Perception of climate change

James Hansen[a,1], **Makiko Sato**[a], **and Reto Ruedy**[b]

[a]National Aeronautics and Space Administration Goddard Institute for Space Studies and Columbia University Earth Institute, New York, NY 10025; and [b]Trinnovim Limited Liability Company, New York, NY 10025

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"Climate dice," describing the chance of unusually warm or cool seasons, have become more and more "loaded" in the past 30 y, 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 (3σ) warmer than the climatology of the 1951–1980 base period. This hot extreme, which covered much less than 1% of Earth's surface during the base period, now typically covers about 10% of the land area. It follows that we can state, with a high degree of confidence, that extreme anomalies such as those in Texas and Oklahoma in 2011 and Moscow in 2010 were a consequence of global warming because their likelihood in the absence of global warming was exceedingly small. We discuss practical implications of this substantial, growing, climate change.

climate impacts | climate anomalies | heat waves

The greatest barrier to public recognition of human-made climate change is probably the natural variability of local 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 recognizes that human-made climate change is underway and perceives that it will have unacceptable consequences if effective actions are not taken to slow the climate change. A recent survey in the United States (1) confirms that public opinion about the existence and importance of global warming depends strongly on their perceptions of recent local climate variations. Early public 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 (2).

It was suggested decades ago (3) that by the early 21st century the informed public should be able to recognize that the frequency of unusually warm seasons had increased, because the "climate dice," describing the probability of unusually warm or unusually cool seasons, would be sufficiently loaded (biased) 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 related to the on-going global warming trend, which has been attributed with a high degree of confidence to human-made greenhouse gases (4).

Summer, when most biological productivity occurs, is probably the season when climate change will have its biggest impact on humanity. Global warming causes spring warmth to come earlier and 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. Therefore, we emphasize in this paper how summer temperature anomalies are changing. However, warmer winters also have important effects, e.g., winter freezes are critical in many regions for minimizing future pest and disease outbreaks. Thus we provide on our Web site (http://www.columbia.edu/~mhs119/PerceptionsAndDice/) more extensive results for winter than we have space for in the present paper.

Although we were motivated in this research by an objective to expose effects of human-made global warming as soon as possible, we use an empirical approach that does not require knowledge of the causes of observed climate change. We also avoid any use of global climate models, instead dealing only with real world data. Moreover, although the location, extent, and duration of regional temperature anomalies is affected by atmospheric blocking situations, El Niños, La Niñas, and other meteorological events, there is no need to understand and analyze the role of these phenomena in our purely empirical approach. Theories for the cause of observed global temperature change are thus separated as an independent matter.

Materials and Methods

We use the Goddard Institute for Space Studies (GISS) surface air temperature analysis (5) to examine seasonal mean temperature variability and how that variability is changing. The GISS analysis is carried out at two spatial resolutions: 1,200 km and 250 km. We use the 250 km analysis because it is better-suited for illustrating variability on regional spatial scales.

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 (6) because it is the version employed in the documented GISS analysis (5). 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 distribution of anomalies in units of the standard deviation, including comparison of the observed distribution of anomalies with the normal distribution ("bell curve") that the lay public may appreciate. Anomalies are defined relative to a specified climatology, the observed climate in a chosen base period. The base period should be long enough to provide sufficient data for statistical analyses—we choose 30 y, consistent with the period used by most weather and climate services. The period should also be fixed because, as we show later, a shifting base period hides potentially important changes in the nature of the anomaly distribution.

We choose 1951–1980 as the base period for most of our illustrations, for several reasons. First, it was a time of relatively stable global temperature, prior to rapid global warming in recent decades. Second, it is recent enough for older people, especially the "baby boom" generation, to remember. Third, global temperature in 1951–1980 was within the Holocene range, and thus it is a climate that the natural world and civilization are adapted to. In contrast, global temperature in at least the past two decades is probably outside the Holocene range (7), as evidenced by the fact that the Greenland and Antarctic ice sheets are both losing mass rapidly (8, 9) and sea level has been rising at a rate [3 m/millennium, (10); updates available at http://sealevel.colorado.edu/] well above the average rate during the past

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See Commentary on page 14720.

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

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several thousand years. Fourth, we have used this base period in scores of publications for both observational and model analyses, so it is the best period for comparisons with prior work.

Below we will illustrate the effect of alternative choices for base period. We will show that a fixed base period prior to the period of rapid global warming allows the effects of that warming to be discerned more readily. This brings to light a disadvantage of the practice of continually shifting the base period to the most recent three decades, which is a common practice of meteorological services.

Results

Seasonal Temperature Anomalies. June–July–August (Northern Hemisphere summer, Southern Hemisphere winter) 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 in recent years are warmer than during 1951–1980, but some areas cooler than the 1951–1980 mean occur every year. The United States, for example, was unusually cool in the summer of 2009. Anomaly maps for the opposite season (December–January–February) are available on the Web site noted above. Anomalies for the spring and fall can be constructed readily from the temperature data available at www.giss.nasa.gov/data.

