In the Gradual Southern Hemisphere case (run 6), the Northern Hemisphere response is again about the same as in the control. Although the response is slightly less in year 2, it is larger in years 3 and 4 because the forcing at lower latitudes makes the effects last longer through ocean cooling. In this case, we see maximum cooling of about 8 °C in the tropics, and much smaller cooling in the Southern Hemisphere. The smaller Southern Hemisphere effect is caused by the much larger thermal inertia due to the much larger percentage of oceans in this hemisphere, as well as the lack of land in the high mid-latitudes on which to produce a snow/albedo feedback. This effect is illustrated in run 7, where the forcing is the same at all latitudes, but the response is much less in the Southern Hemisphere. This is partly because the forcing started in Southern Hemisphere winter. A global run starting in Southern Hemisphere summer (not shown here) produced about the same response in the Southern as in the Northern Hemisphere. The larger Southern Hemisphere thermal inertia almost exactly compensated for the larger forcing.

The effects of using the severe 10,000 MT forcing[1] are shown in run 8. The results during the first year are virtually the same as in the control case, with the maximum cooling not even 2 °C larger. The dramatic difference comes in the second year, where the snow/albedo feedback produces a cooling of more than 16 °C during the summer 1 yr after the war begins. The effects persist for several years after this, with year 4 in this case resembling year 2 in the control case. Although this result is almost a 'worst case' scenario (more latitudinal spread would make it even worse), it should receive serious consideration[1] because it is plausible. Run 9 shows that even the smaller 100 MT–city attack can have virtually the same effects as the control case, in agreement with Turco *et al*[1].

These experiments show that the climatic effects of a nuclear war might persist longer than previously calculated. The use of a model which includes snow and ice feedbacks and ocean response shows that the effects can be large even 1 yr after the war begins. Latitudinal spread of the nuclear smoke and dust can produce large cooling in the tropics where life is more sensitive to cooling due to the absence of a natural seasonal cycle[7], but the cooling there is not as large as would be expected from a global average model.

The results presented here must be considered as preliminary, since the climate model used cannot consider many of the complex interactions that might result. These include the dynamical and radiative interactions between the atmospheric circulation and the smoke, the possibly patchy nature of the smoke distribution, long-wave radiative interactions, ocean circulation and mixed-layer depth responses, atmospheric hydrological cycle responses (including changes in cloudiness and changes in washout rates due to changes in precipitation), the effects of considering diurnal solar forcing (R. Cess, personal communication), and the effects of placing dust over the smoke rather than having them evenly mixed[19]. What the initial distribution of smoke and dust would be is also not well known and depends on untested assumptions about numbers and sizes of fires, number of particles produced per fire, initial rainout and washout, particle size distribution and coagulation rates, vertical distribution, targeting strategies and initial weather conditions. All these processes must be included to produce realistic results. In the absence of proof that these assumptions would drastically change the results, the prospect of a nuclear winter following virtually any scenario for a nuclear war must be taken very seriously.

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Worldwide marine temperature fluctuations 1856–1981

C. K. Folland, D. E. Parker & F. E. Kates

Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ, UK

Paltridge and Woodruff[1] found a warming of global mean sea-surface temperatures (SSTs) of ~1 °C in the first half of the present century, but there are doubts about its reality because spurious temperature fluctuations can arise from changes in measuring instruments[2,3] and because inter-annual fluctuations may contain sufficient variance to allow the observed inter-decadal variations to fall within the limits of sampling error of a stationary series[3]. We present here the results of analyses of worldwide SSTs and night near-surface marine air temperature (MAT) for the period 1856–1981 with the aim of estimating the magnitudes of recent climatic fluctuations of temperature at the ocean surface, taking account of changes in observing procedures. Our results show a worldwide temperature fluctuation of range ≃0.6 °C (in broad agreement with a preliminary analysis of global SST[2]), with the coldest period being centred around 1905–10 and the warmest occurring in the 1940s. The fluctuation has a similar magnitude to, and is nearly in phase with, climatic warmings and coolings near the surface of the Northern Hemisphere land masses for the period after 1900. Before 1900 the trends are sharply different.

