A new face for climate dice

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Although it is not possible to "experience" the 0.5 °C increase in global surface temperature since the 1950s directly, everyone can feel the local and regional effects of extended periods of very hot weather. In PNAS, Hansen et al. (1) present a simple and elegant way to quantify the effects of a 0.5 °C increase in global average temperature on the extremes that have an impact on the way we live, work, play, and grow our food. Hansen et al. (1) show that the thermal climate is tangibly different today compared with what it was like as recently as the mid to late 20th century. The results are quite remarkable. For example, we are now more than 10-fold as likely to endure an extremely hot summer as we were in the decades 1951–1980.

Looking exclusively at global and hemispheric means masks a rich array of climate behavior that is revealed at the study's resolution of 250 × 250 km. For example, in the Northern Hemisphere summer, we see that temperature anomalies (the difference of any given seasonal average temperature from the mean computed over multiple decades) in the 21st century now reach up to 5 standard deviations (5σ) above the mean of the 1951–1980 time interval. Meanwhile, cold anomalies can still reach as low as 3σ below that mean. This asymmetry is reflective of a growing variability in the thermal climate over the past few decades, as shown by the statistical analysis in the article by Hansen et al. (1). We will discuss this important but poorly understood aspect of global warming a bit more later.

The improbability of purely natural causes of such extreme positive deviations was predicted by Hansen et al. (2) decades ago in the 1988 article in which he introduced the idea of "loaded climate dice." As widely reported by the media (3), Hansen used the analogy of a six-faced die to represent the likelihood of experiencing temperature anomalies. If anomalies followed a normal distribution, two faces of the die would represent below-average temperatures (he colored them blue), two near-average temperatures (white), and two above-average temperatures (red). Now, nearly 25 y later, the likelihood of above-average temperatures has more than doubled, and we need an extra two "red" faces on the die to represent the new distribution. Moreover, Hansen et al. (1) clearly explain that the shifted distribution calls into question the argument that the cause of recent extreme events, such as the 2010 Russian heat wave (4), is simply unusual weather patterns. Rather, the sheer number and magnitude of extremes of temperature are consistent with a warmer world that has, with virtual certainty, been linked to human-induced increases in atmospheric greenhouse gases and, to a lesser extent, other human activities (5, 6).

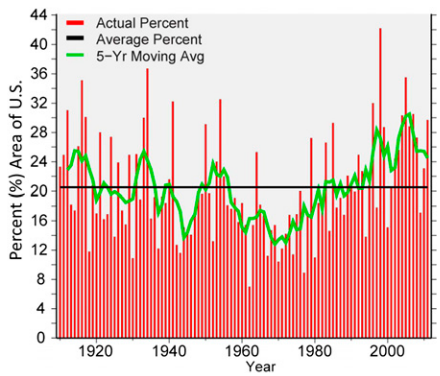

Fig. 1. Annual Climate Extremes Index for the contiguous United States incorporating extremes (upper or lower 10th percentile) of daily mean maximum and minimum temperature, soil moisture deficits and surpluses (as reflected by the Palmer Drought Severity Index), daily heavy precipitation event frequency, days with/without precipitation, and hurricane and tropical storm wind speed (http://ncdc.noaa.gov/extremes/cei) (13).

In addition to the new extreme temperature anomalies observed across the globe, Hansen et al. (1) calculate an increase in the standard deviation (SD) of grid-scale seasonal averages of interannual temperature in recent decades. This is also reflected by the wider span of temperature deviations observed in recent decades compared with the 1951–1980 time period (figure 9 of ref. 1). Of special note is the asymmetrical nature of the expansion of the range of temperature anomalies. The question arises as to why. Could this reflect some subtle but important differences from normality, or is it a function of an increase in variability and mean still within a normal distribution? There is evidence to suggest that it may be both. Karl (7) has shown that during winter and midsummer months, the monthly and seasonal temperatures in the central and western United States deviate significantly from a normal distribution. Interestingly, the asymmetry identified by Karl (7) has similarities to the asymmetrical change in the range of standardized temperature departures found by Hansen et al. (1). Specifically, during the winter in the United States, there are an unusually high number of significantly negatively skewed seasonal mean temperature anomalies (calculated for the years 1895–1983), although the opposite is observed in midsummer with positively skewed distributions. This is attributed to a few seasons or months with unexpectedly (based on a normal distribution) large anomalies. It is quite feasible that the synoptic climatology helping to produce the unusually warm or cold events works in unison with the external greenhouse forcing (e.g., dry soils reinforce and add to already hot conditions) during the summer but less so in the winter (e.g., snow still occurs, and snow cover works to reinforce already cold conditions imposed by atmospheric circulation features). This could very well be the reason why in figure 5 of ref. 1 (first row vs. second row), the percent area of "cold" standardized anomalies in winter is higher than in summer and the area reflected by "hot" standardized anomalies is so much higher in the summer compared with the winter. On the other hand, it may be that temperature anomalies are normally distributed and take on an asymmetrical shape with a gradually increasing mean and SD. For example, Monte Carlo simulations indicate that starting with a standard normal distribution for the first year and increasing the mean by 0.1 per year and the SD by 0.05 per year, the resultant distribution over a decade is skewed, consistent with statistical theory (8), ranging from roughly −3σ to +5σ.

