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Spotlight on Global Temperature

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Early model predictions of global warming proved accurate, the Pacific Ocean seems charged for a potential super-El Nino, and global temperature is poised to reach record, perhaps dangerous, levels.

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In a popular novel Michael Crichton (2004) suggests that observed global warming inferred from weather station measurements is dubious especially because of urban warming effects, and he asserts that, even if measured warming is accepted, climate model predictions made by James Hansen in congressional testimony in 1988 (based on Hansen et al. 1988) proved to be "wrong by 300 percent". Although climate change discussion in a fictional novel might be easily dismissed, Crichton states that his references to real people are accurate. And Crichton's views were welcomed as testimony to the United States Congress (Senate Testimony 2005) and in a personal meeting with President Bush at the White House (Barnes 2006).

We study temperature change on El Nino to paleoclimate time scales, thus addressing Crichton's assertions in a context that we hope has broader scientific interest. We first update our analysis of global temperature change, illustrating that the global pattern of warmth in the first half-decade of the 21st century is of the nature of a real climate change, not an artifact of measurement or data processing error. We next compare observed global temperature change with the predictions of transient global climate change that were made in the 1980s. We then show the pattern of current temperature anomalies in the tropical Pacific Ocean, and we suggest that the planet may be on the verge of a super El Nino. By comparing paleoclimate and recent data, we infer that the Earth is now warmer than at any time in the Holocene and poised to reach the warmest level in the past million years. Finally we discuss implications for dangerous human-made climate change.

RECENT GLOBAL TEMPERATURE ANOMALIES. The highest global surface temperature in more than a century of instrumental data was recorded in 2005 in our analysis. However, the estimated uncertainty in the global mean temperature implies that we can only state that 2005 was probably the warmest year.

Our analysis, summarized in Fig. 1, uses documented procedures for data over land (Hansen et al. 2001), satellite measurements of sea surface temperature (SST) since 1982 (Reynolds and Smith 1994), and a ship-based analysis for earlier years (Rayner et al. 2003). Our estimated 2σ error (95% confidence) in comparing nearby years of global temperature (Fig. 1a), such as 1998 and 2005, decreases from 0.1°C at the beginning of the 20th century to 0.05°C in recent decades. Error sources include incomplete station coverage, quantified by sampling a model-generated data set with realistic variability at actual station locations (Hansen and Lebedeff 1987), and partly subjective estimates of data quality problems (Hansen et al. 1999).

Record warmth in 2005 is notable, because global temperature did not receive a boost from an El Nino in 2005. The temperature in 1998, on the contrary, was lifted 0.2°C above the trend line by a "super El Nino" (see below), the strongest El Nino of the past century.

Global warming is now 0.6°C in the past three decades and 0.8°C in the past century. It is no longer correct to say that "most global warming occurred before 1940". A better summary is that there was slow global warming, with large fluctuations, over the century up to 1975 and in the subsequent three decades there has been rapid warming at about 0.2°C per decade. Global warming was about 0.7°C between the late 19th century (the earliest time at which global mean temperature can be accurately defined) and 2000, and continued warming in the first half decade of the 21st century is consistent with the recent rate of +0.2°C/decade.

The map of temperature anomalies for the first half-decade of the 21st century (Fig. 1b), relative to the 1951-1980 climatology, shows that current warmth is nearly ubiquitous, generally larger over land than over ocean, and largest at high latitudes in the Northern Hemisphere. Our ranking of 2005 as the warmest year depends on the positive polar anomalies, especially the unusual Arctic warmth. In calculating the global mean we give full weight to all regions based on area. Although meteorological stations are sparse in the Arctic, the estimated strong warm anomaly there is consistent with record low sea ice concentration in 2005 (Meier et al. 2005).

Our analysis differs from others by including estimated temperature anomalies up to 1200 km from the nearest measurement station (Hansen and Lebedeff 1987). The resulting spatial extrapolations and interpolations of temperature anomalies usually are meaningful for seasonal and longer time scales at middle and high latitudes, where the spatial scale of anomalies is set by Rossby waves (Hansen and Lebedeff 1987). Thus, despite possible extrapolation error, we believe that the unusual Arctic warmth of 2005 is real. Other characteristics of our analysis method are summarized in the Appendix.

The conclusion that global warming is a real climate change, as opposed to an artifact due to location of some measurements near urban populations, is confirmed in many ways. The warming rate is consistent with surface temperature change inferred from temperature profiles in boreholes at remote locations, with the rate of retreat of alpine glaciers around the world, and with progressively earlier breakup of ice on rivers and lakes. Further proof of climate change, as opposed to local urban influence on thermometers, is provided by the geographical distribution of warming (Fig. 1b). The largest warming occurs in remote regions including high latitudes. There is warming over most ocean areas, far from direct human effects, and the ocean warming is less than warming over land, an expected consequence of a forced climate change due to the ocean's great thermal inertia.

EARLY CLIMATE CHANGE PREDICTIONS. Calculations with a global climate model (GCM) of expected global warming due to a doubling of atmospheric carbon dioxide were made by Manabe and Wetherald (1975). The first GCM calculations with transient greenhouse gas amounts, which allow comparison with observations, were those of Hansen et al. (1988). It is the latter simulations that Crichton (2004) asserts were "wrong by 300 percent".

Figure 2 reproduces the simulations that Crichton refers to, labeled A, B and C, which were the scenarios that Hansen et al. (1988) used to bracket likely possibilities. Scenario A was described as "on the high side of reality," because it assumed rapid exponential growth of greenhouse gases and it assumed that there would be no large volcanoes during the next half century. Scenario C was described as "a more drastic curtailment of emissions than has generally been imagined," specifically greenhouse gases were assumed to stop increasing after

2000. Intermediate scenario B was described as “the most plausible.” Scenario B has continued moderate increase in the rate of greenhouse gas emissions and includes three large volcanoes sprinkled through the 50-year period after 1988, one of them in the 1990s. The congressional testimony of Hansen in 1988 included maps of simulated temperature change only for scenario B and the line graph (Fig. 2) for scenarios A, B and C.

Real world climate forcings (Hansen and Sato 2004) have followed a course close to that of scenario B. The real world even had one large volcano in the 1990s, the eruption of Mount Pinatubo, which occurred in 1991, while Scenario B placed a volcano in 1995.

Figure 2 provides quantitative comparison of the simulations with observations. The red curve, as in Hansen et al. (1988), is our observational analysis based on only meteorological stations, using data sets available now (see Appendix). The black curve is the observed land-ocean global temperature index from Fig. 1, which uses SST changes for ocean areas from analyses of Rayner et al. (2003) and Reynolds and Smith (1994). The land-ocean temperature index, which allows more complete coverage of ocean areas, yields slightly smaller long-term temperature change, because warming on average is less over ocean than over land (Fig. 1b).

