

Using data to attribute episodes of warming and cooling in instrumental records

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The observed global-warming rate has been nonuniform, and the cause of each episode of slowing in the expected warming rate is the subject of intense debate. To explain this, nonrecurrent events have commonly been invoked for each episode separately. After reviewing evidence in both the latest global data (HadCRUT4) and the longest instrumental record, Central England Temperature, a revised picture is emerging that gives a consistent attribution for each multidecadal episode of warming and cooling in recent history, and suggests that the anthropogenic global warming trends might have been overestimated by a factor of two in the second half of the 20th century. A recurrent multidecadal oscillation is found to extend to the preindustrial era in the 353-y Central England Temperature and is likely an internal variability related to the Atlantic Multidecadal Oscillation (AMO), possibly caused by the thermohaline circulation variability. The perspective of a long record helps in quantifying the contribution from internal variability, especially one with a period so long that it is often confused with secular trends in shorter records. Solar contribution is found to be minimal for the second half of the 20th century and less than 10% for the first half. The underlying net anthropogenic warming rate in the industrial era is found to have been steady since 1910 at 0.07–0.08 °C/decade, with superimposed AMO-related ups and downs that included the early 20th century warming, the cooling of the 1960s and 1970s, the accelerated warming of the 1980s and 1990s, and the recent slowing of the warming rates. Quantitatively, the recurrent multidecadal internal variability, often underestimated in attribution studies, accounts for 40% of the observed recent 50-y warming trend.

multidecadal variability | solar influence | Little Ice Age | Maunder Minimum

The world's longest instrumental record of temperature, Central England Temperature (CET), began to be collected in 1659 in an area enclosed by Lancashire, London, and Bristol, a few years after the invention of sealed liquid thermometers. It is the only instrumental record that extends back to the Little Ice Age (LIA), a period of cold climate in Europe, and the time of the Maunder Minimum, when sunspots vanished almost entirely for 70 y (1). The record then covers several subsequent episodes of natural and anthropogenic warming of multidecadal durations. Manley (2) painstakingly compiled most of the early monthly CET series, and Parker et al. (3) the daily data from 1772. Both are updated to present by the Met Office Hadley Centre. This record has previously been analyzed to study interannual and interdecadal variability up to the 25-y period (4); interannual winter variability and its association with solar forcing (5); and its variance at interannual, interdecadal timescales compared with a general circulation model output (6). The lower frequency portion of the record, longer than 50 y, has not been adequately analyzed, the difficulty being that even this long record is not long enough to avoid the cone of influence from the edges of the time series. Here we use a statistical approach to quantify the edge effects. It is this low-frequency portion of the record that contains information about an important multidecadal mode of variability that extends into the modern, industrial era. Wu et al. (7, 8) pointed out the importance of this mode in the modern global temperature record with a period of 65 y: If it is interpreted as natural and related to the Atlantic

Multidecadal Oscillation (AMO) (9–12), then the trend attributed to anthropogenic warming should be significantly reduced after ~1980, when the AMO was in a rising phase. However, if it is forced by time-varying aerosol loadings, it should properly be interpreted as part of an accelerating anthropogenic trend. We argue that the former is true, using information from the preindustrial era.

Fig. 1 shows the Continuous Wavelet Spectrum of CET as a function of frequency and time. It can be seen that there is a highly statistically significant band of oscillation with periods of 50–80 y extending throughout the 353-y record, which coincides with the global-mean HadCRUT4 (14) spectrum (Fig. S1), which is also statistically significant. We will not discuss the oscillation that has a longer average period of 90–100 y because it cannot be properly confirmed by the global-mean record, which is too short for our statistical test. There is, additionally, an oscillation in the 30- to 40-y band that is nonstationary: it exists only during the 19th century when the 50- to 80-y band is temporarily weak. There is little power in this higher frequency band in the global-mean data available after 1850. It is likely that this higher frequency band represents local information along the Atlantic coast and will not be discussed further here, except to point out that one definition of the AMO Index, by Trenberth and Shea (15), tends to emphasize this regional effect for the purpose of aiding the prediction of Atlantic hurricanes by subtracting the global-mean temperature from the North Atlantic mean. We will use the standard AMO Index of Enfield et al. (16), which is defined as the North Atlantic mean sea-surface temperature (SST), linearly detrended.

