Perceptions of Climate Change: The New Climate Dice

James Hansen[a1], Makiko Sato[a], Reto Ruedy[b]

[a]NASA Goddard Institute for Space Studies and Columbia University Earth Institute, [b]Sigma Space Partners, New York, NY 10025

"Climate dice", describing the chance of unusually warm or cool seasons relative to climatology, have become progressively "loaded" in the past 30 years, coincident with rapid global warming. The distribution of seasonal mean temperature anomalies has shifted toward higher temperatures and the range of anomalies has increased. An important change is the emergence of a category of summertime extremely hot outliers, more than three standard deviations (σ) warmer than climatology. This hot extreme, which covered much less than 1% of Earth's surface in the period of climatology, now typically covers about 10% of the land area. We conclude that extreme heat waves, such as that in Texas and Oklahoma in 2011 and Moscow in 2010, were "caused" by global warming, because their likelihood was negligible prior to the recent rapid global warming. We discuss practical implications of this substantial, growing climate change.

The greatest barrier to public recognition of human-made climate change is the natural variability of climate. How can a person discern long-term climate change, given the notorious variability of local weather and climate from day to day and year to year?

This question assumes great practical importance, because of the need for the public to appreciate the significance of human-made global warming. Actions to stem emissions of the gases that cause global warming are unlikely to approach what is needed until the public perceives that human-made climate change is underway and will have unacceptable consequences if effective actions are not taken to slow the climate change. Early recognition of climate change is critical. Stabilizing climate with conditions resembling those of the Holocene, the world in which civilization developed, can only be achieved if rapid reduction of fossil fuel emissions begins soon (1).

It has been suggested (2) that by the early 21st century the informed public should be able to recognize that the frequency of unusually warm seasons has increased. In other words, the climate dice describing the probability of unusually warm or unusually cool seasons will have become sufficiently loaded (biased) so as to be discernible to the public. Recent high profile heat waves, such as the one in Texas and Oklahoma in the summer of 2011, raise the question of whether these extreme events are a consequence of the global warming trend, which itself has been attributed with a high degree of confidence to human-made greenhouse gases (3).

Summer, when most biological productivity occurs, is the most important season for humanity and thus the season when climate change may have its biggest impact. Global warming causes spring warmth to come earlier and it causes cooler conditions that initiate fall to be delayed. Thus global warming not only increases summer warmth, it also protracts summer-like conditions, stealing from both spring and fall. Our study therefore places emphasis on study of how summer temperature anomalies have been changing.

[1] To whom correspondence should be addressed. E-mail: james.e.hansen@nasa.gov

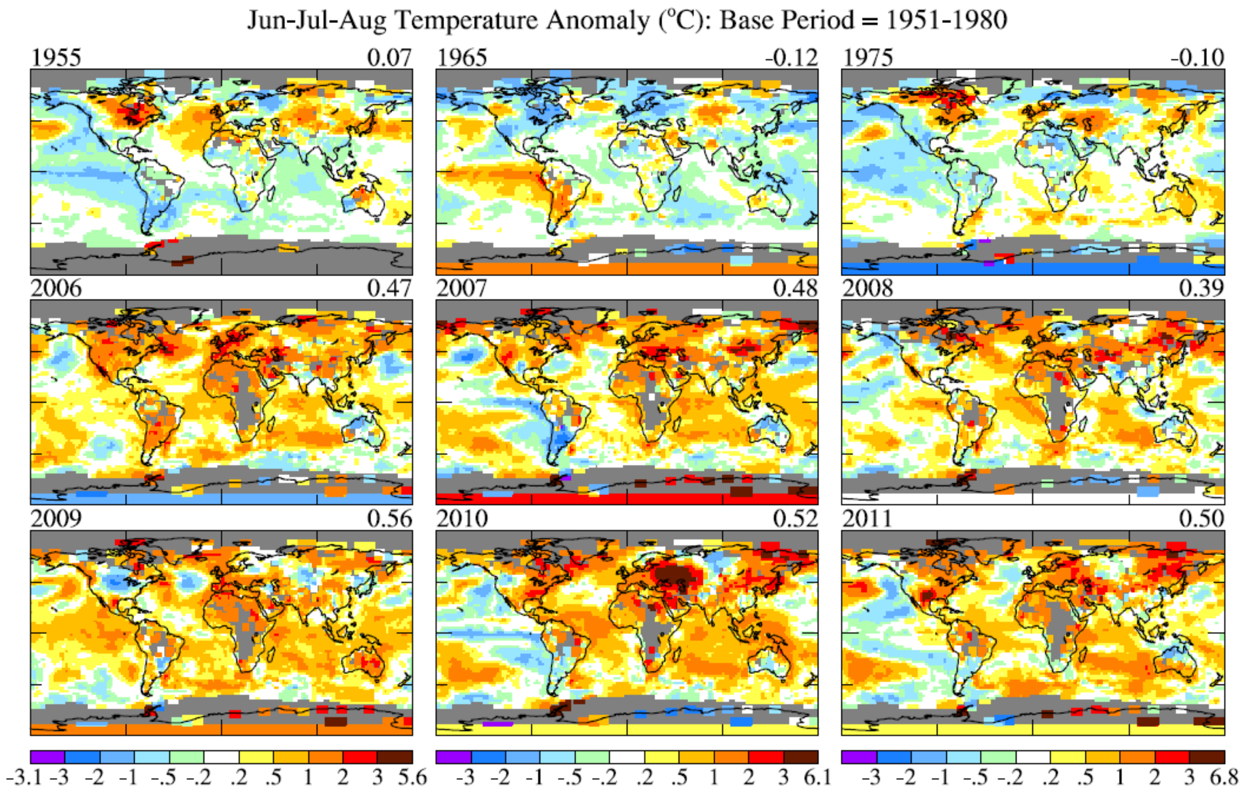

Fig. 1. Jun-Jul-Aug surface temperature anomalies in 1955, 1965, 1975 and in the past six years relative to the 1951-1980 mean. Number on upper right is the global mean (average over all area with data).

We use the Goddard Institute for Space Studies (GISS) surface air temperature analysis (4) to examine seasonal mean temperature variability and how that variability has changed in recent decades. The GISS analysis is carried out at two spatial resolutions: 1200 km and 250 km. We use the 250 km analysis, because it is well-suited for illustrating seasonal-mean climate variability on regional spatial scales and investigating the significance of recent extreme events.

One of the observational records employed in the GISS analysis is the Global Historical Climatology Network (GHCN) data set for surface air temperature at meteorological stations, which is maintained by the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC). We use version 2 (GHCNv2) of this data record (5) here, because it is the version employed in the documented GISS analysis (4). The data record that NCDC currently provides, GHCNv3, initiated in 2011, yields a slightly larger global warming trend (0.75°C for 1900-2010, while GHCNv2 yields 0.72°C), but the changes are too small to affect the conclusions of our present study.

