



# Frontiers in Climate Predictions and Projections

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## INTRODUCTION

Climate change is one of the biggest scientific and geopolitical challenges of our times. Central to the challenge is the idea of using climate science to look into the future and ask what the world might be like. We know some of the basics. For example, the 5th Assessment of the IPCC WG1 concluded that “Continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system.” However, we need more details. The IPCC goes on to further conclude, “Changes in the global water cycle in response to the warming over the twenty-first century will not be uniform.” Precipitation is of huge importance to agriculture and for supplying water for domestic and industrial use and yet, for many regions of the globe, we do not know definitively if the future will bring more or less precipitation. Nor do we know whether an increase or decrease might be temporally uniform or will come in the form of a few extreme events. The same is true for many other climate phenomena e.g., the El Niño-Southern Oscillation. Will climate variability increase or decrease in the future? This Frontiers Grand Challenge concerns climate predictions and projections.

Climate predictions generally refer to near-term assessments of future variability and change in climate—from months to decades. Such prediction systems usually employ some sort of initialization of a model (dynamical or statistical) with observations of the present day and the model is run forward in time, often producing an ensemble of realizations. The expectation is that the real-world climate trajectory lies within the spread of the model trajectories. Climate projections generally refer to longer-term assessments of future variability and change in climate—up to a century ahead and beyond. In this case, models are generally not initialized with the observed present-day, but are forced with scenarios of changing greenhouse gases and other forcing agents. Climate projection simulations are not meant to reproduce the exact timing of real-world weather and climate events, but trends and the statistics of variability should be comparable. Future climate projections show how climate will change compared to historical or pre-industrial simulations under different scenarios. The performance of the model in reproducing past climate should tell us something about the credibility of future projections.

Much work in climate predictions and projections has focused on temperature variability and change. This “thermodynamic” picture of future climate is now quite well advanced, although there is still much scientific debate and effort to quantify the global climate sensitivity, for example. More

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recently, there has been an increased focus on precipitation and the hydrological cycle—a more challenging problem due to the role of the atmospheric circulation. Also, there is much interest in predictions and projections of winds, tropical and extra-tropical cyclones, atmospheric blocking events, monsoons, sea-level etc. These physical variables present many challenges for climate predictions and projections. Sometimes these events cascade or overlap, resulting in compound effects. There is also growing interest in biogeochemical aspects that impact the carbon and nutrient cycles, and atmospheric chemistry, as well as assessing the impacts of climate variability and change on natural and human systems such as ecosystems and economies (Earth Systems Models). A better understanding of the processes involved will allow us to not only detect climate change, but also to attribute observed changes to human activities or natural variability. Hence, there is a huge potential for exciting developments to models and to prediction and projection systems that have significant policy implications.

The main challenge with predictions and projections is that we have models which are not yet perfect in their representation of the climate system, and observations used to constrain these models still have considerable uncertainties or do not have sufficiently long records. Here the term “constrain” takes many meanings. It could be the use of observations in model development, evaluation, skill assessment, initialization or in building confidence in projections. (It is assumed that sensitive dependence on initial conditions can be overcome, as it is in weather forecasting, by the use of ensembles and probabilistic predictions.) Much of the effort in climate prediction and projection comes in dealing with these imperfections i.e., how to derive utility from models which are “biased” in some way or have “errors,” but which we consider to be informative. It should also be noted that the climate system acts on a global scale. Flows of energy, water, and carbon through the climate system are coupled together and are driven by global-scale boundary conditions. Hence it is not possible to easily simplify climate prediction and projection for a particular region or variable.