Temperature change reported in climate models, including that of Hansen et al. (1988), usually refers to temperature of surface air over both land and ocean. Surface air temperature change in a warming climate is slightly larger than the SST change (Hansen et al. 2006), especially in regions of sea ice. Therefore the best observed temperature for comparison with the climate model probably is something between the meteorological station surface air analysis and the land-ocean temperature index.

The general impression from Fig. 2 is that observed warming is comparable to that simulated for scenarios B and C, and substantially smaller than that for scenario A. Modeled global temperature in Fig. 2 starts at a higher value than observations in 1988, so, following Michaels (2000) and Crichton (2004), let us assess "predictions" by comparing the simulated and observed temperature change from 1988 to the most recent year. The modeled 1988-2005 temperature changes are 0.59, 0.33 and 0.40°C, respectively, for scenarios A, B and C. The observed temperature change is 0.31°C and 0.35°C for the land-ocean index and meteorological station analyses, respectively.

The decadal warming rates in the model are 0.35, 0.19 and 0.24°C/decade for scenarios A, B and C., and 0.18°C/decade and 0.21°C/decade for the two observational analyses. Forcings in scenarios B and C are nearly the same up to 2000, so the different responses provide one measure of unforced variability in the model. Because of this chaotic variability a 17-year period is too brief for precise assessment of model predictions, but distinction among scenarios and comparison with the real world will become clearer within a decade.

The close agreement between observed temperature change and the most realistic climate forcing scenario (scenario B) is, of course, accidental, in view of the large unforced variability in both model and real world. Furthermore the sensitivity of the model employed by Hansen et al. (1988), 4.2°C for doubled CO_2, is larger than the best estimate for actual climate sensitivity, which is 3 ± 1°C for doubled CO_2, based mainly on paleoclimate data (Hansen 2005a). In addition, more complete analyses of the industrial era need to include additional climate forcings and cover longer simulation periods. Nevertheless, despite the simplicity of the first transient climate predictions of Hansen et al. (1988), it is apparent that they proved remarkably accurate and certainly were not "in error by 300%" (Crichton 2004).

SUPER EL NINO IN 2006-2007? We suggest that an El Nino is likely to originate in 2006 and that there is a good chance it will be a "super El Nino", rivaling the 1983 and 1997-1998 El Ninos, which were successively labeled the "El Nino of the century" as they were of unprecedented strength in the previous 100 years (Fig. 1 of Fedorov and Philander 2000). Further, we argue that global warming causes an increase of such "super El Ninos". Our rationale is based on interpretation of dominant mechanisms in the ENSO (El Nino Southern Oscillation) phenomenon, examination of historical SST data, and observed Pacific Ocean SST anomalies in February 2006.

In the "normal", La Nina, phase of ENSO the east-to-west trade winds push warm equatorial surface waters far to the west such that some of the warmest SSTs on the planet are located in the West Pacific Warm Pool. In this normal state the thermocline is shallow in the East Pacific near the coast of South America, where upwelling of cold deep water occurs, and deep in the West Pacific (Fig. 2 of Cane 2005). Associated with this tropical SST gradient across the Pacific is a longitudinal circulation pattern in the atmosphere, the Walker Cell, with generally rising motions and heavy rainfall in the West Pacific and sinking motions and drier conditions in the East Pacific. This Walker circulation enhances upwelling in the East Pacific, causing a powerful positive feedback, the Bjerknes (1969) feedback, which tends to maintain the La Nina phase, as the temperature gradient and the resulting higher pressure in the East Pacific support east-to-west trade winds.

This normal state is occasionally upset when, by chance, the east-to-west trade winds slow down, allowing the warm water piled up in the west to slosh back in the direction of South America. If the chance fluctuation is large enough, the Walker circulation breaks down and the Bjerknes feedback loses power. As the east-to-west winds weaken, the Bjerknes feedback works in reverse, and warm waters move more strongly toward South America, reducing the thermocline tilt and cutting off the upwelling of cold water along the South American coast. In this way a classical El Nino is born.

Given the high degree of chaos in weather and climate, there is great variability among El Ninos and some arbitrariness in the definition of when one has occurred. Enough time since the preceding El Nino needs to elapse for the West Pacific to "recharge" with warm water and for the thermocline to regain its strong tilt such that it is deep in the West Pacific and approaches the surface near South America. An El Nino has the best chance of forming in Northern Hemisphere spring, when the Intertropical Convergence Zone (ITCZ) is close to the equator, SST is a maximum, and equatorial upwelling is weakest. Thus, as Mark Cane (priv. comm.) has stated, once the West Pacific is recharged, we can think of Mother Nature as "rolling the dice" each spring to see if there will be an El Nino.

Figure 3a shows global surface temperature in a six-month period (September 1996 through February 1997) preceding the 1997-1998 El Nino (Fig. 3b). The temperature pattern in the equatorial Pacific region in September 2005 through February 2006 (Fig. 3c) is nearly identical to that of nine years earlier. Subsurface temperatures are now "recharged", i.e., the ocean is ready to launch the next El Nino (http://www.pmel.noaa.gov/tao/realtime.html).

Figure 3d, the temperature anomaly for the most recent month (February 2006), shows that a substantial warm SST anomaly has appeared near South America, comparable in strength to the warm anomaly that appeared in March 1997. Coupled with the movement of the cool anomaly across the date line (Fig. 3d), the temperature gradient along the equator is now such that it should weaken the Walker Circulation and the Bjerknes feedback. Thus we suggest that there is a high probability that an El Nino will develop in 2006. Warm anomalies near Peru are not uncommon in La Nina years, but this anomaly is already substantial in February.

We argue further that global warming has increased the likelihood of "super El Ninos", such as those that occurred in 1983 and 1997-1998. This impact of global warming, if true, is important, because the extreme global climate anomalies associated with super El Ninos are more devastating than the effects of more moderate El Ninos. Our inference is based on a simple physical argument, as we wish to skirt the fact that neither climate models (Collins et al. 2005) nor theory (Fedorov and Philander 2000; Cane 2005) as yet provide a clear answer for the effect of global warming on El Ninos.

Figure 4 shows that the Pacific equatorial temperature gradient has increased over the past century. The difference between East and West Pacific SSTs has grown exceptionally large in the past few years (Fig. 5). This change is due to warming in the West Pacific, as there is negligible trend in East Pacific SST over 135 years. Note in Fig. 5b,c the exceptional ("super") El Ninos of 1983 and 1997. The specific locations of these SST anomalies in the East and West Pacific coincide with sites of paleoclimate data discussed below.

