Global temperature variations between 1861 and 1984

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Recent homogenized near-surface temperature data over the land and oceans of both hemispheres during the past 130 years are combined to produce the first comprehensive estimates of global mean temperature. The results show little trend in the nineteenth century, marked warming to 1940, relatively steady conditions to the mid-1970s and a subsequent rapid warming. The warmest 3 years have all occurred in the 1980s.

GLOBAL mean surface air temperature is the most commonly used measure of the state of the climate system. When general issues of climatic change are addressed, global mean temperature change is often used as a yardstick; the age of the dinosaurs was warmer than today, the ice ages were colder, and so on. Paradoxically, in the present era of instrumental meteorology, with data coverage far better than at any earlier time, our knowledge of global mean temperature changes is still uncertain. Variations in global mean air temperature are of considerable importance, as they are a measure of the sensitivity of the climate system to external forcing factors such as changes in carbon dioxide concentration, solar output and the frequency of explosive volcanic eruptions. Quantifying the response of the climate to external forcing changes is a major goal of climatology and a prerequisite for predicting future climatic change. As a step towards this goal, we present here the first global synthesis of near-surface temperature measurements over the land and oceans.

Most earlier estimates of global and hemispheric mean temperature (see refs 1, 2) were based solely on data from land-based meteorological stations. Since >70% of the globe is ocean, one might suspect the global representativeness of such estimates, although on long timescales (≥decades) the thermal coupling between land and ocean should ensure that the land data largely mirror changes occurring over the oceans[1]. Recently, data from ships at sea collected for routine weather forecasting purposes, have been compiled by groups in the United Kingdom[3,4] and the United States[5,6], and these data give us the potential to calculate improved estimates of global mean temperature. Apart from our own work[7], the only previous attempt to analyse both land and marine data is that of Paltridge and Woodruff[8,9]. These authors, however, failed to account for inhomogeneities in the marine data, which are substantial (see below and also refs 4 and 10). The quality and coverage of the land data they used was also less than adequate, but this is understandable because they were primarily interested in sea-surface temperature variations.

The land data we use are those from refs 11, 12. These have been carefully examined to detect and correct for non-climatic errors that may result from station shifts or instrument changes, changes in the methods used for calculating means, urban warming, and so on. Although problems still exist[13,14], the quality of these data is much better than that of material used in earlier studies. Area averages based on these data show medium to long timescale trends (≥10 yr) whose spatial consistency provides a strong pointer to the data's overall reliability[1,11,12]. The marine data we employ are those in the COADS (Comprehensive Ocean Atmosphere Data Set) compilation[6] which extends to 1979, and data from the Climate Analysis Center, NOAA, for 1980–84. We use both sea surface temperatures (SST) and marine air temperatures (MAT).

Marine data problems

Both SST and MAT data contain 'inhomogeneities', variations resulting from non-climatic factors[4,10,15]. For example, early SSTs were measured using water collected in uninsulated, canvas buckets, while more recent data come either from insulated bucket or cooling water intake measurements, with the latter considered to be 0.3–0.7 °C warmer than uninsulated bucket measurements[10]. For marine air temperatures, changes in the size and speed of ships, especially those increases associated with the sail to steam transition, are both thought to have influenced data homogeneity. In addition, many early air temperature observations were not taken in screened locations. Because of these non-climatic factors, both SST and MAT data must be corrected (or 'homogenized') to remove their effects.

Folland *et al.*[4,16] and Folland and Kates[17], using the UK Meteorological Office (UKMO) data bank[3], attempted to overcome these problems by identifying specific sources of error, attempting to quantify these and using this information to make corrections to the raw gridded data. Such corrections have inherent uncertainties because of difficulties in their *a priori* quantification and a lack of knowledge of how most measurements were taken. Information on whether bucket or intake measurements were made has, in most cases, apparently been lost or never recorded. It has also been shown[18] that supposedly homogeneous (that is bucket-only or intake-only) SST data series appear to have non-climatic changes that are similar to those found in mixed data series, suggesting that all historical data sets contain a mix of measurement types. Since 1945, however, it is generally assumed that available SST data contain a reasonably consistent mix of intake and bucket measurements[18].