What is the practical importance of such temperature anomalies? Global warming since 1951–1980 is about 0.5–0.6 °C (about 1 °F) (5, 11–13). This seems small, and indeed it is small compared with weather fluctuations. Yet we will suggest that this level of average warming is already having important effects.

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 seasonal mean surface temperature over a period of years is a measure of the typical variability of the seasonal mean temperature over that period of years. Fig. 2 (*Left*) shows this variability during the base period 1951–1980.

Below we will illustrate 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% 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.

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 great 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 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.

Note in Fig. 2 that there are areas in the Southern ocean in which the standard deviation is less than 0.1 °C in both December–January–February and June–July–August. This unrealistically small variability is the result of an absence of measurements in the presatellite era in a region with very little ship traffic. This artifact does not occur in the standard deviation for 1981–2010 (Fig. 2, *Right*), when satellite observations provided uniform daily observations.

A drawback of using 1981–2010 to define variability is the existence of rapid global warming during that period, a trend that is presumably a human-made effect (4). However, subtracting the local linear temperature trend before calculating the standard deviation only moderately reduces the local variability (Fig. 2, *Center*). This comparison confirms that local year-to-year temperature fluctuations, not the long-term temperature trend, provide the main contribution to σ.

The global mean of the local standard deviation of June–July–August surface temperature increases from 0.50 °C for 1951–980 data to 0.58 °C for 1981–2010 data. Only half of this increase is removed if the 1981–2010 data are detrended (change due to the trend being subtracted) using the local trend before the standard deviation is calculated. Indeed, the maps in Fig. 2 suggest that there are regions in the Northern Hemisphere summer where the variability is greater in 1981–2010 than in 1951–1980, even if the 1981–2010 data are detrended. The increase of variability is widespread, being apparent in North America and Asia, but

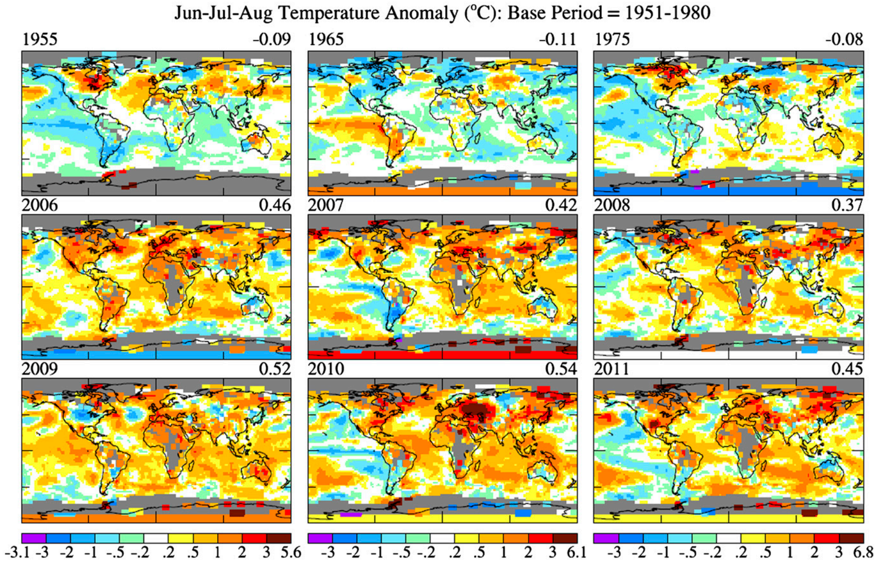

Fig. 1. June–July–August surface temperature anomalies in 1955, 1965, 1975, and the past 6 y relative to the 1951–1980 mean. Number on *Upper Right* is the global mean (average over all area with data).

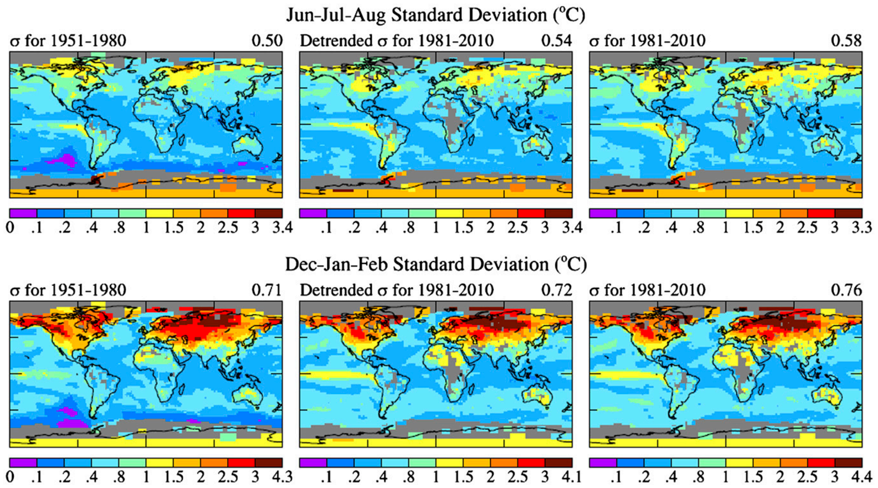

Fig. 2. Standard deviation of local June–July–August (*Upper*) and December–January–February (*Lower*) mean surface temperature for 30-y periods 1951–1980 (*Left*) and 1981–2010. In the *Center* maps the local 30-y (1981–2010) temperature trend was removed before calculating the standard deviation.

also in the equatorial Pacific Ocean (Fig. 2), where the unusually strong El Niños in 1983 and 1997–1998 might be a factor.

