BAMS
Meeting Summary

How to Engage and Adapt to Unprecedented Extremes

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Exploring Unprecedented Extremes

What: Facing the urgent challenge of extreme weather and climate-related events, our societal frameworks for "resilience" and "adaptation" are proving to be insufficient. This paper introduces the "Exploring Unprecedented Extremes" workshop, which was convened to elucidate the research gap in light of such challenges. The workshop tackled a broad spectrum of issues, ranging from assessing out-of-sample climatic events that defy traditional modeling approaches to enhancing the communication of risks and likelihoods associated with such unprecedented events.

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1. Motivations

> We cannot confront what we cannot imagine.
>
> —Lynch and Veland (2018)

Evolution of the global climate system means that regional and local events that were previously considered record breaking very rare singular (one parameter) or compound events are becoming more frequent. While some of these events are present in the historical record and thus the change can be ascribed to a reduction in return period, others were unprecedented or even inconceivable in the observational record. The latter are challenging to predict and represent a break from accumulated, inductive wisdom. In many cases, these occurrences and their impacts are truly unprecedented [many sigmas out of range in a statistical sense (Thompson et al. 2023; Zeder et al. 2023)], pushing the boundaries of our imagination and our communication strategies, while also prompting us to reconsider if "climate change adaptation" and "increased resilience" are enough to handle the future. Rather, they suggest a complete transformation in adaptation governance and how populations operate under and engage with scientific, social, cultural, political, educational, and economic structures for addressing climate-related extremes (O'Brien 2012).

With ongoing climate warming and increasing population in areas with low resiliency and high socioeconomic exposure, the potential for more severe events is concerning as disasters are a product of event intensity, exposure, vulnerability, and adaptative capacity. Insufficient or maladapted preparedness may result in breakdowns within specific sectors or even contribute to societal instability. Effective planning for these types of events involves multiple factors, with the initial challenge lying in forming expectations or integrating such extremes into our planning and adaptation strategies—a task complicated by events that fall far outside our lived experience. Anticipating changes in single and compound extremes of unprecedented intensities demands transformational societal changes. It means critically reviewing and connecting the diverse "ways of knowing" and acting around extreme events and how communities prepare, respond, and recover. Relying solely on climate sciences may prove insufficient for anticipating impactful events and their consequences; embracing coproduction approaches that involve an inter- or transdisciplinary perspective widens the potential to foresee such occurrences. More specifically, we have to begin identifying (or developing storylines/scenarios of) what a black swan may look like, to prepare adequately for the future record-shattering events suggested plausible by climate science. Scientifically, inspecting unprecedented events may fall beyond the scope of our standard problem-solving and statistical methods. Exploring alternative strategies hence becomes necessary.

Novel situations such as unprecedented climate hazards have been illustrated by recent extreme events. For example, Tropical Cyclone Freddy in 2023 set records for duration and energy across the Indian Ocean and became the third-deadliest cyclone in the Southern Hemisphere. Cape Town faced a rare one-in-400-yr drought between 2015 and 2018, nearly depleting its water supply. In 2017, a massive landslide instigated by permafrost degradation in West Greenland triggered an enormous and deadly tsunami in Nuugaatsiaq. The 2021 floods in Germany and wildfires in Europe and North America in recent years highlight the reality of such extreme events in assumed well-prepared regions, underscoring the global challenge of adapting to unexpected climate threats. Additionally, the marine heatwaves of 2023, the record-breaking global ocean temperatures of the past year (365 days and counting!) alongside the Pacific Northwest heatwave of 2021 (~50°C at 50°N), further emphasize the urgency of addressing these challenges. Importantly, climate change may surprise us with unprecedented events resulting from novel combinations of multiple hazards, for instance, hazards from tropical cyclone—deadly heat compound hazards have emerged in the last decades (Matthews et al. 2019). Weather events can be unprecedented across multiple dimensions (e.g., intensity, spatial extent, and occurrence of antecedent conditions), all of which have significantly different implications for preparedness (Heinrich et al. 2024).

