Climate Variability and Climate Change: The New Climate Dice

10 November 2011

J. Hansen, M. Sato, R. Ruedy

Abstract. The "climate dice" describing the chance of an unusually warm or cool season, relative to the climatology of 1951-1980, have progressively become more "loaded" during the past 30 years, coincident with increased global warming. The most dramatic and important change of the climate dice is the appearance of a new category of extreme climate outliers. These extremes were practically absent in the period of climatology, covering much less than 1% of Earth's surface. Now summertime extremely hot outliers, more than three standard deviations (σ) warmer than climatology, typically cover about 10% of the land area. Thus there is no need to equivocate about the summer heat waves in Texas in 2011 and Moscow in 2010, which exceeded 3σ – it is nearly certain that they would not have occurred in the absence of global warming. If global warming is not slowed from its current pace, by mid-century 3σ events will be the new norm and 5σ events will be common.

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, mainly CO_2, are unlikely to approach what is needed until the public perceives that human-made climate change is underway and will have disastrous consequences if effective actions are not taken to short-circuit 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, requires that rapid reduction of fossil fuel emissions begin soon (Hansen et al., 2011).

The Goddard Institute for Space Studies (GISS) surface air temperature analysis (Hansen et al., 2010) is carried out at two spatial resolutions: 1200 km and 250 km. In this paper we use the 250 km analysis, which is well-suited for our objective to illustrate seasonal-mean climate variability on regional spatial scales and investigate the significance of recent extreme events.

Summer temperature anomalies. 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 colder 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.

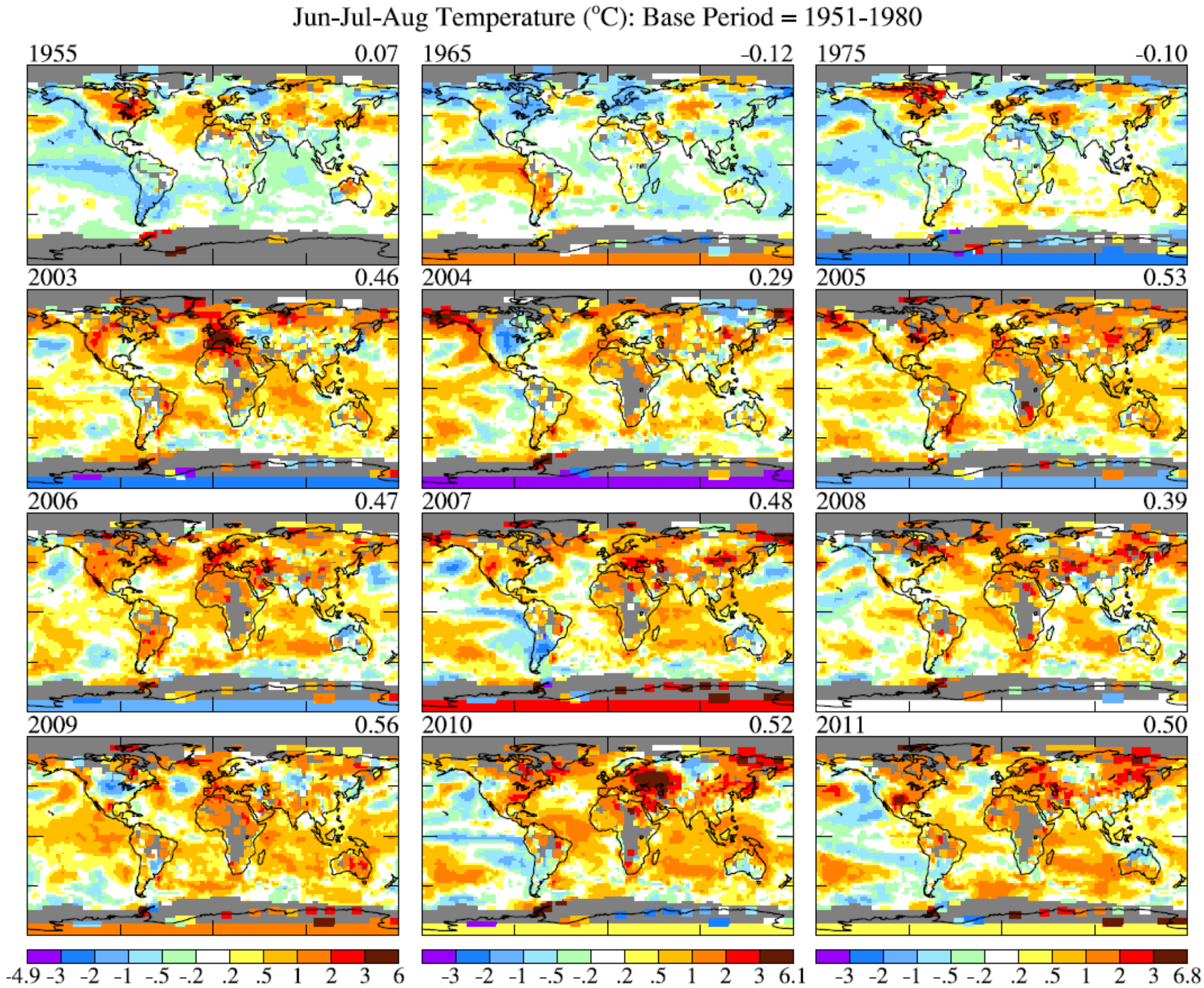

Figure 1. Jun-Jul-Aug surface temperature anomalies in 1955, 1965, 1975 and the past nine years relative to 1951-1980 mean. Number on upper right is the global (area with data) mean.

Jun-Jul-Aug (Northern Hemisphere summer) surface temperature anomalies relative to the base period 1951-1980 are shown in Figure 1 for mid-decade years of the 1950s, 1960s and 1970s, and for the past nine years. Most regions were warmer in recent years than during 1951-1980, even though 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 (Figure 2, left column) is a measure of the typical magnitude of year-to-year variations of seasonal mean (i.e., average) surface temperature during that 30-year base period.

Below we will show the distribution of 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 $+2\sigma$, where σ is the standard deviation, and a 2.3% chance of being colder than -2σ. The chance of exceeding $+3\sigma$ is only 0.13% for a normal distribution of variability, with the same chance of a negative anomaly exceeding -3σ.

