogeneity. As will be shown later in this report, at least 80% of all inhomogeneities in station records can be traced back in the station history information to changes in station location. However, merely searching through the station histories for indications of site changes, of which there may be a number, gives a pessimistic view of the potential homogeneity of a particular station's data. Comparisons with neighbouring stations show that, in the majority of cases, documented site changes have an insignificant effect on the homogeneity of the data.

The station history information given by Bradley et al. (1985) shows that there have also been changes in observation times and/or the way monthly means are calculated at almost every station. Correction of all observations to a common standard is, however, extremely difficult, mostly because sufficient hourly data are not available for the calculation of correction factors. Nevertheless, in many publications (including WWR) both documented and undocumented corrections have been applied to adjust values to a 'true' or 24 hour mean. Such procedures were widely used up until the 1940s. They are discussed in more detail with reference to the United States data in WWR by Bradley et al. (1985).

Changes in the environment around the station, especially the growth of cities, has often been considered to have an important effect on station homogeneity (Mitchell, 1953; Dronia, 1967; Cayan and Douglas, 1984; Kukla et al., 1985). Many more references are cited by Landsberg (1981). From the mass of literature on the subject it would appear that the effect is widespread. However, although effects have been demonstrated in both small and large cities in Europe and North America in particular, relationships between city size and the magnitude of the urbanization effect are not straightforward, being highly dependent on local climate and the exact location of the station in the city. Relationships found in North America cannot be extrapolated to other parts of the Northern Hemisphere, particularly to cities on the Asian and African continents.

Assessment of Homogeneity

There are 2666 stations in the temperature station data set for the Northern Hemisphere. To check all these stations for homogeneity represents an awesome task. There are two possible approaches to this problem: all records could be exhaustively checked using the available station history information as a guide to potential errors; or, inconsistencies between neighbouring stations can be used as a guide to the major inhomogeneities in the data set. For the whole data set, the former approach could only be undertaken by an organization such as the World Meteorological Organization through correspondence with all the member countries of WMO, simply because station history information is seldom published. We have chosen to use the latter method. We are only concerned with errors that are large enough to affect studies of large scale climatic change. For such a purpose, the detailed checking of individual records is not considered necessary.

To test homogeneity, we have compared records from neighbouring stations, searching for discontinuities and trends in station differences. The method assumes that, within small areas (the size depends on data availability and latitude and varies from 10^3 to 10^5 km^2), the effects of changes in climate will be similar. Records from four to five neighbouring sites were compared on climatological time scales of the order of 20 years using the following procedure:

(1) For each station, the entire record was listed as anomalies from the appropriate monthly mean based on the entire station record length. Outliers were detected by inspection and either verified, corrected, or

replaced with a missing observation code. The use of automatic statistical tests to identify outliers is not always effective as, in data sets of less than 30 years, the outliers can easily distort estimates of the monthly standard deviation. Outliers identified were commonly the result of the use of the wrong units, punching errors of exactly 10°C, or by the omission of a minus sign (this occurred in the Jenne (1975) version of WWR at almost every station in Greenland during the Novembers of the years 1951–60). Outlier inspections were carried out for every station, including those which were geographically isolated and could not subsequently be compared with neighbouring stations.

(2) For all groups of neighbouring stations, the record of annual temperature anomalies, after removal of outliers, was compared with all other records in the group by plotting the differences between the annual values as a time series, a method proposed by Conrad and Pollak (1962). If no inhomogeneity exists, the series of differences should be a stationary time series. Abrupt changes in these difference time series point to an inhomogeneity in one of the series. By comparing all possible station pairs, the erroneous stations generally become apparent. In some instances, it was necessary to compare stations with additional stations that were not initially selected in the comparison group. For stations with long records, data were compared with data from the nearest station with an appropriately long record. When inhomogeneities were identified, confirmation was sought in the station history information. For stations with records starting in the nineteenth century, the station history information given in Bradley et al. (1985) was used. For other stations, we used the compilation given in Appendix A.

(3) When a particular record showed a sudden jump or discontinuity, corrections were derived on a monthly basis and the errant data were adjusted. Station records which indicated numerous (generally more than two) discontinuities were not corrected, but were flagged as uncorrectable and unusable in subsequent analyses.