We illustrate observed variability of seasonal mean surface air temperature emphasizing the standard deviation ("bell curve"), which the lay public may appreciate. We choose 1951-1980 as the base period for most of our illustrations, because that is a time of little global temperature trend just prior to the rapid global warming in recent decades. It is a period that older people today, particularly those of the "baby boom" generation, can remember. Global temperature in 1951-1980 is also within the Holocene temperature range, and thus it is a climate that the natural world and civilization is adapted to. In contrast, global temperature in the first decade of the 21st century is probably already outside the Holocene range (6), as evidenced by the fact that the Greenland and Antarctic ice sheets are losing mass rapidly (7, 8) and sea level is now rising at a rate [3 m/millennium, (9); updates available at http://sealevel.colorado.edu/] far exceeding prior sea level rise in the Holocene.

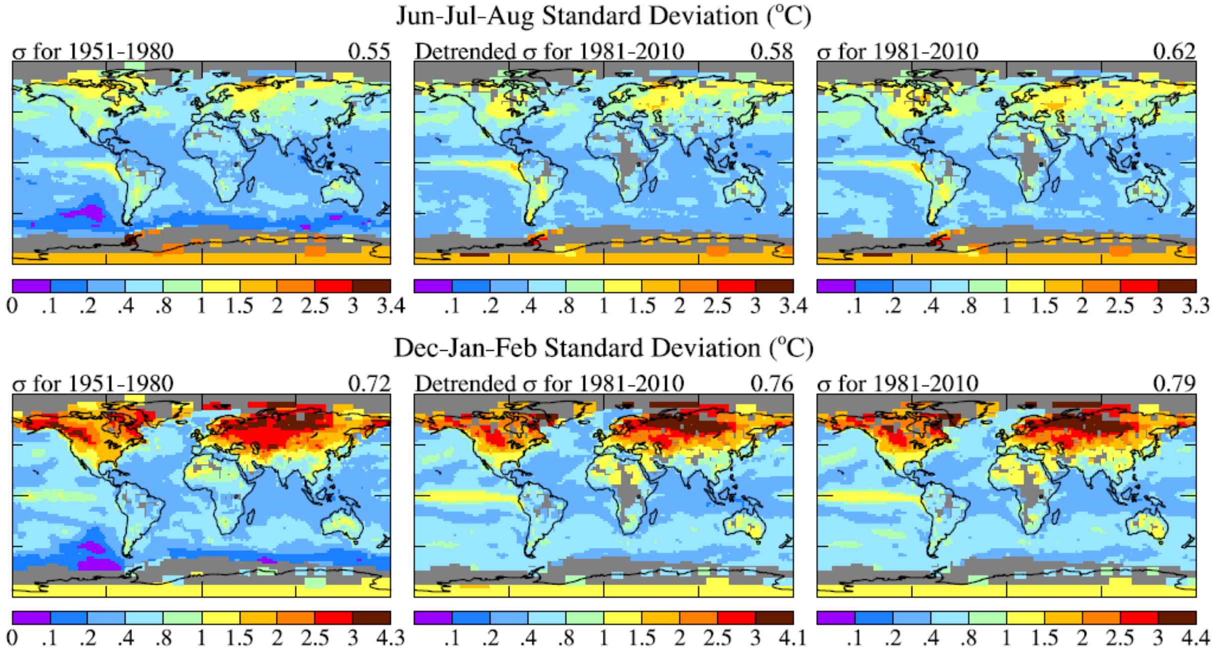

Fig. 2. Standard deviation of local Jun-Jul-Aug (above) and Dec-Jan-Feb (below) mean surface temperature for 30-year periods 1951-1980 (left maps) and 1981-2010. In the middle maps the local 30-year (1981-2010) temperature trend was removed before calculating the standard deviation.

Results

Summer temperature anomalies. Jun-Jul-Aug (Northern Hemisphere summer) surface temperature anomalies relative to the base period 1951-1980 are shown in Fig. 1 for mid-decade years of the 1950s, 1960s and 1970s, and for the past six years. Most regions were warmer in recent years than during 1951-1980, but substantial area cooler than the 1951-1980 mean still occurs. The United States, for example, was unusually cool in 2004 and 2009.

But what is the practical importance of such temperature anomalies? Global warming since 1951-1980 is about 0.5-0.6°C (about 1°F), which may not seem like much.

Natural climate variability and the standard deviation. A good way to gain appreciation of the warming's significance is to compare it to natural year-to-year variability of temperature. The standard deviation of local surface temperature during 1951-1980 (Fig. 2, left column) is a measure of the typical magnitude of year-to-year variations of seasonal mean surface temperature during that 30-year base period.

Below we will show the distribution of observed temperature anomalies about their mean value. It is commonly assumed that this variability can be approximated as a normal (Gaussian) distribution, the so-called 'bell curve'. A normal distribution of variability has 68 percent of the anomalies falling within one standard deviation of the mean value. The tails of the normal distribution (which we illustrate below) decrease quite rapidly so there is only a 2.3% chance of the temperature exceeding +2σ, where σ is the standard deviation, and a 2.3% chance of being colder than -2σ. The chance of exceeding +3σ is only 0.13% for a normal distribution of variability, with the same chance of a negative anomaly exceeding -3σ.

Interannual variability of surface temperature is larger in the winter hemisphere than in the summer and larger over land than over ocean (Fig. 2). The basic reason for the large winter variability is the huge difference of temperature between low latitudes and high latitudes in winter. This allows the temperature at a given place to vary by tens of degrees depending on whether the wind is from the south or north. The latitudinal temperature gradient in summer is much smaller, thus providing less drive for exchange of air masses between middle latitudes and

