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Rates of global temperature change during the past millennium

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ABSTRACT: We examine the characteristics (amplitude and phase) of the temporal variation in the rates of global-mean surface temperature change during the past millennium. The study was conducted by applying 20, 30, and 50 yr sliding windows to the observations of the recent century and reconstructions of earlier times. The analysis focuses on the characteristics of the rate of warming during the 20th century within the context of the past millennium as well as its sensitivity to the low-frequency variability of sea surface temperature (SST) and the time scales. On the 20 yr time scale, rates comparable to that of the 20th century in both amplitude and phase occur in the preceding 9 centuries. The maximum in the amplitude of rates of temperature change in the 20th century on the 30 yr time scale, although not the largest during the past millennium, is the longest lasting. On the 50 yr time scale, the 20th century warming rates are the highest and the most persistent of the past millennium. The results also indicate that although the SST variability does not greatly affect the amplitude of the rates, the phases are quite different, highlighting the importance of the role of oceans in affecting the rates. We also analyze the characteristics of temperature change rates using global climate model (1000 to 1999 AD) simulations with different climate forcing (solar, volcanic, and greenhouse gases). Except for the case driven by solar forcing alone, all produce amplitudes similar to observed ones. However, only greenhouse gas forcing can reproduce the persistent high warming rates of the 20th century.

KEY WORDS: Rates of temperature change · Observation · Reconstruction · Model simulation · 20th century warming · The past millennium

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1. INTRODUCTION

Rates of observed global mean surface temperature change reported in IPCC (2007) indicate that the warming rate averaged over the last 50 yr (0.13 ± 0.03°C decade^{-1}) was nearly twice that of the last 100 yr. However, these 2 rates are estimated from the slopes of a linear trend on different time scales, i.e. 50 and 100 yr. Since the slope of a linear trend in a time series is a time-scale-dependent quantity, differences in these slopes do not provide the answer to whether the warming rate of the second half-century is higher than the first half-century. Therefore, a defined time scale, such as the climatological time scale (30 yr), is required to compare warming rates. In addition, while observational data provides an assessment of the warming rate over the last 50 yr within the context of the century, it is worthwhile to examine how unusual this warming rate is in the context of longer timescales such as the past millennium, which encompasses a period dominated by natural forcing and the recent century dominated by anthropogenic forcing.

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Observational and modeled data show that the long-term internal (natural) variability in sea surface temperature (SST) might contribute to the warming of the 20th century global mean surface temperature over multiple decades (Delworth & Knutson 2000, Hansen et al. 2005, Knight et al. 2005, Swanson et al. 2009, Delsole et al. 2011). Removal of this long-term internal variability from global temperature is thus essential for assessing the contribution of anthropogenic forcing to the 20th century warming. Furthermore, delineating the relative role of anthropogenic forcing, natural forcing, and long-term internal variability in 20th century climate change is also important for our understanding of the climate system (Stott et al. 2000, Broccoli et al. 2003, Meehl et al. 2004, IPCC 2007).

In this study, we analyze observations of the recent century, reconstructions of earlier times, and 1000 yr simulations to examine the characteristics (amplitude and phase) of rates of global-mean surface temperature change during the past millennium. We also assess the sensitivity of these characteristics to the low-frequency variability of SST and to time scales.

2. DATA AND METHODS

Time series of global mean surface temperature used in this study include observations of 1880 to 2009 (http://data.giss.nasa.gov/gistemp/tabledata/GLB.Ts+dSST.txt); reconstructions from tree-rings, ice cores, corals, sediments, and historical data during the last millennium (Jones et al. 1998); and four 1000 yr CCSM2.0 simulations. The reconstruction by Jones et al. (1998) was chosen because it is the only available non-filtered global mean surface temperature reconstruction covering the past millennium (e.g. Mann et al.'s 2008 reconstructions are decadal-filtered). The forcings for the four 1000 yr simulations were solar only, volcanic only, greenhouse gases (GHG) only, and all 3 together (Peng et al. 2009, Shen et al. 2009). The solar and volcanic forcing were taken from Crowley et al. (2003), and GHG forcing was taken from Ammann et al. (2007). The solar forcing denoted as 'Be10/Lean splice' in Crowley (2000) was used. The reconstructed solar forcing was converted into solar irradiance by the solar constant (1365.6 Wm^{-2}). The volcanic forcing represented as radiative forcing in Crowley (2000) was applied as a negative deviation from the solar constant.

