Isaac Newton Institute for Mathematical Sciences

Mathematical and Statistical Approaches to Climate Modelling and Prediction

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Climate change is widely recognised as one of the most important issues facing humanity. From rising sea levels to patterns of drought and political migration, the consequences of climate change are profound. Most scientists agree that emissions of anthropogenic greenhouse gases are at least partly responsible for the observed increases in global air temperature. Much scientific effort is currently directed at understanding past climates as well as predicting our future environment using complex mathematical models on supercomputers. Global leaders rely on these predictions to inform their adaptation and mitigation strategies.

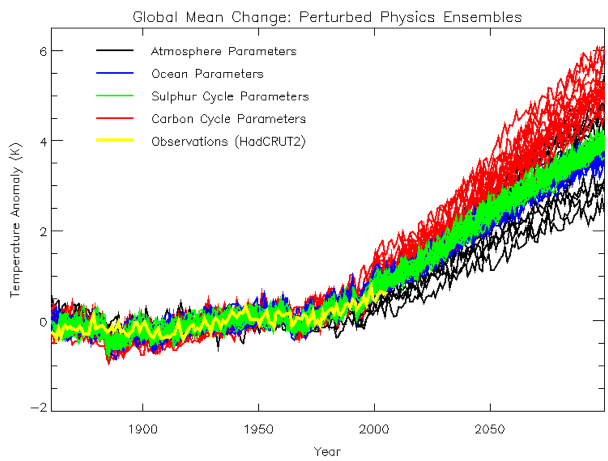
These models of the coupled atmosphere and ocean are called General Circulation Models (GCMs) and are based on dynamic and thermodynamic equations. Although the equations are deterministic, they are sensitive to any small error in their initial state. It is this chaotic feature that renders precise long-range weather forecasts impossible. Climate models are more complex than short-range weather models since they contain many additional equations, for instance to describe sea ice and soil moisture processes. This and the fact that simulations must run for hundreds of years places restrictions on the model resolution – the computational grid upon which the equations are solved. Many important physical processes (e.g. cloud formation, ocean turbulence) are therefore not explicitly represented in GCMs, but are instead parameterised in a way that describes the averaged effect of the unresolved processes at the larger scale.

Uncertainties in climate model predictions are due to the treatment of small scale processes, insufficient knowledge of the initial state, and aspects of the physical world whose physics are not completely understood. A technique that can quantify this uncertainty is the ensemble simulation where several versions of the climate model are run, each with different parameter values and initial conditions. An emerging tool is the use of stochastic-dynamic models that allow random variation in one or more variables within the small scale processes. Stochastic models can simultaneously and systematically represent unresolved time and space scales, and have the potential to improve the variability of ensemble climate simulations when compared against observations.

A statistical measure of uncertainty that inherently treats the smallest scales as stochastic is the entropy, or molecular disorder, within a system. The second Law of Thermodynamics states that the entropy of an isolated system can never decrease. Under certain conditions dynamical systems can increase their entropy at the maximum rate permitted by conservation laws. It is possible that this principle of maximum entropy production (MEP) applies to Earth's climate. Very simple models can produce realistic global temperature and weather patterns when oceanic and atmospheric mixing are maximised. The MEP principle provides a useful test for GCMs and may also lead to better representation of complex feedbacks in climate models (e.g. between the biosphere and the atmosphere).

The vast amount of data produced by climate models requires synthesis in order to deliver the predictions needed by policy makers. Fundamental questions surround the interpretation of probabilistic output and the optimum design of climate model ensemble simulations. Modern developments in statistical modelling can improve the characterisation of model uncertainty, and enhance the usefulness of climate model information. Advanced statistical methods can also guide observations of the Earth system that are needed to validate climate models.

Extreme positions on both sides of the climate debate arise because of the high degree of uncertainty surrounding the amount of future warming and the lack of detailed predictions at the regional level. A major goal for climate scientists is to reduce the uncertainty in their predictions and produce credible assessments of model accuracy. This requires the close collaboration of mathematicians, statisticians and climate scientists in order to improve climate models and the interpretation of their output. This programme will bring together world-leading researchers in those areas in order to make progress.



Projected global warming from an ensemble of Met Office climate models, depicted by the deviation of global mean temperature from a long term average. Uncertainty in the future level of global warming is illustrated by varying key parameters in different components of the climate model as shown in the diagram legend. Observations of global warming are shown in yellow. These experiments took over 5 years to produce on a large supercomputer.