Over the ocean, some of the increased variability could be a consequence of increased spatial and temporal resolution, because the 1981–2010 period has high-resolution satellite data, while the 1951–1980 period is largely dependent on ship data. This issue could be examined by comparing analyses based on full resolution satellite-era data with an analysis of the same period employing subsampling at the resolution of the presatellite era. However, we do not carry out such a study because our interest is primarily in the areas where most people live. Thus in the following analyses we will focus on land data, while including some global data for comparison.

Recent Temperature Anomalies. Let's examine the question: How unusual are recent anomalies? Fig. 3 shows the ratio: local temperature anomaly divided by local standard deviation, σ, where σ is from *e* Fig. 2, *Center*. These maps include Northern Hemisphere summer and Southern Hemisphere winter; later we separate data by hemisphere to focus on a specific season, but it is apparent that observed anomalies in units of standard deviation are of comparable magnitude in the opposite hemisphere/season. Red and brown areas in Fig. 3 have anomalies exceeding 2σ and 3σ, respectively. The numbers on the top of each map are the percentage of the total area with data covered by each of the seven categories in the color bar.

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. In the absence of climate change, and if temperature anomalies were normally distributed, we would expect the brown area to cover only 0.1–0.2% of the planet. In Fig. 3, *Top*, the temperature anomalies in a mid-year of each of the three decades in the 1951–1980 base period, confirms that such extreme anomalies were practically absent in that period. Occurrence of extreme anomalies ($> +3\sigma$) in recent years is an order of magnitude greater than during the 1951–1980 base period.

The recent spate of 3σ events raises several questions. What does the temperature anomaly distribution look like, how is it changing, and how important is a $+3\sigma$ anomaly? Well-publicized extreme conditions in Texas in 2011 and around Moscow and in the Middle East in 2010 had summer temperature anomalies

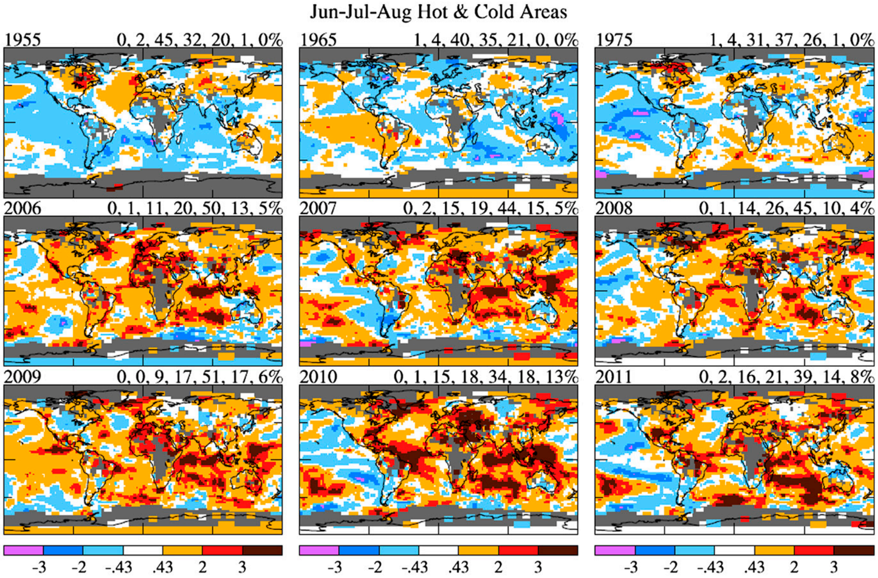

Fig. 3. June–July–August surface temperature anomalies in 1955, 1965, 1975, and in 2006–2011 relative to 1951–1980 mean temperature in units of the local detrended 1981–2010 standard deviation of temperature. Numbers above each map are percent of the area with data covered by each category in the color bar.

reaching the +3σ level (Fig. 3), suggesting that an increase of such extreme events may have large practical impacts.

Temperature Anomaly Distributions. The temperature anomaly distribution defines the frequency of occurrence of anomalies in units of the local standard deviation. We use data from the globe, hemisphere, or land area within a hemisphere, so as to have enough data to define a reasonably smooth anomaly distribution for a period as short as a decade.

The June–July–August temperature anomaly distribution in successive decadal periods is shown in Fig. 4 for the three choices of standard deviation in Fig. 2. The *Upper* row is the global result, thus a combination of summer and winter data. The *Lower* row is summer data for Northern Hemisphere land. The data curves were obtained by binning the local anomalies divided by local standard deviation into intervals of 0.05 (i.e., by counting the number of grid boxes having a ratio within each successive 0.05 interval).