The data (46 million non-duplicated SST data and 24 million non-duplicated night MAT data) were derived from the Meteorological Office Main Marine Data Bank[4]. Observations departing from the whole-period normal by more than ±6 °C for SST and ±10 °C for MAT were rejected. Relaxation of the limits for SST to ±9 °C had little effect even in areas of high natural variability. The observations were composited into

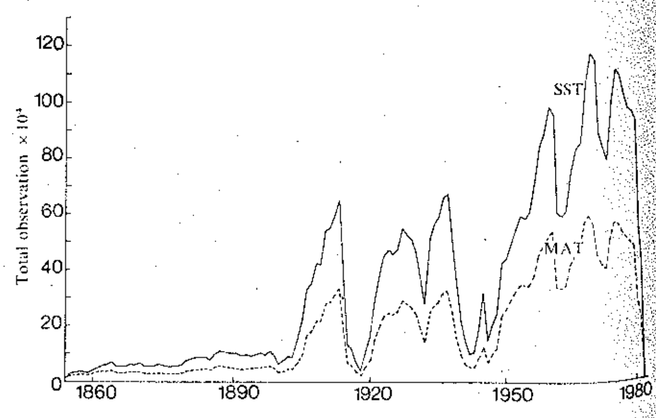

Fig. 1 Annual numbers of marine temperature observations for the globe. SST, sea-surface temperature; MAT, nighttime marine air temperature.

