6.2 RATIONAL ANALYSIS OF TRENDS IN EXTREME TEMPERATURE AND PRECIPITATION

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1. INTRODUCTION

Previous studies have often assumed that climate changes accompanying an enhanced greenhouse effect would simply shift mean values while not changing relative frequency distributions. Our research on daily temperature and precipitation trends across the United States during the 20th century shows that this view is scientifically unwarranted.

2. DAILY TEMPERATURE ANALYSIS

During the past 100 years, the annual average surface air temperature for the 48 contiguous United States has increased at a rate of about 0.04°C per decade. However, this observed rate of temperature rise has not been steady; instead, it is marked by three distinct periods of change. From 1900 to 1939, annual temperatures rose at a rate of 0.18°C per decade. This rise was followed by a temperature decline of 0.12°C per decade from 1940 to 1969. From 1970 to 1997, the temperature again rose at nearly the same rate (0.19°C per decade) as the early century rise (Figure 1). The most recent rise in temperature is often suggested to be a result of anthropogenic alterations to the atmospheric concentration of greenhouse gases and as support for climate model projections of future conditions. Such projections have been used by the United Nations' Intergovernmental Panel on Climate Change (IPCC) and in the recent "United States National Assessment [USNA] of the Potential Consequences of Climate Change" to suggest that the future will be one with increasing temperature extremes and related consequences such as increased heat-related human mortality, the spread of tropical diseases, more severe droughts, more intense precipitation events, and greater stress on agriculture (IPCC, 1996; USNA, 2000; IPCC, 2001).

Many of these consequences result from the assumption that a warmer climate is a more extreme climate (IPCC, 1996; Easterling et al., 2000; IPCC, 2001). Since most extreme events, by definition, occur on a rather fine temporal scale, investigations that are designed to look for changes in such events need to incorporate data collected on a similarly fine scale. For example, attempting to assess changes in temperature extremes using monthly data will likely miss many of the important aspects of how that change took place and would be insufficient to use for model verification. Therefore, in order to capture the temporal patterns of temperature change observed across the United States during the 20th century at a scale necessary to provide a basis against which projections of changes in extremes can be judged, we examined trends in daily observations of maximum and minimum temperatures for a collection of stations across the country.

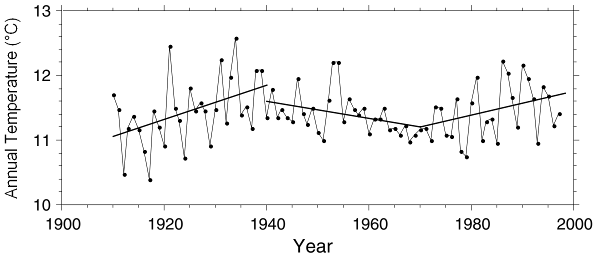

Figure 1. The United States temperature history from 1910 to 1997 showing the pattern of temperature change marked by successive periods of increasing (1910–1939), decreasing (1940–1969), and then increasing (1970–1997) trends.

2.1 Data and Methodology

Our analysis focused on daily temperature trends over the United States within three successive time periods covering most of the 20th century; 1910–1939, 1940–1969, and 1970–1997. These periods were chosen from the available data to be of roughly equal length and to best isolate the different temperature patterns (both in terms of trends and break points) that characterize the U.S. temperature record. Observations show that a strong warming trend of similar magnitude is present in the first and last periods, while a cooling trend is present in the

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middle period (Figure 1). While the magnitude of the trends within each period varies across different regions of the country, the pattern of successive periods of warming, cooling, and warming is generally maintained.

The data used in our analysis were the maximum and minimum temperature observations contained in the 1062-station version of the United States Historical Climate Network daily data for the 48 contiguous United States (HCN/D). The spatial density, daily resolution, and long period of observations make this data set especially useful for the detection and characterization of regional temperature changes across the United States.

