Mechanisms for extreme temperature and precipitation events

Simon Tett, and Gabi Hegerl

GeoSciences, University of Edinburgh, Kings Buildings, W Mains Rd, Edinburgh, EH93JW.
Simon.tett@ed.ac.uk, gabi.hegerl@ed.ac.uk

Summary

Extreme events cause substantial impacts on human society, and are central to climate services including event attribution. Much extreme event research focuses on modelling, but studies comparing long-term changes in the frequency and intensity of extreme events suggest systematic biases not only in model climatology of extremes, but also in model simulated changes in the frequency and intensity of events. Hence, before society can rely on model predictions of changes in extreme events for adaptation decisions, or on model-based changes in the probability of events given external drivers, model simulated extremes need careful evaluation. We aim to evaluate the ability of the current generation of climate models to simulate realistic mechanisms involved in strong extremes, and to simulate realistic climatology and changes in the frequency of extreme precipitation and temperature events through comparison with appropriate observations. We will focus particularly on HadGEM2, as well as the ability of related high resolution models (e.g., HiGEM2) to simulate the statistical and mechanistic characteristics of extreme temperature and precipitation events. Our spatial focus will be on Europe, where dense, long-term station data are available, but we will also analyse global scale changes in extremes. The scale of temperature events is reasonably well captured in CMIP5 type models, but there is evidence for biases. There are also questions about projected changes in variance. For precipitation change, the scale gap will be addressed statistically and by examining behaviour across a range of resolutions. We will also consider circulation states involved in extreme events, determining the ability of models to resolve frequency and intensity in these circulation states. This allows going far beyond a simplistic statistical comparison and will allow to pinpoint the origin of model-data discrepancies. We will supplement our evaluations with a study using the millennium simulation of HadGEM2 to establish the range of "natural" variability in extreme events over Europe and test if analysing extremes separately for circulation states captures rare events well. In doing this we will also be aware of the issues that this and many other models have in simulating the impact of volcanoes on European circulation.

Introduction

Extreme events, particularly precipitation and temperature, have large impacts on human society (e.g., Zwiers et al., 2012, Field et al., 2012). Precipitation extremes affect society through flooding such as fall 2000 (Pall et al., 2011) or summer 2007 and temperature extremes such as summer 2003 or 2006 affect human health and agricultural production (see, e.g., Stott et al., 2004; Hawkins et al., 2012, Peterson et al., 2012 for a review and event attribution for events in 2010). Changes in extreme events are expected to be one major way in which the impacts of climate change affect human society this century.

Climate models are one tool used to understand how extreme events might impact in the future but models are uncertain tools. Without careful evaluation of the ability of a model to simulate the statistical properties of extreme events and the mechanisms which lead to those events little confidence can be given in their predictions or their use as tool to understand recent change in extreme events. For example are recent observed large-scale droughts, such as in North America, expected, given our current understanding of the climate system, or is something else going on? While this problem is important for all of climate science, it is particularly tricky for extreme events, which are rare by definition and hence need a sensible approach that combines study of mechanism with understanding of sampling uncertainty.

One significant issue is that the large-scale observational record of daily temperature and precipitation is restricted to the last 50-60 years over Europe, the USA, Australia and parts of East Asia, limiting the number of samples available particularly for very unusual events. Thus, evaluating model simulation of extreme events needs to focus at least in part on events that occur at least once a decade and preferably once a year. For that, our focus will be on once-a-year/season to once a decade events such as largest and smallest temperature in a year, greatest 1-day, 5-day and 10-day precipitation. We will generally, though not exclusively, focus on Europe and use data from the E-OBS6.0 dataset (updated from Haylock et al, 2008) which is a gridded dataset of temperature, precipitation and pressure at a nominal resolution of 25 x 25 km covering Europe from 1950 to 2011.

Understanding observed changes in short-term events that occur several times a year provides important scientific underpinning for attributing more rare extreme events (see, e.g. Zhang et al., 2012). Quantitatively comparing simulated and observed changes in well sampled 'moderate extremes' evaluates model ability to capture synoptic situations responsible for extremes (for example, blocking), as well as feedbacks that contribute to the severity and amplitude of extremes (for example, soil moisture changes), both of which also play key roles in more rare extremes. Analysing the frequency of synoptic situations leading to large-scale precipitation extremes on multi-day scales as well as to hot and cold extreme events also evaluates if the models resolve key contributors to events in their physics (structure, interconnectivity, teleconnections) as well as their statistics (frequency, intensity) and is a necessary tool to better understand mechanisms for extremes and problems that lead to errors in model simulations of such events (Hanlon et al, 2012), even based on observations only (Cattiaux et al., 2010).

