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Framing the way to relate climate extremes to climate change

Kevin E. Trenberth

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Abstract The atmospheric and ocean environment has changed from human activities in ways that affect storms and extreme climate events. The main way climate change is perceived is through changes in extremes because those are outside the bounds of previous weather. The average anthropogenic climate change effect is not negligible, but nor is it large, although a small shift in the mean can lead to very large percentage changes in extremes. Anthropogenic global warming inherently has decadal time scales and can be readily masked by natural variability on short time scales. To the extent that interactions are linear, even places that feature below normal temperatures are still warmer than they otherwise would be. It is when natural variability and climate change develop in the same direction that records get broken. For instance, the rapid transition from El Niño prior to May 2010 to La Niña by July 2010 along with global warming contributed to the record high sea surface temperatures in the tropical Indian and Atlantic Oceans and in close proximity to places where record flooding subsequently occurred. A commentary is provided on recent climate extremes. The answer to the oft-asked question of whether an event is caused by climate change is that it is the wrong question. All weather events are affected by climate change because the environment in which they occur is warmer and moister than it used to be.

1 Introduction

How big is the human influence on climate? Is it big enough that a question such as "*Is this event due to global warming?*" even makes sense? Here these questions are addressed along with improved ways to frame the questions that inevitably arise when new climate extremes occur, and there have been many over the past 2 years. Clearly natural variability plays a major role. Accordingly a brief commentary on some of these extremes and how they relate to both natural variability and climate change is provided.

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K. E. Trenberth (✉)
National Center for Atmospheric Research, P. O. Box 3000, Boulder, CO 80307, USA
e-mail: trenbert@ucar.edu

Climate change from human influences is difficult to perceive and detect because natural weather-related variability is large. Even with a significant climate change, most of the time, the weather is within previous bounds. However, human-induced climate change is persistent and tends to be in one direction, at least insofar as the increases in greenhouse gases are concerned (IPCC 2007). So one way of detecting such an influence is through long-term changes in mean conditions, preferably guided by climate model studies as to which variables and how they should change. This requires long averages to overcome the effects of natural variability (climate noise), and for quantities such as global temperatures, about 17 years is needed (Santer et al. 2011). With global warming, the thermodynamic variables have much stronger signal-to-noise ratios than dynamic variables (Deser et al. 2010). Accordingly, changes in temperature and the water holding capacity of the atmosphere are more robust than changes that depend on winds in any way.

If the problem is generalized to look at the entire probability distribution function (pdf) of the climate variables, then the biggest changes percentagewise occur in the tails of the distribution, where they can easily exceed several hundred percent (Trenberth 2011b). Accordingly, a change in climate is most likely to be perceived by encountering new “weather” and breaking records: changes in the extremes. Changes in certain extremes, such as higher temperatures and increases in heavy rains and droughts are expected with climate change (IPCC 2007; Trenberth 2011a).

Attribution (IPCC 2007; Stott et al. 2010) of the extremes requires a model to separate out the human influence from natural variability using numerical experimentation. This requires considerable integrity in the model’s ability to simulate both, but models typically have great difficulty in simulating extremes well (Lin et al. 2006; Kharin et al. 2007) especially throughout the tropics for precipitation. In many model studies, the metric of Fraction of Attributable Risk (FAR) (e.g., Allen 2003) is used to express the fraction of risk of a particular threshold being exceeded. This is a relative rather than absolute metric.

However, methodological issues arise about the null hypothesis and where to assign the errors (Trenberth 2011b). The issue is whether the benefit of doubt errs on the side of natural variability (as has been the case) or on the side of a human influence.

Extremes are always expected to happen as the climate record gets longer, but certain extremes related to heating are becoming more evident. For example in the United States, extremes of high temperatures have been occurring at a rate of twice those of cold extremes (Meehl et al. 2009), and this has accelerated considerably since June 2010 to a factor of 2.7, and in the summer of 2011 to a factor of over 8 (Skolnik 2011). Texas, Oklahoma, New Mexico and Louisiana all suffered their hottest June-July-August (JJA) 2011 since 1895 (average temperature over 30 °C in Oklahoma and Texas), according to NOAA. Texas also experienced the driest JJA on record.

