Global warming trend and multi-decadal climate variability

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Climate evolution during the last century has shown evidence of multi-decadal variability (1–8). One interpretation of non-uniformity of the global temperature trend is that it is due to a superposition of human-induced warming and a multi-decadal climate oscillation (9–11). Evidence for such intrinsic climate variability has also been found in coupled general circulation models [GCMs] (12, 13, 14). Here we further explore this hypothesis by constructing a three-parameter statistical model of the global temperature evolution, in which we use the concept of the delayed-feedback oscillator (15) to represent intrinsic multi-decadal signal, the values of the parameters being determined from the observed data. The model predicts non-uniform temperature changes prior to, and a net warming by Year 2100, which is smaller than that predicted by GCMs. Rapid temperature rise in 1980–2005 is rationalized as the result of a warming swing of the multi-decadal oscillation reinforcing a small positive anthropogenic trend.

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Reliable detection and attribution of climate trends crucially depends on our knowledge of intrinsic climate variability (16). Of particular relevance to the observed, during the past century, warming of the global surface air temperature (GST; Fig. 1) are multi-decadal climate oscillations. Recent estimate (9) of the residual between the total GST variations and those due to combined anthropogenic and solar forcing (1854–1991) shows strong evidence of a 70-yr cycle of internal climate variability. This signal may arise due to the dynamics of the North Atlantic ocean–atmosphere–sea-ice system (10–13), but clearly affects global climate change (3, 9): inferred amplitude of the associated GST variations is as large as 0.2°C — about 1/3 of the total GST change during the past century (see Fig. 1). The goal of the present essay is to quantify further the above hypothesis about the nature of the observed global warming and estimate potential predictability of GST associated with the multi-decadal signal by constructing a predictive statistical model of the observed temperature evolution.

The proposed statistical model is the delayed-action oscillator written for the detrended GST $\tilde{T}(t) = T(t) - \kappa_1 t - \kappa_3$, where t is the time, κ_1 is the rate of linear trend, and κ_3 is the intercept. The equation for $\tilde{T}$ is thus assumed to have the following form:

$$\dot{\tilde{T}} = \kappa_2 \tilde{T}(t-\tau), \qquad (1)$$

where the dot denotes time derivative, k_2 measures the strength of the delayed feedback, and τ is the delay time. Substituting the expression for $\tilde{T}$ into (1) and redefining $\kappa_2(\kappa_1\tau + \kappa_3) \to \kappa_3$, we get

$$\dot{T} = \kappa_1 + \kappa_2[T(t-\tau) - \kappa_1 t] - \kappa_3. \qquad (2)$$

Equation (2) thus represents the GST variability as a sum of a linear, presumably human-induced trend, with a rate κ_1, and an intrinsic variability parameterized as a delayed feedback describing possible oscillatory behavior about linearly increasing mean; the parameter κ_2 governs the sign and strength of this delayed feedback. The parameter κ_3, along with the choice of initial time [we arbitrarily chose t=0 to correspond to year 1890], adjust the initial magnitude of temperature anomaly; mathematically, this parameter is different from κ_1 in that the latter parameter enters (2) in two places simultaneously — as a free term and as a factor in the product $\kappa_1\kappa_2 t$ — while κ_3 only appears as a free term. The delay τ reflects the climate system's adjustment time associated with relevant processes (presumably with the thermohaline circulation). Such delayed-feedback oscillators (15) have been used before in process-model studies of El Niño/Southern Oscillation [ENSO] (17, 18), as well as the North Atlantic decadal climate variability (19). Here we apply this concept in a slightly different context of statistical data analysis.

For our analysis, we use two different annual-mean GST records (1880–2005; see Fig. 1): the one from the Goddard Institute for Space Studies (GISS), as well as an updated version of the data set used for the 2001 Intergovernmental Panel for Climate Change (IPCC) report (20). The two data sets have a high linear cross-correlation, but the details of both the short-term (interannual) and longer-term (interdecadal) variability are different (21), presumably due to differences in the computation of the global average.

