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Climate of the Past Discussions

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 recent century and reconstructions of earlier times. The analysis focuses on the characteristics of the 20th century within the context of the millennium as well as their sensitivity to the low frequency variability of sea surface temperature (SST) and time scales. On 20-yr time scale, comparable rates to that of the 20th century in both amplitude and phase occur in earlier nine centuries. The peak in the amplitude of rates in the 20th century on 30-yr time scale, although is not the largest during the past millennium, but is the most persistent. On 50-yr time scale, the 20th century warming rates are the highest and the most persistent during the past millennium. The results also indicate that although the SST variability does not affect much the amplitude of the rates, but the phases is quite different, thus highlighting the importance of the role of oceans in affecting the rates. We also analyzed the characteristics from global climate model (1000–1999 AD) simulations with different climate (solar, volcanic, and greenhouse gases) forcing. Except for the one driven by the solar forcing, other forcing simulates similar amplitudes as the observed ones. However, only greenhouse gases (GHG) forcing can reproduce the persistent high warming rates of the 20th century.

1 Introduction

Observational global mean surface temperature shows that the rate of warming averaged over the last 50 yr ($0.13 \pm 0.03\,^{\circ}$C per decade) is nearly twice that for the last 100 yr (Solomon et al., 2007). However, the warming of the 20th century global mean surface temperature has not been monotonic. Temperatures reached a relative maximum around 1940, cooled until the mid 1970s, and have warmed from that point to the present (Solomon et al., 2007; Swanson et al., 2009). Given on a uniform time scale, similar warming rate to that of the last 50 yr might occur in the early 20th century. Therefore, it is difficult to assess how unusual the warming rate for the last 50 yr is in the context of millennium without using a uniform time scale in the computation of temperature change rates. Rates of global temperature calculated on uniform time scales are thus essential for assessing this issue.

On the other hand, observational and modeled data show that the long-term internal variability in SST might contribute to the warming of the 20th century global mean surface temperature over multiple decades (Delworth and 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 the global temperature is thus essential for assessing 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 the 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; Solomon et al., 2007). Here we analyze the observations of recent century, reconstructions of earlier times, and 1000-yr simulations to examine the characteristics (amplitude and phase) of the rates of global-mean surface temperature change during the past millennium.

2 Data and methods

Time series of global mean surface temperature used in this study include the observations of 1880–2009 (http://data.giss.nasa.gov/gistemp/tabledata/GLB.Ts+dSST.txt); reconstruction 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. Those four simulations are driven by solar, volcanic, GHG, and all forcings (Peng et al., 2009; Shen et al., 2009). The reconstruction by Jones et al. (1998) is chosen because it is only available non-filter global mean surface temperature reconstruction covering the past millennium we can find, although some new reconstructions have been published (e.g. Mann et al., 2008).

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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 time-scale-dependent quantity. In order to reveal the temporal variations of rates for evaluating how unusual the warming rates over the last 50 yr is and elucidating the characteristics (amplitude and phase) of the 20th century rates within the context of the millennium, 30-yr sliding window are used to construct time series on rates of observational, reconstructed, and modeled global temperature change. To assess the sensitivity of rates to the time scale, 20- and 50-yr sliding windows are also applied to these data.

50–80-yr oscillation is statistically significant multidecadal signal in observational global surface air temperature (Wu et al., 2007). This oscillation is also found in temperature of Northern Hemisphere by Schlesinger and Ramankutty (1994) who suggested that this oscillation arises from the internal variability of the ocean-atmosphere interaction. Since 50–80-yr oscillation is the major long-term variability of the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO) (Enfield et al., 2001; Shen et al., 2006). It thus is reasonable to assume that the origin of this multidecadal oscillation is from the long-term variability in SST. It should be noted that the 50–80-yr band just covers major part of low frequency variability in SST. To evaluate the sensitivity of rates to the low frequency variability of SST, rates are calculated from temperature time series maintaining and excluding the 50–80-yr oscillation. This multidecadal oscillation is isolated from the time series using wavelet filtering (Torrence and Campo, 1998).