The Folland *et al.*[4] corrected MAT and SST series have been compared with averages of land-based data by Jones *et al.*[11,12]. Agreement is reasonable since the start of the twentieth century, although MAT values for the years 1942–45 appear to be too warm in both hemispheres. Before 1900, the marine and land series diverge markedly, with both marine series being about 0.3 °C warmer than the land data.

Correcting the COADS data

The COADS compilation contains some 63.25 million non-duplicated SST observations, of which 0.96 million have been 'trimmed' to remove extreme outliers[5]. While these are more data than in the UKMO SST set (which has about 46 million non-duplicated observations[4]), the effective area and density of coverage is very similar in both data sets. However, unlike the UKMO data set used by Folland *et al.*[4], none of the data in COADS have been corrected for non-climatic effects. Our first task, therefore, was to homogenize the COADS data. We did

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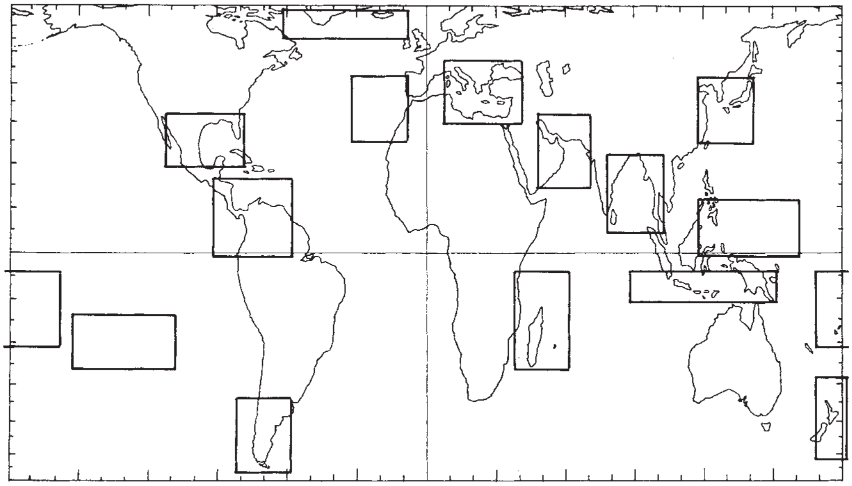

Fig. 1 Map showing the 15 regions where marine air temperatures and land-based temperatures were compared (Peters equal-area rectangular projection).

this by comparing marine and land data in areas where the two abut or overlap (coastal areas and around ocean islands).

The trimmed COADS data include monthly means and medians on a $2^\circ \times 2^\circ$ grid, together with the number of observations in a month and the mean observation date. We compressed the data onto a more manageable grid ($5^\circ \times 5^\circ$ for MAT, $4^\circ \times 10^\circ$ for SST) after first eliminating values where the number and distribution of observations was likely to have produced unrepresentative monthly means, and expressed the values as anomalies from a 1950–79 reference period. As a test of data quality at this stage we calculated hemispheric mean values by appropriately weighting the gridded MAT and SST data (NH, Northern Hemisphere; SH, Southern Hemisphere). Year-to-year variations for these uncorrected data were found to be in excellent agreement with the UKMO corrected data (NHSST, $r = 0.86$; NHMAT, $r = 0.87$; SHSST, $r = 0.88$; SHMAT, $r = 0.75$ over 1856–1979: correlation coefficients calculated using residuals from a 10-yr gaussian filter), but, as expected, the long-term (≥ 10 yr) fluctuations showed marked differences. Similar high frequency correlations between SST and MAT for the uncorrected COADS data (NH, $r = 0.91$; SH, $r = 0.89$) were higher than in the corrected UKMO data (NH, $r = 0.81$; SH, $r = 0.80$).

