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Combining large model ensembles with extreme value statistics to improve attribution statements of rare events

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ABSTRACT

Gaining a better understanding of rare weather events is a major research challenge and of crucial relevance for societal preparedness in the face of a changing climate. The main focus of previous studies has been to apply a range of relatively distinct methodologies to constrain changes in the odds of those events, including both parametric statistics (extreme value theory, EVT) and empirical approaches based on large numbers of dynamical model simulations.

In this study, the applicability of EVT in the context of probabilistic event attribution is explored and potential combinations of both methodological frameworks are investigated. In particular, this study compares empirical return time estimates derived from a large model ensemble with parametric inferences from the same data set in order to assess whether statements made about events in the tails are similar. Our analysis is illustrated using a case study of cold extremes and heavy rainfall in winter 2013/14 in Europe (focussing on two regions: North-West Russia and the Iberian Peninsula) for a present-day (including 'anthropogenic' influences) and an alternative 'non-industrial' climate scenario.

We show that parametric inferences made about rare 'extremes' can differ considerably from estimates based on large ensembles. This highlights the importance of an appropriate choice of block and sample sizes for parametric inferences of the tails of climatological variables. For example, inferences based on annual extremes of daily variables are often insufficient to characterize rare events due to small sample sizes (i.e. with return periods >100 years). Hence, we illustrate how a combination of large numerical simulations with EVT might enable a more objective assessment of EVT parameters, such as block and sample size, for any given variable, region and return period of interest.

By combining both methodologies, our case study reveals that a distinct warming of cold extremes in winter has occurred throughout Europe in the 'anthropogenic' relative to the non-industrial climates for given sea surface temperatures in winter 2013/14. Moreover, heavy rainfall events have become significantly more frequent and more pronounced in North and North-East Europe, while other regions demonstrate no discernible changes.

In conclusion, our study shows that EVT and empirical estimates based on numerical simulations can indeed be used to productively inform each other, for instance to derive appropriate EVT parameters for short observational time series. Further, the combination of ensemble simulations with EVT allows us to significantly reduce the number of simulations needed for statements about the tails.

1. Introduction

It is a major scientific challenge to better understand extreme meteorological events and potential changes in the odds of their occurrence in a warming climate (Seneviratne et al., 2012; Zhang et al., 2014). This is due to a number of reasons, including limitations of the observational record to capture rare extreme events, and issues of data availability and quality. Moreover, structural and parametric model uncertainties, as well as the proverbial chaotic

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nature of weather (Lorenz, 1963) hinder any straightforward attribution of causality between climatic drivers and any particular extreme weather event.

To overcome these difficulties, many scientific studies use either one of the following approaches:

First, *extreme value theory* (EVT) has been developed to provide a means to model the tails of statistical distributions based on mathematical theory (Coles et al., 2001). Such an analysis allows statistical statements to be made based on parametric extreme value distributions (see Wigley, 2009, for illustrative examples). For example, scientific assessments have been made to investigate trends in temperature and precipitation extremes in the 21st century in atmosphere–ocean coupled models (Kharin and Zwiers, 2000; Kharin et al., 2007, 2013), allowing the estimation of return levels and their associated statistical uncertainties. Further illustrative applications of the (univariate) EVT framework elucidate causes for geophysical extremes, such as the connection between atmospheric modes of variability and cold extremes (Sillmann et al., 2011). However although EVT is increasingly used in climatological studies to constrain the odds of rare events (Katz, 2010), including extensions to account for non-stationarity, multivariate and spatial extremes (see Ghil et al., 2011, for a review), Katz et al. (2013) argues that its full potential has not yet been tapped for many geophysical applications.

Second, an alternative approach to improve the understanding of extremes and their changing odds in a non-stationary climate has been to deploy very large ensembles of dynamical models, namely *probabilistic event attribution* (PEA, Stone and Allen, 2005; Allen, 2003). This methodology is used extensively to sample rare events and subsequently estimate their probabilities under different climate forcing scenarios (Stott et al., 2004; Otto et al., 2012; Massey et al., 2014). The latter often serves to estimate the anthropogenic contribution (fraction of attributable risk) to changes in the meteorological risk of present-day weather and climate extremes (Allen, 2003; Stott et al., 2013; Bindoff et al., 2013; Christidis et al., 2013). Importantly, an assessment of this type addresses the odds of specific extreme weather events – often those that had happened in a particular year such as droughts, heat waves or cold spells (Herring et al., 2014). Notable extensions to the PEA methodology include the attempt to account for more impact-related variables, for instance through a coupling with hydrological models to assess floods (Pall et al., 2011). Nonetheless, PEA assessments are typically based on rather data-intensive empirical estimates of return times, and rely to a large extent on dynamical model simulations.