3 Results

3.1 Rates during the observational times

Figure 1a shows the variation of global land-ocean surface temperature from 1880 to 2009. In its original temperature time series, negative anomalies occurred before 1937; it is followed by a short interval of 1937–1944 with positive anomalies; negative anomalies occurred again between 1944 and 1978; temperature reached their maxima

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after 1978. 50–80-yr oscillation is statistically significant multidecadal signal in this time series. Its wavelet filtering show that 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 original time series. Furthermore, the cool period of 1950s–70s disappears in the new time series.

Figure 1b–d shows rates of temperature change on 20-, 30-, and 50-yr time scales computed from two 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 climatological time scale, the time series of rates for original temperature exhibits two peaks and two valleys. The warming rates (positive rate) higher than 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, rates show a different phase in temporal pattern although the rates still show two peaks and two valleys. The highest warming rates occur in 1930s-1960s instead of the last 50 yr. Statistically, rates for two time series are significantly different from each other, as suggested by the independent-samples t-test. On 20- and 50-yr time scales, the characteristics in temporal evolutions of rates for two temperature time series maintaining and excluding the low frequency oscillation are similar to that on the climatological time scale. The highest warming rates occur over the last 50 yr in original temperature time series, however, they are replaced by relatively low rates in time series excluding the low frequency oscillation. Instead of the last 50 yr, the highest rates occur in earlier 23 yr from 1880 to 1901 on 20-yr time scale, and in 1920s–1970s on 50-yr time scale.

Our analyses of observational global land-ocean surface air temperature indicate that the last 50 yr experiences the highest rates on three time scales, if 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.

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3.2 Rates during the last millennium

Figure 2a shows observational and reconstructed global surface air temperature. During their overlap time period (1880–1991), reconstructed temperature closely matches the observational temperature in both magnitude and temporal evolution with a significant correlation, suggesting that this reconstruction is reliable. Using the same technique as observational temperature, rates on three time scales during the last millennium were computed from reconstructed temperature maintaining and excluding low frequency oscillations (Fig. 2a and e). Although uncertainties in reconstructed temperature (Jones et al., 2001) might induce somewhat uncertainties in calculated rates of temperature change, significant changes apparently existed in rates during the last millennium.

On the climatological time scale, the amplitude of rates comparable to that in observational times also occur in earlier centuries during the past millennium no matter whether the 50–80-yr oscillation is removed or not from reconstructed temperature time series (Fig. 2c and g). It indicates that the 20th century warming, even the warming of the last 50 yr, is not unusual in the amplitude of rates. The duration with positive rates in reconstructed global temperature is shorter than half century. The duration of rate peaks in 1920s–1940s and the last 50 yr are longer than that of those in earlier centuries (Fig. 2c), whereas the 20th century warming, especially the warming in 1920–70s is the most persistent as the 50–80-yr oscillation is removed from temperature time series (Fig. 2g). On 20-yr time scale, larger rates than that in observational times occurred before 1880, no matter whether the 50–80-yr oscillation is removed or not (Fig. 2b and f). There exist a lot of intervals with rates equal to or larger than that of the recent 50 yr. This implies that the rates of the 20th century, even the last 50 yr are not distinct from those before observational times in the context of the last millennium on this time scale. On 50-yr time scale, the highest rates over the last 50 yr stand out if the 50–80-yr oscillation is not removed from temperature time series (Fig. 2d). However, the rates over the last 50 yr are not distinct from those before

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the observational times if the 50–80-yr oscillation is removed (Fig. 2h), and the rate maxima occurred in 1920s–70s instead of the last 50 yr. On the other hand, the 20th century as a whole experienced the most persistent and highest warming rates during the last millennium.