The rate of global temperature change is defined here as the slope of a simple linear trend on the climatological time scale (30 yr). It is evident that this rate is a time-scale-dependent quantity. Rates of observational, reconstructed, and modeled global temperature change were calculated using 30 yr sliding windows. The rates' 95% confidence intervals were estimated using regular linear regression without taking into account the possible autocorrelation of residuals. To assess the sensitivity of calculated rates to the time scale used, 20 and 50 yr sliding windows were also applied to these data.

As mentioned in the introduction, another focus of our study was to assess the sensitivity of rates of global temperature change to the low-frequency variability of SST. A multidecadal (~65 yr period varying from 50 to 80 yr) oscillation was found by Wu et al. (2007, 2011) in observational global surface air temperature. Their study suggests a possible link of this oscillation to low-frequency variations in the strength of the ocean thermohaline circulation (Wu et al. 2011). Schlesinger & Ramankutty (1994) identified a 65 to 70 yr oscillation in global mean temperature lying within the timescale band of 50 to 88 yr, and they suggested that this oscillation arises from internal variability of ocean–atmosphere interactions. We used the multi-taper method to analyze the 1000 yr reconstructed and modeled temperatures. Each time series was first pre-processed by applying a cubic polynomial best-fit and then a 21 yr moving average was taken to remove trend and high-frequency oscillations (>0.05 yr^{-1}). The results showed that statistically significant low-frequency oscillations with periods of 54–91 and 49–91 yr exist in reconstructed and modeled temperatures, respectively, both significant at the 95% confidence level (red noise null hypothesis). The spectral analysis indicates that this multidecadal oscillation characterizes the 1000 yr reconstructed and modeled temperatures. Based on the previous studies and our analysis, this multidecadal oscillation is here defined as one with the timescale band of 50 to 80 yr, i.e. 50 to 80 yr oscillation. Since the major long-term variability of the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO) is a 50 to 80 yr oscillation (Enfield et al. 2001, Shen et al. 2006), it seems reasonable to assume that the origin of this multidecadal oscillation is from the long-term variability in SST. It should be noted that the 50 to 80 yr band probably does not cover all low-frequency variability in SST. To evaluate the sensitivity to the low-frequency variability of SST, rates were calculated from temperature time series maintaining and excluding the 50–80 yr oscillation. This multidecadal oscillation was isolated from the time series using wavelet filtering (Torrence & Campo 1998) because regional oscillations are not constant and might change within the 50–80 yr band through the period of record. We chose the Morlet wavelet, with an adjustable parameter of 8, and frequency limits of 1/50 and 1/80.

3. RESULTS

3.1. Rates of global temperature change during observational periods

Fig. 1a shows the variation of global land–ocean surface temperature (anomalies from the 1961–1990 mean) from 1880 to 2009. In its original temperature time series, negative anomalies occurred before 1937; this was followed by a short interval from 1937 to 1944 with positive anomalies; negative anomalies occurred again between 1944 and 1978; and temperatures reached their maxima after 1978. The signal of the 50–80 yr oscillation is substantial in this time series. Wavelet filtering shows that the 50–80 yr oscillation accounts for 24.6% of the total variance of this time series. As the low-frequency oscillation is removed from the original time series, the difference between cool and warm periods is not as large as that in the original time series. Furthermore, the cool period of the 1950s to 70s disappears in the new time series.

