THE ROYAL SOCIETY

CLIMATE CHANGE : SCIENCE AND SOLUTIONS | BRIEFING 1

# Next generation climate models: a step change for net zero and climate adaptation


**In brief**

Climate models are fundamental to understanding climate change and anticipating its risks. They provide the basis for predicting impacts, guiding adaptation decisions and setting mitigation targets. Society now needs more detailed and precise information to enable robust decision-making in the face of rapidly amplifying climate change and for achieving its goal of net zero by 2050.

Existing technological potential and scientific capability can be harnessed through a new level of international cooperation and investment in next-generation super-computing and Earth system science. This step-change transformation could deliver the robust science required to support greater ambition in mitigation and adaptation in the coming decades.


## INSIGHTS

- An international next-generation climate modelling centre, based on an exascale computing and data facility, can bring about the step-change that is now possible in modelling capacity to support the technology roadmap to net zero and investment in climate adaptation.
- A dedicated facility, of unprecedented scale, with a role similar to that of CERN in particle physics, would overcome the scientific and technical barriers of delivering timely, detailed, consistent and actionable climate predictions for the coming century, building on the construction of Earth system models that has been one of the great scientific achievements of the last 50 years.
- Recent studies have shown that a new generation of high-resolution models can revolutionise the quality of information available for mitigation and adaptation, from global climate and regional climate impacts, to risks of unprecedented extreme weather and dangerous climate change.
- Through partnership and collaboration with such a new global facility, national climate modelling and services around the world will be propelled to a new level of capability, to the benefit of the citizens of their countries, and indeed, the world.
- To ensure uptake and use of the latest predictions, the facility can also contain a dedicated operational data service that will embrace the latest digital technologies in data analytics and informatics, such as Artificial Intelligence (AI), machine learning and advanced visualisation.
- Ongoing evolution can be driven by an 'Incubator' to stimulate new ideas for next generation modelling, an 'Open Data Lab' to foster public-private partnership on cutting-edge digital solutions based on the Data Cloud and Application Programming Interfaces (APIs), alongside an academy to train developers and users of climate model information.

# 1. The story so far

## 1.1. Predicting future changes in the Earth's climate

The Earth's climate is immensely complex. Although scientists can detect many changes in our climate from observations, these observations alone cannot explain why the climate is changing, nor how it will change in the future. For that climate models are needed.

As early as 1896, Arrhenius had postulated that a doubling of carbon dioxide would lead to 4°C of global warming, based on simple energy balance arguments[1]. It was only with the advent of computers in the 1950s, that climate models, capable of simulating the response of the global circulation, were developed alongside numerical weather prediction systems. These models were based on simulating the weather, and thereby the climate, from first principles using fundamental physical laws. These laws, represented by mathematical equations, have to be solved using sophisticated numerical techniques. By dividing Earth's atmosphere, oceans, land and ice into millions of grid cells and solving the equations forward in time, simulations of the evolution of the world's weather and climate in each cell over the coming hours to decades can be created[2].

The main challenge for models has always been how best to represent processes such as cloud formation and cumulus convection that occur on scales that are finer than the grid of the model. Such processes are critical for determining the magnitude and pace of climate change, for predicting changes in precipitation, and for capturing severe weather events, such as tropical cyclones and floods. Despite great progress in improving the representation of these processes in climate models, the lack of capacity to simulate them in fine detail accounts for the most significant uncertainties in future climate, especially at regional and local levels[3].

## 1.2. Harnessing the available computing power and fundamental science for the benefit of humanity

Since their inception, climate models have been computing-intensive, and the availability of computing power has dictated the level of sophistication and the type of simulations that can therefore be performed. Today these models represent some of the most complex applications of supercomputing and typically include well over a million lines of code.

Building on the established strengths in simulating physical weather and climate, Earth system processes have been added to the models in recent years with the introduction of atmospheric chemistry and bio-geochemical cycles associated with marine and terrestrial ecosystems, such as the carbon and nitrogen cycles. These models enable specialists to go beyond the physical attributes of climate change, to consider the role of natural and managed resources and ecosystems in determining our future climate and its impacts[4] (Figure 1).

The construction of computer models that simulate the Earth system and enable scientists to predict, from fundamental physical principles, how the weather and climate will evolve, is one of the great scientific achievements of the last 50 years. This has allowed society to look into the future and recognise the implications of a warming world. As a result, all nations now agree that tackling climate change is a defining challenge for the 21st century[5,6].

