Marine and Land Temperature Data Sets: A Comparison and a Look at Recent Trends

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ABSTRACT. Comparisons are made among the various data sets of marine and land temperatures. Emphasis in the analyses is placed on the first intercomparison of the two marine data sets, the United Kingdom Meteorological Office (UKMO) and the Comprehensive Ocean-Atmosphere Data Set (COADS). The results of the analyses show that the two data sets are not the same, as some authors have assumed. Important differences are noted prior to 1940, with hemispheric averages differing by up to 0.2°C for some decades during the nineteenth century. Patterns of regional temperature change over the two major periods of global warming this century, 1920–39 and 1967–86, are shown.

1. INTRODUCTION

Temperature data from land and marine areas often form the basis for studies of climatic variations on local, regional and hemispheric scales, and the global-mean temperature series is a fundamental measure of the state of the climate system. The global-mean series, however, masks all the regional and seasonal variations that it encompasses. This paper seeks to set out the guidelines necessary for studies on these smaller scales.

Foremost, it is necessary that all the temperature data used in any analysis be homogeneous. Several studies have discussed strategies for assessing the homogeneity of land-based data (see, e.g., Bradley and Jones, 1985). Few, however, have considered the homogeneity of marine data. Here we consider this aspect in detail and show examples of the first comparison of the United Kingdom Meteorological Office (UKMO) and the Comprehensive Ocean-Atmosphere Data Set (COADS) marine data bases. The combined analysis of both marine and land data is vital if we are to understand, and in time explain, the course of regional temperature variations over the last 140 years.

The paper concludes by comparing the regional temperature trends over the two major periods of global warming this century, namely, 1920–39 and 1967–86.

2. LAND DATA SETS

For data over the land areas, three global-scale data sets of temperature anomalies are available: Jones *et al.* (1986a,b) and Jones (1988), hereafter J; Hansen and Lebedeff (1987, 1988), hereafter HL; and Vinnikov *et al.* (1987), hereafter V. These data sets are either gridded on a regular latitude/longitude grid (J,V) or "boxed," that is, condensed to a set of latitude/longitude boxes (HL). For simplicity, we will refer to all three data sets as "gridded." They are all based on the same basic set of station temperature data, but there are important differences. For example, J have added many additional stations to the data set, especially in the early years of the record, and they have carried out quite detailed station-by-station assessments of homogeneity (see below) and corrected many of the individual station time series (see Jones *et al.*, 1985, 1986c for details). The data sets have been compiled independently, except for the V results for the Southern Hemisphere which are based on the J data set, gridded and averaged using different methods from J.

Hemispheric means based on the three data sets are shown in Figs. 1 and 2. These hemispheric means have been compared by a number of authors (e.g., Grotch, 1987; Wigley *et al.*, 1989). Correlations between the various time series are extremely high, but the three versions disagree on the amount of warming that has taken place since about 1880. For example, in the HL Northern Hemisphere estimate, the warming over 1880 to 1987 is about 0.2°C greater than in both the J and V series (Wigley *et al.*, 1989). The extra warming in HL is believed to be due either to coverage differences and/or to the fact that they did not carry detailed station-by-station intercomparisons to ensure the homogeneity of the individual station data. The good agreement between V and J suggests that V was also careful in the basic station data used, but this is not clear in their published material.

Unless corrected, most of the potential inhomogeneities in station temperature time series are likely to affect a gridded data base at the gridpoint level, with the magnitude of the effect depending on how many stations go into a gridpoint or gridbox series. However, on larger spatial scales, many types of inhomogeneity will tend to have cancelling effects, and so have little influence on the homogeneity of hemispheric or global means. For example, changes in site or in methods used to calculate monthly means are equally likely to warm or cool the measured surface air temperature. When the gridded data are averaged to annual hemispheric estimates, such local effects are likely to cancel out. Other types of inhomogeneity, however, are less benign. The prime example is the inhomogeneity caused by the growth of cities around sites during the twentieth century. In this case the effects at individual stations will all be of the same sign, a warming of the city site relative to its rural environs.

Studies of the urbanization effect, on individual cities, have found that individual night minimum temperatures can have a warm bias of up to 20°C (see Oke, 1979). However, these types of study are not relevant to the monthly time scale and monthly means for which the effect is considerably reduced by temporal averaging. Furthermore, for gridded data, additional dilution of the effect occurs due to the mix of rural and urban stations used in the gridding and the averaging of gridpoint data over a wide area.

For monthly mean gridded data, the magnitude of the effect can be assessed by comparing regional time series from the gridpoint networks with regional analyses based principally on rural stations. The best available data set for such a comparison is the Historical Climate Network (HCN) for the contiguous United States, produced by Quinlan *et al.* (1987). This data set is composed mainly of rural stations and has also been assessed

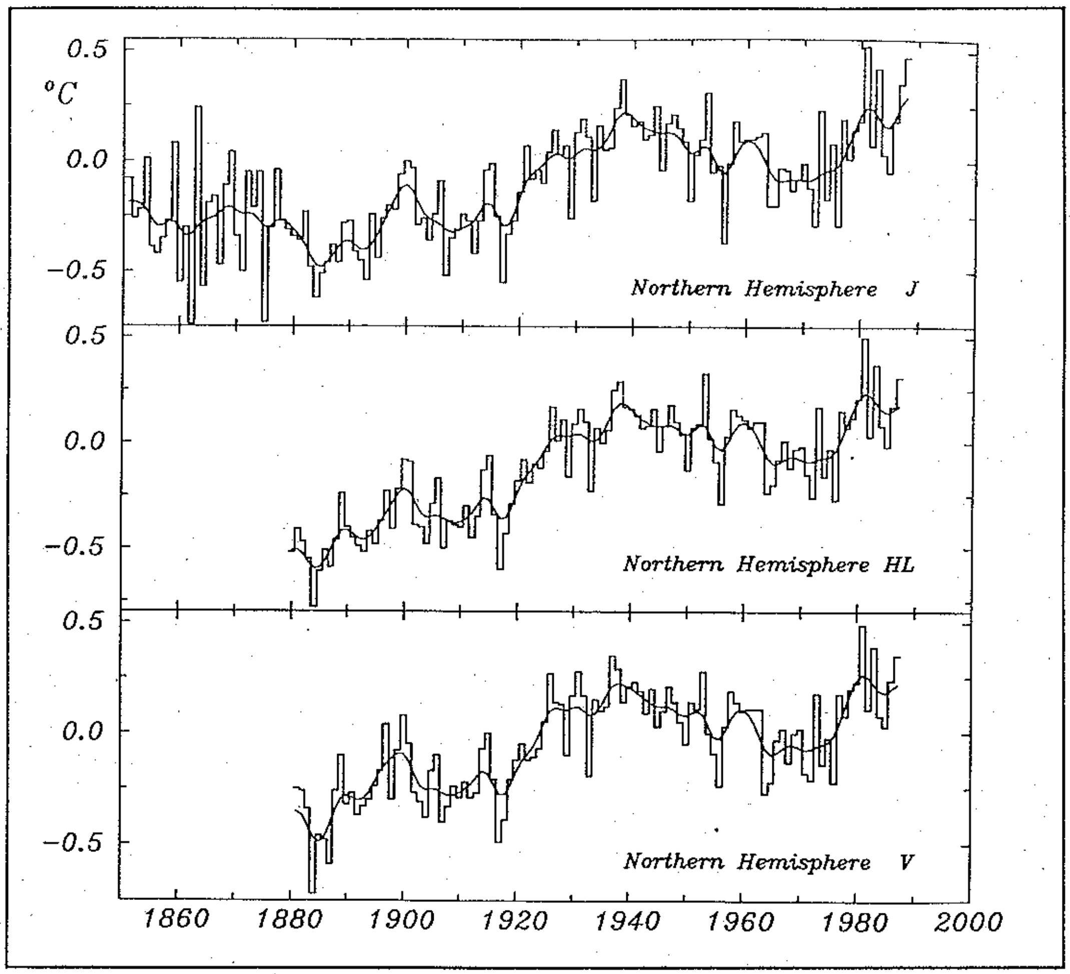

Figure 1. Comparison of the J, HL and V estimates for the Northern Hemisphere. The reference periods used by the three analyses are 1951–70, 1951–80 and 1951–1975, respectively.

for station inhomogeneities (Karl and Williams, 1987). Urban sites have been corrected for urban warming using population data (Karl *et al.*, 1988). Comparisons between estimates of the average contiguous U.S. temperature based on HCN and that from the J and HL data sets show a surplus warming in the gridded data sets of 0.1 and 0.4°C, respectively, over the 1901–84 period (Karl and Jones, 1989; Jones *et al.*, 1989).