Within HCN/D there are sources of variability that are unrelated to climate. Sources of these non-climatological signals include time of observation changes, station moves, urbanization, and instrument changes. It is possible to isolate several of these factors within this data set and to select stations that are free from their effects. To this end, we examined the station history for each station that had a sufficiently long period of record within each of our analysis periods. An adequate period of record was defined to be one with valid data for at least 90% of the total number of years in an analysis period. Up to 10 non-consecutive missing daily observations were allowed in a valid year. These missing values were interpolated as the linear average between the temperature measured on the preceding and following days. Any year containing successive missing daily observations, or more than 10 non-successive days with missing observations, was removed from the analysis. Once stations with adequate data were identified, we then checked for consistency in station location, observation time, and instrument type within each analysis period. We eliminated stations that had station moves of more than 0.1 minute of longitude or latitude or an elevation change of more than 6 meters. We also eliminated those stations that had a time of observation change of more than one hour. And lastly, during the 1970–1997 period of study, we removed those stations where the liquid-in-glass thermometers in Cotton Region Shelters that were historically used to record daily maximum and minimum temperatures in the Cooperative Station Network were replaced with a thermistor-based temperature observing system (Maximum-Minimum Temperature System or MMTS). This changeover was begun in the mid-1980s.

For each of the remaining stations within each analysis period, the daily data within each year were ranked from the coldest to the warmest. The data were then collected into 365 annual time series for each temperature variable (maximum and minimum temperatures)—one time series for each ranked day of the year. Note that these time series do not represent a consistent ranking in time (i.e., the Julian day is not constant), but instead represent a consistent ranking in temperature (i.e., a time series of the first coldest day of each year, a separate time series for the second-coldest day of each year, etc.). An ordinary least-squares regression line was then fit through each of the 365 time series. Within each analysis period, we averaged the least-squares trends from all available stations within seven roughly equal-area geographic regions across the United States for each ranked day. Regional averages were used to reduce the effects of spatial inhomogeneity of the station distribution, while still allowing some illustration of regional variation of change.

2.2 Results and Discussion

2.2.1 The Period 1910–1939

During the earliest period, 39 stations met our criteria for inclusion. Figure 2 shows the average temperature trend among all valid stations averaged across our seven geographic regions, along with the 95% confidence range as defined by two standard errors from the mean. There was only one station in our southwestern region, and therefore, this region was not included in our national average. The country as a whole exhibited an overall significant warming trend both in maximum and minimum temperatures (Figure 2). The warming trends of minimum temperatures increased both toward the colder and warmer ends of the ranking, while the trends in maximum temperatures increased more toward the warmest half of the temperature ranking. This resulted in the greatest warming trends being found in the days with the highest maximum temperature. This is a climatic tendency toward more extreme heat.

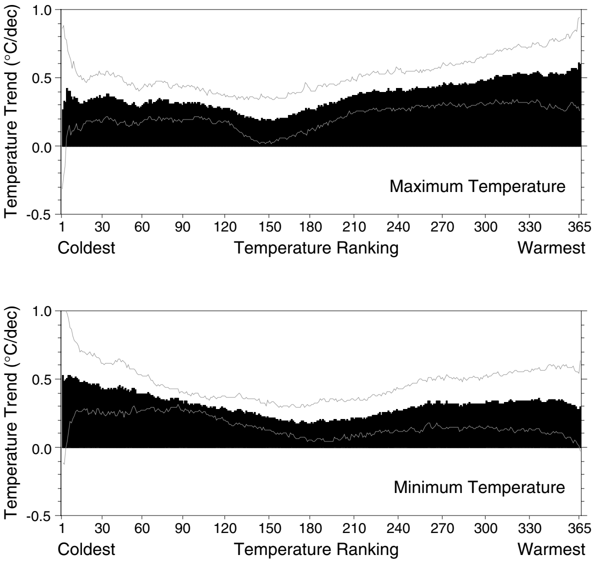

Figure 2. The U.S. national average trends through ranked daily temperatures for the period 1910–1939. The vertical bars represent the average trend for each ranked day across each station in the analysis, sorted from coldest to warmest (x-axis), while the thin white lines represent the upper and lower 95% confidence limit of this average.

2.2.2 The Period 1940-1969

In contrast to the early period warming, the years from 1940 to 1969, with 99 valid stations, were marked by a general tendency for days with lower maximum and lower minimum temperatures to cool at a rate greater than that observed during warmer days (Figure 3). On a national scale, this period was characterized by a general reduction in both the daily maximum and daily minimum temperatures. A significant cooling trend in daily maxima was found at both ends of the temperature range, while the significant cooling trends in the daily minima were found primarily during the days with the lowest temperatures. In other words, the coldest days became colder.