Clearly, more work is needed to understand this potentially important characteristic of the climate system better. It has important planning and adaptation implications, particularly if this observed change turns out to be part of the climate's response to sustained changes in atmospheric composition. Fortunately, in 2013, the National Oceanic and Atmospheric Administration (NOAA) plans to release a more comprehensive worldwide land air temperature daily dataset that includes both daily high and low temperatures, and should shed additional light on this topic.

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One important challenge in these data will be to ensure that any time-dependent biases are identified and removed from the climate record. Most work on removing time-dependent biases in the historical temperature record has focused on monthly time scales (9). There are significantly different challenges at the daily time scale (10, 11).

Hansen et al. (1) make a compelling case that recent extreme temperature anomalies, like those in 2011 (southern United States), 2010 (western Russia), and 2003 (France), would not have occurred without global warming. Other recent research teams have also successfully linked anthropogenic increases in greenhouse gases to a number of worldwide extreme events of 2011 (12). Hansen et al. (1) also investigate the broader ramifications of climate change. They cite other changes associated with increases of global temperature. Do we see any evidence for such changes in other extremes in the United States? Observational data do reveal significant increases in several other types of extremes, some of them expected to occur in a warming world.

A Climate Extremes Index has been developed for the contiguous United States (http://ncdc.noaa.gov/extremes/cei) (13, 14). The index includes six separate indicators. Extremes in each indicator are defined by the proportion of the United States being in either the upper or lower 10th percentile of 20th century values. The index has statistically significant increases in several of its components, and overall, shows a steady climb since the 1960s (Fig. 1). Table 1 indicates the components that display statistically significant trends. Noteworthy in the Climate Extremes Index is the absence of any statistically significant changes in land-falling hurricanes or tropical storm wind speeds. Soil moisture deficits do not reveal significant increases because of the large and widespread extreme drought of the 1930s, but soil moisture increases (as measured by the Palmer Drought Severity Index) in recent decades are significant. In 2011, a record 55% of the United States was affected by either too much or too little water. This intensification of the hydrological cycle is consistent with climate model projections of drier conditions in the southwestern United States and wetter conditions in the northern United States as greenhouse gases continue to increase.

Table 1. Trend in individual components of the US Climate Extremes Index (1910–2011) based on Kendall's tau (15–17) (a nonparametric test for trend)

Component	Winter half	Summer half
Extremely cold (daytime) highs	–	
Extremely warm (daytime) highs		
Extremely cold (nighttime) lows	–	–
Extremely warm (nighttime) lows		+
Palmer Drought Severity Index: "extremely dry"		
Palmer Drought Severity Index: "extremely wet"	+	+
1-d "extreme" precipitation events		+
Days with precipitation	+	+
Days without precipitation	–	–
Hurricane/tropical storm winds/duration	n/a	

Statistically significant trends (0.01 level) are depicted by pluses (+) or minuses (–) to reflect the sign of the trend. Extremes in each component are defined by either the upper or lower 10th percentile. n/a, not applicable.

What about 2012? The first seven months of 2012 have registered the highest Climate Extremes Index (without hurricanes) ever observed (14). The primary contributors to such a large value this year are the daily maximum and minimum temperature extremes, with over 75% of the nation affected by temperatures in the upper 10th percentile. Drought is also covering an unusually large area this year, and it has likely contributed to the daily maximum temperature extremes. The current year has also seen a highly unusual month-to-month persistence of extremely warm temperatures. The national average temperature has been above average (upper ⅓ of the distribution) each month for 14 consecutive months through July 2012. In a stationary climate, even after accounting for the reduction in degrees of freedom due to month-to-month persistence, such an episode would be expected to occur only once in about 500,000 y.

Hansen et al. (1) have made the case that we are no longer waiting for evidence of global warming. It is clearly here now, affecting a wide variety of weather and climate events, and it will continue to grow as we burn more fossil fuels. However, there still are issues that need further clarity, including the details of how the distribution of extreme events will change. As noted here, even the apparently normal distribution of temperature can display nonnormal behavior, and this can lead to extremes of even greater magnitude than might otherwise be expected.

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