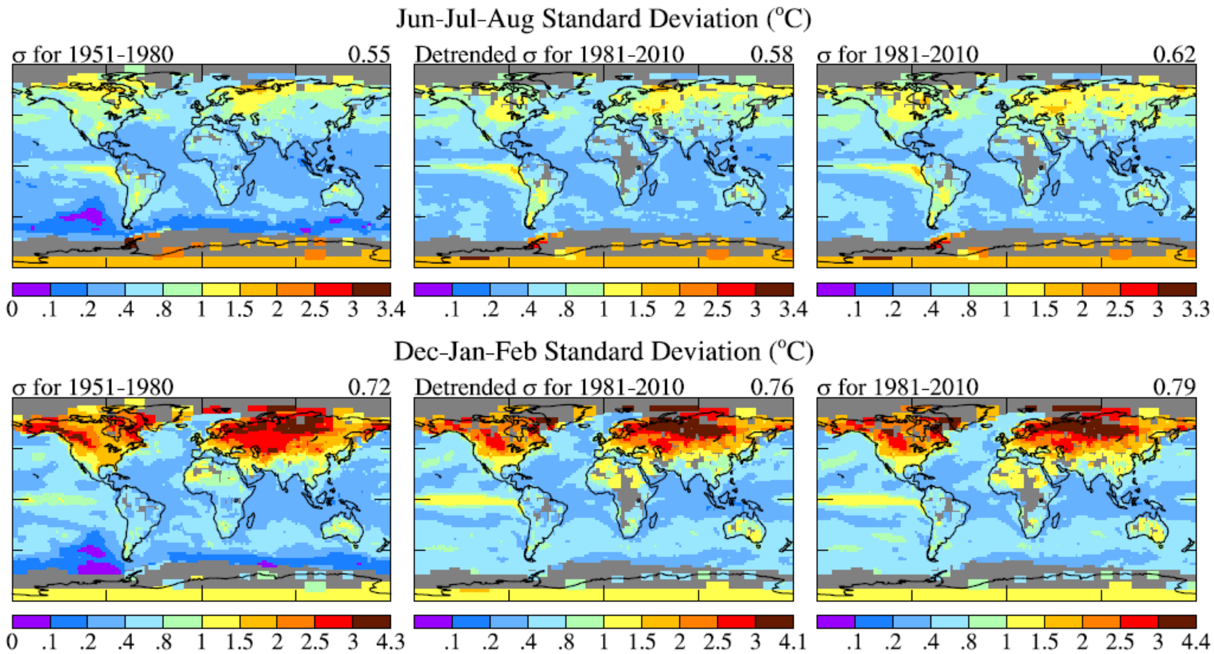

Figure 2. Standard deviation of local Jun-Jul-Aug (above) and Dec-Jan-Feb (below) mean surface temperature for 30-year periods 1951-1980 (left maps) and 1981-2010. In the middle maps the local 30-year (1981-2010) temperature trend was removed before calculating the standard deviation.

Interannual variability of surface temperature is larger in the winter hemisphere than in the summer and larger over land than over ocean (Figure 2). The basic reason for the large winter variability is the huge difference in 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 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, temperature cannot be so rigidly fixed. Small variability there is an artifact of limited measurements during 1951-1980. As a result, 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 Figure 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 Figure 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 Figure 2) in subsequent global maps, but that choice has little effect, as we will illustrate.