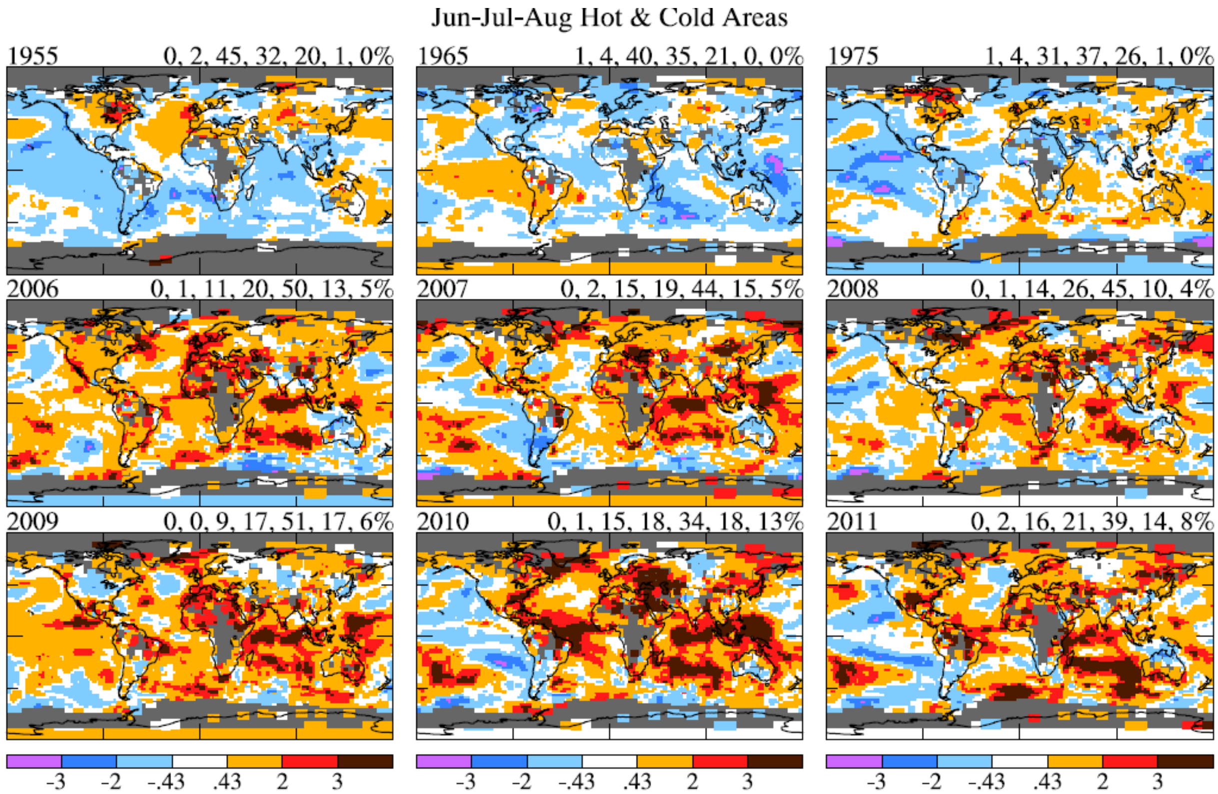

Fig. 3. Jun-Jul-Aug surface temperature anomalies in 1955, 1965, 1975 and in 2006-2011 relative to 1951-1980 mean temperature in units of the local standard deviation of temperature. The numbers above each map are the percent of surface area covered by each of the categories in the color bar.

polar regions -- and when exchange occurs the effect on temperature is less than that caused by a winter 'polar express' of Arctic (or Antarctic) air delivered to middle latitudes.

Careful examination reveals something amiss in the standard deviation maps for 1951-1980. How can variability be less than 0.1°C in the Southern Ocean? Given weather variability there, surely temperature cannot be so rigidly fixed. The small variability there must be an artifact of limited measurements during 1951-1980. Ocean temperature analyses there were based on limited sampling and climatology, and thus did not include realistic year-to-year changes.

Fortunately, satellite measurements of sea surface temperature provide near-global data in recent decades for ice-free regions. Resulting maps of standard deviation for 1981-2010 (right column in Fig. 2) remove the Southern Ocean artifact of the 1951-1980 maps.

One drawback of using 1981-2010 to define natural variability is the existence of rapid global warming during that period, a trend that is primarily a human-made effect. However, subtracting the local linear trends of temperature before calculating the standard deviation only modestly reduces the result (middle column in Fig. 2). This comparison shows that the main contribution to σ is the large year-to-year fluctuations.

It does not matter much which of the three standard deviation maps are used in our further analyses except in the Southern Ocean near Antarctica. We will use the standard deviation for the detrended 1981-2010 data (middle column of Fig. 2) for subsequent global maps, but the effect of that choice is small, as we will illustrate.

Now we can examine how unusual recent summer temperature anomalies were. Fig. 3 shows the ratio: local temperature anomaly divided by local standard deviation, σ, where σ is from the middle column in Fig. 2. The red and brown areas in Fig. 3 have anomalies that exceed 2σ and 3σ, respectively. The numbers on the top of each map are the percentage of the total area covered by each of the seven categories of the color bar.

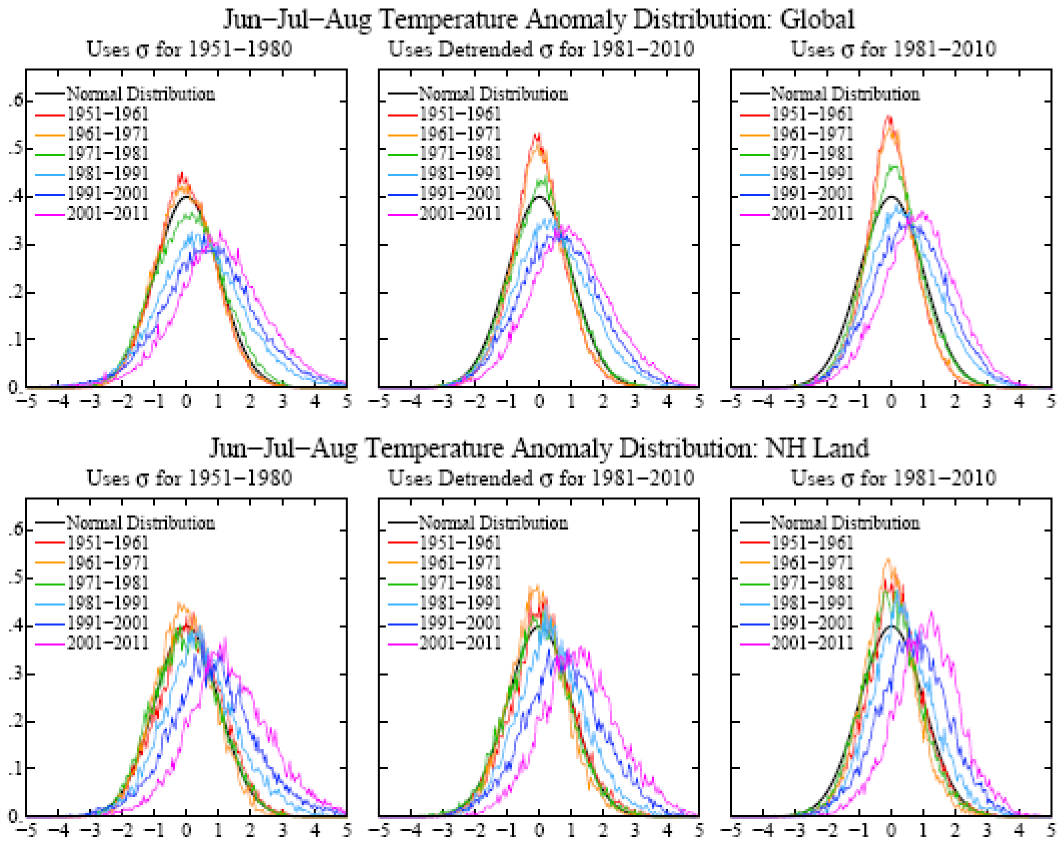

Fig. 4. Frequency of occurrence (y-axis) of local temperature anomalies divided by local standard deviation (x-axis) obtained by binning all local results for 11-year periods into 0.05 intervals. Area under each curve is unity.