Climate models, and the predictions made for different emission scenarios, form much of the bedrock of the evidence base for mitigation and adaptation[7]. Scientists have learned that the ocean, with its huge capacity to store heat, is fundamental to how climate change will manifest itself in the coming decades[8]. They have learned that climate change will lead to more extreme rainfall and flooding, as well as more severe droughts[9]. They have learned that the response of the terrestrial biosphere to warming and to changes in rainfall patterns may mean that it becomes a less efficient carbon sink and that this in turn may amplify the greenhouse effect from human carbon emissions[10].

Climate models have also allowed scientists to explore the possibility that the warming Earth system may tip over into states that are far more dangerous than currently anticipated[11] and possibly irreversible. These tipping points can involve the physical climate system, for example rapid icesheet loss or collapse of the oceans' thermohaline circulation, as well as the terrestrial carbon cycle, such as thawing permafrost or loss of the Amazon rainforest. Changes of this nature would have huge implications for the world's adaptive capacity and for international mitigation policies by, for example, reducing allowable carbon 'budgets' for future emissions.

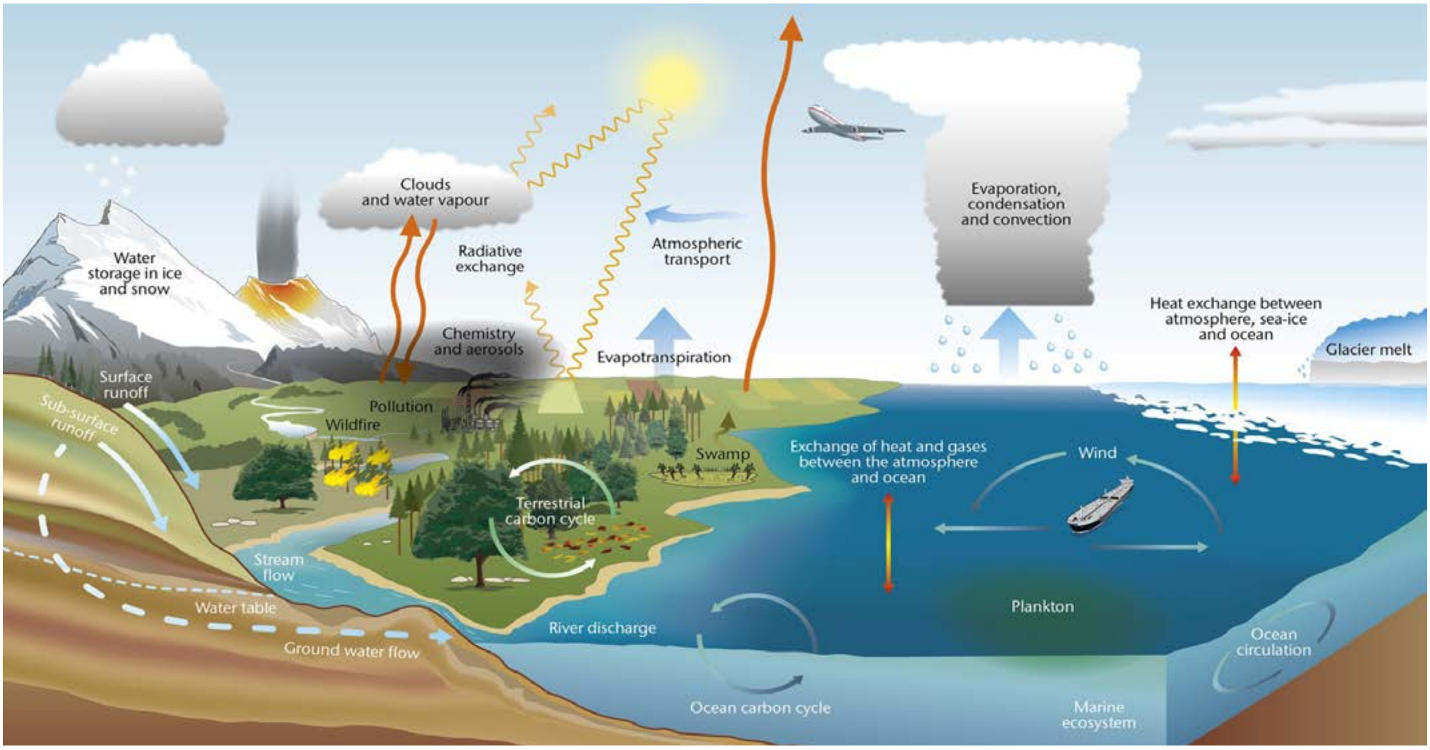
Despite all these advances, climate scientists know that climate models and their predictions still have serious shortcomings, partly from gaps in fundamental knowledge of the Earth system, but also due to scientific limitations imposed by supercomputing power. This challenge must be addressed as a matter of urgency if the modelling community is to succeed in its collective scientific goal of providing the detailed information needed to support the full range of planned adaptation and mitigation actions.

