Weather and Climate Extremes 11 (2016) 17–27

Contents lists available at ScienceDirect

Weather and Climate Extremes

journal homepage: www.elsevier.com/locate/wace

Detection and attribution of climate extremes in the observed record

David R. Easterling [a,*], Kenneth E. Kunkel [b], Michael F. Wehner [c], Liqiang Sun [b]

[a] Center for Weather and Climate, NOAA's National Centers for Environmental Information, Asheville, NC, United States
[b] Cooperative Institute for Climate and Satellites, NC State University, NOAA's National Centers for Environmental Information, Asheville, NC, United States
[c] Lawrence Berkeley National Laboratory, Berkeley, CA, United States

ARTICLE INFO

Article history:
Received 12 August 2015
Received in revised form
13 January 2016
Accepted 17 January 2016
Available online 18 January 2016

Keywords:
Observed climate change
Extremes
Detection
Attribution

ABSTRACT

We present an overview of practices and challenges related to the detection and attribution of observed changes in climate extremes. Detection is the identification of a statistically significant change in the extreme values of a climate variable over some period of time. Issues in detection discussed include data quality, coverage, and completeness. Attribution takes that detection of a change and uses climate model simulations to evaluate whether a cause can be assigned to that change. Additionally, we discuss a newer field of attribution, event attribution, where individual extreme events are analyzed for the express purpose of assigning some measure of whether that event was directly influenced by anthropogenic forcing of the climate system.

1. Introduction

Contemporary climate change presents one of the most pressing challenges for human society. As the climate continues to change, the risks associated with climate extremes takes on ever greater importance. Changes in the mean climate, particularly since the middle of the 20th century, have been linked to anthropogenic-induced increases in greenhouse gases (Hegerl et al., 2010). Indeed, a number of recent climate assessments have concluded that observed changes in the climate system over the past century are largely a result of human activities (Seneviratne et al., 2012; Bindoff et al., 2013; Walsh et al., 2014a, 2014b).

Climate extremes, by definition, are rare events, however climate change has resulted in changes in the occurrence of extreme events (Easterling et al., 2000, Seneviratne et al., 2012). Climate extremes can result from external forcing of the climate system, such as from increasing greenhouse gases, or natural variability, or more likely some combination of the two. For example, some of the more robust climate change signals related to extremes in both the observed record and in model simulations for the future are decreases in the number of unusually cold days and nights, and increases in the number of unusually warm days and nights (Seneviratne et al., 2012; Min et al., 2013; Kim et al., 2015). Other changes include an increase in the number of heavy precipitation events (Kim et al., 2015) and a likely increase in the incidence of hurricanes in the north Atlantic since about 1970 (Kunkel et al., 2013; Seneviratne et al., 2012) while longer-term trends in hurricanes remain a subject of inquiry (Landsea, 2015; Kossin et al., 2015). Once a signal of change in an extreme is found, the question most often becomes how the change is related to human-induced climate change (Hulme, 2014).

Detection of climate change in the observed record refers to the identification of a statistically significant change in some part of the climate system. The change could be in some highly averaged mean quantity or in some measure of extreme weather or climate. Observed climate change over various time scales for many parts of the climate system is well summarized in the IPCC 5th Assessment Report (Bindoff et al., 2013) and continues to be extensively monitored (Blunden and Arndt, 2015). It has been clear for some time that changes in the occurrence of weather and climate extremes are major players in producing changes in the natural environment and society, and these kinds of changes have increasingly been the subject of research papers and scientific assessments (e.g. CCSP, 2008; Seneviratne et al., 2012).

However, it is not enough to show that a change in the climate has occurred; indeed once a change has been detected it is important to attribute that change to some cause. Attribution, especially to human greenhouse gas emissions, lends confidence to model projections of the future driven by anthropogenic forcing as well as predictions of extremes at shorter time scales (Seneviratne and Zwiers, 2015). Attribution also provides information for more robust decisions in adaptation activities related to weather and climate extremes (Sippel et al., 2015). Traditionally, detection and attribution studies focused on mean changes (e.g. Hegerl et al., 2007; Bindoff et al., 2013); however in the past decade or so climate extremes have become a focus of detection and attribution studies. A number of recent papers have included

* Corresponding author.

http://dx.doi.org/10.1016/j.wace.2016.01.001

overviews of detection and attribution science related to extremes.

Furthermore, when an extreme event occurs climate scientists are increasingly queried by the news media, policy makers, private enterprise and the public as to the likely cause of the event. The question of attribution of these events to human-induced climate change is of particular interest (Stott et al., 2013; Zwiers et al., 2013; Hulme, 2014; Hegerl, 2015). Through the process of answering this question valuable information regarding risk due to climate extremes is provided, which is useful to a wide range of stakeholders for disaster risk reduction activities.

Two schools of thought have emerged in this rapidly developing field and are described in Section 4. The first, referred in this paper as “Oxford”, where the technique was first envisioned, quantifies the change in probability of an extreme event of a particular observed magnitude caused by the human alteration of the climate system. The second, referred to here as “Boulder”, introduced first in a series of paper by researchers from NOAA's Earth System Research Laboratory, examines the human induced change in magnitude of an extreme event. While providing different types of information to stakeholders, both these probabilistic and mechanistic schools of thought have been shown to be equivalent.

