Reflections on weather and climate research

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To celebrate the first anniversary of *Nature Reviews Earth & Environment*, we asked six researchers investigating weather and climate to outline notable developments within their discipline and provide thoughts on important work yet to be done.

Q Broadly, what are some of the key advances and exciting future prospects in your discipline within weather and climate research?

Wenjia Cai. To date, countries and cities that account for more than half of global GDP have set or intended to set carbon neutrality goals, leading to a vast amount of literature focused on the impacts of different carbon mitigation pathways. Of this booming research area, distinct progress has been made in incorporating additional dimensions to the impacts, improving analysis resolution and developing solution-oriented results.

Traditionally, research in mitigation impacts was very much focused on understanding the technical or macroeconomic costs. Such a narrow focus, however, is no longer satisfactory. Instead, thanks to interdisciplinary research and advances in integrated assessment models with multiple modules, great attempts have been made to assess the multiple dimensions of mitigation impacts, including environmental, ecological, employment, health, equity and other social costs¹. In this way, research can compare and select a specific carbon mitigation pathway that does not conflict with other sustainable development goals.

Studies within the field of mitigation impacts are also usually focused on global or national scales, or, at best, at provincial scales with sectoral details. However, to achieve a just transition, provincial-level and sectoral-level results are not enough. Owing partially to the emergence of multi-source data and big data, researchers are now zooming in to explore the distributional

effects. For example, there are capabilities to assess how mitigation impacts are distributed among different regions or even emission sources, and between groups with different age, income, gender, race and educational backgrounds. With this knowledge, policymakers can more effectively choose a carbon mitigation pathway that rectifies structural inequalities and addresses factors that privilege some while disadvantaging others.

Although most current studies can identify benefits and trade-offs for the predefined carbon mitigation pathways, they are usually powerless when faced with the ‘now what’ question raised by the policymakers. That is, most studies cannot provide practical solutions and quantitative suggestions on how to maximize the benefits and reduce the trade-offs. Therefore, due to the policy need, incorporating these impacts analyses into policymaking has become a new area of considerable growth. Such studies can take the two-way interactions between pathways and impacts into consideration and help identify a solution with the least social cost or the most social benefit.

Despite these advances, we should not forget the original intentions of analysing carbon mitigation pathways — that is, to push for early and adequate climate action. Have we achieved this intention after decades of development in economics of climate change? Yes and no. Yes because an increasing number of countries are making pledges for carbon neutrality by around the 2050s. No because global greenhouse gas emissions in the last decade are still rising at a rate of 1.5% per year, contrasting to the 7.6% annual average reduction rate required

by the 1.5°C target. Although COVID-19 puts most economies on pause and gives them a chance to choose a green recovery, we still see many recovery plans highly associated with fossil fuels. Why is the gap widening between the reality and the target? From my perspective, it is because the academic efforts to date still fail to solve the temporal and spatial mismatch problem that has long been embedded in the impacts analyses of addressing climate change.

In particular, early and adequate actions imply getting over the reluctance to transform business and life today and, yet, the benefits, or the avoided damages, are usually expected in the far future, at the risk of being free-riden by someone in other regions. For policymakers who look no further ahead than the next election, those huge benefits can be easily ignored if not cashable within their political term.

Therefore, it is important to further specify the temporal and spatial details of the impacts of different carbon mitigation pathways. To be clearer, the academic community needs to better explore the short-term (or even immediate) and local mitigation impacts². For example, the newly built renewable energy power plants are becoming cheaper than new coal or gas-fuelled power plants, even when the environmental externalities from coal and gas are excluded³. This cost competitiveness will push for spontaneous decarbonization of the power system today, reduce the energy cost of the whole economy and spare money for extra investment and consumption. Moreover, the better air quality brought by renewable energy would reduce the local health burden immediately and improve human well-being and labour productivity. Both of the above-mentioned effects would contribute to short-term local economic growth, which is the eternal pursuit of local policymakers around the world. Cases like these should become an important supplement to existing studies.