Despite huge progress in the last 50 years, climate models and their predictions still have serious shortcomings. This is primarily due to scientific limitations imposed by supercomputing power and must be addressed as a matter of urgency.

**FIGURE 1**

## Current generation climate models

Schematic showing the physical and biological processes included in current generation climate models. It emphasises the importance of atmospheric and ocean flows in driving fundamental cycles of the Earth – water, carbon, atmospheric chemistry and ocean biogeochemistry.



# 2. Why climate models are so important for climate action

Today climate science is at a watershed moment. Science and technology have advanced to the point where a quantum leap to a new generation of climate models is now in prospect.

In the few critical years to 2030, climate models will provide essential information for both mitigating and adapting to climate change.

### 2.1. Understanding the implications of various mitigation strategies

The viability of national and international emission mitigation policies must be tested using assessments based on climate model simulations and predictions. These will serve to inform society of the consequences of failure to achieve the necessary emission reductions, on regional impacts and risks from extreme events. Only with the best possible climate models can we show what is at stake, what might be lost, and what the future climate damage and costs of inaction will be.

Pathways to net zero will transform landscapes, place greater reliance on weather-driven renewables, such as wind, solar and hydropower, and potentially put pressure on the water-food-energy nexus (See briefings 9: *Climate change and land*; and 10: *Nourishing ten billion sustainably*). A strong climate science base will be essential for ensuring that mitigation actions are compatible with the way weather changes with climate, and do not have unexpected consequences.

### 2.2. Informing adaptation strategies and long-term resilience

In terms of adaptation, there is a need to establish plans to climate-proof lives, towns and cities that also protect the natural environment. As UN Secretary General Antonio Guterres has said, the "'race to resilience' is as important as the 'race to net zero'"[12]. There is growing evidence that human influences are increasing the likelihood and severity of many extreme weather events[13]. Further climate change is inevitable, even if emissions fall, because of the existing accumulation of carbon within the atmosphere and the inertia of the system.

Climate model predictions are fundamental for informing this process of adaptation at global, regional and local levels, with implications for protecting lives, livelihoods and critical infrastructure, to securing sustainable supplies of food, water and energy.

The scale of the potential investments in adaptation and the increasing vulnerability of societies across the world, together, place a very high value on more detailed and precise information about how weather and climate, and especially extreme weather hazards, are likely to change over the next decades and beyond. Detailed, location-specific climate information can safeguard the trillions of dollars' worth of investment in infrastructure projects made over the coming decades by ensuring they are resilient to the projected impacts of climate change in terms of their location, construction and management. (See briefing 8: *Weathering the storm: how science can contribute to improving global climate resilience through adaptation*).

Today climate science is at a watershed moment. Science and technology have advanced to the point where a quantum leap to a new generation of climate models is now in prospect, models that can deliver the detailed scientific evidence base for mitigation and adaptation that society urgently requires to further support decision-making and guide and safeguard the investments that the world must make. International negotiations offer a forum for policymakers to initiate work with the climate science community to deliver this rapid progress.

# 3. Next generation climate models: the potential for a revolution in climate modelling and its application

### 3.1 The distinct challenges of predicting future climate

Existing models have significant shortcomings in simulating local weather and climate because of available computer power. They cannot resolve the detailed structure and lifecycles of systems such as tropical cyclones, depressions and persistent high-pressure systems, which drive many of the more costly impacts of climate change, such as coastal inundation, flooding, droughts and wildfires; nor are they able to resolve ocean currents that are fundamental to climate variability and regional climate change[14].

