Reflections and projections on a decade of climate science

To mark the tenth anniversary of *Nature Climate Change*, we asked a selection of researchers across the broad range of climate change disciplines to share their thoughts on notable developments of the past decade, as well as their hopes and expectations for the coming years of discovery.

Much has changed in the last 10 years since the *Nature Climate Change* inaugural issue in April 2011. The effects of climate change are now more apparent, global leaders have reached a climate agreement, and public awareness and engagement, particularly in the younger generation, continues to grow. Here, ten researchers discuss advances in their field, highlighting the progress and drawing attention to what still needs to be done.

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Veronika Eyring: machine learning-based physics-aware climate modelling

Over 20 years ago, the Coupled Model Intercomparison Project (CMIP) of the World Climate Research Programme (WCRP) started with the coordination of a handful of early-generation atmospheric models coupled to a dynamic ocean, a simple land surface and thermodynamic sea ice. CMIP has since evolved over six phases into a major international research activity central to climate change assessment reports. Across the years, climate models have continued to be developed, and the number of CMIP models has substantially increased. In the past decade, many have been extended into Earth system models that, in addition to physical climate, simulate interactive carbon and other biogeochemical cycles important to climate change. Compared to earlier generations, CMIP6 models have increased spatial resolution (~100 km in the horizontal) and improved physical process representation (like clouds and land biogeochemistry), and they include additional Earth system processes (for example, nutrient limitations on the terrestrial carbon cycle) and components (such as ice sheets). Benchmarked with an increasing wealth of observations, the simulation of recent mean climate has improved in CMIP6 compared to previous CMIP phases.

Nevertheless, uncertainties in climate projections remain. For example, the range of simulated effective climate sensitivity — the change in global mean surface temperature for a doubling of atmospheric CO_2 — has not decreased since the 1970s. It is still between 2.1 and 4.7 °C, even increasing in CMIP6. A major cause of this is differences in the representation of clouds and other processes occurring at small spatial scales. These need to be approximated through parameterizations that represent the statistical effect of that process at the grid scale of the model. Additional uncertainty arises from the carbon cycle's response to climate warming and to increased atmospheric CO_2. This impacts models' ability to accurately project global and regional climate change, climate variability, extremes and impacts on ecosystems and biogeochemical cycles.

New approaches are required that exploit opportunities from increasing computational power while building on the knowledge gained from theory and observations, and continually including missing processes in models. I expect breakthroughs in particular from the combination of three research areas: high-resolution simulations that can resolve small-scale and fast processes, the wealth of observational data and machine-learning (ML) techniques.

Combining multi-disciplinary expertise in ML and process-based modelling has huge potential. High-resolution, cloud-resolving models (horizontal grid resolution of a few kilometres) alleviate many biases of coarse-resolution models for deep clouds and convection, wave propagation and precipitation, but they cannot be run at climate timescales of multiple decades or longer due to computational costs. And even these simulations still use parameterizations for smaller-scale processes like shallow clouds, turbulence or microphysics, which are key to the Earth's energy balance and climate. Yet, short simulations from high-resolution models together with observations can serve as information to develop ML-based parameterizations that are then incorporated into Earth system models. This combination can drive a paradigm shift in current Earth system modelling and analyses towards a new data-driven, yet still physics-aware, science. The key goal is a hybrid modelling approach that maintains physical consistency and realistically extrapolates to unseen climate regimes while reducing climate projection uncertainties and improving Earth system understanding.

The application of ML to better understand and model the Earth system is still in its infancy. It is a promising field that requires a new generation of scientists being trained at the interface of climate science and artificial intelligence. I cannot wait to see their contribution!

Vimal Mishra: hydroclimate and its changing extremes

A warmer atmosphere holds more water vapour, and this thermodynamic relationship is important for understanding the global hydrological cycle's response to warming. The past decade of research has confirmed that global water vapour is increasing at ~7% per °C, but that global precipitation increases less, around 1–3%. Research aimed at understanding this discrepancy has afforded some of the most robust and theoretically supported predictions for hydroclimate: at the global scale, these moisture changes make the tropics and polar regions wetter, and the subtropics drier. As a result, subtropical dry zones are expanding and pushing the adjacent extratropical storm tracks poleward.