Christa Clapp. Just three years ago, researchers were lamenting the scarcity of journal articles on climate finance, and investors were being urged by non-governmental organizations and student protestors to consider the moral imperative of divesting from fossil fuels⁴.

That has now changed. We have new journals and special issues, university courses and programmes dedicated to sustainable finance, a shift in the discourse from a moral imperative to risk-framing, and companies answering questions related to the climate, environment and sustainable development goals from active investors.

As awareness of climate change has increased in the financial sector, research has expanded to understand investors' motivations for acting on climate risk, assess the willingness of investors to pay a premium for green-labelled financial products, quantify the investments required to transition to a low-carbon economy and recognize stranded assets resulting from a transition to higher carbon prices.

However, the research community is still catching up to the change in pace of the financial sector, and far greater understanding is required in the environmental impacts of finance. In particular, there remains very little interdisciplinary research on how financial regulations and investment decisions can impact the climate, vital for understanding how the financial sector can support the transition to a low-carbon and climate-resilient economy. This imbalance may arise, in part, from a lack of data, but is also undoubtedly linked to research

silos, specifically, financial implications being separate from environmental studies. Future efforts are required to break down these silos, particularly given that crossover between finance, environmental science and policy is increasingly required to influence sustainable development decisions.

The recent growth in voluntary and regulatory initiatives for climate risk disclosure can provide increased transparency to investors, but to make an environmental impact, the disclosed information needs to be analysed, compared and incorporated into financial decisions. The European Union Taxonomy tool on sustainable finance aims to facilitate disclosure (including on the energy efficiency of new buildings), yet, cannot fully substitute for environmental regulations, such as stricter building codes or stronger carbon pricing mechanisms. However, there is very little research on the market implications and environmental impacts of climate risk disclosure regulation. For instance, what is the expected impact on financial markets, and, ultimately, on the environment, of the EU directive to large companies on 'non-financial' reporting of climate risk?

To meet these growing demands on climate risk disclosure, investors are asking

questions about how to align investment portfolios comprised of a range of diverse companies with the Paris Agreement. Decision-makers in the financial sector today face a confusing array of climate risk information, either reported in an inconsistent manner by companies themselves or wrapped up in aggregated environmental, social and corporate governance scores. There are many new tools for assessing risk, but these generally lack transparency on methods and data⁵. At the firm level, the IPCC and the International Energy Agency have a whole new customer base for their climate and energy scenarios. Yet, being focused on mid-century or end-of-century trajectories, existing scenarios are ill-suited to guide very-near-term risk-based investment decisions, presenting challenges for debt decisions with a 3–5-year time frame.

At the macro level, central banks are increasingly concerned about financial instability and macroeconomic impacts of climate risk resulting from tightening carbon prices or increasing damage costs from flooding, fires and other extreme events. Explorations on potential instability require coordination across financial and climate change modelling and research communities. Indeed, the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) calls for increased risk disclosure from financial institutions. However, with 37 different case studies of environmental risk analysis showcased by the NGFS, all with different scope and perspective, the overall effect could be described as scattershot⁶.

These challenges in assessing market and system impacts and improving climate risk data for financial decisions highlight that sustainable finance is a rich field for further research. In the coming years, researchers in the fields of finance, climate science and policy must further integrate interdisciplinary perspectives to bring new insights to the burgeoning field of sustainable finance, in particular, to understand how financial sector regulations and initiatives can support, or hinder, climate action.

Indrani Das. Some of the most compelling science questions in glaciology have focused on West Antarctica, including the inherent instability and potential irreversible retreat of the West Antarctic Ice Sheet (WAIS).

Driving advances in such questions has been enormous progress in satellite and airborne technologies, making it possible

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to monitor ice sheets and their floating extensions — ice shelves — on a continental scale, and ice elevation on a global scale, all with better accuracy. The combined data from NASA's ICESat and ICESat-2, for example, have shown that the WAIS contributed ~7.5 mm of sea level equivalent during 2003–2019 (REF⁷). In addition, multiple national and international satellites with various sensors are now collecting critical ice-sheet-wide parameters, including ice surface elevation, ice surface velocity, surface melt features and albedo, and gravimetric ice mass change, shaping our fundamental knowledge of dominant processes impacting ice sheet mass balance and ice dynamics required to improve projections of sea level rise.