Fig. 1b–d shows rates of temperature change on 20, 30, and 50 yr time scales computed from 2 time series maintaining and excluding the low-frequency oscillation. The calculated rates are time-scale dependent. Generally, rates vary within ±0.2, ±0.1, and ±0.05°C per decade on 20, 30, and 50 yr time scales, respectively. On the 30 yr time scale, the time series of rates for original temperature exhibits 2 peaks and 2 valleys. Warming rates (positive rate) >0.1°C per decade occur in the intervals of 1907–1949 and 1961–2009; and cooling rates (negative rate) exist in the intervals of 1888–1927 and 1935–1972. The highest rates are witnessed in the last 50 yr. As the low-frequency oscillation is removed from the time series, the rates show a different phase in temporal pattern although the rates still show 2 peaks and 2 valleys. The highest warming rates occur in the 1930s to 1960s instead of the last 50 yr. Rates for the 2 time series are significantly different from each other, as indicated by the independent-samples *t*-test. Meanwhile, on the 20 and 50 yr time scales, the characteristics of the temporal evolution of rates for the 2 temperature time series maintaining and excluding the low-frequency oscillation are similar to those on the 30 yr time scale. The highest warming rates occur over the last 50 yr in the original temperature time series; however, they are replaced by relatively low rates in time series that exclude the low-frequency oscillation. Instead of occurring in the last 50 yr, the highest rates occur from 1880 to 1901 on the 20 yr time scale, and in the 1920s to 1970s on the 50 yr time scale.

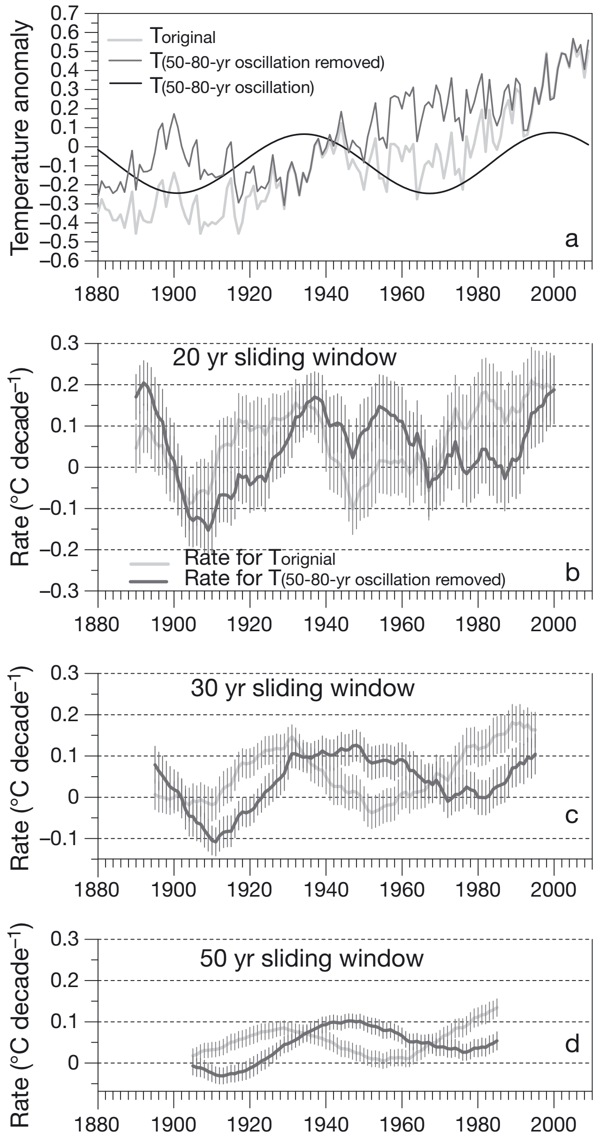

Fig. 1. (a) Annual global surface air temperature (T) anomalies from 1880–2009 relative to the 1961–1990 mean, maintaining and excluding the 50–80 yr oscillation; (b–d) rates of temperature change on 20, 30, and 50 yr time scales. Bars: 95% CI (estimated using regular linear regression without taking into account possible autocorrelation of residuals, so CI for some sliding windows are relatively narrow)

Our analyses of observational global land–ocean surface air temperature indicate that the last 50 yr experienced the highest rates of temperature change on 3 different time scales when the low-frequency oscillation is not removed from temperature time series. However, the rate maxima in the last 50 yr disappear as the low-frequency oscillation is removed.