Generalizing this result to other parts of the world is not a simple task. The degree of urban warming depends on such factors as the growth of urban population and per capita energy consumption. The effect on large-area averages depends on the mix of urban and non-urban stations, and on how well individual records have been homogenized—which, in turn, depends on station density for intercomparisons. Few regions of the world can have experienced growth rates comparable to North America over the present century, but this may not be the case over the last twenty years in some developing countries. Studies in some other industrialized regions of the world tend to indicate that North America is more affected by urban warming (Jones *et al.*, 1990).

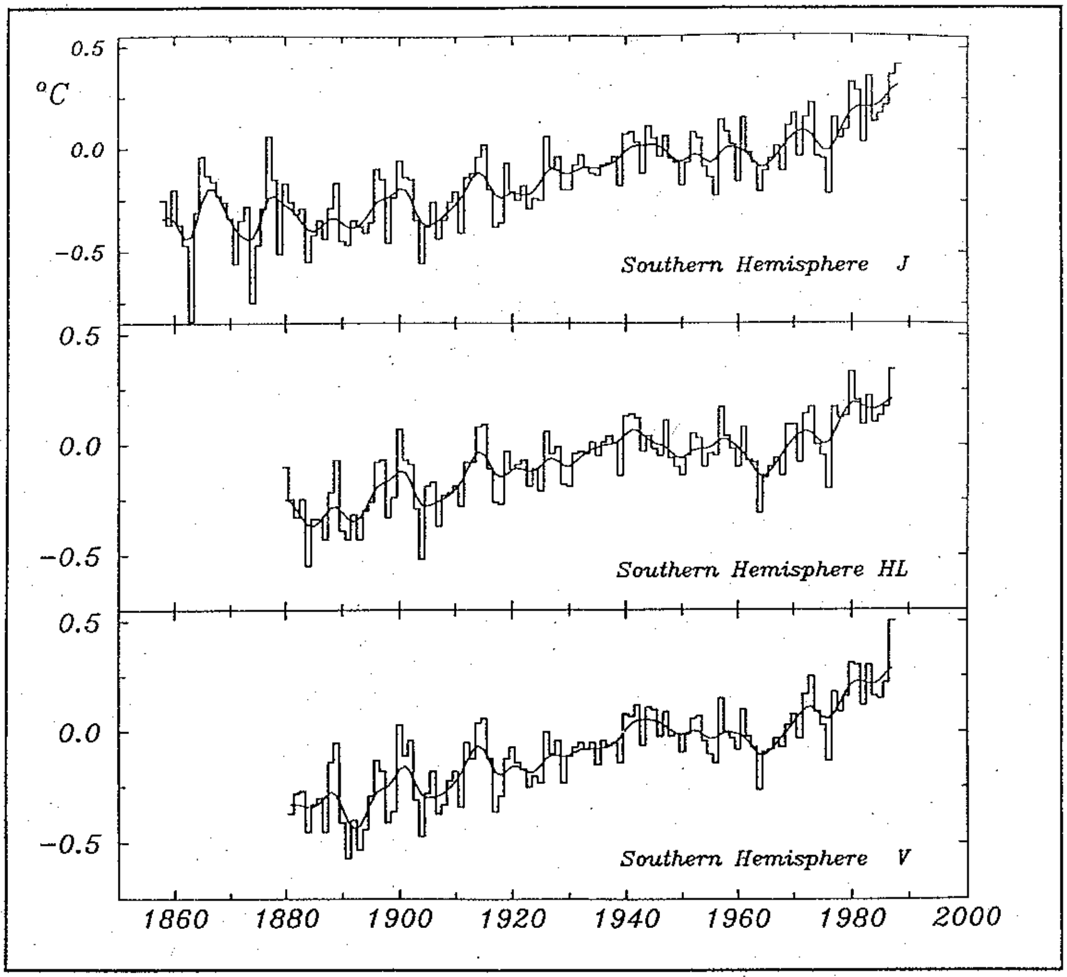

Figure 2. Comparison of the J, HL and V estimates for the Southern Hemisphere. The reference periods used by the three analyses are 1951–70, 1951–80 and 1951–1975, respectively.

3. MARINE DATA SETS

Two global compilations of marine data have been assembled. These are the United Kingdom Meteorological Office (UKMO) marine data bank (Shearman, 1983; Bottomley *et al.*, 1990) and the Comprehensive Ocean-Atmosphere Data Set (COADS) (Slutz *et al.*, 1985; Woodruff *et al.*, 1987). The analysed part of the UKMO data set contains only observations of sea surface temperatures (SST) and nighttime marine air temperatures (NMAT), while COADS contains the complete set of shipboard observations. There is considerable overlap between the two data sets, but the COADS set contains 40% more raw individual SST observations than UKMO (mainly since 1950) and does not distinguish between nighttime and daytime marine air temperatures (Woodruff *et al.*, 1987; Bottomley *et al.*, 1990). The UKMO data set for SST contains extra analysed data supplied by the Massachusetts Institute of Technology (Folland *et al.*, 1984; Bottomley *et al.*, 1990) for the period 1949–1979. These data are mainly in the Pacific. In addition, the

UKMO analysed data sets of SST and NMAT currently use telecommunicated observations beginning in January 1982, but the UKMO marine data bank contains no telecommunicated observations.

It is generally agreed that both types of marine data require some form of adjustment or correction, particularly before 1945. Although this has been known for some time (Saur, 1963; Tabata, 1978; Barnett, 1984, 1985), some authors have, nevertheless, failed to realize the primary importance of the inhomogeneities (e.g., Paltridge and Woodruff, 1981; Oort *et al.*, 1987). Corrections are necessary because of changing methods of measuring SST, changes to ships, including the change from sail to steam and trends in ship sizes, and changes to shipping routes. Before considering how adjustments to the marine data should be made we will first compare the two data sets.

The basic raw UKMO and COADS data sets are made up of the mean SST or MAT value for each available "square" of the ocean for each pentad (UKMO) or month (COADS) since the beginning of recording during the 1850s. The only other difference between the two data sets at this stage, apart from the greater number of raw SST observations in COADS and the rejection of daytime MAT observations in UKMO, is that the box size for UKMO is 1° by 1° while for COADS it is 2° by 2°. Because the gridbox sizes are small, the coverage is "spotty" in some regions and the number of boxes is too large for studies of global and hemispheric temperatures. The basic data have therefore been combined to form larger boxes, 5°×5° for UKMO (Bottomley *et al.*, 1990) and 4°×10° (SST) and 5°×5° (MAT) for COADS (Wright and Jones, 1986). [For the COADS data, the MAT observations have been gridded, as in Jones *et al.* (1986a,b) rather than simply averaged into boxes.]