Where satellite technology does not exist, airborne surveys have been conducted to further understanding. NASA's Operation IceBridge, a major airborne mission, recently concluded after surveying both poles for a decade. IceBridge provided measurements of critical parameters such as ice surface elevation changes from laser altimetry; ice thickness, bedrock topography and snow accumulation rates from ice-penetrating radars; and bathymetry using gravimeters. These critical remote sensing datasets are used in continental-scale ice sheet and ocean models, in the evaluation of regional climate models, and to better understand how ice sheets and ice shelves interact with the warming atmosphere and the ocean.

In addition to data advances, progress has been made in understanding the potential instability of West Antarctica. The WAIS is considered to be fundamentally unstable because it is situated on a reverse-sloping (sloping inland) bed located largely below sea level. The grounding line of the WAIS — that is, the region where the ice sheet loses contact with the bedrock and starts to float, forming an ice shelf — is theoretically susceptible to runaway retreat via a process called marine ice sheet instability⁸ (MISI). MISI progresses when the grounding line retreats on a reverse bed slope where ice is progressively thicker. Any further retreat on this slope always produces a progressively larger ice flux because of increased ice thickness and because ice starts to move faster to counter the increased mass loss. This process, although may be initially triggered by climate, can become irreversible because of the positive feedback between ice dynamics and mass balance. Indeed, the IPCC Special Report on the Ocean and the Cryosphere suggests that rapid ice loss from glacier acceleration in the

Amundsen Sea could indicate the onset of MISI, but that observational records are too limited to assess the irreversibility⁹.

In the meantime, studies have now clearly demonstrated that ocean-induced basal melt is responsible for faster grounding line retreats and rapid thinning of ice shelves in the warmer Amundsen Sea sector of the WAIS. This thinning includes the large, fast-moving and fast-changing Thwaites Glacier and its equally impressive neighbour, the Pine Island Glacier. The warm circumpolar deep water from the Amundsen Sea thins their ice shelves, transports heat to their grounding lines and carves melt channels underneath their ice shelves. Surface-melt-induced ice shelf hydrofracture, subglacial hydrology and bed conditions impact the mass loss but are harder to constrain. In addition, poorly understood theories need to be tested for their feasibility, such as the marine ice cliff instability. The ice shelf of Thwaites Glacier, in particular, has suffered extensive damage from basal melting, crevassing and calving of icebergs. If Thwaites Glacier retreats completely, it may cause structural damage to the nearby areas too. This area holds enough water to raise the sea level by ~3 m, although complete retreat may take a few centuries based on our current understanding of important processes that govern the mass loss¹⁰. However, because of the interrelations and feedbacks between some of the processes, it is often challenging to isolate the main drivers of mass loss.

Sustained observations, both remote sensing and field-based, are, therefore, crucial to improve our understanding of the hierarchy of physical processes and for their accurate parameterization in the continental-scale ice sheet models to identify the main drivers of change and improve projections of sea level rise. Ongoing international observation and modelling efforts such as the International Thwaites Glacier Collaboration are a good step forward. Integrating high-resolution observations with Earth system models that accurately represent dominant physical processes is critical for improving projections of sea level rise, as is evaluating these models against further observations. However, as ice sheets are continually evolving in response to climate, this task is not trivial and requires huge coordinated efforts. We are experiencing climate change right now. Therefore, continued science activities should also progress together with coastal planning and management to effectively mitigate the impacts of climate change and sea level rise.

Sarah Perkins-Kirkpatrick. Over the last two decades, we have endured a litany of high-impact extreme events across the globe. Catastrophic wildfires have simultaneously raged over North America and Australia. Heatwaves have collectively caused tens of thousands of deaths over Europe, India and Pakistan. Severe hurricanes have ravaged communities spanning the USA to the Philippines. And new types of extremes, such as marine heatwaves, have been discovered, along with their devastating impacts on marine ecosystems.

