ADVANCES IN MODELLING AND SEAMLESS PREDICTION

DEUTSCHER WETTERDIENST

The first comprehensive climate prediction models evolved from numerical models[1] used for weather forecasting. Over the years, weather and climate prediction systems have diverged more and more. For example, priorities for weather prediction systems have focused on the development of numerical accuracy and optimal data assimilation methodologies, whereas Earth-system complexity has been the focus of climate prediction research. Both weather and climate prediction models use truncated versions of the underlying partial differential equations of physical and dynamical processes, with approximate empirically based parametrization schemes used to represent unresolved processes.

Reliable weather prediction continues to be critically important for the protection of life and property, particularly under extreme weather conditions. Recently, the demand for reliable climate prediction has increased dramatically as the issue of anthropogenic climate change has had a higher and higher profile on the global stage. Climate predictions are now used to guide policy on climate mitigation and, increasingly, regional investment decisions on, for example, infrastructure to adapt to climate change and its variations.

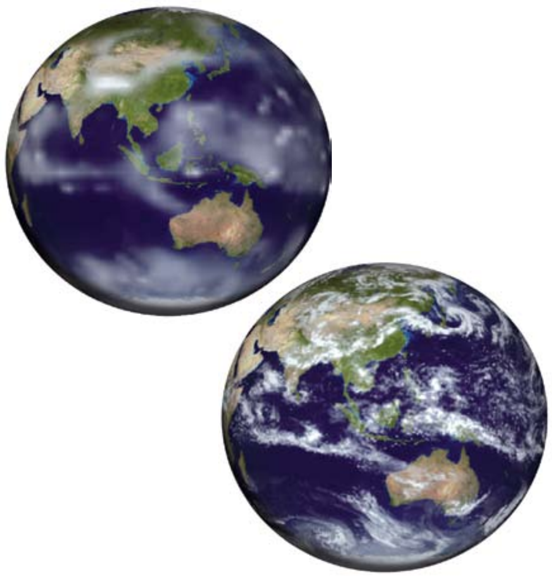
While the skill to forecast weather has improved substantially over the past few decades, uncertainties in predicting the impact of anthropogenic climate change on weather patterns continue to be substantial. To some extent, climate prediction uncertainties can be diagnosed by using multi-model ensembles of climate change predictions. However, using multi-model ensembles to diagnose uncertainty is not sufficient because there are sources of uncertainty in climate predictions associated with biases and errors common to all climate prediction models. For example, as acknowledged in the IPCC Fourth Assessment Report, we know that there are a range of climatic phenomena on timescales ranging from diurnal to multi-annual that are poorly simulated by most contemporary climate models.

The need for scientific advances and grand challenges in climate modelling was the background of the WCRP World Modelling Summit for Climate Prediction, held at the European Centre for Medium-Range Weather Forecasts in Reading, UK, on 6–9 May 2008. That Summit was co-sponsored by the World Weather Research Programme (WWRP/CAS) and the International Geosphere-Biosphere Programme (IGBP) in order to develop a strategy to revolutionize climate prediction during the twenty-first century that would provide the basis for reliable science-based adaptation and mitigation strategies designed to avoid the dire consequences of climate-related extreme events and management of their risks.

One of the key issues of that Summit was how the insights and constraints of numerical weather prediction could be brought to bear on the problem of quantifying and reducing uncertainty in climate predictions. For example, it is known that the representation of clouds in climate models is central to predicting global warming. However, the intrinsic processes associated with clouds occur on relatively fast timescales, and the quality of parametrizations of clouds can be tested in very short-range numerical weather prediction.

1 Numerical model: Computational representation of complex mathematical equations of motion in the atmosphere or ocean.

However, that raises a problem. If the models used in weather and climate prediction are fundamentally different from one another (cf. the divergence mentioned at the beginning of this article), then insights gained on the short weather timescale cannot readily be transferred to the longer climate timescale, and vice versa. For that reason, the notion of seamless prediction, a core pillar of WCRP strategic development, was one of the major issues discussed at that Summit.



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An illustration of the limitation of coarse-resolution, multi-decadal climate-projection models to resolve regional high-impact weather events routinely predicted by today's 14-day operational forecast systems. Top, global cloud distribution in a 320-km resolution climate simulation experiment. Lower globe, same as top but for a 20-km resolution simulation model, comparable in resolution to the most advanced weather forecast models of today.