Climate extremes are typically treated individually, but many are not unrelated. The clustering of extremes occurs when natural variability creates anomalies that are in the same direction as global warming. This occurs especially in association with the dominant mode of natural variability: El Niño-Southern Oscillation (ENSO) during and following the warm El Niño phase (Trenberth et al. 2002) as heat leaves the ocean. During ENSO, large regional changes occur in Sea Surface Temperature (SST) throughout the tropics. Large positive SST anomalies in the central and eastern Pacific during El Niño tend to focus convective activity (thunderstorms, tropical storms, etc.) into those regions while suppressing activity elsewhere via both changes in atmospheric stability and wind shear. Meanwhile lighter winds and decreased evaporative cooling, and sunny skies in the tropical Atlantic and Indian oceans result in higher than normal SSTs 3–7 months after the peak SSTs in the Niño 3.4 region

(Trenberth et al. 2002). As noted below, this happened in 2010 following the end of the El Niño in May 2010.

As climate varies or changes, several direct influences alter precipitation amount, intensity, frequency, and type (Trenberth et al. 2003; Trenberth 2011a). Warming accelerates land-surface drying as heat goes into evaporation of moisture, and this increases the potential incidence and severity of droughts, which has been observed in many places worldwide (Dai 2011). The moisture in the atmosphere, which has been widely observed to be increasing in association with increased SSTs, then gets carried around by atmospheric winds to where storms are favored. Typical storms reach out a distance of about three to five times the radius of the rain dimension, and gather in the water vapor, to produce precipitation. In weather systems, convergence of increased water vapor leads to more intense precipitation and the risk of heavy rain and snow events, but may also lead to reductions in duration and/or frequency of rain events, given that total amounts do not change much. The result is longer dry spells, as observed in the United States (Groisman and Knight 2008). Basic theory, climate model simulations, and empirical evidence all confirm that warmer climates, owing to increased water vapor, lead to more intense precipitation events even when the total annual precipitation is reduced slightly (Trenberth et al. 2007). A warmer climate therefore increases risks of both drought—where it is not raining—and floods—where it is—but at different times and/or places.

2 Is this extreme due to global warming?

Changes in atmospheric composition from human activities are the main cause of anthropogenic climate change by enhancing the greenhouse effect, although with important regional effects from aerosol particulates (IPCC 2007). Anthropogenic global warming inherently has decadal time scales and can be readily masked by natural variability over periods less than a decade or so. To the extent that interactions are linear, below normal temperatures can be fully consistent with climate change but are likely warmer than they otherwise would have been.

Globally on a day-to-day basis the climate change effects are 1–2 % of the natural energy flow, as elaborated on below. However, because global warming is always of one sign, a much bigger impact is from the cumulative effects of these radiative perturbations on the climate. The main memory is through the warming of the oceans, manifested in part through the ongoing rise in sea level, and the loss of Arctic sea ice and glacier mass. SSTs have risen by 0.5–0.6 °C since the 1950s, and over the oceans this has led to 4 % more water vapor in the atmosphere since the 1970s (Trenberth et al. 2007). As a result, the air is on average warmer and moister than it was prior to about 1970 and in turn has likely led to a 5–10 % effect on precipitation and storms that is greatly amplified in extremes. The warm moist air is readily advected onto land and caught up in weather systems as part of the hydrological cycle, where it contributes to more intense precipitation events that are widely observed to be occurring (IPCC 2007; Trenberth 2011a; Groisman and Knight 2008; Min et al. 2011; Pall et al. 2011).