Our planned analysis of decadal temperature extremes will also use a few multi-century daily temperature records from Europe (Central England, Stockholm, Uppsala, e.g.) that provide instrumental records for the 19th and 20th centuries, and long, high-resolution climate simulations like the CMIP5 millennium run with HadGEM2. Both provide the opportunity to look at the changing statistics and inter-decadal and secular variability in rare events, and put the most recent period into context.

Near-term predictions (Hanlon et al. 2012) base skill in changes in extremes largely on external forcing, not initial conditions. However, there are hints that the initial conditions may add to skill over decadal average seasonal anomalies, emphasizing the role of long-term variability in, for example, changes in heat waves (Hanlon et al., 2012b,c).

Key questions that will be addressed in our proposed work include:

- How reliable are models in simulating and predicting changes in the probability of extreme temperature and precipitation?
- What are the contributors, driving factors and predictable components of changes in the probability of extreme events?
- What circulation states and precursors contribute to extremes that have been observed across a range of climatic background states, and how do these compare to those leading to extreme events in climate models?
- Is the frequency and intensity of those circulation states properly represented in key climate models (HadGEM2/3 & HiGEM)?
- How important is sampling variability across decades and centuries (i.e., variability on multi-decadal scales) in changing probability of extremes, and how can it be addressed, and how important is external forcing (e.g., volcanism, greenhouse gases)?

Analysis of extreme events in model simulations and data

We propose to initially focus on moderately extreme events (once/year to once/decade). The first task is to evaluate current climate models to test if they are doing a reasonable job of simulating once-a-year and greater events over Europe. Rather than comparing two sets of rather noisy gridded datasets we will pool extreme events spatially. For temperature extremes with their large spatial coherence this pooling is unlikely to make much difference. For precipitation extremes which naturally have rather small spatial extents this is likely to improve the reliability of comparison between models and observations. We aim to break Europe into 5-6 relatively homogeneous regions including the British

Isles. We will concentrate our work on HadGEM2 but also include other simulations carried out for the CMIP5 project, and, as available, high resolution simulations performed in Reading.

Our expectation is that temperature extremes will be reasonably well simulated, although possibly not at the right amplitude for daily maxima (Morak et al., 2012; Hanlon et al., 2012b) and that precipitation extremes will be less well simulated. For precipitation we will explore if differences between simulation and observation are a consequence of inadequate resolution or more are unrealistic due to more fundamental reasons. We will also explore if errors are different in summer, when convection is more active, or in autumn/winter when frontal systems are more active. Working with others in NCAS we will extend this evaluation work to the recently available very high resolution global atmospheric simulations of HadGEM-2A. Simulations at 25 and 50 km resolution have been done with this model. Bringing this into our analysis will enable us to test if any model/observational differences can be explained by resolution changes and if some form of correction could be applied to the simulation of precipitation in the lower resolution IPCC models.

However, this approach has the danger of being over statistical. We will, in parallel, examine relationships between precipitation/temperature extremes and circulation. One approach we will take is to consider the average circulation pattern, or a small set of typical circulation patterns, associated with extreme events in each of our homogeneous regions (e.g., Cattiaux et al., 2010). We will do this for both model and observations and test if the circulation patterns and their strength are consistent with one another. This allows us to verify if the simulated extremes are occurring for the correct reasons. We will include in our analysis results from the high resolution HadGEM2-A simulations to see if this is performing better or worse than CMIP5 models allowing a systematic study into the impact of resolution on the simulation of extreme events. This will link to earlier work (e.g.,Kenyon and Hegerl, 2008; 2010) that has shown that circulation states, such as the NAO and, to a more limited extent over Europe, ENSO and interdecadal Pacific variability impact the frequency of events. The analysis of HadGEM and HiGem simulations will show if extreme events are associated with similar synoptic situations. This will lead to a small number of key synoptic situations associated with the most important precipitation and temperature events. Their frequency, intensity, pattern and the extreme temperature or precipitation events associated with them will be compared across model simulations and observations. If time permits, we will also analyse the Met Office or Reading decadal predictions to determine if these provide a more realistic synoptic background states than uninitialized simulations. However, as Hanlon et al. (2012b) show that the benefit from this for Europe is limited if using the DePreSys system (although it may be slightly larger using other prediction systems; Hanlon et al., 2012c), we will pursue this later in the project.

