AN INTERDISCIPLINARY APPROACH TO THE STUDY OF EXTREME WEATHER EVENTS

Large-Scale Atmospheric Controls and Insights from Dynamical Systems Theory and Statistical Mechanics

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Weather extremes affecting large regions—including heat waves, cold spells, and intense storms—can cause large socioeconomic losses and garner scientific interest (e.g., Guirguis et al. 2011) and widespread media coverage (e.g., Ludwig et al. 2015). Advancing our mechanistic understanding of their drivers and our ability to predict them, in both a forecasting and a risk assessment context, is a compelling scientific goal.

A common approach to this problem is to identify recurring, large-scale atmospheric patterns for each extreme event class. This has proved fruitful for a wide range of events, from temperature extremes over North America (Harnik et al. 2016; Lee and Grotjahn 2016) to windstorms over Europe (Messori and Caballero 2015; Priestley et al. 2017). Such an analysis hinges on applying suitable metrics and approaches to identify and study the atmospheric patterns of interest. So far, these have primarily been drawn from the conventional toolbox of the atmospheric sciences: composites, empirical orthogonal functions, clustering algorithms, recurring Lagrangian trajectories, and many others (e.g., Grotjahn et al. 2016). Cross-pollination with recently developed techniques from different disciplines has been relatively limited.

The workshop on "Large-Scale Atmospheric Controls of Extreme Weather Events and Novel Predictability Pathways" gathered speakers with a wide range of backgrounds to foster such cross-disciplinary interactions. A specific focus was on identifying novel analysis techniques to describe large-scale atmospheric flows and their links to extreme weather events.

The workshop's outcomes are summarized around three themes: extratropical cyclones, temperature extremes in the mid- and high latitudes, and

LARGE-SCALE ATMOSPHERIC CONTROLS OF EXTREME WEATHER EVENTS AND NOVEL PREDICTABILITY PATHWAYS

What: Scientists and industry experts from six countries gathered to focus on the mechanistic understanding and prediction of societally relevant extreme weather events in the mid- and high latitudes. These included warm and cold temperature extremes, extratropical cyclones, and precipitation extremes. The aim was to bring together speakers from a diverse range of backgrounds spanning the atmospheric sciences, the private sector, applied mathematics, and statistical mechanics to present their latest findings and trace an avenue for the future development of this very active research field.

When: 5–6 October 2017

Where: Stockholm University, Stockholm, Sweden novel statistical mechanics and dynamical systems approaches. We conclude by reporting some future perspectives and challenges issued from a roundtable discussion that closed the workshop. Video recordings of most presentations are freely available from the YouTube channel of the Department of Meteorology of Stockholm University.

EXTRATROPICAL CYCLONES. Tim Woollings analyzed the eddy-driven jet stream's variability on daily to decadal time scales. He showed a complex interplay between these time scales, with decadal variations in jet speed modulating the shorter-term variability in the jet's latitudinal location. This implies that some decades are more variable than others and therefore more likely to exhibit persistent seasonal extremes, affecting in turn the North Atlantic storm track.

On subseasonal time scales, extratropical cyclones in the exit region of the North Atlantic storm track tend to occur in clusters, potentially leading to widespread socioeconomic impacts associated with recurrent episodes of extreme winds, precipitation, and storm surges. Joaquim Pinto analyzed large-scale conditions associated with cyclone clustering. He noted that persistent anomalies in the jet stream associated with specific planetary–wave breaking configurations can explain seasons of anomalously high clustering. For example, the winter of 2013/14 was characterized by a strong, straight, and persistent jet stream and a recurrent clustering of intense extratropical cyclones, leading to widespread flooding in the British Isles.

Lynn McMurdie focused in more detail on intense precipitation events associated with extratropical cyclones. This type of precipitation is systematically underestimated by regional and global numerical models. A recent field campaign in Washington State (United States) showed that this bias originates from inadequate handling of warm-rain processes by microphysical model schemes.