The rationale for these numbers is as follows. The radiative forcing (IPCC 2007) is about 1.6 $\mathrm{W m^{-2}}$ for both carbon dioxide increases alone and also the total with all other effects included (0.6–2.4 as 95 % confidence limits), and the net energy imbalance of the planet is estimated (Trenberth et al. 2009) to be 0.9 ± 0.5 $\mathrm{W m^{-2}}$. The net energy flow through the climate system is equivalent to about 240 $\mathrm{W m^{-2}}$. The difference between the net imbalance and the radiative forcing is because of the response of the climate system to the forcing, namely the warming of the planet and moistening of the atmosphere (Murphy et al. 2009). Water vapor is a powerful greenhouse gas. The increased water vapor roughly doubles the direct radiative forcing, giving the 1–2 % value, although this will vary from day to day. However, the average 4 % increase in water vapor becomes amplified in weather systems because it adds buoyancy to the air flowing into all storms, promoting them to become more intense and multiplying the effect (Trenberth et al. 2003; Trenberth 2011a). Instabilities can magnify effects further, although changes in wind shear and atmospheric stability as a consequence of the enhanced vertical motion may have reverse effects elsewhere. These lead to the approximate 5–10 % effect overall. For major droughts that last a month or longer, cumulative effects again become important as the absence of moisture means that all heating goes into sensible heating, creating higher temperatures, that in turn desiccate plants, and promote heat waves and wild fires. Lau and Kim (2012) quantify these effects for the Russian heat wave in 2010. During drought the memory stems from the changes in soil moisture.

Whether or not these values are accepted, the key point is that the anthropogenic climate change effect is not zero or negligible, nor is it large relative to the mean, but it is systematic. While natural variability clearly plays a major role in all events, such as those detailed below in 2010 and 2011, the record high SSTs did as well. In part the high SSTs were a consequence of the previous El Niño (Trenberth et al. 2002) but there is surely a significant global warming component (Gillett et al. 2008). Hence anthropogenic global warming has an identifiable role in the extreme weather (Trenberth and Fasullo 2012; henceforth TF12).

3 Some examples of recent climate extremes

3.1 SSTs

ENSO played a major role in climate extremes in 2010 and 2011 (TF12). El Niño conditions persisted through April 2010 but rapidly gave way to La Niña conditions by June. The SST anomalies for the northern summer (JJA) of 2010 (Fig. 1) reveals the La Niña conditions in

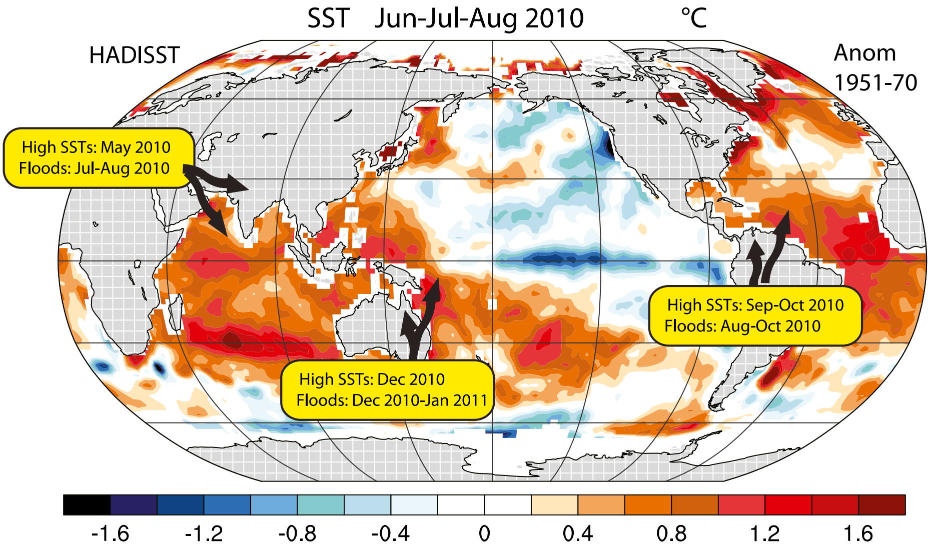

Fig. 1 Seasonal Jun-Jul-Aug 2010 SST anomalies relative to 1951–70, based on HADISST data (Rayner et al. 2003). Record high SSTs were recorded in the locations and at the times indicated with record flooding nearby