The parameter estimation procedure involves the construction of a smoothed time series of GST (T) and its tendency ($\dot{T}$). Both time series were obtained by moving a 20-yr window along the observed GST record (Fig. 1) and finding the "running" slope $b(t)$ and intercept $a(t)$ of the corresponding linear least-square fit (the results for 10-yr and 40-yr windows [not shown] are similar). The smoothed temperature and its time derivative are then given by (recall that we chose time t =0 to correspond to year 1890) $T(t) = a(t) + 10b(t)$ and $\dot{T}(t) = b(t)$ [in these formulas, time is measured in years, so b has units of $^{o}\mathrm{C\,yr}^{-1}$]. The time series of $T(t)$ so obtained is shown, as a blue line, for GISS and IPCC data sets in Figs. 1a and 1b, respectively.

The parameters of the model (2) — $\kappa_1, \kappa_2, \kappa_3$, and τ, are then estimated by minimizing root-mean-square (rms) distance between left- and right-hand side of (2) using the smoothed T and $\dot{T}$ time series obtained as described above. We repeat this parameter estimation for portions of GST time series of various lengths. In particular, we use 46 "training" intervals, all of which start from 1880, and end in 1961, 1962, … , 2005, respectively. Table 1 lists the average values of the parameters among the 46 estimates, as well as their standard deviations, for both GISS and IPCC data sets.

The estimates of our statistical model parameters based on the two data sets are consistent with each other within standard uncertainties, and indicate that the model equation indeed describes a delayed *negative* feedback ($\kappa_2 < 0$), which is known to produce oscillatory behavior with periods related to the lag τ (15, 17–19). The theory of delayed-feedback oscillators (15, 17–19) predicts that the period of the oscillation can typically be 3–4 times the delay τ or longer, depending on model parameters; our statistical analysis thus argues for the presence of intrinsic oscillation with a period of about 40–70 yr, consistent with recent studies (2, 3, 9, 13). Note that the anthropogenic warming rate κ_1 computed by fitting the model (2) to data is consistent with the simple linear regression estimate of the trend; the statistical procedure thus attributes a large fraction (about the half) of a roughly twice faster, compared to the whole record, GST increase rate in 1980–2005 to transient behavior associated with the multi-decadal oscillation.

In addition to slow time scales associated with human-induced warming and multi-decadal climate variability, the total variability of the GST has also a fast component due to "weather." Inspection of the residual GST (the difference between the raw and smoothed GST time series) shows that the weather component of the variability can be represented by a Gaussian-distributed white noise (lag-1 autocorrelation of the residual GST is of about 0.2 for both GISS and IPCC data sets) with the standard deviation σ also given in Table 1.

We next employ the statistical model (2) to produce synthetic realizations of the GST for comparison with the observed time series, as well as to forecast the GST evolution in the 21st century. In these simulations, we use the time step of 1 year, so that the time derivative at a given time t is given by $T(t+1)-T(t)$. The weather effects are allowed for by employing a two-step integration with stochastic forcing. The first step computes the "total" temperature T_{total} (which includes both interdecadal and interannual variability) at time $t+1$:

$$T_{total}(t+1)=T(t)+\kappa_1+\kappa_2[T(t-\tau)-\kappa_1]-\kappa_3+\sigma\dot{w}. \qquad (3a)$$

Here $\dot{w}$ is the standard Gaussian random deviate (with zero mean and unit standard deviation). For the second step, we use the newly estimated total temperature above, along with the T_{total} values from the past 20 years, to do a least-squares straight-line fit to this segment of the time series. If the estimates of the straight-line parameters are a for the intercept and b for the slope, and $t=0$ is redefined every time to correspond to the earliest of the 21 points used for linear regression, then the smoothed GST is given by

$$T(t+1)=a+20b. \qquad (3b)$$

Black lines in Figs. 1a,b show the results of 1000-member ensemble integration of the statistical model trained on 1880–1981 portion of data. Ensemble-mean forecast for 1982–2005 is plotted as a solid line, while dashed lines show 2.5th and 97.5th percentiles of the forecasted GST values. Both GISS and IPCC-based models produce the forcasts that capture the observed trends fairly well; *i.e.*, the models both seem to be a fairly probable representation of observations. We therefore use these models to forecast the GST evolution during 21st century (Fig. 1; magenta lines: same conventions as for the 1982–2005 forecast).