The past decade has also highlighted that at the regional scale, hydroclimate changes are still highly uncertain, mainly driven by climate model disagreement in how regional climates respond to warming. Placing better constraints on future circulation patterns and storm systems will alleviate some of this uncertainty. Particularly important at these scales are precipitation extremes; the heaviest rainfall events are exponentially more sensitive to warming, and this is a product of changes to both temperature (thermodynamics) and regional circulation (dynamics). Understanding how local precipitation will change or intensify with warming relies on continued improvement in observations and climate modelling.

Another important aspect that has come out of the last decade of research is a more fundamental understanding of, and appreciation for, land–atmosphere interactions, including the response of vegetation to higher temperatures and atmospheric CO_2. This is exemplified by prolonged droughts that impact local water availability. Several regions, including the intensively irrigated Indo-Gangetic Plain, have witnessed frequent droughts in the past decade; continued work on the connections between the biosphere and atmosphere is necessary to more accurately estimate future water availability and demand.

The past decade has also seen important advances in understanding the impact of hydroclimate on the land surface. Flash floods, particularly in urban regions, can affect transportation, infrastructure and local economies. Atmospheric rivers and prolonged wet spells cause large-scale floods that impact agriculture. Land surface conditions, including soil moisture, play an essential role in these outcomes, and the role of climate change on flood extremes is better understood thanks to improved hydrological modelling and observational networks. An important next step here is constraining the sensitivity of streamflow and surface water to warming, particularly in mountain regions where seasonal runoff can comprise a large fraction of local water resources.

Reflecting on this last decade, three advances typify the gains that I find most exciting in hydroclimate research. First, new in situ and satellite-based measurements of the hydrological cycle have helped the field more comprehensively understand the hydrological cycle's sensitivity to warming. The Gravity Recovery and Climate Experiment (GRACE) and the follow-on (GRACE-FO) mission, for example, have allowed researchers to see underground and measure changes in groundwater storage. Second, a recent and growing focus on urban hydrology has enabled researchers to better describe and study the interactions between hydroclimate and the built environment. Third, ongoing developments related to improvements in physical processes and resolution in global climate and impact models have helped answer some of the most challenging questions on changing risks to hydrological cycle extremes in a warmer world. Together, these areas will continue to progress our understanding of regional hydroclimate change and its impacts in the decade to come.

Gary Griffith: coming to recognize marine ecosystems as complex adaptive systems

The last decade has seen revolutionary advances in understanding how climate change impacts — including ocean warming and acidification, sea-level rise and the intensification of extreme events — affect marine ecosystems and the essential services they provide to human society. The encouraging advance that resonates with me is that marine ecosystems and human interactions with them are becoming increasingly recognized as complex adaptive systems in which small changes from climate change threats and human stressors can be magnified through non-linear interactions that scale up and play out across space and time, and ecological and social organization. This calls into question the fundamental paradigm of a stable linear world that guides current conservation and sustainable marine management. Instead, in the changing world, the possibility of sudden and unexpected shifts in marine resources, an increased potential for tipping points, alternative stable states and the emergence of novel adaptation and evolutionary strategies can be expected.

During this next decade, a big question for me is how to evolve the complex adaptive systems' perspective to understand how to increase the resilience of marine ecosystems that provide critical sustainable (for example, fisheries) or conservation (for example, marine protected areas) ecosystem services. Resilience in this context is the emergent adaptive capacity of the ecosystem to absorb the cumulative effects of global climate change and human stressors. Key questions remain on how resilience scales in time and space with the complex interactions of both climate change (for example, ocean warming, ocean acidification and sea-level rise) and local human stressors (for example, fisheries, pollution and human-induced introduction of alien species). Can some of the exciting data-driven causal inference methods and developments from network science be sensibly applied to tease out those key causal interactions? It remains to be understood which of those causal interactions will result in amplified or mitigating effects, whether they are stable or dynamically changing, and how that impacts on positive feedback interactions. Continuing advances in ocean robotics and the combination of remote and in situ observations with research initiatives such as the Decade of Ocean Science will provide the quality and amount of data for the sophisticated mathematical approaches needed to consider dynamic complexity.