Results from the long HadGEM2-AO 'millennium' simulation will be analysed to determine the low-frequency variability in the frequency of those circulation states, and in the extremes associated with them. We will also analyse which extremes (for example, unusually warm or wet winters in Northern Europe, or dry conditions in the Mediterranean; as well as anomalously cold summers; Hegerl et al., 2011) occur more frequently following volcanic eruptions in the model. This may provide important predictive capacity for the near-term in the event of a major volcanic eruption (which tend to happen every few decades; Hyde and Crowley, 2000). One issue that we will take account of is that this model, like many other IPCC models, does not generate much of a NAO response to volcanoes (Driscoll et al, 2012).

Results from the "millennium" simulation will allow us to provide an estimate of "natural" climate variability in extreme events. It will also provide a very useful test for methods that infer the frequency of more rare events based on purely statistical approaches, such as, for example the General Extreme Value Distribution (Zwiers et al., 2012).

Finally, we will also determine if bias correction and similar methods of post processing can address model weakness (see, e.g. Hawkins et al., 2012; Hanlon et al., 2012b). For example if we conclude that correction of precipitation for resolution is appropriate and such corrections result in a good evaluation of the simulation, we would have more confidence in such results than if this is not the case.

Workplan

We have prepared a three year plan. Beyond that we see the research being increasingly driven by the PDRA in response to NCAS strategic plans in the area of extreme events and climate change.

Year 1: A study into the mechanisms and circulations responsible for extreme hot temperature events in HadGEM2, compared to observations. In essence are current state-of-the-art models simulating hot extremes for the right reasons? Is the frequency of key circulation states simulated realistically, and what is the long-term variability in it? Does the model simulate realistic extremes given that circulation state? If time permits, this will be cross-compared against key CMIP5 models that show either good decadal predictability (e.g., Matei et al., 2012) or promising simulations of extremes (building on Hanlon et al., 2012c).

Year 2: A statistical evaluation of HadGEM2 extreme precipitation against observations and a study into the impact of resolution on the simulation of extreme precipitation. We expect to consider both warm and cold season and break Europe up into about 5-6 regions one of which will the British Isles. We will consider monthly-mean, 5-day and daily precipitation in our analyses. An analyses of the HadGEM2-ES millennium simulation will also be done to study the range of natural variability in circulation states underlying extreme precipitation and temperature events, and to characterise the post-volcanic response.

Year 3: Finishing publication of the results from years 1 and 2. Evaluation of how extremes for particular circulation states change in intensity given external forcing. Evaluation of the return time of key events based on using the GEV distribution for the last 50 years and the long HadGEM simulation. Our focus here will particularly be on the circulation and atmospheric states associated with extreme precipitation in both the model and the observations.

Modelling and Key datasets

We will focus much of our attention on HadGEM2 simulations of 20th century and the SST/sea-ice/forced HadHGEM2 simulations. Evaluating the ability of UK models to simulate extreme events or other climate related phenomenon is key to the NCAS strategy. We will supplement these with analysis of very high resolution (50 & 25km) HadGEM2 simulations currently being performed by Pier-Luigi Vidale. We will supplement this data with other simulations from the CMIP5 database to examine robustness to model formulation. To study multi-decadal variability in extremes we will use data from the CMIP5 simulation of the last millennium with HadGEM2-AO currently being performed on MoNSOON. We are already working with daily variability from CMIP5 20th century and prediction systems and key model data sets on site.

Model evaluation and understanding requires observations. To this end we plan to use daily observations from gridded and long station data for temperature and precipitation; as well as the ERA reanalysis, and, for a longer-term perspective, the 20th century reanalysis, which appears to be very skilful (Compo et al, 2012). Our approach combines, in a unique way, statistical approaches with insights into mechanisms of extremes in order to better understand where limitations in some extremes originate from, and how they might be corrected in modelling, or by post-processing.