Both data sets use very similar techniques to compress the data onto the more manageable grids. First, all small-box values are reduced to anomalies from a common reference period (1951–80 for UKMO; 1950–79 for COADS). Small boxes with too few observations to form a reference-period mean or individual monthly anomaly values are ignored. Only a small number of observations are required to form a monthly value because of the high temporal autocorrelation between successive observations (Parker, 1984). Generally, only 3 measurements were considered sufficient (see Wright and Jones, 1986) or three 5-day means for UKMO (Bottomley *et al.*, 1990). With the COADS data, some effort was made to ensure that, if the number of observations was small, they were reasonably well distributed throughout the month, based on the mean day of the month for observations (see Wright and Jones, 1986). For the UKMO data, the use of three 5-day means and other quality control procedures (Bottomley *et al.*, 1990) largely achieves the same end. The small-box values are then averaged to the larger units, with distance weighting in the COADS MAT case (cf. Jones *et al.*, 1986a,b). In data-sparse regions, only one small square was considered sufficient to produce a large-box value. These procedures are valid only if anomaly values are used. Use of anomalies is an important aspect of the analyses, since it allows greater coverage than would otherwise be possible.

The area of ocean covered by the two data sets is similar up to 1960, although UKMO SST coverage is better than COADS SST over the Southern Hemisphere between 1910 and 1980. Since 1961, however, the area covered by the COADS data set in the Northern Hemisphere has been consistently greater. Coverage tends to increase for both marine variables in both data sets in a linear fashion from the 1860s to the 1980s if the marked reductions in coverage during the early 1900s and the two world-war periods are ignored. Despite the relatively poor coverage during the nineteenth century in both hemispheres, studies using the "frozen grid" method of Jones *et al.* (1986a,b) show that there should be no systematic biases in either hemispheric estimates (Parker, 1987).

Direct comparison of the uncorrected hemispheric estimates from UKMO and COADS using MAT and SST reveals that there are important differences between the

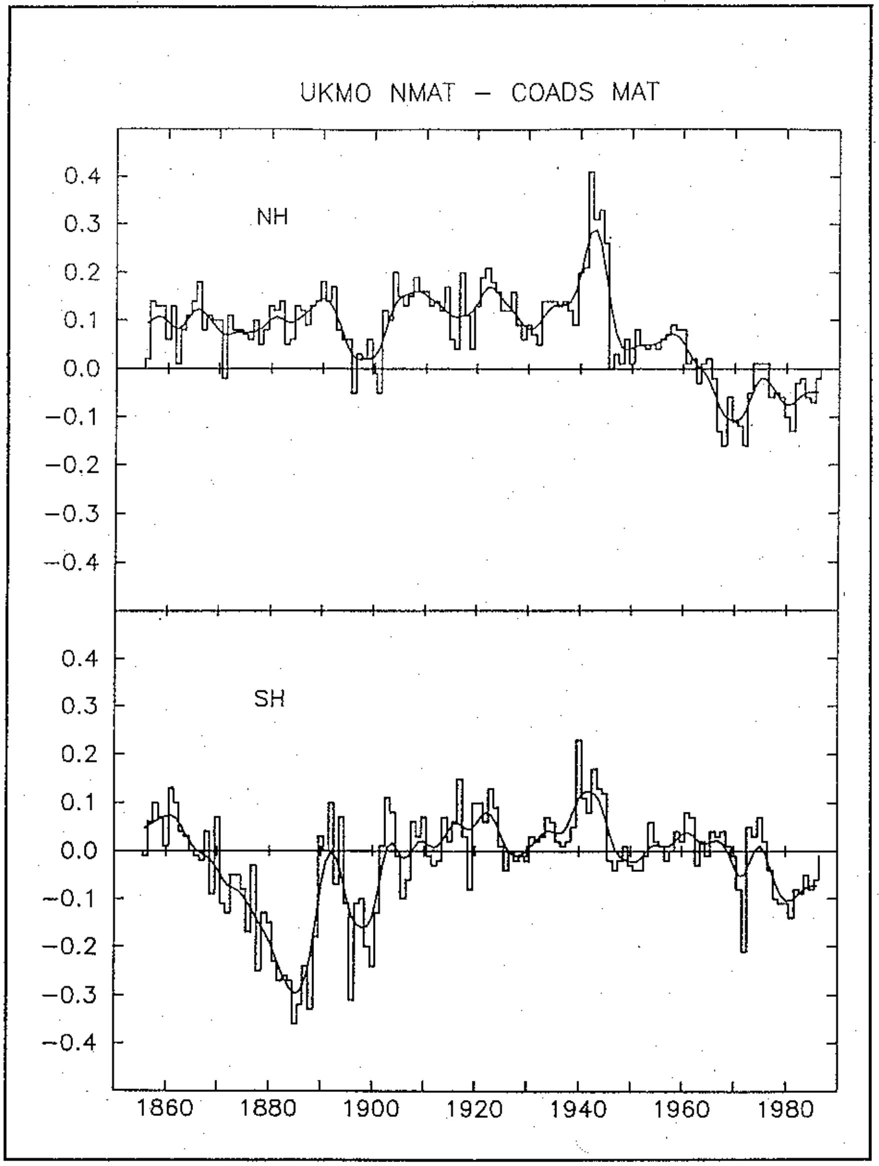

Figure 3. Differences of hemispheric means of uncorrected marine air temperatures (MAT) between UKMO and COADS [UKMO (NMAT) minus COADS (MAT)]. The reference periods used by UKMO and COADS are 1951–80 and 1950–79, respectively.

two data sets (Fig. 3, MAT, and Fig. 4, SST). The scale of these differences has not been generally realized. Indeed, they are somewhat surprising since there is so much common data.

For MAT (NH), UKMO is consistently warmer than COADS by between 0.10-0.15°C up to 1940. Since 1950, UKMO is warmer up to 1960, then generally cooler. In the Southern Hemisphere, the difference is near zero during the twentieth century. Between 1870 and 1900, UKMO is about 0.2°C cooler, particularly during the late 1880s. More detailed comparisons using 10° zonal means show similar patterns to those in each