## ADAPTING TO A CHANGING CLIMATE

We may consider different policy drivers when considering how to make predictions and projections of climate change. For adaptation to variability and change, information is usually required at “local” level, where local implies the scale at which decisions can be made—town, city, country or, perhaps, groupings of countries (such as the EU). Models can successfully reproduce large-scale aspects of the observed climate, but imperfections show up at smaller scales. A positional error of a few degrees of latitude for a tropical rainfall convergence band makes all the difference when looking even at the country scale. Bias correction techniques, such as removal of drift in prediction systems and use of anomalies or quantile mapping in projections, are often employed out of necessity rather than design. Can we do better? Is dynamical downscaling the answer or should we concentrate our efforts on improving the resolution of global models? Could more be gained from statistical down scaling using modern techniques from e.g., machine learning? A further challenge is to link the predictions of physical, chemical and

biogeochemical variables to impact variables such as agricultural yields, transport, economics, etc.

One possible answer to the problem of model imperfections is in quantifying or characterizing the uncertainties in predictions and projections. Various techniques have been proposed for this. Large ensemble techniques, generated by making small perturbations to initial conditions, are very useful for separating signal from noise and can be used for quantifying the reducible uncertainty from natural variability or, indeed, future changes in that natural variability. Bayesian techniques have been used for quantifying modeling uncertainty, but their implementation tends to be quite challenging and projections may depend on the choices made during that implementation (e.g., the expert-specified ranges on parameters that are varied in a perturbed parameter ensemble). Some studies suggest that probabilities are not useful if they depend on methodological choices and prefer the use of scenarios or storylines. What are the best approaches for quantifying and characterizing uncertainty in climate predictions and projections to inform adaptation policy?

## PREVENTING DANGEROUS CLIMATE CHANGE

Policy for the mitigation of climate change is organized at the global level through the United Nations Framework Convention on Climate Change. It is arguable whether additional climate science is needed to inform mitigation policy and that there is enough evidence for cutting emissions of greenhouse gases. Nevertheless, the investigation of long-term climate change remains both an intellectually stimulating activity as well as a policy relevant while the global negotiation process continues. Much is still to be understood about changes in extremes, abrupt changes and tipping points. A recent field of enquiry that has emerged is that of ocean extreme events, such as marine heatwaves, that are like heatwaves over the land but in the upper part of the ocean and at the sea surface. These are becoming more frequent and severe and can have devastating impacts on marine organisms and ecosystem services. Another is the field of compound events and cascading impacts whereby changes overlap e.g., in the case of mean sea level rise compounded by an increase in the severity of storm surges associated with strengthening tropical cyclones. The likelihood of abrupt changes and tipping points, such as the Atlantic Meridional Overturning Circulation, have proved difficult to quantify, yet they remain physically plausible scenarios of future climate change and much can be learnt about their impacts. What can we further learn about the sensitivity of the climate system to increasing greenhouse gases? Just as in the case of adaptation, linking physical and biogeochemical to impacts of long-term climate change, especially at the global scale, is a challenge for modelers.

While much of what is required to solve the problem of climate change involves technologies to reduce emissions of greenhouse gases, in the armory of approaches are solutions that require information from climate science. Many geoengineering options are being investigated and it is important to understand both the impact on global change as well as any deleterious side effects of such solutions. Assessing

pathways of emissions reductions e.g., employing overshoots requires climate science to assess the likelihood of, for example, crossing a threshold or tipping point that is not easily reversed. How can climate predictions and projections contribute to climate solutions?

Many of the problems in climate predictions and projections would be solved if we have a model which provides a near-perfect simulation of the climate of the Earth (both past, present and future). Perhaps this is an unrealistic goal but the field of improving climate models is a significant component of the global research on climate variability and change. Generations of model inter-comparison projects (MIPs) have revealed persistent biases such as the “double intertropical convergence zone.” How can we best improve models? How do we best exploit a hierarchy of climate models. Also, can we use new techniques from data science, machine learning and artificial intelligence?

Climate prediction and projections is one of the grand challenges of climate science. It is not only an intellectual, scientific and technical problem but also a policy-relevant problem. For predictions and projections to be useful, policy makers must be able to access the best and most relevant information and to appreciate inherent uncertainties, both reducible and irreducible. The ultimate goal of Frontiers in Climate Predictions and Projections is to publish articles that help provide actionable information for climate policy for adaptation and mitigation.

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All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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