An Introduction to Trends in Extreme Weather and Climate Events: Observations, Socioeconomic Impacts, Terrestrial Ecological Impacts, and Model Projections*

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ABSTRACT

Weather and climatic extremes can have serious and damaging effects on human society and infrastructure as well as on ecosystems and wildlife. Thus, they are usually the main focus of attention of the news media in reports on climate. There are some indications from observations concerning how climatic extremes may have changed in the past. Climate models show how they could change in the future either due to natural climate fluctuations or under conditions of greenhouse gas–induced warming. These observed and modeled changes relate directly to the understanding of socioeconomic and ecological impacts related to extremes.

*This is the first of five papers in the "Understanding Changes in Weather and Climate Extremes" series.

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Understanding Changes in Weather and Climate Extremes and Their Impacts

The following series of five articles was motivated by a need to develop a more comprehensive assessment of changes in weather and extreme climate events. We were interested not only in the impact of extreme weather and climate events, but whether these events were changing in frequency or intensity along with their impacts. Impacts were viewed in terms of loosely managed ecosystems where wildlife flourishes, as well as socioeconomic systems and more heavily managed ecosystems such as agriculture. From a climate perspective, this included a focus both on the historical record and projections for future change.

During the summer of 1998 a group of nearly 30 climate scientists, social scientists, and biologists met for 10 days at the Aspen Global Change Institute to discuss what we now know, and how we could reduce some of our major uncertainties. These articles summarize much of the work during that meeting and new information since the meeting.

—Tom Karl, Stan Changnon, Dave Easterling, Jerry Meehl, and Camille Parmesan

1. Introduction

Though weather and climate extremes can have negative effects on society and ecosystems in many obvious ways (floods, droughts, damaging high winds, extreme heat, and cold, etc.), for some systems in some areas, extreme events are beneficial. Bird breeding in wetlands in the arid zone of Australia may only occur after, say, a one in 5-yr rainfall event (i.e., the biota could be poorer without sporadic extreme rainfall events and perhaps even better off with more of them). The record warm and unusually dry winter in the northern United States resulting from the influence of El Niño 1997–98 brought major gains in reduced energy costs ($5.6 billion), record retail and home sales ($5 billion), and a reduction of about 800 lives normally lost to winter conditions. Conversely, losses in the southern and western states amounted to over $4 billion with 200 lives lost due to storm activity. Parts of the northwest coast of Australia receive most of their rainfall from sporadically occurring tropical cyclones, and even human systems (e.g., water storage) would be damaged without them. Therefore, we need a comprehensive understanding not only of what has happened and what may happen with changes in weather and climate extremes, but also what those changes could mean in a variety of different contexts in human and natural systems.

2. Defining changes of extremes

To understand how changes in weather and climate extremes could influence society and ecosystems, it is useful first to conceptually address how such extremes could change in a statistical sense. Figure 1 presents a typical distribution of a climate variable that is normally distributed, such as temperature. The solid curve represents the present-day frequency distribution of a weather phenomenon (such as the daily maximum temperature). Shading indicates the extreme parts of the distribution, representing events in the tails of the distribution that occur infrequently (i.e., values that are far from the mean or median value of the distribution). If there is a simple shift of the distribution in a future climate, there will be an increase in extreme events on one end and a decrease at the other (Fig. 1a). This can occur through a change of the mean where, for example, if the temperature at a location warms by a certain amount, this will almost certainly produce an increase in the number of extreme hot days and a de-

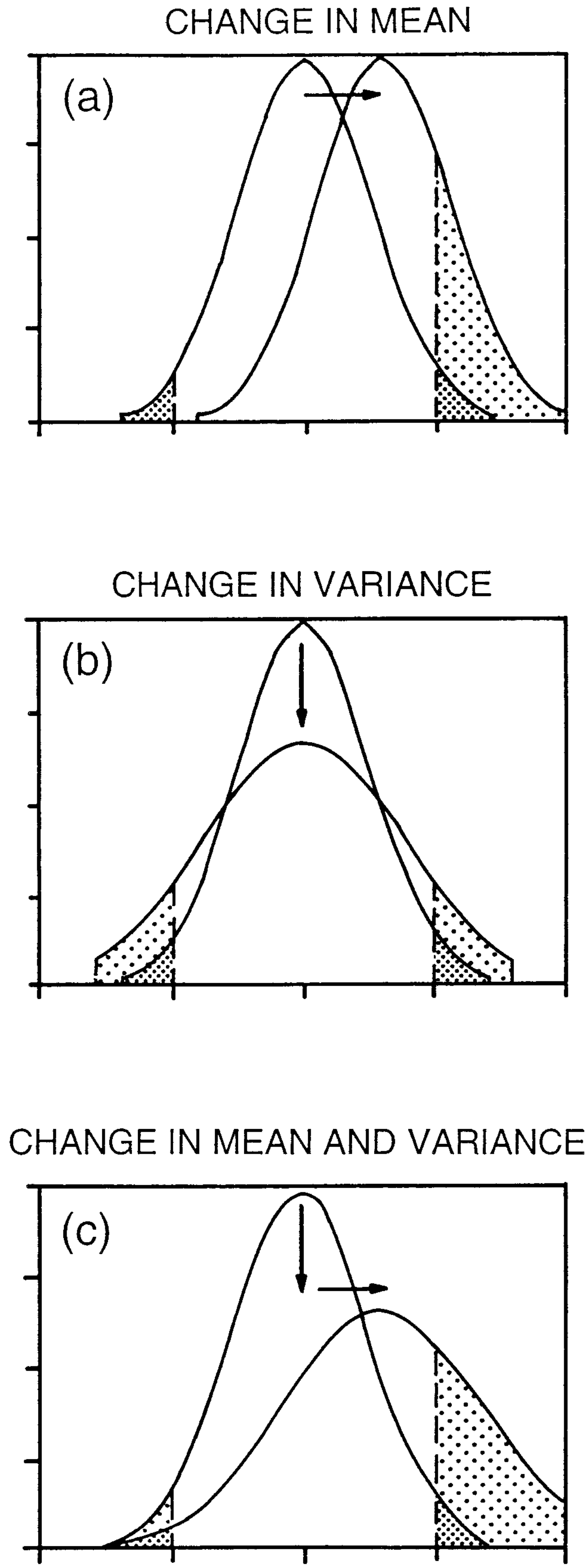

FIG. 1. Schematic diagram depicting how changes in mean and variance can affect extreme weather and climate events.