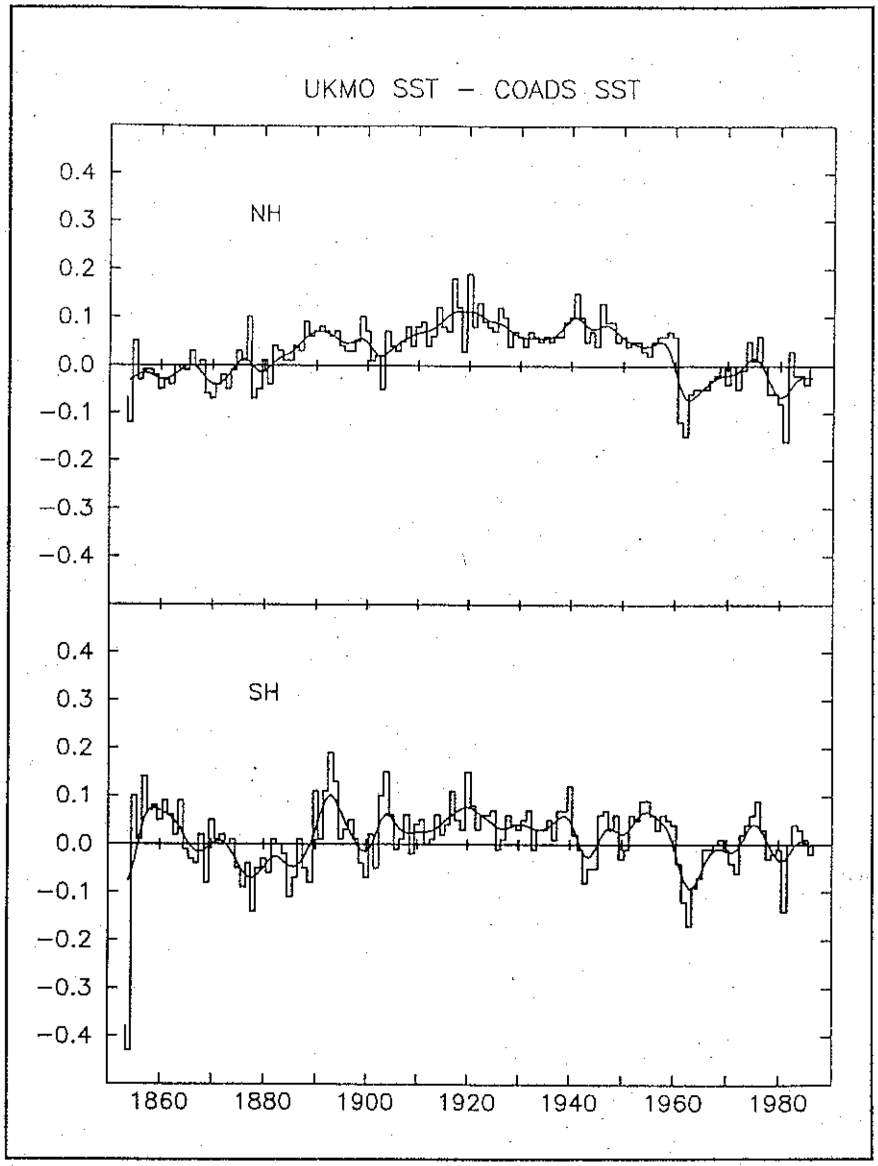

Figure 4. Differences of hemispheric means of uncorrected sea surface temperatures (SST) between UKMO and COADS [UKMO (SST) minus COADS (SST)]. The reference periods used by UKMO and COADS are 1951–80 and 1950–79, respectively.

hemisphere, except for the most-poleward zones (70-60°N, 60-50°N and 40-50°S) where differences, although highly variable, do not show the consistent variations of other zones. A further seasonal breakdown shows that most of the features are common to all seasons. These differences cannot be related to the use of only NMAT data in UKMO and both day and night MAT in COADS, since both are analysed in anomaly terms. Differences may arise if the bias in either daytime or nighttime MAT observations varied with time (e.g., due to changing ship characteristics or observation practices), or if the mix of day and night temperatures in COADS varied with time, and/or if the UKMO NMAT data were contaminated with varying amounts of daytime data.

For SST (Fig. 4) there is a greater similarity between the corresponding hemispheric-mean time series. Up to 1880, differences are small, although there is a cooling in UKMO relative to COADS in the Southern Hemisphere. Between 1880 and the 1960s, UKMO is warmer than COADS by between 0.05 and 0.10°C, nearer the higher value in Northern Hemisphere and the lower value in the Southern Hemisphere. After 1960 there is a sharp drop in the difference to near zero. Analysis of zonal-mean differences shows that these features are apparent in all but the most-poleward zones, but are strongest in the mid-latitude zones between 20–50°N and 20–40°S. There appears to be no immediate causes for these differences, although the sharp jump at 1960 may be related to the inclusion in UKMO of Massachusetts Institute of Technology (MIT) data in the Pacific during the early 1960s.

While it may not be immediately apparent what the exact causes of the differences between the UKMO and COADS data sets are, the differences mean that any corrections for instrumental-practice changes should be different between the two data sets. The fact that corrections are necessary to either one or both measures of marine temperature can be seen by plotting the difference in hemispheric MAT and SST values for the COADS data set (Fig. 5). If instrumentation had remained constant, there should be little difference between annual anomaly values of MAT and SST, with no change on time scales of 5 years and upwards. Figure 5 shows MAT significantly, and erroneously, higher than SST prior to 1940. From the 1850s to the 1890s, the air is relatively warm by about 0.6°C in the NH and 0.45°C in the SH. This drops to around 0.4°C (NH) and 0.3°C (SH) from 1900 to 1940.

Two different approaches to the correction of marine data series have been made. We will refer to these as the *a priori* and *a posteriori* approaches.

In the *a priori* approach, exemplified by Folland *et al.* (1984), Bottomley *et al.* (1990) and Folland and Parker (1989b), the adjustments are made partly on theoretical grounds. Folland and Parker (1989b) refer to the approach as an *a priori/a posteriori* mix. In order to avoid confusion with the *a posteriori* approach discussed later, we refer to it here as *a priori*. In this approach, it is assumed that the causes of inhomogeneities in the data are understood, and correction factors derived based on a model of the causal factor(s). For SST, Folland and Hsiung (1986) have assessed, with the aid of a model, the amount of cooling that will take place while a canvas bucket is being hauled onto and left to stand on deck before reading. The evaporative cooling that takes place depends on temperature, the air-sea temperature difference, relative humidity and windspeed. The correction factor so derived varies according to month and to the region of the ocean.

The implied seasonal and spatial variability of the correction factor provides a way of verifying that the model is producing reasonable results. Because of the changing mix of bucket and intake measurements with time, the observed seasonal cycle of SST for the period prior to 1940, when observations were mainly made using canvas buckets, should have a slightly different amplitude compared with more recent (mainly intake) measurements. This difference in annual cycles should also vary spatially. In practice, these differences will show up as spurious annual cycles in the anomaly data, since the reference period spans an interval of virtually constant measurement techniques. After correction, both the temporal and spatial variability of the amplitude of the annual cycle should be substantially reduced.

Climatological values are used for most of the parameters in the bucket model. The only unknown is the length of time between taking the sample and the temperature measurement. Folland and Parker (1989a,b) estimate this by finding the time that best minimizes the spurious annual cycles. This turns out to be 3-6 minutes, which agrees with some recommendations (see, e.g., WMO, 1954). Furthermore, as anticipated, the same inferred exposure time applies to all regions of the world's oceans. Figure 6 shows the

