comment

Ambitious partnership needed for reliable climate prediction

Current global climate models struggle to represent precipitation and related extreme events, with serious implications for the physical evidence base to support climate actions. A leap to kilometre-scale models could overcome this shortcoming but requires collaboration on an unprecedented scale.

Julia Slingo, Paul Bates, Peter Bauer, Stephen Belcher, Tim Palmer, Graeme Stephens, Bjorn Stevens, Thomas Stocker and Georg Teutsch

Water is Earth's life blood and fundamental to our future. Hydro-meteorological extremes (storms, floods and droughts) are among the costliest impacts of climate change, and changes in the seasonality and natural variability of precipitation can have profound effects on many living systems, in turn threatening our food security, water security, health and infrastructure investments. Yet the current generation of global climate models struggles to represent precipitation and related extreme events, especially on local and regional scales[1,2]. The model precipitation biases are substantial in both space and time, and in the tropics they overwhelm the projected signal of climate change[3]. Despite decades of enormous efforts by the community, these biases have remained stubbornly intractable[1,2] (Box 1). Consequently, future scenarios of precipitation remain very uncertain in the IPCC assessments so far[4]. As water is an essential resource for humans and ecosystems, these shortcomings complicate efforts to effectively adapt to climate change, particularly in the Global South, and to assess the risk of catastrophic regional changes.

There are, however, even more fundamental reasons to be concerned about these biases. The heat released when tropical precipitation is formed is a fundamental driver of the global circulation — from the Hadley and Walker circulations to the position and variability of mid-latitude jet streams and related weather patterns. So, these precipitation biases have impacts throughout the climate system. For example, latent heat release plays a key role in spreading the effects of El Niño globally, with consequences for regional climate and weather regimes across the world[5] (Box 1).

The global precipitation biases of current models cannot be ignored. They affect many parts of our physical climate science evidence base, from mitigation through to adaptation and climate risk assessment. If the water cycle and global circulation patterns are affected, then so may be cloud feedbacks, contributing to ongoing uncertainties in climate sensitivity. Likewise, the regional-to-local downscaling methods that underpin our climate change impact assessments are also likely to be compromised. Regional models cannot correct the inherent biases in the weather and climate systems fed from the global models. Consequently, future statistics of local extreme events, on which the design of adaptation measures rely strongly, come with substantial uncertainties.

With advancements in our understanding of climate processes and modelling, and with new supercomputing and data management technologies, the pieces are falling into place to make a step change in our ability to address these challenges.

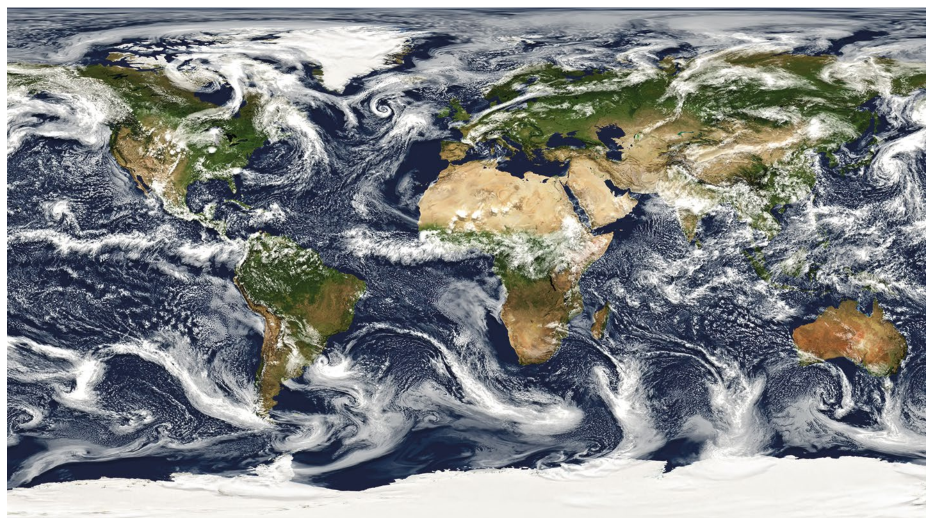


Fig. 1 | The realism of k-scale global climate modelling. Snapshot of clouds from a simulation with a global k-scale climate model, showing the detailed structures of tropical clouds, mid-latitude storms and evidence of MCSs across West Africa and the US Great Plains[13]. Base map provided by NASA's Earth Observatory.

