The variability of extreme precipitation and its synoptic scale drivers

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Summary

In the original version of this thesis, we analysed intra-annual to multi-decadal variability of observed extreme precipitation and their synoptic-scale drivers from a statistical downscaling perspective (Maraun et al., 2010a):
(1) seasonality in extreme precipitation is in general different from that of mean precipitation and needs to be modelled separately. For the UK, it is strongest along the west coast (where it peaks during the winter storm season) and in the east (where it peaks during the summer thunderstorm season). To capture very rare events, extreme value theory is required (Maraun et al., 2009; Rust et al., 2009).
(2) Extreme precipitation in the UK exhibits strong interannual to decadal variability (Maraun et al., 2008). A large fraction of this variability at regional scale can be explained by the variability in the occurrence of synoptic weather types (Maraun et al., 2010b). In particular recent trends in winter extreme precipitation can be well explained by an unusually persistent positive phase of the North Atlantic Oscillation (Maraun et al., 2011)
(3) Extreme winter time precipitation over the Mediterranean is linked to anomalously strong moisture advection and a strong southward displacement of the polar jet stream (Toreti et al., 2011).
The additional articles published in this context since 2012 comprise two major research strands: the evaluation, critique and development of regional climate modelling approaches, and the application of downscaling in the context of climate change studies.

Evaluation and development of regional climate modelling approaches
(1) Based on the developed statistical model, we developed an approach for a process-based evaluation of dynamical regional climate models (RCMs), and applied this approach to 14 RCMs of the European ENSEMBLES project. We calibrate the model linking synoptic weather types and extreme precipitation both to observed and RCM data and compare the results (Maraun et al., 2012). We find that the RCMs well represent the influence of the main westerly flow on extreme precipitation, but fail to represent the influence of the flow direction, i.e., the influence of more rare situations of northerly or easterly flow.
(2) We developed a statistical model of the annual cycle of extreme precipitation based on a modern Poisson point process formulation of extreme events. We employed this model to evaluate the performance of the same RCM ensemble. We find that the RCMs capture the timing of seasonality in extreme precipitation, but have considerable difficulties in simulating the amplitude of seasonality (Schindler et al., 2012a).
(3) We use both statistical models to assess the performance of the E-OBS observational data set, which is widely used for RCM evaluation. In comparison with a high-resolution high-quality reference data set provided by the UK MetOffice, E-OBS shows considerable biases in the flow direction dependence (Maraun et al., 2012) as well as biases in the amplitude of extreme precipitation seasonality (Schindler et al., 2012a).
(4) We applied pair copula constructions, a new statistical approach to flexibly model multivariate-dependence, to, for the first time, evaluate spatial aspects of mean and extreme precipitation in an RCM ensemble (Hobaeck-Haff et al., 2015). We estimate spatial dependence of mean and extreme precipitation over southern Norway both in observations and RCM data, and compare the results. The overall dependence is well represented, but substantial biases are evident. In particular, small-scale orographic features are not well captured.
(5) We investigate the dependence of the representation of extreme precipitation on climate model resolution (Volosciuk et al., 2015). To this end we analyse extreme precipitation, simulated by the ECHAM5 global climate model at different horizontal and vertical resolutions ranging from a rather low T42 resolution, which is often used in studies employing big model ensembles, to a T213 resolution, which can be considered state-of-the-art in future climate simulations. Where possible, we evaluated the model performance relative to daily observational data sets. Resolution affects the simulation of precipitation in two distinct ways: by the effect of averaging across the chosen grid-box size; and by the representation of the underlying physical processes at the chosen resolution. We separate these effects by comparing averaged high-resolution simulations with lower resolution simulations. We find that a strong drop in performance between T106 and T63 resolutions. Vertical resolution strongly affects the position of the inter-tropical convergence zone (ITZC).
(6) A very popular approach to post-process regional climate model simulations, in particular to improve the representation of extreme precipitation compared to observations, is quantile mapping. This approach estimates a deterministic transformation between simulated and observed precipitation, and applies this transformation to post-process simulated precipitation. We investigated the influence of quantile mapping on spatial aspects of extreme precipitation (Maraun, 2013a). It turned out that the approach, when used to bias correct and downscale