As a first tentative step to developing a community of practice, an international workshop entitled "Exploring Unprecedented Extremes" was convened in November 2023, held by Ouranos in Montreal as a hybrid event with both physical attendees and online participation. This event brought together experts from diverse fields to deliberate on innovative approaches to climate change adaptation and mitigation. Emphasizing cocreation and interdisciplinary collaboration, the workshop addressed key themes such as the integration of various sectors into climate change strategies, the complexities of decision-making under uncertainty, and the crucial role of transdisciplinary research in comprehensively understanding and effectively responding to climate extremes through sessions with predetermined orientations. The event raised the need for transformational learning to enable communities, NGOs, and research institutions to respond hopefully rather than being overwhelmed by the scale of the challenges (Kettleborough 2023). Participants with expertise in risk governance and foresight research, including research into the use of imagination and storytelling, along with climate modelers and analysts comprised the participants. The following sections provide an overview of the different topics addressed during the sessions.

2. Uncharted horizons

At the complex interface between climate science and policymaking, the interpretation and application of climate data play a critical role in shaping effective responses to climate change. It can be challenging to grasp the nuances between terms like "unprecedented" and "extremes," highlighting a fundamental divide between the realms of scientific research and decision-making. Scientists focus on empirical or simulated data to identify climatic anomalies, often dealing with data that, by nature, possess varying but quantifiable degrees of confidence. On the other hand, decision-makers interpret these terms through the tangible impacts of disasters, emphasizing socioeconomic, human, and environmental concerns but with a high robustness to uncertainty. The challenge lies in effectively bridging the gap between the scientific and decision-making communities when it comes to understanding terms like unprecedented and extremes. This highlights a crucial communication challenge: The scientific community must find effective ways to convey the complexities and uncertainties of climate data, ensuring that it is both comprehensive and practical for policy and decision-making processes.

One aspect of this governance partnership is communication. The content of the communication is entirely dependent on the receiver, sender, and the message that is to be delivered (Ingemann 2003). Communicating extremes has some severity to it that can stress the urgency or extreme consequences of climate change. It can be seen as less politically relevant, since the likelihood is lower and uncertainty is higher, which does not speak to policymakers' demands (Garvin 2001), but it relates to a true story present in the public memory—and therefore of relevance to the public (van der Wiel et al. 2021; Zscheischler et al. 2018; Zscheischler and Lehner 2022; Bevacqua et al. 2023; Shepherd et al. 2018). Communicating extremes in an understandable and engaging manner is clearly an active choice to stress the importance of knowledge and action on the current climate change progression.

For example, storytelling and the use of interactive polls and media can serve as effective tools for conveying information to meet the demands for a focus on consequences and guidance from entities such as municipalities. As an example of meteorological institutes employing this approach, some countries are using story maps to communicate climate change through user-friendly platforms with interactive visuals (https://storymaps.arcgis.com/stories/d7e3520fbf0e4b23ae06eb665288d2ca; https://www.klimaateffectatlas.nl/en/map-narratives, imaginative story: https://unseenheat.com/).

3. Coproduction

In the realm of coproduction, knowledge about out-of-sample events does not necessarily equate to understanding extreme impacts from such events. Extremes must be contextualized with changing contexts and vulnerabilities. Stakeholder engagement has emerged as a central element in planning and policy development processes addressing climate change adaptation responses. It has been widely applied in case studies around the world (e.g., Brunner et al. 2004; Brunet et al. 2014; Alcamo 2008; Tompkins et al. 2008; Brunner and Lynch 2010; Cairns et al. 2013) and is a proven approach to effecting adaptive governance. Conclusions drawn from these studies point toward the shortcomings of using isolated workshops and argue for a more continuous knowledge-rich stakeholder engagement process. Yet the structural and continuous engagement of a broad set of decision-makers to support the establishment of sustained learning communities of practice has rarely been pursued (Kasemir et al. 2003). With the Exploring Unprecedented Extremes workshop, one aspiration was to involve scholars accustomed to this agenda in recognizing the necessity of asking: What kinds of extremes might require a paradigm shift from the building of resilience to transformation? Are these extremes influenced by climate change alone or are they dominated by other factors? What can we learn about adaptation and/or transformation (O'Brien 2012; Pelling et al. 2015) across different physical settings and events?