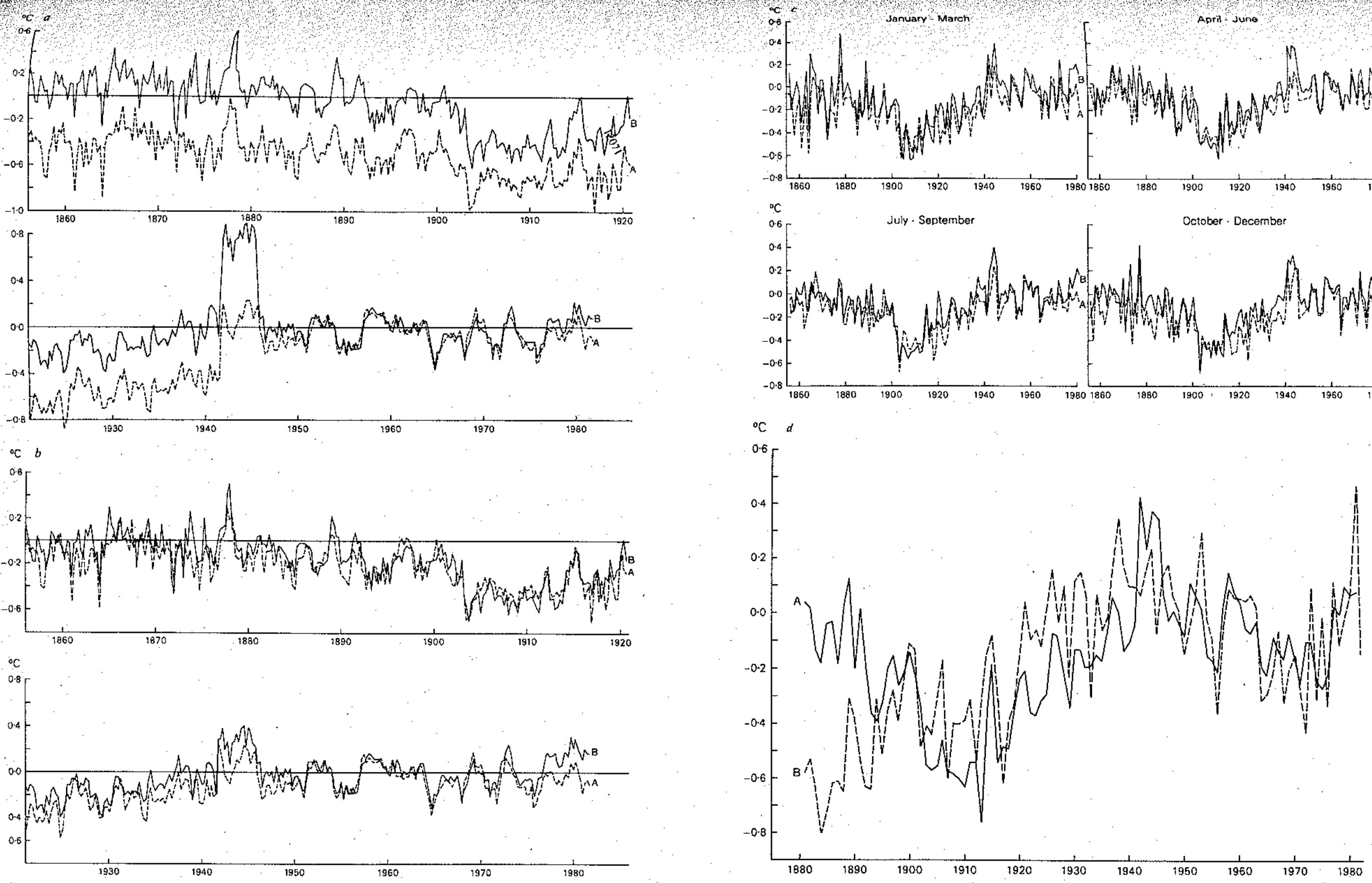

Fig. 2 *a*, Uncorrected anomalies (relative to 1951–60) of: A, global sea-surface temperature; and B, nightime marine air temperature. *b*, Corrected anomalies (relative to 1951–60) of: A, global sea-surface temperature; and B, global nighttime marine air temperature. *c*, Corrected anomalies (relative to 1951–60) of: A, global sea-surface temperature, and B, global nighttime marine air temperature, for the seasons taken separately. *d*, Annual anomalies (relative to 1951–60) for the Northern Hemisphere of: A corrected nighttime marine air temperature; and B, mainly land temperature after ref. 17.

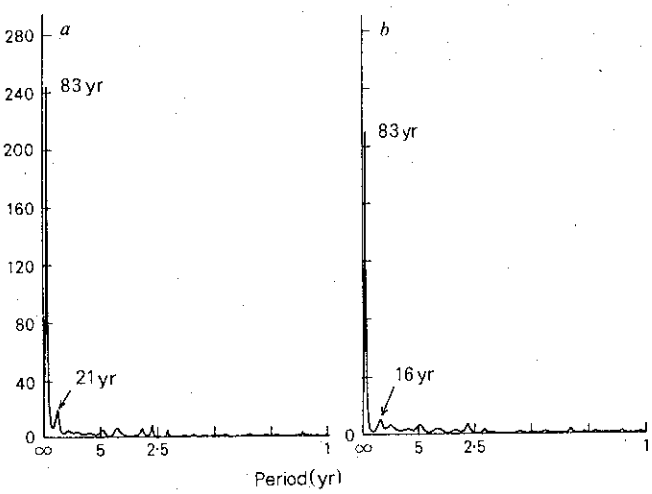

Fig. 3 Maximum entropy power spectra of corrected global seasonal marine air temperature (a) and sea-surface temperature (b), 1861–1980.

monthly anomalies from the 1951–60 normal for 5°×5° grid areas, taking account of the uneven spatial distribution of observations and also the space–time variations of the climatological average within each area. Areas with insufficient observations for these processes were omitted. Some areas of the Pacific with data missing in the 1960s were filled, after further quality control, with analysed data obtained from the Massachusetts Institute of Technology (MIT) (J. Hsiung, unpublished data). Note that the analysis of SST reported in ref. 2 used about 40 million data including some duplicates.