I also see that the complex adaptive systems framework and its evolving techniques can help us understand questions related to difficult 'triage' decisions on the allocation of finite resources to preserving critical ecosystem services. A feature of anthropogenic climate change realized from the last decade of research is that previous strategies to escape climate change effects through evolutionary adaptation, refugia and migrations may not work. Understanding whether many of our current and planned conservation strategies such as 'safe operating spaces' or 'climate refugia' are appropriate is a critical question.

I am excited that, in the next decade, it seems increasingly possible to step out of our comfort zone and focus on addressing the complex changes. In my own area of research, I anticipate that changing our conservation and sustainable management paradigm to also include dynamic complexity will help us develop realistic strategies to avoid further erosion of marine biodiversity and help rebuild critical marine life.

Lei Chen: phenology and climate change, looking back and moving forward

Phenology is the study of the relations between climate and periodic biological events. Because phenology is especially sensitive to climate variations, changes in phenology — including shifts in flower and leaf opening in plants, and changes in animal migration timing — has provided the first clear visible signals of how global climate change influences living organisms.

Over the past decade, one of the most notable developments has been the increasing numbers of phenological data networks all over the world. It is exciting to see local citizens sharing numerous timely phenological observations online via notebooks or mobiles. These site-monitoring observations provide detailed insights into organisms' phenological responses to climate change, from small to broad spatial scales. For example, by 2020, citizen scientists have contributed more than 24 million phenological records of plants (for example, leaf-out and flowering) and animals (for

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example, bird migration and frog calling) to the USA National Phenology Network.

In addition, phenological records are far more diverse and comprehensive than previously expected. For instance, automatic digital pheno-cameras and camera traps are increasingly being used over a broad spatial scale, improving data reliability and quantification. Advances in remote-sensing technology over the past decade have enabled more detailed and comprehensive (global-scale) monitoring of land-surface phenology. Historical patterns of phenology across species and geographical regions are also being incorporated by using specimen-based data. The microcore sampling method has been extensively used to detect the intra-annual growth dynamics of tree stems in response to climate change.

Despite these technological advances and expansions of data sources, many key questions related to climate–phenology relationships remain unanswered, and it remains unclear how phenology will continue to change under future climate warming. For plant species in temperate forests, for example, warmer temperature in spring may stimulate earlier leaf-out or bud break. However, as many plants must first experience sufficient cold temperature before they break dormancy, the effects of warmer winters may delay spring leaf-out or flowering. In this context, will spring phenology continue to advance under future climate warming scenarios? Similarly, both advances and delays in autumn phenology of plants have been observed during the past decade.

A core issue is that the multiple stimuli and mechanisms involved in phenology remain poorly understood. There are therefore urgent needs to elucidate how biotic and abiotic stresses, such as temperature, photoperiod, snow cover, water and food availability, habitat loss and fragmentation, influence the phenology of plants and animals. In addition, phenological responses to climate change may vary between sexes, populations and species, and little is known about ecosystem-level consequences of such phenological mismatches. More studies are also needed to understand variations in climate–phenology relationships among multiple phenological stages in different taxa and seasons, the effects of phenological changes on organisms' fitness and trophic interactions, as well as phenological effects of genomic variations and their interactions with environmental changes.

On the one hand, global warming has led to shifts in phenology across multiple taxa. On the other hand, changes in phenology — particularly that of plant producers — may, in turn, drive further climate change. However, we have limited knowledge of potential feedback effects of warming-driven shifts in changes in phenology on the climate system. Therefore, increasingly deep and integrated multidisciplinary cooperation in phenological studies is both required and anticipated in coming decades.