3.2. Rates of temperature change during the last millennium

Fig. 2a shows observed and reconstructed global surface air temperature (anomalies from the 1961–

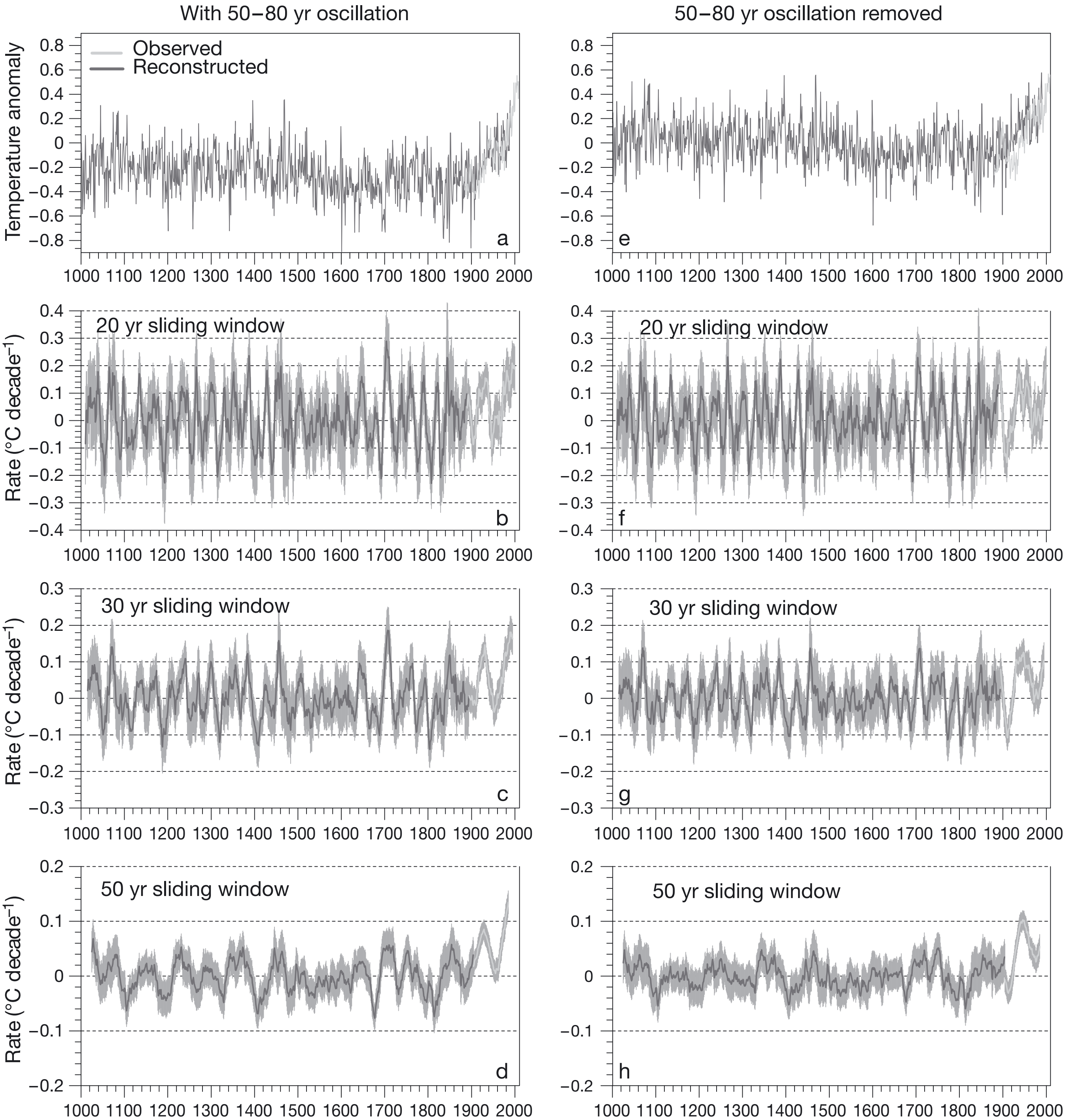

Fig. 2. (a,e) Reconstructed global surface air temperature anomalies over the last millennium relative to the 1961–1990 mean, (a–d) maintaining and (e–h) excluding the 50–80 yr oscillations and their rates of change on 20, 30 and 50 yr time scales. Light gray: 95% CI (see Fig. 1 for details)

1990 mean). During their overlap time period (1880 to 1991), reconstructed temperature closely matches the observed temperature in both magnitude and temporal evolution, with a significant correlation. As in the analyses using observed temperature, rates of temperature change on 3 time scales were computed from reconstructed temperature over the last millennium, maintaining and excluding low-frequency oscillations (Fig. 2a,e). Although uncertainties in reconstructed temperature (Jones et al. 2001) add some uncertainty to calculated rates of temperature change, significant changes apparently exist in these rates during the last millennium (Fig. 2b–d,f–h).

On the 30 yr time scale, rates of change that are comparable to those in observational times also occur earlier in the past millennium, no matter whether the 50–80 yr oscillation is removed or not from the reconstructed temperature time series (Fig. 2c,g). Thus, the 20th century warming and even the warming of the last 50 yr are not unusual in their amplitude of warming rates. The duration of positive rates in reconstructed global temperature is shorter than a half century. The duration of warming in the 1920s to 1940s and in the last 50 yr is longer than that in earlier centuries (Fig. 2c), however, and the 20th century warming, especially the warming in the 1920s to 1970s, is the most persistent once the 50–80 yr oscillation is removed from the temperature time series (Fig. 2g). On the 20 yr time scale, warming rates larger than those in observational times occurred before 1880, no matter whether the 50–80 yr oscillation was removed or not (Fig. 2b,f). There exist many intervals with rates of warming equal to or larger than those of the most recent 50 yr. This implies that the rates of the 20th century warming, even for the last 50 yr, are not distinct from those during the last millennium on the 20 yr time scale. On the 50 yr time scale, the warming rates over the last 50 yr stand out as the largest of the last millennium if the 50–80 yr oscillation is not removed from the temperature time series (Fig. 2d). However, if the 50–80 yr oscillation is removed, the rates over the last 50 yr are not distinct from those before observational times (Fig. 2h) and the maximum rate occurs in the 1920s to 1970s instead of over the last 50 yr. The 20th century taken as a whole, though, experiences the most persistent and highest warming rates of the last millennium.

3.3. Modeled rates of temperature change during the last millennium

Fig. 3 shows a comparison of observed, reconstructed, and modeled global temperature and their rates of change during the last millennium. Generally, modeled global temperature anomalies are somewhat underestimated compared to reconstructed temperature (Fig. 3a). However, modeled and reconstructed temperature time series match well (Fig. 3e) once the 50–80 yr oscillation is removed. This might suggest that the model overestimates the amplitude of the low-frequency oscillations.