Daytime MAT observations on board ship are known to be affected by solar heating of the ship's fabric[5–9]. Therefore, only MAT at night (solar elevation <0°) was used. Local environmental effects cause MAT to be relatively too warm early in the night and slightly too cool later on[9], so that night MAT as a whole has little bias. The MIT data, being daily averages, could not be inserted into the night MAT data sets, but comparisons between SST and night MAT for the Pacific for the 1960s indicate that the gaps in night MAT will not prejudice conclusions on large-scale changes. Because of the gaps, the shorter reference period 1951–60, rather than a longer period, such as 1951–80, was used to calculate SST and MAT anomalies; the general characteristics of the time series of anomalies were found to be unaffected by this choice.

Figure 1 shows the annual numbers of SST and night MAT observations used. Note the reduction during the world wars. Graphs (not shown) for individual oceans are similar but there are more Northern Hemisphere than Southern Hemisphere data after 1880. Global coverage, measured as an areally weighted proportion of grid areas with monthly data, averaged 20% before 1900, nearly 60% between the world wars and over 80% in the 1970s. Monthly grid area anomalies were averaged over successive 3-month periods (January–March and so on) and the results averaged globally with appropriate areal weighting. These global 'seasonal' averages, uncorrected for changing instrumental and procedural biases, are presented sequentially in Fig. 2a. The SST and night MAT cyrves are not parallel and demonstrate the need to investigate instrumental and procedural changes.

The night MAT data are affected by the gradual increase in average elevation of thermometer screens above the sea from ~6 m before 1900 to >20 m in the most recent years (R. C. Cameron, personal communication) as ships increased in size. Corrections to reduce temperatures to the mean screen elevation (15 m) considered appropriate during 1951–60 were computed using atmospheric surface boundary layer similarity theory[10], with an estimated global average Richardson number $Ri=-0.01$. This value was deduced from (1) monthly average fields of approximate air–sea-temperature differences, computed from night MAT and estimated night SST data with the aid of published data on the diurnal range of SST[11] and including a first-guess adjustment to MAT for changes in screen height; (2) a globally-averaged wind speed. The corrections were found to be insensitive to likely uncertainties in the value of Ri. The marine surface air layer is, on average, superadiabatic: the corrections to MAT reflect this and are: up to 1900, −0.13 °C; 1901–15, −0.07 °C; 1916–60, 0.0 °C; 1961–70, +0.02 °C; 1971–75, +0.06 °C; 1976–81, +0.09 °C.

The extreme warmth in night MAT between 1942 and 1945 (Fig. 2a) merits investigation, especially as the SST series did not behave similarly. Comparison of sequences of day and night MAT during World War 2 showed that the warm episode was much less marked by day. The reason is thought to be that it was forbidden, at least on UK ships, to shine a torch in an exposed place, so night MAT was observed well in-board, with consequential larger heating errors (G. V. Mackie, personal communication). Daytime MAT was observed normally and was thus unaffected. The small peak in daytime MAT around 1942–45 may have been connected with the Southern Oscillation: there was a strong El Niño in 1940–41[12,13]. Adjustments to night MAT were made assuming homogeneity of wartime day MAT, as follows: −0.1 °C for April 1940 to the end of 1941; −0.5 °C for January 1942 to September 1945, a period having more belligerents.