the Pacific and hence the cooler than normal conditions mean that this was the region where the thunderstorms, tropical storms, and other convective activity were not occurring. However, as shown in TF12, very high SST anomalies from 0.5 to 1.5 °C, indeed record high SSTs in many instances (Fig. 1), occurred in the Indian Ocean and Indonesian region as well as throughout the tropical Atlantic (relative to a 1951–1970 normal that precedes most anthropogenic warming), regions that are normally very warm anyway (TF12). The total SSTs exceeded 29 °C over broad regions and were at an all time high in May 2010 (30.4 °C) in the northern Indian Ocean encompassing the Arabian Sea and Bay of Bengal (TF12). SSTs were also very high (second highest on record) north of Australia for September to November 2010, and by December they were the highest on record for that month. SST anomalies were also highest on record in the Gulf of Mexico in August 2010 and in the Caribbean in September 2010 (TF12). In 2011, SSTs were well above normal in the Gulf of Mexico in April but had cooled off by May. However, SSTs were still very high in the tropical Atlantic.

Because the water holding capacity of the atmosphere increases exponentially with temperature (e.g., Trenberth et al. 2003), a positive anomaly on top of already high SSTs has much greater effect than if located elsewhere. Indeed, the high SSTs were accompanied by very high water vapor amounts. The high SSTs provide ample moisture to the atmosphere and the resulting evaporative cooling of the ocean dropped the subsequent SST values down, but meanwhile heavy rains, often record breaking in intensity, occurred nearby to where the winds carried the moisture. This happened in China, India and Pakistan (June to early August 2010); Queensland, Australia (December 2010 and January 2011), and Colombia (October to December 2010) (Fig. 1). It also seems to have been a factor from 19 to 25 April 2011 when exceptionally heavy rains, exceeding 300 mm, occurred over southern Missouri, parts of Arkansas, eastern Oklahoma, and southern Illinois, and extended along the Ohio River Valley http://earthobservatory.nasa.gov/IOTD/view.php?id=50243, as a prelude to the flooding in the Mississippi.

3.2 La Niña and the Americas

La Niña conditions are well known to be associated with major anomalies in the Americas, and precipitation and flooding risk increase substantially in northern South America, such as in Colombia (Poveda et al. 2011). In La Niña summer and autumn the hurricane season is more active owing to a more favorable tropical circulation that allows storms to form in an environment of reduced wind shear and stability (Vecchi et al. 2008).

The SSTs (Fig. 1) in the Atlantic sector throughout the region north of Colombia were above 29 °C from July to September, and August 2010 was the warmest on record in both the Caribbean and in the Gulf of Mexico: anomalies exceeded 0.5–1.5 °C relative to the 1971–2000 base period (Fig. 1) (TF12). SST anomalies were especially large off the Colombian coast. The much cooler conditions to the west of the Central American isthmus both in absolute and anomaly terms understandably focused convective activity as a whole into the Atlantic and away from the Pacific. North of the equator, the result was a much above normal Atlantic hurricane season, in which there were 19 named storms, and 12 hurricanes, of which 4 were category 4 or 5, likely making it the second most active year after 2005. These aspects related to specific extremes are documented in TF12, including links between the heavy rains and the Russian heat wave of 2010, and the Colombian rains and the drought in the Amazon.

When La Niña is present, it strongly influences where the storms track across the United States, and the storms track in such a way as to miss the South. Consequently, Texas and surrounding areas (especially parts of Arizona, New Mexico and Oklahoma) suffered severe drought, and subsequently heat waves and wild fires in the northern spring and summer 2011. Nevertheless in spring, the storms crossing the central Midwest were able to link up with the warm moist air from the Gulf of Mexico, creating extra instability and buoyancy for the air that was entrained into the storms. This led to extensive heavy rains, flooding and tornado outbreaks. The pattern of rainfall in the spring is characteristic of La Niña although the extreme nature of the changes is not. The intense heat wave and "exceptional drought" continued in Texas through August. Many of these events are described in detail on line at the NOAA National Climatic Data Center, State of the Climate, Global Hazards site: http://www.ncdc.noaa.gov/sotc/hazards/2010/m (or 2011/m) where m is the month.

