INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **29**: 317–319 (2009)
Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/joc.1861

Editorial

Climate extremes: progress and future directions

This Special Issue of the *International Journal of Climatology* arose from two similar symposia held by the International Union of Geophysics and Geodesics (IUGG) and American Geophysical Union (AGU) in 2007. The IUGG session 'Extreme Weather and Climate Events: Past Occurrences and Future Likelihoods', jointly run with the International Association of Meteorology and Atmospheric Science (IAMAS), was held in Perugia, Italy in July 2007 and the AGU session 'Extreme Weather and Climate Events: Observed and Projected Future Changes' was held at the annual AGU Fall meeting in San Francisco, USA in December 2007. The motivation behind both symposia was the vulnerability of communities and ecosystems to climate variability and the likelihood that it will depend more on the change in intensity and frequency of extreme events than on changes in mean climate (Lynch and Brunner, 2007). For this reason the study of climate extremes in a changing climate has come to the fore in recent years but primarily since the Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report (SAR) in 1995. The SAR concluded that although there was no evidence globally that extreme weather events or climate variability had increased, data and analyses were 'poor and not comprehensive' inspite of changes in extreme weather events observed in some regions where sufficient data were available (Nicholls *et al*., 1996). There was also little information or conclusive evidence on what effect anthropogenic climate change had had, or would have, on climate extremes. One reason for such ambiguity was that while there were studies of regional changes in climate extremes (such as evidenced by this Special Issue), the lack of consistency in the definition of extremes between analyses meant that it was impossible to provide a comprehensive global picture. These ambiguities in the SAR conclusions led to a number of workshops and globally co-ordinated efforts, which have made significant progress in our analysis of extremes (Nicholls and Alexander, 2007). In addition, extreme events in recent years have not only been extremely damaging but also in some cases have caused unprecedented mortality such as the extreme European heat of the 2003 summer (Foullet *et al*., 2007) and the intense hurricane season of 2005 (Trenberth and Shea, 2006) and have been a catalyst for more urgent analysis of the relationship between extreme weather and climate change.

The impacts of most extremes are typically felt at a local or regional scale; so regional studies of climate extremes are of the highest priority for most countries for assessing potential climate impacts. However, given that climate change signals in climate extremes are difficult to detect at a regional scale, to understand fully how the climate varies and the extent to which humans have influenced the climate system requires a global approach. This in turn requires a consistent approach for analysis. Groups such as the World Meteorological Organisation (WMO) CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI), the European Climate Assessment (ECA) and the Asia–Pacific Network (APN), in addition to their primary aim of filling in data gaps, have aimed to provide a framework for defining and analysing observed climate extremes so that the results from different countries can be combined seamlessly. It was early realized that countries were more likely to exchange information on seasonal and/or annual climate indices e.g. heatwave duration, heavy precipitation events than they were to release raw daily or sub-daily meteorological observations. In addition, temperature and precipitation were the most widely available long-term climate variables; so most global studies have focused on analysis of these data. The first study to attempt a global analysis of temperature and precipitation extremes under the auspices of the ETCCDI was that of Frich *et al*. (2002) who showed that there had been significant changes in extreme climate indices, such as reductions in frost days and increases in warm nights and heavy rainfall events over the last 50 years. This approach has also been pivotal in 'data mining' in regions where previously little or no data had been readily available, developing ongoing capacity in these data-sparse regions and enhancing international collaboration (Peterson and Manton, 2008). Modelling groups have also now taken a similar approach through the Joint Scientific Committee (JSC)/CLIVAR Working Group on Coupled Models so that observations and model output can be compared consistently. The study by Tebaldi *et al*. (2006) was the first to use the multi-model approach to assess potential future changes in climate extremes showing that the twenty-first century would bring global changes in temperature extremes consistent with a warming climate. While that study also showed that global changes in precipitation extremes were consistent with a wetter world with greater precipitation intensity, the consensus and significance amongst the models were weaker when regional patterns were considered. This indicates the importance of combining global results with more regionally relevant studies to assess the impacts of these changes. These and other multi-national efforts such as that of Alexander *et al*. (2006) meant that by the time of the IPCC's Third Assessment Report (TAR) and Fourth

Assessment Report (AR4) in 2001 and 2007 respectively, much stronger conclusions could be drawn about how extremes had changed and how they might change in the future. This was largely due to increased data coverage and the availability of longer timeseries, which enabled better detection of changes by enhancing the signal-to-noise ratio. Because of the availability of global datasets, studies such as that of Christidis *et al.* (2005) were for the first time able to detect a discernible human influence on recent trends in global temperature extremes. By AR4, it was 'likely' that there would be increases in droughts, intense tropical cyclones and extreme high sea level, 'very likely' that warm spells and heavy precipitation events would increase and 'virtually certain' that there would be more warm nights and fewer cold nights at the end of the twenty-first century compared to the end of the twentieth century (IPCC, 2007).

This Special Issue draws from selected presentations at the IUGG and AGU symposia to highlight the current wide ranging scientific research on climate extremes. This research includes statistical challenges, approaches for filling in data gaps, accounting for long-term climate variability, the ability of models to reproduce observed changes, future projections and studies driven by the needs of stakeholders in the impacts community.