Because of the high SST–MAT correlation (see also ref. 19), SST data can be corrected by comparison with MAT data, once the latter have been corrected. For the MAT data, any attempt to assess, *a priori*, the magnitudes of errors arising from instrumental changes, changes in observation methods, and the effects of changes in ships' thermal inertia, speed and size (the latter determines the height at which observations were taken), must be fraught with uncertainty. Data reliability and long-term homogeneity can be far more convincingly demonstrated for the gridded land data than for the marine data because land station data homogeneities can be more easily identified, explained and corrected[11,12]. We therefore use these data directly to correct the marine data. Fifteen regions (see Fig. 1) were chosen in which land and marine data are in close proximity. Area averages of annual mean MAT and land air temperature were calculated for each region using the uncorrected COADS data and the homogenized land data produced by Jones *et al.*[11,12]. No attempt was made to consider night-time observations only, as used by Folland *et al.*[4]. In addition to the 15 pairs of area averages, annual mean coastal land time series were produced for both hemispheres and compared with the uncorrected hemispheric-mean MAT series.

The 17 land minus MAT time series were then examined for systematic differences between the land and marine data. For the period 1861–1979 (both marine and Southern Hemisphere land data are unrepresentative before 1861 because of poor data coverage), five distinct periods could be discerned in all 15 regional land minus MAT time series and in the two hemispheric land minus MAT time series. The latter are shown in Fig. 2. The three main periods are: the period up to the 1880s when the MAT data appear to be too warm by 0.4–0.5 °C; the period from the 1900s to 1941 when the MAT data are too cold by 0.1–0.2 °C; and 1946–79 when there is no obvious bias. There is a strong upward trend in the land-minus-MAT difference between the mid 1880s and the late 1900s, and the war years, 1942–45, are marked by anomalously warm MAT values. The consistency between the hemispheres is clear from Fig. 2, and the land minus MAT data for the individual smaller regions, although showing greater inter-annual variability, all show the same features.

The nineteenth century land minus MAT data also show differences between the values before and after about 1873 (see Fig. 2). By examining land, MAT and SST data it can be shown that this difference is also likely to reflect a non-climatic

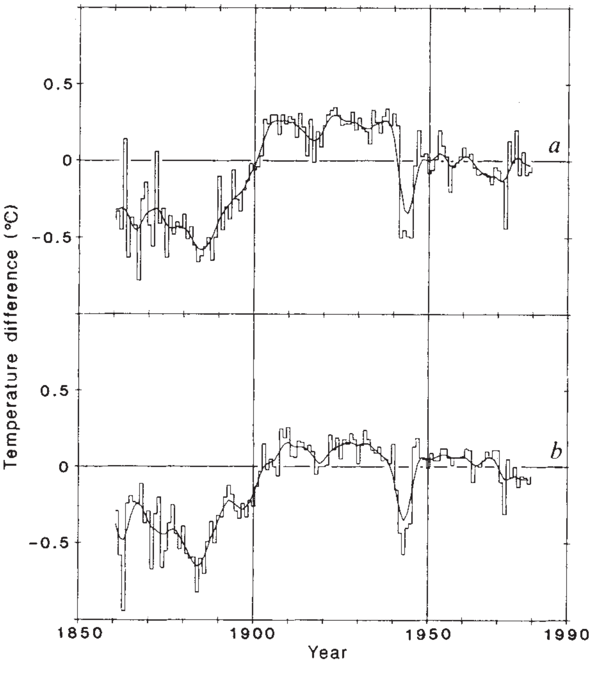

Fig. 2 Temperature differences: coastal land values minus uncorrected COADS marine air temperature values for the Northern (*a*) and Southern (*b*) Hemispheres. Smooth curves show 10-yr gaussian filtered values, padded at each end as described in ref. 11.