On all 3 time scales analyzed, the amplitudes of rates in simulations driven with solar forcing only and GHG forcing only are smaller than observed and reconstructed rates. Rates comparable to those observed can be found in simulations driven with volcanic forcing only and with full forcing. Most of the major cooling intervals in reconstructed global temperature are also hinted at in these 2 simulations. It is evident that the intervals with large rates of change are caused by large volcanic eruptions. If the 50–80 yr oscillation is not removed, the warming rates over the last 50 yr on the 30 and 50 yr time scales are higher in simulations driven with full forcing and GHG forcing alone than in the other simulations (Fig. 3b–d). However, if the 50–80 yr oscillation is removed (Fig. 3f–h), the maximum rate of the last 50 yr is present only on the 30 yr time scale, and the most persistent and highest rates occur in the mid-late 20th century on the 50 yr time scale. Most of major warming intervals in the reconstructed global temperature time series are associated with high solar forcing in the simulations. However, the simulation driven with solar forcing alone cannot reproduce the persistent warming rate in the 20th century. The amplitude of warming rates in the simulation driven with GHG forcing alone is still smaller than that for reconstructed global temperature, but it is close to observational rates. Furthermore, only simulations driven with GHG forcing alone and with full forcing can reproduce the persistent warming rate in the 20th century, indicating that the high warming rates of the 20th century could be due, in part, to the increase of GHG.

4. DISCUSSION AND CONCLUSIONS

The rate of global temperature change is a time-scale-dependent quantity, and our results show differences in the rates using 3 different time scales: 20, 30, and 50 yr. The rate decreases as the time scale increases. When the same scale is used, no significant difference exists in the rates of warming between the first and second half-century of the 20th century: the rates of warming are 0.08 and 0.085°C per decade respectively with the 50 yr scale. There-