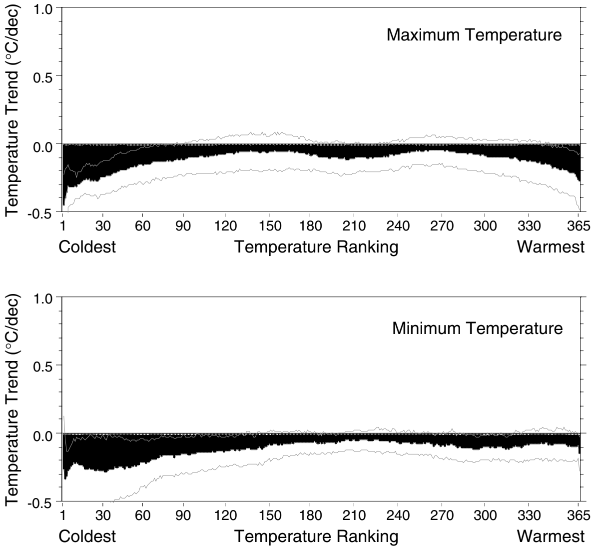

Figure 3. The U.S. national average trends through ranked daily temperatures for the period 1940–1969 (The vertical bars and white lines are as defined in Figure 2.)

2.2.3 The Period 1970-1997

The period from 1970 to 1997 had 100 stations that met the inclusion criteria. The primary feature of temperature change during this period was the large warming trend during the coldest days of the year. The nationwide average trends are dominated by significant increases during the days with the lowest temperatures (Figure 4), although increasing temperatures are evident throughout the rankings. This is a climatic tendency primarily characterized by less extreme cold.

These daily results are generally consistent with studies that have investigated changes in minimum and maximum temperatures using data at the monthly time scale (Karl al., 1991, Karl et al., 1996, Easterling et al., 1997), but provide for a more detailed analysis of the patterns of change.

2.3 Temperature Analysis Conclusions

During the most recent period (1970–1997), human alterations to the earth/atmosphere system should have exerted their greatest influence on temperatures, since this corresponds to the time of the greatest rate of accumulation of greenhouse gases in the atmosphere as well as the period of the largest concentration of these gases. There have been many studies that have looked for and reported to have found a connection between observed temperatures and greenhouse gases (e.g., Michaels et al., 2000; Barnett et al., 1999). Our results show that the nature of temperature changes in the United States during this period of warming are quite different from those that occurred during an earlier period of comparable warming with much less human modification of the composition of the atmosphere.

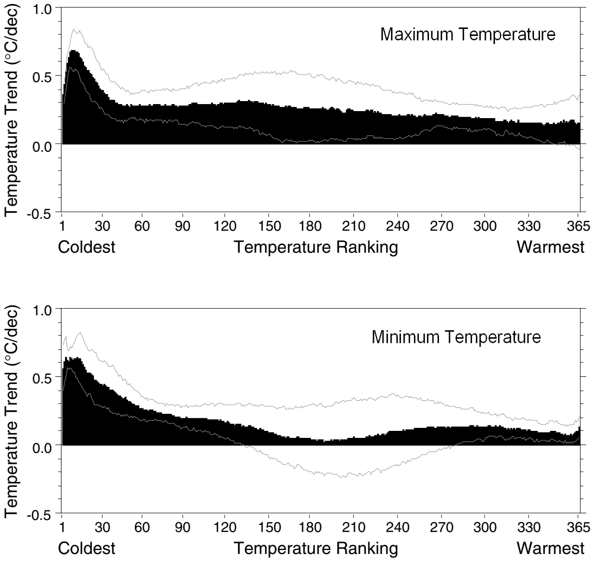

Figure 4. The U.S. national average trends through ranked daily temperatures for the period 1970–1997 (The vertical bars and white lines are as defined in Figure 2.)

The warming from 1910 to 1939, the period during the last century that had the least anthropogenic influence, was one in which the greatest rise in temperature was observed during the hottest days of the year. The decade that marked the culmination of the warming, the 1930s, was characterized by very hot summer days and widespread extreme drought conditions across the United States. This early-century warming, widely considered to be predominantly of natural origin—from variations in the solar and volcanic output—displayed the characteristics of a climate that was becoming more severe. By contrast, the warming observed during the past three decades of the twentieth century largely does not display these types of characteristics. The temperature increase has occurred mainly during the days of the year with some of the lowest maximum and minimum temperatures, while the days with the highest temperatures have shown far less of an increase. These findings add to a growing body of evidence (Balling et al., 1998; Michaels et al., 1998; Michaels et al., 2000) that the temperature change that has occurred during the period of the greatest human influence on the climate is dominated by increases of extremely low temperatures rather than by increases of high temperatures. This is a characteristic of a climate tending toward moderation rather than the extreme. Prognostications of dire consequences built upon climate model projections of a future climate that is dominated by increasing high temperatures should be reassessed.