Note that both GISS and IPCC forecast curves show non-uniform trends, with temperatures peaking at about 2020, decreasing further to reach a local minimum at

2060, and then increasing again. The models thus produce an intrinsic oscillation with half the period of about 40 years. Our statistical models assume, by construction, external forcing, including carbon dioxide emissions, to remain at present level, and predicts a net warming by year 2100, which is, however, smaller than that predicted by coupled GCMs (20). Furthermore, the estimated delayed oscillators turn out to be unstable in the sense that the amplitude of the 80-yr oscillation grows in time. One possible interpretation of this property is that while the direct effect of anthropogenic green-house gases emissions may have remained fairly limited, the associated warming may have affected the stability characteristic of the intrinsic climatic mode to make it increasingly more pronounced.

Rapid multi-decadal climate change, at a rate consistent with that actually observed during 1980–2005, is thus due, in our statistical model of global surface temperature (GST) evolution, to a combination of a linear trend (presumably associated with human-induced warming) and amplifying warming phases of intrinsic multi-decadal oscillation. The above interpretation of the observed global warming and ensuing statistical analysis results in that the estimate of human-induced warming rate during 1980–2005 is about twice as small as the actual rate observed; the remainder of the trend is due to intrinsic multi-decadal climate variability. In other words, the recent increased warming rate is interpreted as the consequence of intrinsic dynamics of the climate system, rather than “most up-to-date” estimate of the anthropogenic climate change.

The latter difference in interpretations may be one of the key reasons for enormous future warming seen in GCMs. A related property of most GCM forecasts of GST evolution is that their ensemble-mean forecasts are typically uniformly linear, consistent with the notion that potentially important intrinsic climate modes are most likely to be strongly damped and the modeled climatological change is a mere linear response to amplifying radiative forcing. Our statistical results motivate experimentation with global climate GCMs in less viscous parameter regimes than currently used for global change forecasts.

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Table captions

Table 1. Statistical model parameters and their standard uncertainties. The parameters are estimated using two different global surface temperature (GST) data sets, GISS and IPCC, and 46 different training periods: 1880–1961, 1880–1962, … , 1880–2005. Shown for each parameter is the average parameter value along with the standard deviation based on 46 estimates of this parameter.

GISS	**IPCC**
τ =16 ± 1 yr	τ =14 ± 2 yr
κ_1 = 0.0047 ± 0.0003 ^{o}C yr $^{-1}$	κ_1 = 0.0052 ± 0.001 ^{o}C yr $^{-1}$
κ_2 = –0.14 ± 0.01 yr $^{-1}$	κ_2 = –0.126 ± 0.007 yr $^{-1}$
κ_3 = 0.0396 ± 0.0035 ^{o}C yr $^{-1}$	κ_3 = 0.051 ± 0.004 ^{o}C yr $^{-1}$
σ = 0.1129 ± 0.0013 ^{o}C	σ = 0.0934 ± 0.0011 ^{o}C