The normal (a.k.a. Gaussian or bell-curve) distribution of anomalies is shown by the black line. The normal curve is a simple mathematical function independent of the temperature data.

The temperature anomaly distribution with standard deviation based on 1951–1980 data falls close to the normal distribution for each decade in the 1951–1980 base period. The anomaly distributions for these decades become more peaked than the normal distribution if they employ the standard deviations of 1981–2010 because of greater temperature variability in 1981–2010. Northern Hemisphere land results (Fig. 4, *Lower*) confirm this conclusion, while avoiding any possible effect of artificially small standard deviations over poorly sampled ocean areas.

The probability distribution shifts to the right in each successive decade in the past 30 y and the distribution becomes broader, with the broadening adding to the increase of hot anomalies. 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. Occurrence of seasons cooler than the 1951–1980 average (temperature anomaly <0 °C) is greatly diminished in recent decades, as we will quantify below.

Loaded Climate Dice. "Loading" of the climate dice is one way to describe a systematic shift of temperature anomalies. Hansen et al. (3) represented the climate of 1951–1980 by colored dice with two sides red for "hot," two sides blue for "cold," and two sides white for near average temperature. With a normal distribution of anomalies the dividing points are ±0.43σ to achieve equal (one-third) chances for each of these three categories in the base period (1951–1980).

Hansen et al. (3) used a climate model to project 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 close to reality, led to four of the six dice sides being red early in the 21st century, based on their climate model simulations. Although our dice metaphor thus originated as a prediction of observable impacts of human-made climate forcings, the dice loading is an expected effect of global warming, regardless of what caused the warming.

Fig. 5 reveals that the occurrence of "hot" summers (seasonal mean temperature anomaly exceeding +0.43σ) has reached the level of 67% required to make four sides of the dice red in both the Northern Hemisphere (Fig. 5, *Top*) and Southern Hemisphere (Fig. 5, *Bottom*). The loading of the dice in winter (Fig. 5, *Middle*), i.e., the shift to unusually warm seasons, is not as great as in summer, despite the fact that observed warming in winter is larger than in summer (5). The reason for the smaller apparent change in winter is the much larger chaotic climate variability of temperature in that season, as summarized by the standard deviation (Fig. 2).

Probably the most important change is the emergence of a new category of "extremely hot" summers, more than 3σ warmer than the base period mean. Fig. 6 illustrates that +3σ anomalies practically did not exist in 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 the Southern Hemisphere and for December–January–February are included on the Web site http://www.columbia.edu/~mhs119/PerceptionsAndDice to allow examination of trends for both winter and summer in both

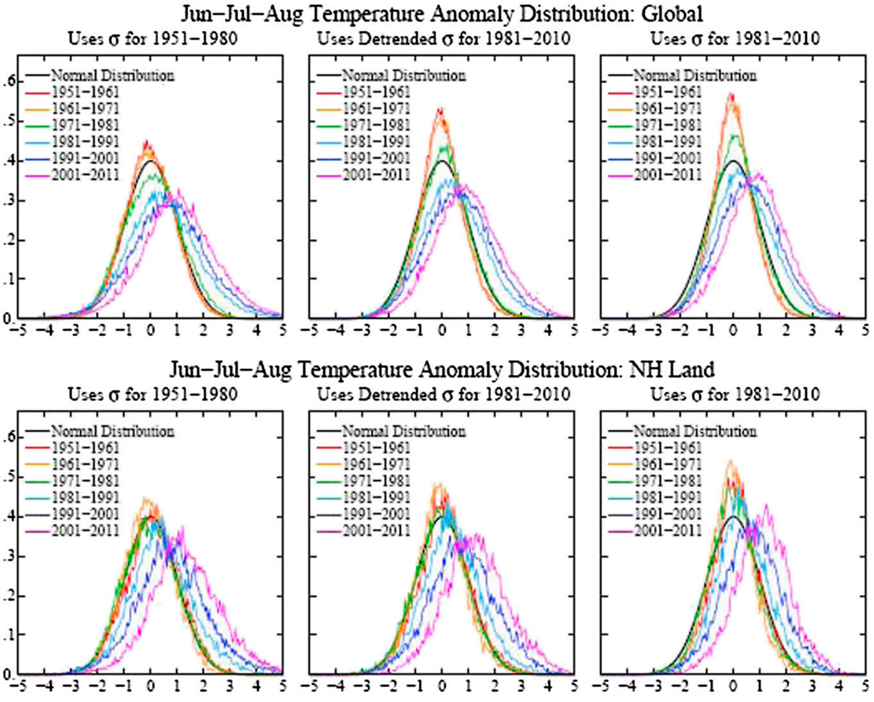

Fig. 4. Frequency of occurrence (*y* axis) of local temperature anomalies (relative to 1951–1980 mean) divided by local standard deviation (*x* axis) obtained by counting gridboxes with anomalies in each 0.05 interval. Area under each curve is unity.