Coproduction is usually applied to a transdisciplinary approach bringing together diverse ways of knowing, both within the formal scientific academy, and extending to other knowledge systems in other social worlds, from local and traditional knowledge to crafts and professions (Scott 1998). It is justified as a way of building more comprehensive understandings of phenomena—like extremes—as well as a normatively good way of engaging with affected parties and instrumentally empowering groups to put actionable knowledge to use. But what counts as knowledge—its norms and criteria of quality and its methods and means of communication—varies widely across social contexts and can be opaque to "outsiders." Connecting these different worlds demands a transparent process of dialog wherein participants critically engage with their own and other ways of knowing (Daly 2021). When carried out thoughtfully and ethically, such processes take time and cannot be rushed, demanding that trust between collaborators is built over time (Brunet et al. 2014). Speeding this process up may be achieved based on working with "trusted partners"—that is the idea of using existing professional networks for onward communication/dissemination. Hence, when concluding a project, they become the mechanism for disseminating the results and also feeding back questions to the science community being useful to scope future studies. This is a challenge to many research agendas driven by the timelines of funding schemes and to some individuals that may not always fully appreciate the complexity of establishing trust, when this involves elements from an entirely different approach toward knowledge generating—the cognitive element of the entire exercise. Here, the notion of extended ways of knowing (Heron 1996) offers direction in how such trust might be achieved.

4. State-of-the-art extreme modeling approaches and gaps

Typically, there is a prevailing assumption that our existing understanding of the current climate state can be extrapolated to the future. Unexpected out-of-sample events raise several crucial yet challenging questions, including the following: Could this event have been predicted using the available climate data? Could this event have been even more severe? How long until we surpass these records? And ultimately, do our existing approaches enable us to accurately model and apprehend such events? These questions prompt a more fundamental scientific question: What tools are "best suited" to possibly evolving evidence for unprecedented extremes? And related to this: Can we evolve ways to evaluate the credibility of "black swans" that derive from different tools?

In the last decade, several approaches have been developed and some of these were discussed during the workshop. Research into climate and weather phenomena has primarily progressed along two main paths: statistical and physically based approaches. The statistical approach has focused on developing methodologies for analyzing the likelihood of extreme events. This involves examining occurrences characterized by their exceptionally high values, thus their notable rarity.

As computing resources have expanded, there has been a surge in the number of physical approaches to studying climate change, with the pseudo–global warming (PGW) method emerging as both popular and accessible. Initially introduced by Schär et al. (1996), this approach investigates how past weather situations might have behaved under future or preindustrial climate conditions, akin to anticipated climate changes (Aalbers et al. 2023; Hawkins et al. 2023). This method has several limitations [inaccuracies in future atmospheric dynamic representations (Rasmussen et al. 2011; Zhou et al. 2023) and distortions from anomalies in lateral boundary conditions (Matte et al. 2022)].

Recent advances have enabled research centers with global models to enhance the study of extreme weather events, including compound events like hot-dry summers (Bevacqua et al. 2023), through large ensembles (Deser et al. 2014), creating diverse climate trajectories by slightly changing initial conditions. Using such ensembles of initialized climate models, it can be assumed that extreme events identified are physically plausible—providing biases in the model itself are assessed and understood (Thompson et al. 2017; Kelder et al. 2022). Still, large ensembles often suffer from low spatial model grid spacing to reduce computing costs nor does this approach guarantee to fully scoping out what is "possible." This limits the accuracy of extreme event simulations and makes specific event detection challenging, further complicated by discrepancies between simulated and actual events. To mitigate this shortcoming, regional large ensemble simulations have emerged in recent years (Fyfe et al. 2017; Aalbers et al. 2018; Leduc et al. 2019; von Trentini et al. 2020; Tucker et al. 2022).

A novel method (ensemble boosting; see Fischer et al. 2023) presented at the workshop uses the initial condition uncertainty in order to efficiently sample very rare extremes, assessing if short-term natural variability could have made an event more severe. Reinitiating simulations before a model event using perturbed initial states allows exploring worst-case scenarios. A small change in the initial state, in a similar manner to the "butterfly flaps its wings" analogy, enables the model to evolve differently, sometimes leading to a more extreme event, which could have occurred, given the initial climate state.