The case for kilometre-scale modelling

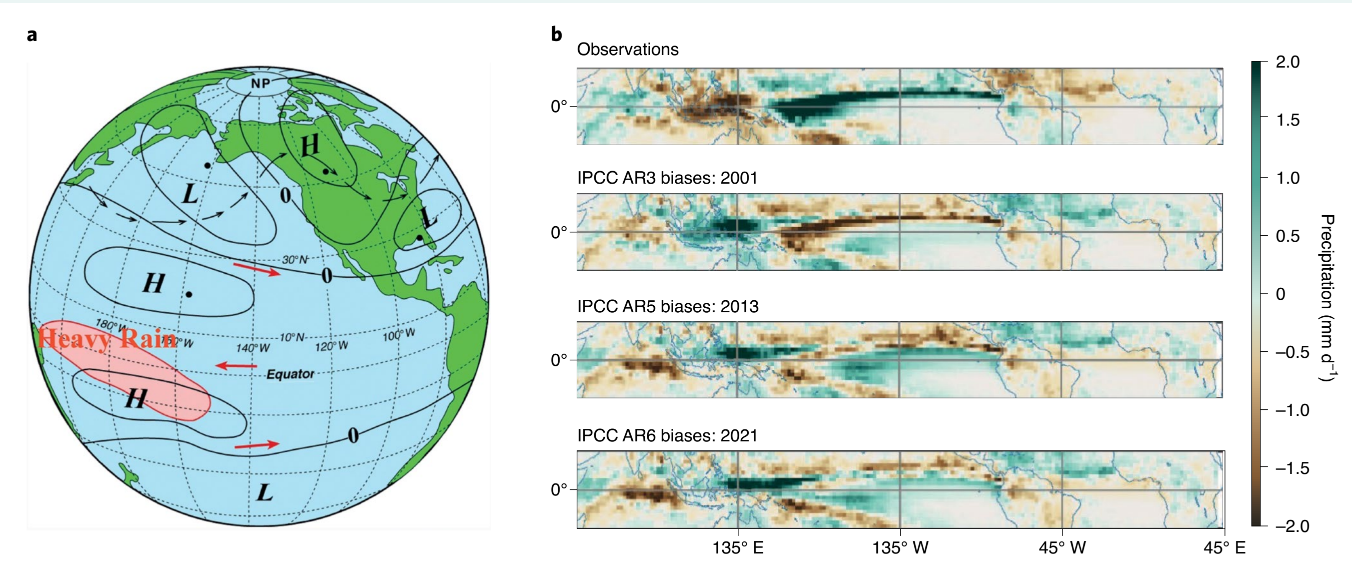
These fundamental shortcomings in simulating precipitation can be overcome. The solution lies in representing, explicitly, the nature of rain-bearing systems. For many parts of the world, these are dominated by mesoscale convective systems (MCSs) or complexes (Box 2). MCSs account for much of Earth's precipitation[6], they generate severe weather events and flooding, and they affect the evolution of the larger-scale regional and global circulation.

The organization, structure and maintenance of MCSs are governed first by the basic ingredients for deep convection (moisture, instability and lift), but more importantly, by how vertical wind shear interacts with convective updrafts, downdrafts and related cold pools[7] (Box 2). This symbiotic relationship between thermodynamic heating and the kinematics

Box 1 | The fundamental role of tropical precipitation in driving the global circulation

The warm oceans of the Indonesian region supply an abundance of moisture to the atmosphere, turning the whole region into an atmospheric 'boiler box'. Deep convective clouds release huge amounts of energy into the atmosphere through condensation. This heat source drives giant, overturning circulations in the atmosphere, the Hadley and Walker cells, which feed into the jet streams and lead to weather and climate changes far downstream[5] (panel a in the figure). The circulation anomalies generated by deep heating from tropical rainfall excite Rossby waves that perturb the jet stream and create conditions that favour high-impact weather situations in the extra-tropics. These global teleconnections are therefore fundamental to predicting regional climate change. Consequently, variations in these warm ocean temperatures, such as El Niño, can drive large shifts in tropical rainfall with profound worldwide consequences[1].