For many prediction research centres, practical seamless prediction must wait for the next generation of modelling systems. Much of the discussion at the Summit concerned the practical development of next-generation seamless prediction systems. What would be the right balance between high resolution on the one hand and a more complete representation of the Earth system complexity on the other? How many independent climate models were desirable, as the global research community worked together on model development? As mentioned above, multiple models provide a means of estimating prediction uncertainty. However, quite different techniques were being developed based on stochastic representation of sub-grid processes, and a central question was whether those more systematic approaches to the representation of model uncertainty could in principle supersede the more ad hoc multi-model ensemble.

The issue of model resolution (horizontal and vertical) for climate prediction is complicated. On the one hand, we know that climate simulations are sensitive to parametrization of deep-convective[2] processes in the atmosphere. Hence, it seems natural that global climate modellers should strive to resolve deep-convective clouds explicitly. On the other hand, we appear to have no robust theoretical basis to quantify the expected decrease in uncertainty in climate predictions if deep-convective clouds were indeed resolved properly. For example, it may be that when deep convection is resolved, remaining uncertainties in cloud microphysics will still lead to substantial uncertainty in climate change predictions. In short, there seems to be

2 Convection: vertical motion of molecules driven by buoyancy forces arising from static instability leading to cloud formation.

little alternative to doing the numerical experiments and finding out. However, the global research community does not yet have the computing infrastructure to carry out those experiments.

The issue of computing infrastructure was also discussed at great length at that Summit, and there is general agreement that climate prediction is among the most computationally challenging problems in science and that progress in climate simulation and prediction is limited by the availability of computing resources. All climate centres around the world would like to have cutting-edge (so called "track one") high-performance computing technology that is becoming available to climate science. At present, that technology has reached petaflop[3] speed. However, there are currently no plans to use those computers exclusively for climate prediction, the importance of the issue notwithstanding.

One of the key outcomes of the Summit was the initiation of the Climate Prediction Project, coordinated by WCRP in collaboration with WWRP/CAS and IGBP and involving national weather and climate centres as well as the wider research community. The project's fundamental goal is to improve climate prediction, including prediction in changes in the probability of regional high-impact weather. It is strongly believed that improved predictions will be of particular help to developing countries whose national capabilities need to be increased substantially.

A key element of the Climate Prediction Project is a world climate research facility for climate prediction that will enable national centres to accelerate improvement of operational climate prediction. The central component of that world facility will be one or more dedicated multi-petaflop high-performance computing facilities to allow the numerical experimentation that currently cannot be done.

Advocacy at very high levels will be needed if such a facility is to become a reality, and that advocacy is already active. In addition, WCRP must take the lead in coordinating and facilitating the science underlying the Climate Prediction Project.

One of the most significant aspects of the World Modelling Summit for Climate Prediction was that it brought together, perhaps for the first time, a diverse set of experts from a range of disciplines. There were experts on short-range weather forecasting and on centennial prediction, on the underlying theory of weather and climate predictability, on practical issues related to

For too long, understanding and predicting weather and climate have been seen as separate problems. Getting them back together recognizes their intimate interrelationship and is essential for consideration of the impacts of regional climate change. A seamless-prediction approach provides a consistent basis for developing and testing models focussed on prediction on particular timescales.

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3 Petaflop: 10^{15} operations per second in computing.

the design of high-resolution dynamical cores that could scale across large numbers of processing elements, on representation of Earth-system complexity, on data assimilation, on deterministic parametrization of deep convection and on stochastic representation of unresolved processes.

As is well recognized in many areas of science, big leaps forward often occur when ideas cross from one area of science to another. However, the Climate Prediction Project will need a focus, and one clearly emerged from discussions at the Summit: seamless prediction on timescales ranging from a season to a few decades ahead. Why is decadal prediction such a relevant focus for WCRP seamless prediction activities? The following issues are pertinent.

- The internal dynamics of the coupled climate system and externally forced climate change truly interact at decadal timescales. Decadal prediction combines both the need for accurate initial conditions, central to weather forecasting, and the need for scenarios of greenhouse gases, central to centennial climate prediction. In that way, the experiences of numerical weather prediction and seasonal forecast communities on the one hand and centennial climate change communities on the other are extremely important in solving that problem. Initial studies have shown that there is skill in decadal prediction over and above the expected impact of increasing greenhouse-gas concentrations.