The change from uninsulated bucket measurements of SST to chiefly engine intake measurements seems to have taken place around the beginning of World War 2. Since World War 2, however, insulated buckets have been used extensively[14], and in recent years globally-averaged SSTs derived from buckets and from engine intake probes appear from our own researches to differ by <0.1 °C. Early investigations using uninsulated buckets[15,16] suggest that SST data derived from these instruments are likely to be depressed below their true magnitudes because of the cooling effect of evaporation from the wet walls. Thus the pre-World War 2 SST data require a positive correction to make them homogeneous with the 1951–60 reference period, whereas corrections to later SST data are likely to be small. We have used the corrected night MAT data as a reference and find that this yields a single positive correction of 0.3 °C to the globally-averaged SST data before April 1940, a slightly smaller correction of 0.25 °C between April 1940 and December 1941, and zero correction thereafter. This provides a consistent set of curves of global SST and night MAT (Fig. 2b). Note, however, that for regional studies the SST corrections needed may vary with season, because of annual cycles of dewpoint depression and wind speed which determine the evaporative effects.

The mid-nineteenth century values appear close to those of the 1951–60 reference period; there is a gradual fall of 0.2 °C in the late nineteenth century followed by a sudden fall of about 0.3 °C shortly after 1900; the warming of almost 0.6 °C up to the 1940s is followed by a steady cooling of about 0.25 °C in MAT, but the warmest decade in SST is 1951–60. Renewed warming appears to have set in after the early 1970s. The three-month 'seasons' show similar sequences (Fig. 2c). Although the time-lag of the long period variations of SST behind those of MAT is greatest (>one decade) in the mid-twentieth century, it is not entirely absent in the earlier years. Except before 1900, the annual night MAT curve for the Northern Hemisphere is in good agreement with the annual Northern Hemisphere land curve presented by Jones *et al.*[17] (Fig. 2d). The reality and physical significance of the apparent slight time-lag of the MAT curve relative to the land curve should be investigated.

The sequences in Fig. 2b were subjected to analysis of variance to test for the significance of inter-decadal changes when compared with within-decade 'seasonal' fluctuations. The F-ratio of 55.6 for night MAT was considered to have only 5 decadal and 50 within-decade degrees of freedom because of autocorrelation in the data[18], but nonetheless has a probability of ≪0.1%, so