Since the first IPCC Assessment Report (AR1) in 1990, models have gradually evolved in terms of resolution and complexity, and more countries have engaged in the process. AR1 climate models used a horizontal grid spacing of 300 kilometres, whereas today, for IPCC AR6, climate models have a resolution of around 100 kilometres. This has been hard won with the available computing resources – each time the resolution is halved (such as from 100 kilometres to 50 kilometres), 10 times more computing power is required.

Meanwhile, over those same 30 years of IPCC reports, there has been a 'quiet revolution' in weather forecasting[15]. Weather models are now delivering global predictions at 10-kilometre resolution, and regional forecasts at the kilometre-scale. These advances have provided indisputable evidence that resolutions nearer a kilometre are needed for accurate modelling of important weather components such as cloud systems, convection, organised monsoon rainfall belts and tropical cyclones, as well as for local extreme events.

So why hasn't climate modelling followed the same path? Quite simply it is because the scale of computing power required to perform multi-century global simulations for multiple scenarios at pace eclipses what is needed to make operational weather forecasts for the next few weeks.

### 3.2 Modelling the global climate system to inform action at all levels, from global to local

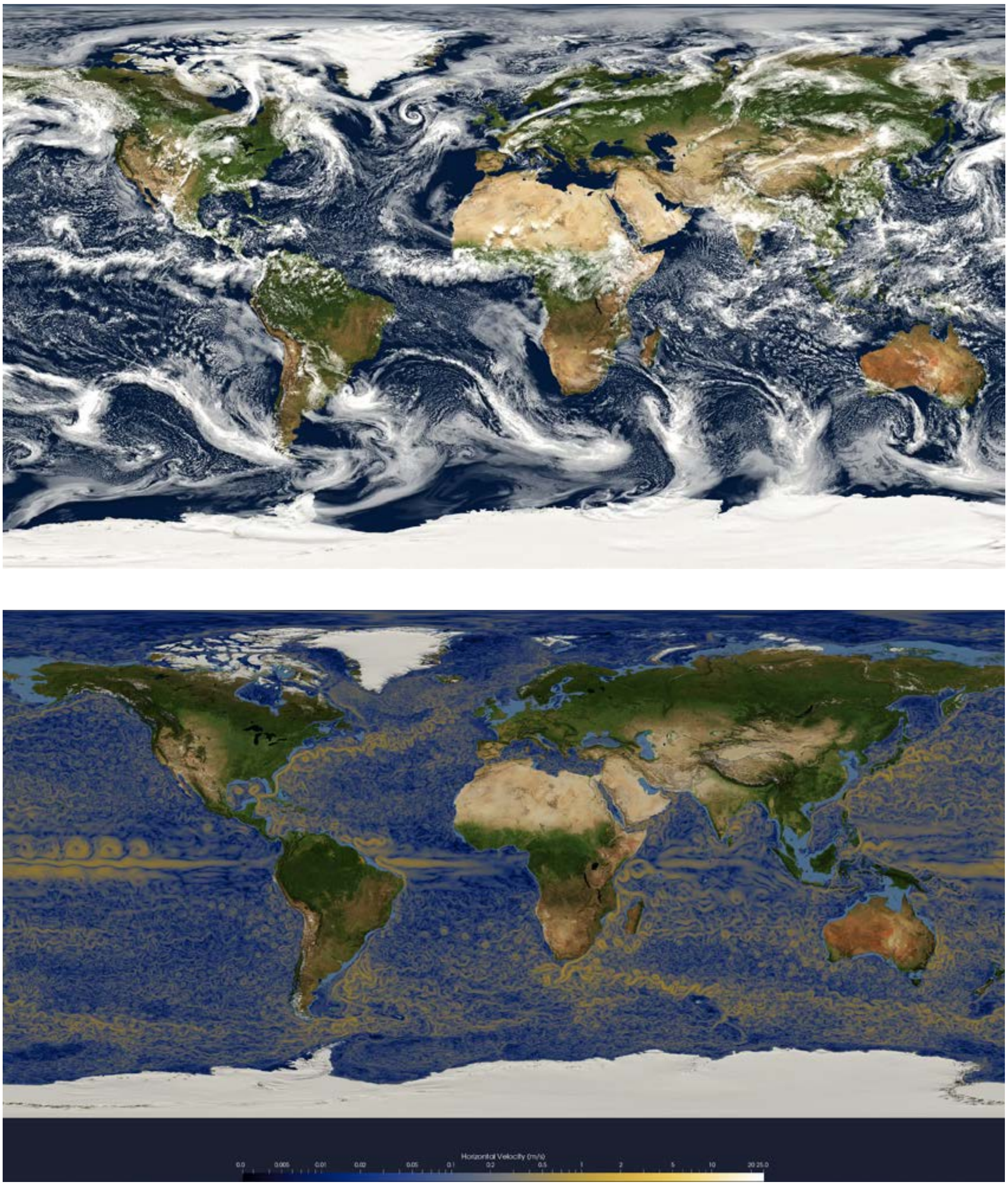
At the heart of the problem is the need to simulate the entire global climate system – especially the atmosphere and ocean – at kilometre scale resolutions and for time periods of decades to centuries. This is necessary because the extreme weather events that cause the greatest damage are generated by processes operating at kilometre scales, while, crucially, their properties are also shaped by the much larger-scale circulation of the ocean and atmosphere. Moreover, there are two-way interactions between large and small scales; in other words, weather and climate are a continuum of energy cascades from the very smallest scales to the very largest planetary circulations and back again.