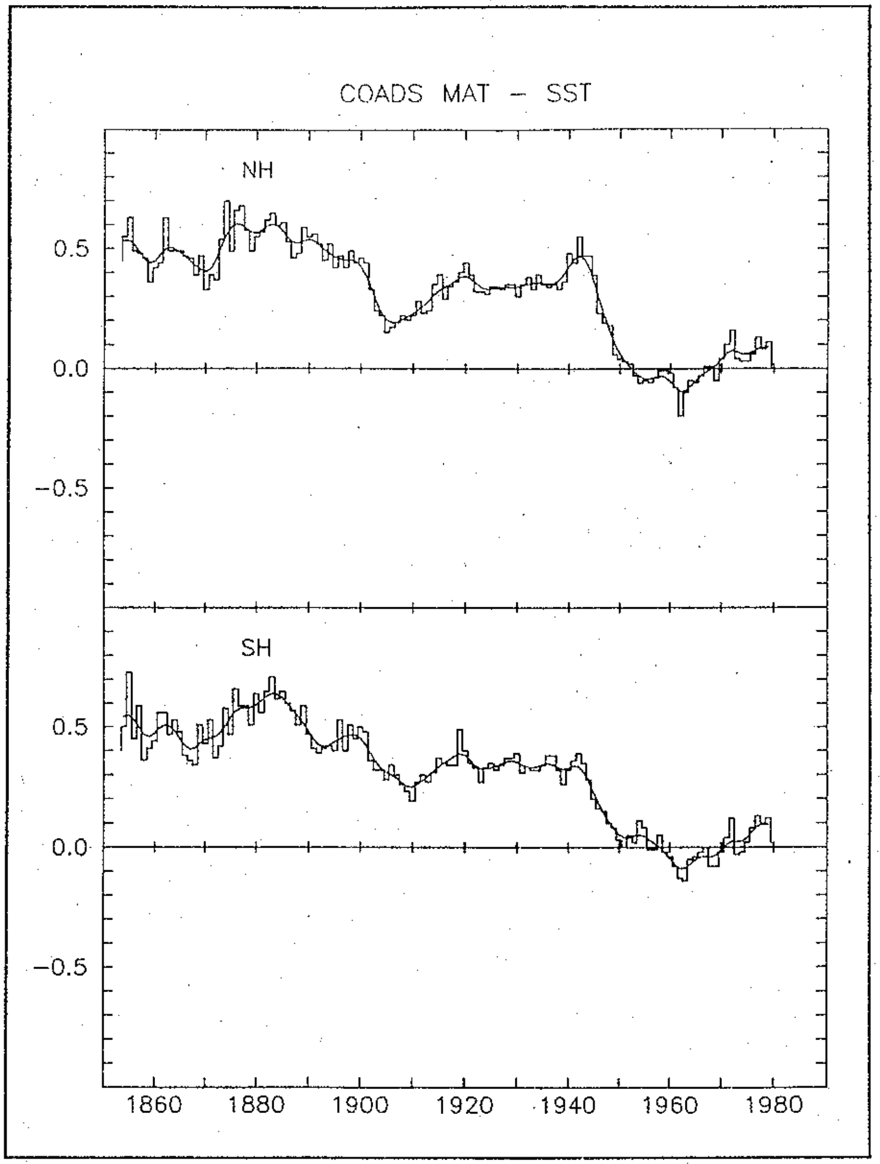

Figure 5. Difference between hemispheric means based on MAT and SST values using COADS.

average hemispheric correction between 1856 and 1941. The slight variations from year to year result from slightly changing coverage in each year. The average correction is slightly larger in the Northern Hemisphere because of a greater proportion of high-latitude ocean where the corrections required are greater.

In the *a posteriori* approach, exemplified by Jones *et al.* (1986d), adjustments are made so that the mean hemispheric and regional estimates of MAT and SST are in accord with adjacent land-based data on decadal and longer time scales. For this approach to be valid, the land-based data must be homogeneous. In the previous section and elsewhere (Jones *et al.*, 1985; Wigley and Jones, 1988; Jones *et al.*, 1989) we have detailed the methods used to ensure this homogeneity.

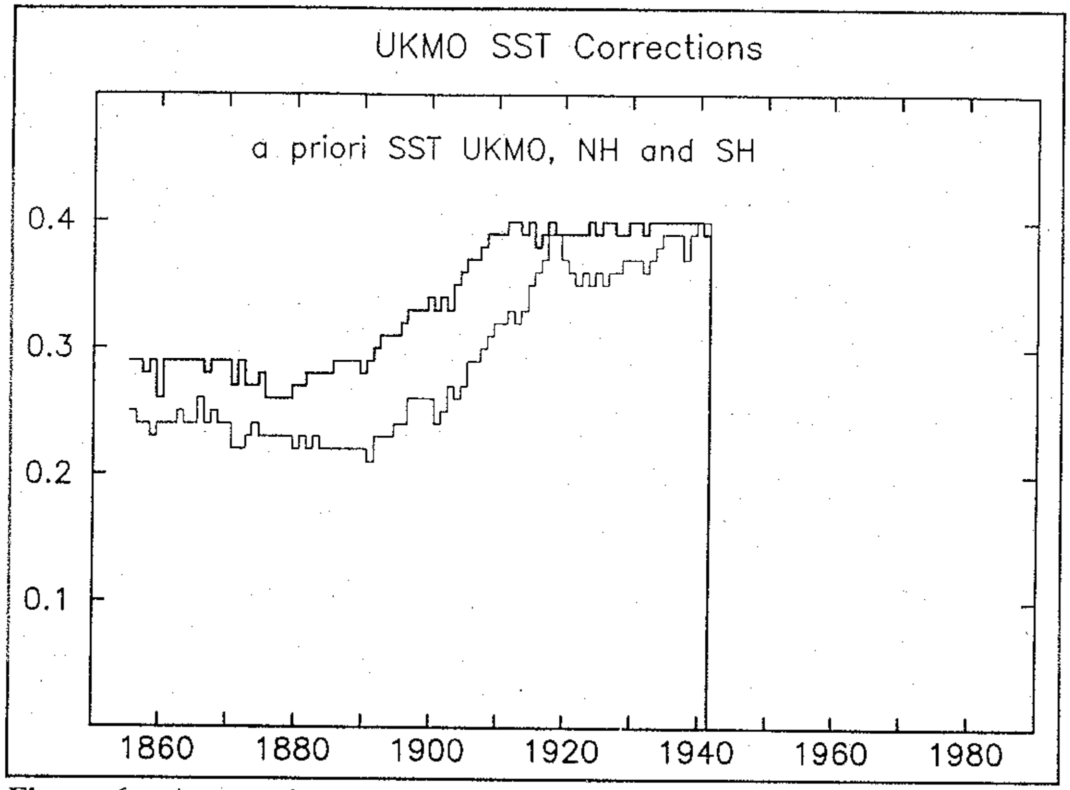

Figure 6. Average hemispheric correction between 1856 and 1941 using the Folland and Parker (1989a,b) bucket model.

In Jones *et al.* (1986d), 15 different regions of the world were chosen where both MAT (COADS) measurements and adjoining coastal and island data from the land-based data exist. Both types of measurement purport to measure the same quantity. In addition to these 15 region-by-region comparisons, the two hemispheric-mean MAT series (for the NH and SH) were compared with the appropriate means of the coastal and island temperatures from the land data set. The similarity of all 17 annual-difference time series implied that the MAT data were affected by consistent inhomogeneities, which were similar in both hemispheres. Corrections to the MAT data are derived from the hemispheric differences.

The same approach is used to correct the SST data. Hemispheric means of the uncorrected SST data and the corrected MAT data are compared. These show long periods of roughly constant differences which are similar in both hemispheres. The differences are presumed to relate to changes in SST instrumentation, and correction factors for SST are based on these differences. The basic character of the SST corrections derived this way is similar to that for the *a priori* corrections, with one important difference. Based on the *a posteriori* approach, the corrections required in the nineteenth century differ from those required between 1900 and 1940. We presume that this reflects the change over from (relatively well-insulated) wooden buckets to uninsulated canvas buckets, a presumption which is supported by historical evidence on instrumentation. Although one could account for this using the *a priori* method, this has not yet been done. It would be quite difficult to do because the quality of the nineteenth-century data is insufficient to pin down an exposure time with any confidence. This point is discussed further below.

Here we repeat part of the *a posteriori* correction exercise with the UKMO NMAT and SST data. In Jones *et al.* (1986d) we compared both the differences between NMAT and coastal land data for both 15 regions where the two data sets overlap and for the hemispheric averages. Here, simply for comparative purposes we use the hemispheric differences. The differences between hemispheric NMAT and the coastal and island hemispheric estimates are shown in Fig. 7. When this figure is compared with the corresponding result using the COADS data (Jones *et al.*, 1986d, Fig. 2), there are marked differences in the Southern Hemisphere during the nineteenth century. Such differences were to be expected, however, given the difference between the COADS MAT and UKMO NMAT data shown in Fig. 3. Using UKMO NMAT there is a clear discrepancy between the implied corrections necessary for the NMAT data in the two hemispheres. This was not evident for the COADS MAT data used by Jones *et al.* (1986d).