(4) The time series of station differences often showed trends or gradual changes. It was often possible to identify such warming or cooling trends with a particular station, but it was not possible to adequately correct such records. These were, therefore, also flagged as uncorrectable and unusable. Stations with inhomogeneous warming trends which were likely to be caused by urbanization were classed in a separate "affected by urbanization" category.

Some examples of the approach are shown in Figures 1 to 4. Each is discussed in the appropriate figure caption. The examples are:

Figure 1, Gordon Castle (WMO No. 030680) minus Aberdeen (030910) (United Kingdom)

Figure 2, Vishakhapatnam (431280) minus Begampet (431280) (India)

Figure 3, Nemuro (474200) minus Sapporo (474120) (Japan)

Figure 4, Rome (162420) minus Naples (162890) (Italy).

Further examples are given in Jones et al. (1985).

For each of the 2666 stations, a few (generally two) of the neighbouring stations used in the homogeneity comparisons are listed in Appendix A together with the years over which comparisons were made. In general, more intercomparisons were made than are listed. Only the relevant stations which supplied the necessary evidence of homogeneity or inhomogeneity have been included.

Correcting Errant Station Records

When an abrupt change in a station's record was identified and sufficient overlap with neighbouring correct stations available, correction factors were calculated on a monthly basis to produce a homogeneous series for that site. In the above examples, the records for Aberdeen, Begampet, Sapporo and Naples were adjusted or "homogenized". Correction factors were obtained by differencing the mean temperature before and after the discontinuity and comparing this with a similar difference at correct neighbouring station(s). Corrections were always made to adjust an earlier part of the errant station record to the most recent period. Correction factors were derived on a monthly basis despite the errant stations having

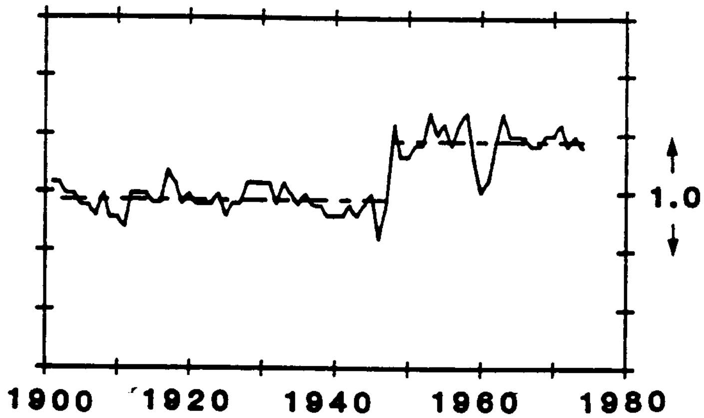

Fig. 1: Station temperature difference time series: Gordon Castle (57.6°N, 3.1°W) minus Aberdeen (57.2°N, 2.1°W), 1901-1974. The analysis identifies Aberdeen as the errant station as a similar jump at 1948 also occurs when the station is compared with Glasgow (55.9°N, 4.3°W) and Edinburgh (55.9°N, 3.4°W). The station history information reveals that the site was moved to Dyce airport in 1948. The straight lines are the mean station differences for the two periods, 1901-1947, 1948-1974. Correction details are given in Appendix A.

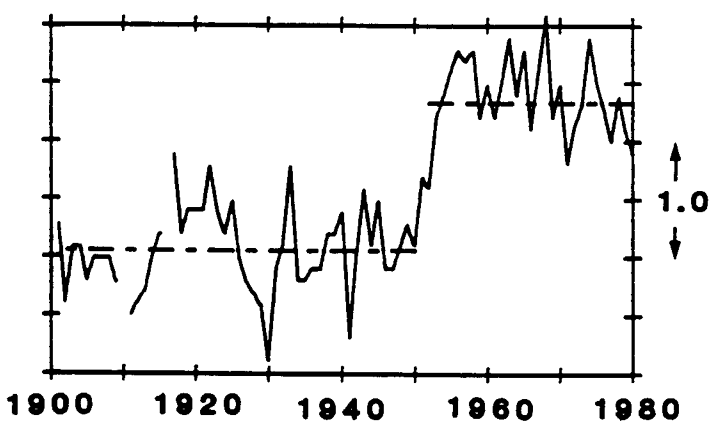

Fig. 2: Station temperature difference time series: Vishakhapatnam (17.7°N, 83.3°E) minus Begampet (17.5°N, 78.5°E), 1901-1980. The analysis identifies Begampet as the errant station as a similar jump at 1951 also occurs when the station is compared with Akola (20.7°N, 77.0°E) and Jagdalpur (19.1°N, 82.0°E). The station history information reveals that the station was moved to the airport in 1951. The straight lines are the mean station differences for the two periods, 1901-1950, 1951-1980. Correction details are given in Appendix A.