Our rationale is that an unusually warm West Pacific SST, with normal East Pacific SST, yields the potential for a super El Nino. If the Bjerknes feedback maintaining strong easterlies relaxes, as seems likely with the occurrence of a warm East Pacific anomaly such as that of February 2006, the water that sloshes toward the East Pacific will be unusually hot. Inspection of the maps in Fig. 3, in Plates 9a and 9b of Hansen et al. (1999), and in maps for all years since 1880 available at http://data.giss.nasa.gov/gistemp, reveals that the 1983 and 1997 super El Ninos were preceded by 0.5-1°C anomalies in the West Pacific, while none of the El Ninos earlier in the century had such large preceding anomalies.

We make no suggestion about changes of El Nino frequency, and we note that an abnormally warm West Pacific does not assure a strong El Nino. The origin and nature of El Ninos is affected by chaotic ocean and atmosphere variations, the season of the driving anomaly, the state of the thermocline, and other factors, so we infer only that unusually high temperatures in the West Pacific increase the potential for super El Ninos.

Will the increased contrast between West and East Pacific SSTs be maintained or even increase with further global warming? Clement et al. (1996) propose an ocean dynamical thermostat mechanism that could account for the absence of warming in the East Pacific. Using the Zebiac and Cane (1987) perturbation model for ENSO, they find that a uniform positive (warming) forcing increases upwelling of cold water in the East Pacific. SST change in the past century (Fig. 4) seems consistent with this mechanism. On long time scales the temperature of source waters for upwelling may increase, but, to the extend that Antarctic Intermediate Water is a contributing source for upwelling water in the East Pacific (Pierrehumbert 2000), it seems likely that the contrast between East and West Pacific temperatures will continue to increase in the foreseeable future.

This conclusion suggests an interpretation of the effect of global warming on El Ninos analogous to that inferred by Emanuel (1987) for the effect of global warming on tropical storms. For both El Ninos and tropical storms the effect of global warming on the frequency of the phenomenon is unclear, because that depends on many factors, but the intensity of the most powerful events is likely to increase.

MODERN VS PALEO TEMPERATURES. Modern SST measurements are compared with proxy paleoclimate temperature in the Pacific Warm Pool (Ocean Drilling Program site 806B, 0° 19’ N, 159° 22’ E; the site is circled in Fig. 4) in Fig. 6. Paleoclimate data is from Medina-Elizade and Lea (2005), while modern data is from Rayner et al. (2003) for 1870-1981 and subsequently from satellite data of Reynolds and Smith (1994). In the concatenation of Reynolds and Smith data with Rayner et al., as illustrated in Fig. 5a, we adjust Reynolds and Smith temperatures down slightly so that the 1982-1992 mean temperature matches Rayner et al.

The paleoclimate SST is based on the Mg content of foraminifera shells, which provides an accuracy of the order of 1°C (Lea at el. 2000). Thus we cannot be sure that we have precisely aligned the paleo and modern temperature scales. Accepting the paleo and modern temperatures at face value implies that the 1870 SST in the Warm Pool was in the middle of the Holocene temperature range. If we were to shift the scale to align the 1870 SST with the lowest Holocene value, this would raise the paleo curve at most by ~0.4°C. Even with such a shift, the 2001-2005 SST in the Warm Pool exceeds any Holocene proxy temperature at that location, and note in Figure 5a that the Pacific Warm Pool is ~0.2°C warmer in 2005 than the 2001-2005 average.

We argue that the Tropical Pacific is a primary driver of the global atmosphere and ocean, and that the temperature of the Warm Pool is of fundamental importance. The tropical Pacific atmosphere-ocean system is the main source of heat transported by both the Pacific and Atlantic Oceans (Pierrehumbert 2000). Heat and water vapor fluxes to the atmosphere in the Pacific also have a profound effect on the global atmosphere, as demonstrated by ENSO climate variations. As a consequence, warming of the Pacific ultimately has worldwide repercussions. Even distant local effects, such as the thinning of ice shelves, are affected on decade-to-century time scales by subtropical Pacific waters that are subducted and mixed with Antarctic Intermediate Water and thus with the Antarctic Circumpolar Current.

Thus it is probably not an exaggeration to say “as the Pacific goes, so goes the world”, a contention implied by Pierrehumbert (2000) and Lea (2004). It seems a fairly safe bet that if the Warm Pool is at a record warm temperature in the Holocene, so is global temperature. However, let us examine that issue more closely.

Figure 7 compares proxy temperatures for the past 150 thousand years with instrumental temperatures for the past century at several locations. The Indian Ocean, due to rapid warming in the past 3-4 decades, is now warmer than at any time during the Holocene, independent of any plausible shift of the modern temperature scale relative to the proxy Holocene temperature. In contrast, the East Equatorial Pacific and Central Antarctica (Vostok) do not show significant warming this century and are probably cooler than their Holocene peak values. However, as shown in Figs. 1 and 4, those are small exceptional regions, as most of the world, and the global mean, have warmed by an amount at least as great as observed in the West Pacific. We infer that global temperature today is at its highest level in the Holocene.

There is further rationale for the latter conclusion. The pattern of global temperature response to most climate forcings, natural and human-made, is congruent (Hansen et al. 2005), with a pattern that has larger response over land than over ocean and general polar amplification. This pattern is consistent with glacial to interglacial temperature changes of ~3-5°C in the tropics, ~10°C in polar regions, and ~5°C on global average, and with the fact that glacial to interglacial temperature changes are largely accounted for by greenhouse gas and surface albedo changes (Hansen 2005a). Thus, to first order, the temperature change in a fundamental region such as the Pacific Warm Pool (Fig. 6) has global significance.

Figure 6 suggests that the recent rapid warming of the Pacific Warm Pool has brought its temperature within several tenths of a degree Celsius of its maximum value during the past million years. There is extensive evidence that the peak Eemian (marine isotope stage 5e) temperature exceeded that in the Holocene by 1-2°C (Lea et al. 2006), but comparison of 5e SSTs with today’s level is dependent on the absolute calibrations for the proxies. The paleoclimate evidence of Lea et al. (2006) is consistent with Fig. 6 and our conclusion that the Earth is now within ~1°C of its maximum temperature in the past million years, because recent rapid warming has lifted the current temperature out of the prior Holocene range. We infer that global temperature today is probably within ~1°C of its maximum value of the past million years.