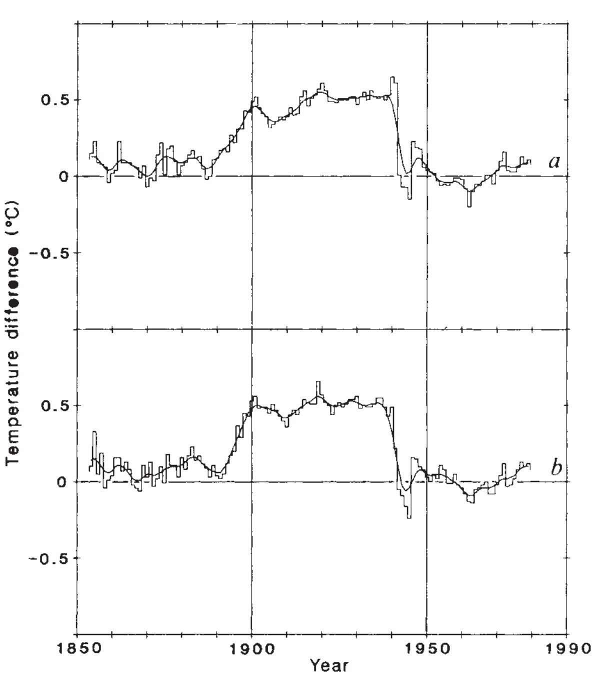

Fig. 3 Temperature differences: corrected marine air temperatures minus uncorrected sea surface temperatures for the Northern (a) and Southern (b) Hemispheres. Smooth curves show 10-yr gaussian filtered values.

inhomogeneity in either the MAT data or the land data, probably the former.

The means and standard deviations of the land minus MAT values are shown in Table 1. The consistency of these values strongly suggests that these land/MAT discrepancies are not climatic in origin. They may, therefore, be used to estimate annual correction factors for the MAT data in order to make these data compatible with the existing homogenized land data. Except for the 1942-45 period, when war conditions apparently prompted observers to measure temperature in unconventional locations[4], the specific reasons for these non-climatic MAT fluctuations are not known. Although their reality cannot be questioned, there is clearly some uncertainty in the magnitude of the implied corrections.

The correction values we have used (added to the raw MAT data) are (°C): 1861-73, −0.40; 1874-89, −0.48; 1903-41, 0.17; 1942-45, −0.54; 1946-79, 0.0; with linear interpolation between 1889 and 1903. Slightly different corrections were judged necessary for Southern Hemisphere data between 1941 and 1945: 1941, −0.14; 1942-45, −0.44. Most of the transition dates for these correction factors, which are based on a number of considerations, could be altered slightly with no appreciable effect on the resulting corrected MAT values. Although the 0.08 °C difference in the MAT corrections before and after 1873 may be inappropriate if it arises from a land data inhomogeneity, we judge this to be unlikely. It has the effect of slightly reducing the magnitude of the long-term MAT warming between the period before 1873 and today. The corrections generally reflect the mean land minus MAT values shown in Table 1, but the precise values used and the transition dates also take MAT-SST comparisons into account. Our corrections differ markedly from those applied by Folland *et al.*[4] to their night-time MAT data. This is a clear indication of incompatibilities between the corrected UKMO MAT data and the homogenized land data (see also refs 11 and 12).

Table 1 Comparison between coastal land and MAT data

		1861-73	1874-89	1903-41	1942-45	1946-79
NH	$\bar{X}$	−0.35	−0.50	0.23	−0.49	−0.02
	s	0.26	0.11	0.09	0.02	0.12
SH	$\bar{X}$	−0.36	−0.53	0.10	−0.44	0.03
	s	0.23	0.14	0.09	0.09	0.10
NH (9 region	$\bar{\bar{X}}$	−0.36	−0.42	0.17	−0.54	−0.03
average	$s(\bar{X})$	0.40	0.21	0.10	0.10	0.05
SH (6 region	$\bar{\bar{X}}$	−0.61	−0.52	0.17	−0.44	0.05
average	$s(\bar{X})$	0.57	0.36	0.22	0.15	0.08
Correction		−0.40	−0.48	0.17	−0.54	0.00

$\bar{X}$ = mean land minus MAT value; s = corresponding standard deviation defined by $s^2 = (Y-1)^{-1}\Sigma(X_j = \bar{X})^2$ where X_j is the value in year j, and Y is the number of years; $s(\bar{X})$ = standard deviation of the means defined by $(s(\bar{X}))^2 = (n-1)^{-1}\Sigma(\bar{X}_i - \bar{\bar{X}})^2$ where n is the number of regions (6 or 9), $\bar{X}_i$ is the mean for region i and $\bar{\bar{X}}$ is the average value of $\bar{X}_i$. The last line shows the inferred correction which was added to the uncorrected annual MAT data.

