HISTORICAL CONTEXT

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The occurrence of high-impact extreme weather and climate variations invariably leads to questions about whether the frequency or intensity of such events have changed, and whether human influence on the climate system has played a role. Research on these questions has intensified in recent years, culminating in two recent assessments (Karl et al. 2008; Field et al. 2012), and in proposals to formalize "event attribution" as a global climate service activity (Stott et al. 2012). In order to provide historical context for later sections, this section discusses the extent to which human influence has caused long-term changes in the frequency and intensity of some types of extremes.

The nature of extreme events. The term "extreme" is used in a number of contexts in climate science. It refers to events that may in fact not be all that extreme, such as the occurrence of a daily maximum temperature that exceeds the 90th percentile of daily variability as estimated from a climatological base period, or it may refer to rare events that lie in the far tails of the distribution of the phenomenon of interest. A characteristic of extremes is that they are understood within a context—and thus seasonal or annual means may be "extreme" just as an unusual short-term event, such as a daily precipitation accumulation, may be extreme. Certain phenomena, such as tropical cyclones that have been classified on the Saffir–Simpson scale, or tornadoes that have been classified on the Fujita scale, are considered extreme as a class. The general definition of extremes that was adopted by the IPCC for its Special Report on Extremes (Field et al. 2012) applies to most extremes considered in this report, and across the range of space and time scales that are considered here. That definition describes an extreme as the "occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed

values of the variable." A full discussion of the definition of an extreme can be found in Seneviratne et al. (2012). In addition, Zwiers et al. (2012, unpublished manuscript) provide a discussion of the language surrounding extremes that is used in the climate sciences.

Challenges in detection and attribution of extremes. The discussion in this section reflects the fact that most detection and attribution research on long-term changes in the probability and frequency of extremes thus far has focused on short duration events that can be monitored using long records of local daily temperature and precipitation observations. These changes are generally captured as indices that document the frequency or intensity of extremes in the observed record rather than focusing on individual rare events. In contrast, many of the events considered in later sections of this report are individual events, often of longer duration than the extremes considered here, and are also usually events with longer return periods. Nevertheless, the finding that human influence is detectable in some types of short duration events that can be conveniently monitored from meteorological observations provides important context for the interpretation of other types of events. For example, feedbacks and physical processes that influence individual large events (Fischer et al. 2007; Seneviratne et al. 2010) will often also be at play in events that are reflected in indices. Thus, index-based studies are helpful for providing context for the attribution of individual events, and evaluate the ability of models to realistically simulate events that are affected by different feedbacks from those affecting mean climate.

While not discussed in this section, the detection and attribution of changes in the mean state of the climate system often also provides important context for the understanding of individual extreme events. An example is the European 2003 heat wave, which can be characterized both by very extreme warm daily maximum and minimum temperatures, and by an extremely warm summer season. The demonstration that human factors had influenced the climate of southern Europe in a quantifiable way over the latter part of the twentieth century was an important element in establishing that human influence had probably substantially increased the likelihood of an extreme warm summer like that experienced in the region in 2003 (Stott et al. 2004).

The frequency and intensity of extremes can be affected by both the internal variability of the climate system and external forcing, and the mechanisms involved can be both direct (e.g., via a change in the local energy balance) and indirect (e.g., via circulation changes). This makes the attribution of events to causes very challenging, since extreme events in any location are rare by definition. However, global-scale data make it possible to determine whether broadly observed changes in the frequency and intensity of extremes are consistent with changes expected from human influences, and inconsistent with other possibilities such as climate variability. Results from such detection and attribution studies provide the scientific underpinning of work determining changes in the likelihood of individual events.

Observed changes in extremes. We briefly consider historical changes in frequency and intensity of daily temperature and precipitation extremes. There is a sizable literature on such events, in part because reliable long-term monitoring data are gathered operationally by meteorological services in many countries. Many other areas remain understudied, such as whether there have been changes in the complex combinations of factors that trigger impacts in humans and ecosystems (e.g., Hegerl et al. 2011), or areas that are subject to greater observational and/or process knowledge uncertainty, such as the monitoring and understanding of changes in tropical cyclone frequency and intensity (e.g., Knutson et al. 2010; Seneviratne et al. 2012).