A remarkable feature of Fig. 3 is the large brown area (anomalies > 3σ), which covered between 4% and 13% of the world in the six years 2006-2011. If temperature anomalies were normally distributed, and if anomalies were similar to those of 1951-1980, we would expect the brown area to cover only 0.1-0.2% of the planet.

The recent spate of 3σ events raises some questions: what does the temperature anomaly distribution look like and how is it changing? And how important is a +3σ anomaly? Well-publicized extreme conditions in Texas in 2011 and around Moscow and in the Middle East in 2010 had summer temperature anomalies reaching the +3σ level, suggesting that increase of such extreme events may have large practical impacts. However, this issue is complex, e.g., depending upon choice of climatology, as considered in the Discussion section.

Thus let us first examine how the temperature anomaly distribution is changing. The Jun-Jul-Aug temperature anomaly distribution in successive decadal periods is shown in Fig. 4 for the three choices of standard deviation in Fig. 2. For comparison the normal (a.k.a. Gaussian or bell-curve) distribution of anomalies is shown by the black line. The upper row is the global result and the lower row is for Northern Hemisphere. The data curves were obtained by binning the local anomalies divided by local standard deviation into intervals of 0.05

The global data for 1951-1980 fit the normal distribution well when the standard deviation includes the effect of unrealistically small Southern Ocean variability (left column in Figs 2 and 4), as that small variability artifact broadens the distribution of anomaly divided by standard deviation. More realistic standard deviations yield a temperature anomaly distribution more peaked at small anomalies than the normal distribution, and thus observed anomalies in the base period have less chance of being in the 1σ-3σ range than occurs in the normal distribution. However, the normal distribution provides a rather good fit to anomalies in land areas (Fig. 4).

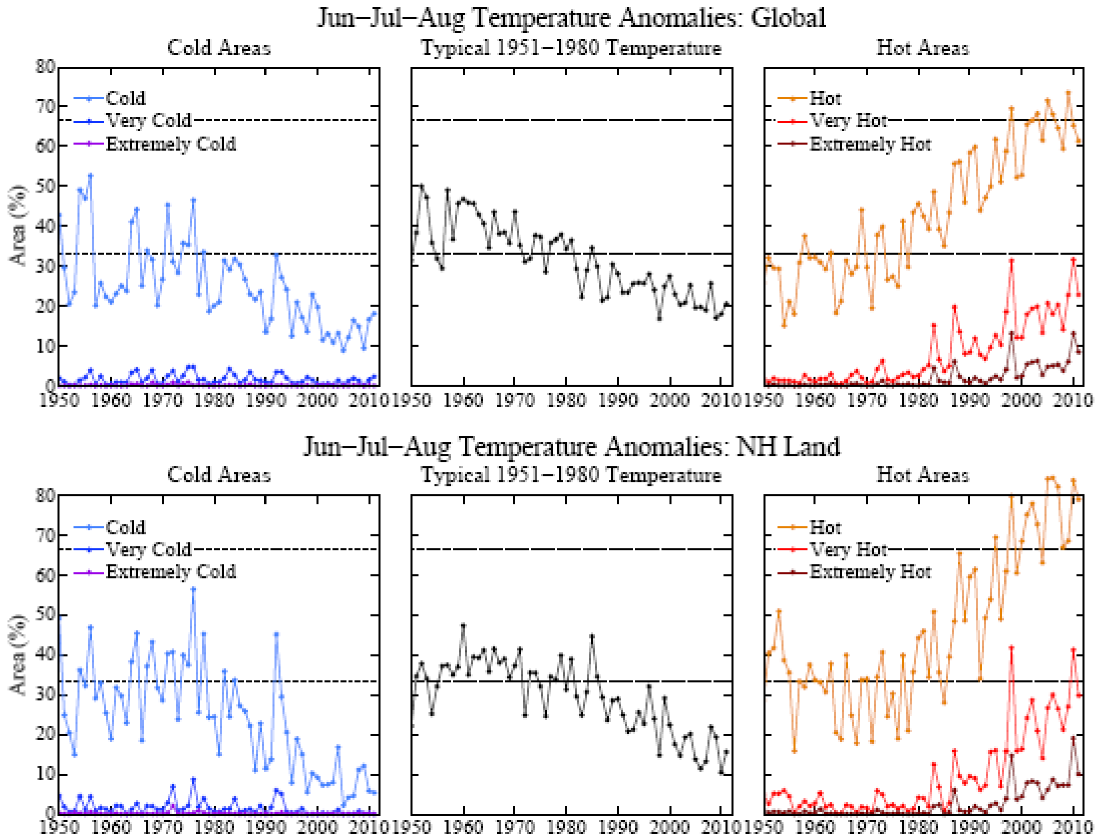

Fig. 5. Area of the world covered by temperature anomalies in the categories defined as hot (> 0.43σ), very hot (> 2σ), and extremely hot (> 3σ), with analogous divisions for cold anomalies. These anomalies are relative to 1951-1980 climatology with σ from the detrended 1981-2010 data, but results are similar for the alternative choices for standard deviation.

An important point to note is the large shift of the probability distribution function toward the right in each successive decade in the past 30 years, the shift being even larger for land areas in summer (lower half of Fig. 4). Another point is the fact that the distribution becomes broader in recent decades. The occurrence of 3σ, 4σ and 5σ anomalies, practically absent in 1951-1980, is substantial in the past decade, consistent with the large brown areas in Fig. 3. Unusually cold seasons are greatly diminished. In 2001-2011 the frequency of Jun-Jul-Aug being cold (left column of Fig. 5) was 13% on global average and 8% for Northern Hemisphere land.

Loaded climate dice. "Loading" of the "climate dice" describes the systematic shift of the frequency distribution of temperature anomalies. Hansen et al. (2) represented the climate of 1951-1980 by colored dice with two sides colored red for "hot", two sides blue for "cold", and two sides white for near average temperatures. With a normal distribution of temperatures the dividing point would be at 0.43σ to achieve equal (one third) chances of being in each of these three categories in the period of climatology (1951-1980).

A climate model was used (2) to project how the odds would change due to global warming for alternative greenhouse gas scenarios. Scenario B, which had climate forcing that turned out to be very close to reality, led to four of the six dice sides being red early in the 21st century based on global climate model simulations.