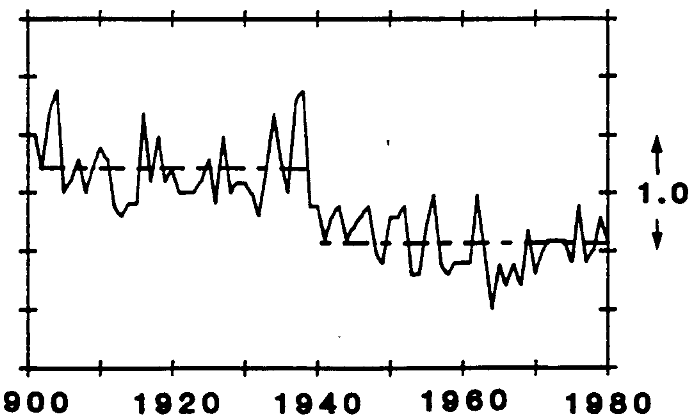

Fig. 3: Station temperature difference time series: Nemuro (44.3°N, 145.6°E) minus Sapporo (43.1°N, 141.4°E), 1901-1980. The analysis identifies Sapporo as the errant station as a similar jump during 1939 also occurs when the station is compared with Abashiri (44.0°N, 144.3°E) and Akita (39.7°N, 140.1°E). The station history information reveals that the station was moved to a new site approximately 2km southeast of its earlier position. The straight lines are the mean station differences for the two periods, 1901-1938, 1940-1980. Correction details are given in Appendix A.

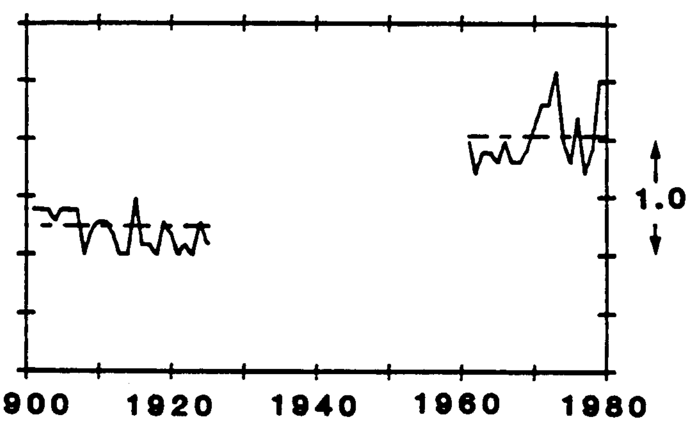

Fig. 4: Station temperature difference time series: Rome (41.7°N 12.5°E) minus Naples (40.9°N, 14.3°E), 1871-1980. The two parts of Naples record 1871-1925 and 1961-1980 were records from different sites. The straight lines are the mean station differences for the two periods, 1901-1925, 1961-1980. Correction details are given in Appendix A.

been identified on an annual basis. The correction factor in a particular month is given by

$$C = X_0 - X_1 - \frac{1}{N} \sum_{i=1}^{N} (Y_{i0} - Y_{i1}) \qquad (1)$$

where subscripts 0 and 1 refer to the time periods before and after the discontinuity, X is the monthly mean temperature at the errant site and Y_i is the monthly mean temperature at the ith (of N) neighbouring sites with a homogeneous record.

In the Sapporo example in Figure 3, N=3, 0=1900-1938, 1=1940-1970. The monthly correction factors for Sapporo (and all other corrected stations) are given in Appendix A. The corrections were applied to all months prior to July 1939 as it was known that the station moved to a new site at the beginning of July 1939. If the exact month of the station move were known, it was used. This detail was generally only known for the United States, Canada and Japan. In other cases, such as the other three examples illustrated above, the corrections were applied through to December of the year in which the discontinuity was identified.