The corrections which must be applied to the NMAT data are +0.08°C over 1903-41, – 0.59°C (– 0.32°C in SH) over 1874-89 and – 0.44°C (– 0.36°C in SH) over 1861-73. During the war period of 1942-45 there is again a difference between the hemispheres of – 0.81°C in NH and – 0.56°C in SH. This, however, also occurs with the COADS data and can be readily explained (see, e.g., Jones *et al.*, 1986d). Over the period 1890 and 1902, a gradual change between the two correction levels is necessary. Although the corrections are similar to the COADS corrections derived by Jones *et al.* (1986d), there are differences (as noted above, and in addition) which reflect the differences inherent in Fig. 3. However, the times of transition between different correction factors are the same, even though these have been estimated independently.

Possible reasons for the MAT corrections have been given by Jones *et al.* (1986d). The corrections required during the nineteenth century might imply that the screens were poorly exposed or that they were not used at all. With the UKMO data it can also be argued that the NMAT data are contaminated by a higher percentage of daytime MAT observations than during the twentieth century. The difference between the two implied hemispheric corrections for NMAT arises partly from the fact that NMAT has been shown to be erroneously warm in the Mediterranean Sea and North Indian Ocean between 1876 and 1893 (Folland and Parker, 1989b).

Once the NMAT data have been corrected, it is a simple matter to correct the SST by comparison with the corrected NMAT. The implied SST corrections necessary to ensure compatibility with the NMAT series are: 1903-41, + 0.45°C (+ 0.40° in the SH) and 1856-89, + 0.10°C. No correction is necessary for the data after 1941. As with NMAT, gradual changes take place between 1890 and 1902. A value between 0.40 and 0.45°C between 1903 and 1941 is consistent with the change from uninsulated bucket measurements to engine-intake readings. The value lies in the range 0.3-0.7°C, estimated for such a correction independently by James and Fox (1972), Barnett (1984) and Ramage (1984).

The corrections derived by the two methods, *a priori* and *a posteriori*, are compared in Figure 8. The implied corrections during the twentieth century are extremely similar. Both methods even agree in finding slightly lower average correction factors in the Southern Hemisphere compared to the Northern Hemisphere. The major difference between the methods occurs during the nineteenth century and is of the order 0.2°C between 1856 and 1889. The difference hinges entirely on the type of bucket used during the last century. Folland and Parker (1986; 1989a,b) have assumed that canvas buckets, which were undoubtedly in general use during the first half of the twentieth century, were also used in the nineteenth century. At the first international meeting in Brussels which set up the current system of marine data collection, it was recommended that wooden buckets should be used (Quetelet, 1853). It is also clear that wooden buckets were in use around this time and probably for some time subsequently (Maury, 1855). This is also supported

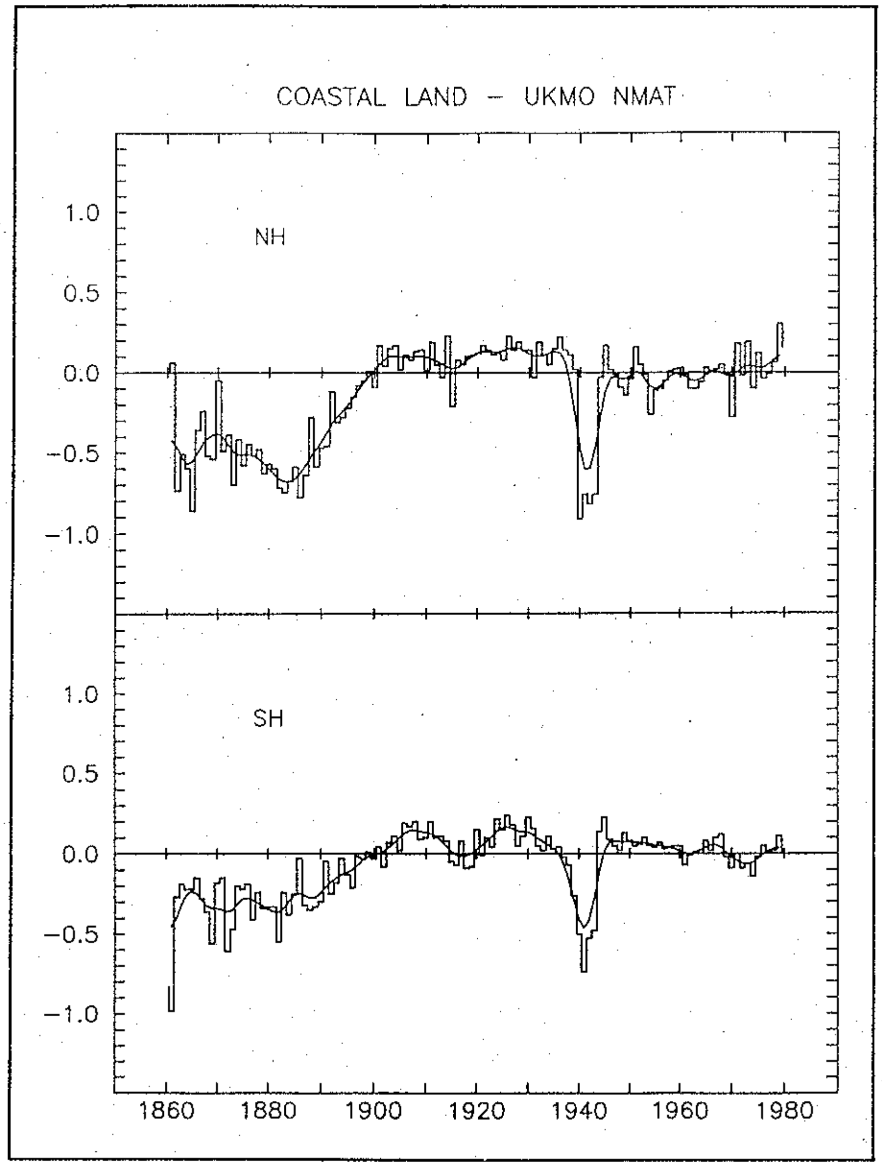

Figure 7. Difference between hemispheric estimates made using NMAT and those made using coastal and island temperature data from the Jones *et al.* (1986a,b) land-based data set.

by Krummel (1907), who refers to the canvas bucket as being a recent innovation. It is thus likely that there was a mix of bucket types in use during the nineteenth century, with a transition to a preponderance of canvas buckets probably occurring over the last few decades of the nineteenth century. Both wooden and tin buckets (which might also have been used) are considerably better insulated than their canvas counterparts and would not be affected as much by evaporative cooling.