DANGEROUS HUMAN-MADE WARMING. Considerations of "dangerous anthropogenic interference" (DAI) with global climate often focus upon possible dynamical instabilities of the climate system. Much attention has been placed on possible slowdown or shutdown of the Atlantic thermohaline circulation, described as the potential "Achilles heel" of the climate system, sometimes with fanciful discussion of effects in Europe or the United States. We argue that global temperature itself is the best metric for assessing proximity to DAI, as global temperature is related straightforwardly to the principal dangers that the Earth faces.

We suggest that two principal foci in considerations of DAI should be sea level and extinction of species. Further, it is useful to contrast two distinct scenarios for the future: (1) "Business-as-Usual" growth of climate forcings, which, for nominal climate sensitivity yields a global warming of at least 2.5-3°C by the end of this century (IPCC 2001), (2) an "Alternative Scenario" in which aggressive programs to limit both CO_2 and non-CO_2 forcings are undertaken promptly, such that additional global warming (above the temperature in 2000) never reaches 1°C. The Alternative Scenario requires declining CO_2 emissions and an absolute decrease in atmospheric amount of some non-CO_2 forcings, e.g., one specific combination of forcings has CO_2 peaking at 475 ppm in 2100 and a sufficient decrease of CH_4, O_3 and black carbon aerosols to balance continued increase of N_2O and decrease of sulfate aerosols (Hansen et al. 2006).

Sea level implications of Business-as-Usual and Alternative scenarios can be considered in two steps: the equilibrium (long-term) sea level change and the ice sheet response time. Global warming under 1°C would keep maximum temperature close to the peak of the warmest interglacial periods during the past million years. Sea level may have been a few meters higher than today in some of these periods. For comparison, sea level was 25-35 meters higher the last time that the Earth was 2.5-3°C warmer than today, i.e., during the Middle Pliocene about three million years ago (Dowsett et al. 1994).

Ice sheet response time, and thus the potential rate of sea level rise, can be judged from empirical evidence, but this is limited by imprecise dating of climate and sea level changes, and by the fact that paleoclimate forcings changed more slowly than the human-made forcing. In some cases sea level rise lagged tropical temperature change by a few thousand years (Medina-Elizalde and Lea 2005), while in others, such as Meltwater Pulse 1A about 14,000 years ago (Kienast et al. 2003), sea level rise and tropical temperature increase were nearly synchronous. Hansen (2005b) argues that Business-as-Usual warming would assure that ice sheet disintegration is a wet process and that a substantial fraction of the response must occur within centuries.

Thus sea level rise in the Alternative Scenario may be significant, possibly of the order of 1 meter/century. However, this is dwarfed by the disastrous Business-as-Usual, which may yield sea level rise as much as several meters per century with an unstoppable eventual rise of tens of meters, enough to transform global coastlines.

Extinction of animal and plant species present a picture analogous to that of sea level for the Alternative and Business-as-Usual scenarios. Extinctions are already occurring as a result of a variety of stresses, mostly human-made, climate change being only one factor (Hare 2003).

Changes of precipitation and temperature patterns cause stress and induce change, as, indeed, the global distribution of plants and animals are a reflection of such climate parameters. Thus plants and animals attempt to migrate in response to climate change, but their paths may be blocked by human-imposed or natural barriers, such as coast lines.

Parmesan and Yohe (2003), in a study of 1700 biological species, find a poleward migration rate of 6 km/decade and vertical migration in alpine regions of 6 m/decade in the second half of the twentieth century. Not all species are equally mobile, and ecosystems involve interactions among species, so even these rates cause noticeable stress. Thomas et al. (2004) conclude that climate change will have severe impact on species survival because of interactions with other stresses, habitat loss and fragmentation, and new invasive species.

Flannery (2005) estimates that 1°C global warming, the upper limit of the Alternative Scenario, may cause 20% species loss by the end of the century, and Business-as-Usual would eliminate a majority of species (about 60%). Such projections are speculative but not out of line with the Business-as-Usual effects at mid-century in the study of Thomas et al. (2004) or the sensitivity of stress effects to scenario tabulated by Hare (2003).

These staggering implications of Business-as-Usual, for sea level and species, reflect the fact that 2.5-3°C global warming would yield “a different planet” (Hansen 2005a). The Arctic would become ice free in the warm season and seasonal mean temperature in land areas would increase by 5-10 times the standard deviation of seasonal temperature during the 20th century (Hansen et al., 2006). Thus many species at high latitudes, alpine regions, and near coastal borders would, under Business-as-Usual, in effect be pushed off the planet.

In contrast, climate changes and their impacts are relatively mild in the Alternative Scenario. Even the Arctic sea ice can be saved, if the forcings that are especially effective there, such as methane, ozone and black carbon are reduced to partially compensate for CO_2 increase (Hansen et al. 2006). The optimistic Alternative Scenario remains feasible today, but another decade of business-as-usual growth of emissions is likely to make it infeasible (Hansen et al. 2006).

APPENDIX: TEMPERATURE ANALYSIS

Analyses of global temperature change by different groups, particularly, NASA Goddard Institute for Space Studies (GISS), the NOAA National Climate Data Center (NCDC), and the combination of the British Meteorological Office and the University of East Anglia (BMO/UEA), are generally in close agreement. The ranking of individual years, however, often depends upon differences of only several hundredths of a degree, which is finer than the accuracy that any method can claim given observational limitations.

One major source of differences is the fact that the GISS method extrapolates temperature anomalies to all areas that have at least one station located within 1200 km, using weights for these stations that decrease linearly with distance from the station. At any given location the temperature anomaly estimated in this way can be substantially in error, but the resulting increase of spatial coverage usually allows an improved estimate of the global temperature anomaly, as judged from tests made using spatially and temporally complete data sets generated by a general circulation model (Hansen and Lebedeff 1987). However, in some cases this method increases the error by giving undue weight to a single isolated station with anomalous temperature.

Another source of difference is the method of averaging over the world, given the fact that data is not available everywhere. In the GISS method, the Earth is divided into four latitude belts. Within each belt all regions having at least one station within 1200 km are included and weighted by area. The anomaly for the entire belt is taken as the anomaly for the portion of the belt that is thus defined. The global anomaly is then the area-weighted mean of the four belts. This method gives equal weight to the hemispheres, but if one of the belts has little data and if that data is not actually representative of the entire belt, substantial error can occur.