Details for each corrected station are given in Appendix A in the relevant station history information. For each station where corrections were made, the twelve monthly correction factors are listed, together with the homogeneous or part-homogeneous stations used in their derivation and the periods over which they were calculated and applied.

<u>Results of the Station Homogeneity Assessment</u>

Full details of the homogenization analyses are listed in Appendix A. From the many-station intercomparisons undertaken, each station has been assigned a quality control code. Details of the code are given at the beginning of Appendix A. For each station, the stations used to define this code and the stations used to correct errant stations are listed in Appendix A. Approximately 24% of the 2666 stations could not be tested for homogeneity. Some station records were too short for comparison with neighbouring stations, whilst other stations were located in regions or operated in time periods for which neighbouring station data were not available. The lack of availability of comparison data is evident at many island stations, particularly in the Pacific. Such stations were, however, checked carefully for extreme outliers.

In order to summarise the information contained in Appendix A, the numbers of stations in each homogenization category have been totalled for seven regions of the Northern Hemisphere. The regions were selected on the basis of their World Meteorological Organization station numbers, and therefore correspond to large geographical areas. The station counts are listed in Table 1. 65.5% of all the stations in the data set were classed in either the correct or corrected category. Only 10.5% of stations were classed as uncorrectable and, of these, less than 2% were found to be affected by urban warming.

The small number of stations identified as affected by urbanization may be due in part to the method of analysis. It is possible that the urbanization effect might be seasonally specific and not easily identified by an analysis of annual data. If so, then errors could occur in our monthly data; but any errors in the annual data must, of course, be minimal. Urbanization effects could also escape detection by our methods if all the stations in a large area were affected. In such cases, we would only fail to identify an urbanization effect if all stations were affected almost equally. This seems unlikely. Nevertheless, some of the data which we have judged to be correct may still have spurious trends due to urbanization, and more detailed analyses are certainly warranted in regions like eastern USA and western Europe, especially if regional studies of the hemispheric data set are contemplated.

Further discussion of the results of the homogeneity assessment can be found in Jones et al. (1985).

TABLE 1. Numbers of stations in each homogenization category for different regions of the Northern Hemisphere.

	A	B	C	D	E	F
Europe (excl. USSR)	290	12	170	58	7	537
USSR	188	8	0	7	0	203
Asia (excl. PRC)	149	30	91	7	0	277
PRC	42	0	70	10	0	122
Africa (N of 2.5°S)	160	39	144	16	0	359
Americas (N of 2.5°S)	588	160	136	131	31	1046
Indonesia, Philippines, Pacific Is.	78	0	34	10	0	122
All 7 regions	1495	249	645	239	38	2666
% of 2666	56	9.5	24	9	1.5	

A: Stations correct after a specified year. (The specified year is not always the first year of record; in such cases, the earlier untested parts of the record were not used in any subsequent analyses. The length of the discarded section of records can be found by comparing the first year of record with the first reliable year of record, both of which are listed in Appendix A.)

B: Stations homogenized.

C: Stations not examined (record too short or no adjacent stations for comparison).

D: Stations incorrect (e.g. numerous jumps and/or trends including non-climatic cooling trends).

E: Stations with non-climatic warming trends.

F: Station totals.

GRIDDING THE STATION SURFACE AIR TEMPERATURE DATA

Having assessed, where possible, the homogeneity of each station record in our Northern Hemisphere data bank, we have over 2000 potentially usable stations. The stations are irregularly distributed over the land masses of the Northern Hemisphere with the majority of stations located in Europe and over the United States. Station density is considerably less in the less densely populated areas, particularly over Saharan Africa and parts of Asia. In order to reduce the effects of this irregular distribution, it is necessary to interpolate the data onto a regular grid.

Because of differing station altitudes, differing methods of calculating monthly means and differing observation times, it is not appropriate to interpolate raw station data. Almost all previous analyses overcome this problem by using anomalies from a selected reference period. (Of course, reference period means and anomalies must be calculated using the homogenized data.) A decision must be made concerning how many years of data are necessary to calculate a suitable reference period mean. For example, Yamamoto (1981) selected a near-hundred year reference period but, because so few stations have such long records, he was forced to omit many stations. The best method is to calculate anomalies from a period of good data coverage; for example, Jones et al. (1982) used the period 1946-60.