The observed, average rainfall response to El Niño events (panel b in the figure) shows large reductions in rainfall over Indonesia and a tropics-wide pattern of reduced and enhanced rainfall. Climate model average rainfall biases for simulated El Niño events across successive IPCC assessments demonstrate an inverse pattern of similar magnitude to the observed signal (panel b in the figure), which has remained largely unchanged for more than two decades[1]. The failure of models to capture the observed rainfall response limits confidence in predictions of the current and future impacts of El Niño, and may disproportionately affect regions of the world where population growth is largest and the needed capital for adaptation is the scarcest.



Response to tropical convection and the impact of model biases. a, Schematic showing the high (H) and low (L) pressure anomalies and the waves in the jet stream (black arrows) generated by deep heating from tropical convection[5]. NP, North Pole. **b**, Observed average tropics-wide precipitation response (mm d^{-1}) to an El Niño event, and the biases in climate model simulations for the current climate from successive IPCC assessments[1]. Panel **a** reproduced with permission from ref. [5] under a Creative Commons licence (https://creativecommons.org/licenses/by/4.0/). Panel **b** adapted with permission from ref. [1] under a Creative Commons licence (https://creativecommons.org/licenses/by/4.0/).

of the system is crucial for the growth and intensity of MCSs. Yet this occurs on scales finer than can be explicitly represented by current global (and many regional) models that form the basis of our present climate information system.

The traditional approach of using parameterization to represent deep convection is not proving to be a tractable approach for capturing MCSs, nor is it any longer an approximation borne of necessity. Kilometre-scale (k-scale) limited-area models have already demonstrated that a step change to these scales revolutionizes the simulation of local precipitation and its spatial and temporal characteristics, including extreme events, by explicitly representing the kinematics of MCSs[8,9]. Moreover, we now have access to global climate impact models, such as flood and water resource models, that are ready to ingest k-scale precipitation to determine the future impact of water cycle changes on humanity with much greater confidence[10].

Beyond precipitation, k-scale global models will solve many of the problems standing in the way of reliable predictions of regional and local climate change. The realism afforded by these systems will inform future changes in climate and weather regimes, in damaging local weather events, in the interactions between landscape management and the climate, in ocean currents and the take up of heat and carbon, along with the consequences for marine and terrestrial biospheres. The benefits will go far beyond just the future of our water to tell us about other societally relevant issues such as coastal inundation, habitat loss, disease spread, wildfire risk, air quality, crop, fishery and forest yields, and renewable energy potential.