simulated precipitation to local rain gauge precipitation, systematically overestimates the spatial extent of both heavy rainfall events and dry events. The reason lies in a methodological flaw: local grid-scale precipitation is not fully determined by grid-box average precipitation, but exhibits additional random variability. Quantile mapping, however, does not add randomness, but rather inflates simulated precipitation simultaneously at all locations within a grid box. An application of quantile mapping to distributed impact models (requiring input at several nearby locations) might result in substantially wrong impact assessments.
(7) Inspired by the problems of quantile mapping, we developed a novel concept of stochastic bias correction (Wong et al., 2014): instead of a deterministic approach, we explicitly include randomness: the mismatch between simulated and observed precipitation is separated into a systematic bias and a random component, which needs to be added stochastically. Our approach does not simulate deterministic corrected values, but rather a time-varying probability distribution. This distribution is a mixture model of a gamma distribution, describing the bulk of the precipitation distribution, and a generalised Pareto distribution, describing extreme events. From the distribution, random series can be simulated to drive impact models. As such, the approach opens up a new research avenue for bias correction weather generators.

Climate change studies of precipitation extremes

Finally, we studied the influence of climate change on precipitation extremes. We both applied a classical approach based on ensemble climate change simulations, as well as a novel storyline and conditional event attribution approach. The questions we addressed were: how is extreme precipitation projected to change in the future, and what are the associated uncertainties? How did climate change affect individual events? What is the added value of very high resolution simulations in simulating changes in extreme precipitation?
(1) We used the statistical model of the seasonal cycle to – for the first time – infer potential future changes in the seasonality of extreme precipitation over the UK, based on an ensemble of RCM simulations forced by medium strong scenario of future greenhouse gas emissions (Schindler et al., 2012b). We find a robust signal in the timing of the annual cycle: peak times tend to shift to early autumn, either from the winter season (in the northwest) or the summer season (in the east). For the amplitude of seasonality we find no robust signal. Uncertainties are mostly resulting from the driving global climate models.
(2) We analysed the role of irreducible internal variability for projecting mean and extreme precipitation over Europe (Maraun, 2013b). To this end we defined a time of emergence as the time, when the climate change signal is so strong that it emerges from changes due to internal variability. We found that over Northern Europe, a signal of heavier precipitation, as well as a signal towards less heavy precipitation over Southern Europe, will emerge already over the coming decades. In the transition region between these opposing trends, however, internal climate variability completely dominates changes in extreme precipitation.
(3) In July 2012, an unprecedented extreme precipitation event happened in the Black Sea town of Krymsk, ultimately leading to the death of more than 170 people. We investigated the influence of Black Sea warming – 2°C over the last 30 years – on the magnitude of the event. To this end, we applied a conditional event attribution and storyline approach: we simulated the event with an RCM at 600m horizontal resolution under present conditions as they happened in reality during the event, and additionally under a series of counter-factual conditions representing cooler and warmer Black Sea temperatures (Meredith et al., 2015a). We found that the event, if it had happened over a Black Sea with 1980s temperatures, would still have been extreme, but far less so. Further warming, however, would not increase the magnitude of the observed event much further. The storyline approach helped us to study the underlying mechanisms in detail: the sea surface warming helped to destabilise the atmosphere and triggered deep convection. Further warming, however, would lead to the development of cold pools by convective downdrafts which would ultimately limit the further intensification. Our study was the first to demonstrate the effect of climate warming on a small-scale extreme event.
(4) We compared the simulations of the Krymsk event for observed and counter-factual conditions at the 600m resolution with simulations at a standard 15km resolution (Meredith et al., 2015b). The standard simulation was not able to correctly reproduce the observed extreme event. Even more, the response to the range of sea surface temperatures was not realistically represented by the standard simulation: the magnitude of vertical velocities, extreme precipitation rates, and the cold pool development were not realistically captured. We found similar problems for a wide range of different parameterisation schemes as typically used in RCM simulations. These findings indicate that standard RCM simulations as currently used for impact studies might heavily misrepresent changes in summertime extreme precipitation.