In spring, when land-sea contrasts transition to zero, strong westerly winds blow from the Pacific Ocean across the United States. Because the Rockies block the wind at low levels, the result is a strong westerly jet stream aloft while at low levels the air east of the Rockies comes from elsewhere including the Gulf of Mexico when there is a pronounced southerly component ahead of cold fronts. Both the change in wind speed and direction with height (southerlies at low levels, strong westerlies aloft) create wind shear, which sets the stage for super-cell thunderstorms to form tornadoes as the shear gets converted into rotation. According to NOAA, there were 539 deaths from over 1075 (actual count) tornadoes in April and May 2011 in the United States, the most deadly on record. Trends in the tornado record are not reliable, as increases in population over previously rural areas lead to more reporting of tornadoes, but the exceptional nature of the 2011 spring is not in doubt.

Global warming does not contribute directly to tornadoes themselves, but it does contribute to the vigor of the thunderstorms that host them through the increased warmth and moisture content (moist static energy) of the low level air flow. The increase in buoyancy of the air flowing through the Gulf of Mexico helps fuel the storms. Similarly, the extra moisture provided incremental amounts to the heavy rains that ultimately led to flooding along the Mississippi and later, farther north, heavy rains and melting snows contributed to extensive flooding of the Missouri River.

3.3 The Asian sector

The heavy rains and flooding in China, India, and Pakistan in JJA 2010 were associated with the very high SSTs to the south (Fig. 1) that provided extra moisture for the monsoon rains. The strong monsoon circulation then played a role in the Russian heat wave from mid-June to mid-August 2010 (Barriopedro et al. 2011; TF12), perhaps not unlike that in 2003 (Black and Sutton 2007) although influences from the Atlantic likely also played a role. The drought and famine in East Africa was also related to the high Indian Ocean SSTs (Williams and Funk 2011). Very large anomalies also existed at this time in Arctic sea ice and, in conjunction with positive Arabian Sea SST anomalies, connections to the events in Eurasia are suggested (Sedláček et al. 2011).

In the Asian sector, as the northern monsoon faded in late August of 2010, activity began to pick up in Australia, which switched to become very wet in September, continent wide, again reflecting the very high SSTs to the north (second highest on record), abundant moisture and the La Niña conditions. This was a fore-runner to the exceptionally heavy rains in Queensland in December 2010, and January 2011 where the southern monsoon rains kicked in with the presence of record high SSTs. Category 5 hurricane Yasi made landfall in Queensland in early February 2011.

4 Conclusions

The above commentary describes how natural variability in the presence of record high SSTs led to exceptional flooding events and extremes in 2010–11; see TF12 for details. Note that the La Niña in 2011–12 has different character owing to the absence of the high SSTs in the Indian and Atlantic Oceans. The SST changes feature contributions from climate change as well as strong regional contributions from ENSO.

The climate has changed; global warming is unequivocal (IPCC 2007) and human activities have undoubtedly changed the composition of the atmosphere and produced warming. Moreover there is no other plausible explanation for the warming. The human-induced changes are inherently multi-decadal and provide a warmer and moister environment for most weather events, even in the presence of large natural variability. In attribution studies, changing the null hypothesis from "there is no anthropogenic global warming effect" to one that recognizes the changed environment can completely change the outcome (Trenberth 2011b). In Bayesian statistics, this change might be thought of as a "prior".

Scientists are frequently asked about an event "Is it caused by climate change?" The answer is that no events are "caused by climate change" or global warming, but all events have a contribution. Moreover, a small shift in the mean can still lead to very large percentage changes in extremes. In reality the wrong question is being asked: the question is poorly posed and has no satisfactory answer. The answer is that ***all weather events are affected by climate change because the environment in which they occur is warmer and moister than it used to be***.

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