Fig. 5 confirms that the global occurrence of "hot" anomalies (seasonal mean temperature anomaly exceeding +0.43σ) has approximately reached the level of 67% required to make four sides of the dice red, with the odds of either an unusually "cool" season or an "average" season

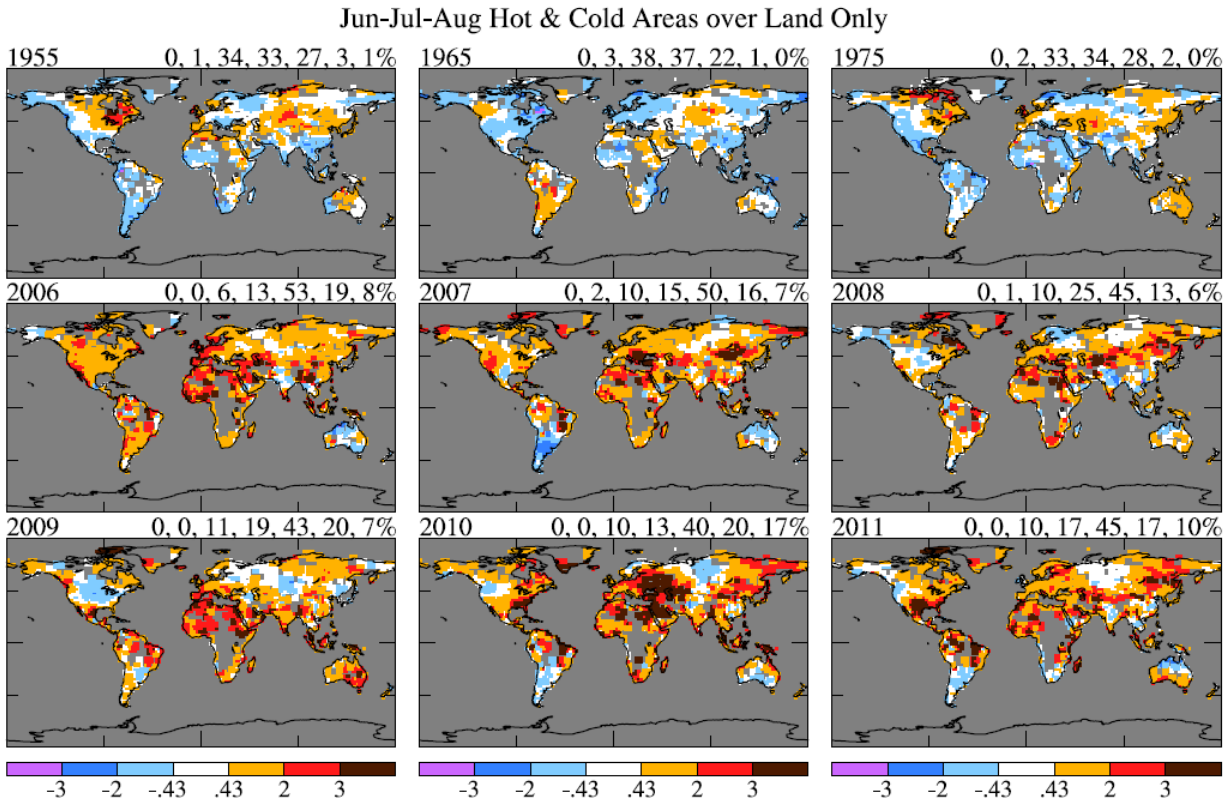

Fig. 6. Jun-Jul-Aug surface temperature anomalies over land in 1955, 1965, 1975 and 2003-2011 relative to 1951-1980 mean temperature in units of the local standard deviation of temperature. The numbers above each map are the percent of surface area covered by each of the categories in the color bar.

now each approximately corresponding to one side of the six-sided dice. However, the loading of the dice over land area in summer is even stronger (Fig. 5, lower row).

Probably the most important change is the emergence of a new category of "extremely hot" summers, more than 3σ warmer than climatology. For practical purposes it is important to look at the changes over land areas, where most people live, rather than the global mean for which anomalies are more constrained by the ocean's thermal inertia. Fig. 6 illustrates that $+3\sigma$ anomalies practically did not exist in the period of climatology (1951-1980), but in the past several years these extreme anomalies have covered of the order of 10% of the land area.

Maps analogous to Fig. 6 but for Dec-Jan-Feb are included in our Supporting Information to allow examination of trends for winter and summer in both hemispheres. Winter trends in units of standard deviations are comparable to those in summer, but tend to be slightly smaller. Warming is larger in winter than in summer, but this tends to be more than offset by the much larger natural variability in winter (Fig. 2), which makes it harder for the public to notice climate change in winter. Another factor affecting the public's perception of winter warming is the fact that snowfall amounts increase with global warming (in regions remaining cold enough for snow), and there is a tendency of the public to equate heavy snowfall and harsh winter conditions, even if temperatures are not extremely low.

The increase, by more than a factor 10, of area covered by extreme hot anomalies ($> +3\sigma$) in summer reflects the shift of the anomaly distribution in the past 30 years of global warming, as shown succinctly in Fig. 4. One implication of this shift is that the extreme summer climate anomalies in Texas in 2011, in Moscow in 2010, and in France in 2003 almost certainly would not have occurred in the absence of global warming with its resulting shift of the anomaly distribution. In other words, we can say with a high degree of confidence that these extreme anomalies were a consequence of global warming.

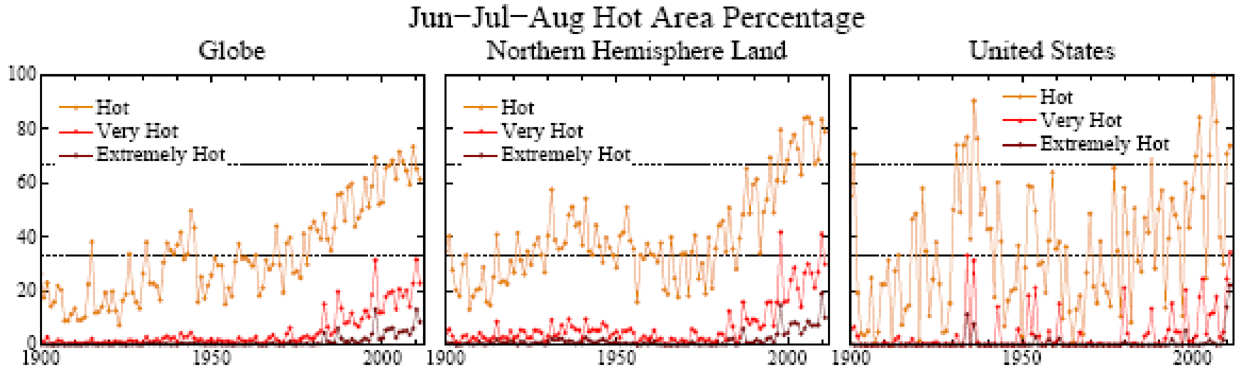

Fig. 7. Percent area covered by temperature anomalies in categories defined as hot (> 0.43σ), very hot (> 2σ), and extremely hot (> 3σ). Anomalies are relative to 1951-1980 climatology; σ is from detrended 1981-2010 data, but results are similar for the alternative choices in Fig. 2.

How will the "loading" of the climate dice continue to change in the future? Fig. 4 provides a clear, sobering, indication. The extreme hot tail of the distribution of temperature anomalies shifted to the right by more than +1σ in response to the global warming of about 0.5°C over the past three decades. Additional global warming in the next 50 years, if business-as-usual fossil fuel emissions continue, is expected to be at least 1°C. In that case, the further shifting of the anomaly distribution will make +3σ anomalies the norm and +5σ anomalies will be common. Possible implications of such extreme changes are considered in the Discussion section.