3.3 Modeled rates during the last millennium

Figure 3 shows a comparison of global temperature and its rates between observational, reconstructed, and modeled global temperature during the last millennium. Generally, modeled temperature shows somewhat underestimates comparing to reconstructed temperature (Fig. 3a). However, modeled and reconstructed temperature time series match well (Fig. 3e) as the 50–80-yr oscillation is removed. It might suggest that the model overestimate the amplitude of the low frequency oscillation.

The amplitude of rates in simulations driven by solar forcing and GHG forcing is smaller than observational and reconstructed rates on three time scales. Comparable rates to observed one can be found in simulations driven by volcanic forcing and full forcing. Most of major cooling intervals in reconstructed global temperature also have their hints in these two simulations. It is evident that these intervals with large rates are caused by large volcanic eruptions. If the 50–80-yr oscillation is not removed, the rates over the last 50 yr are the highest in simulations driven by full forcing and GHG forcing on 30-yr and 50-yr scales (Fig. 3b–d). However, if the 50–80-yr oscillation is removed (Fig. 3f–h), this rate peak of the last 50 yr only exhibits on 30-yr scale, and the most persistent and highest rates occur in mid-late 20th century on 50-yr scale. And most of major warming intervals in reconstructed global temperature time series are associated with those with high solar forcing in simulations. However, the simulation driven with solar forcing only can not reproduce persistent warming rate in the 20th century. Amplitude of rates in simulation driven with GHG forcing is still smaller than reconstructed global temperature, but close to observational rates. Furthermore, only simulations driven with GHG forcing and full forcing can reproduce persistent warming rate in the 20th century, indicating that the 20th century high warming rates could be due, in part, to the increase of GHG.

4 Discussion and conclusions

Rate of global temperature change defined here is a time-scale-dependent quantity. The rate decreases as the time scale increases, as shown by our results. That the rate of warming averaged over the last 50 yr is nearly twice that for the last 100 yr in IPCC report (Solomon et al., 2007) just means the difference in the scale (twice) used to calculate the rate of warming not the rate itself. If the same scale is used, no significant difference exists in the rates of warming for the first and second 50 yr of the 20th century. For example, the rates for the first and late 20th century are 0.08 and 0.085 °C per decade on the 50-yr scale. On the other hand, the amplitude of the rates depends on how large the temperature changes on a certain scale not how much the temperature itself is. Large rates occur in both cold and warm periods. For example, high warming rates exist in the cold period of 17th–18th centuries and warm period of 20th century on any scales. However, significant difference in the phases of the rate exists in different periods. The last 50 yr experiences the most persistent warming if the effect of the low frequency variability of SST on the temperature is not considered. However, the phase of rates is quite different if the effect of the low frequency variability of SST on the temperature is removed from the temperature time series. The rates of the last 50 yr are not highest and persistent during the last millennium. It is evident that the extreme temperature records during the last 50 yr stand out in the observational times mainly because the general global warming trend coincides with the warming phase of 50–80-yr oscillation, as suggested by previous study (Wu et al., 2007).

Our results indicate that the low frequency variability of SST affect both the amplitude and phase of rates. Significant difference exists in temporal evolutions of rates as this low frequency variability is kept in or removed from temperature time series. Rates from original temperature time series show that the warming rates of the last 50 yr are unusual during the past millennium in aspect of both amplitude and phase of rates, especially on longer than 30-yr time scales. The warming rates of the last 50 yr are not unprecedented in the amplitude on three times scales during the past millennium, if the effect of low frequency oscillation in SST is removed from temperature time series. However, the 20th century experiences the most persistent warming rates on three time scales no matter whether the low frequency oscillation in SST is removed or not.

Our analyses on the modeled temperature show that the amplitude of rates in simulations driven with solar forcing is smaller than observed one. Major cooling rates are mainly associated with volcanic forcing. And simulations driven with GHG forcing and full forcing can reproduce persistent high warming rates in the 20th century.

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References

Broccoli, A. J., Dixon, K. W., Delworth, T. D., Knutson, T. R., Stouffer, R. J., and Zeng, F.: Twentieth-century temperature and precipitation trends in ensemble climate simulations including natural and anthropogenic forcing, J. Geophys. Res., 108(D24), 4798, doi:10.1029/2003JD003812, 2003.