Having corrected the MAT data, we can now estimate the SST corrections required to ensure overall compatibility between the land, MAT and SST data by comparing the corrected MAT and raw SST values. Table 2 and Fig. 3 show the hemispheric mean differences between the corrected MAT data and the raw SST data. As with the MAT analysis, three distinct periods can be discerned: pre-1890 when the SST data are slightly but consistently cooler than the MAT data; 1903-41 when SSTs are markedly cooler than MATs; and post-1945 when there is no consistent difference. Rather complex transitions exist between these three phases. The MAT-SST difference curves are essentially the same in both hemispheres. This is a strong indication that the differences reflect non-climatic effects, and it provides a valuable consistency check on the MAT corrections.

Table 2 Comparison between corrected MAT data and uncorrected SST data

		1861-89	1903-41	1942-45	1946-79
NH	$\bar{X}$	0.08	0.49	−0.07	0.02
	s	0.08	0.08	0.07	0.09
SH	$\bar{X}$	0.07	0.50	−0.14	0.02
	s	0.04	0.05	0.08	0.08
Correction		0.08	0.49	−0.10	0.00

$\bar{X}$ = mean MAT minus SST value; s = corresponding standard deviation. The correction is the number added to the uncorrected annual SST data.

The implied SST corrections, are (°C): 1861-89, 0.08; 1903-41, 0.49; 1942-45, −0.10; 1946-79, 0.0; with linear interpolation between 1889 and 1903. For 1941 we applied a slightly different correction in the Southern Hemisphere, 0.19 °C. As for MAT, these corrections also differ somewhat from those used by Folland *et al.*[4]. In their analysis, SST values were adjusted to ensure compatibility with corrected MAT values, just as we have done. However, since their corrected MAT values must differ noticeably from those produced here, differences in the SST corrections will, in part, reflect these MAT differences.

In our analysis, the difference between the twentieth century SST correction factor before 1941 and after 1946 is 0.49 °C. This difference is in the range (0.3-0.7 °C) generally accepted for the difference between uninsulated bucket and intake SST measurements[18,20,21]. The precise reasons for the differences that we obtain between the nineteenth century and early twentieth century MAT and SST corrections are uncertain. For MAT, the change is likely to be related to the transition from sail to steam. Between 1880 and 1910, the percentage of steamship tonnage as a fraction of total shipping tonnage rose from ~25 to 75% (ref. 22). Noticeable increases in ship speed occurred over the period 1880-1900, and in ship size over the period 1890-1910

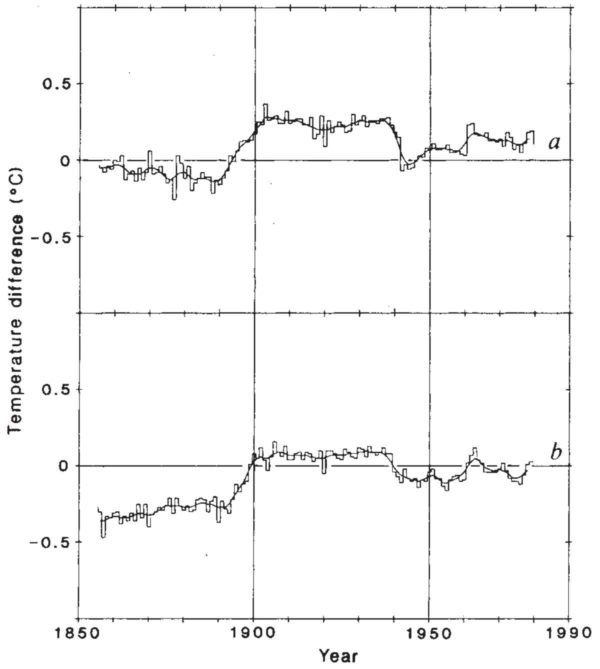

Fig. 4 Differences between the hemispheric-mean sea surface temperature values produced in the present work and those of Folland *et al.*[4]; Northern Hemisphere (*a*), Southern Hemisphere (*b*). Smooth curves show 10-yr gaussian filtered values. The implied warmth of the Folland *et al.* SH data relative to the NH (by ~0.2 °C), is due to their use of 1951–60 as a reference period. Conditions during this decade differed noticeably from the mean conditions during the reference period, 1950–79, used here (see Fig. 5).