The land (meteorological stations) data sets in the GISS, NCDC and BMO/UEA analyses have considerable commonality, but they are not identical. Our approach, described in more detail by Hansen et al. (1999), uses GHCN (Global Historical Climatology Network) meteorological station data obtained from NCDC supplemented by Antarctic station data from the British Antarctic Survey website (www.Antarctica.ac.uk/climate /surfacetemps). Quality control of GHCN data relies primarily on data checking at NCDC, described by Peterson et al. (1998), which occurs prior to our receipt of the data. Additional quality check at GISS is minimal, as described by Hansen et al. (1999), e.g., flagging stations with temperatures that differ by five standard deviations from their long-term mean, so that these can be checked against neighboring stations. Urban station data are adjusted so that the long-term trend of the urban station matches that of neighboring rural stations, with the distinction between urban and rural based on either population or nightlights observed by satellite (Hansen et al. 2001).

Our ocean data is version 2 of the "OI" analysis of Reynolds and Smith (1994) for the period of satellite data, i.e., after 1982. Earlier ocean data is from Rayner et al. (2003). These two ocean data sets are combined by working with anomalies for both data sets and defining anomalies relative to a common period, specifically 1982-1992.

Two minor changes in our analysis were made in March 2006 for the sake of simplicity and transparency. First, our calculation of global temperature anomaly, which had been based on a rather complex way of combining anomalies of sub-boxes, boxes, and latitude zones, as described by Hansen and Lebedeff (1987), was replaced by simple integration over the globe of the mapped anomalies at resolution 2° by 2°. Division of the globe into four latitude zones, each weighted by area, was retained, thus affording high latitudes full weight even if the region is data sparse. Second, the ocean area where we used data of Rayner et al. (2003) was reduced to be identical to the ocean area where data are reported by Reynolds and Smith (1994). This eliminated the time variation of ocean area that occurs in the Rayner et al. data as sea ice area changes. Temperature anomalies at the times and small areas where Rayner et al. (2003) data are no longer used are based on weighted means of anomalies in all gridboxes within 1200 km, thus giving slightly more weight to surface air measurements as opposed to SST. The net effect of these two changes on global temperature can be as much as a few hundredths of a degree.

REFERENCES

Barnes, F., 2006: *Rebel in Chief: Inside the Bold and Controversial Presidency of George W. Bush*, Crown Forum, New York, 24 pp.

Bjerknes, J., 1969: Atmospheric teleconnections from the equatorial Pacific. *Mon. Wea. Rev.* **97**, 163-172.

Cane, M.A., 2005: The evolution of El Nino, past and future. *Earth Plan. Sci. Lett.* **230**, 227-240.

Clement, A.C., R. Seager, M.A. Cane and S.E. Zebiak, 1996: An ocean dynamical thermostat, *J. Climate* **9**, 2190-2196.

Collins, M. and CMIP Modeling Groups, 2005: El Nino- or La Nina-like climate change? *Clim. Dyn.*, **24**, 89-104.

Crichton, M., 2004: *State of Fear*, Harper Collins, New York, 624 pp.

Dowsett, H. et al., 1994: Joint investigations of the Middle Pliocen climate I: PRISM paleoenvironmental reconstructions. *Global Plan. Change* **9**, 169-195.

Emanuel, K., 1987: The dependence of hurricane intensity on climate. *Nature,* **326**, 483-485.

Fedorov, A.V. and S.G. Philander, 2000: Is El Nino changing? *Science* **288**, 1997-2002.

Flannery, T., 2005: *The Weather Makers*, Atlantic Monthly Press, New York, 357 pages.

Hansen, J. and S. Lebedeff, 1987: Global trends of measured surface air temperature. *J. Geophys. Res.* **92**, 13345-13372.

Hansen, J., I. Fung, A. Lacis, D. Rind, S. Lebedeff, R. Ruedy, G. Russell and P. Stone, 1988: Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model. *J. Geophys. Res.*, **93**, 9341-9364.

Hansen, J., R. Ruedy, J. Glascoe, and M. Sato, 1999: GISS analysis of surface temperature change. *J. Geophys. Res.* **104**, 30997-31022.

Hansen, J., R. Ruedy, M. Sato, M. Imhoff, W. Lawrence, D. Easterling, T. Peterson, and T. Karl, 2001: A closer look at United States and global surface temperature change. *J. Geophys. Res.* **106**, 23947-23963.

Hansen, J. and M. Sato, 2004: Greenhouse gas growth rates. *Proc. Natl. Acad. Sci.* **101**, 16109-16114.

Hansen, J., 2005a: Is there still time to avoid 'dangerous anthropogenic interference' with global climate? A tribute to Charles David Keeling, Amer. Geophys. Union, U23D-01, Dec. 6, avail http://www.columbia.edu/~jeh1/

Hansen, J., 2005b: A slippery slope: How much global warming constitutes "dangerous anthropogenic interference"? *Clim. Change* **68**, 269-279.

Hansen, J. et al., 2005: Efficacy of climate forcings. *J. Geophys. Res.* **110**, D18104, doi:10.1029/2005JD005776.

Hansen, J. et al., 2006: Dangerous human-made interference with climate: a GISS modelE study. Submitted to *J. Geophys. Res.*

Hare, W., 2003: Assessment of Knowledge on Impacts of Climate Change, www.wbgu.de/wbgu_sn2003.html

Intergovernmental Panel on Climate Change (IPCC), 2001: *Climate Change 2001: The Scientific Basis*, J.T. Houghton *et al.*, Eds. (Cambridge Univ. Press, New York.

Kienast, M., T.J.J. Hanebuth, C. Pelejero and S. Steinke, 2003: Synchroneity of Meltwater Pulse 1A and the Bolling warming: New evidence from the South China Sea. *Geology* **31**, 67-70.

Lea, D.W., D.K. Pak and H.J. Spero, 2000: Climate impact of late Quaternary equatorial Pacific sea surface temperature variations. *Science*, **289**, 1719-1724.

Lea, D.W., 2004: The 100,000-Yr cycle in tropical SST, Greenhouse forcing, and climate sensitivity. *J. Climate*, **17**, 2170-2179.

Lea, D.W., D.K. Pak, C.L. Belanger, H.J. Spero, A.M. Hall, and N.J. Shackleton, 2006: Paleoclimate history of Galapagos surface waters over the last 135,000 years. *Quaternary Sci. Rev.* (in press).

Manabe, S. and R.T. Wetherald, 1975: The effects of doubling the CO_2 concentration on the climate of a general circulation model. *J. Atmos. Sci.*, **32**, 3-15.

Medina-Elizade, M. and D.W. Lea, 2005: The mid-Pleistocene transition in the tropical Pacific. *Science* **310**, 1009-1012.

Meier, W., J. Stroeve, F. Fetterer, T. Arbetter, W.N. Meier, J. Maslanik, and K. Knowles, 2005: Reductions in Arctic sea ice cover no longer limited to summer. *EOS Trans. Amer. Geophys. Union* **86**, 326.

Michaels, P.J., 2000: Transcript of Science Policy Forum. *Social Epistemology*, **14**, 131-180.