The way forward

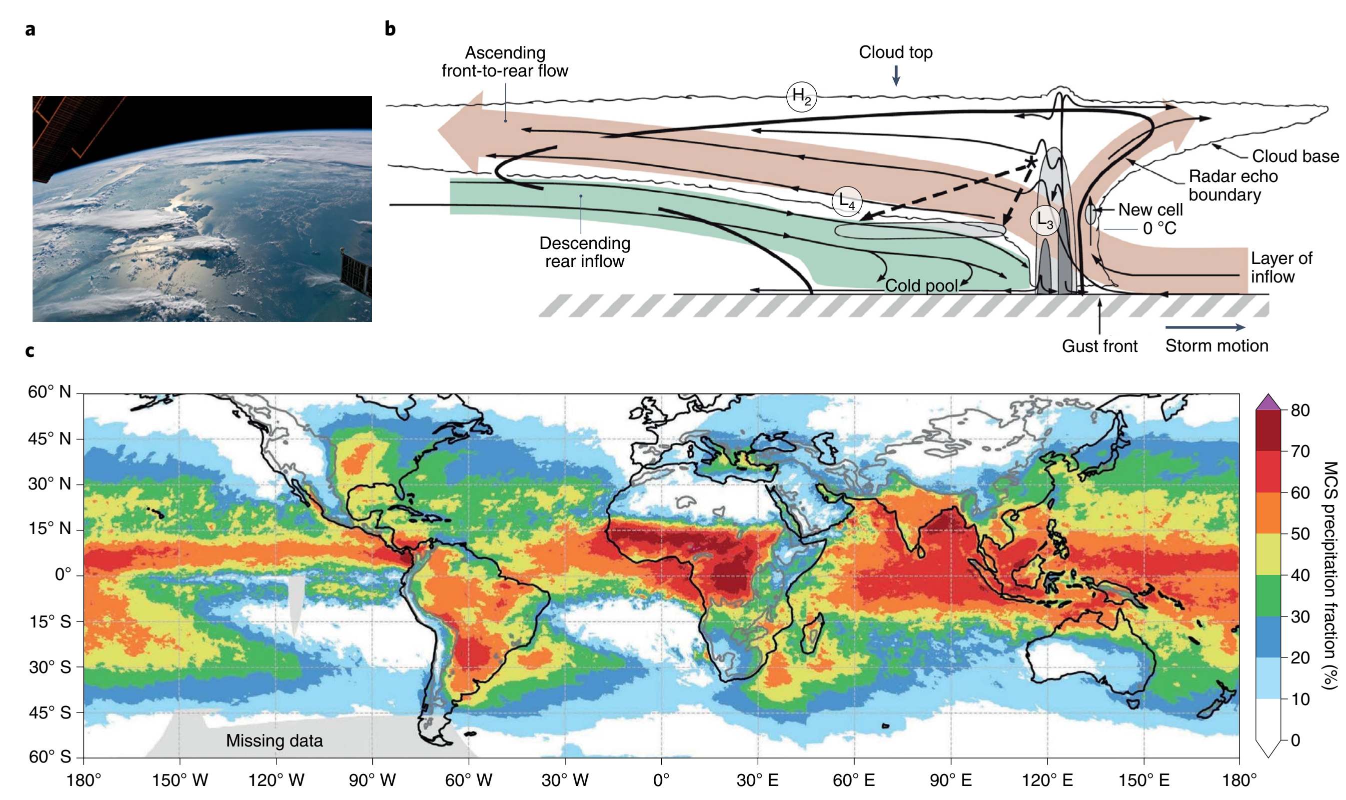
The scientific case for moving to k-scale global climate modelling is irrefutable, but the task is formidable. Nevertheless, the

Box 2 | MCSs

MCSs describe important organized groupings of convective storms in the tropics and mid-latitudes (panel a in the figure). The conceptual model of an MCS shows the flows of air through the system and how they contribute to intensification of the updraft along the storm front (panel b in the figure)[7]. Medium and dark shading indicate regions of intense precipitation. The spatial extent of the whole MCS is typically 100 km or larger, but the updrafts that generate the intense precipitation are typically less than 10 km.

MCSs dominate precipitation over many parts of the world (panel c in the figure)[6]. They generate severe weather events and flooding, and they affect the evolution of the larger-scale regional and global circulation. Over the Great Plains of the United States, MCSs account for around 50% of the annual warm season rainfall, and also drive tornado development. Over West Africa, nearly all the rainfall is associated with MCSs, and it is these systems that form the embryos of Atlantic hurricanes.

Much of the extreme rainfall in mid-latitude land areas also comes from MCSs, often causing deadly and destructive flash flooding, as was the case in summer 2021 in the severe floods in Germany, the inundation of New York from Storm Ida and the staggering amounts of rain that fell in Liguria, northern Italy (181 mm of rainfall in just 1 hour and over 900 mm in 24 hours). In all cases, the most intense downpours were associated with clusters or lines of MCSs.