Trevor F. Keenan: the terrestrial carbon sink and its feedback to climate

It is said that there are decades where nothing happens, but for those focused on the terrestrial carbon sink and its feedback to climate, this past decade certainly has not been one of them. The fields involved have dramatically changed over the past 10 years, driven by a confluence of technological advances, theoretical developments and the widespread embrace of open science practices. The result has been a deluge of observations and derived products, and a more holistic understanding of the role of the terrestrial biosphere in the Earth system.

Technological and data science advances, combined with the recent move toward open science practices (such as depositing data and code in repositories), have colluded to vastly increase the amount and quality of observations available for public use and have lowered the barrier for researchers around the world to advance the science. Large national research initiatives such as the National Ecological Observatory Network (NEON) and the AmeriFlux Management Project in the USA, and many others globally, were funded in the past decade with a mandate to provide harmonized and quality-controlled observations from hundreds of carbon-cycle measurement sites for broader public use. In tandem, technological advances are making novel sensors more widely available, such as methane flux sensors based on optical spectroscopy, forest structural measurements from LiDAR, airborne hyperspectral measurements of canopy characteristics and fluorescence sensors that provide information on photosynthesis. Not to mention the expanding constellations of Earth-observing sensors from both the world's space agencies and a growing private industry.

The resulting data deluge has led to a more holistic understanding of the terrestrial carbon sink by facilitating the integration of theory with observations of different components of ecosystems and their feedbacks to the climate system. For example, plants and microbes were previously examined primarily in isolation, but their interactions are increasingly recognized as important for understanding whole-ecosystem regulation of the carbon sink. We are learning that individuals and ecological communities adapt to change, particularly through advances in eco-evolutionary optimality theory, and that they work together to sequester a large proportion of emissions. Much remains unknown, however, about the degree to which ecosystems can adapt to ameliorate the impacts of a rapidly changing climate,

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how long they will continue to sequester carbon or how long-term ecological change will feed back to the climate system.

The increased accessibility and diversity of available data has also created challenges. The ease with which complex statistical approaches can now be applied to large datasets means that collaborations must include the right expertise to avoid misinterpretation of results. This is important, as the resulting data products typically lack real-world ecophysiology and often, by design, have incorrect assumptions embedded (for example, photosynthesis is commonly and incorrectly assumed to not respond to CO_2). The challenges involved are more than offset by progress resulting from the holistic understanding provided for understanding long-term changes in the terrestrial carbon sink, but the new data paradigm emphasizes the need for graduate training focused on both ecophysiological theory and data science skills.

Merritt R. Turetsky: the impermanence of permafrost and its role on climate

The past decade of research on permafrost thaw has been a community effort, with research networks around the world changing the way we do science. Long described as the 'glue of the Arctic', permafrost creates the literal foundation that affects most life in the Arctic, and its presence regulates water, energy and nutrient cycling. Storing more than twice as much carbon as is currently held in our atmosphere, permafrost is a legacy of past climate but almost certainly will play a role in shaping our climate future. When I began my research career 20 years ago, we knew just enough to be concerned about the uncertain fate of permafrost carbon. Because we knew little, the value of every new study was high. Over the past decade, enough data became available that research networks took up a synthesis charge. These efforts have improved our confidence on some issues, but have opened up new questions and uncertainties.

We have learned that permafrost emissions are unlikely to occur as a carbon or methane 'bomb', but rather will be more sustained. While they will remain smaller than anthropogenic emissions, permafrost emissions could impede our ability to achieve emission reduction targets. Future research is thus likely to focus on global and regional permafrost change hotspots related to both the pace of thaw and the magnitude of emissions. To achieve this, we need to move beyond temperature as the core of permafrost monitoring, assimilating, for example, new spatially-explicit information on ground-ice content or Yedoma carbon stocks. Several other challenges await — multi-scale measurements of atmospheric CO_2 and CH_4 have created heightened awareness of cold season emissions; no longer can we rely solely on understanding from summertime studies. Global models are powerful tools, but none deal with permafrost complexity. These models need to tackle the challenges of representing fine-scale thaw mechanisms and reducing uncertainties related to Arctic vegetation, which could offset thaw-related carbon losses. Earth history provides an actual record of past climate and permafrost change, yet we currently lack a framework for how to use permafrost responses to previous interglacials as an analogue to today's rapid warming. Innovation will come from merging understanding from paleo-permafrost reconstructions, modern observations across spatial scales and future projections of permafrost change.