Peterson, T.C., R. Vose, R. Schmoyer and V. Razuvaev, 1998: Global historical climatology network (GHCN) quality control of monthly temperature data. *Int. J. Climatol.* **18**, 1169-1179.

Pierrehumbert, R.T., 2000: Climate change and the tropical Pacific: The sleeping dragon wakes. *Proc. Natl. Acad. Sci.*, **97**, 1355-1358.

Reynolds, R.W. and T.M. Smith, 1994: Improved global sea surface temperature analyses. *J. Clim.* **7**, 929-948.

Rayner, N.A., D.E. Parker, E.B. Horton, C.K. Folland, L.V. Alexander, D.P. Rowell, E.C. Kent, and A. Kaplan, 2003: Global analyses of SST, sea ice and night marine air temperatures since the late nineteenth century. *J. Geophys. Res.* **108**, doi:10.1029/2002JD002670.

Saraswat, R., R. Nigam, S. Weldeab, A. Mackensen and P.D. Naidu, 2005: A first look at past sea surface temperatures in the equatorial Indian Ocean from Mg/Ca in foraminifera. *Geophys. Res. Lett.*, **32**, L24605, doi:10.29/2005GL024093.

Senate Testimony, 2005: *The Role of Science in Environmental Policy-Making.* Hearing of the U.S. Senate Committee on Environment and Public Works, September 28.

Thomas, C.D. et al., 2004 : Extinction risk from climate change. *Nature* **427**, 145148.

Trenberth, K.E. and T.J. Hoar, 1997: El Nino and climate change, *Geophys. Res. Lett.*, **24**, 3057-3060.

Vimeux, F., K.M. Cuffey and J. Jouzel, 2002: New insights into Southern Hemisphere temperature changes from Vostok ice cores using deuterium excess correction. *Earth Planet. Sci. Lett.*, **203**, 829-843.

Zebiak, S.E. and M.A. Cane, 1987: A model El Nino/Southern Oscillation. *Mon. Wea. Rev.*, **115**, 2262-2278.

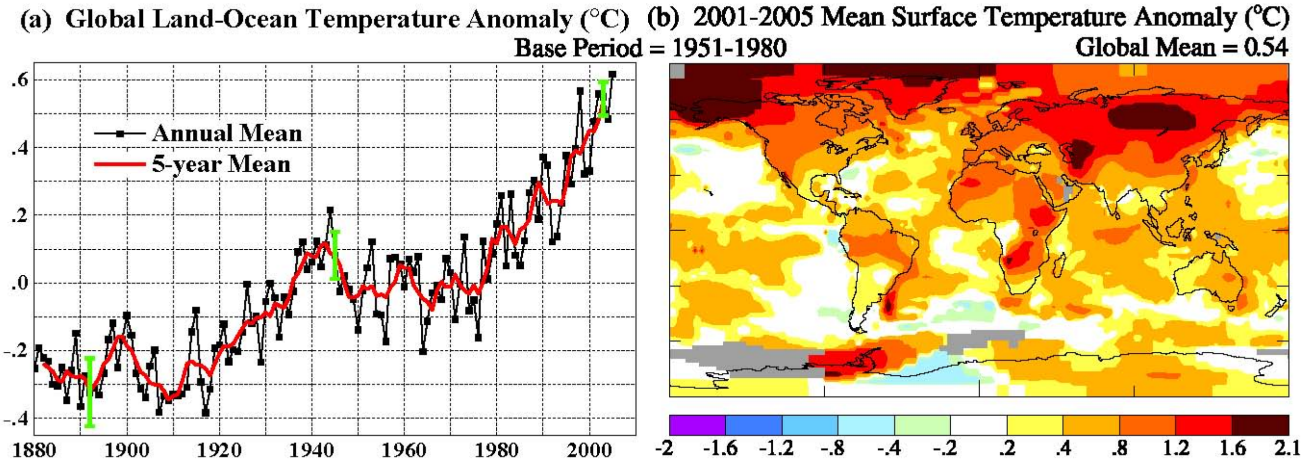

Fig. 1. (a) Global annual surface temperature relative to 1951-1980 mean based on surface air measurements at meteorological stations and ship and satellite measurements for sea surface temperature. (b) Surface temperature anomaly for the first five years of the 21st century.

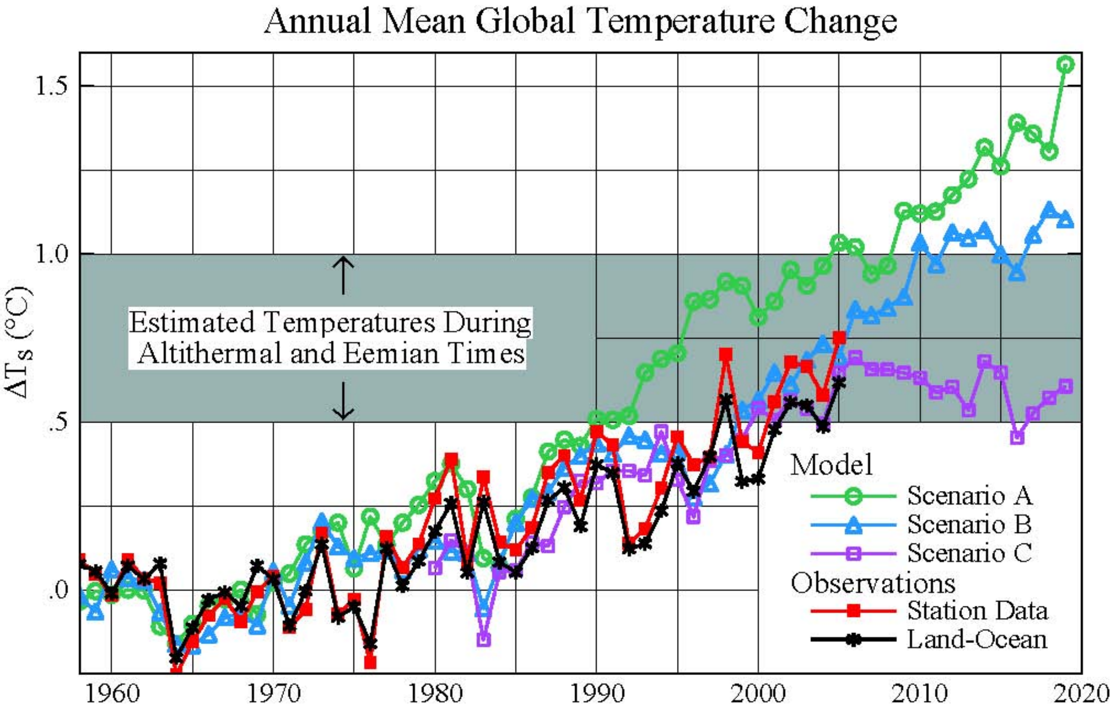

Fig. 2. Global surface temperature computed by Hansen et al. (1988) for scenarios A, B and C, compared with observed global temperature based on two alternative analyses of observational data. The 'station data' result is an update of the temperature analysis of Hansen et al. (1988) that employs only meteorological stations, while the 'land-ocean' temperature index adds SST data for ocean areas. The 0.5°C and 1°C temperature levels, relative to 1951-1980, were estimated by Hansen et al. (1988) to be the maximum global temperature in the Holocene and the prior interglacial period, respectively.

