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Understanding, modeling and predicting weather and climate extremes: Challenges and opportunities

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ABSTRACT

Weather and climate extremes are identified as major areas necessitating further progress in climate research and have thus been selected as one of the World Climate Research Programme (WCRP) Grand Challenges. Here, we provide an overview of current challenges and opportunities for scientific progress and cross-community collaboration on the topic of understanding, modeling and predicting extreme events based on an expert workshop organized as part of the implementation of the WCRP Grand Challenge on Weather and Climate Extremes. In general, the development of an extreme event depends on a favorable initial state, the presence of large-scale drivers, and positive local feedbacks, as well as stochastic processes. We, therefore, elaborate on the scientific challenges related to large-scale drivers and local-to-regional feedback processes leading to extreme events. A better understanding of the drivers and processes will improve the prediction of extremes and will support process-based evaluation of the representation of weather and climate extremes in climate model simulations. Further, we discuss how to address these challenges by focusing on short-duration (less than three days) and long-duration (weeks to months) extreme events, their underlying mechanisms and approaches for their evaluation and prediction.

1. Introduction

The recent Fifth Assessment Report of the Intergovernmental Panel on Climate Change affirmed that our climate and its extremes are changing (IPCC 2013). Reliable predictions of extremes are needed on short and long time scales to reduce potential risks and damages that result from weather and climate extremes (IPCC, 2012; Seneviratne et al., 2012). Understanding, modeling and predicting weather and climate extremes is identified as a major area necessitating further progress in climate research and has thus been selected as one of the World Climate Research Programme (WCRP) Grand Challenges, which is hereafter referred to as the Extremes Grand Challenge. The WCRP Extremes Grand Challenge (Zhang et al., 2014; Alexander et al., 2016) is organized around four overarching research themes: Document (focusing on observational requirements), Understand (focusing on the relative roles of different spatial scales and their interactions), Simulate (focusing on model reliability and improvement), and Attribute (focusing on unraveling the contributors to extreme events). Underlying all research themes is a focus on four core types of extreme events: Heavy Precipitation, Heatwaves, Droughts, and Storms.

As part of the implementation of the WCRP Extremes Grand Challenge, and in particular contributing to the Understand and Simulate themes, a workshop on "Understanding, modeling and predicting weather and climate extremes" was held (see http://www.wcrp-climate.org/extremes-modeling-wkshp-about). It brought together international experts and early career scientists from the weather, climate and statistical sciences to discuss the main theoretical and modeling challenges and opportunities around extreme events. The workshop focused on various processes underlying weather and climate extremes, and how an improved understanding of these processes may lead to advances in their

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simulation and prediction. More details of the workshop format, talks and participants are given in Appendix A.

The purpose of this paper is to provide an overview for a wider audience of climatologists and statisticians on the current state of knowledge, the prevailing challenges and the potential ways forward based on the expert discussions form the workshop supplemented with current literature. We conclude with a summary of the key points, as well as ideas for future research and opportunities for cross-disciplinary collaborations.

2. Scientific challenges

To better serve local and national climate adaptation planning and decision-making, there is a clear need for improved understanding and prediction of extreme weather events. This is a cross-community challenge that requires collaboration between global programs such as the WCRP and the World Weather Research Programme (WWRP). One example is WWRP's HiWeather project (www.wmo.int/pages/prog/arep/wwrp/new/high_impact_weather_project.html) that aims to build resilience to high-impact weather events by improving their forecasts and predictability across temporal and spatial scales. Other good examples of collaborative research programs funded by the European Commission are projects such as EUPORIAS (European Provision Of Regional Impacts Assessments on Seasonal and Decadal Timescales), SPECS (Seasonal-to-decadal climate Prediction for the improvement of European Climate Services) and EUCLEIA (European Climate and Weather Events: Interpretation and Attribution). Building on the insights gained from these (and many other) projects, we address current challenges and opportunities for scientific progress in various aspects of understanding and predicting weather and climate extremes.

As illustrated in the conceptual Fig. 1, the development of an extreme event depends on some or all of the following: a favorable initial state, the presence of large-scale drivers, and positive local feedbacks, as well as stochastic processes (noise). We therefore structured the scientific challenges into large-scale drivers of extreme events (section 2.1) and local-to-regional feedback processes of extreme events (section 2.2) that we need to be better understand to improve the prediction of extremes (section 2.3) and to assess model performance by process-based evaluation of climate extremes (section 2.4).