The period of best data coverage in the data set described here is 1951-70. For stations to be used in the gridding analysis we require at least 15 years of the data between 1951-70. Even using this reference period omits many valuable long records that ceased recording in 1950 or 1960. In order to use some of these data, reference period means were estimated using data from nearby stations. The accuracy of these reference period means is probably better than $\pm 0.2^{o}$C.

Inevitably, some station data cannot be used because reference period means cannot be calculated. This reduces the number of usable stations to 1584. These stations are listed in Appendix B and their locations are shown in Figure 5. Station counts for the seven regions (used in Table 1) are listed in Table 2.

Most of the previous methods of data interpolation have been discussed in Jones et al. (1982, 1985). Further information may also be found in Ellsaesser et al. (1985) and Wigley et al. (1985). Previous analyses can be

TABLE 2. Stations with sufficient data in the reference period mean, 1951-70.

	A	B	C	D
Europe (excl. USSR)	227	12	44	283
USSR	134	8	0	142
Asia (excl. PRC)	118	26	19	163
PRC	42	0	0	42
Africa (N. of 2.5°S)	141	37	8	186
Americas (N of 2.5°S)	534	149	7	690
Indonesia, Philippines, Pacific Is.	78	0	0	78
All 7 regions	1274	232	78	1584
% of 1584	80.4	14.7	4.9	

A: Stations correct after a specified year.

B: Stations homogenized.

C: Stations not checked.

D: Totals.