3. DAILY PRECIPITATION ANALYSIS

During the past 100 years, observations indicate that the annual average total precipitation for the 48 contiguous United States has increased at a rate of about 0.28 inches per decade, which, over this time, has led to about a 10% rise in annual precipitation. Unlike the U.S. temperature history, the rise in precipitation has been relatively constant, and does not exhibit distinct multi-decadal periods of behavior, although perhaps there is some evidence for an increase in the trend in annual precipitation since the middle part of the 20th century (Figure 5).

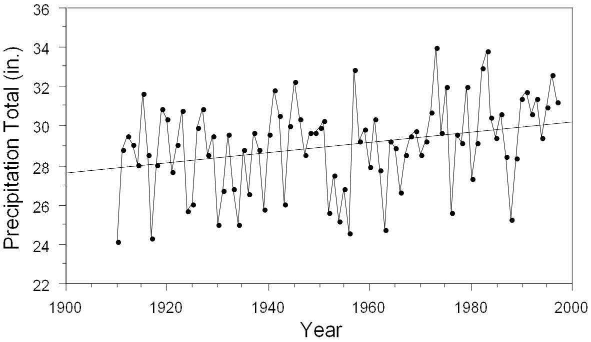

Figure 5. The U.S. precipitation history from 1910 to 1997.

The suggestion has been made that this general rise in precipitation has been dominated by a disproportionate rise in extreme precipitation events (Karl and Knight, 1998; Easterling et al., 2000)—an occurrence that has also been linked to greenhouse gas increases. This claim has been made despite the fact that there has never been an assessment of whether the observed rise in extreme precipitation events has been "disproportionate." In fact, Groisman et al. (1999) show that due to the distribution of daily precipitation (a gamma-type distribution) an increase in the annual total precipitation (without an increase in the frequency of events) should lead to a greater increase in the heavy precipitation extremes. Therefore, the simple observation that extreme precipitation is increasing greater than other categories does not, in itself, imply that the increase has been disproportionate. To date, an investigation to address this issue has not been undertaken.

Additionally, despite the claim that "extreme" precipitation has been increasing, there is not strong evidence that the primary detrimental effect of such an increase—increased flooding—has been occurring. Lins and Slack (1999), in an analysis of U.S. stream flows during the 20th century found that it was the low- to medium-flow regimes that were increasing, while the high daily flows had remained unchanged. Groisman et al. (2001) have challenged the results of Lins and Slack (1999); however, procedural differences between the two studies likely explain most of the differences and a satisfactory consensus has not been reached on the matter.

In any case, since detrimental effects from increased precipitation have proven difficult to detect, it seems that the definition of "extreme" is more likely rooted in relative rather than in absolute values. The impacts of a relative extreme event are likely to be less than those of an absolute extreme event (i.e. a 2.5-inch daily rainfall in Montana is not likely to have large negative consequences, despite the fact that such an event has a 10-year return interval). However, in the literature that is most cited on this topic (Karl and Knight, 1998), the methodology does not allow for the distinction between relative and absolute extremes to be made, so the true implication of the results in impossible to gauge. In fact, the methodology has been developed such that an increase in precipitation that is not fully explained by an increase in precipitation events MUST result in an increase in the most extreme category.

Karl and Knight (1998) employ percentiles to divide daily precipitation into bins of equal counts (as opposed to fixed amounts). The upper percentile in this case is unbounded in terms of daily precipitation amount. Also, the percentiles are static in time (i.e., they are defined over a certain period) rather than dynamic (i.e., allowed to vary from year to year). Changes of precipitation within each percentile are expressed as a percentage of the long-term mean in annual precipitation. In this way, the sum of the trends across all percentiles equals the trend in overall precipitation.