The original time series can be reconstructed from the wavelet transform and divided into several frequency bands (13) (Fig. S2). It can be verified that these “band-filtered” data, when summed, give back the original CET time series.

The 50-y low-pass filtered time series (containing the wide frequency band with periods longer than 50 y) is shown in Fig. 2 with the global mean from HadCRUT4, similarly low-passed, superimposed. It is seen that CET agrees quite well with the global-mean data. Both datasets contain a multidecadal oscillation that is statistically significant at above the 95% confidence level (Fig. 1 and Fig. S1). This result is important because the statistical significance of this multidecadal oscillation in the long records has not been established previously either in Greenland ice core data (17) or in a previous analysis of CET (18). The 50- to 90-y band (which is approximately the same as the 50- to 80-y band) is here referred to as the “AMO” mode and is shown in Fig. 3A. The CET's AMO agrees well with both the global and the North Hemispheric (NH) mean surface temperature, showing that the AMO is a near-global phenomenon. The NH mean is slightly larger than the global mean. The closeness of the global mean and

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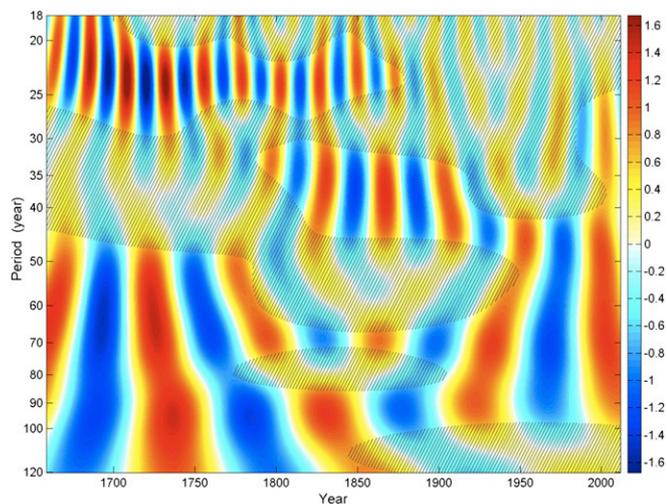


Fig. 1. Continuous wavelet spectrum of CET. Wavelet coefficient [calculated using equation 2 of Torrence and Compo (13)] is shown as a function of period and time, using a Morlet wavelet with the parameter chosen to emphasize time resolution. Regions below the 95% confidence level are hatched. The statistical test is based on an autoregressive of order 1, AR (1), noise model. The formula used is the χ^2 test (13).

the NH mean before the early 20th century may be due to the lack of data south of 60° S. The AMO should be out of phase in the region of the Antarctic circumpolar ocean (21), where deep water from the North Atlantic upwells. The global-mean oscillation exhibits a peak-to-peak amplitude of about 0.3–0.4 °C with an average period of about 70 y, based on its recent cycles.

AMO

CET is regional data. Although it has been a common practice in studying paleoclimate data to use proxy data from, for example, an ice core in Antarctica, to represent global climate after dividing the former by a factor of ~ 2 or by a model-determined, latitude-dependent scaling factor, theoretical justification is only beginning to be emphasized (22). The present finding that the low-frequency portion of the regional data agrees with the global mean (with a scaling that is slightly larger than 1) during the 162-y overlap period supports the notion (but does not prove) that a single time series can, in fact, be used to represent the global mean variation. To validate the CET time series for the preindustrial era in its ability for near-global representation, we use the multiproxy data of Delworth and Mann (12), which has near-global coverage (Fig. 3*B*). Before 1850, the CET AMO agrees with this multiproxy data in phase; the amplitudes in the proxy data are only relative. The spatial pattern of this multi-decadal variability in the multiproxy data is similar to that in the recent global instrumental record—a monopole with emphasis on the North Atlantic region extending to the Pacific and North American region (23, 24). However, after 1850, there is a gradual divergence in time of the multiproxy record from the global instrumental record. This is well recognized, but the cause is unclear (25). CET, being an instrumental record, does not suffer such a divergence. England, being near the Atlantic coast, is strongly influenced by the Atlantic sea-surface temperature. Indeed, Fig. 3*B* shows that CET coincides with the often used AMO Index (16) over the past 150 y. We therefore argue that CET can be used as a proxy AMO index, extending the latter back to 1659. The amplitude of the global AMO in the preindustrial era can also be calibrated against the CET AMO. Wood et al. (20) considered a 200-y record of surface air temperature reconstructed from four stations in the Atlantic–Arctic boundary. Their undetrended data are shown in Fig. 3*C* and compared with CET data. The phases of