It is not a stretch to say that our scientific understanding of climate and weather extremes has exploded over recent years. A notable facilitator of this expansion is the availability of data at spatial and temporal scales on which many (though not all) extreme events occur. Observations, reanalyses and climate models, for instance, now readily encapsulate daily or sub-daily timescales, a marked development since pre-CMIP3. In a similar manner, the increased spatial resolution of models and observational products has allowed for a better understanding of how extremes are changing, as well as the physical mechanisms underpinning them. For example, finer-scale regional models have more realistic representations of tropical cyclones compared with global climate models. Moreover, models that simulate the type and persistence of blocking highs associated with heatwaves also provide better representations of heatwaves themselves. It is a certainty that accessibility to high-resolution spatio-temporal data has been fundamental in allowing scientists to categorize, measure, detect changes in and understand the drivers of many types of climate and weather extremes.

However, whilst high-resolution data are necessary for improving our understanding of extremes, it is not sufficient. Extremes, by their definition, are rare events, and, thus, adequate sampling is critical. Large, multi-member climate model ensembles have helped to address this undersampling and have been key in demonstrating the important role internal climate variability has on extremes¹¹. Indeed, trends in extremes can differ greatly even in the same climate model, where otherwise identical realizations have miniscule changes in their initial conditions, suggesting the crucial importance of the timing and periodicity of variability phases on the overall detected signal. Such findings are not possible in smaller samples of extreme events — inclusive of observations — where only

one representation of a plausible temporal pattern of variability is present.

Moreover, we have now reached a point where increasing resolution is no longer enough to advance our understanding of extreme events. For example, simply increasing the resolution of contemporary CMIP6 climate models does not improve the simulation of precipitation extremes¹². Whilst high(er) resolution data were, therefore, initially critical in adequately detecting extremes in climate models, the inclusion of key physical processes and their exchanges is now equally important in understanding how extreme events evolve, decay, interact and change over decadal or longer timescales. Appropriately developing fine-scale physics in a climate model is a monumental task, further compounded by access to adequate computational resources and the number of climate models that require this improvement. These roadblocks are likely impediments on further leaps in advancing knowledge of climate extremes that will exist for some time yet.

Detection and attribution research is another noteworthy advance, quantifying the role of anthropogenic climate change behind extreme events. This field has rapidly advanced over the last 15 years, supported by robust statistical methods and advances in high-resolution and larger sample sizes of model data. However, assessments of how anthropogenic climate change has altered the frequency and/or intensity of a specific (perhaps record-breaking) event, or driven long-term changes in that event for a particular region, are only as good as the model(s) employed. For example, if a model cannot adequately simulate a known physical mechanism of an extreme, then it is very unlikely to simulate how climate change affects that mechanism, and, thus, the corresponding extreme in the attribution assessment. Attribution assessments are undoubtedly powerful tools and an extraordinary development, but could also benefit from increasing process-scale understanding of extremes within climate models in the future.

A new era of climate extremes is now emerging, with black-swan events in the form of wildfires, heatwaves (marine and atmospheric), tropical cyclones, droughts and floods occurring over many parts of the globe. Compound extremes are also being recognized, where different extreme events closely occur together in time and/or space¹³. If we are to adapt to, and effectively mitigate, anthropogenic climate change, we must advance our understanding of these types of extremes — and soon — as it is changes

in extremes that have the most devastating impacts. While climate model resources will continue to be useful to study changes in extreme events, we require a major development in the understanding and modelling of physical mechanisms on a scale similar to the availability of daily data in the mid-2000s to obtain anything more than an incremental advance over the next 15 years.