The next decade of permafrost research will be even more convergent. We need to translate permafrost knowledge for community planning to make projections over more policy-relevant time frames. Permafrost is shaped not only by climate but also by human behaviour and land use. Placing permafrost thaw in a socio-ecological framework will move our questions into the realm of adaptation and management. We must stay focused on using broader climate policy to keep as much permafrost as possible frozen. But where we know permafrost is likely to thaw in the near future, can anything be done? Can we, or should we, modify surface conditions or alter fire management to slow thaw rates? Can we modify soil microbes or vegetation to minimize carbon loss or maximize ecosystem carbon uptake? These questions feel uncomfortable now, but because we know so little in this context, the value of every new study will be tremendous.

Sally Brown: be prepared to expand and retreat to adapt to sea-level rise

Pioneering a new product can take years of development. In the last decade, we have witnessed the birth of climate services and improved methods for adapting to rising sea levels. In this product life cycle, we have shifted from the 'introduction' to 'growth' stage as damage from sea-level rise increases. This may make adaptation sound like a business opportunity, but the willingness to adapt has been recognized: the Bangladesh Delta Plan, a giant sea wall proposed around Jakarta and climate-smart developments though community and ecosystem resilience in Palau and other small islands as well as storm surge barriers under construction worldwide are a few examples.

In 10 years, our knowledge of sea level has become more targeted. Instead of numerous projections with large uncertainties, we have come to understand what is important surrounding uncertainty, such as high rates of melt from the Greenland Ice Sheet. Big data in both climate and socioeconomic development have enabled more detailed and local impact assessments. Society has gained an appreciation for nature-based solutions to sustain and improve resilience of vulnerable

Credit: Peter Cade/Stone/Getty

communities — solutions that mitigate climate change and help reverse the ecological crisis.

Big questions for the future fall under the themes 'expand' and 'retreat'. As population and blue growth in towns and cities has expanded, the amount of reclaimed land, especially in Asia, has been growing. But will this reclaimed land offer protection against sea-level rise? Can atolls be artificially raised? Are there sufficient sand resources for reclamation and nourishment? Can nature-based solutions expand sufficiently to protect coastlines? Can we expand the resolution of digital elevation data for improved impact modelling? For those experiencing frequent flooding or at threat from erosion, what are the mental health impacts?

Retreat offers other challenges: if ice sheets rapidly retreat, will we see a step change in sea-level rise, and if so, when? With rising groundwater, erosion and flooding, how can we prepare to retreat? How will low-lying islands and deltas cope, where there are limited places to retreat to, while preserving cultural values? How can the world's poorest areas increase their resilience so their livelihoods are not eroded?

Moving into the United Nations Decade of Ocean Science for Sustainable Development and targeting the Sustainable Development Goals, we need to answer these questions around our ecological, sustainable and inclusive values. Inclusivity applies to all scientists across all career stages, but especially for nations that are projected to suffer most. Academic studies are lacking in many African nations, which needs urgent attention. For all nations, new science needs to include education and support for local residents so they are able to sustain their livelihoods as the coast changes. Educating politicians who can influence coastal policies, such as retreat, is increasingly important.

Regardless of mitigation, we are committed to adapt to sea-level rise. Over the next 10 years, for places that need to adapt but are not yet ready, I would like to see greater open and accessible data that is interpretable for those with a range understanding and skills relating to coastal change and adaptation, and inclusion of new multi-scale coastal change models where appropriate, so the right decisions can be made at the right time. Adapting to sea-level rise takes many guises, and growth and integration in all disciplines and nations is needed to help those at risk adapt.

