Global temperature change

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Global surface temperature has increased ≈0.2°C per decade in the past 30 years, similar to the warming rate predicted in the 1980s in initial global climate model simulations with transient greenhouse gas changes. Warming is larger in the Western Equatorial Pacific than in the Eastern Equatorial Pacific over the past century, and we suggest that the increased West–East temperature gradient may have increased the likelihood of strong El Niños, such as those of 1983 and 1998. Comparison of measured sea surface temperatures in the Western Pacific with paleoclimate data suggests that this critical ocean region, and probably the planet as a whole, is approximately as warm now as at the Holocene maximum and within ≈1°C of the maximum temperature of the past million years. We conclude that global warming of more than ≈1°C, relative to 2000, will constitute ''dangerous'' climate change as judged from likely effects on sea level and extermination of species.

climate change | El Niños | global warming | sea level | species extinctions

Global temperature is a popular metric for summarizing the state of global climate. Climate effects are felt locally, but the global distribution of climate response to many global climate forcings is reasonably congruent in climate models (1), suggesting that the global metric is surprisingly useful. We will argue further, consistent with earlier discussion (2, 3), that measurements in the Western Pacific and Indian Oceans provide a good indication of global temperature change.

We first update our analysis of surface temperature change based on instrumental data and compare observed temperature change with predictions of global climate change made in the 1980s. We then examine current temperature anomalies in the tropical Pacific Ocean and discuss their possible significance. Finally, we compare paleoclimate and recent data, using the Earth's history to estimate the magnitude of global warming that is likely to constitute dangerous human-made climate change.

Modern Global Temperature Change

Global surface temperature in more than a century of instrumental data is recorded in the Goddard Institute for Space Studies analysis for 2005. Our analysis, summarized in Fig. 1, uses documented procedures for data over land (4), satellite measurements of sea surface temperature (SST) since 1982 (5), and a ship-based analysis for earlier years (6). Estimated 2σ error (95% confidence) in comparing nearby years of global temperature (Fig. 1*A*), such as 1998 and 2005, decreases from 0.1°C at the beginning of the 20th century to 0.05°C in recent decades (4). Error sources include incomplete station coverage, quantified by sampling a model-generated data set with realistic variability at actual station locations (7), and partly subjective estimates of data quality problems (8). The estimated uncertainty of global mean temperature implies that we can only state that 2005 was probably the warmest year.

The map of temperature anomalies for the first half-decade of the 21st century (Fig. 1*B*), relative to 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. Meteorological stations are sparse in the Arctic, but the estimated strong warm anomaly there in 2005 is consistent with record low sea ice concentration and Arctic temperature anomalies inferred from infrared satellite data (9).

Our analysis includes estimated temperature anomalies up to 1,200 km from the nearest measurement station (7). 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 (7). Thus, we believe that the unusual Arctic warmth of 2005 is real. Other characteristics of our analysis method are summarized in *Supporting Text*, which is published as supporting information on the PNAS web site.

Independent analysis by the National Climate Data Center (www.ncdc.noaa.gov/oa/climate/research/2005/ann/global.html), using a ''teleconnection'' approach to fill in data sparse regions, also finds 2005 to be the warmest year. The joint analysis of the University of East Anglia and the Hadley Centre (www.met-office.gov.uk/research/hadleycentre/obsdata/globaltemperature.html) also yields high global temperature for 2005, but a few hundredths of a degree cooler than in 1998.

Record, or near record, warmth in 2005 is notable, because global temperature did not receive a boost from an El Niño in 2005. The temperature in 1998, on the contrary, was lifted 0.2°C above the trend line by a ''super El Niño'' (see below), the strongest El Niño 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 ''most global warming occurred before 1940.'' A better summary is: slow global warming, with large fluctuations, over the century up to 1975, followed by rapid warming at a rate ≈0.2°C per decade. Global warming was ≈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 per decade.

The conclusion that global warming is a real climate change, not an artifact due to measurements in urban areas, is confirmed by surface temperature change inferred from borehole temperature profiles at remote locations, the rate of retreat of alpine glaciers around the world, and progressively earlier breakup of ice on rivers and lakes (10). The geographical distribution of warming (Fig. 1*B*) provides further proof of real climate change. Largest warming is in remote regions including high latitudes. Warming occurs over ocean areas, far from direct human effects, with warming over ocean less than over land, an expected result for a forced climate change because of the ocean's great thermal inertia.

Early Climate Change Predictions. Manabe and Wetherald (11) made the first global climate model (GCM) calculations of warming due

Author contributions: D.W.L. and M.M.-E. contributed data; J.H., M.S., R.R., K.L., D.W.L., and M.M.-E. analyzed data; and J.H. wrote the paper.

The authors declare no conflict of interest.

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Abbreviations: SST, sea surface temperature; GHG, greenhouse gas; EEP, Eastern Equatorial Pacific; WEP, Western Equatorial Pacific; DAI, dangerous antrhopogenic interference; BAU, business as usual; AS, alternative scenario; BC, black carbon.

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www.pnas.org/cgi/doi/10.1073/pnas.0606291103