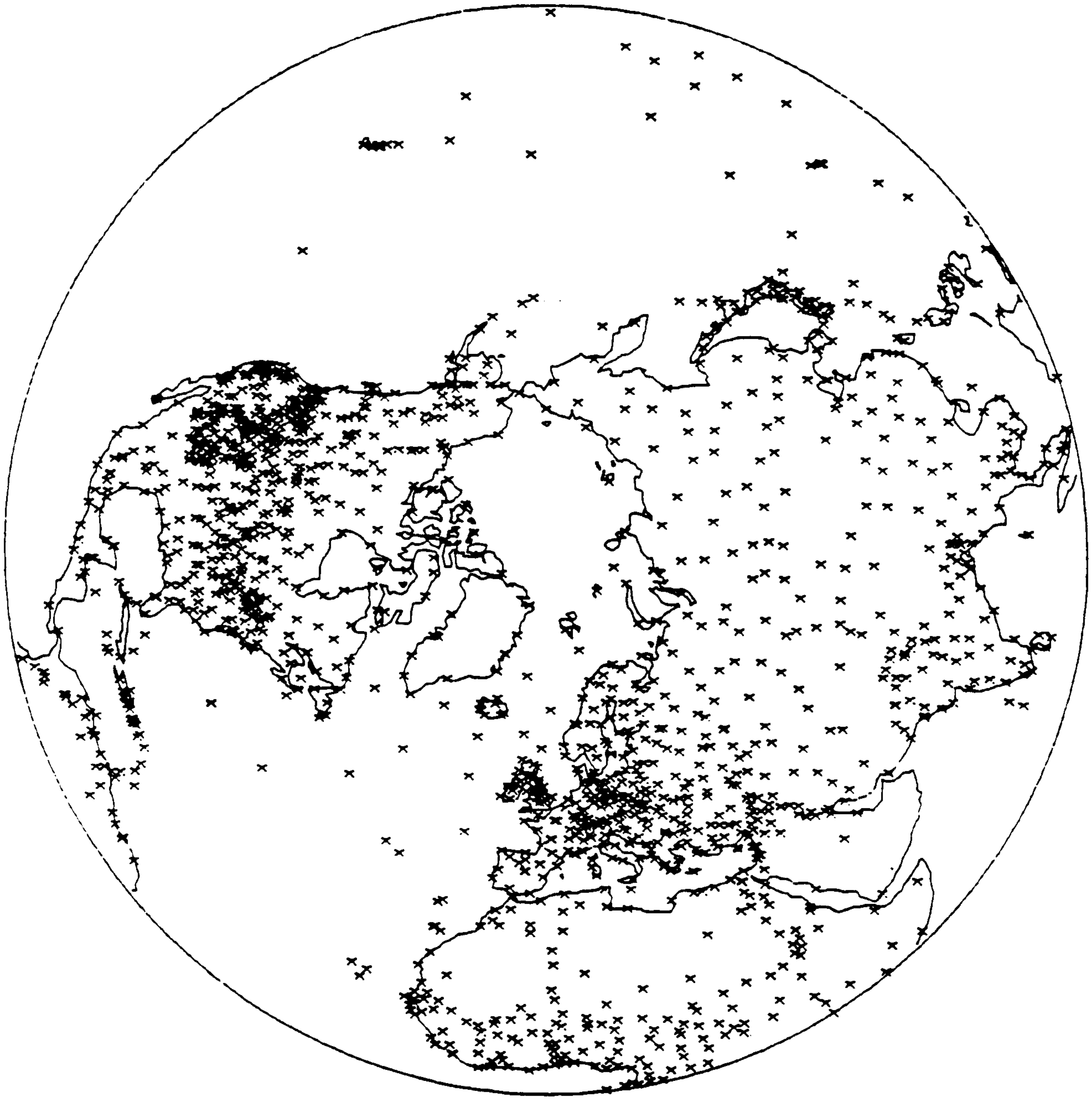

Fig. 5: Locations of the 1584 stations used in the gridding technique.

classed into two main categories, subjective or objective techniques.

Subjective techniques have been used almost entirely by Soviet workers, in particular by Borzenkova et al. (1976) and Vinnikov et al. (1980). In these studies, station temperature data were hand plotted onto hemispheric charts for each month over the period of analyses, in this case 1891-1978. The maps were contoured subjectively and grid point values extracted onto a 5^o latitude by 10^o longitude grid. Recent workers have essentially built on earlier analysis of a chart series available in the Soviet Union; see, for example, Sharov (1960-67), Budyko (1969) and Vinnikov (1977). Further details of the techniques are given by Vinnikov (1977), Jones et al. (1982) and Robock (1982).

Objective methods have employed numerical techniques to extrapolate or interpolate grid point temperature from the irregular distribution of station data. Examples are the works of Yamamoto and co-workers (e.g. Yamamoto and Hoshiai, 1980; Yamamoto 1981), Hansen et al. (1981), and Jones et al. (1982).

All of the published methods (both subjective and objective) have deficiencies. The method of Vinnikov et al. (1980), involving nearly 1200 maps, is both time-consuming and subjective. The results could not practically be repeated even if the precise data sources were known. Yamamoto's (1981) results are not strictly comparable to the other analyses discussed here because a zero anomaly value was assumed for all grid points where interpolation could not be made. This assumption reduces the variance of their Northern Hemisphere average series by about one half compared to the other analyses (Kellogg and Bojkov, 1982). Hansen et al's (1981) method is difficult to assess as no complete description of the method has been published.

The method of Jones et al. (1982) is described in detail, but there are also problems with their method. They used the six stations nearest to a grid point in order to calculate the grid point value. However, because the station density increases through time, the six stations nearest to a grid point change. The stations used during the period of best data coverage in the 1950s were, on average, nearer the grid point than at other times. In some regions, particularly Arctic regions, stations were used to interpolate grid point values at more than one grid point. This could raise the degree of spatial autocorrelation above the real value. In data-dense areas, particularly over the United States and central Europe, much of the station data was not used at all.

In order to eliminate some of these problems, a new method of gridding has been employed. The grid spacing used in the present analysis is 5° latitude by 10° longitude involving 649 grid points over the Northern Hemisphere. At each grid point, anomaly values for all stations that have this as their nearest grid point are averaged using inverse distance weighting:

$$T_g = \sum_{s=1}^{n} \alpha_s T_s \Big/ \sum_{s=1}^{n} \alpha_s \qquad (2)$$

where T_g is the interpolated grid point temperature anomaly
T_s (s=1,n) is the station temperature anomaly
α_s (s=1,n) is the inverse of the great circle distance between the station and grid point. (αs was constrained to $1/\alpha s < 0.02$ nautical miles, since some stations are located very close to grid points.)

This method has two advantages: data for a particular station are used for interpolation at only one grid point; and all the available station data are used. For some grid points, when only one station record is available, the station anomaly value becomes the grid point value. In data dense areas of North America and Europe, up to 40 stations may be averaged to calculate a single grid point value. The method has a slight disadvantage in that T_g values based on large N may have lower inter-annual variance compared with those based on smaller N. However, spatial correlation effects and the inverse distance weighting factors tend to minimise this problem.