Roles & Responsibilities

The PDRA will conduct research into mechanisms involved in changes in extreme events in temperature and precipitation, and model capability in resolving events and key processes. The PDRA will also provide general scientific support to colleagues working in general area of Climate & Atmospheric Sciences in the School of Geosciences, University of Edinburgh. The School of Geosciences has agreed to provide "back stop" funding for the PDRA though with the expectation that Tett and Hegerl will find funding through external funding for the PDRA's work on extremes and long-term variability in circulation states and its effect on extremes. Funding agencies tend to be interested in this topic, so we are hopeful we can contribute to the PDRA's funding.

Why Edinburgh?

Edinburgh's general theme of confronting models with observations encompasses unique capability in **detection and attribution of climate change**, where strong collaboration with the Met Office exists. Edinburgh is part of the PAGODA consortium, identifying fingerprints for mechanisms of changing water cycle (Noake et al., 2011; Polson et al., 2012), and of the EQUIP consortium, evaluating near term predictions (Hanlon et al., 2012b). With funding from NCAS Tett and Hegerl have been investigating the processes responsible for climate response to strong tropical volcanic eruptions due to their impact on European climate. The results revealed that the pathway to a change in Northern Hemispheric circulation in response to such events is noisy and likely involves eddy driving of the Brewer-Dobson circulation leading to a cold polar Stratosphere (Bozzo and Tett, 2012). The present proposal would continue this work and extend it to extreme events, while benefiting from results from the volcanic response work. Edinburgh is also performing the CMIP5 simulation of the last millennium with HadGEM2-ES, contributing to work identifying causes of climate variability and change on longer time horizons.

Edinburgh PIs are strongly linked to international activities on extremes research. Hegerl has given invited talks on changes in extremes in many meetings (e.g., ECS COST conference on changing extremes, Cambridge, Dec 2010; CLIVAR Workshop 'Extremes in a changing climate', De Bilt, Netherlands, May 2008), and is a member of the CLIVAR expert team on climate change detection and indices (ETCDII), which has a strong focus on extremes. She is also a co-author on the recent BAMS special issue on attributing events (Peterson et al., 2012) and both Hegerl and Tett are involved in 'ACE Europe' planning. Hegerl has a proposal in review (ERC) where event attribution is a key component, and Tett is planning such a proposal.

Edinburgh Climate Science focuses on confronting climate models with observations. We do this for a variety of topics ranging from aiming to understand the reasons for past climate change, constrain the future response to human driven climate change and understand model biases and errors that are relevant to climate prediction. Within this broad area we have a specific focus on changing climate extremes. For example, a NERC grant on the last millennium will study extremes in long-term station data. Work led by Hegerl with funding from NERC and the US National Science Foundation has focused on the causes of changes in the frequency and intensity of climate extremes for both temperature and precipitation. Over the last 50 years there have been significant observed changes in the frequency of unusually warm days and nights in the cold and warm season, as well as in the frequency of multi-day warm and cold spells in winter (Morak et al., 2011, 2012). There is some indication that some models, e.g. HadGEM1, overestimate the change in the warm tail of the temperature distribution, and may underestimate the change in the cold tail, possibly because feedbacks during hot periods are too strong in the model (see also Hanlon et al., 2012b). The spatial patterns of change indicate that several factors may be causing these changes and that are worth further investigation include land use changes (Hegerl is collaborating with the Met Office's Nikos Christidis on this; Christidis et al., 2012), aerosols, and changes in circulation (e.g., Portmann et al., 2009).

Collaborations

This proposed work will be collaborative with NCAS at Reading University, particularly their emphasis on high resolution modelling. We aim to use recent simulations and compare the statistics of circulation states and extremes with CMIP5 simulations in order to determine if the frequency and intensity of extremes or the capability of simulating relevant circulation states have improved.

References

Bozzo, A.; **Tett**, S. F. B.; The Northern Annular Mode and large volcanic eruptions: the role of the early-winter conditions, in preparation.
Cattiaux et al. 2010 *Geophys. Res. Lett. 37*, L20704