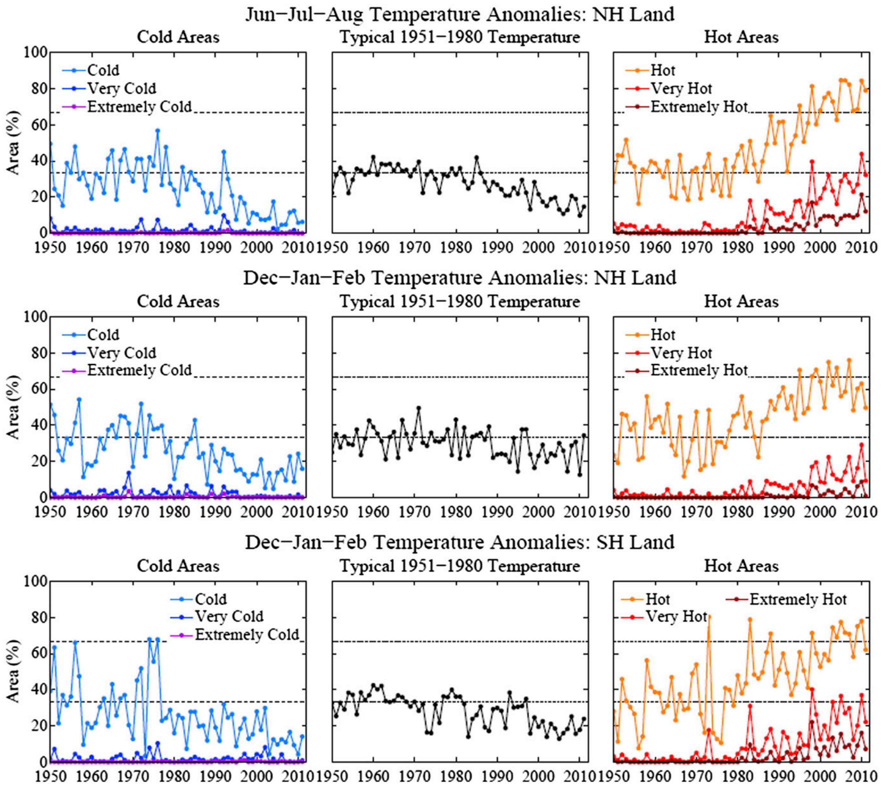

Fig. 5. Area covered by temperature anomalies in the categories defined as hot (> 0.43σ), very hot (>2σ), and extremely hot (>3σ), with analogous divisions for cold anomalies. Anomalies are relative to 1951–1980 base period, with σ also from 1951–1980 data. Lowest row is Southern Hemisphere summer.

hemispheres. Winter trends in units of standard deviations are comparable to those in summer but tend to be smaller. Another factor making it difficult for the public to recognize global warming in winter, in addition to the large natural variability in winter (Fig. 2), is a tendency of the public to equate heavy snowfall with harsh winter conditions, even if temperatures are not extremely low. Observations (14, 15) confirm expectations that a warmer atmosphere holds more water vapor, and thus warming may cause snowfall to increase in places that remain cool enough for snow.

The increase, by more than a factor 10, of area covered by extreme hot summer anomalies ($> + 3\sigma$) reflects the shift of the anomaly distribution in the past 30 y 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 high confidence that such extreme anomalies would not have occurred in the absence of global warming.

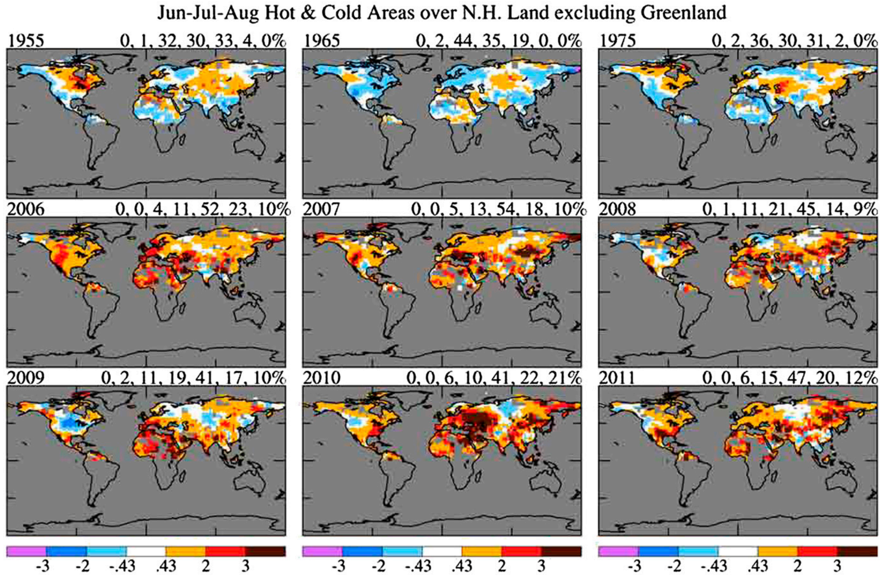

Fig. 6. June–July–August surface temperature anomalies over Northern Hemisphere land in 1955, 1965, 1975, and 2006–2011 relative to 1951–1980 base period in units of the local 1951–1980 standard deviation. Numbers above each map are percent of surface area covered by each category in the color bar.