In addition to the methods discussed, some researchers have utilized kilometer-scale modeling. However, the main challenge with these high-resolution convective-permitting models (CPMs; see Prein et al. 2015) lies in their significant computational requirements, confining their use to a few well-resourced climate research centers. However, innovative methods such as storyline simulations (Kawase et al. 2021; van Garderen et al. 2021) or downscaling of extreme weather situations from large ensembles with kilometer-scale models (Huang and Swain 2022) emerge as promising pathways forward.

5. A call for future work in research and practice

The compelling drive behind efforts to explore unprecedented climate extremes is shaped by the urgent necessity for a profound transformation in our societal, cultural, political, and economic frameworks in response to the escalating frequency and severity of extremes that are unexpected and out of sample. The traditional concepts of "resilience" and "adaptation," while valuable, may not be adequate to meet the complex challenges posed by these phenomena. This realization underscores the importance of innovative thinking and the adoption of transdisciplinary approaches to effectively anticipate and mitigate the impacts of such events.

The motivation for the Exploring Unprecedented Extremes workshop was deeply rooted in the recognition that to effectively prepare for and address the irreducible uncertainties of climate extremes, a shift in perspective is essential. This includes moving beyond conventional resilience-building efforts toward embracing comprehensive strategies for societal—and scientific—transformation. The workshop will serve as a foundation for examining how extremes, influenced by ongoing climate change, necessitate a reevaluation of our approaches to adaptation and the identification of strategies that can foster transformation across various physical settings and events. The format and ideas of the workshop could be replicated in different countries around the world, bringing together, for example, scientists, NGOs, communities, and governments both local and national.

The workshop enabled the establishment of foundational guidelines for various types of climate-related extremes. The first category refers to record-breaking events, which are theoretically anticipated meteorological/climatological extreme occurrences. These events fall within our existing understanding of physical and statistical norms, meaning they are confined to the bounds of recognized natural variability. The second category, out-of-sample events, encompasses events that fall outside both the observational record and previous experience and can only be adequately researched retrospectively.

The third category consists of conceptualized extreme events, which stretch the limits of what could potentially occur within the constraints of scientific knowledge and stakeholder insights. These unknown events are initially conceptualized in collaboration with stakeholders, for instance, by identifying thresholds that might signify a critical breakpoint in their respective sectors. Following this, these scenarios undergo analysis to evaluate their probability and physical feasibility, distinguishing them from the observed out-of-sample events as they are constructed events reflecting our current state of resilience.

The fourth category includes observed high-impact events (from the physical climate and/or impact side) which represent disasters of a more intricate nature, arising not solely from record-breaking or out-of-sample events (though they may also originate from these) but significantly influenced by societal factors (Bouchard et al. 2023). To effectively analyze such events, reliance on physical sciences alone falls short. Only through a transdisciplinary approach can these events be fully understood, processed, and potentially guide the development of suitable plans for adaptation or transformation.

The fifth category represents complexity of a higher order: It is both unlikely and yet unseen, lying outside the realm of our current imagination. Similar to the fourth category, this requires a transdisciplinary approach. However, the difficulty is in predicting meteorological or climatic events that are outside our current understanding but still have a nonzero probability of occurrence. When these events interact with evolving societal conditions, they could trigger unexpected collapses in various societal sectors, leaving us completely unprepared.

The workshop demonstrated some limitations of current approaches. Ultimately, it also became evident that the scientific community focused on climate issues which make it difficult to get rid of the myth of the knowledge deficit model (Lemos et al. 2012; Bradley et al. 2020). This model presumes that public skepticism or resistance toward scientific discoveries and technological advancements stems chiefly from a shortfall in knowledge or comprehension. Within this framework, the concept of coproduction away from the largely discredited knowledge deficit model should be a core element in research on climate-related extremes. The workshop underlined the urgency of the tasks facing society and the crucial importance of helping individuals, communities, and organizations understand that wise action is needed now.

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