Delsole, T., Tippett, M. K., and Shukla, J.: A significant component of unforced multidecadal variability in the recent acceleration of global warming, J. Clim., 24, 909–926, 2011.

Delworth, T. L. and Knutson, T. R.: Simulation of early 20th century global warming, Science, 287, 2246–2250, 2000.

Enfield, D. B., Mestas-Nuñez, A. M., and Trimble, P. J.: The Atlantic multidecadal oscillation and its relationship to rainfall and river flows in the continental U.S., Geophys. Res. Lett., 28, 2077–2080, 2001.

Hansen, J., Nazarenko, L., Ruedy, R., Sato, M., Willis, J., Del Genio, A., Koch, D., Lacis, A., Lo, K., Menon, S., Novakov, T., Perlwitz, J., Russell, G., Schmidt, G. A., and Tausnev, N.: Earth's energy imbalance: Confirmation and implications, Science, 308, 1431–1435, 2005.

Jones, P. D., Briffa, K. R., Barnett, T. P., and Tett, S. F. B.: High-resolution palaeoclimatic Records for the last millennium: Interpretation, integration and comparison with general Circulation model control-run temperatures, The Holocene, 8, 455–471, 1998.

Jones, P. D., Osborn, T. J., Briffa, K. R., Folland, C. K., Horton, E. B., Alexander, L. V., Parker, D. E., and Rayner, N. A.: Adjusting for sampling density in grid box land and ocean surface temperature time series, J. Geophys. Res., 106, 3371–3380, 2001.

Knight, J.R., Allan, R. J., Folland, C. K., Vellinga, M., and Mann, M. E.: A signature of persistent natural thermohaline circulation cycles in observed climate, Geophys. Res. Lett., 32, L20708, doi:10.1029/2005GL024233, 2005.

Mann, M. E., Zhang, Z., Hughes, M. K., Bradley, R. S., Miller, S. K., Rutherford, S., and Ni, F.: Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia, P. Natl. A. Sci., 105(36), 13252–13257, 2008.

Meehl, G. M., Washingon, W. M., Amman, C. M., Arblaster, J. M., Wigley, T. M. L., and Tebaldi, C.: Combinations of natural and anthropogenic forcings in twentieth-century climate, J. Clim., 17, 3721–3727, 2004.

Peng, Y., Xu, Y., and Lin, J.: Climate changes over eastern China during the last millennium in simulations and reconstructions, Quat. International, 208, 11–18, 2009.

Schlesinger, M. E. and Ramankutty, N.: An oscillation in the global climate system of period 65-70 years, Nature, 367, 723–726, 1994.

Shen, C., Wang, W.-C., Gong, W., and Hao, Z.: A Pacific Decadal Oscillation record since 1470 AD reconstructed from proxy data of summer rainfall over eastern China, Geophys. Res. Lett., 33, L03702, doi:10.1029/2005GL024804, 2006.

Shen, C., Wang, W.-C., Peng, Y., Xu, Y., and Zheng, J.: Variability of summer precipitation over Eastern China during the last millennium, Clim. Past, 5, 129–141, doi:10.5194/cp-5-129-2009, 2009.

Swanson, K. L., Sugihara, G., and Tsonis, A. A.: Long-term natural variability and 20th century climate change, Proc. Natl. Acad. Sci. U. S. A., 106, 16120–16123, 2007.

Solomon, S., Qin, D., Manning, M., Alley, R., Berntsen, T., Bindoff, N., Chen, Z., Chidthaisong, A., Gregory, J., Hegerl, G., Heimann, M., Hewitson, B., Hoskins, B., Joos, F., Jouzel, J., Kattsov, V., Lohmann, U., Matsuno, T., Molina, M., Nicholls, N., Overpeck, J., Raga, G., Ramaswamy, V., Ren, J., Rusticucci, M., Somerville, R., Stocker, T., Whetton, P., Wood, R., and Wratt, D.: Technical Summary, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the FourthAssessment Report of the Intergovernmental

Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M., and Miller, H., Cambridge University Press, Cambridge, United Kingdom and NewYork, NY, USA, 2007.