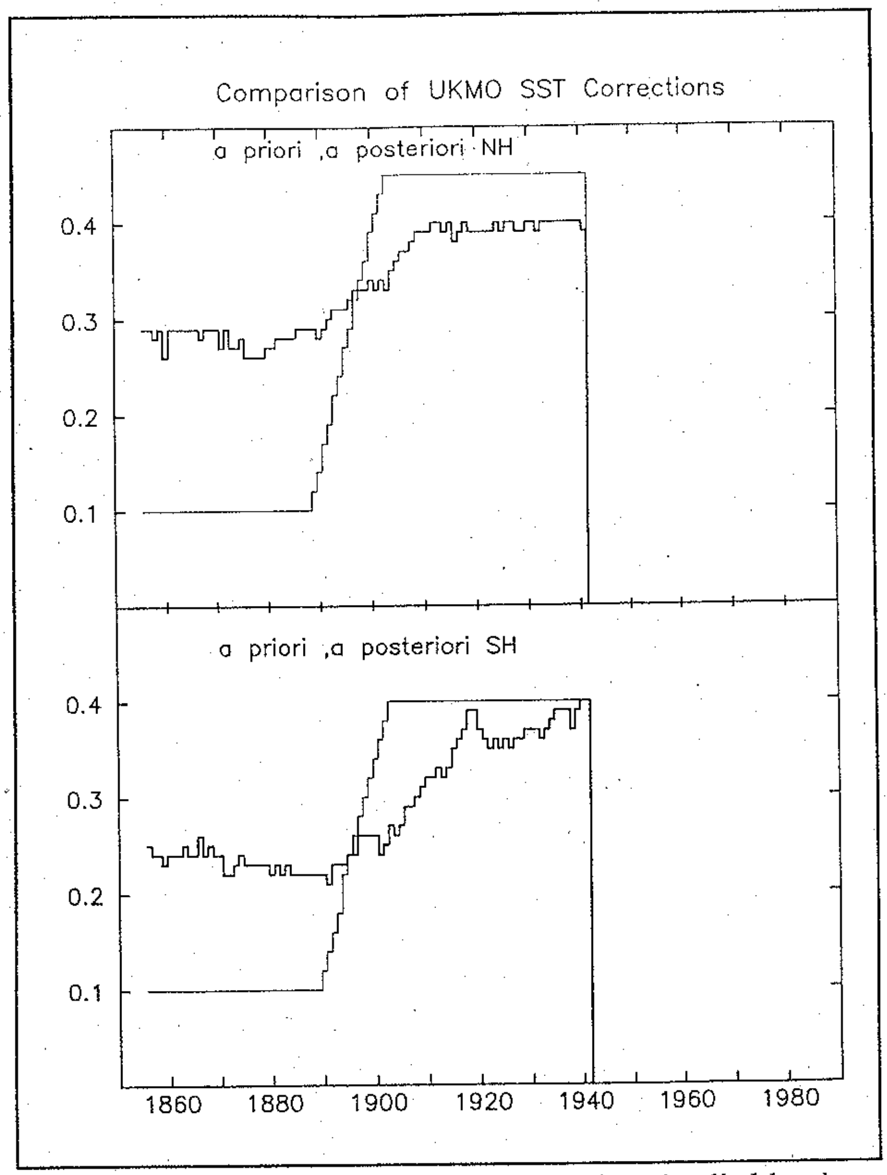

Figure 8. Comparison between the corrections implied by the *a priori* (Fig. 6) and *a posteriori* approaches.

4. REGIONAL TEMPERATURE CHANGES

Figures 1 and 2 show time series of hemispheric-average temperatures based on the three data sets discussed earlier J, HL and V. Clearly, not all regions show the same fluctuations, and there are important spatial differences. Here we will show spatial patterns of the linear trend in annual-mean temperature over the two major warming periods in the global-mean temperature record, 1967–86 and 1920–39 (Figs. 9 and 10, respectively).

The maps combine land-based estimates from the J data set and marine data from COADS (MAT). The choice of MAT rather than SST is somewhat arbitrary. There is excellent agreement between anomaly patterns of MAT and SST, as has been shown by

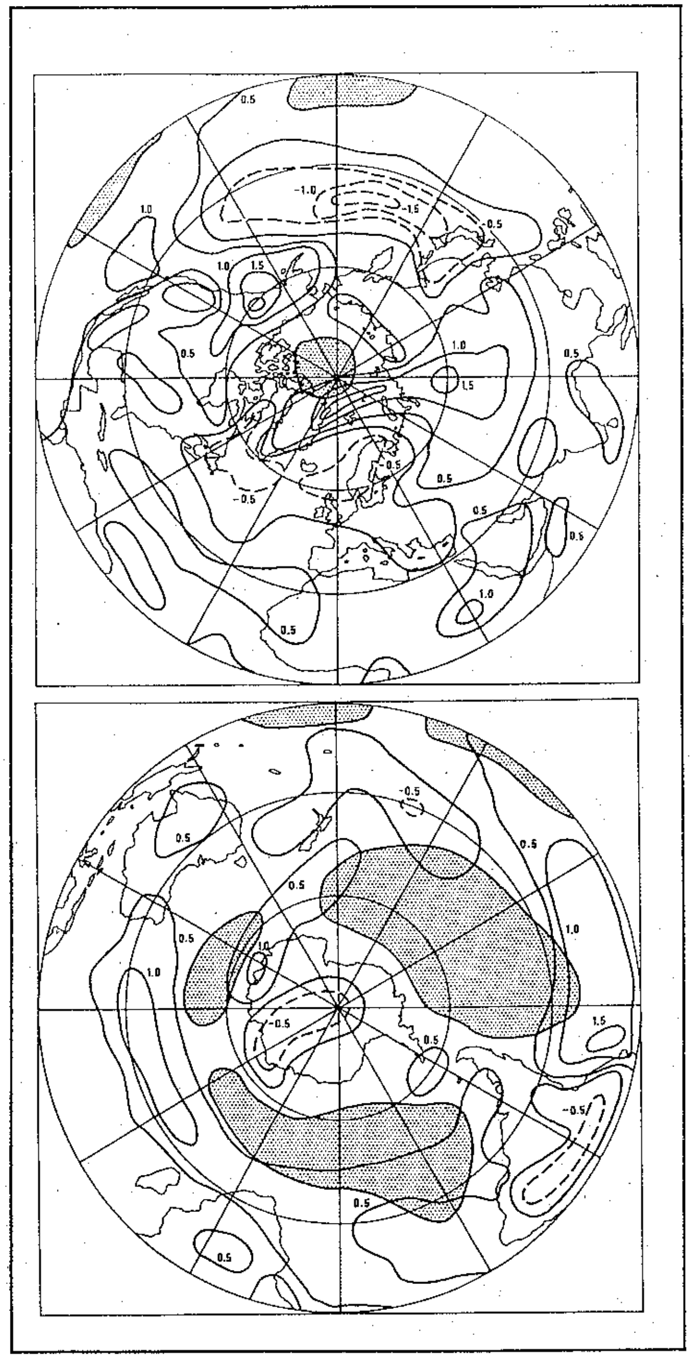

Figure 9. Change in temperature (°C) over 1967–86 accounted for by a linear trend fitted to each annual gridpoint time series. Calculations over the oceanic areas are made using COADS MAT data. Shading indicates areas with no data.