Frank Jotzo: successes and future of climate policy

A decade ago, keeping warming to 2 °C seemed all but impossible. The Stern Review instead focussed on 3 °C. Global CO_2 emissions grew by 31% over the century's first decade. Things look better now. Emissions grew by about 10% from 2010 to 2019. Net-zero emissions has become a rallying point, and the 'below 2 °C' ambition seems no longer outlandish. What has changed? One major factor is technology. The cost of important zero-emissions technologies has fallen far faster than any mainstream projection anticipated. Solar or wind power are now the cheapest forms of energy in many places of the world. Energy storage is becoming much more affordable, electric car technology has made leaps that were unimaginable a decade ago and ways to decarbonize industry are opening up. Low-carbon pathways are open to all countries.

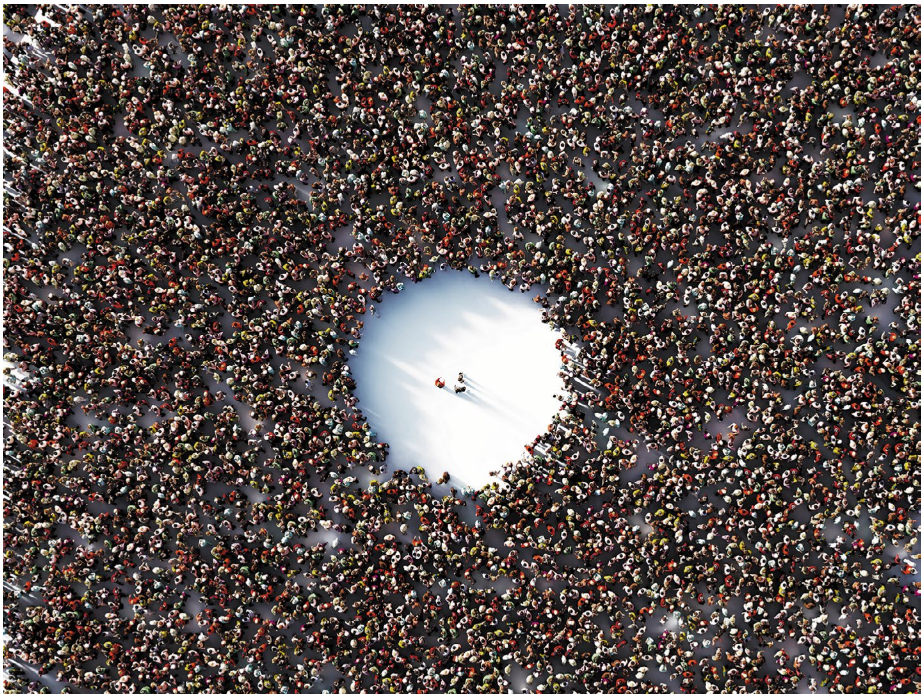
The other is that businesses now see the shift to zero-emissions systems as an opportunity, and in any case see it as inevitable given observed climatic changes. Many governments view climate action as a way to reap macroeconomic benefits from a new investment drive. It is evident in some of China's growth strategy, Europe's 'green deal' and President Biden's agenda. Good climate policy now ranges over multiple objectives and many dimensions of policy.

Add to this the practical experience that emissions reduction policies typically don't hurt. Much analytical effort has gone into designing policies to minimize economic costs and avoid making politically influential players worse off. Governments have implemented them, and they work. Carbon pricing is effective, and emissions trading schemes have typically performed at lower prices than expected. Many other policies are in place, from process regulation to innovation support, and demand side measures. They are usually effective and don't seem to affect economic growth. There are other benefits, from cleaner air to industrial modernization.