A longer time scale and regional detail. Jun-Jul-Aug data on a longer time scale, 1900-present, including results averaged over the conterminous United States, are shown in Fig. 7. The longer time scale is useful for examining changes in the United States, because of well-known extreme heat and droughts of the 1930s. The small area of the contiguous 48 states (less than 1.6% of the globe) causes temperature anomalies for the United States to be very "noisy". Nevertheless, it is apparent that the long-term trend toward hot summers is not as pronounced in the United States as it is in hemispheric land as a whole. Also note that the extreme summer heat of the 1930s, especially 1934 and 1936, is comparable to the most extreme recent years.

Year-to-year variability, which is mainly unforced weather variability, is so large for an area the size of the United States that it is perhaps unessential to find an "explanation" for either the large 1930s anomalies or the relatively slow upturn in hot anomalies during the past few decades. However, this matter warrants discussion, because, if the absence of a stronger warming in recent years is a statistical fluke, the United States may have in store a relatively rapid trend toward more extreme anomalies.

Some researchers have suggested that the high summer temperatures and drought in the United States in the 1930s can be accounted for by sea surface temperature patterns plus natural variability (10, 11). Other researchers (12-14), have presented evidence that agricultural changes and crop failure in the 1930s contributed to changed surface albedo, aerosol (dust) production, high temperatures, and drying conditions. Furthermore, both empirical evidence and climate simulations (14, 15) indicate that agricultural irrigation has a significant regional cooling effect. Thus increasing amounts of irrigation over the second half of the 20^{th} century may have contributed a summer cooling tendency in the United States that partially offset greenhouse warming. Such regionally-varying effects may be partly responsible for differences between observed regional temperature trends and the global trend.

Prediction of regional climate change is difficult because of the multiple factors that can affect regional climate and the high degree of chaotic (unforced) variability. In addition to a general warming trend, we might expect to find evidence in the data of a poleward shift of

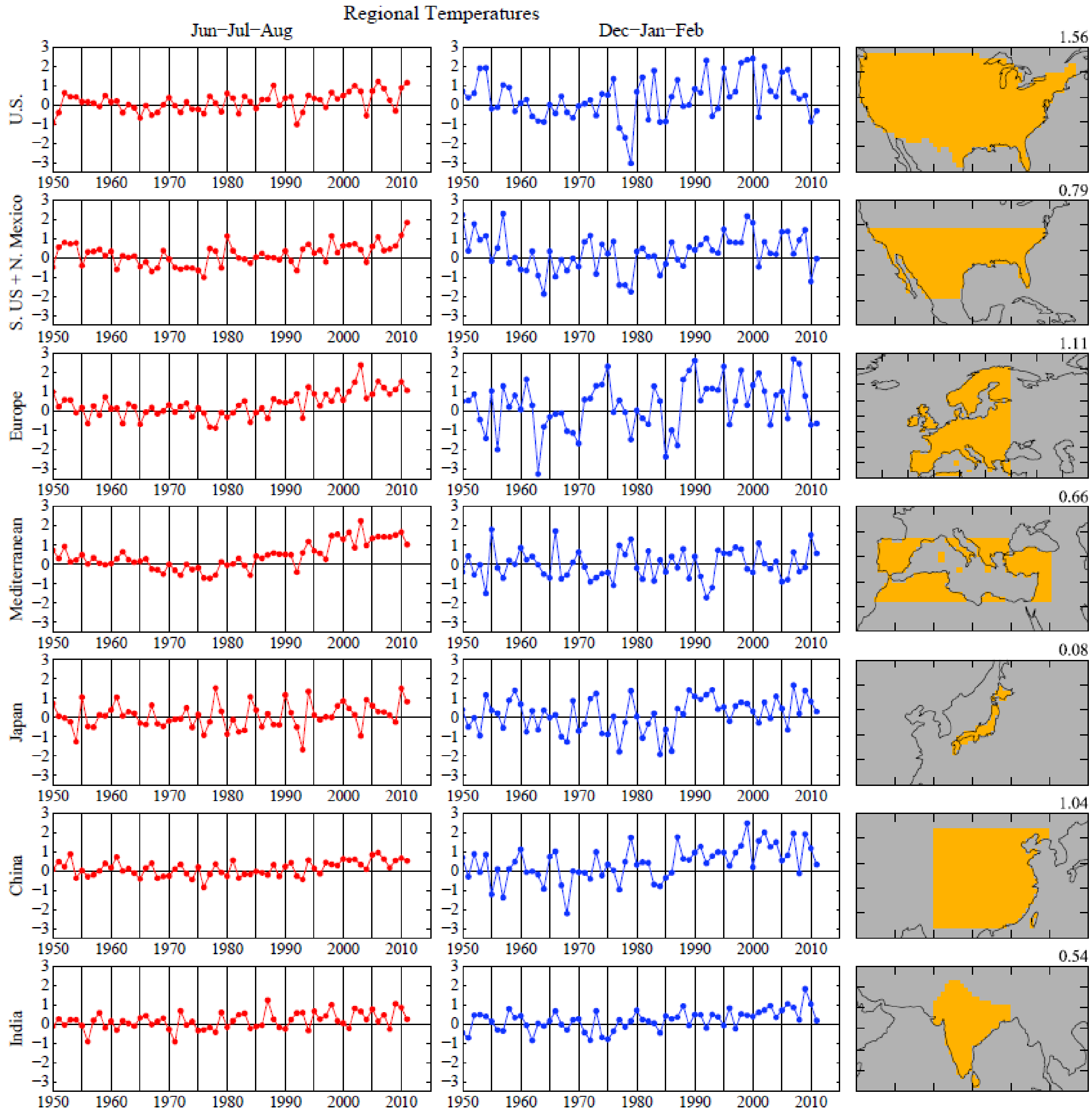

Fig. 8. Jun-Jul-Aug and Dec-Jan-Feb temperature anomalies (°C) for areas shown on the right.

climatic zones. Theory and climate models indicate that the overturning tropical circulation, the Hadley cell, will expand poleward with global warming (16, 17). There is evidence in satellite and radiosonde data and reanalyses output for poleward expansion of the tropical circulation of as much as a few degrees of latitude during the past three decades (18), but changes of several of the indicators used to define the tropical boundary are not statistically significant (19).

Impacts of expansion of the overturning tropical circulation in the Northern Hemisphere might be anticipated in the southern United States and Mediterranean region in the summer, when the descending branch of the Hadley circulation extends into those areas. Overall, global warming causes the atmosphere to hold more water vapor, thus allowing for more extreme precipitation events where and when these occur. However, regions experiencing intensification of subtropical conditions may see periods of increased aridity and higher temperatures (20, 21), which could contribute to increased forest fires that burn hotter and are more destructive (22).