Adelle Thomas. Several recent notable advances have been apparent within climate adaptation research, expanding understanding of how societies are adapting, the limits of adaptation, as well as loss and damage. Early research, for example, largely focused on theoretical ideologies and justifying the need for adaptation on top of mitigation. More recently, however, there has been a concentration of literature that explores the lived experiences of adaptation in different contexts and scales, increasing and diversifying the evidence base on how societies are responding to climate risks. For instance, the recent growth of research on community-based adaptation stems from acknowledgement of the importance of harnessing local knowledge and increasing local adaptive capacities to address the impacts of climate change¹⁴.

The expanding adaptation literature has also supported key advances in recognizing the limits of adaptation. Recent empirical studies have built on prior theories of potential tipping points and boundaries of adaptation to show how specific communities and ecosystems are already experiencing adaptation limits. For example, small-scale farmers are finding that existing adaptation strategies are insufficient to prevent loss of crops and are, therefore, shifting to different livelihoods as a result. Analysis of the constraints and limits to adaptation echoes the early period of adaptation research when there was an assumption that successful mitigation would negate the need for adaptation. We now increasingly understand that there are limits to the ability of adaptation to reduce climate risk and that, despite adaptive efforts, climate impacts still remain.

Moreover, loss and damage literature has broadened, spanning analysis of the many conceptualizations of what the term encompasses, to acknowledgement of the importance of the non-economic negative impacts of climate change (such as loss of sense of place and damage to culturally and spiritually significant landscapes). Indeed, the importance of loss and damage in the United Nations Framework Convention on Climate Change (UNFCCC) spurred

inclusion of this research for the first time in the IPCC in the SR1.5 (REF.¹⁵). The increasing evidence base on loss and damage responds to calls from particularly vulnerable nations and communities that are already experiencing impacts of climate change despite adaptive efforts.

These advances point to the need for a focus on transformation in future adaptation research, particularly as it becomes increasingly evident that small-scale and incremental adaptation measures currently being planned and implemented are insufficient to prevent climate risks. Although the IPCC SR1.5 underscored the necessity of widespread and unprecedented levels of both mitigation and adaptation to address the challenges of climate change, there is still limited research on these topics. Research that explores transformational adaptation possibilities and modalities for a range of actors reflecting different contexts and scales, and also how actors must collaborate to facilitate transformation, is desperately needed.

However, when considering future prospects for adaptation research, the events of 2020 cannot be ignored. The COVID-19 pandemic has had significant effects on all of us, including those that are already most vulnerable to climate change. Research plans have been cancelled or postponed, and modalities that have served more qualitative adaptation research in the past — such as in-person interviews and focus groups — are increasingly unfeasible. The global Black Lives Matter movement brought to the fore long-standing systemic and institutionalized racism that is present not only in the United States but in many nations around the world. Such racial injustice has resulted not only in the deaths of black people as a result of police brutality but also in the increased vulnerability of black people and other communities of colour to the impacts of climate change. Systemic racism also results in the marginalization of black climate experts, who face additional burdens of operating within unjust structures. These events signal the need for more inclusive, equitable and innovative approaches to adaptation research moving forward.

There is, thus, also a need for transformation in our approaches to adaptation research. We must look at our own roles in economic and social power relations that have historically been unjust and act to facilitate change. How can we contribute to closing the research gap of studies that originate from the Global South and that consist not only of case studies but also of contributions to and

critiques of adaptation theory¹⁶? How can we bolster the sparse literature that includes or even centres racial disparities that are present in adaptation processes? How can we support development of truly transformational adaptation that does not reinforce existing unjust structures but also transforms underlying systems that have led to existing inequalities? How can we conduct meaningful research to enact change when modalities are restricted? These are big questions and there are no easy fixes. Simple steps such as being more inclusive of locally based researchers, working with civil society organizations and developing community science approaches to more actively engage and work with at-risk communities are a start to addressing issues of justice, as well as to developing innovative research processes. Continuing and expanding such measures even when the pandemic is a memory and the racial justice protests are no longer in the media is critical to transform the practice of adaptation research to be more inclusive, just and innovative.