A massive leap to kilometre-scale global models can finally allow the fine scales of motion to condition the larger scale motions and vice versa. This is the fundamental reason why regional modelling approaches, while useful, are not in themselves adequate. The possibility exists today for predictions of the world's climate to be delivered by a new generation of global models which explicitly resolve kilometre-scale phenomena, such as storms and ocean eddies.

## FIGURE 2

Next generation global storm and ocean eddy resolving climate models explicitly represent weather systems (upper panel) and ocean eddies and currents (lower panel)[16]

This realism will deliver more confident predictions of changes in water availability, in damaging weather, in how the oceans take up heat and carbon, and in related impacts on natural ecosystem services. This knowledge will enable us to quantify societally relevant factors, such as habitat loss, disease spread, wildfire risk, air quality and crop, fishery and forest yields.




Images courtesy of the Max Planck Institute for Meteorology (MPI-M) and German Climate Computing Centre (DKRZ) via Professor Bjorn Stevens and Professor Jochem Marotzke.

Prototypes of such kilometre-scale models are now being built to simulate limited time periods, typically 10s of days, and their level of realism is ground-breaking (Figure 2)[17, 18]. This new generation of models will revolutionise the quality of climate information that underpins climate change decisions – from global climate sensitivity (typically quantified by the change in temperature for a doubling of carbon dioxide levels) and regional climate impacts, to risks of unprecedented extreme weather and dangerous climate change[19].

Beyond the physical climate system, these models will also provide new insights into how other components of the Earth system, such as carbon, aerosols and marine nutrients, depend on fine-scale atmospheric and oceanic circulations (Figure 3), in ways that may materially alter climate trajectories (See briefing 7: *The carbon cycle*). The detailed representation of the complex interactions between vegetation and soil carbon, between ocean circulations and marine ecosystems, as well as human activities, paves the way for a new generation of climate/Earth system models to investigate how risks arising from climate instabilities, extremes, and irreversible transitions might affect society and natural systems.

**FIGURE 3**

## Predicting the future of phytoplankton blooms

Predicting the future of phytoplankton blooms is critical for understanding the future health of marine ecosystems as well as future ocean carbon uptake. Phytoplankton blooms are linked to fine scale structures in the ocean circulation (such as eddies, fronts and coastal upwelling zones) which new kilometer-scale Earth system models are able to capture for the first time.