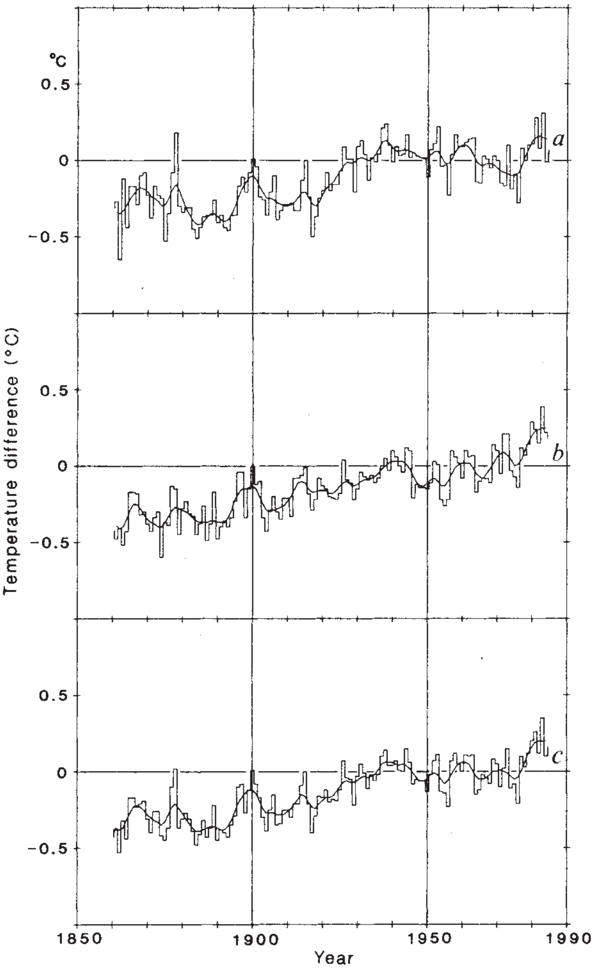

Fig. 5 Global (*c*) and hemispheric (Northern, *a*; Southern, b) annual mean temperature variations since 1861, based on sea-surface temperature data to represent the marine domain and using weights corresponding approximately to the maximum coverage for the four domains (method two in the text). Smooth curves show 10-yr gaussian filtered values. 1980–84 values are based on SST data obtained from the Climate Analysis Center, U.S. National Oceanic and Atmospheric Administration (see ref. 29 for information about this data source). These data were adjusted to be compatible with the values in earlier years by comparing values in both hemispheres over the overlap period, 1970–79. The CAC data correlate highly with the COADS data ($r = 0.984$ for the Northern Hemisphere mean and $r = 0.991$ for the Southern Hemisphere mean).

(ref. 22). These dates should be compared with the duration of the rising trends in land minus uncorrected-MAT data in both hemispheres shown in Fig. 2. Changes in MAT may be related to exposure changes attendant on the above, and to other changes in instrument exposure procedure which occurred over the same period. For SST, the main reasons for the change may be the standardization of the measuring technique and the introduction of more reliable instruments[23]. It is also possible that, in the mid to late nineteenth century, many bucket temperatures were not taken in the shade[24]. In addition, some of the earlier measurements may have been made with wooden rather than canvas buckets. The latter, being uninsulated and subject to evaporative cooling, produce lower temperature readings.

The overall differences between the hemispheric mean SST values produced here and those of Folland *et al.*[4] are shown in Fig. 4. The results for an MAT comparison are similar. The discrepancies are large and comparable in magnitude to either set of corrections. The reasons for these differences stem mainly from the different correction factors applied to what are essentially similar raw data. Because there are several sources of data inhomogeneity, we have not attempted to correct for these individually. The result should be more complete than Folland *et al.*[4] who attempted to make specific corrections for identified sources of inhomogeneity based on physical arguments. Our corrections synthesize the effects of several different factors. However, while they ensure compatibility between the marine and land data, the fact that the reasons for these corrections are uncertain must point towards some remaining uncertainty in our corrected marine data, especially in the nineteenth century.