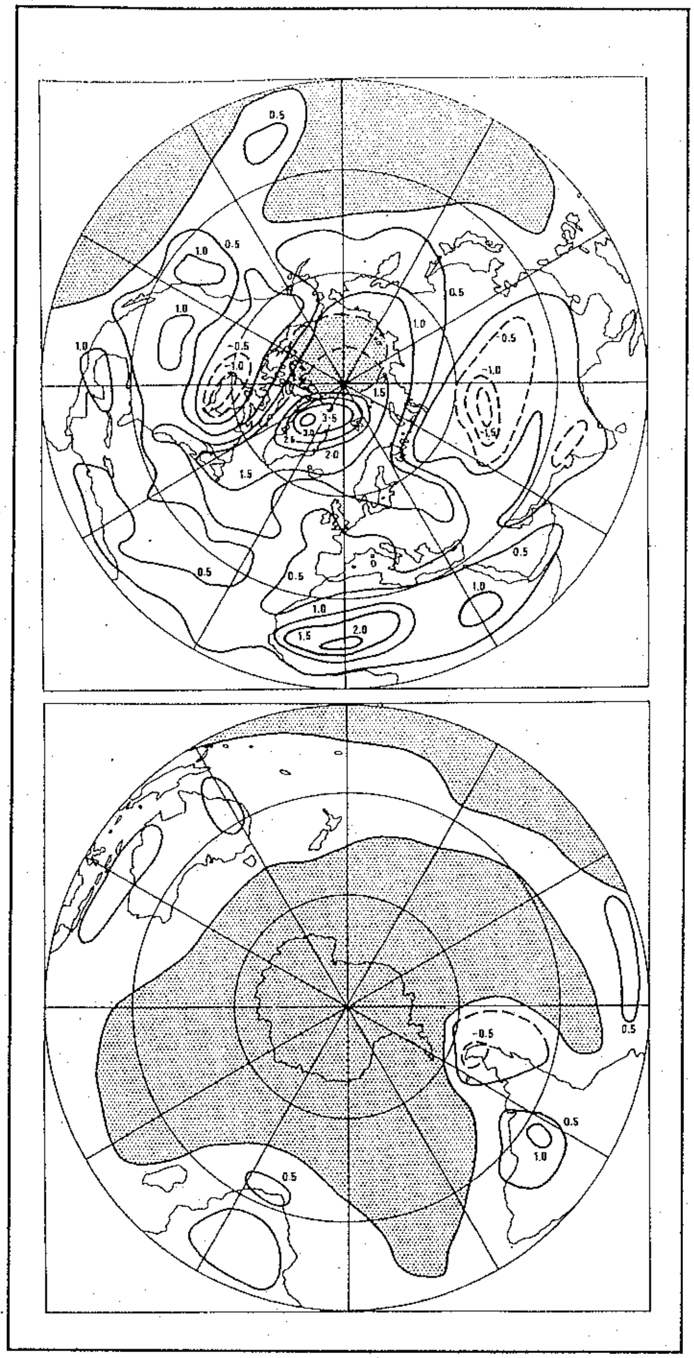

Figure 10. Change in temperature (°C) over 1920–39 accounted for by a linear trend fitted to each annual gridpoint time series. Calculations over the oceanic areas are made using COADS MAT data. Shading indicates areas with no data.

other workers (Cayan, 1980; Barnett, 1984; Jones *et al.*, 1988), and our own comparisons confirm this. Similar trend maps to those presented here have been calculated using land (J) and marine (UKMO SST) data by Jones *et al.* (1988) for the 1947–86 period. Trend maps based only on land data have also been produced by van Loon and Williams (1976a,b; 1977), Jones and Kelly (1983), Mo and van Loon (1985) and Hansen and Lebedeff (1987).

In the last section we saw that marine data are considered usable without correction only over the past 40 years. Prior to this, spatially and seasonally varying corrections are required and, furthermore, coverage is particularly poor during 1940–45. This does not mean, however, that we need to confine ourselves to periods since 1946. Provided we choose periods between the major changes in marine instrumentation and observation practices we can produce meaningful results. The period 1920–39, between the two world wars, is one in which a correction to the marine data is required, but over which the correction is thought to have remained relatively constant (Jones *et al.*, 1986d; Bottomley *et al.*, 1990). Another period which could be chosen is the 1861–1889 period. Periods which would not be appropriate are 1889 to 1905 and any period encompassing 1940–45.

Over the Northern Hemisphere between 1967–86 (Fig. 9), cooling is confined mainly to two regions, the northern halves of the North Pacific and North Atlantic Oceans. The cooling areas extend over the adjacent coasts to cover Japan, northwestern Europe, Iceland and the maritime states in Canada. Elsewhere, warming dominates and is strongest over the Soviet Union (particularly Siberia), western North America (particularly Alaska and the Yukon), and parts of North Africa. Warming is also evident over the eastern equatorial Pacific, the central Atlantic and the Indian Oceans.

Coverage over the Southern Hemisphere is poorer than in the Northern Hemisphere, with inadequate data over much of the 45–60°S zone and in the southeastern Pacific except near the South American coast. Warming tends to dominate. There are only three small areas of cooling, the largest of which is centred on the Amazon Basin. Warming is strongest, and the most significant statistically, over the eastern equatorial Pacific Ocean and over other mid-latitude (20–40°S) zones of the Atlantic and Indian Oceans.

Figure 10 shows patterns of temperature change over the period 1920–39. The most notable feature is the markedly poorer coverage during the period, particularly over the Southern Hemisphere where, apart from southern South America, there are no data south of 40°S. Coverage is also poorer over the North Pacific Ocean, except for the shipping route from North America to Australia via Hawaii.

The pattern of temperature change over the Northern Hemisphere between 1920 and 1939 shows the strongest warming over the entire North Atlantic basin extending over Europe, North Africa and the United States. Warming is strongest over Greenland, Sahelian Africa and the United States. The warming during this period over the North Atlantic basin is in striking contrast to the 1967–86 picture. Cooling affects two main areas, central Asia from western Siberia to southern China, and central northern Canada from Hudson Bay to southern Alaska. Over the Southern Hemisphere, warming tends to dominate over the tropical oceans. Cooling is found only over the southern half of South America.

5. CONCLUSIONS

Comparison of the MAT and SST data in the two main marine data banks, UKMO and COADS, has shown that the two data sets are not the same, as might have been believed from their large common data source. Although the differences (0.1–0.2°C in terms of hemispheric averages) may appear small, they are particularly important in the context of the overall global warming trend over the last 100 years (0.5°C).

The necessity of applying some form of correction to both types of marine data, MAT and SST, was illustrated by simply plotting the differences between the hemispheric means of these two variables (Fig. 5). The two major approaches that have been used to quantify the degree of correction required were compared. The *a priori* approach makes assumptions about the main sources of inhomogeneities in MAT and SST data and makes appropriate corrections using physical reasoning and models. The *a posteriori* approach, on the other hand, makes corrections to ensure conformity with the land data over common regions. The homogeneity of the land data has been previously assessed using independent methods.

Comparison of the correction factors for SST data on a hemispheric basis shows that they are in excellent agreement during the early twentieth century (1900–41). During the nineteenth century, the two methods differ, with the *a priori* approach implying, on average, an additional 0.2°C correction and producing warmer corrected data. The reason for this difference appears to be related to the types of bucket used during the nineteenth century. The *a priori* calculations carried out by Folland and Parker (1989a,b) and Bottomley *et al.* (1990) assume that the predominant bucket type in the nineteenth century was as in the 1900–41 period, viz. uninsulated canvas buckets. More likely, a mix of wooden, tin and canvas buckets was used, making a smaller hemispheric correction necessary. Although, in application, the *a priori* approach has produced results that are probably too warm in the nineteenth century, the method is clearly superior in that it is essential in order to derive regional and seasonally specific correction factors.

In the final section of this paper, the land and marine data have been used to derive and compare the spatial patterns of temperature change over two periods, 1920–39 and 1967–86. These periods cover the two main global warming episodes this century. Although warming dominates, the patterns of temperature change over the Northern Hemisphere in both periods show two large areas of cooling. These are not the same regions, however, and the cooling areas are considerably larger during the 1967–86 period. The contrast in trends over the North Atlantic is particularly striking.

ACKNOWLEDGEMENTS

This work was supported by the United States Department of Energy, Carbon Dioxide Research Division under grant No. DE-FG02-86ER60397 and United Kingdom Natural Environment Research Council Grant GR3/6565. Special thanks go to C. K. Folland and D. E. Parker of the U.K. Meteorological Office for permission to use the Meteorological Office marine data bank.

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