- Decadal prediction combines elements from all existing WCRP projects. Ocean-atmosphere and land-atmosphere interactions are absolutely paramount. However interactions with the cryosphere are also important on decadal timescales, as are interactions between the troposphere and stratosphere.

- The weather forecasting community has shown unambiguously the benefits of increased resolution

We are entering a very exciting era in which forecasts of increasing accuracy and fidelity can be made at the important decadal and regional scales of interest and concern to society. Such efforts will allow us to link climate change impact with human actions and drivers and to include in models feedback and interplay among physical changes, human-induced change (e.g., land use or engineered systems) and ecosystem changes. The new sets of probabilistic forecasts will need to be extensively validated, but will be of early use to many sectors of the economy and society. All of this will require the upkeep of an end-to-end "enterprise" model for the development and deployment of sophisticated Earth system codes. These codes will have to be extensible, portable and scalable in the context of modern computational architectures. We will need to focus on the development of human capital, as well as on building the needed cyberinfrastructure for this challenging task.

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for forecasting accuracy, but the climate community has been reluctant to embrace high resolution as a priority, not least because there are so many other demands for computing resources arising from the representation of Earth-system complexity. It is on the decadal timescale that we may see the first inklings about the potential benefits of using high resolution models for climate prediction and indeed of the benefits of striving for convectively resolved models. It is possible that the biggest impact of high resolution will be in the tropics. Therefore, the work of the Climate Prediction Project may benefit more than most, some of the world's developing countries.

- The issue of reliably representing forecast uncertainty in ensembles of climate predictions is critical. The weather and seasonal prediction community has made major strides in the analysis not only of multi-model ensembles but also using stochastic parametrization and perturbed-parameter methods. Assessing which of these methods, or indeed which combination of them, is likely to give the most reliable climate predictions is a central question for the future, and that can be assessed on decadal prediction timescales.

- A key focus for decadal and multi-decadal prediction will be modes of variability. For example, in the coming decades, can we make any useful predictions about changes in the Atlantic Meridional Overturning Circulation? Issues about the linearity versus non-linearity of such modes and the existence of regime-like structures continue to play a prominent feature in theoretical discussions of the nature of climate, and once again, decadal prediction will provide a focus for the analysis of such studies.

I have no doubt that within the next decade or so, major global numerical weather prediction, climate and Earth prediction centers will be providing a set of high-resolution environmental products, including assessments, forecasts and projections over a large range of timescales, often with an associated estimate of accuracy, and produced by a set of highly integrated Earth system simulation models, so-called seamless prediction.

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- The problem of model error is absolutely critical for decadal prediction. Is it important that many of the modes of variability of climate are not well simulated? Is simple bias correction sufficient to remove the effects of model drift, or is the non-linearity of climate such as to cause bias to destroy any useful predictability that may exist on the decadal timescale?

- In weather prediction, improvements in ten-day forecasts is almost entirely due to improvements in forecasts at day 1. Is it likely that the skill of decadal prediction will depend on the skill of predicting the first season?

- Decadal prediction studies will need to assess carefully whether the current observing network is adequate, thus establishing important links between observational and modelling communities.

- Prediction on timescales of one to a few decades ahead is central for guiding investment decisions on infrastructure for climate adaptation. For such investments, prediction of precipitation and storminess will be just as important as prediction of changing temperature.

In conclusion, the notion of seamless prediction, the unification of weather and climate science so that the insights and constraints of one can be brought to bear on the other, is a major issue of the Climate Prediction Project (an outcome of the recent World Modelling Summit for Climate Prediction). WCRP must play a central role in coordinating and facilitating the work of a very diverse range of experts who can be expected to contribute to this project. The seamless seasonal to decadal and multi-decadal prediction approach can also be expected to contribute significantly to the IPCC Fifth Assessment Report.

WCRP promoted the Modelling Summit statement and Climate Prediction Project at the 60th session of the WMO Executive Council in Geneva, Switzerland, in June 2008. The Executive Council considered the Summit statement in its deliberations and established an ad hoc task team to identify opportunities for coordination and integration of WMO research activities towards the goal of seamless weather, climate, water and environmental prediction and associated services that can benefit WMO Member countries and its partners.

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