Consider the theoretical signal of a 10% increase in annual precipitation under such a scheme. The precipitation increase may be due to either more events, more intense events, or a combination of the two. In the first case, assuming that the extra precipitation simply arises from an additional 10% of events (drawn from the same distribution as the original), more of the extra precipitation is incrementally contained in the higher percentiles (Figure 6a). In the second case, where the extra precipitation is simply provided by a 10% increase in the intensity of each event, the extra precipitation is primarily contained in the highest percentile (Figure 6b). This arises from the fact that the intensity within each category is fixed by the analysis, with the lone exception of the last, unbounded percentile.

Figure 7a shows the results from Karl and Knight (1998) for the proportion of the U.S. precipitation increase due to a change in the number of events, while Figure 7b shows their results for the proportion from an increase in intensity. Their results bear a remarkable resemblance to the theoretical results in Figure 6ab. Therefore, they indicate nothing more than the fact that precipitation has been increasing across the United States due both the increases in the number of events and increases in the intensity of events. The fact that such increases are primarily manifested in the heavy and extreme percentiles is expected, and therefore cannot be considered "disproportionate," at least in comparison with the expectations.

Another problem with using equal-count percentiles is that the actual precipitation amounts that define the percentile bounds differ from location to location, and therefore are unknown (or at least unreported) when combining stations into regional or national aggregates. Without this information however, one is unable to judge the actual intensity of the events within each percentile, and therefore, cannot make a useful assessment as to the implication of changes within them. For instance, averaged across the United States, about 80% of all daily precipitation events are less than 0.50 inches, 92.5% are less than 1.00 inches, and 96.5% are less than 1.50 inches. Therefore, of the 20 percentile categories employed by Karl and Knight (1998), about 18 represent events of less than one inch per day, and the highest category includes events that are only greater than about 1.25 inches. And, due to the shape of the distribution of daily precipitation, the majority of events in this category will be close to the lower bound. In an absolute sense, these events would hardly be considered “extreme.”

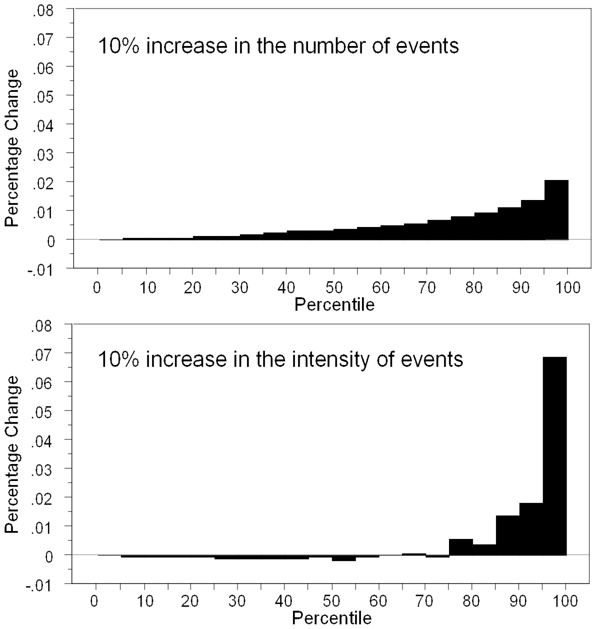

Figure 6a (top). The theoretical increase in percentiles of precipitation due to a 10% increase in the number of events. Figure 6b (bottom). The increase in percentiles of precipitation due to a 10% increase in the intensity of each event.

Therefore, it would seem that the information that would be most useful in assessing the impacts of changing precipitation would be based upon a bin analysis in which the bounds of the bins are known (and reported) and that remain constant for each station, region, and national aggregate. In this manner, planners can assess changes in actual precipitation amounts and use these changes to address current and future design issues.

3.1 Data and Methods

We used the same set of high-quality daily precipitation stations that were used by Karl and Knight (1998). However, instead of filling in missing values by random draws from a distribution fit to the available data (as done in Karl and Knight (1998)), we simply ignored the missing values. We selected only stations that had fewer than 5 missing values per year and had continuous data from 1910 to 1993. This reduced the original 187-station dataset to 54 stations (this was reduced to 11 if data were extended through 1997). For each station, we simply counted the number of events that fell into 10 0.5-inch wide bins (starting from 0.01 inches) during each year. An 11th bin was unbounded above 5 inches. National totals were obtained by simply summing the counts within each bin across all stations.

