Should weather and climate prediction models be deterministic or stochastic?

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Stochastic parametrization is a controversial topic in atmospheric science. It represents uncertainty in forecasts by including random numbers, or noise terms, in the forecast model. However, it is not clear whether including these random terms also has detrimental effects on the forecast which might be avoided by using traditional deterministic schemes. This National Meeting of the Society, held at Imperial College London in April 2013, was opened by the organiser, *Paul Williams* (University of Reading). He explained how the origins of this meeting could be found ten years ago, in an article in The New Scientist magazine (Samuel Reich, 2003). This article describes results from Williams' PhD work, where he was surprised to find that including noisy stochastic terms improved the performance of his model; the two experts quoted in the article commenting on his results gave the opening talks at this meeting.

A recurring theme of the meeting was the limitations of our models. There are many sources of error in a forecast, and the error-growth models of Lorenz and Leith describe how such errors propagate from small to large scales, and can limit the long term predictability of a system. However, as *Kerry Emanuel* (Massachusetts Institute of Technology) pointed out, these calculations may not be directly relevant to the atmosphere, where the assumptions of homogeneity and isotropy are at odds with the organised structure observed in frontal systems and tropical cyclones. In fact, small-scale features such as fronts and cyclones exhibit a large degree of predictability which deterministic models can exploit if run with sufficient resolution. Does using stochastic physics mask the deficiencies in our model, and prevent forecasters from making use of these sources of predictability? Or can it actually account for the variability associated with these organised structures?

Tim Palmer (University of Oxford) argued that stochastic parametrizations can account for variability due to unresolved scales. The rationale for formulating deterministic parametrizations, and representing sub-grid scale processes as a function of the grid-scale variables, seems to be flawed. There is no break in the spectrum of processes which occur in the atmosphere at which we can truncate, so there will always be unresolved processes occurring at the grid-box scale whose effects cannot be captured by a deterministic parametrization scheme. Instead, stochastic parametrizations should be used which represent unresolved processes by a probability distribution conditioned on the grid-scale variables. The correct probability distribution can be estimated using 'coarse-graining' experiments, whereby high resolution simulations are used to analyse the sub-grid variability consistent with a particular forcing. Not only do stochastic schemes result in reliable probabilistic weather forecasts, Palmer showed how they can reduce systematic errors in a model's climate, and how their use could go hand in hand with the exciting new field of energy-efficient stochastic computing.

And now for something completely different, began *Anders Persson* (Swedish Meteorological Society). He showed mathematically how issuing probabilistic forecasts can be valuable to users when deciding whether to pay for protection, or risk the chance of losses. In fact, even qualitatively acknowledging uncertainty *as such* greatly improves forecast utility. How we quantify that uncertainty is an important, but secondary, issue. For example, in December 2011, the UK Met Office was faced with a difficult forecasting situation, with an incoming severe storm off the Atlantic. By abstaining from making a deterministic forecast and by showing instead different possible developments, they were able to communicate both the consistent threat of the storm and the uncertainty in its location to the authorities and the public, who responded positively to this additional information. Since the ultimate goal, perfect deterministic forecasts, will always be unattainable, producing a well-calibrated probabilistic forecast should be our main objective.

Over the last 30 years, a large improvement has been observed in the skill of weather forecasts. *Terry Davies* (UK Met Office) showed how this progress can be largely attributed to developments in the deterministic core of the models. For example, the semi-Lagrangian advection scheme, currently used at the Met Office, is a vast improvement on the centred schemes used in the 1980s, and results in very accurate calculations. Davies then moved on to discuss parametrization schemes. These are applied column by column in an atmospheric model, conditioned on the grid-scale variables at a point. This highlights one of the fundamental issues with stochastic parametrizations: diabatic forcing should not vary at the grid scale as this can result in unrealistic circulations. Davies concluded that stochastic schemes applied at a larger smoothed scale could be useful, though he ultimately agreed with Kerry Emanuel: stochastic forcing should not be applied across strong gradients such as those found in fronts and discontinuities.

There is much scope for further improvement in forecast models. Bayesian statistics can be used to mathematically formulate a scientist's beliefs, explicitly stating what is already known about a system (the 'prior') and updating these beliefs as new information is learnt. *Dan Cornford* (Aston University) explained that a forecaster's 'prior' is his or her atmospheric model, and that Bayesian statistics allow the forecaster to learn about and improve this model. In order to use an atmospheric model as a prior, it must be probabilistic and use stochastic physics to represent uncertainty. Instead of 'noising up' existing models, stochastic models should be designed from first principles and constrained using high-resolution simulations. Cornford concluded by stressing the importance of developing the deterministic part of the model since this will result in sharper and more skilful forecasts. However, it must be developed alongside treatment of the unresolved or unknown stochastic components to ensure the forecasts remain well calibrated and thus useful.

The panel discussion after the talks highlighted the range of opinions on this topic. However, the main conclusions were clear. Useful forecasts must be probabilistic, and stochastic parametrizations seem a skilful way of generating reliable probabilistic forecasts. While it is wrong to consider sub-grid scale fronts or cyclones as noise, since they exhibit predictability which should be exploited, stochastic parametrizations can represent the uncertainty in these processes. Future work should focus on improving the deterministic representation of such processes, and the development of physically-motivated stochastic schemes to represent their uncertainty.

Reference

Samuel Reich E. 2003. Making waves. *New Scientist* **180**(2423): 30–33.

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