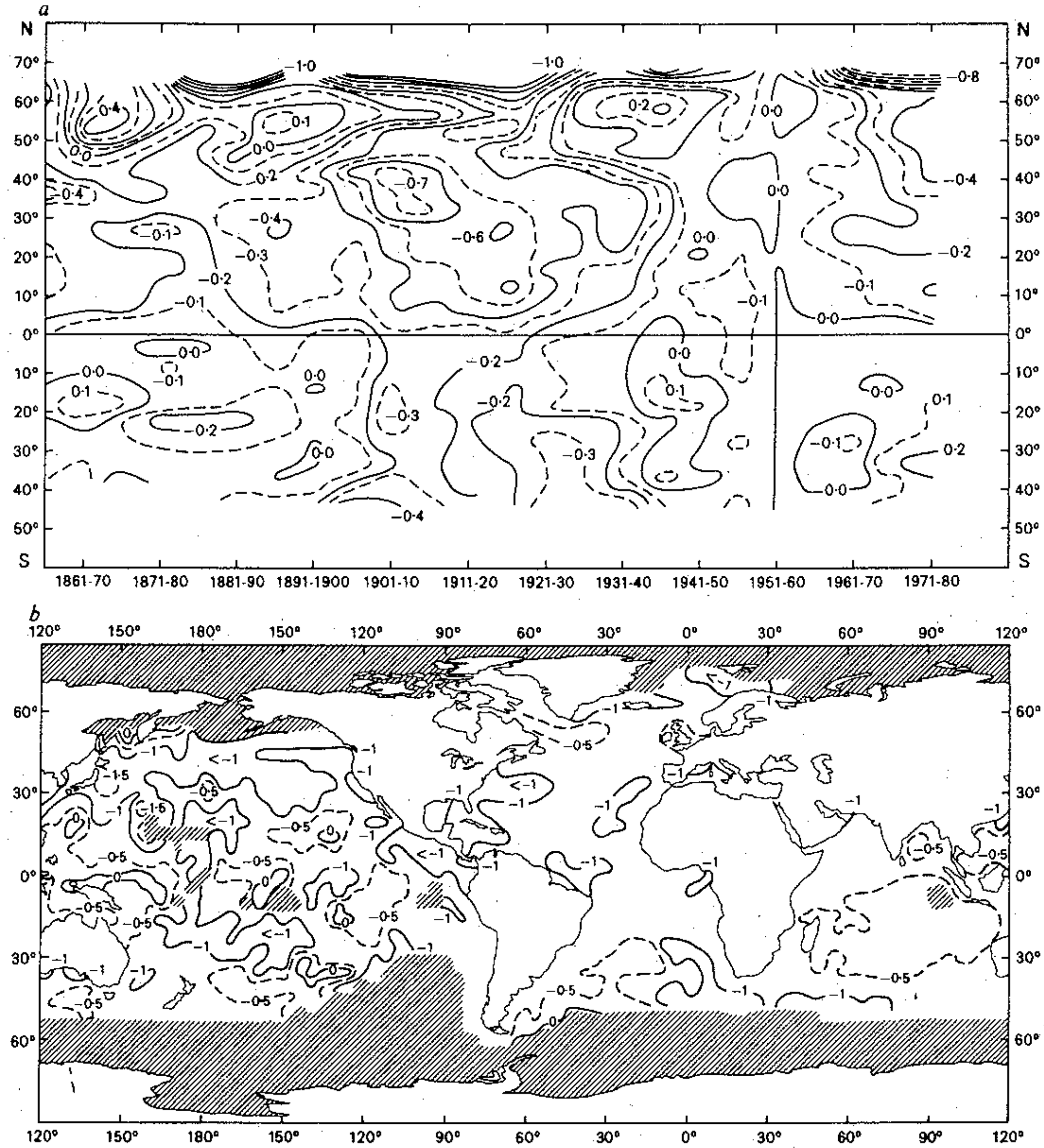

Fig. 4 *a*, Zonally-averaged sea-surface temperature anomalies (relative to 1951–60) (°C). Values are for 5-yearly overlapping decades and are corrected for instrumental changes. *b*, Corrected decadal sea-surface temperature for 1903–12 relative to 1951–60 (°C). Hatching denotes missing data.

the null hypothesis of no inter-decadal climatic variation must be rejected confidently. Similar results hold for SST (*F*-ratio of 45.7 with 4 decadal and 44 within-decade degrees of freedom: probability $\ll 0.1\%$).

Detrended maximum entropy power spectral analyses on the sequences in Fig. 2*b* (Fig. 3*a*, *b*) both show a dominant peak at a period of 83 yr, expressing the major climatic fluctuation visible in Fig. 2*b*. Minor peaks at periods in the range 3–5 yr appear, according to work in progress, to be associated with the Southern Oscillation. An analysis (not shown) of Northern Hemisphere SST over the period 1945–80, when the long time scale climatic fluctuation was weak, shows fluctuations on a dominant time scale of 8–10 yr.

Figure 4*a* presents a latitude–time section of zonally-meaned corrected SST from 65° N to 45° S. The major climatic fluctuation in the first half of the present century occurred simultaneously in both hemispheres but with greater amplitude in the Northern Hemisphere. The mid-latitudes of the two hemispheres now appear to be fluctuating out of phase, as they were to some extent before 1900. MAT gives quite similar results.

Figure 4*b* shows fields of difference in corrected SST between the globally warmest decade (1951–60) (anomaly 0.0 °C) and the coldest (1903–12) (anomaly −0.44 °C). The worldwide nature of the major fluctuations is clear. The corresponding warmest and coldest decades for night MAT are probably 1940–49 (anomaly 0.11 °C) and more definitely 1903–12 (anomaly −0.50 °C).

We consider that our results are the best estimates hitherto made of global climatic fluctuations of temperature at the ocean surface. They should provide valuable clues to the mechanisms of climatic change.

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