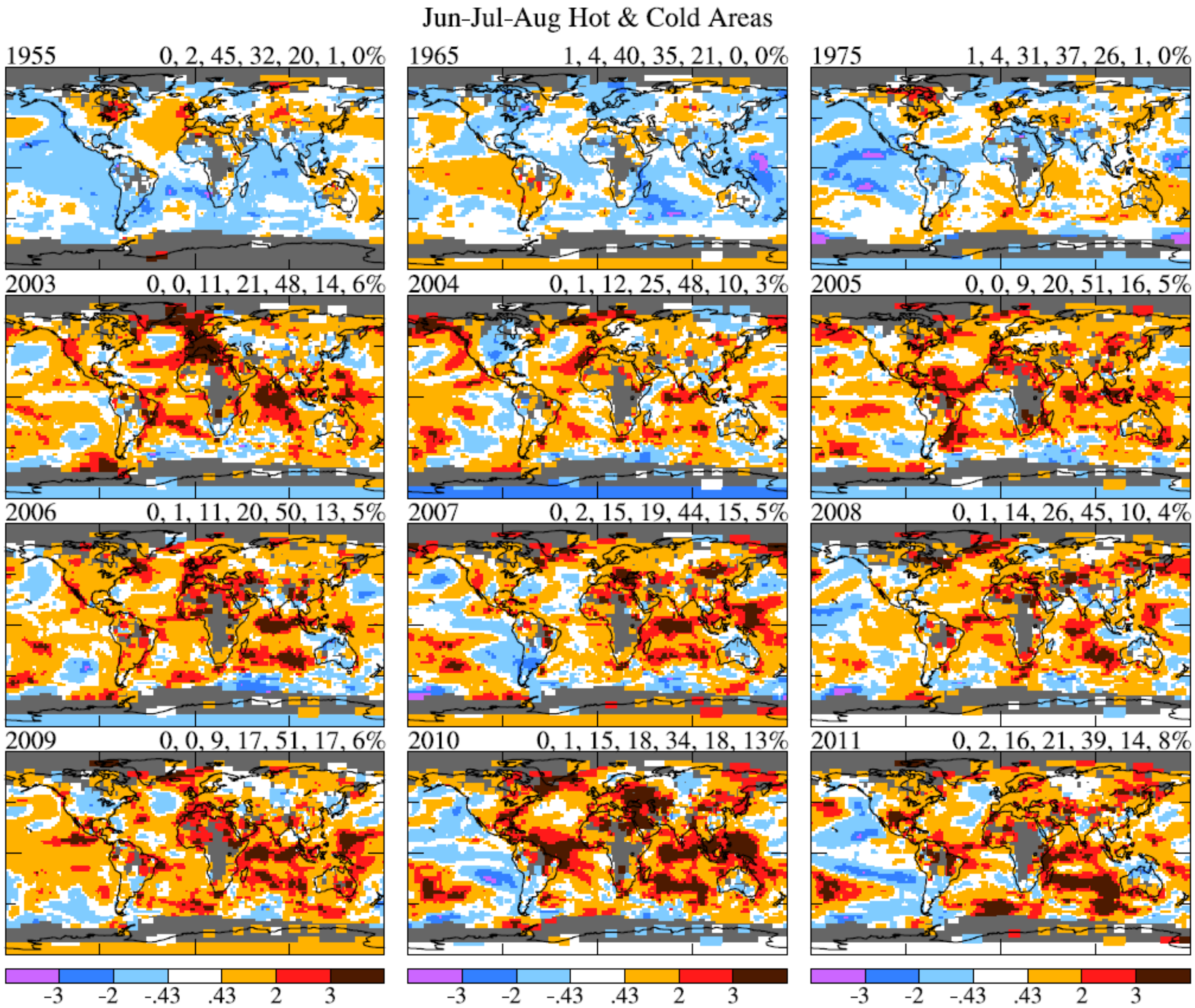

Figure 3. Jun-Jul-Aug surface temperature anomalies in 1955, 1965, 1975 and 2003-2011 relative to 1951-1980 mean temperature in units of the local standard deviation of temperature.

Now we can examine how unusual recent summer temperature anomalies were. Figure 3 shows the ratio: local temperature anomaly divided by local standard deviation, σ, where σ is from the middle column in Figure 2. The red and brown areas in Figure 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.

A remarkable feature of Figure 3 is the large brown area (anomaly > 3 σ), which covered between 3% and 6% of the world in 2003-2008, and between 6% and 13% in the past three years. 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.

That raises some questions: what does the actual distribution of temperature anomalies look like and how is it changing? And how important is a +3σ anomaly? A good indication of the impact of a large anomaly is provided by the fact that Texas in 2011 and large regions around Moscow and in the Middle East in 2010 had summer temperature anomalies that reached the +3σ level. But let us first look at how the distribution of temperature anomalies is changing.

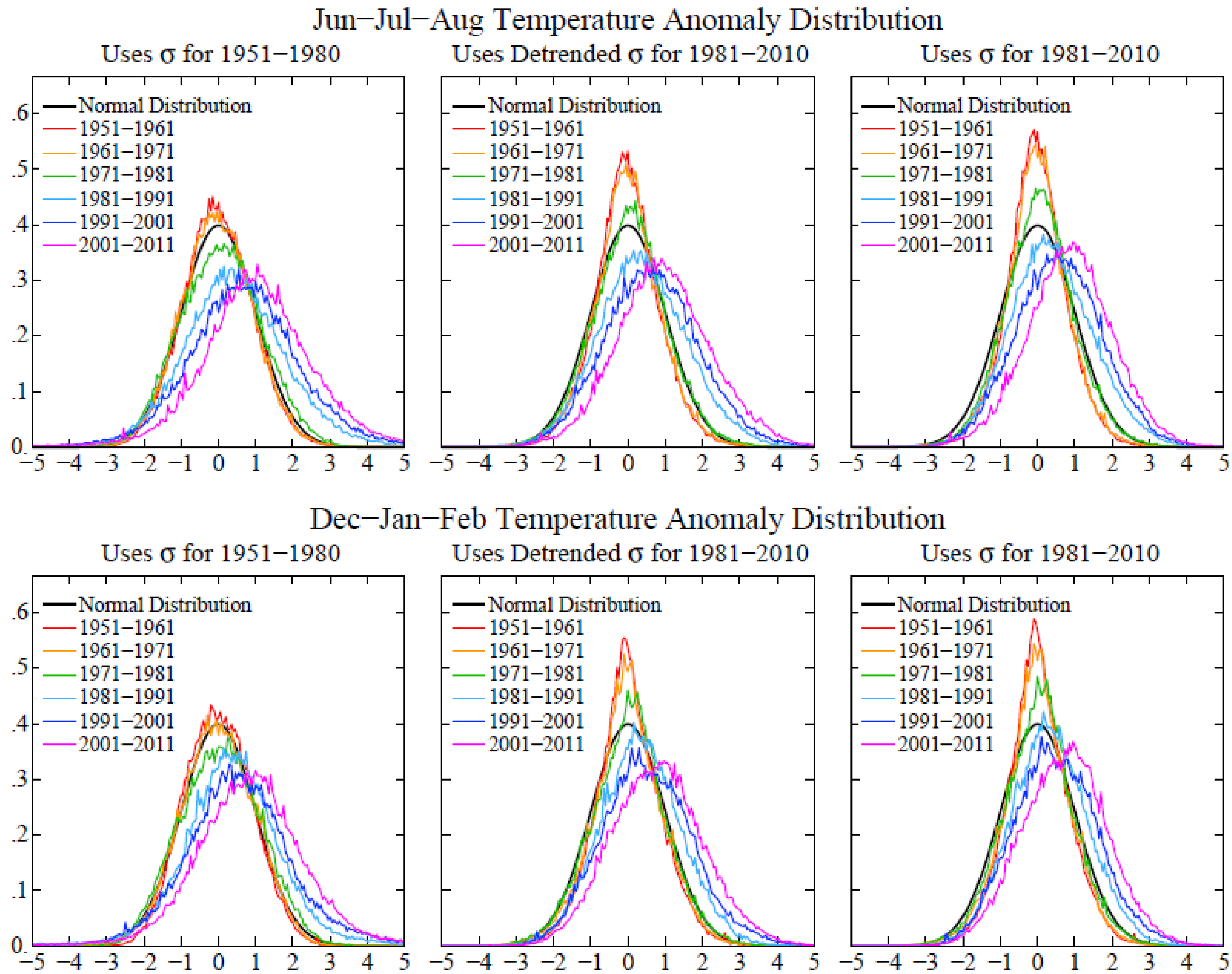

Figure 4. Frequency of occurrence (y-axis) of local temperature anomalies divided by local standard deviation (x-axis) obtained by binning all local results for 11-year periods into 0.05 intervals. Area under each curve is unity.

The distribution of Jun-Jul-Aug and Dec-Jan-Feb temperature anomalies divided by the standard deviation for 11-year periods beginning in 1951 is shown in Figure 4 for the three choices of standard deviation in Figure 2. For comparison the normal (a.k.a. Gaussian or bell-curve) distribution of anomalies is shown by the black line. The data curves were obtained by binning the local anomalies divided by local standard deviation into intervals of 0.05

The data for 1951-1980 happen to fit the normal distribution best when the standard deviation includes the effect of unrealistically small Southern Ocean variability (left column in Figures 2 and 4), as the data artifact broadens the distribution of anomaly divided by standard deviation. More realistic standard deviations based on 1981-2010 data yield a frequency distribution for observed temperature anomalies that is more peaked at small anomalies than the normal distribution. Observed anomalies in the base period have a smaller chance of being in the range 1-3σ than for the normal distribution.