Changes in extreme temperature and the intensification of extreme precipitation events are expected consequences of a warming climate. A warmer climate would be expected to have more intense warm temperature extremes, including longer and more intense heat waves and more frequent record-breaking high temperatures than expected without warming. It would also be expected to show less intense cold temperature extremes and fewer record-breaking low temperatures than expected before. Both of these expected changes in the occurrence of record-breaking temperatures have indeed been observed (e.g., Alexander et al. 2006; Meehl et al. 2009). Further, a warmer atmosphere can, and does, contain more water vapor, as has been observed and attributed to human influence (Santer et al. 2007; Willett et al. 2007; Arndt et al. 2010). This implies that more moisture is available to form precipitation in extreme events and to provide additional energy to further intensify such events. About two-thirds of locations globally with long, climate-quality instrumental records [e.g., as compiled in the Hadley Centre Global Climate Extremes dataset (HadEX); Alexander et al. 2006] show intensification of extremes in the far tails of

the precipitation distribution during the latter half of the twentieth century (Min et al. 2011).

Detection and attribution of changes in intensity and frequency of extremes. A number of studies (e.g., Christidis et al. 2005, 2010; Zwiers et al. 2011; Morak et al. 2011, 2012) have now used various types of detection and attribution methods to determine whether the changes in temperature extremes predicted by climate models in response to historical greenhouse gas increases and other forcings are detectable in observations. The accumulating body of evidence on the human contribution to changes in temperature extremes is robust, and leads to the assessment that "it is likely that anthropogenic influences have led to warming of extreme daily minimum and maximum temperatures on the global scale" (Seneviratne et al. 2012). Results tend to show that the climate models used in studies simulate somewhat more warming in daytime maximum temperature extremes than observed, while underestimating the observed warming in cold extremes in many locations on the globe. It remains to be determined if this model-data difference occurs consistently across all models, or whether it is specific to the small set of phase 3 of the Coupled Model Intercomparison Project (CMIP3) climate models used in the studies.

Heavy and extreme precipitation events have also received a considerable amount of study. Heavy precipitation has been found to contribute an increasing fraction of total precipitation over many of the regions for which good instrumental records are available (Groisman et al. 2005; Alexander et al. 2006; Karl and Knight 1998; Kunkel et al. 2007; Peterson et al. 2008; Gleason et al. 2008), indicating an intensification of precipitation extremes. Direct examination of precipitation extremes, such as the largest annual 1-day accumulation, or the largest annual 5-day accumulation, also shows that extreme precipitation has been intensifying over large parts of the global landmass for which suitable records are available (Alexander et al. 2006; Min et al. 2011; Figs. 1 and 2), with an increase in the likelihood of a typical 2-yr event of about 7% over the 49-yr period from 1951 to 1999 (Min et al. 2011). It should be noted, however, that the spatial extent of regions for which long records of daily and pentadal precipitation accumulations are available is still severely limited (e.g., Alexander et al. 2006; see also Fig. 1), and that spatial patterns of change are still noisy.

The intensification of extreme precipitation is an expected consequence of human influence on the climate system (e.g., Allen and Ingram 2002; Trenberth et al. 2003) and is simulated by models over the latter half of the twentieth century in response to anthropogenic forcing, albeit with weaker amplitude than observed, which is at least partly due to differences in the spatial scales resolved by climate models and station-based local records (Chen and Knutson 2008). Nevertheless, Min et al. (2011) recently showed, using an ensemble of models and an index of extreme precipitation that is more comparable between models and data than records of intensity of events, that the observed large-scale increase in heavy precipitation cannot be explained by natural internal climate variability, and that human influence on climate provides a more plausible explanation. The body of research available on precipitation extremes is in an earlier stage of development than for temperature extremes, and thus Seneviratne et al. (2012) did not give a quantified likelihood assessment concerning precipitation extremes, but rather stated that "there is medium confidence[2] that anthropogenic influences