the oscillations in the two data sets are in agreement. The amplitude of the Arctic data is larger due to polar amplification. The extra years before 1850 coincided with the weaker AMO cycle shown in the middle cycle of the CET AMO. Without the benefit of seeing the earlier cycles shown in Fig. 3, Wood et al. conjectured that the early 20th-century warming is a singular internal variability event without a regular period.

Using 800 y of ice-core data from Greenland, Broecker (26) in 1975 extracted two recent cycles of an oscillation by combining an 80-y Fourier harmonic with a 180-y harmonic and correctly predicted the end of cooling in the 1970s and the ensuing decades of accelerating warming. Neither harmonic, however, is statistically significant in his record. Gray et al. (27) considered tree-ring-based reconstruction of the AMO back to 1567. However, the cycle earlier than CET has an unusually large excursion; the tree rings may have been contaminated by the severe cooling during the Little Ice Age, caused likely by the very large volcano explosions. Chylek et al. (17) examined five ice-core datasets in Greenland for the overlapping period of 1303–1961 and reported finding two timescales for the AMO, a 20-y and a 45- to 85-y oscillation. Although the 20-y spectral peak was found to be statistically significant, the lower frequency oscillation that we are interested in was found to be below statistical significance, due possibly to the spectral windowing used. Wu et al. (8), using global-mean data, revealed a statistically significant 2.5 cycles with a 65-y period. DelSole et al. (28) also found 2.5 cycles by extracting the spatial pattern in the Intergovernmental Panel on Climate Change, Fourth Assessment Report (IPCC AR4) (29) model control runs that best characterizes internal variability and by projecting the observed global data onto this pattern. Wu et al. (8), DelSole et al. (28), and Delworth and Mann (12) related the global-mean oscillation to a spatial pattern emphasizing the North Atlantic, with Pacific and global extensions. The five cycles found here argue that this oscillation is primarily natural and recurrent (10). The phenomenon likely involves thermohaline circulation variability in the Atlantic Ocean. As described in refs. 30 and 31, the oscillation is the result of negative feedbacks between the strength of the thermohaline circulation that brings warm SST to the North Atlantic and the Arctic ice melt in response to the warm SST. With reduced deep-water formation, the latter then slows the thermohaline circulation after a delay of 20 y. Recently a 55- to 80-y AMO has been model-simulated as arising from the variability of the meridional overturning circulation in the Atlantic (32). Using CET as supporting evidence, we have shown here that these same 2.5 cycles in the global data are a part of a recurrent oscillation going back at least 350 y, and it is unlikely that they can be attributed to volcanic aerosols, whose eruptions were not periodic nor aligned with the troughs (Fig. 3*A*).

Booth et al. (33) simulated AMO-like variability in the 20th century with time-varying aerosol forcing, incorporating its indirect effect. However, Zhang et al. (34) showed that they overestimated the indirect aerosol effect. The vertical subsurface temperature in the tropical Atlantic should have a characteristic anticorrelation pattern with the upper ocean in the observed AMO, but is not produced in Booth et al. (33) (see also ref. 35). Although it may be possible to simulate half of a cycle (i.e., the early 20th-century warming) using time-varying anthropogenic aerosols within their uncertainty, it is very unlikely that they can be the cause of the five cycles found here.