The important point is the large shift of the probability distribution function toward the right in each successive decade in the past 30 years. The distribution also becomes broader in recent decades. The frequency of occurrence of 3σ, 4σ and 5σ anomalies, close to zero in 1951-1980, is substantial in the past decade, consistent with the large brown areas in Figure 3. The frequency of seasons colder than the 1951-1980 average temperature (cases with σ < 0 in Figure 4) is much smaller than it was in 1951-1980, but it is still far from zero.

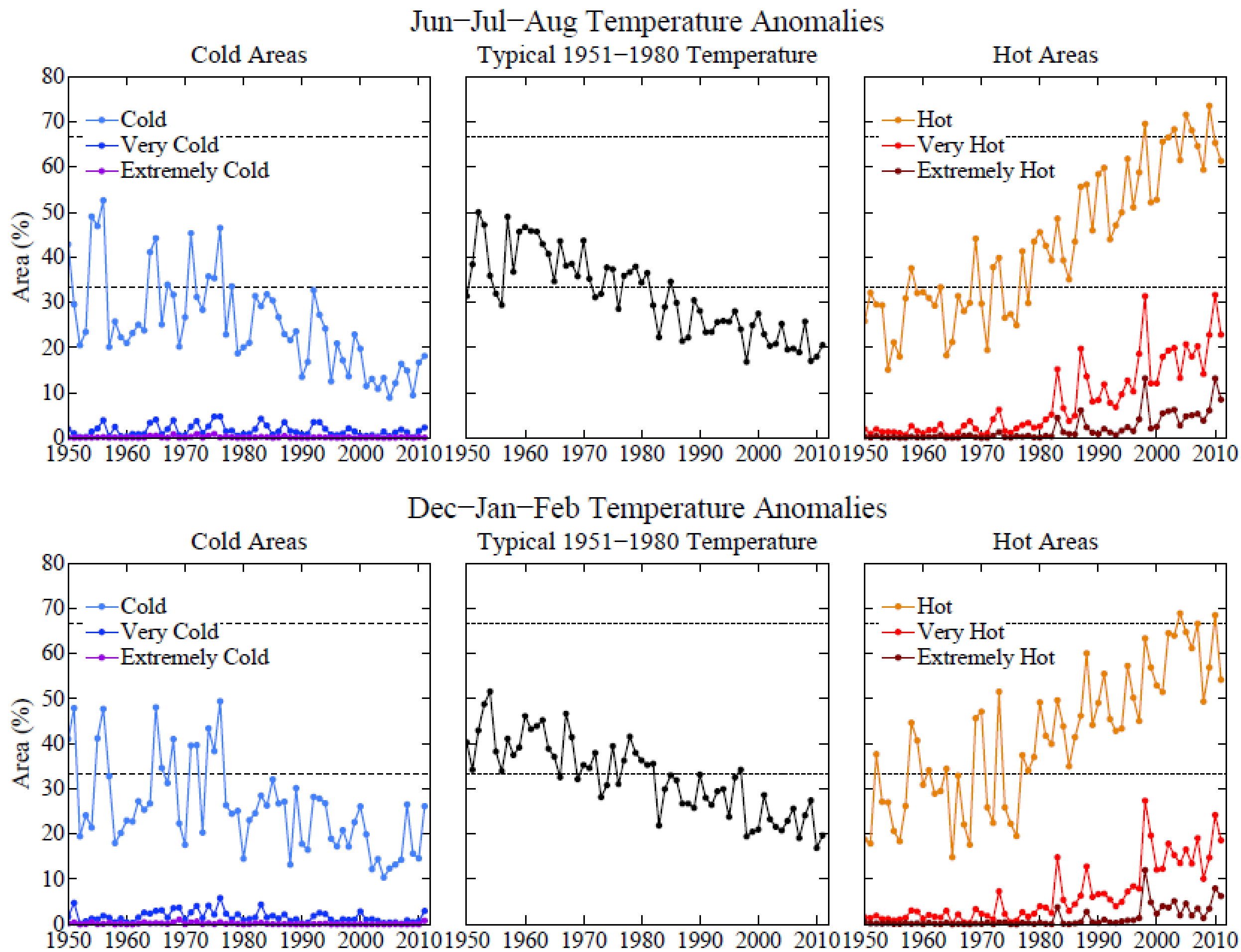

Figure 5. Area of the world covered by temperature anomalies in the categories defined as hot (σ > 0.43), very hot (σ > 2), and extremely hot (σ > 3), with analogous divisions for cold anomalies. These anomalies are relative to 1951-1980 climatology with σ from the detrended 1981-2010 data, but results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

Loaded climate dice. "Loading" of the "climate dice" describes the systematic shift of the frequency distribution of temperature anomalies. Hansen et al. (1988) 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 0.43 σ to achieve equal (one third) chances of being in each of these three categories in the period of climatology (1951-1980).

Hansen et al. (1988) projected how the odds would change due to global warming for alternative greenhouse gas scenarios. Their 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.

Figure 5 confirms that the actual occurrence of summers in the "hot" category (seasonal mean temperature anomaly exceeding +0.43 σ) has approximately reached the level of 67% required to make four sides of the dice red. The odds of a "cold" season or an "average" season now each correspond to one side of the six-sided dice, to a good approximation. However, note that the odds of an unusually cool Jun-Jul-Aug (by the standards of 1951-1980) have fallen more than the odds of having an unusually cold Dec-Jan-Feb.