Global mean temperatures

It is a relatively simple matter to produce estimates of annual global mean surface air temperature using the available (corrected) marine data and the most recent compilations of land data[11,12]. There are three different ways in which global or hemispheric (land plus marine) averages can be calculated. The first method is to average only those grid point values (with appropriate cosine weighting) for which data exist. This is the way hemispheric means have been produced for the land data[11,12]. The second and third methods assume that each of the four independent time series (NH and SH land and NH and SH marine, either SST or MAT) are, at all times, representative either of their maximum coverage or of the total areas of the four domains. The results obtained differ but little, and the use of either SST or MAT to represent the marine domains produces only minor differences. We therefore show only results using the second method based on SST data, obtained using

$$T\,\text{global} = 0.25\text{NH land} + 0.25\text{NH SST} + 0.2\text{SH land} + 0.3\text{SH SST}$$

(Fig. 5) where, after 1957, SH land includes Antarctic data from

Raper *et al.*[25], updated. The insensitivity to the precise method of weighting arises because all time series are quite strongly correlated.

The reliability of the time series given in Fig. 5 as true hemispheric and global averages can be questioned because the spatial coverage, even at best, is less than 75% and because the coverage changes with time. Coverage is always much better in the Northern Hemisphere. Coverage before 1900 is generally less than one third of the globe, down to <20% in the 1860s. The question of representativeness of the land data has been considered in detail in refs 1, 11 and 12. Although marine coverage before 1900 is sparse, the spatial correlation length over the oceans is large and limited coverage should still give results representative of a much larger area. Nevertheless, there are large parts of the Southern Hemisphere that nearly always lack data, especially the southern oceans south of 45 °S and the whole of the southeastern Pacific (except near the South American coast). Before 1957, when most Antarctic data first became available, there are essentially no data at all for the globe south of 45 °S (refs 25, 26). Although this represents only ~15% of the area of the globe, temperature fluctuations at high latitudes are known to be larger than at lower latitudes and so can have a disproportionate effect on the global average[12,27]. Any interpretation of Fig. 5 must bear in mind both these basic data deficiencies and the marine data uncertainties implied by Fig. 4. We note, however, that the latter do not affect the gross features of the global mean changes observed this century.

The global curve is extremely interesting when viewed in the light of recent ideas of the causes of climatic change[1,2]. The data show a long timescale warming trend, with the three warmest years being 1980, 1981 and 1983, and five of nine warmest years in the entire 134-yr record occurring after 1978. With regard to the hypothesized warming due to increasing concentrations of carbon dioxide and other greenhouse gases, the overall change is in the right direction and of the correct magnitude[1,7,28]. However, the relatively steady conditions maintained between the late 1930s and mid 1970s requires either the existence of some compensating forcing factor or, possibly, a lower sensitivity to greenhouse gas changes than is generally accepted.

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LETTERS TO NATURE

Observation of terrestrial orbital motion using the cosmic-ray Compton–Getting effect

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Using underground observations, we have found a small diurnal amplitude modulation of the cosmic-ray muon intensity which agrees in amplitude and phase with a first-order relativistic effect due to the Earth's motion, as discussed by Compton and Getting more than fifty years ago. The parent particles are sufficiently rigid (~1.5 TeV/*c*) that solar and geomagnetic effects should be minor. The muon flux deep underground is relatively insensitive to near-surface meteorological effects, and temperature effects at production height would produce intensity variations nearly out of phase with the observed effect. Analysis of the arrival times of 5×10^8 muons during a period of 5.4 yr yields a fractional amplitude variation of $2.5^{+0.7}_{-0.6}\times10^{-4}$, with a maximum near dawn, at 08:18 ± 1.0 h local mean solar time (LT). The expected amplitude is 3.40×10^{-4}, with the maximum at 06:00 LT.

Compton and Getting[1] showed that a cosmic-ray detector with an energy threshold would observe an enhanced intensity when it moved along its direction of maximum sensitivity with respect to the rest frame of the cosmic-ray plasma. If the cosmic-ray energy distribution were a power law of the form $E^{-\gamma}$, then the fractional intensity enhancement above a fixed energy threshold should be

$$\frac{\Delta I(\theta)}{\langle I\rangle}=(2+\gamma)\frac{v}{c}\cos\theta$$

where θ is the angle between the direction of detector sensitivity and its velocity vector. A term v/c arises because the detector sweeps out a column of the cosmic-ray plasma, another term $2v/c$ because the solid angle transformation increases the intensity in the direction of motion, and a term $(\gamma-1)v/c$