We compare summer and winter temperature anomalies for several regions in Fig. 8, with the area in China being the part with most of the population. This figure reveals that even for these small regions (maximum size about 1.5% of globe) a systematic warming tendency is apparent, especially in the summer. However, at most places seasonal mean temperatures cooler than the 1951-1980 mean still occur occasionally, especially in the winter.

Discussion

Seasonal-mean temperatures have changed dramatically in the past three decades. The global shift of the probability distribution for seasonal mean temperature anomalies is more than one standard deviation and the shift is even larger for land areas (Fig. 4). In addition, there is a broadening of the probability distribution, the warming shift being greater at the high temperature tail of the distribution than at the low temperature tail (Fig. 4).

Seasonal-mean temperatures in the category defined as "cold" in 1951-1980 climatology (mean temperature below -0.43σ), which occurred about one-third of the time in 1951-1980, still occur with a probability about 10% over land areas. Thus an occasional unusually cool winter is not evidence against global warming. Temperature is less "noisy" in the summer than winter. The chance of summer falling in the "hot" category of 1951-1980 is now about 80% (Fig. 7). The climate dice are now loaded to a degree that the perceptive person (old enough to remember the climate of 1951-1980) should recognize the existence of climate change.

The most important change of the climate dice is the appearance of a new category of extremely hot summer anomalies, with mean temperature at least three standard deviations greater than climatology. These extreme temperatures were practically absent in the period of climatology, covering only a few tenths of one percent of the land area, but they have occurred over about 10% of land area in recent years. The increased frequency of these extreme anomalies, by more than an order of magnitude, implies that we can say with a high degree of confidence that events such as the extreme summer heat in the Moscow region in 2010 and Texas in 2011 were a consequence of global warming. Rahmstorf and Coumou (23), using a more elegant mathematical analysis, reached a similar conclusion for the Moscow anomaly.

It is not uncommon for meteorologists to reject global warming as a cause of these extreme events, offering instead a meteorological explanation. For example, it is said that the Moscow heat wave was caused by an atmospheric "blocking" situation, or the Texas heat wave was caused by La Nina ocean temperature patterns. Certainly the locations of the extreme anomalies in any given case are related to specific weather patterns. However, blocking patterns and La Ninas have always been common, yet the large areas of extreme warming have come into existence only with large global warming. Today's extreme anomalies occur because of simultaneous contributions of specific weather patterns and global warming.

However, we must ask: do our conclusions depend on the base period chosen for climatology? Can we just redefine climatology based on the most recent decades, perhaps leading to a conclusion that the only climate change has been a small shift of mean temperature that may be insignificant?

The effect of alternative base periods on the frequency of temperature anomalies is shown in Fig. 9. Use of a recent base period alters the appearance of the probability distribution function for temperature anomalies, because the frequency of occurrence is expressed in units of the standard deviation. Because climate variability increased in recent decades, and thus the standard deviation increased, if we use the most recent decades as base period we "divide out" the increased variability. Thus the distribution function using 1981-2010 as the base period (right graph in Fig. 9) does not expose the change toward increased climate variability.

Reports of climate anomalies to the public often use the most recent three decades, prior to the current decade, to define "normal" climate, i.e., to define the base period. This is fine if the objective is to define anomalies relative to a recent period that most people will be familiar with.

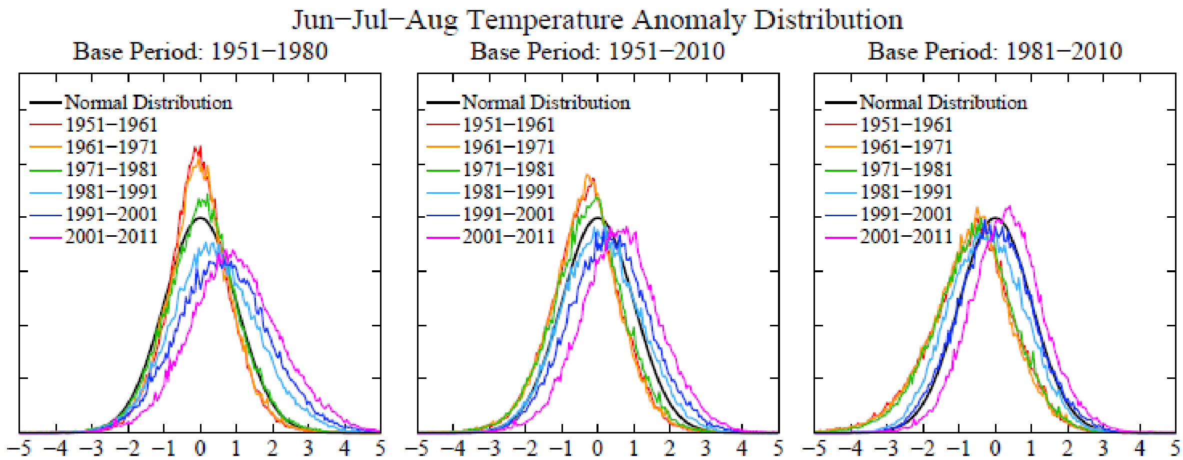

Fig. 9. Frequency of occurrence (y-axis) of local temperature anomalies divided by local standard deviation (x-axis) obtained by binning all local results for 11-year periods into 0.05 intervals. Area under each curve is unity. Base periods, left to right, are 1951-1980, 1951-2010 and 1981-2010.

However, this practice tends to hide the fact that climate variability itself is changing on decadal time scales. Thus, at least for research purposes, we recommend keeping the base period fixed.

The question then becomes, what is the most appropriate base period to use. We will argue that the appropriate base period is close to our initial choice, 1951-1980. Also we suggest that the "small" 0.5°C global warming of the past three decades already has practical effects, which will become major impacts if projected global warming of 2°C or more this century is allowed to occur.

The most useful base period, we suggest, is one representative of the climate to which life on Earth is adapted. Paleoclimate data show that global temperature has been quite stable for a long period, more than ten thousand years, the Holocene period (Fig. 5, (6)). However, (6) argue that the climate of the most recent few decades must be warmer than prior Holocene levels, given the fact that the major ice sheets in both hemispheres are presently losing mass rapidly and global sea level is rising at a rate of more than 3 m/millennium, much greater than at any time in the past several thousand years. Global temperature in 1951-1980, which is the earliest period with good global coverage of meteorological stations, is more representative of the Holocene and the climate to which plant and animal life on the planet is adapted.

Changes of global temperature are likely to have their greatest practical impact via effects on the hydrologic cycle. Amplification of hot, dry conditions by global warming is expected, based on qualitative considerations. For example, places experiencing an extended period of high atmospheric pressure develop dry conditions, which we would expect to be amplified by global warming and by ubiquitous surface heating due to elevated greenhouse gas amounts.