RESULTS

The Gridded Data Set

The new gridding method has been used to interpolate from station anomalies, with respect to the 1951-70 reference period, to the regular grid, for each month from January 1851 to December 1984. Grid point anomalies have been calculated to an accuracy of 0.01°C. Such an accuracy, however, does not necessarily reflect the accuracy of the original data and has only been used for computer storage purposes. Individual monthly grid point anomalies are probably accurate to ±0.2°C.

The number of stations (n) available at each grid point varies through time and from grid point to grid point. In some cases, n is one, and the station anomaly value is used as the grid point value. In order to assess the reliability of the interpolated grid point temperature anomaly, two quantities other than the temperature anomaly itself have been stored in our gridded data file. These two quantities are the number of stations used (n) and the quantity $\beta = 1/n \sum_{s=1}^{n} \alpha_s$ for every gridpoint for each month for each year. β is a measure of how close the stations are to the relevant grid point; $1/\beta$ being a mean distance in nautical miles.

The data set is available on a computer magnetic tape.

CONCLUSIONS

The Hemispheric Average Series

The method of calculation of the area average surface air temperature series is relatively straight forward; each grid point is averaged after being weighted by the area of the hemisphere it represents. Weighting is achieved using the cosine of the latitude of the grid point.

$$NHT = \sum_{g=1}^{M} T_g \cos(\phi_g) \ / \ \sum_{g=1}^{M} \cos(\phi_g) \qquad (3)$$

where M is the number of grid points with temperature anomalies (T_g) in a particular month and ϕ_g is the latitude of the grid point.

The number of grid points for which a value can be calculated increases between 1851 and 1950. The estimates of hemispheric mean temperature are, therefore, more reliable in recent decades (especially since 1930) than during the nineteenth century. The spatial representativeness of the series over the 1851 to 1930 period has been assessed by Jones et al. (1985). The hemispheric temperature series appears to be reliable on a year to year basis after about 1875 despite the marked changes in spatial coverage. Prior to 1875, yearly temperature estimates are less reliable. Although the general trends of temperature over the 1851-1874 period are considered reliable by Jones et al. (1985), differences between land and marine data exist which stil require explanation.

The nineteenth-century data shows a slight cooling between the 1870s and the late 1880s. The mean temperature prevailing between 1851 and the late 1870s was similar to that of the 1900s and 1910s. Around 1920, a rapid warming took place and the period 1921-1984 was about 0.4°C warmer than the earlier period 1851-1920. Most of the warming between 1921 and 1984 took place over the periods 1921 to 1940 and 1965 to 1984. A cooling of about 0.28°C is evident between 1940 and 1965. The magnitude of this cooling in the present analysis is considerably smaller than in the earlier analyses of Vinnikov et al. (1980), Hansen et al. (1981) and Jones et al. (1982), amounting to about 0.38°C in those studies.

There is no doubt that further errors could be eliminated from the data set, but not without considerable effort. For studies of hemispheric-scale temperature variations the consistency between various independent data sets (upper air data, marine data and surface station data) attests to the reliability of the data set produced here (see Wigley et al., 1985). Further discussion of the data set is given in Jones et al. (1985).

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APPENDIX A

Station History Information and Homogeneity Assessment Details

Column Headings

Line 1:

WMO Number (generally with additional 0)
Station Name
Country
Latitude
Longitude
Height
First year of data (In some cases this may be the first year with precipitation data. Temperature data starts later.)
Last year of data
Quality code
First reliable year of data

Line 2:

Source: Codes used by Bradley et al. (1985)

Subsequent lines:

Notes and homogeneity details.

Additional Information

Missing Codes:

Latitude - 999
Longitude - 1999
Height - 999

Quality Code:

First Digit

1 - Reliable back to first reliable year
2 - Corrected back to first reliable year
4 - Affected by urban warming
5,8 - Non-homogeneous and uncorrectable
6 - Not compared with neighbouring stations
7 - Reliable back to first reliable year, uncorrectable for earlier years

Second Digit

0 - Record 90% complete
1 - Short record of less than 20 years
2 - Record less than 90% complete, generally containing many years of missing data
3 - Antique record with data almost entirely from the nineteenth century or earlier