crease in the number of extreme cold days. It is important to note that the frequency of extremes changes nonlinearly with the change in the mean of a distribution, that is, a small change in the mean can result in a large change in the frequency of extremes (Mearns et al. 1984).

Other aspects of the distribution may also change. For example, the standard deviation in a future climate may increase, producing changes in extreme events at both ends of the frequency distribution (Fig. 1b). A change in the variance of a distribution will have a larger effect on the frequency of extremes than a change in the mean (Katz and Brown 1992), though these events must be "extreme" enough (i.e., more than one standard deviation from the mean) for this result to hold. Relatively speaking, a 1°C change in the standard deviation of the distribution will have a greater impact on the frequency of an extreme temperature than a 1°C change in the mean of the distribution. To complicate matters, the mean, standard deviation, and even the symmetry of the distribution may change at the same time, consequently altering the occurrence of extremes in several different ways (Fig. 1c, showing changes in both mean and variance). Not only can the parameters of the distribution change as noted above (mean, variance, etc.) but for variables like precipitation, which is not normally distributed but better represented by a gamma distribution, a change in the mean also causes a change in the variance (Groisman et al. 1999). This helps to explain why increases in total precipitation are disproportionately expressed in the extremes as discussed by the Easterling et al. paper in this series (Easterling et al. 2000). However, the relationship between the mean and variance arises because each statistic depends on both the shape and scale parameters of the gamma distribution. It is possible to change those parameters in a way that adjusts the mean while holding the variance constant.

Fortunately, it is often possible to estimate changes in infrequent extremes, such as those that might occur once every 10–100 years, without detailed knowledge of the parent distribution. This is because statistical science provides a well-developed asymptotic theory for extreme values (see, e.g., Leadbetter et al. 1983), which predicts that the largest observation in a large sample, such as the annual maximum temperature or 24-h precipitation amount, will tend to have one of only three extreme value distributions depending only upon the shape of the upper tail of the parent distribution. One of these three distributions is the familiar Gumbel distribution (Gumbel 1958). This approach to extreme value analysis, together with related techniques based on the study of the crossing of high thresholds (e.g., Davison and Smith 1990), has been used extensively and reliably in meteorology, climatology, and hydrology to predict the rare extremes of phenomena such as precipitation, streamflow, temperature, and wind speed. Statistical science continues to make advances in extreme value theory (e.g., Smith et al. 1997; Dupuis and Field 1998).

3. Consequences

The frequency and/or intensity of extremes can change, and both can cause major problems. For example, during the 1990s the number of insured catastrophes (weather events causing more than $5 million in losses) in the United States doubled over prior frequencies. Losses soared, but the average loss per event did not increase.

When we discuss extremes we must consider them from the point of view of the statistical characteristics described above and from the socioeconomic or ecological effects of the event. The latter can be thought of in terms of thresholds of the physical systems beyond which serious impacts occur. For example, there is an effect on human mortality and morbidity if there is an occurrence of a series of days in summer when minimum temperatures exceed 30°C (Kalkstein and Smoyer 1993). This relationship can also apply to domesticated animals. For cattle in the central Great Plains, THI values (a combined temperature and humidity index) greater than 84 for a series of three days results in significant cattle deaths from heat stress (Hahn and Mader 1997).

These are seemingly straightforward consequences, but often the relationship between human society, natural ecosystems, domesticated animals, wildlife, and weather and climate extremes is not always linear and not intuitive. Thus, the effects of these thresholds are not universal since the vulnerability of the human and natural systems contributes to how severe the impact will be, independent of the physical system itself. In this sense, the impact of climate on society and ecosystems could change due to changes in the physical climate system (including both natural and anthropogenic causes) or due to changes in the vulnerability of society and ecosystems (even if the climate does not change; e.g., Kunkel et al. 1999).

For example, if the level of hurricane activity of the more active hurricane seasons in the 1940s and 1950s were to occur today, societal impacts would be substantially greater than in earlier decades. The impact of a higher tropical storm frequency could be made worse by population increases and density, more people living near the coast, greater wealth, and other factors (Pielke and Pielke 1997; Diaz and Pulwarty 1997), though human choices have produced this situation. Thus, it is worth noting in this context that the vulnerability of systems to particular extremes also may change as a result of adaptation to changing climatic means. Consider the following case: reduced frost frequency may be interpreted as meaning a reduced risk of frost damage to crops. But farmers simply may use the opportunity this presents to plant earlier in the season, and effectively maintain their current or even greater risk of a damaging frost. One could also imagine some similar adaptations in natural ecosystems that would have the effect of reducing the impact of the change in the frequency of extremes due to the change in the mean.

4. Aspects of weather and climate extremes

The series of papers that follows describes the current state of our knowledge concerning the effects of weather and climate extremes from several points of view, all of which are interrelated. First we examine statistical changes in extremes already observed. Then we address the socioeconomic and ecological impacts that are closely tied to changes in extremes, and look at projections from climate model experiments concerning how weather and climate extremes could change in the future.

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