The other extreme of the hydrologic cycle, unusually heavy rainfall and floods, is also expected to be amplified by global warming. The amount of water vapor that the atmosphere holds increases rapidly with atmospheric temperature, and thus a warmer world is expected to have more rainfall occurring in more extreme events. What were "100-year" or "500-year" events are expected to occur more frequently with increased global warming. Rainfall data reveal significant increases of heavy precipitation over much of Northern Hemisphere land and in the tropics (3) and attribution studies link this intensification of rainfall and floods to human-made global warming (24-26).

Although extreme heat waves and record floods receive most public attention, we wonder if there is not also a more pervasive effect of warming that affects almost everyone. Natural ecosystems are adapted to the stable climate of the Holocene. Climate fluctuations are normal, but the rapid monotonic global trend of the past three decades, from an already warm level, is highly unusual. The fact that warmer winters have led to an epidemic of pine bark beetles and widespread destruction of forests in Canada and western United States is well known. However, as an anecdotal data piece suggesting the possibility of more widespread effects, consider that several tree species (birch, pin oak, ash, some maple varieties) on the eastern Pennsylvania property of one of us (JH) exhibit signs of stress. Arborists identify proximate causes (borers and other pests, fungus, etc.) in each case, but climate change, including longer summers with more extreme temperature and moisture anomalies, could be one underlying factor. The tree species in this region have existed for millennia; it is implausible that Native Americans had to water the birch trees to keep them alive, as is the case at present during summers with anomalously hot summers.

Climate change of recent decades is also having effects on animals, birds and insects that are already noticeable (17, 27, 28). Although species migrate to stay within climate zones in which they can survive, continued climate shift at the rate of the past three decades is expected to take an enormous toll on planetary life. If global warming approaches 3°C by the end of the century, it is estimated that 21-52% of the species on Earth will be committed to extinction (3). Fortunately, scenarios are also possible in which such large warming is avoided by placing a rising price on carbon emissions that moves the world to a clean energy future fast enough to limit further global warming to several tenths of a degree Celsius (29). Such a scenario is needed if we are to preserve life as we know it.

References

1. Hansen, J., *et al.*, 2011: The case for young people and nature: A path to a healthy prosperous future. *Proc. Natl. Acad. Sci.*
2. Hansen, J., *et al.*, 1988: Global climate changes as forecast by Goddard Institute for Space Studies 3-dimensional model. *Journal Of Geophysical Research - Atmospheres,* **93** (D8), 9341-9364.
3. Intergovernmental Panel on Climate Change (IPCC), 2007: *Climate Change 2007: The Physical Science Basis*, Solomon, S., *et al.* eds., Cambridge University Press, 996 pp.
4. Hansen, J., Ruedy, R., Sato, M., and Lo, K., 2010: Global surface temperature change. *Rev Geophys,* **48** RG4004.
5. Menne, M. J., Williams, C. N., and Vose, R. S., 2009: The US Historical Climatology Network Monthly Temperature Data, Version 2. *B Am Meteorol Soc,* **90**, 993-1007.
6. Hansen, J. E., and M. Sato, Berger, A., Mesinger, F., and Sijacki, D., 2012: *Paleoclimate implications for human-made climate change.* . Springer, ~350 pp. pp.
7. Velicogna, I., 2009: Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE. *Geophys Res Lett,* **36** L19503.
8. Rignot, E., Velicogna, I., van den Broeke, M. R., Monaghan, A., and Lenaerts, J., 2011: Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophys Res Lett,* **38** L05503.
9. Nerem, R. S., Leuliette, E., and Cazenave, A., 2006: Present-day sea-level change: A review. *Cr Geosci,* **338**, 1077-1083.
10. Nigam, S., Guan, B., and Ruiz-Barradas, A., 2011: Key role of the Atlantic Multidecadal Oscillation in 20th century drought and wet periods over the Great Plains. *Geophys Res Lett,* **38** L16713.
11. Hoerling, M., *et al.*, 2011: On the increased frequency of Mediterranean drought. *J. Clim.*

12. Cook, B. I., Miller, R. L., and Seager, R., 2009: Amplification of the North American "Dust Bowl" drought through human-induced land degradation. *Proc. Natl. Acad. Sci.*, **106**, 4997-5001.
13. Cook, B. I., Terando, A., and Steiner, A., 2010: Ecological forecasting under climatic data uncertainty: a case study in phenological modeling. *Environ Res Lett*, **5**.
14. Cook, B. I., Puma, M. J., and Krakauer, N. Y., 2011: Irrigation induced surface cooling in the context of modern and increased greenhouse gas forcing. *Clim Dynam*, **37**, 1587-1600.
15. Puma, M. J. and Cook, B. I., 2010: Effects of irrigation on global climate during the 20th century. *J Geophys Res-Atmos*, **115** D16120.
16. Held, I. M. and Soden, B. J., 2006: Robust responses of the hydrological cycle to global warming. *J. Clim.*, **19**, 5686-5699.
17. Intergovernmental Panel on Climate Change (IPCC), 2007: *Climate Change 2007, Impacts, Adaptation and Vulnerability*, M.L. Parry, E. A. ed., Cambridge Univ Press, 996 pp.
18. Seidel, D. J., Fu, Q., Randel, W. J., and Reichler, T. J., 2008: Widening of the tropical belt in a changing climate. *Nature Geosci*, **1**, 21-24.
19. Davis, S. M. and Rosenlof, K. H. (2011) A multi-diagnostic intercomparison of tropical width time series using reanalyses and satellite observations. in *J. Clim.*
20. Barnett, T. P., *et al.*, 2008: Human-induced changes in the hydrology of the western United States. *Science*, **319**, 1080-1083.
21. Levi, B. G., 2008: Trends in the hydrology of the western US bear the imprint of manmade climate change. *Phys. Today*, **61**, 16-18.
22. Westerling, A. L., Hidalgo, H. G., Cayan, D. R., and Swetnam, T. W., 2006: Warming and earlier spring increase western US forest wildfire activity. *Science*, **313**, 940-943.
23. Rahmstorf, S. and Coumou, D., 2011: Increase of extreme events in a warming world. *Proc. Natl. Acad. Sci.*, **108**, 17905-17909.
24. Allan, R. P. and Soden, B. J., 2008: Atmospheric warming and the amplification of precipitation extremes. *Science*, **321**, 1481-1484, <Go to ISI>://000259121800038.
25. Pall, P., *et al.*, 2011: Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature*, **470** (7334), 382-385.
26. Min, S. K., Zhang, X. B., Zwiers, F. W., and Hegerl, G. C., 2011: Human contribution to more-intense precipitation extremes. *Nature*, **470** (7334), 378-381.
27. Parmesan, C., 2006: Ecological and evolutionary responses to recent climate change. *Annu Rev Ecol Evol S*, **37**, 637-669.
28. Hansen, J., 2006: The threat to the planet. *New York Rev. Books*, **53**, 12-16.
29. Hansen, J., *et al.*, 2012 (to be submitted): The Case for Young People and Nature: A Path to a Healthy Prosperous Future. *Proc. Natl. Acad. Sci.*