Comparable loading of the dice has occurred in winter, where "hot", i.e., mild, winters now occur almost two-thirds of the time. Figures 4 and 5 show that the "loading of the dice" is

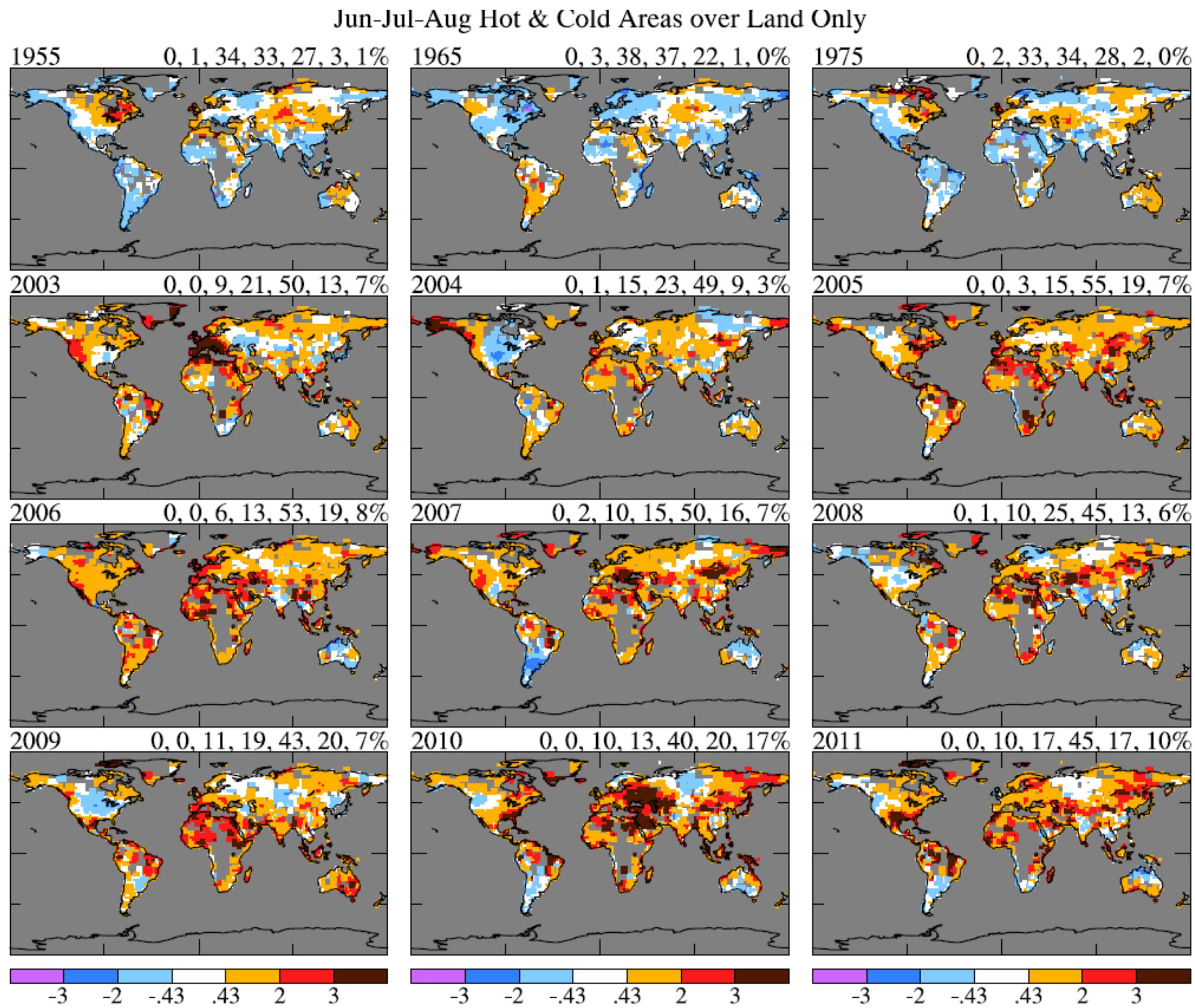

Figure 6. Jun-Jul-Aug surface temperature anomalies over land in 1955, 1965, 1975 and 2003-2011 relative to 1951-1980 mean temperature in units of the local standard deviation of temperature.

less in winter than in summer, despite the fact that warming has been larger in winter. Larger winter warming is more than offset by the fact that interannual variability is much larger in winter than in summer, as shown in Figure 2. Thus climate warming may not be as obvious to the public in winter as in summer, especially because snowfall amounts increase with global warming (in regions remaining cold enough for snow) and there is a tendency to equate heavy snowfall with harsh winter conditions, even if temperatures are not extremely low.

The most important change is the emergence of the new category of "extremely hot" summers, more than 3σ warmer than climatology. The frequency of these extreme anomalies shown in Figure 5 is calculated for the entire area (land and ocean) that has data. However, for practical purposes it is more important to look at the changes over land areas, where most people live, as shown in Figure 6 for Jun-Jul-Aug temperature anomalies. "Extremely hot" (temperature anomaly exceeding +3σ) almost never occurred during 1951-1980, as shown in Figure 6 for the mid-decade years of the 1950s, 1960s and 1970s. In the past several years the area covered with extreme anomalies, exceeding +3σ, has been of the order of 10% of the land area.

The increase, by more than a factor 10, of area covered by these extreme anomalies reflects the shifting of the distribution of anomalies over the past 30 years of global warming, as shown in the prior figures, most succinctly in Figure 4. One implication of this shift is that