Our study addresses the following research questions:

1. Is the statistical framework of EVT applicable in the context of a probabilistic assessment of extreme events? Accordingly, can both methodological frameworks be productively combined to inform each other?
2. Using a *combined* methodology, how have meteorological extremes at daily time scales in the European winter of 2013/14 changed relative to a pre-industrial climate?

Based on our first research question, we envision an application in which both methodological frameworks could inform each other in order to (a) derive insights about appropriate parameter choices (i.e. required sample and block sizes) for the application of statistical models based on EVT for the meteorological characteristics of any variable or region of interest; and (b) given informed parameter choices, how many numerical simulations are actually needed to estimate a given ‘target return period’ to a satisfactory degree of accuracy?

Hence, our study details a joint assessment of both methodologies and evaluates whether statements made about the tails of meteorological variables such as temperature and precipitation are comparable. This methodological comparison might serve as a starting point to reconcile the two statistical frameworks for climatological applications, i.e. to inform each other about relevant parameter choices (EVT) or the number of samples needed to estimate a specific return level. To illustrate this comparison and to address the second research question, a large ensemble of atmosphere-only regional climate simulations for the European 2013/14 winter season is investigated as a case study along with a ‘non-industrial’ climate scenario of winter 2013/14 (i.e. with anthropogenic forcings removed Schaller et al., 2014, see Section 2).

The particular season of interest, winter 2013/14 in Europe, provides an interesting case study, because it came along with exceptionally mild temperatures, severe storm depressions, both winter dryness and heavy precipitation on regional to sub-continental scales. Significant but diverse societal impacts were associated with those events, for instance exceptionally early vegetation greening and a reduction of fossil fuel consumption for heating due to the absence of severe frosts in some regions.[1] Seasonal temperatures ranked among the highest ever recorded in a range of countries according to national weather services (e.g. Austria, Denmark, France, Germany, the Netherlands, Norway, Poland, Slovakia, Switzerland, and the UK, e.g. Fig. 1, Deutscher Wetterdienst, 2014). When it comes to seasonal rainfall anomalies, a remarkable east–west divide persisted over most of the winter, where central and south-eastern parts of the continent received exceptionally low rainfall, whereas its most western stretches, such as Ireland and the UK, experienced a record wet season (Huntingford et al., 2014, Fig. 1). These remarkable patterns resulted from a synoptic situation with many storm depressions that moved along the English Channel, over the British Isles and into the North Sea, hence advecting warm air into Central and East European regions, and causing rainfall and severe winds in Britain and along the Atlantic coast. This synoptic situation is also reflected by seasonal geopotential height anomalies (Fig. 1), which were strongly negative over the North Atlantic and the British Isles, whereas positive anomalies prevailed over Eastern Europe (see Huntingford et al., 2014 for a more detailed discussion).

This study's analysis focuses on cold temperature and heavy rainfall extremes, which allows us to state how the odds of occurrence of extremes in these two variables have changed between a ‘non-industrial’ climate and the contemporary winter climate in 2013/14. These two variables provide a good case study, because we expect temperature to be relatively spatially coherent, and precipitation to be somewhat noisier both in space and time. We illustrate our methodological approach as well as the attribution analysis for two spatially averaged regions, North-West Russia and the Iberian Peninsula, as well as for the entire European model domain.

In Section 2, we describe the experimental setup, evaluate and bias-adjust the regional climate model and outline the statistical methodology to estimate return times. In Section 3, we first outline the results of the methodological comparison (EVT vs. empirical return time estimates), and discuss related issues such as parameter choices for a potential combination of both methodologies. Second, the illustrative attribution case study of winter minimum temperatures and precipitation is presented. Lastly, we draw some conclusions about the applicability of EVT based return time estimates in the context of probabilistic event attribution (Section 4).

[1] http://www.pecad.fas.usda.gov/highlights/2014/03/EU_12march2014/