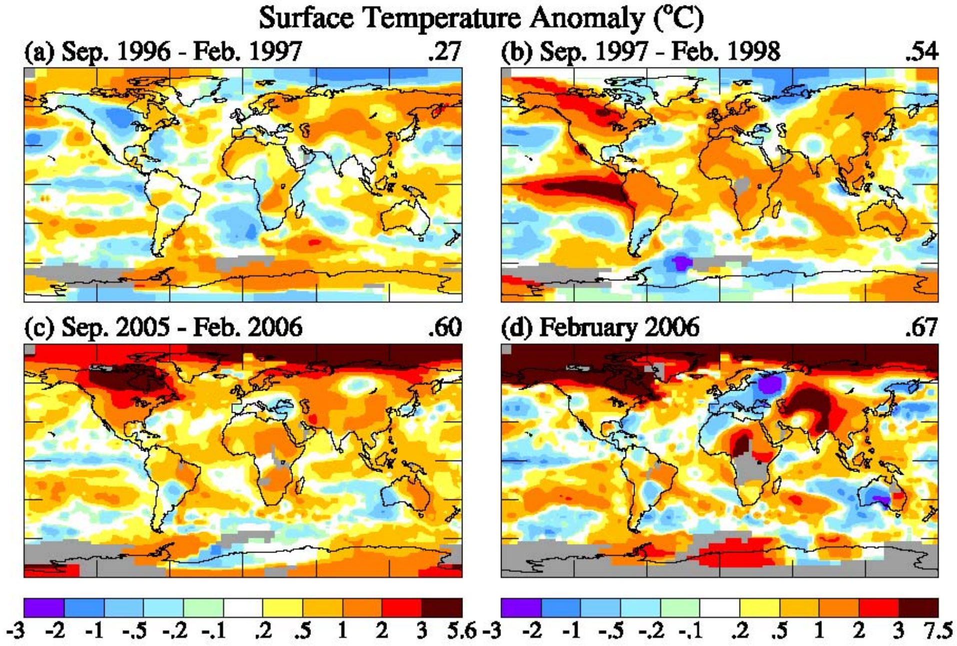

Fig. 3. (a) and (c) compare 6-month September-February surface temperature anomalies relative to 1951-1980 for the time preceding the "super El Nino" of 1997-1998 and the current year. (b) is the same period of year, but during the 1997-1998 El Nino. (d) is the February 2006 anomaly relative to 1951-1980 Februaries.

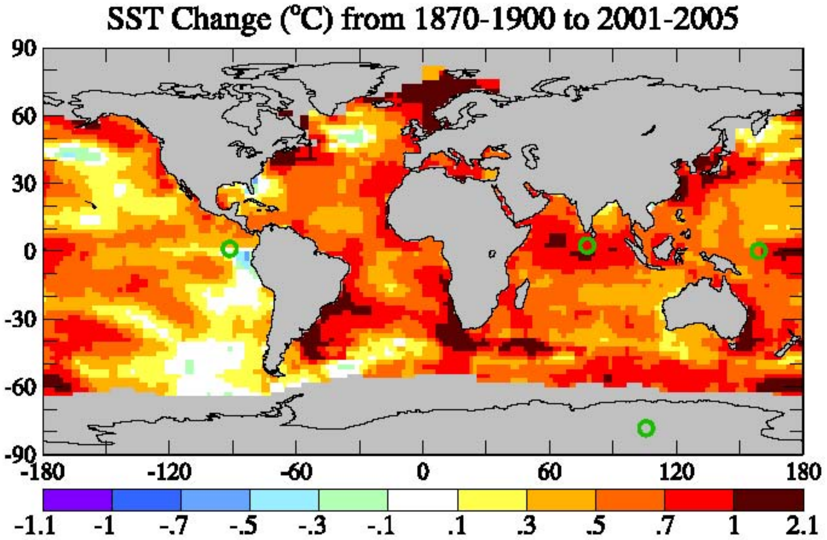

Fig. 4. SST during 2001-2005 relative to 1870-1900 mean, with the 2001-2005 data being the concatenated data set (combination of Reynolds and Smith 1994 with Rayner et al. 2003) and with the 1870-1900 data from Rayner et al. (2003).