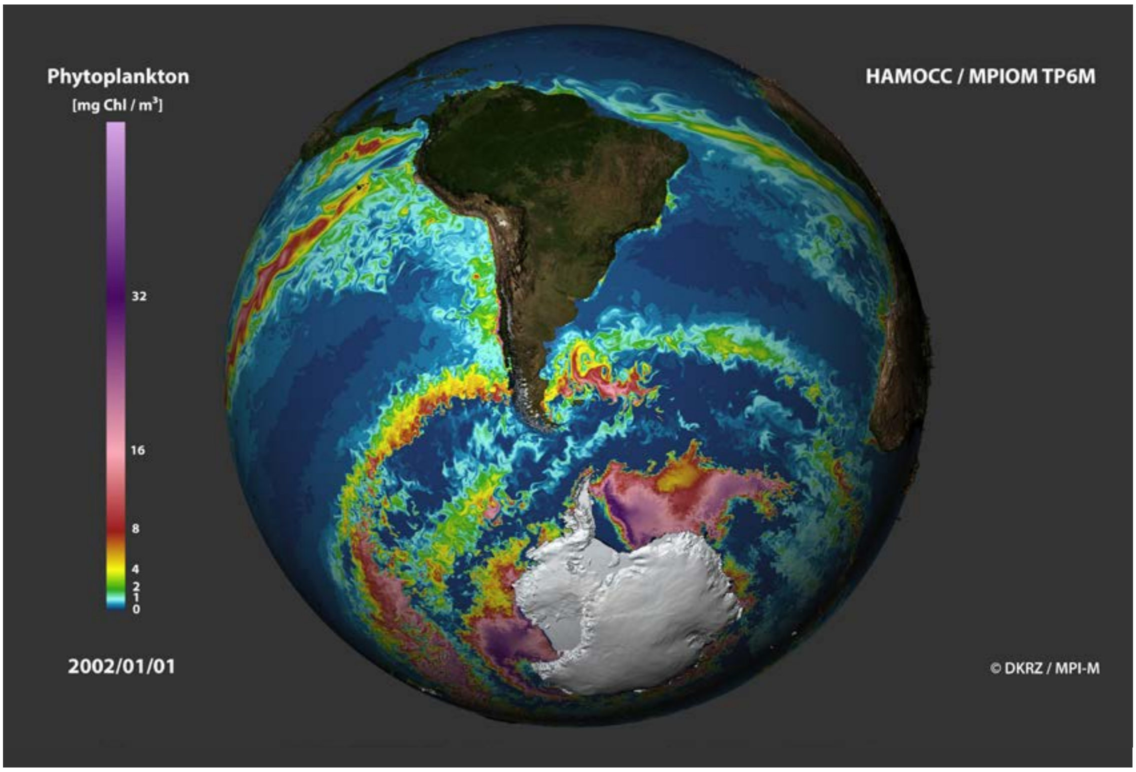



Image courtesy of the Max Planck Institute for Meteorology (MPI-M) and German Climate Computing Centre (DKRZ) via Professor Bjorn Stevens and Professor Jochem Marotzke.

# 4. An international endeavour?

The next decade will bring challenges that can only be addressed through a worldwide, co-ordinated effort by a trained and well-resourced scientific workforce.

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The next decade will bring challenges that can only be addressed through a worldwide, co-ordinated effort by a trained and well-resourced scientific workforce. The twin goals of net zero and climate resilience require a substantial acceleration in the delivery of action-able climate information. The technological potential exists to move from the incremental improvements of climate models of the past 30 years to a step change in capability. The task is formidable: not only is it scientifically and technically complex, but it also needs to address societal needs at every level from local to global. To succeed, this effort must be supported by strong global partnerships.

### 4.1 Global cooperation for global benefits

Today, the scale of the enterprise needed to build and execute state-of-the art global climate models is becoming the domain of the few; the human, computing, data and energy resources required are substantial and are beginning to exceed the capacities of individual nations. To approach the optimal model resolutions, Exascale computing ($10^{18}$ or one billion billion calculations per second) of unprecedented power and cost is required[20]. At the same time the scale of the data challenge is immense, with the potential for exabyte data production (one billion gigabytes) to be reached very soon.

On the positive side, the technological and scientific solutions are within the grasp of the modelling community. As in other major global scientific challenges, such as nuclear fusion (ITER) and finding the Higgs Boson (CERN), the goal can be pursued by bringing together infrastructure and intellectual fire power at an international level to deliver the necessary step-change[21, 22].

The core requirement is a computing and data facility of unprecedented scale, dedicated to the timely simulation, prediction and data analytics of the Earth system, sharing its outputs with the whole world and acting as the hub of a network of national climate facilities. At every stage, it must be guided by societal needs at all levels, from local to global.

Such an initiative could provide a way to overcome the scientific and technical barriers of delivering timely, detailed, consistent and actionable climate predictions for the coming century at the kilometre-scale and with increasing Earth system complexity.

The facility could be a single physical entity, akin to CERN, or a tightly networked constellation of national/international exascale facilities. The overarching goal would be to deliver kilometre-scale global climate predictions and services, which can be accessed by all nations according to their needs and capabilities. Success will depend critically on sustaining and growing the network of expertise and intellectual capabilities of the worldwide climate science, modelling and services community – from across academia, national climate research centres and climate service providers.