Better understanding of the drivers of cyclone clustering is of great interest to the insurance industry, which is liable to large financial losses during anomalously stormy winters. Steve Jewson outlined the modeling techniques adopted by that industry to quantify the financial losses associated with extratropical cyclones. These primarily revolve around the creation of large "event sets" of hundreds of thousands of realistic cyclones through model simulations. The insurance sector mostly adopts contracts with a duration below 2 years, so the modeling effort focuses on seasonal to yearly time scales.

The variability in extratropical cyclone activity is also driven by much slower signals. Gwendal Rivière explored the importance of decadal or longer modulations in extratropical cyclonic activity in a long reanalysis dataset. He linked slow oscillations in cyclone activity over the last century to well-known modes of ocean variability including the Atlantic multidecadal oscillation and the Pacific decadal oscillation.

TEMPERATURE EXTREMES IN THE MID- AND HIGH LATITUDES. Nili Harnik discussed the circumglobal teleconnection pattern (CTP): a pair of zonally oriented hemispheric waves of zonal wavenumber 5 in quadrature with each other. These have previously been associated with wintertime cold extremes over North America. Some phase 5 of the Coupled Model Intercomparison Project (CMIP5) models show a clear trend toward a specific phasing of the CTPs over North America or Asia under greenhouse forcing. Such phasing may have important implications for future changes in wintertime cold spell occurrences over these regions.

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More generally, recurrent large-scale meteorological patterns (LSMPs) can be associated with regional temperature anomalies. Richard Grotjahn investigated LSMPs associated with cold air outbreaks over the U.S. West Coast. The LSMP develops in stages, beginning with a strong ridge over eastern North America, an equatorial Rossby wave with a cyclonic center near Hawaii, and a ridge in the central North Pacific. Warm advection builds the ridge over Alaska, displacing the cold air southward along western North America.

Gabriele Messori discussed the LSMPs associated with wintertime warm and cold air outbreaks in the high Arctic. Warm extremes are systematically associated with a meridionally oriented large-scale circulation favoring large moisture intrusions from the Atlantic into the Arctic Basin. These are associated with both cyclones crossing the Nordic seas and local cyclogenesis in the Arctic Basin. The cold extremes are instead associated with an intensification of the climatological high-latitude westerlies, resulting in an intense radiative cooling of the Arctic region.

The LSMP paradigm was also used to investigate the origin of wet-bulb temperature extremes in southern Pakistan. Rodrigo Caballero showed that this region has repeatedly approached wet-bulb temperatures at the edge of human physiological survivability, with severe impacts on public health. Such extreme episodes are triggered by wavelike disturbances in the upper-level circulation leading to increased advection of moist air from the Arabian Sea onto land. Projected increases in global-mean surface air and sea surface temperatures will further aggravate the problem.

While model projections of mean temperature increases are robust, greater care is needed when interpreting the modeled changes in variability. David Battisti showed that CMIP5 models display large biases in temperature variability in historical simulations, which can be primarily ascribed to an incorrect modeling of processes related to soil moisture. This result enables us to better evaluate the robustness of forecasted changes in temperature variability and hence in the occurrence of temperature extremes.

NOVEL APPROACHES TO THE STUDY OF WEATHER EXTREMES. Pascal Yiou presented some recent applications of weather analogs, namely, days with similar large-scale sea level pressure fields over the North Atlantic region. His analysis found an increasing intraseasonal recurrence of atmospheric patterns in winter, which can be interpreted as an increased potential predictability of the atmosphere. Weather analogs can also provide the basis for a stochastic weather generator, allowing one to produce large samples of extreme events.

The sampling problem is common to the study of most weather extremes. Geographically extensive observational datasets are relatively short, and obtaining large numbers of extreme events in long climate model simulations is computationally expensive. Freddy Bouchet presented a possible solution to this problem by using rare event algorithms based on large deviation theory developed in the statistical mechanics community. The approach samples the tail of the probability distribution function of a numerical model's extreme climatology and generates large samples of rare events at a comparatively very low numerical cost.