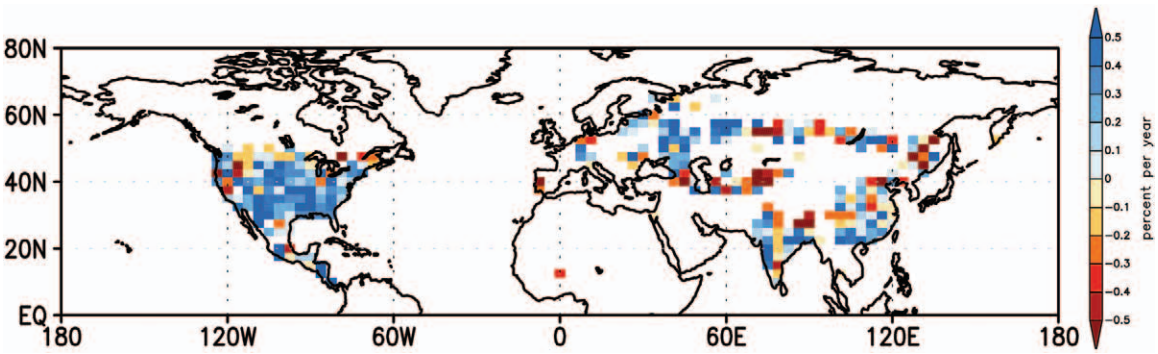

Fig. 1. Geographical distribution of trends of probability-based indices (PI) of extreme precipitation during 1951–99 for 1-day precipitation accumulations. Annual extremes of 1-day accumulations were fitted to the Generalized Extreme Value distribution, which was then inverted to map the extremes onto a 0%–100% probability scale. Blue colors indicate intensification of extreme precipitation, which is observed at about two-thirds of locations. From Min et al. (2011).

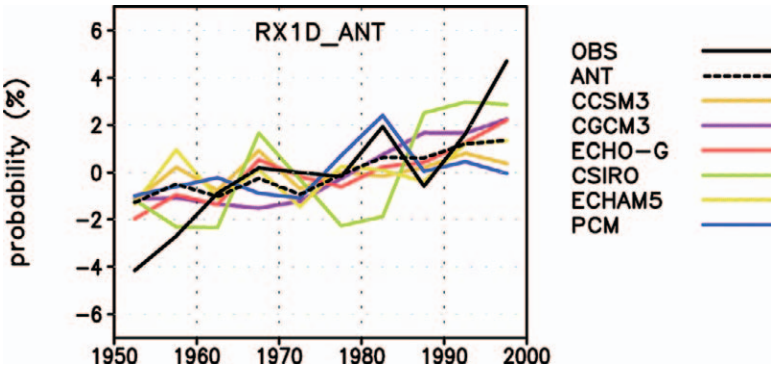

Fig. 2. Time series of five-year mean area-averaged PI (as defined in Fig. 1) anomalies (%) for 1-day annual extreme precipitation anomalies over Northern Hemisphere land during 1951–99. Black solid line represents observations and the dashed line represents the multi-model mean for the models indicated in the legend. Model simulations were run with anthropogenic forcings. Colored lines indicate results for individual model averages [see Supplementary Table 1 of Min et al. (2011) for the list of climate model simulations and Supplementary Fig. 2 of Min et al. (2011) for time series of individual simulations]. Each time series is represented as anomalies with respect to its 1951–99 mean.

have contributed to intensification of extreme precipitation on the global scale."

Few detection and attribution studies that include observations of temperature or precipitation extremes in the first decade of the twenty-first century have yet been performed (exceptions include Morak, et al. (2011, 2012, manuscript submitted to *J. Climate*), who detect anthropogenic influence in the frequency of occurrence of temperature extremes in data that extend to 2005]. However, studies of changes in extremes that include more recent observations show that ongoing changes in temperature extremes are regionally consistent with those observed in the latter half of the twentieth century. Examples include studies of the frequencies of warm and cold days and nights in North America (Peterson et al. 2008); the frequency of record breaking temperatures in the United States (Meehl et al. 2009); and the frequency of temperature extremes in multiple regions globally (Morak et al. 2011, 2012, manuscript submitted to *J. Climate*). Results from recent studies of precipitation extremes are more mixed. Some studies do show changes consistent

[2] See Mastrandrea et al. (2010) for a description of IPCC confidence language used in the IPCC Fifth Assessment, including the Special Report on Extremes (Field et al. 2012).