Christidis, N., Stott, P.A., **Hegerl** G.C. and Betts R. (2012): The role of land use change in the recent warming of daily extreme temperatures. Submitted for publication.
Compo et al, 2011, "The Twentieth Century Reanalysis Project", Q. J. Roy. Met. Soc. 137: 1–28, January 2011 Part A DOI:10.1002/qj.776:
Driscoll, S., A. **Bozzo**, L. J. Gray, A. Robock, and G. Stenchikov (2012), Coupled Model Intercomparison Project 5 (CMIP5) simulations of climate following volcanic eruptions, J. Geophys. Res., doi:10.1029/2012JD017607, in press.
Hawkins et al., 2012, PNAS, in press.
H. Hanlon, D. S. Stone, M. R. Allen, K. Mogensen and P. A. Stott. "What were the main influences on temperature during the 200 European Heatwave?" submitted to Climate Dynamics.
Hanlon H., Morak S., **Hegerl G.C**. (2012b): Detection and Prediction of mean and extreme European Summer temperatures with a CMIP5 multi-model ensemble. Submitted to JGR.
Hanlon H., **Hegerl, G.C., Tett**, S.F.B., (2012c): Can a decadal forecasting system predict temperature extreme indices? Submitted to J Climate.
Haylock, M. R., Hofstra, N., Tank, A. M. G. K., Klok, E. J., Jones, P. D., and New, M. (2008). A european daily high-resolution gridded dataset of surface temperature and precipitation. Journal of Geophysical Research, 113(D20119).
Hegerl, G. C, J. Luterbacher, F. Gonzalez-Ruoco, S.F.B. Tett and E. Xoplaki (2011): Influence of human and natural forcing on European seasonal temperatures. *Nature GeoScience*, 4, 99-103
Hegerl, G., H. Hanlon, and C Beierkuhnlein, 2011: Elusive Extremes. Perspective in Nature GeoScience, 4, 142-143.
Hyde and Crowley, 2000: Probability of future climatically significant volcanic eruptions. J Climate 13,9: 1445-1450
Kenyon, J and G. C. **Hegerl** (2008): Influence of modes of variability on global temperature extremes. J. Climate 21, 3872-3889
Kenyon, J and G. C. **Hegerl** (2010): Influence of models of climate variability on global precipitation extremes. *J. Climate* 23, 6248-6262.
Morak, S., **Hegerl** G. Kenyon J (2011): Detectable Regional Changes in the Number of Warm Nights. *Geophys. Res. Let.*, 38, L17703.
Morak, S., **Hegerl**, N. Christidis (2012): Detectable Changes in Temperature Extremes. J. Climate, in press.
Noake, K., D. Polson, G. C. **Hegerl** and X. Zhang (2011): Changes in seasonal land precipitation during the twentieth century. *Geophys. Res. Let.* 39, L03706
Pall P et al 2011: Nature, 470, 382.
Peterson, TC, PA Stott, S Herring, Eds., 2012: Explaining Extreme Events of 2011 from a Climate Perspective. *Bull. Amer. Meteorol. Soc.*, July 2012, 1041-1067
Polson, D., G. **Hegerl**, X. Zhang (2012): Causes of robust seasonal land precipitation changes. Submitted to J Climate.
Portmann R. W., S. Solomon and G.C. **Hegerl** (2009): Linkages between climate change, extreme temperature and precipitation across the United States. *PNAS*, 106, 7324-7329
Schurer, A., **Hegerl**, G.C., Mann, M., **Tett**, S.F.B., Phipps, S (2012): Separating forced from chaotic variability over the last millennium. Submitted to Nature Climate Change.
Field C. et al, eds: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)
Stott PD et al. 2004 Nature 432: 610-614.
Zhang, X, L. Alexander, G.C. **Hegerl**, P.D. Jones, A. Klein-Tank, T.C. Peterson, B. Trewin and F. Zwiers (2011) Indices for Monitoring Changes in Extremes based on Daily Temperature and Precipitation Data. *WIREs Clim Change* 2011. doi: 10.1002/wcc.147
Zwiers, FW, GC **Hegerl**, S-K Min, X Zhang, 2012: Historical Context. In Peterson, TC, PA Stott, S Herring, Eds., 2012: Explaining Extreme Events of 2011 from a Climate Perspective. *Bull. Amer. Meteorol. Soc.*, July 2012, 1041-1067
Zwiers, FW, LV Alexander, GC **Hegerl**, J Kossin, TR Knutson, P Naveau, N Nicholls, C Schar, SI Seneviratne, X Zhang, 2012: Challenges in Estimating and Understanding Recent Changes in the Frequency and Intensity of Extreme Climate and Weather Events. Accepted for inclusion in an edited compilation of *community papers* commissioned for the WCRP Open Science Conference, 24-28 October 2011, Denver, CO, USA