Stott, P. A., Tett, S. F. B., Jones, G. S., Allen, M. R., Mitchell, J. F. B., and Jenkins, G. J.: External control of 20th century temperature by natural and anthropogenic forcings, Science, 290, 2133–2137, 2000.

Torrence, C. and Campo, G. P.: A practical guide to wavelet analysis, B. Am. Meteor. Soc., 79, 61–78, 1998.

Wu, Z., Huang, N. H., Long, S. T., and Peng, C.-K.: On the trend, detrending, and variability of nonlinear and nonsationary time series, Proc. Natl. Acad. Sci. U. S. A., 104, 14889–14894, 2007.

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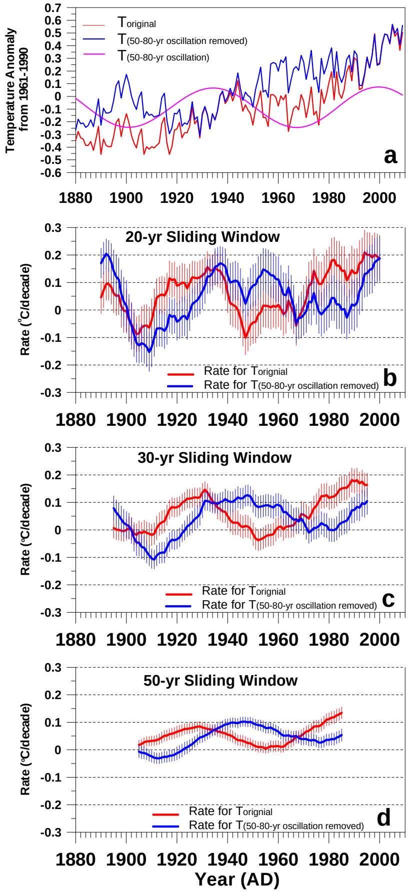

Fig. 1. (a) Annual global surface air temperature anomalies from 1961–1990 mean maintaining and excluding the 50–80-yr oscillation in 1880–2009; **(b–d)** their rates on 20-yr, 30-yr, and 50-yr time scales. Rates' 95 % confidence intervals (bar) are also shown.