How will loading of the climate dice continue to change in the future? Fig. 4 provides a clear, sobering, indication. The temperature anomaly distribution shifts to the right and broadens with global warming, the broadening presumably the expected effect of global warming on the water cycle, as discussed below. The hot tail of the temperature anomaly distribution shifted 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 y, if business-as-usual fossil fuel emissions continue, is expected to be at least 1 °C (4). In that case, the further shifting of the anomaly distribution will make +3σ anomalies the norm and +5σ anomalies will be common.

Regional Temperature Anomalies. We used global data for the purpose of having enough data points to show clearly temporal change of the temperature anomaly distribution (Fig. 4). Global or hemispheric anomaly distributions provide an approximate indication of the likelihood of temperature anomalies in all regions because anomalies are becoming more positive all over the planet, as shown in Fig. 1. However, regional variations are expected because of greater climate "noise" (unforced variability) on small scales, possible regional climate forcings, and known mechanisms that affect the large scale spatial variation of global warming.

Summer data for 1900–present are shown in Fig. 7 for the land area in each hemisphere and for the United States. Temperature anomalies are "noisy" for the United States because of the small area of the contiguous 48 states (less than 1.6% of the globe), yet we can discern that the long-term trend toward hot summers is not as pronounced in the United States as it is for hemispheric land as a whole. Indeed, the extreme summer heat of the 1930s, especially 1934 and 1936, is comparable to the United States temperature in the most extreme recent years.

The large 1930s and 1940s anomalies in the United States do not obviate the conclusion that recent global warming, with high probability, is responsible for recent extreme anomalies. Our *SI Text* shows maps of temperature anomalies for 6 y with the greatest "hot" area (1931, 1934, 1936, 1941, 1947, 1953) in that early warm period. Those years were warmer (globally and in the United States) than the 1951–1980 mean, so it is not surprising that the area with 3σ anomalies was greater than in the 1951–1980 climatology. The year with the largest area of 3σ anomalies was 1941, when it reached 2.7% of Northern Hemisphere land area. This compares with recent values as great as 20% and a recent average of about 10%.

Year-to-year variability is so large for an area the size of the United States that it is not essential to find an external mechanism for the deviation from the hemispheric mean. However, interpretation of the weak warming trend in the United States matters because, if it is a statistical fluke, the United States may have in store a rapid trend toward more extreme anomalies.

Some researchers suggest that high summer temperatures and drought in the United States in the 1930s can be accounted for by natural variability of sea surface temperature patterns (16, 17). Other researchers (18–20) have presented evidence that agricultural changes (plowing of the Great Plains) and crop failure in the 1930s contributed to changed surface albedo, aerosol (dust) production, high temperatures, and drying conditions. Empirical evidence and simulations (20, 21) show that agricultural irrigation, which is now more common, has a significant regional cooling effect. Such regionally varying effects may partly account for differences between observed regional global temperature trends, and such effects must be understood to achieve accurate knowledge of how the climate dice are now loaded in specific regions.

Summer and winter temperature anomalies for additional small regions are shown in Fig. 8, with the area in China being the part with most of its population. This figure reveals that even for such small regions (maximum size about 1.5% of globe) a systematic warming tendency is apparent, especially in the summer. However, seasonal mean temperatures cooler than the 1951–1980 average still occur occasionally, especially in the winter.

Discussion

Principal Findings. Seasonal-mean temperature anomalies have changed dramatically in the past three decades, especially in summer. The probability distribution for temperature anomalies has shifted more than one standard deviation toward higher values. In addition, the distribution has broadened, the shift being greater at the high temperature tail of the distribution.

The climate dice are now loaded to a degree that a perceptive person old enough to remember the climate of 1951–1980 should recognize the existence of climate change, especially in summer. Summers with mean temperature 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, now occur about 10% of the time, while those in the hot category have increased from about 33% to about 75% (Fig. 7).

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 are occurring over about 10% of global land area in recent years. The increase 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 (22), 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 extreme atmospheric "blocking" situation, or the Texas heat wave was caused by La Niña ocean temperature patterns. Certainly the locations of extreme anomalies in any given case depend on specific weather patterns. However, blocking patterns and La Niñas 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 as

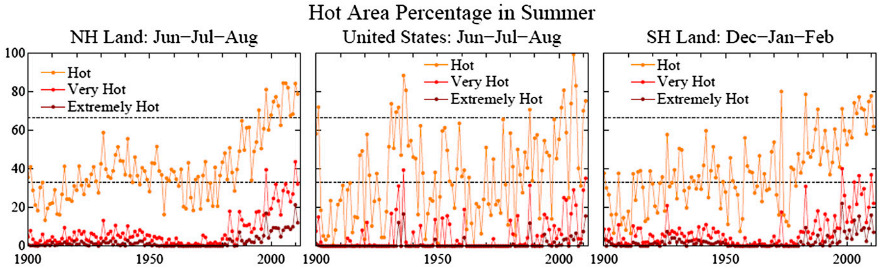

Fig. 7. Percent area covered by temperature anomalies in categories defined as hot (>0.43σ), very hot (>2σ), and extremely hot (>3σ). Anomalies are relative to 1951–1980 base period; σ is from 1951–1980 data.