Zhang *et al.* (this issue) address some of the issues associated with raw meteorological data, highlighting the problems that researchers can come across before they even start to identify extreme events. In this case, they identify biases that are introduced both by rounding observational values and by defining a temperature percentile index. They propose an adjustment for this bias, which restores the precision of the counts of threshold exceedance. Temperature percentile indices have now been used widely in many regional studies following the free dissemination of ETCCDI software both at regional workshops and online. This has meant that countries or regions where there has previously been little or no information on climate extremes can provide information to fill in some of the gaps in our knowledge. An example of one such study is by Rahimzadeh *et al.* (this issue) who show how the ETCCDI approach has been successful at filling in data and knowledge gaps in Iran, a region where little previous information on climate extremes has been available. The results indicate evidence of significant changes in temperature extremes consistent with warming, while most arid parts of the country have experienced significant trends in both total and extreme precipitation consistent with long-term drying. In other parts of the world, analysis has been applied to more 'extreme extremes'. Roy's study (this issue), investigating change in extreme hourly rainfall, is a prime example of this type of analysis. This study found widespread increases in extreme heavy precipitation events across India, particularly during the summer monsoon season. The results are obviously important for a country with high population density and growth where monsoonal rains are already responsible for widespread destruction.

In addition to the previous studies, it is important to understand how climate has varied over century to multi-century timescales in order to assess how anthropogenic climate change may play out in the future. Northern Europe is particularly fortunate in this respect as it contains some of the longest running continuous meteorological observations in the world. Two of the papers in this Special Issue (Allan *et al.* and Barring and Fortuniak) analyse some of the longer-term data of 'storminess' over north–west Europe. Both studies point to the modulating role of inter-decadal to multi-decadal variations and large-scale natural climate variability on trends in severe storm events hence putting the destruction of recent windstorms in Europe into a long-term perspective.

Another important aspect is to determine how skilful climate models are at reproducing the observed trends and variability of climate extremes in order to increase our confidence in future projections. Fowler and Ekström and Alexander and Arblaster (this issue) both analyse how well multiple climate model simulations represent climate extremes and how these events are likely to change in the future in the United Kingdom and Australia, respectively. Fowler and Ekstrom use the output from 13 regional climate model integrations from the European Union (EU) PRUDENCE project to assess changes in seasonal precipitation extremes across the United Kingdom. Multi-model ensemble estimates calculated by weighting models relative to how well they simulate current climate indicate that extreme precipitation will increase across the United Kingdom in all seasons except summer. Alexander and Arblaster use multiple simulations from nine global climate models to investigate how well temperature and precipitation extremes are represented during the second half of the twentieth century across Australia. While the skill of each model depends on the index under consideration, the indices that are well reproduced show model consensus of significant increases in extreme warming across much of Australia by the end of the twenty-first century.

Della Marta *et al.* (this issue) examine some of the events that are more directly applicable to climate impacts on communities, including safety, engineering and reinsurance applications. In fact, their study investigating extreme wind indices over Europe was sponsored by a reinsurance company. Windstorms over Europe in the past few decades have been costly for the insurance industry, so the Della Marta study provides analyses on the return periods of 200 of the most prominent events. In the future it is probable that much of the work on climate extremes will be motivated by the needs of policy makers and industry.

There are still many questions regarding the definition and analysis of climate extremes. For instance, there is still some debate as to the role of anthropogenic climate change on the frequency and intensity of tropical cyclones (Walsh *et al.*, 2008) for example. Another important question relates to how to adequately address the scale discrepancy between observations and models i.e. the mismatch between the spatial representativeness of observations on the one hand, which are generally collected at observation sites (points), and that of climate model output data on the other hand, for which grid point values are often assumed to represent area mean values. Other questions include (but are not limited to) how to improve the simulated representation of extremes, the extent of the influence of modes of variability on extremes and the adequate prediction of the risk of certain extremes. In addition, most of the discussion here has focused on global climate models, which are generally not useful for local impact studies. A proliferation of high-resolution studies, now ongoing, using regional climate models may help to improve the simulation of more high-impact events although even in the case of regional models the representation of precipitation extremes for example is still often poor, particularly in summer months (Fowler and Ekstrom, this issue; Fowler *et al*., 2007). Improvements may be obtained by better observations for comparison, understanding the mechanisms and processes which act on different spatial and temporal scales or perhaps a new generation of higher-resolution regional climate models (capable of resolving convective processes for summer extremes for example). Above all, data quality is of the utmost importance in underpinning any research.

Perhaps, what is obviously lacking in this Special Issue is an emphasis on impacts and adaptation. This Special Issue has focused mostly on the types of extremes preferred by the ‘climate community’ i.e. generally those, which are statistically robust, cover a wide range of climates and have a high signal-to-noise ratio for use in ‘detection and attribution’ studies. This differs generally from the types of extremes required by the ‘impacts community’, for design purposes for example, which are usually high-impact, region-specific events. While the two criteria may not necessarily be mutually exclusive, a gap definitely exists between what is currently possible from one community and what is needed from the other. A new dialogue has begun between climate modellers and the climate change impacts community to help bridge this gap and one way forward would be to utilize integrated regional climate modelling studies, for example, the EU’s PRUDENCE project (see Fowler and Ekstrom, this issue) to examine impacts. Ultimately, much more collaboration between the different communities is required if we are to adequately address the scientific problems that still exist together with the needs of stakeholders and policy makers. This Special Issue is intended to be a first step towards this goal.

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