Climate Variation Since the LIA

Fig. 2 shows almost four centuries of climate variations recorded in CET. First, we note that the record can be divided into three eras, consisting two perturbed climates—the rapid warming after the end of LIA and the modern period of anthropogenic warming after the Second Industrial Revolution—separated by a background climate when Europe experienced a century (1738–1849) of mild temperature with no trend. (See also the objectively

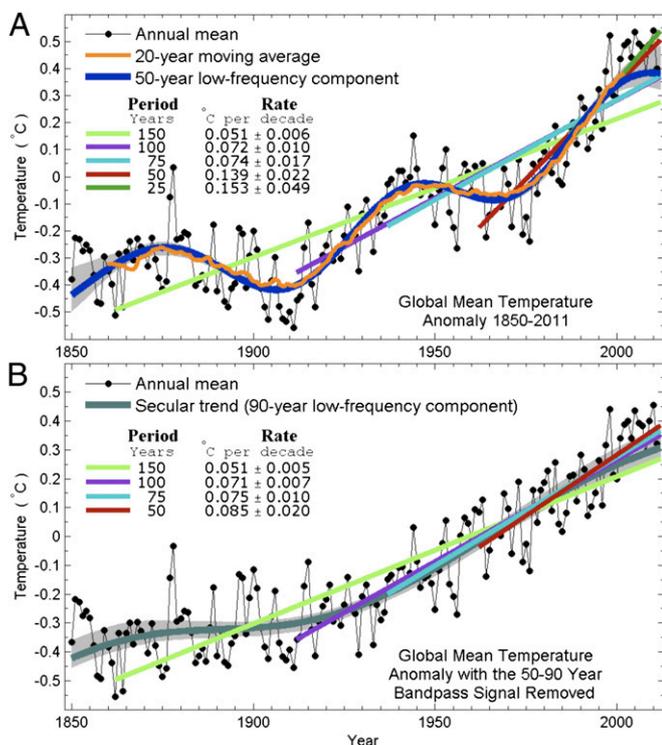


Fig. 4. Understanding global-mean trends. (A) The result in IPCC AR4 is updated using HadCRUT4 from 1850 to 2011, and their 150-, 100-, 50-, and 25-y linear trends (with labeled magnitudes) are shown. Even though the annual means are shown, the linear trends are calculated using the raw monthly-mean data. The 50-y wavelet low-passed global mean is superimposed (in blue). It gives a smoothed fit to the raw data and agrees with the running-time mean (in orange). (B) The black dots represent adjusted annual-mean global-mean temperature data with the 50- to 90-y wavelet band removed. The removed band is shown in Fig. 3. The linear trends are recalculated. Although the 150-y trend is the same as in A, trends for the shorter periods are reduced and become more stable. The 90-y low-pass data (in dark green) is the secular trend for the 162-y period, showing a slow start of the anthropogenic warming in the first 50 y and an almost constant warming trend after 1910. The thin gray curves are the 90-y low pass of 3,000 Monte-Carlo synthetic data of 37,000 mo long, obtained by random resampling in 100-y blocks for the purpose of quantifying the edge effect.

is demonstrated in Fig. 5, where Foster and Rahmstorf's analysis is repeated, but for the longer period of 1856–2011 and using HadCRUT4. The residual plus the regressed linear trend is shown in Fig. 5A. The same anthropogenic trend since 1979 of 0.17 °C/decade is obtained. However, one can see clearly that a 70-y oscillation is still present in the residual (see the orange running mean). In Fig. 5B, we add the AMO Index (16) to the multiple linear regression analysis. The 33-y net anthropogenic warming rate obtained, at 0.07 °C/decade, is less than half of Foster and Rahmstorf's. In fact, the net anthropogenic warming trend has been remarkably steady for the past 100 y at 0.07–0.08 °C/decade. Further discussions of the multiple regression analysis can be found in Zhou and Tung (56).

Conclusion

Although there is a competing theory that the observed multi-decadal variability is forced by anthropogenic aerosols during the industrial era (33), our present work showing that this variability is quasi-periodic and extends at least 350 y into the past with cycles in the preindustrial era argues in favor of it being naturally recurrent and internally generated. This view is supported by model results that relate the variability of the global-mean SST

to North Atlantic thermohaline circulation (30, 31, 35) and by the existence of an AMO-like variability in control runs without anthropogenic forcing (28). If this conclusion is correct, then the following interpretation follows: The anthropogenic warming started after the mid-19th century of Industrial Revolution. After a slow start, the smoothed version of the warming trend has stayed almost constant since 1910 at 0.07–0.08 °C/decade. Superimposed on the secular trend is a natural multidecadal oscillation of an average period of 70 y with significant amplitude of 0.3–0.4 °C peak to peak, which can explain many historical episodes of warming and cooling and accounts for 40% of the observed warming since the mid-20th century and for 50% of the previously attributed anthropogenic warming trend (55). Because this large multidecadal variability is not random, but likely recurrent based on its past behavior, it has predictive value. Not taking the AMO into account in predictions of future warming under various forcing scenarios may run the risk of overestimating the warming for the next two to three decades, when the AMO is likely in its down phase.