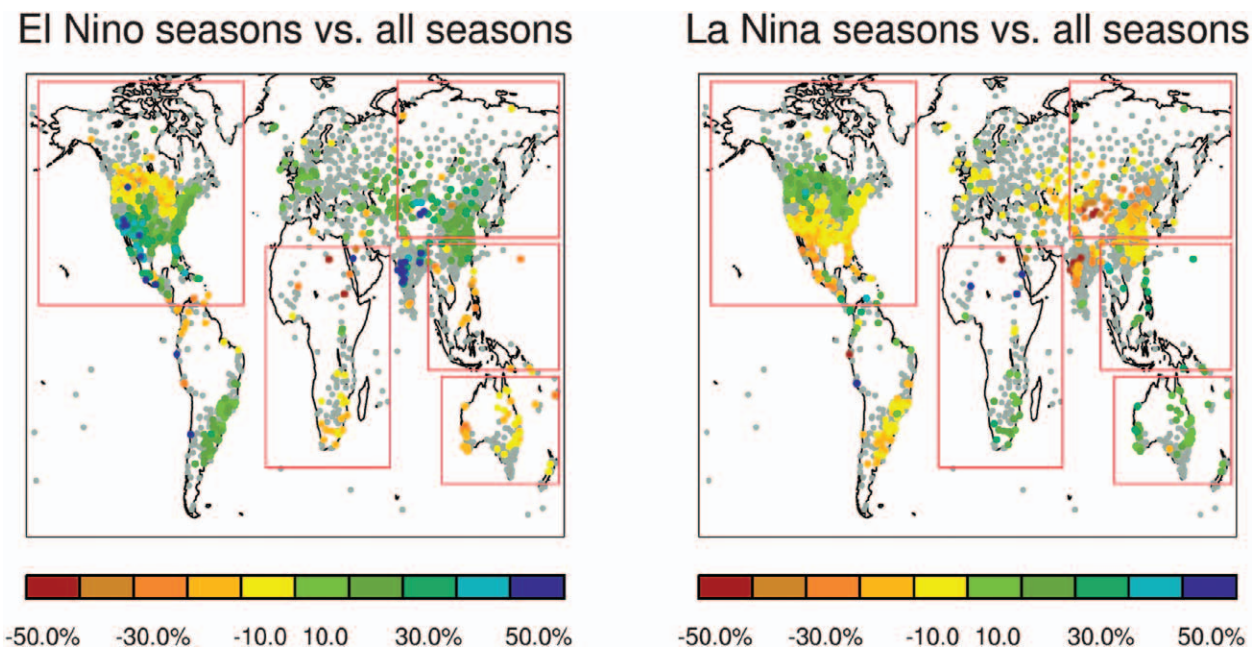

Fig. 3. Impact of (left) El Niño and (right) La Niña on the intensity of the largest 1-day precipitation event monthly in the November–April half of the year. Based on station data from the Global Historical Climatology Network-Daily (GHCN-D) for 1949–2003. From Kenyon and Hegerl (2010).

with those observed in the latter part of the twentieth century [e.g., the fraction of U.S. land area affected by extreme precipitation (Gleason et al. 2008), change in various extreme precipitation indicators in North America (Peterson et al. 2008), and heavy precipitation in Europe (Zolina et al. 2010)], while others do not demonstrate evidence of statistically significant trends [e.g., Choi et al. (2009) for the Asia-Pacific region and Aguilar et al. (2009) for central Africa; see also the assessment of Seneviratne et al. (2012)]. Overall, changes in precipitation remain regionally mixed, testifying to the high spatial variability of precipitation.

Natural low frequency internal variability of the climate system also affects the intensity and frequency of temperature and precipitation extremes, generally with a mixed pattern of increasing and decreasing responses depending on regions and seasons. For example, El Niño strongly influences both temperature and precipitation extremes globally (Kenyon and Hegerl 2008, 2010; see Fig. 3) and can alter the likelihood of rare damaging wintertime precipitation events by more than a factor of 4 in some parts of the United States, particularly in the southwest (Zhang et al. 2010). Any human influence on extreme weather risk combines with these episodic variations and the chance fluctuations that are inevitable when dealing with rare events; hence we should not assume that, if human influence is making a particular type of event more likely over time, it will necessarily occur with greater than average likelihood every year.

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