Structure of MCSs and their importance for precipitation. a, International Space Station image of typical MCSs. **b**, Conceptual model of an MCS showing the complex kinematics and microphysics[7]. The warm updrafts and cold downdrafts are shown in red and green shading. Several meso-lows and meso-highs are formed, indicated by L and H, respectively. Ice crystals (depicted by the star) fall slowly (dashed arrows) from the updraft region into the melting layer depicted by the horizontal shaded region. **c**, Percentage of MCS precipitation to total precipitation[6]. Panel **a**: image courtesy of the Earth Science and Remote Sensing Unit, NASA Johnson Space Center. Panels reproduced with permission from: **b**, ref. [7], American Meteorological Society; **c**, ref. [6] under a Creative Commons licence (https://creativecommons.org/licenses/by-nc-nd/4.0/).

scientific and technological advances are within our grasp[11,12], with prototype systems already demonstrating the realism of k-scale simulations (Fig. 1)[13]. The international scientific workforce now needs to be mobilized to bring together the intellectual firepower and the computational resources to achieve this quantum leap.

We therefore call for a new level of international collaboration that optimizes our resources around this common goal — to build, at pace, a new generation of k-scale global ensemble prediction systems that can provide reliable and regularly updated predictions of our evolving physical climate risks, embracing everything from daily weather to decadal climate variability, conditioned by global warming trends.

The steps to realizing this grand ambition require the creation and resourcing of a federated group of leading modelling centres, linked to state-of-the-art exascale computing and data facilities, providing a shared environment in which the development and evaluation of this new generation of models can be accelerated beyond current national efforts. There needs to be a shared research and development programme designed around the goal of delivering timely, detailed, consistent and actionable k-scale global climate predictions within five years.

As a rough estimate, based on experience with current k-scale simulations, expected technological advances and other evidence[12], moving from 100-km to k-scale climate model horizontal grids implies an increase of the order of 2^{20} in computer power. Machines with that level of capability are being built (https://www.exascaleproject.org/about/), but they are general purpose machines, not dedicated solely to climate prediction. Thus, climate simulations compete with other applications for computing resources on these machines, meaning that they are not able to reach their full potential. Only with dedicated machines that are able to deliver the capability to optimally schedule and perform the diverse range of workflows (for example, executing physics-based model simulations alongside a variety of machine-learning training/application suites) will the quantum leap to k-scale predictions be achievable within the near future when it matters most.

The challenge is not just one of computational throughput, however. The avalanche of data from k-scale models will also mean a profound shift in how users will interact with the predictions. The applications will need to be taken to the data, and this will mean using new hard and soft technologies, such as federated data management, advanced visualization and machine learning. New data platforms and data management techniques, to store the data and provide the tools to extract information from the model output, will need to be part of this endeavour. These breakthrough predictions will be an invaluable resource for the global community to take the necessary measures to adapt to and mitigate climate change. They are effectively the first and fundamental steps towards building digital twins of the Earth's physical climate system[14] and its interaction with human behaviour.

So how much will this all cost? Considering current costs of experiments with k-scale models and assumptions on future computing systems, we estimate that such a project would cost a sustained investment of US$200 million per year in computational and data technologies, and a further US$50 million per year in dedicated human resources. 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. At COP26, the call to at least double finance for adaptation was welcomed by the parties, taking it to 50% of the pledge to provide US$100 billion annually from developed to developing countries. We have the responsibility to ensure that these investments are spent wisely, based on the best possible climate evidence base. Observed through such a lens, the benefits of this initiative outweigh the investment by many orders of magnitude. ❐

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Author contributions

J.S. led the writing of the manuscript, drawing on expertise from all the authors; she also contributed expert knowledge of tropical convection and its role in the global climate system. P. Bates provided expertise in hydrological modelling; P. Bauer provided expertise in exascale computing and digital technologies; S.B. provided evidence of the impact of k-scale regional climate projections; T.P. provided expertise on multi-scale atmospheric dynamics and climate predictability; G.S. provided expertise on clouds and Earth observation; B.S. contributed pioneering global k-scale simulations; T.S. provided expertise in IPCC climate evidence base; and G.T. provided supporting evidence for k-scale models based on climate applications. All authors reviewed, revised and approved the final version.

Competing interests

The authors declare no competing interests.