The research community needs to make sure that analysis, and the advice that flows from it, is not hobbled by outdated assumptions. Too many of the models used for climate policy assessment have economic and technological pessimism baked into them by low-balling substitution options and future technology improvements. Too often modellers use outdated technology cost assumptions and omit co-benefits of cutting emissions. And too rarely do modelling scenarios cover a truly broad range of future possibilities.

Research is needed on how to bring about decarbonization of heavy industry, trade in zero-emissions energy, emissions reductions in agriculture and carbon uptake on land, and how to prepare for technological CO_2 removal. More knowledge is also needed on how policies can support effective climate change adaptation across the spectrum.

A huge policy challenge ahead is the decline of coal, oil and gas. As these industries shrink, we will see economic and social disruption concentrated in some regions and countries. It is a breeding ground for political polarization, which fossil fuel lobbies and opportunistic politicians can stoke. Research on how policy can make transitions smoother will become more important. Finally, we need to keep in mind that climate change is deeply integrated with development. Transformations to zero-emissions systems



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will be made only if they help people achieve a reasonable standard of living. And they will take place while climate change already affects a large share of the world's population.

Frances C. Moore: the expanding and maturing field of climate change economics

When I began my PhD a decade ago, climate change economics was an extremely niche area. Just a few topics dominated — especially discounting and the relative merits of different climate policy instruments — and the number of researchers was small, incommensurate with the scale of the environmental, economic or policy challenges that climate change presents. However, since then, the field has broadened, deepened and strengthened links to climate science.

Notably, there has been an explosion of studies documenting the sensitivity of social and economic systems to temperature. This literature, using statistical approaches designed to identify causal relationships in non-experimental data, has uncovered the effects of temperature across a wide range of outcomes: conflict risk, pre-term birth, classroom learning as well as overall economic productivity across many sectors. This discovery of pervasive and, in some cases, large temperature impacts, even in wealthy countries, is a sharp break with previous work, which understood effects to be mostly limited to a few highly exposed sectors, such as agriculture and coastal infrastructure.

Important advances have come from questioning assumptions underlying the cost–benefit assessment of climate policy. Ten years ago, conventional wisdom held that substantial emissions reductions by 2050, required to limit warming to less than 2 °C, could not be justified on a cost–benefit basis. Many studies now show that this finding is overturned under alternate but justifiable models of how climate change affects the economy and human welfare. Two prominent examples are the question of whether climate change affects the underlying growth rate of the economy, and disentangling risk and time preferences in the utility function.

A welcome development has been growing interest across the entire economics discipline, with scholars from labour, development, macro, health and financial economics working on questions of weather and climate. Even more important has been recognition of systemic climate risk within major financial institutions. Central banks, institutional investors and credit rating agencies direct capital investment flows and manage economic risks, and will play a critical role in structuring future adaptive transitions. Markets, communities, households and businesses will have to adapt both to a continuously changing climate, and to a low-carbon economy. Forward-looking regulations and investments that anticipate these changes will lower the costs of these transitions.

I see several important areas still in need of substantive work. Firstly, an assessment of alternative policy instruments that better incorporates the political and technological feedbacks that will accompany major climate policy. Economists tend to favour carbon pricing because of its cost-effectiveness. But how do pricing policies perform given a richer representation of other relevant market failures or real political constraints? Examples include subsidy-driven declines in technology costs or strategic interest group dynamics, where policies themselves create or undermine powerful interest groups and therefore alter the space of political possibility. Collaboration with engineers and political scientists can help address these questions. An expanded focus on desirable policies for low- and middle-income countries, essential to meet ambitious decarbonization goals and which present distinct challenges, is also critical.

More work is needed on understanding climate damages, particularly those that fall outside of traditional market measures, such as losses of cultural heritage, conflict risk or biodiversity loss. These are extremely difficult to value and are not adequately incorporated into current estimates of aggregate climate damages, such as the social cost of carbon. Also critical is understanding the transition and adjustment costs associated with a continuously changing climate. Too many studies estimate equilibrium damages or assume costless adjustment. But infrastructure is long-lived, and natural hazards are already under-priced in many property markets. In this context, climate change risks creating stranded assets, price bubbles and unsustainable liabilities for local or even national governments, all of which could add substantially to climate change cost estimates.