Methods

The time series was first linearly detrended, and a modulated annual cycle of an average period of 1 y was removed in the wavelet 9- to 15-mo band (the second mode in Fig. S2). This procedure does not affect the wavelet spectrum but is needed for the statistical test. In Fig. 2, the trend is added back.

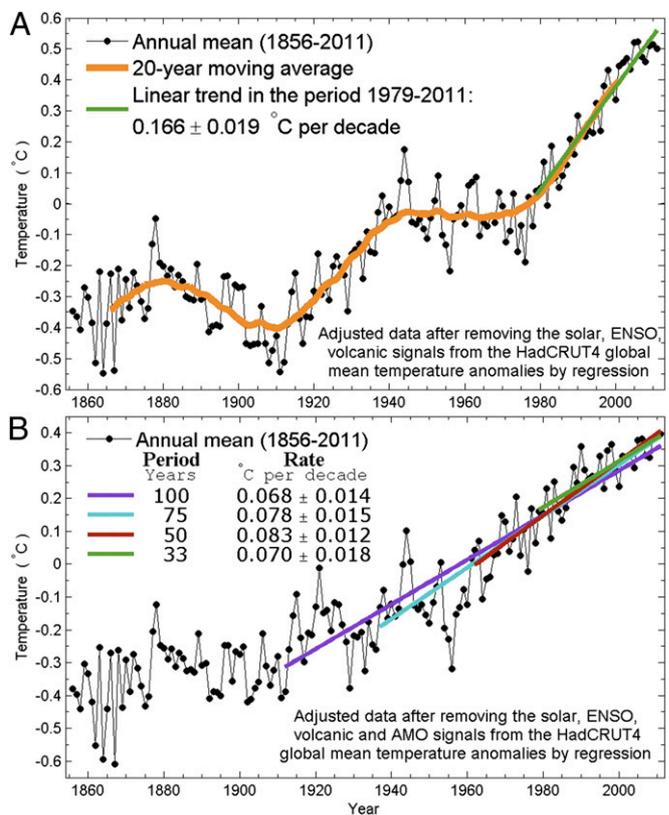


Fig. 5. Multiple-regression analysis of global-mean temperature, (A) Adjusted data after the removal of ENSO, volcanic, and solar influence. Time lags for ENSO and volcano are 4 and 6 mo, respectively, determined by optimizing the goodness of fit. A running-time mean (in orange) shows a long-period oscillation still present in the residual. (B) Adjusted data after the removal of ENSO, volcanic, and solar influence, plus the AMO. The AMO index (16) is shown in Fig. 3. The correlation between solar secular forcing trend and the global forcing trend is not small, and so there is a concern of collinearity in the regressors in this method, but the influence on the results is negligible. The noise model used in the multiple linear regression is AR(p), with p = 4 for A and p = 2 for B. The error bar for linear least squares fit is ±2 SDs.

We assume that the missing past and future data have similar spectral shape and autocorrelation as the available data. A synthetic time series, as long as desired with the real observations residing in the middle, can be produced using the so-called moving-block bootstrap method (57). We generated a large number of synthetic monthly time series to mimic the natural temperature data over a long period of 37,002 mo. Trend removal from each data block was first performed to reduce artificial oscillations resulting from the discontinuous trends between blocks. These blocks are time-reversed when used to create the future data to avoid large discontinuities at 2011. The least-squares linear trend and its upper and lower 95% confidence limits are taken out, separately, from the central part of each synthetic time series, to account for the influence of the regression errors in the wavelet analysis, and then added back after band pass of the wavelet modes. These form the

range of possible edge errors, replacing the common method of showing the cone of influence in the wavelet spectrum without quantifying the range of errors. Other ways of generating the synthetic data, such as using a seasonal autoregressive integrated moving average noise model, produce smaller error bars.

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