In this paper we present an overview of practices and challenges related to the detection and attribution of observed changes in climate extremes. In particular we mainly examine temperature and precipitation extremes, while acknowledging that trends in other kinds of extremes, such as tropical cyclones, droughts, and even extreme snow storms may exist and deserve attention. However, we do discuss a newer field of attribution, event attribution, where individual extreme events, such as storms or heatwaves, are analyzed for the express purpose of assigning some measure of the extent to which that event was directly influenced by anthropogenic forcing of the climate system.

2. Detection of trends in extreme temperature and precipitation

Extreme weather and climate events are a natural part of the climate system. For example, an examination of the paleoclimate record shows that megadroughts and pluvials have happened in the Western and Central United States throughout the last 2000 years (Woodhouse and Overpeck, 1998). Yet, true climate extremes are rare events. Because of this rarity researchers often relax the definition of extremes in such a way as to increase the number of observations that can be used in a statistical analysis. For example, in the case of studies of changes in the occurrence of hot daily maximum temperature extremes, rather than defining the extreme threshold such that it is observed only once every few years, the definition is often set to a threshold value (e.g. 90th percentile value) that is not truly extreme but produces a larger number of observations that exceed the threshold allowing more robust statistical results.

But what about the data sets used in these analyses? To detect an observed change in the climate system, particularly a change suitable for an attribution study, a data set of sufficient temporal and spatial coverage is necessary. Depending on the climate extreme, there is often a lack of observed climate data to document these events for many parts of the world. If the observations exist they often are not in digital form. Also, although the situation is changing, many countries continue to be reluctant to share them with the research community (Easterling et al., 2013; Kunkel and Frankson, 2015).

As noted above, since the analysis of climate extremes often involves examination of the tails of a statistical distribution, a threshold value may be used to determine the number of observations that exceed that value over time creating a time series of exceedance counts. Data quality can impact the counts if there are a number of erroneous values that are not screened out by quality assurance methods, or if the quality assurance methods, which are often more concerned with mean values, are too rigorous and exclude true values. Additional issues include missing data, especially if those missing data would exceed an established threshold or would affect the calculation of the threshold itself. In terms of global analyses, data may be missing for large regions of the globe resulting in a less than true global analysis (Donat et al., 2013). Finally, if longer term data are available they are often observed at weather observing stations, such as at airports, and may be impacted by issues such as urbanization or less than ideal station siting which may result in lower quality data.

The homogeneity of climate data may also impact analyses of climate extremes (Trewin, 2010). Climate data are considered homogenous when all trends and variations are the result of the climate system itself. Inhomogeneities in climate data occur for a variety of reasons. Observing stations often are moved multiple times over longer periods (e.g. 50–100 years) resulting in changes in the local characteristics of the site (e.g. more trees, slight difference in elevation, etc.) Reasons for moves vary but examples include relocation from a city center to an airport, a change in a volunteer observer who also hosts the equipment, or the need to use the site for other purposes. A common inhomogeneity source is urbanization around a station, which will generally cause localized warming, primarily in $T_{\min}$ (Karl et al., 1988), the magnitude of which can be several degrees in the largest urban areas. This warming is real and relevant to impacts on urban residents, but will not be representative of real trends at a larger regional scale; thus, for attribution applications, this urban warming should be removed. Changes in instrumentation such as a new type of thermometer, the installation of a wind shield on a raingauge, or changes in observing practices such as the time observations are taken all can result in an inhomogeneous time series. The impact on the observed time series is typically either a discontinuity (jump up or down), or a gradual change that can appear as a trend (Menne and Williams, 2009), either of which can impact the analysis of changes in extremes. Methods for identifying and correcting for inhomogeneities have typically been applied to time series based on longer averaging periods, such as monthly, seasonal, or annual time series (e.g. Easterling and Peterson, 1994, Menne and Williams, 2009). In the past decade or so approaches to assess and correct for inhomogeneities in daily and even subdaily data have been developed (e.g. Della-Marta and Wanner, 2006, Trewin, 2013), but still have not been widely implemented. However, even without corrections applied to higher temporal resolution data, results of analyses of extremes are consistent with what would be expected based on analyses of mean values (e.g. Alexander et al., 2006, Zwiers et al., 2011, Min et al., 2011).

Incomplete spatial coverage of observing stations for a region or the globe is another potential source of uncertainty. Since there are a number of regions in the world that are not covered in global-scale data sets used for climate analyses, particularly for extremes (Cowtan and Way, 2014), it is unknown how the addition of these regions would impact detection and attribution studies. Even in regions that have observing stations, the question of lower spatial density could prove problematic. Kunkel et al. (2007) used Monte Carlo techniques to examine the impact of lower spatial density of observing stations in the western United States and missing data in detecting changes in heavy precipitation over the contiguous United States. They found that limited spatial density was more important than missing data in detection studies, but that neither issue was severe enough to reduce statistical significance values below standard confidence levels.

Satellite and reanalysis products have the advantage of global