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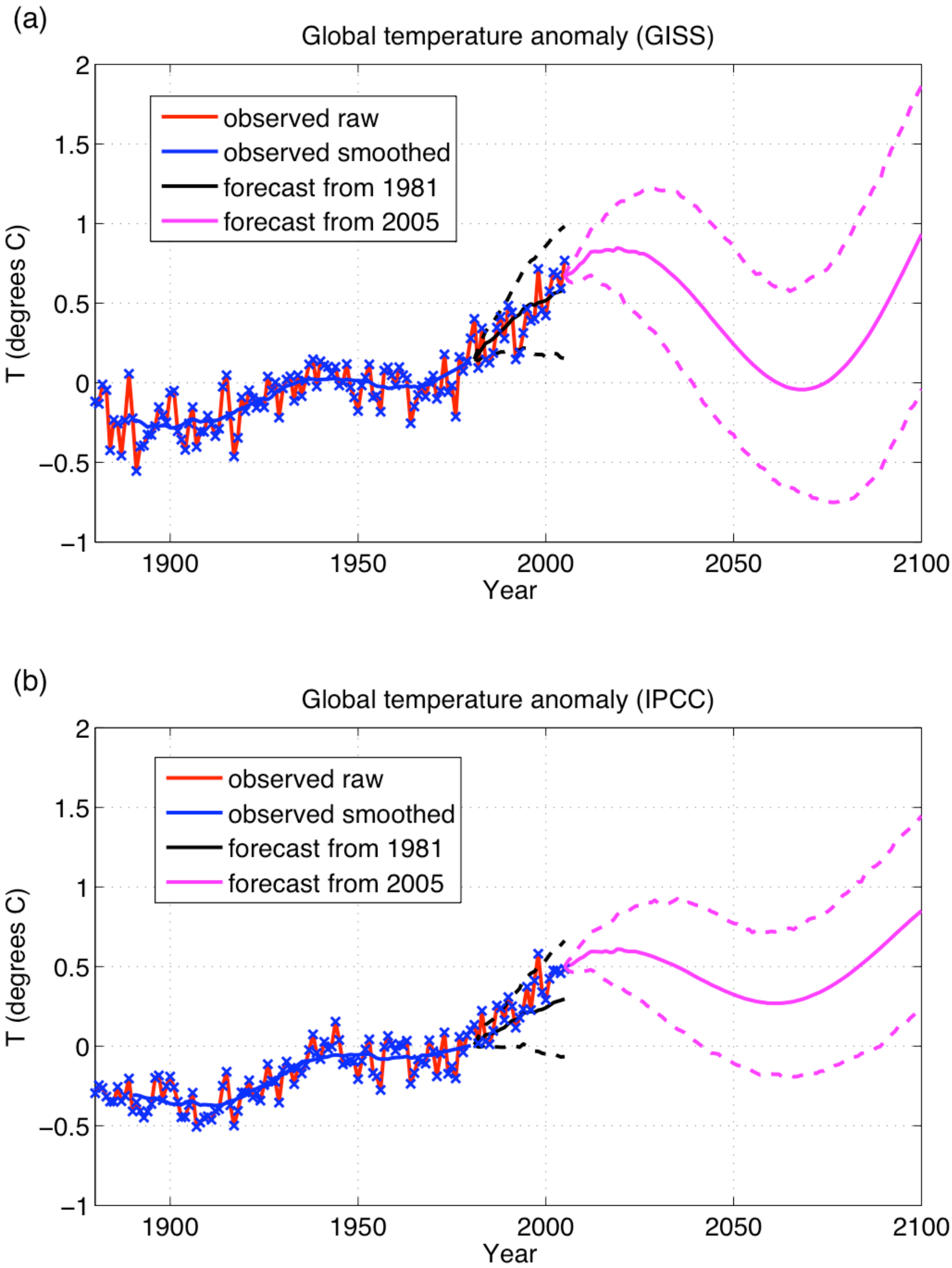
Figure captions

Figure 1. Time series of global-mean atmospheric surface temperature (GST) anomaly (red line, blue x-signs), based on: (a) Goddard Institute for Space Studies (GISS) data set (**http://data.giss.nasa.gov/gistemp**); (b) an updated version of the GST data set used for the 2001 Intergovernmental Panel for Climate Change (IPCC) report (20). Also shown in both panels are smoothed GST time series (blue line; see text for details of smoothing), as well as ensemble-mean forecasts using statistical model trained on the data prior to 1981 (black line) and prior to 2006 (magenta line). Corresponding dashed lines show 2.5th and 97.5th percentiles of forecasted GST values, based on 1000 forecasts.



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