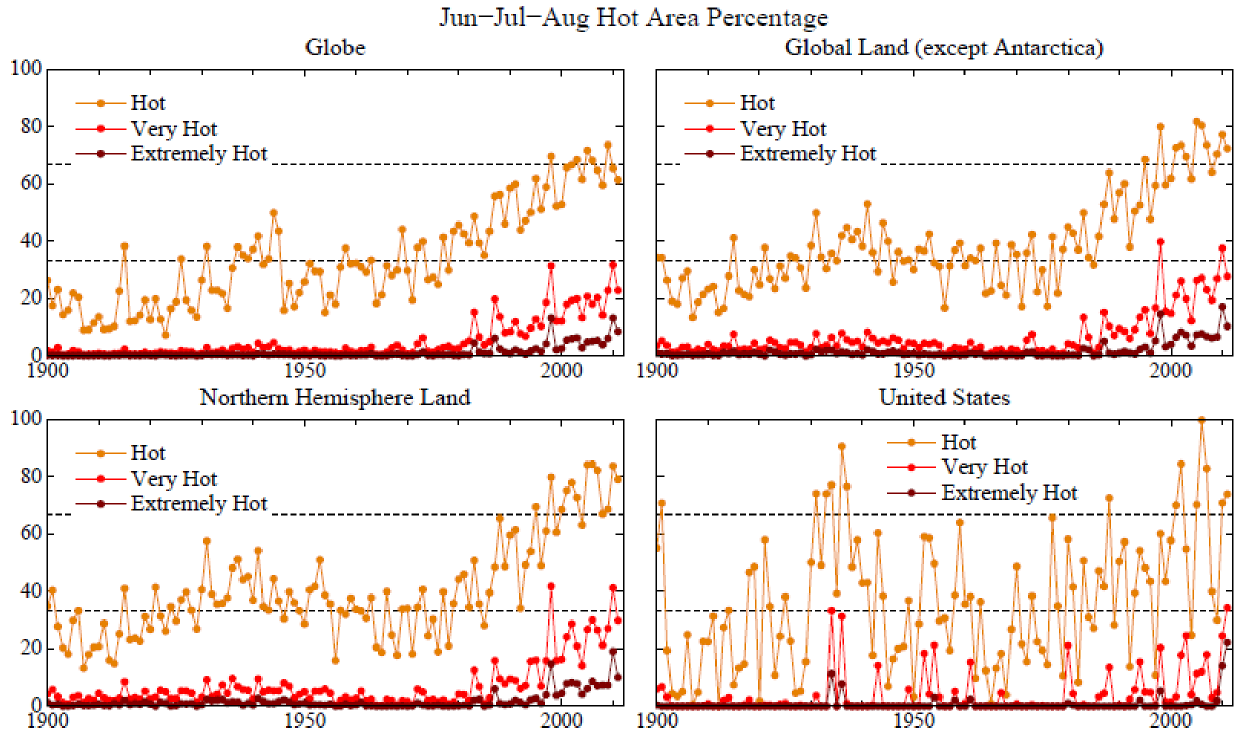

Figure 7. Percent area covered by temperature anomalies in categories defined as hot (σ > 0.43), very hot (σ > 2), and extremely hot (σ > 3). Anomalies are relative to 1951-1980 climatology; σ is from detrended 1981-2010 data, but results are similar for the alternative choices in Figure 2.

the extreme anomalies in Texas in 2011, in Moscow in 2010, and in France in 2003 almost certainly would not have occurred in the absence of the global warming with its resulting shift of the distribution of anomalies. In other words, we can say with a high degree of confidence that these extreme anomalies were a result of the global warming.

How will the "loading" of the climate dice continue to change in the future? Figure 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.

A longer time scale and regional detail. Jun-Jul-Aug data on a longer time scale, specifically 1900-present, and different spatial scales are shown in Figure 7. The frequency of extreme anomalies is only slightly larger for land than for land plus ocean, because temperature variability is smaller over the ocean, thus largely compensating for the smaller warming over the ocean. Restricting the data to Northern Hemisphere land, thus restricting the data to summer, also has rather little effect.

Nevertheless, these minor adjustments have an impact on the "climate dice" that people living in the Northern Hemisphere must deal with in the remainder of the current decade. The graph in the lower left of Figure 7 suggests that in this decade 5 of the 6 sides of the dice (~83% probability) will be red ("hot"). More important, two of these sides (~33% probability) will be at least into the category of dark red ("very hot", > +2σ) relative to the climatology of 1951-1980. Most important, the chances of an "extremely hot" summer (> +3σ, represented by brownish-red) seems likely to increase to the point of earning one side of the dice (~17% probability).

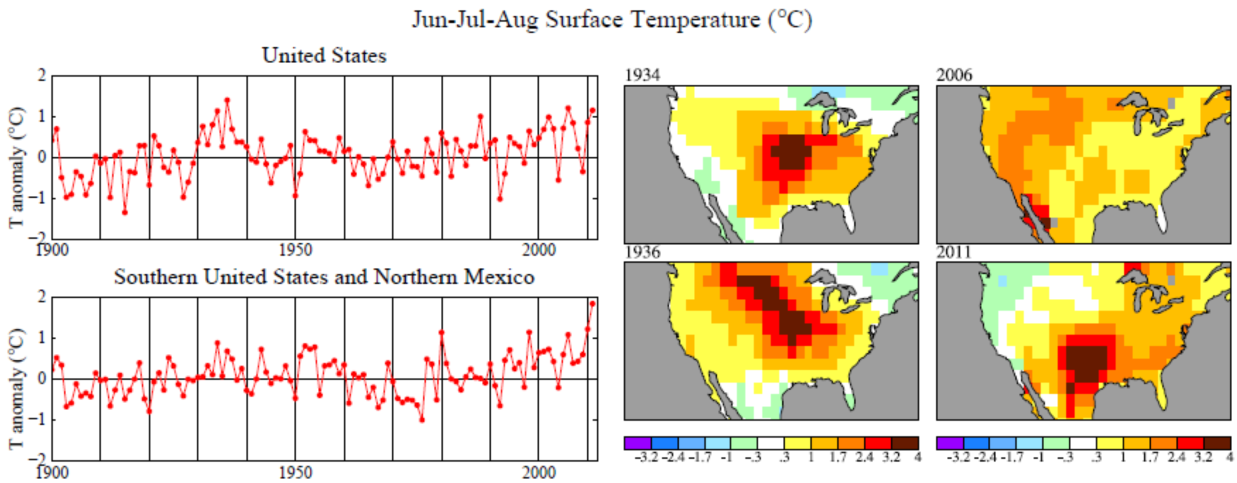

Figure 8. Temperature anomalies for the area covered by the 48 contiguous states of the United States and for an area of the southern U.S. and northern Mexico defined in Figure 9.

The longer time scale is important for the United States, because of the well-known extreme heat and droughts of the 1930s. The frequency of occurrence of the three categories of hot summers in the contiguous 48 states of the United States is shown in the lower right of Figure 7. The 48 states cover less than 1.6% of the global area and thus the results are very "noisy". Despite the noise, we can discern that the trend toward hot summers in recent decades is not as pronounced in the United States as it is in hemispheric land area as a whole. Also the extreme summer heat of the 1930s, especially 1934 and 1936, is comparable to the most extreme recent years.