References

Hobaeck-Haff, I., A. Frigessi and **D. Maraun** (2015): *How well do regional climate model simulate the spatial dependence of precipitation? An application of pair-copula constructions.* J. Geophys. Res., 120 (7): 2624-2646.

Meredith, E.P., V. Semenov, **D. Maraun**, W. Park and A. Chernokulsky (2015a): Crucial r*ole of sea surface warming in amplifying the 2012 Krymsk precipitation extreme.* Nature Geoscience, 8: 615-619

Meredith, E.P., **D. Maraun**, V.A. Semenov and W. Park (2015b): *Evidence for added value of convection-permitting models for studying changes in extreme precipitation*. J. Geophys. Res. 120, 12,500-12,513.

Maraun, D., T.J. Osborn and N.P. Gillett (2008): *United Kingdom Daily Precipitation Intensity: Improved Early Data, Error Estimates and an Update from 2000 to 2006*, Int. J. Climatol. 28, 833-842.

Maraun, D.*, H.W. Rust and T.J. Osborn (2009): The annual cycle of heavy precipitation across the UK: a model based on extreme value statistics, Int. J. Climatol. 29: 1731-1744.*

Maraun, D., F. Wetterhall, A.M. Ireson, R.E. Chandler, E.J. Kendon, M. Widmann, S. Brienen, H.W. Rust, T. Sauter, M. Themessl, V.K.C. Venema, K.P. Chun, C.M. Goodess, R.G. Jones, C. Onof, M. Vrac and I. Thiele-Eich (2010a): *Precipitation Downscaling under climate change. Recent developments to bridge the gap between dynamical models and the end user*, Rev. Geophys. 48, RG3003.

Maraun, D., H.W. Rust and T.J. Osborn (2010b): *Synoptic airflow and UK daily precipitation extremes. Development and validation of a vector generalised linear model*, Extremes 13(2): 133.

Maraun, D., T.J. Osborn and H.W. Rust (2011): *The influence of synoptic airflow on UK daily precipitation extremes. Part I: observed spatio-temporal relationships*, Clim. Dyn. 36 (1-2), 261-275.

Maraun, D., T.J. Osborn and H.W. Rust (2012): *The influence of synoptic airflow on UK daily precipitation extremes. Part II: regional climate model and E-OBS data validation*, Clim. Dyn. 39, 287-301.

Maraun, D. (2013a): *Bias Correction, Quantile Mapping and Downscaling. Revisiting the Inflation Issue*, J. Climate 26(6), 2137-2143.

Maraun, D. *(2013b): When will trends in European mean and heavy daily precipitation emerge? Env. Sci. Lett. 8, 014004.*

Rust, H.W., **D. Maraun** and T.J. Osborn (2009): *Modelling Seasonality in Extreme Precipitation*, Europ. Phys. J. Special Topics 174:99-111.

Schindler, A., **D. Maraun** and J. Luterbacher (2012a): *Validation of the present day annual cycle in high precipitation events over the British Islands simulated by 14 RCMs*, J. Geophys. Res. 117, D18107.

Schindler, A. **D. Maraun**, A. Toreti and J. Luterbacher (2012b): *Changes in the annual cycle of heavy precipitation across the British Isles within the 21st century*, Env. Sci. Lett. 7, 044029.

Toreti, A., F.G. Kuglisch, E. Xoplaki, **D. Maraun**, H. Wanner and J. Luterbacher (2010): *Characterization of extreme winter precipitation in the Mediterranean and associated anomalous atmospheric patterns*, Nat. Haz. Earth Syst. Sci. 10, 1037-1050.

Volosciuk, C., **D. Maraun**, V. Semenov and W. Park (2015): *The influence of spatial resolution on the representation of extreme precipitation in a climate model.* J. Climate 28, 1184-1205.

Wong, G., **D. Maraun**, M. Vrac, M. Widmann, J. Eden and T. Kent (2014): *A Stochastic Model Output Statistics Approach for Downscaling and Correcting Daily Precipitation Including Extremes*, J. Climate 27, 6940-6959.