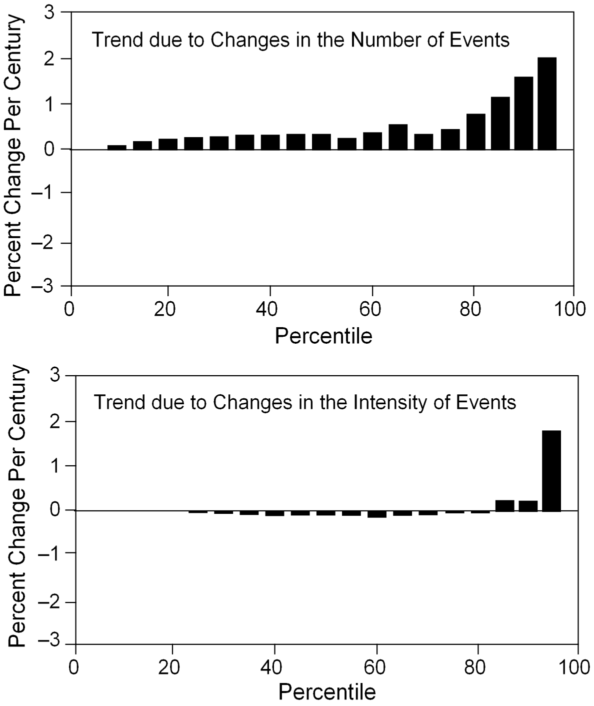

Figure 7a (top). The observed increase in percentiles of precipitation due to an increase in the number of events. Figure 7b (bottom). The observed increase in percentiles of precipitation due to a 10% increase in the intensity of each event (from Karl and Knight, 1998).

3.2 Results and Discussion

Figure 8 shows the linear trend of the time series of the nationally aggregated counts within each bin presented as a percent change per century of the frequency of occurrence of events within each bin (trends significant at the 0.05 level are represented by filled bars). Also presented is the mean count within each bin. Space limitations prevent the display and discussion of regional analyses.

These results support the findings of Karl and Knight (1998) in that they show that the greatest percentage increase in precipitation events from 1910 to 1993 has occurred in the what would be their 95th percentile. The significant increases are mainly contained in the daily precipitation bins that include amounts less than 3 inches, with the exception of the 5 inch or more category. However, of importance is the fact that the actual frequency of the events greater than 1 inch is very small. Therefore, even a large increase in the percentage occurrence of these events is, in reality, an exceedingly small increase in the actual number of events. For instance, a 30% per century increase in the frequency of events in the 2.5-to 3-inch bin results, over 10 years, in the occurrence of about one additional event within the entire population of the 54 stations analyzed. These results are similar, in fact, to the earlier results of Karl et al. (1995), who, using a similar technique, noted that the increase in daily precipitation events of intensity of greater than 2 inches resulted in one additional "extreme" precipitation event every two years (somewhere in their 187-station data set).

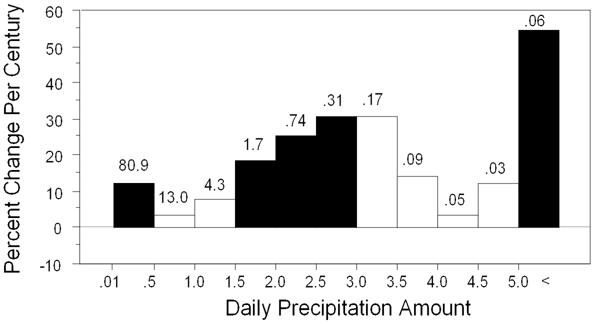

Figure 8. The change in the frequency of occurrence of precipitation amounts within 0.5-inch bins across the United States from 1910–1993 expressed in terms of percent change per century. Filled bars indicate that the change is significant at the 0.05% level. The number above each bar represents the average number of events per year.

3.3 Conclusions

We conclude that indeed the increase in annual precipitation observed across the United States during the 20th century has been accompanied by greater increases in the heavier precipitation categories, much as would be expected to occur with long-term annual precipitation increases. The biggest increases are found primarily in events of less than 3 inches per day and in the one category that rarely occurs. This fact, given the absence of strong evidence that flood events are increasing across the country, leads us to believe the benefits of increased precipitation in agricultural, domestic, and commercial uses far exceed the negative consequences.

We therefore conclude that the era of greenhouse enhancement is concurrent with a reduction in relative thermal extremes of in the United States, and an increase in a precipitation class that is a clear benefit to our society. Policies directed at reducing greenhouse emissions are likely to mute or reduce these salutary trends.

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