Summer temperature anomalies for the United States are shown in Figure 8, including maps for 1934, 1936, 2006 and 2011. The mean temperature anomalies in these four warm summers (approximately +1°C or +2°F) are practically indistinguishable, as the differences among them are smaller than the uncertainty. 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 difficult and 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 (Nigam et al., 2011; Hoerling et al., 2011). However, others (Cook et al., 2009, 2010, 2011) have presented evidence that agricultural changes and crop failure contributed to changed surface albedo, aerosol (dust) production, high temperature and drying conditions. Furthermore, there is empirical evidence, supported by climate simulations (Puma and Cook, 2010; Cook et al, 2011), that agricultural irrigation has a significant regional cooling effect, and increasing amounts of irrigation over the second half of the 20th century probably contributed a summer cooling tendency in the United States that partially offset greenhouse warming. Such regionally-varying effects may be partially responsible for differences between observed global change and observed change in specific regions.

Regional variations of the climate dice changes are expected even for greenhouse gas warming. Climate models may not be capable of simulating changes for specific regions as yet, but one important regional effect that may be robust is expected poleward expansion of climate zones as the world warms. Theory and climate models indicate that subtropical regions

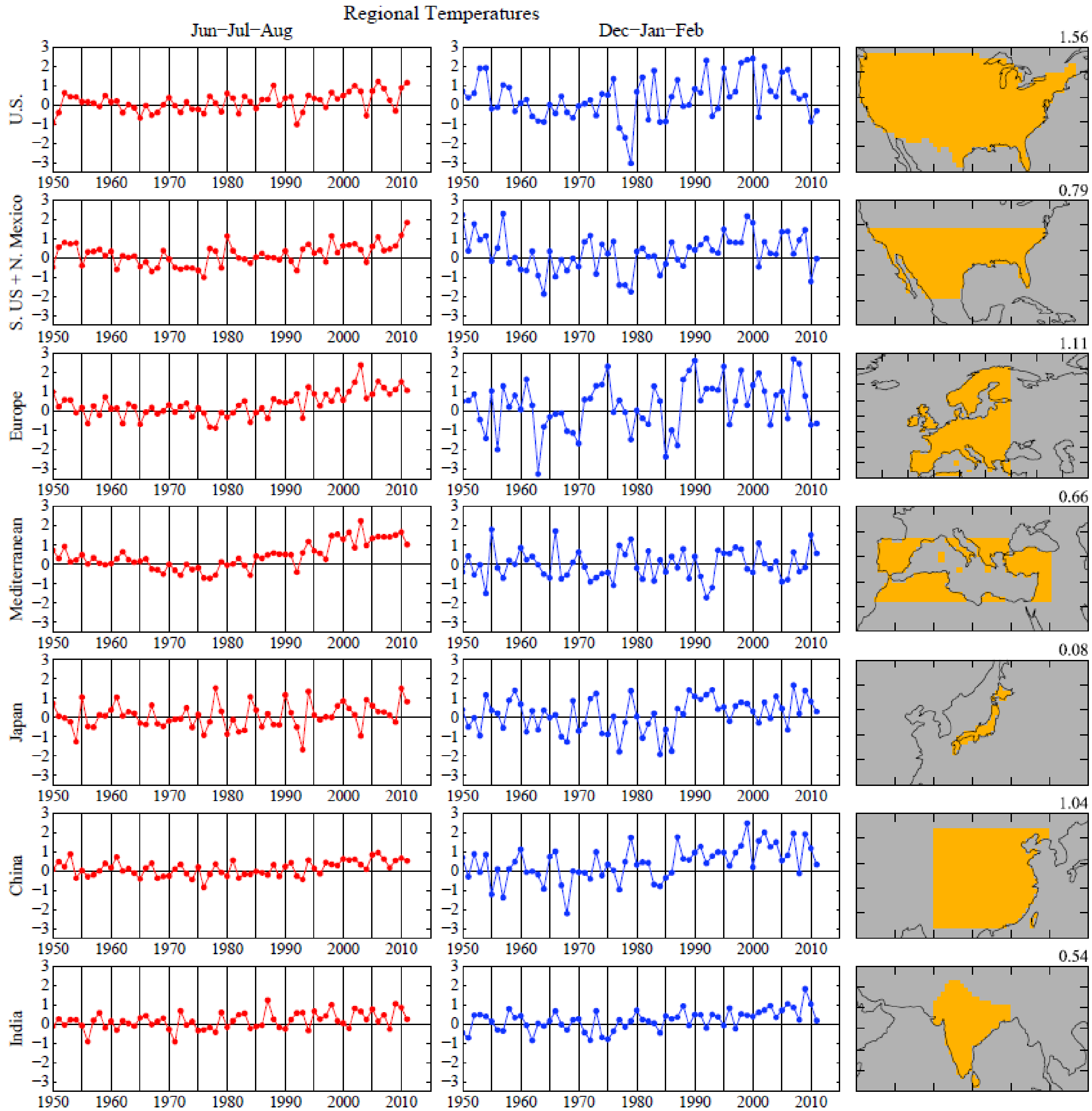

Figure 9. Jun-Jul-Aug and Dec-Jan-Feb temperature anomalies (°C) for areas shown on the right.

expand poleward with global warming (Held and Soden, 2006; IPCC, 2007). Observations already reveal a 4-degree latitude average poleward expansion of the subtropics (Seidel and Randel, 2006), yielding increased aridity in the southern United States (Barnett et al., 2008; Levi, 2008), the Mediterranean region, and Australia. Increased aridity and temperatures contribute to increased forest fires that burn hotter and are more destructive (Westerling et al., 2006).

Summer and winter temperature anomalies for several regions are shown in Figure 9. The objective of this figure is to show that even for these small regions (the area in China includes only the part with most of the population) there is already a systematic warming tendency, a loading of the climate dice, that should be noticed by the perceptive person. One of the strongest signals seems to be the summer warming in the (subtropical) Mediterranean, which includes Spain, Italy and Greece.

Discussion. Seasonal-mean temperature probability has shifted dramatically over the past three decades. As illustrated in Figure 4, the probability distribution has shifted toward higher temperatures by more than one standard deviation. But there is also a broadening of the distribution, a larger shift at high temperatures than at low temperatures.

Seasonal-mean temperatures that were in the "cold" category in 1951-1980 (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 (Figure 6). However, the chance of summer falling in the "hot" category of 1951-1980 is now about 70%. The climate dice are now loaded to a degree that the perceptive person (old enough to remember the climate of 1951-1980) should be able to recognize the existence of climate change.