The theme of recurrent patterns was also addressed from a dynamical systems' perspective. Atmospheric flows are characterized by both chaotic dynamics and recurrent large-scale patterns, which point to the existence of an atmospheric attractor. Davide Faranda showed that the local properties of this attractor can be used to describe the predictability and persistence of an instantaneous state of the atmosphere. Days with similar local properties typically correspond to similar atmospheric configurations. Extreme values in the local properties correspond to specific atmospheric patterns and match regional extreme weather occurrences.

FUTURE PERSPECTIVES AND CHALLENGES IN THE FIELD. The workshop provided compelling evidence that the study of recurrent large-scale atmospheric flows affords powerful insights into the mechanisms and predictability of regional weather extremes and revealed promising synergies between this paradigm and novel analysis tools drawn from dynamical systems theory and statistical mechanics. These tools provide a means of obtaining large samples of extreme events and the associated large-scale atmospheric patterns, something that is impossible to recover from observational datasets and very costly to generate from long climate model simulations (Ragone et al. 2017). They also provide a framework to diagnose changes in the atmospheric dynamics—and the associated extremes—in both past and future climates by using mathematically robust atmospheric indicators whose definition is independent of the variable, geographical domain, or season chosen. An example is the local properties of atmospheric attractors, which are entirely general properties of a chaotic system (Faranda et al. 2017). This synergy does not diminish the relevance of more "traditional" atmospheric analyses, such as LSMPs based on composites, but will instead provide novel tools to enhance their statistical robustness and complement them.

Discussions during the workshop also highlighted a number of obstacles that hamper the process of sharing knowledge and prevent the community from reaping its full benefits. A fundamental issue is that different disciplines have different definitions of what constitutes an extreme. In meteorology, extreme events are often defined as very large/small values of an observable relative to a threshold, following the approach of Pickands (1975). In dynamical systems theory, this definition is extended to all rare states of the system (Lucarini et al. 2016), which may not always be associated with very large/small values of a given variable. From a societal viewpoint, the extreme nature of an event is primarily linked to its impact on human lives, property, and infrastructure. The same event might therefore be classified as an extreme or not depending on whether property and population were affected or not. Links between these definitions have only recently begun to be explored: recurrences in dynamical systems have been linked to the classical statistical extreme value theory (Freitas et al. 2010), and there is evidence that meteorological extremes are associated with rare configurations of the underlying dynamical system (Faranda et al. 2017). We note that the different definitions do not necessarily need to be unified, since each of them captures a different aspect of "unusual" occurrences that may be well suited to a specific need. However, a more systematic approach needs to be adopted in order to reconcile these complementary views of what constitutes an extreme.

A similar difficulty extends to reconciling the interpretation and application of the different classifications of large-scale atmospheric patterns. An example is how weather analogs and LSMPs are used. The similarity of LSMP members is evaluated statistically to isolate key synoptic/dynamic features (Grotjahn 2011), and the members should thus match weather analogs for a specific type of extreme. However, there has been no systematic examination of the differences between these two approaches and their potential for capturing extreme events in warmer climates. A second example is the interpretation of the atmospheric flow during the winter 2013/14. By the regional jet index of Woollings et al. (2010), the Atlantic eddy-driven jet during that season was very static and intense. In contrast, analyses focusing on hemisphere-wide wave packet activity singled this out as a particularly "wavy" winter (e.g., Davies 2015). Finally, according to dynamical systems metrics, the same winter was very low dimensional (and hence predictable). None of these approaches is incorrect, and indeed they are only apparently inconsistent: a more intense eddy-driven jet means more eddy momentum deposit and hence more wave-breaking activity (Rivière and Drouard 2015). The different viewpoints discussed above therefore provide complementary (and sometimes overlapping) information. However, this may not be immediately evident since they focus on different aspects of the circulation and can cause confusion when they are compared.

The general consensus was that these challenges can be overcome. For example, one may imagine using dynamical systems' techniques to characterize the different definitions of large-scale patterns with a unique set of robust parameters. At the same time, this can only happen if the obstacles are clearly outlined and defined, and concerted initiatives are developed to tackle them.

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