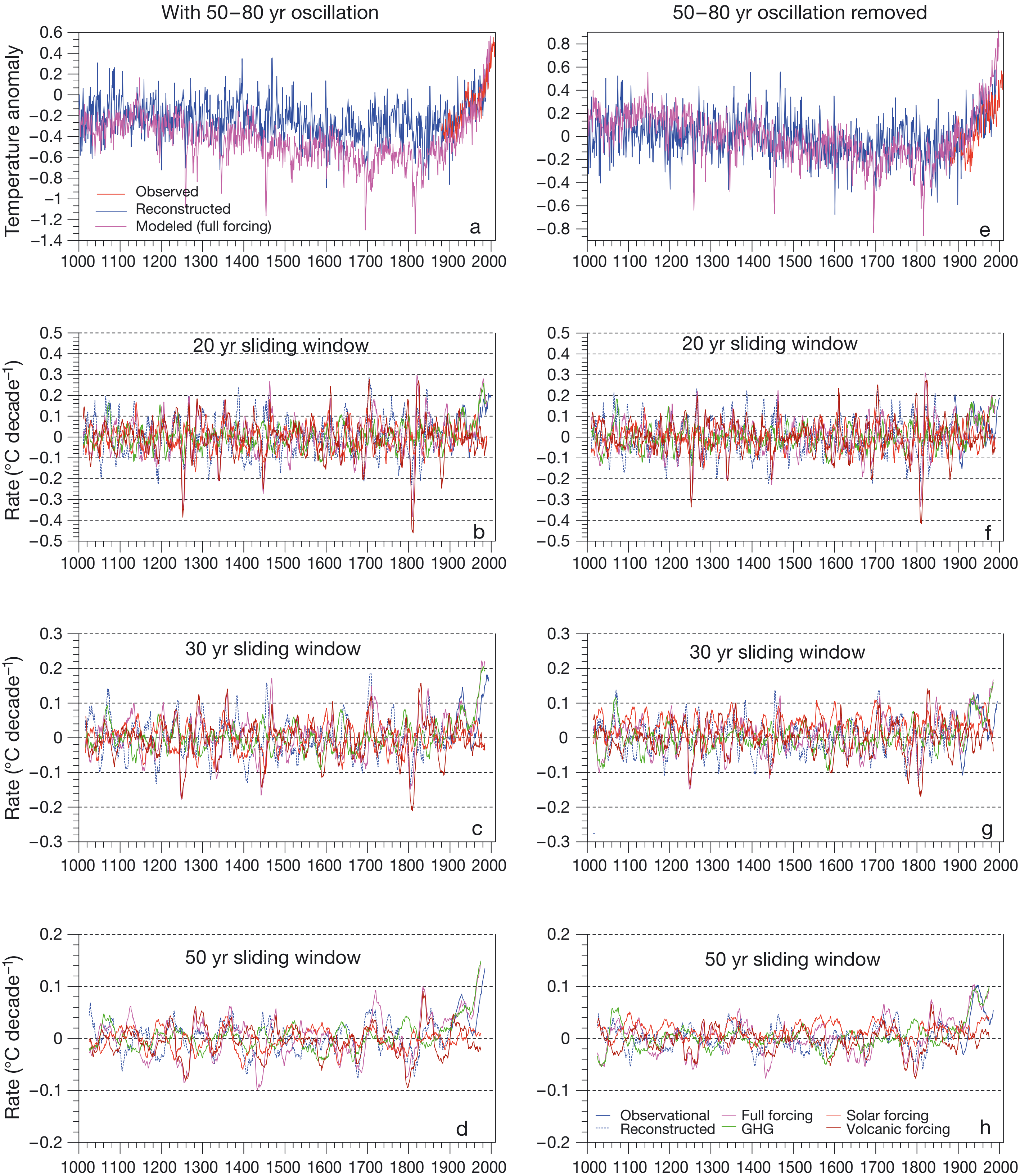

Fig. 3. Comparison of rates of change between observational, reconstructed, and modeled global temperature; temperatures (a–d) maintaining and (e–h) excluding the 50–80 yr oscillation and their rates on 20, 30, and 50 yr time scales

fore, the statement in the IPCC report that the rate of warming averaged over the last 50 yr was nearly twice that for the last 100 yr (IPCC 2007) just reflects the difference in the time scale (50 versus 100 yr) used to calculate the rate and not the rate itself. On the other hand, the amplitude of the rates depends on how large the temperature change is on a certain scale but not on the temperature regime itself. Large rates of change occur in both cold and warm periods. For example, high warming rates existed in the cold period of the 17th and 18th centuries and the warm period of the 20th century on all 3 time scales analyzed. However, the 20th century taken as a whole experiences the most persistent and highest warming rates of the last millennium on the 50 yr scale rather than on the 20 and 30 yr scales, no matter whether the 50–80 yr oscillation is removed or not. This finding indicates the importance of timescale in identifying a slowly evolving anthropogenic warming signal, as suggested by Santer et al. (2011).

Our results further indicate that the low-frequency variability of SST affects both the amplitude and the phase of rates of temperature change. Rates from the original temperature time series show that the warming rates of the last 50 yr are unusual during the past millennium in regards to both amplitude and phase, especially on longer than 30 yr time scales. However, when the effect of the low-frequency oscillation in SST is removed from the temperature time series, the warming rates of the last 50 yr are not unprecedented in their amplitude on the 3 different time scales during the past millennium. It is evident that the extreme temperature records of the last 50 yr stand out mainly because the general global warming trend coincides with the warming phase of the 50–80 yr oscillation, as suggested by a previous study (Wu et al. 2007). Nevertheless, the 20th century experiences the most persistent warming on the 3 time scales no matter whether the low-frequency oscillation in SST is removed or not. Our results indicate that both internal variability and external forcing contribute to the amplitude and phase of the temporal variation in the rates of global-mean surface temperature change. As we assess the causes of global warming in certain periods such as the 20th century, the internal variability of the climate system must be considered.

Our analyses of the modeled temperature show that the amplitude of rates of temperature change in simulations driven with solar forcing alone is smaller than that from the observational record. Major cooling rates are mainly associated with volcanic forcing. Simulations driven with GHG forcing alone and with full forcing can reproduce the persistent high warming rates of the 20th century.

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