The most important change of the climate dice is probably the appearance of extreme hot summer anomalies, with mean temperature at least three standard deviations greater than climatology, over about 10% of land area in recent years. These extreme temperatures were practically absent in the period of climatology, covering only a few tenths of one percent of the land area. Therefore 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 (2011), using a more elegant mathematical analysis, reached a similar conclusion for the Moscow anomaly.

People who deny the global warming cause of these extreme events usually offer 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. Of course the locations of the extreme anomalies in any given season are determined by the 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. For example, places experiencing an extended period of high atmospheric pressure will tend to develop drought conditions that are amplified by the ubiquitous warming effect of elevated greenhouse gas amounts.

Why is this climate shift important? Can't we just say, o.k., we have a new climate, we will adapt to this new temperature probability distribution?

Biology and ecosystems on our planet are adapted to the rather stable climate of the Holocene, the past 10,000 years or so. Local climate effects of global warming, arguably, are already noticeable and significant[1], but the big problem is that more warming is already in the pipeline without further increase of greenhouse gases and the gases are continuing to increase. The most important effects of the warming probably come via the effect of warming in exacerbating the extremes of the hydrologic cycle: more intense droughts at times and places where it is dry and more extreme precipitation and floods at other times.

If fossil fuel use continues along the business-as-usual pathway, the dramatic impacts of extreme 3σ events such as the 2011 Texas-Oklahoma heat wave and drought will become more common. The United States has not suffered many such events recently, but that good fortune will surely end if CO_2 emissions continue to increase and the temperature probability shifts substantially further toward higher temperatures.

One of the major candidates in the current Presidential primary in the United States has declared (http://www.cbsnews.com/8301-503544_162-20093535-503544.html) that human-

[1] One of us (JH) suggests that effects of ~1σ warming already are apparent on his property in eastern Pennsylvania. Several tree species (birch, pin oak, ash, maple…) exhibit stress. Proximate causes (borers, fungus, etc.) can be identified, but changing climate (some long hot dry summers, some periods of excessively moist conditions) seems to be a major underlying cause. Native Americans presumably did not need to water birch trees to keep them alive.

made global warming is a hoax, and he has issued an official Proclamation: " I, Rick Perry, Governor of Texas, under the authority vested in me by the Constitution and Statutes of the State of Texas, do hereby proclaim the three-day period from Friday, April 22, 2011, to Sunday, April 24, 2011, as Days of Prayer for Rain in the State of Texas. I urge Texans of all faiths and traditions to offer prayers on those days for the healing of our land, the rebuilding of our communities and the restoration of our normal way of life."

Science cannot disprove the possibility of divine intervention. However, there is a relevant saying that "Heaven helps those who help themselves."

Science does show that business-as-usual fossil fuel emissions will cause atmospheric CO_2 to continue to increase rapidly. The increasing greenhouse gases will cause the rapid global warming of the past three decades to continue, and this warming will cause the climate dice to become more and more loaded with greater and greater extreme events. The probability that this conclusion is wrong is about as close to zero as one can get.

Fortunately, it is not necessary to continue business-as-usual. In a paper that we are working on with a number of distinguished colleagues we argue that an appropriately rising price on carbon emissions could move the world to a clean energy future fast enough to limit further global warming to several tenths of a degree Celsius. Such a scenario is needed if we are to preserve life as we know it.

References

Barnett, T.P, et al., 2008: Human-induced changes in the hydrology of the Western United States. *Science*, 319, 1080-1083. Doi:10.1126/science.1152538.

Cook, B.I., R.L. Miller, and R. Seager, 2009: Amplification of the North American "Dust Bowl" drought through human induced land degradation. *Proc. Natl. Acad. Sci.*, **106**, 4997-5001, doi:10.1073/pnas.0810200106.

Cook, B.I., A. Terando, and A. Steiner, 2010: Ecological forecasting under climatic data uncertainty: A case study in phenological modeling. *Environ. Res. Lett.*, **5**, 044014, doi:10.1088/1748-9326/5/4/044014.

Cook, B.I., M.J. Puma, and N.Y. Krakauer, 2011: Irrigation induced surface cooling in the context of modern and increased greenhouse gas forcing. *Clim. Dynam.*, **37**, 1587-1600, doi:10.1007/s00382-010-0932-x.

Hansen, J., I. Fung, A. Lacis, D. Rind, 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, doi:10.1029/JD093iD08p09341.

Hansen, J., R. Ruedy, M. Sato, and K. Lo, 2010: Global surface temperature change. *Rev. Geophys.*, **48**, RG4004, doi:10.1029/2010RG000345.

Hansen, J. et al., 2011: The case for young people and nature (in preparation).

Held, I,M., Soden, B.J., 2006: Robust responses of the hydrologic cycle to global warming, *J. Climate*, **19**, 5686-5699.

Hoerling, M., J. Eischeid, J. Perlwitz, X.-W. Quan, T. Zhang, P. Pegion: On the Increased Frequency of Mediterranean Drought, *J. Climate* in press.

Intergovernmental Panel on Climate Change (WGII), *Climate Change 2007: Impacts, Adaptation and Vulnerability*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, C.E. Hanson (eds., Cambridge Univ. Press, 996 pp.

Levi, B.G., 2008: Trends in the hydrology of the western U.S. bear the imprint of manmade climate change, *Phys. Today*, April 16-18.

Nigam, S., B. Guan, and A. Ruiz-Barradas, 2011: Key role of the Atlantic Multidecadal Oscillation in 20th century drought and wet periods over the Great Plains. *Geophys. Res. Lett.*, **38,** L16713, doi:10.1029/2011GL048650.

Puma, M.J., and B.I. Cook, 2010: Effects of irrigation on global climate during the 20th century. *J. Geophys. Res.*, **115**, D16120, doi:10.1029/2010JD014122.

Rahmstorf, S. and D. Coumou, 2011: Increase of extreme events in a warming world, www.pnas.org/cgi/doi/10.1073/pnas.1101766108

Seidel, D.J., and W.J. Randel, 2006: Variability and trends in the global tropopause estimation from radiosonde data., *J. Geophys. Res.*, 111, D21101, doi:10.1029/2006JD007363.

Westerling, A., H. Hidalgo, D. Cayan, T. Swetnam, 2006: Warming and earlier spring increases western U.S. forest wildfire activity, *Science*, **313**, 940-943.