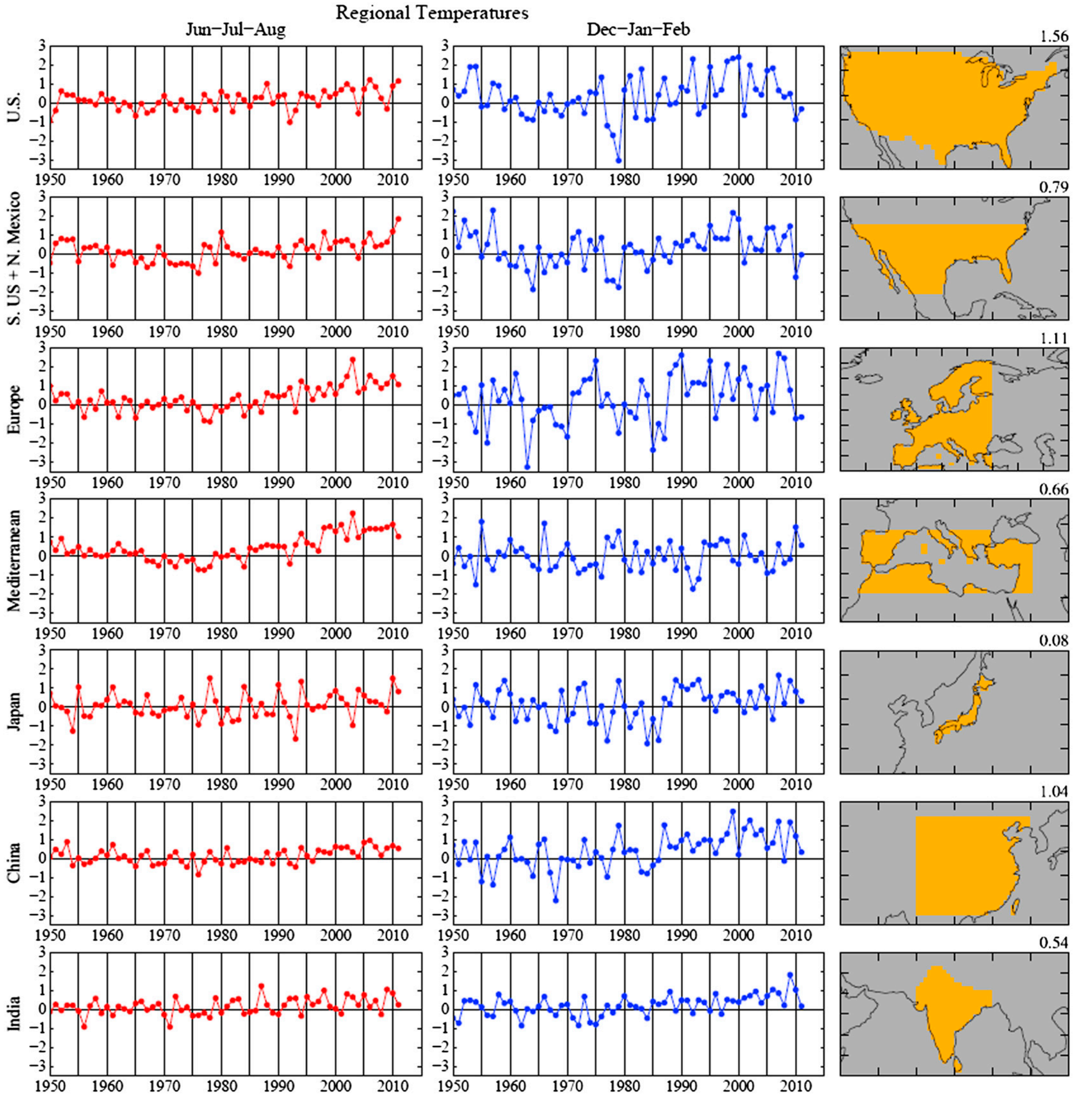

Fig. 8. June–July–August and December–January–February temperature anomalies (°C) relative to 1951–1980 base period for areas shown on the right. Number above each map is the colored region's percent of global area.

a result of simultaneous contributions of specific weather patterns and global warming.

Reference Period. Although we had multiple reasons for choosing 1951–1980 as a base period to define temperature anomalies, as discussed under *Materials and Methods*, we must ask: Do our conclusions depend on the chosen base period? Could 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 temperature anomaly distribution is shown in Fig. 9. Use of a recent base period alters the appearance of the distribution. Climate variability increased in recent decades, and thus the standard deviation increased. Therefore, 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 (Fig. 9, *Right*) does not expose the change that has occurred toward increased climate variability.