Sander van der Linden: behavioural insights

Acceptance of anthropogenic climate change varies widely around the world. From perception to action, there has been tremendous progress over the last 10 years in our collective understanding of the social, cultural, political and psychological factors that shape individual views about climate change. For example, an important advance has been our ability to combine high-resolution geospatial data with survey data on human cognition. This has helped answer questions such as whether people are accurately perceiving local and global environmental changes, the extent to which perceptions of extreme weather

Box 1 | Contributors

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Gary P. Griffith is a research scientist at the Norwegian Polar Institute and a visiting research fellow at the Department of Ecology and Evolutionary Biology, Levin Lab, Princeton University. His research focuses on applying complexity science to investigating anthropogenic climate change and human stressors on marine ecosystems.

Lei Chen completed his PhD in ecology at Hokkaido University and postdoctoral training at Texas Tech University. He is a distinguished research fellow at the College of Life Sciences, Sichuan University, China. His current research mainly focuses on how global climate change influences plant growth and vegetation ecosystems.

Trevor Keenan is an ecosystem scientist with a background in mathematics. His interests are centred on understanding the terrestrial carbon sink and feedbacks to climate by integrating ground observations of land-surface dynamics with models and remote-sensing data. He is an assistant professor at UC Berkeley and faculty scientist at Lawrence Berkeley National Lab.

Merritt R. Turetsky is an ecologist and carbon cycle scientist who has worked in permafrost landscapes for more than two decades. She is the director of the Institute of Arctic and Alpine Research and a professor in the Ecology and Evolutionary Biology Department at the University of Colorado, Boulder. Turetsky is equally passionate about northern ecosystems and the people who rely on them.

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patterns impact climate change concern and how prior beliefs about the world impact understanding of climatic change. More generally, through large meta-analyses, we have accumulated a wealth of knowledge on key determinants of people's belief in climate change, such as public perceptions of the scientific consensus on climate change.

At the same time, the chasm between belief and action remains. Medium-sized correlations between climate change beliefs and individual and collective action to mitigate the problem has led some scholars to suggest that scholarly work on beliefs should be abandoned and focus shifted toward interventions that can change behaviour directly. I remain hesitant about such recommendations. For example, consider that while behavioural interventions that directly target social norms have seen relative success, what underlies the efficacy of many of these interventions are changes in beliefs about what others believe. In other words, second-order normative beliefs. Attempting to change behaviour without understanding the beliefs and motivations that underpin people's decision-making risks short-term success over long-term failure.

Looking to the future, one of the most exciting and important areas focuses on how to sustain changes in beliefs and behaviours over time. Despite some progress, very little is known about the long-term effectiveness of interventions, as most studies do not include longitudinal measurements. Do people forget climate information over time because of real-world interference, or do they lose motivation to sustain belief and behaviour change? I look forward to research which better integrates such cognitive and motivational explanations and moves beyond single-dose exposure in a controlled laboratory setting to evaluate the effect of repeated campaign messages in real-world environments.

In addition, I hope for more engagement from colleagues who conduct neurophysiological research. Although they might not see the immediate relevance of their work to climate change, the next frontier needs to answer difficult questions, such as: do fearful messages about climate change actually elicit differential neural activity? What physiological changes are experienced when people engage with climate change stimuli? Are risk–reward centres of the brain active when people evaluate climate change risks? Existing work in other areas (such as health) has already started to look at how survey and neuroimaging data diverge in predicting people's responses to persuasive messages.

Lastly, there is a need to shift from intention-based research to more policy-relevant and impactful behaviours that have the technological potential to mitigate climate change. Although those behaviours are more difficult to study and change, our theories need to explain how people make costly mitigation and adaptation decisions in ecologically valid settings across diverse cultures. Doing so will not only advance the behavioural sciences, but also make our insights more integral to climate policy. ❐

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