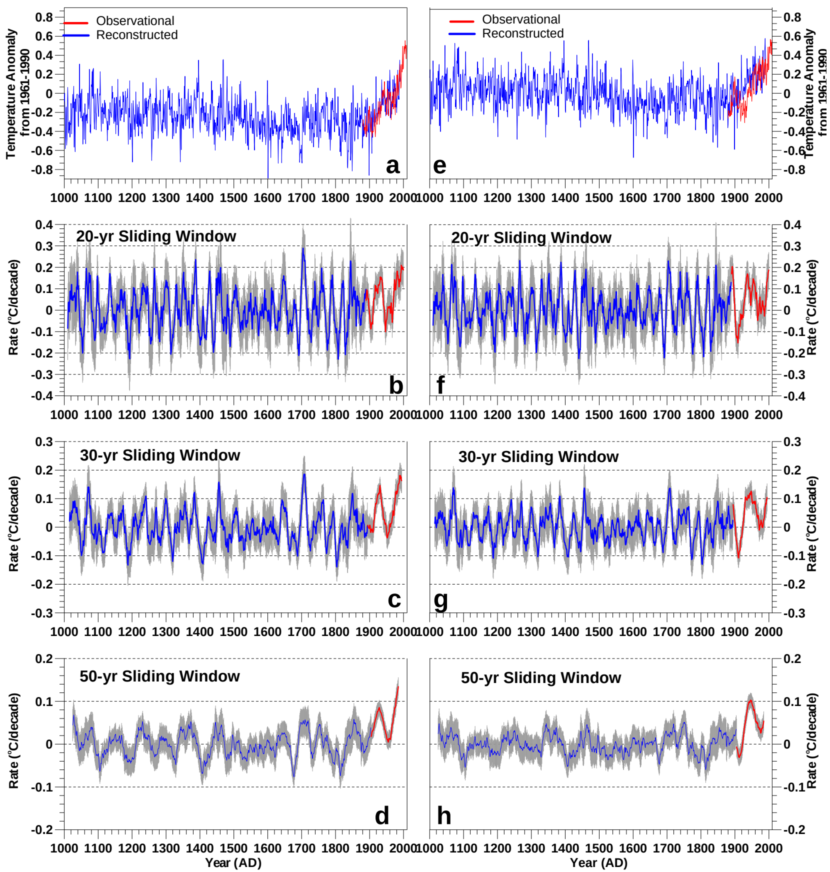

Fig. 2. Reconstructed global surface air temperature anomalies from 1961–1990 mean maintaining and excluding the 50–80-yr oscillations during the last millennium **(a, e)**, and their rates on 20-yr **(b, f)**, 30-yr **(c, g)**, and 50-yr time scales **(d, h)**. Rates' 95 % confidence intervals (gray shadow) are also shown.

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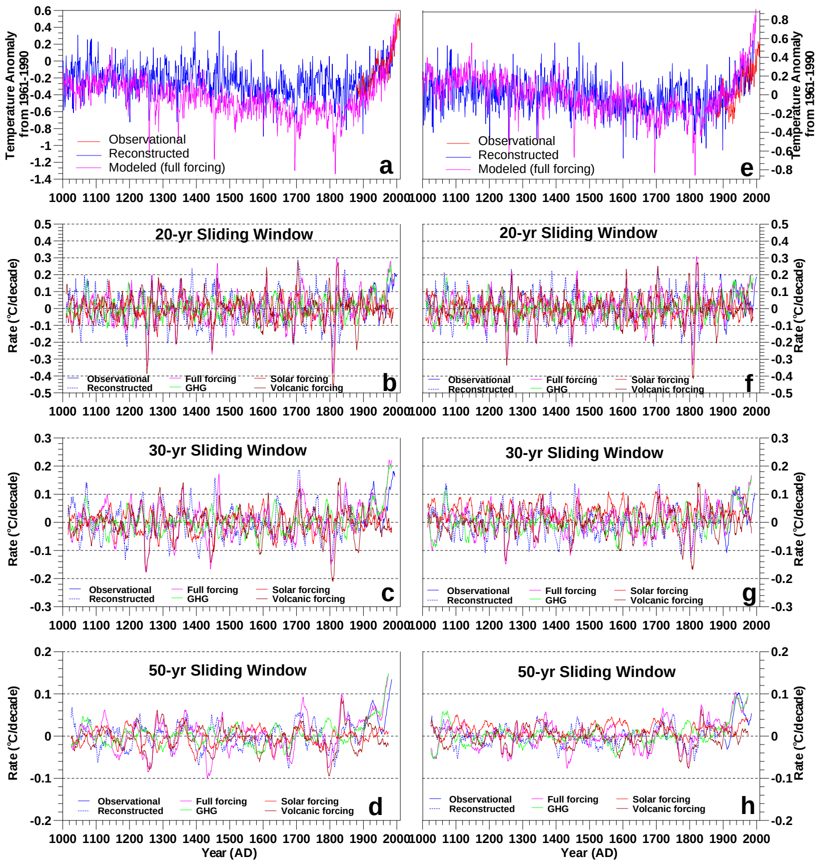

Fig. 3. A comparison of change rates between observational, reconstructed, and modeled global temperature; **(a–d)**, temperature maintaining the 50–80-yr oscillation and their rates on 20-yr, 30-yr, and 50-yr time scales; **(e–h)**, temperature excluding the 50–80-yr oscillation and their rates on 20-yr,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

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