This is a huge undertaking and one that will need new investment and cooperation at an international level. But this investment must be weighed against the cost of not doing it. The world already bears huge human and financial losses from weather and climate events, and these will only grow as climate changes. The UN Office for Disaster Risk Reduction estimates that 1.23 million lives have been lost since 2000 due to disaster events, with economic losses of around $3 trillion or $150 billion annually[23]. Observed through such a lens, the benefits of this initiative outweigh the investment by many orders of magnitude.

## 4.2 Accelerating scientific progress and innovation

To achieve its purpose, such a centre would utilise and incentivise innovations in computer and data science and technology to provide a unique range of cutting-edge facilities and services that will build on, engage with, and enhance existing national capabilities. It would take advantage of the huge investments in Earth Observation by providing a computational platform in which these can be contextualised and used for advancing Earth system science, and for initialising predictions and evaluating model performance.

This step change also offers the opportunity to create a dedicated operational data service alongside the modelling capacity. This will ensure that predictions are acted upon, using the latest digital technologies in data analytics and informatics, such as AI, machine learning and advanced visualisation. This will provide an authoritative source of information and data services for the benefit of all. This service portal may be a single entity or tightly networked group of major regional climate service providers, such as the EU Copernicus Climate Change Service[24].

Such a step forward will also be reinforced by an 'incubator' to stimulate the creation and development of new ideas, as well as providing a forum where experts can meet and work together. Following the example of CERN, the modelling effort can also benefit from an 'Open Data Lab', a unique public-private partnership that will work to accelerate the development of cutting-edge digital solutions for the worldwide climate science and user community.

In terms of human capability, such a centre will be staffed by a truly global workforce of scientists and engineers and can feature an exchange programme with national climate science efforts across the globe, as well as a world climate science academy to train future developers and users of climate model information.

The core requirement is a computing and data facility of unprecedented scale, dedicated to the timely simulation, prediction and data analytics of the Earth system.

# 5. What might climate modelling look like in 2030 and 2050?

By 2030, if the challenge of exascale computing can be overcome and next generation kilometre scale global storm-resolving climate models can be deployed, a revolution in climate change information for decision-making will have been achieved.

Societies across the world will know what is likely to happen to their weather and to local extremes that test their resilience. They will know how and why precipitation may change, in distribution, frequency and intensity, and how ocean currents may move and affect regional climates and sea level rise. With this knowledge of the physical climate system, food, water and energy resources can be managed more effectively, with the goal of providing a safe, sustainable and healthy future for all.

By 2050, it is possible to envisage an Earth life system simulator that can predict the multiple relationships between the physical and natural environments, and potentially with society, at both global and national levels. Essentially, this would constitute Earth's physical digital twin – a dynamic representation of the Earth system, optimally blending models and observations and drawing in digital twins of human activity – to enable an exploration of present, and possible futures of the whole Earth system. The feasibility of such an enterprise is already being explored in the EU programme, Destination Earth (DestinE): Shaping Europe's digital future[25] (See briefing 2: *Computing for net zero*).

Finally, it is worth reflecting on the words of Vice-Admiral Robert Fitzroy, the Captain of the *Beagle*, who took Charles Darwin on his momentous voyages, but who was also the founder of the UK Met Office and who issued the first public weather forecasts. After the loss of the *Royal Charter* in a terrible storm in 1859 he wrote to the *The Times* newspaper: "Man cannot still the raging of the wind, but he can predict it. He cannot appease the storm, but he can escape its violence, and if all the appliances available for the salvation of life [from shipwreck] were but properly employed the effects of these awful visitations might be wonderfully mitigated."

Over 150 years ago, Fitzroy embarked on the long journey of making predictions as a means of reducing and managing the impacts of severe weather. These now apply also to managing climate change. From the global to the local and from hours to decades, understanding of weather and climate – indeed the whole Earth system – and the predictions that ensue, enable society to plan for the future and keep its people and the natural environment safe.

This briefing is one of a series looking at how science and technology can support the global effort to achieve net zero emissions and adapt to climate change. The series aims to inform policymakers around the world on 12 issues where science can inform understanding and action as each country creates its own road map to net zero by 2050.

To view the whole series, visit **royalsociety.org/climate-science-solutions**
To view contributors to the briefings, visit **royalsociety.org/climate-solutions-contributors**

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