The World Meteorological Organization uses the most recent three decades to define climatology (23). This is a useful procedure when the objective is to define anomalies relative to a recent period whose climate most people will be familiar with. 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 use of a fixed base period.

The question then becomes, what is the most appropriate base period. Our initial choice, 1951–1980, seems to be nearly optimum. It was a period of relatively stable global temperature and the earliest base period with good global coverage of meteorological stations, including Antarctica. The temperature in 1951–1980 was also more representative of the Holocene (24) than any later period would be, which is important because it is desirable to have a base period with climate zones that plant and animal life on the planet are adapted. Hansen and Sato (7) argue that the climate of the most recent few decades is probably warmer than prior Holocene levels, based on the fact that the major ice sheets in both hemispheres are presently losing mass rapidly (9) and global sea level is rising at a rate of more than 3 m/millennium (25), which is much greater than the slow rate of sea level change (less than 1 m/millennium) in the latter half of the Holocene (26).

The 30-y period 1951–1980 with relatively stable climate is sufficiently long to define a climatological temperature distribution, which is near normal (Fig. 9, *Left*), yet short enough that we can readily see how the distribution is changing in subsequent decades. This exposes the fact that the distribution is becoming

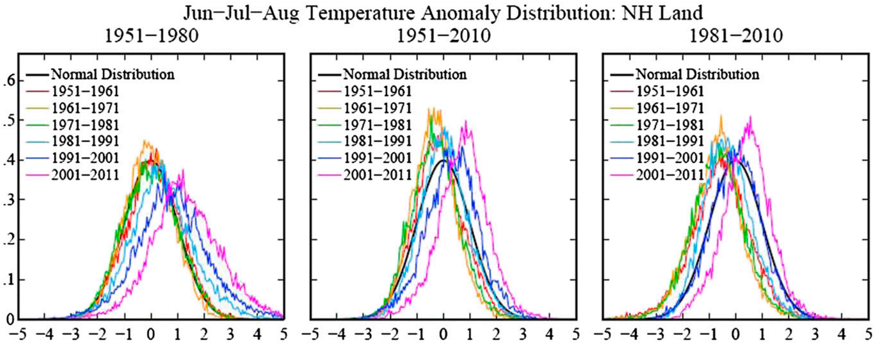

Fig. 9. Frequency of occurrence (*y* axis) of local temperature anomalies divided by local standard deviation (*x* axis) obtained by counting gridboxes with anomalies in each 0.05 standard deviation interval. Area under each curve is unity. Standard deviations are for the indicated base periods.

broader and that there is a disproportionate increase of extreme hot outliers. In contrast the 60-y base period, 1951–2010, and the 1981–2010 base period, which include the years of rapidly changing climate within the base period, make it more difficult to discern the changes that are taking place.

Broader Implications. Changes of global temperature are likely to have their greatest practical impact via effects on the water cycle. Indeed climate changes occurring with global warming involve intimate interactions of the energy and water cycles, and we suggest that the change in the shape of the temperature anomaly distribution is a product of these interactions. The $+3\sigma$ summer anomalies, for example, are usually in places experiencing an extended period of high atmospheric pressure. With the temperature amplified by global warming and ubiquitous surface heating from elevated greenhouse gas amounts, extreme drought conditions can develop.

The other extreme of the water cycle, unusually heavy rainfall and floods, is also amplified by global warming. A warmer world is expected to have more extreme rainfall occurrences because the amount of water vapor that the atmosphere holds increases rapidly with temperature, a tendency confirmed by observations. Indeed, rainfall data reveal significant increases of heavy precipitation over much of Northern Hemisphere land and in the tropics (27) and attribution studies link this intensification of rainfall and floods to human-made global warming (28–30).

Extreme heat waves and record floods receive public attention, yet we wonder if there are not more pervasive impacts of warming. Natural ecosystems are adapted to the Holocene climate. Although climate fluctuations are normal, the rapid global warming in the past three decades, from an already warm level, is highly unusual. Warmer winters have led to an epidemic of pine bark beetles and widespread destruction of forests in Canada and the western United States (28). Global warming is already affecting the geographical and seasonal range of animals, birds, and insects (31) to a degree that is sometimes noticeable to the public (32). Such changes should be more perceptible to the public during the next decade as the distribution of temperature anomalies continues to shift toward higher values.

Many species may be able to migrate, if necessary, to stay within climate zones in which they can survive. The science needed to estimate species survival rates if global warming continues throughout this century is not well developed, but it has been suggested that prolonged global warming could take a heavy toll on planetary life (27). There are many other human-induced stresses on life, including land conversion with habitat destruction, species overharvesting, homogenization of biota, and ubiquitous toxins, which must be dealt with, yet global warming caused by fossil fuel burning may be a unique threat because of the millennial time scale of anthropogenic carbon within surface carbon reservoirs. It has been argued that a scenario phasing out carbon emissions fast enough to stabilize climate this century, limiting further warming to a maximum of several tenths of a degree Celsius, is still possible, but it would require a rising price on carbon emissions sufficient to spur transition to a clean energy future without burning all fossil fuels (33).

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