2.1. Large-scale drivers of extreme events

Our understanding of the mechanisms that lead to the occurrence of

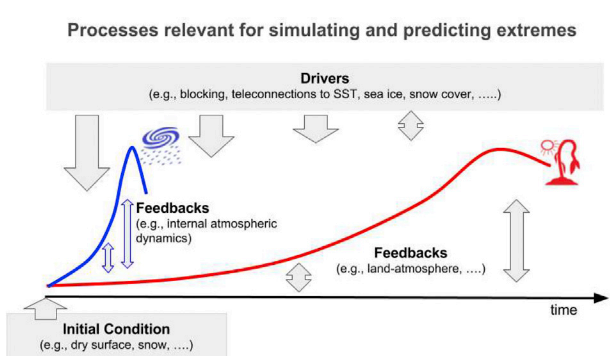

Fig. 1. The development of an extreme event depends on a favorable initial state, the presence of large-scale drivers, and positive feedbacks, as well as stochastic processes (noise). The relative importance of these factors varies for different types of extremes. For example, feedbacks for short lived events (blue) like convective storms are typically associated with unstable atmospheric dynamics, whereas longer duration events (red) like heatwaves or droughts typically involve soil moisture - atmosphere interaction. External factors like global warming can influence extremes through these various factors. For example, the increased water vapor in a warmer atmosphere can enhance convective feedbacks, or increased surface evaporation might amplify heat waves and droughts. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

extreme events will be the basis to assess their predictability and enable their prediction using model simulations. It is convenient and attractive to try to separate dynamic (i.e., circulation induced changes) and thermodynamic (i.e., temperature induced changes) processes when diagnosing mechanisms. However, the separation is artificial as forced dynamical changes are ultimately caused by thermodynamic processes. For instance, changes in temperature have a direct impact on the hydrological cycle (i.e., Clausius-Clapeyron relationship, Held and Soden (2006)) but can also have an indirect impact in extreme precipitation through changing circulation patterns (e.g., displacement of circulation systems). Despite this obvious deficiency, the separation between dynamical and thermodynamic changes is used particularly in event attribution studies to better understand the underlying processes contributing to a specific extreme event (Mitchell et al., 2016, Vautard et al., 2016, Yiou et al., 2017) or in a recent study by Pfahl et al. (2017) to better understand regional changes in extreme precipitation. Two examples from the event attribution where such a separation proved useful were the extreme precipitation event in the UK in winter 2014/15 (Schaller et al., 2016) and the European heatwave in summer 2003 (Mitchell et al., 2016). In these studies, it was illustrated that both dynamical and thermodynamic processes (e.g., changes in atmospheric patterns and soil moisture) can be respectively relevant for generating an extreme event. It is important to mechanistically assess the physical characteristics of the extreme event in terms of what processes are mainly driving the event occurrence and whether they are affected by anthropogenic forcing (e.g., Hauser et al. (2016)).

In Europe, for instance, extreme temperatures can occur during atmospheric blocking conditions, whereas the processes driving the temperature extremes differ for summer (local processes) and winter (advection of cold air) (Pfahl and Wernli, 2012). In addition, processes can even differ within a season, such as described in (Brunner et al., 2017) for spring, but even this may change with global warming (Cassou and Cattiaux, 2016). There seems to be a distinct regional dependency of the relationship between blocking anticyclone locations and the corresponding surface heat or cold extreme event as illustrated in Fig. 2 (Bieli et al., 2015).

Furthermore, the weakening of the equator-to-pole temperature gradient due to global warming, particularly in boreal summer, is associated with a decrease in eddy kinetic energy (EKE), a measure of transient wave activity (Lehmann and Coumou, 2015). This may lead to more persistent summer weather and enhanced anti-cyclonic flow regimes in some regions. The European summers of 2003 and 2010 are good examples in which high-amplitude quasi-stationary waves were associated with extreme heat waves (Coumou et al., 2015). Climate models need to be evaluated based on their performance simulating such kinds of underlying large-scale processes to be able for us to have confidence in their representation of related surface extremes.

This said, climate models can have large biases in some regions and may not be able to simulate key dynamical patterns such as atmospheric blocking or other weather regimes, jet stream position and intensity, tropical dynamics and teleconnections, or stratosphere-troposphere connections. A key challenge is to evaluate and improve models by targeting key processes that are relevant for a realistic, or at least a sufficient, representation of extremes. Approaches to improve them include developing theories and hierarchies of models to untangle complex processes, further increasing model resolution and using novel approaches for parameterizing sub-grid scale processes.

A combination of high-resolution simulations with lower resolution ensemble simulations would be beneficial to study effects of internal variability and better quantify the signal-to-noise ratio, particularly for precipitation extremes (Palmer, 2014). Such efforts require an international collaboration to pool resources for coordinated high-resolution modelling on a global scale (such as in PRIMAVERA, https://www.primavera-h2020.eu/ or HighResMIP (Haarsma et al., 2016)). Detecting, and even predicting the changes in large-scale circulation is a major challenge to be overcome in order to better predict changes in the odds of