Jessica E. Tierney. Atmospheric CO₂ levels now exceed 400 ppm — a value that the Earth has not experienced in 3 million years — and most of this rise occurred in the last 60 years. As a palaeoclimatologist, this is frightening. The rate of anthropogenic carbon emissions is higher than any known event in geological history. We are already seeing the impacts unfold, right before our eyes: melting ice, rising sea level, more acidic oceans.

Where are we headed in the future? We know that a high-CO₂ world is a warmer world, but how much warmer will it get? Climate model projections diverge on this because models have different sensitivities to rising CO₂. Many of the new models participating in the CMIP6, which will guide the next IPCC assessment, have high climate sensitivity, meaning that they predict a large warming by the end of the century. How do we know whether this is realistic? And, beyond temperature changes, what about the water cycle? How will regional water availability change in a warmer world? Even with all of the improvements that have been made regarding the representation of land and atmospheric processes, climate models still disagree about both the sign and the magnitude of precipitation change in most regions across Earth.

In my view, the past is the key to the future. As we seek to narrow projections of future change, there is a renewed role for palaeoclimate studies to understand what is possible. Past climates can be used

to constrain climate sensitivity, study what happens during extreme CO₂ emissions, understand regional-scale and seasonal-scale changes in the water cycle, and determine the response of the cryosphere¹⁷. In particular, ancient warm climates — such as the Pliocene (3 million years ago), the Eocene (50 million years ago) and the middle Cretaceous (90 million years ago) — offer key opportunities to study what happens to the Earth in a high-CO₂ world.

While constraining metrics like Earth's climate sensitivity and the strength of climatic feedbacks has long been a fundamental goal of palaeoclimatology, a number of recent advances in both palaeoclimate modelling and reconstruction techniques have allowed for a firmer connection to form between studies of past and future climate. As a community, we are developing more quantitative methods to rigorously represent uncertainty, such as using Bayesian inference, and we are starting to adapt spatio-temporal reconstruction techniques like data assimilation for use in palaeoclimates¹⁸. We are also seeing increasing efforts to collate, synthesize and analyse large datasets from key intervals in time, like the Last Glacial Maximum (the coldest climate of at least the last 100 million years)¹⁸ and the early Eocene 'greenhouse' (50 million years ago)¹⁹. In addition to serving as 'targets' for climate models to be tested against, temperature and CO₂ data from these time periods can be used to constrain climate sensitivity in radically altered climates. Encouragingly, palaeoclimate information tends to suggest values around 3–4 °C that have long been the climate community's 'best guess'^{18,19}. On the flip side, we are discovering that Earth system models with a sensitivity above 5 °C per doubling of CO₂ (of which there are several in CMIP6) fail to simulate past climates, producing results that are either too cold or too hot because they are too sensitive to CO₂ (REF.²⁰). Unfortunately, these studies tend to happen after the climate model development phase, rather than during it. Palaeoclimatologists are trying to encourage modern climate researchers to involve us in the model development phase and benchmark the models against palaeoclimates. In this way, we can avoid using models to predict future climate that cannot predict the past (which, arguably, are not trustworthy, especially under high-emissions scenarios) and narrow projections.

The water cycle is the new frontier for palaeoclimatology. Tree rings have given us an amazing view of regional drought

changes over the last few thousand years, but, before that, our understanding gets hazy. In particular, we do not yet have a good handle on what happens to regional patterns of precipitation in warm climates. While there is a long-held view that high CO₂ causes "wet regions to get wetter and dry regions to get drier", we know from theory that this maxim does not really hold over land. In the subtropics in particular, we need to consider changes in the seasonal cycle in rainfall and how the monsoon systems respond to warmer temperatures. The palaeoclimate evidence that is out there already is intriguing. For example, the presence of ancient lake basins in the region where I live (the south-west USA) that date to the Pliocene suggests that, somewhat counter-intuitively, the south-west region was wetter in this warmer world. I am confident that, with more study — using both on-the-ground data and climate model simulations — we can get a better view of what happens to the regional water cycle in warm climates and that this will be key to understanding future water availability.

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