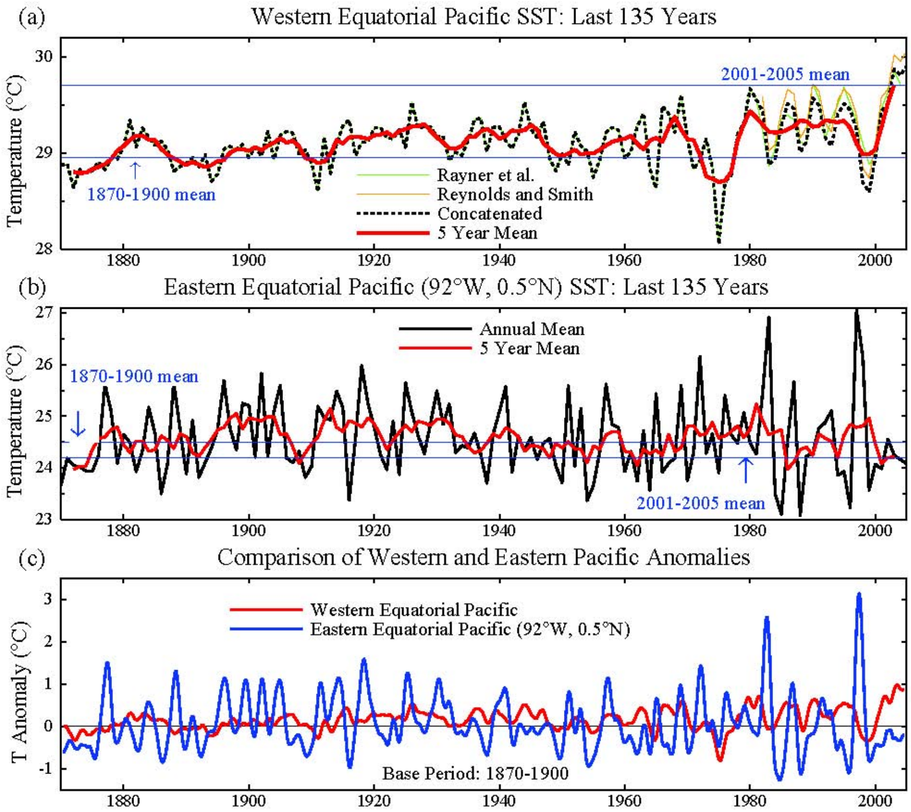

Fig. 5. SSTs in the Western and Eastern Pacific based on Rayner et al. (2003) for 1870-1981 and subsequently on satellite data of Reynolds and Smith (1994). Reynolds and Smith data are adjusted by a small constant, as shown explicitly in (a) so that 1982-1992 mean temperature matches that of Rayner et al. (c) is the 12-month running mean of the two time series relative to their 1870-1900 means.

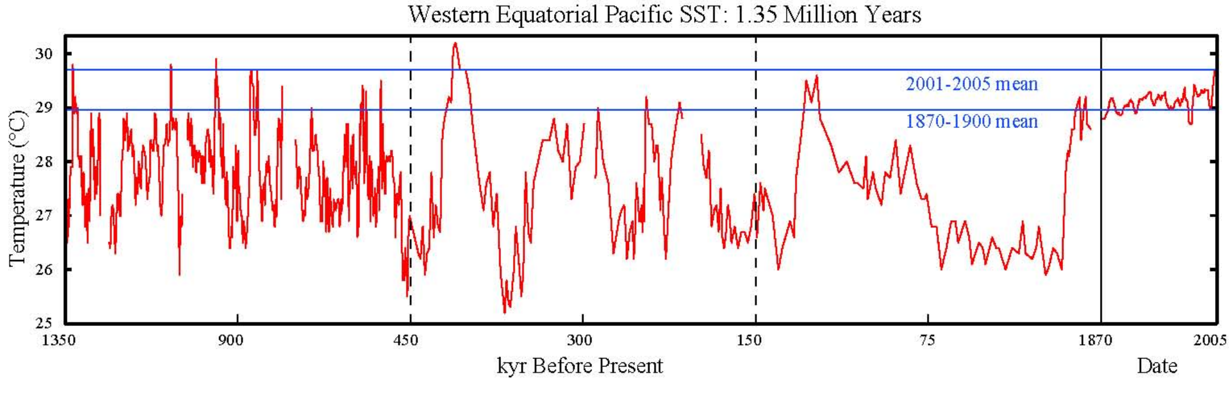

Fig. 6. Comparison of modern SST measurements with proxy paleoclimate temperature in the Pacific Warm Pool. Paleoclimate data is from Medina-Elizade and Lea (2005), while modern data is from Rayner et al. (2003) for 1870-1981 and subsequently from satellite data of Reynolds and Smith (1994). In the concatenation, as shown in Fig. 5a, the Reynolds and Smith data are adjusted slightly so that 1982-1992 mean temperatures match those of Rayner et al.

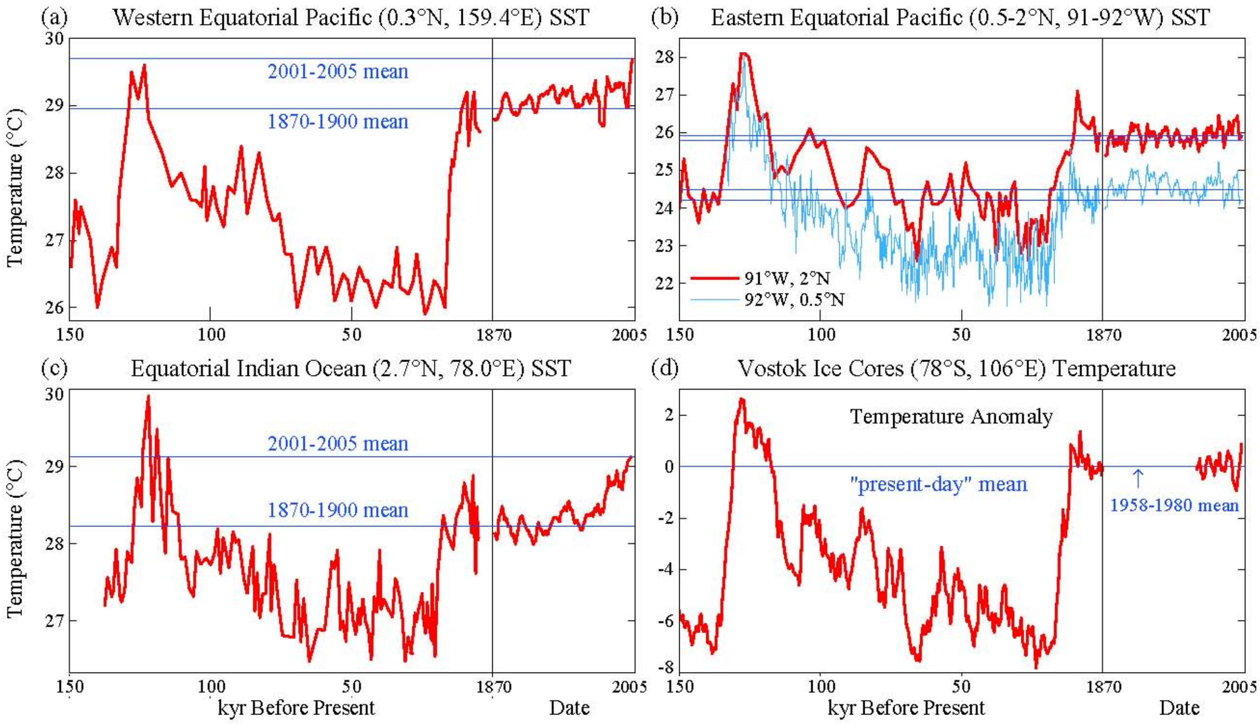

Fig. 7. Comparison of modern surface temperature measurements with paleoclimate proxy data. The modern data are based on Rayner et al. (2003) for 1870-1981 and subsequently on satellite data of Reynolds and Smith (1994) adjusted as in Fig. 5. Paleoclimate data sources are Western Pacific (Medina-Elizade and Lea 2005), Eastern Pacific (Lea et al. 2000, 2004, 2006), Indian Ocean (Saraswat et al. 2005), and Vostok Antarctica (Vimeux et al. 2002).