Stochastic-Dynamic Parametrisation in Weather and Climate Prediction Models: An Introduction

T.N.Palmer

ECMWF, Shinfield Park, Reading, RG2 9AX, UK,
t.palmer@ecmwf.int

1. Introduction

These workshop proceedings are devoted to a relatively new topic in weather and climate prediction in general, and for ECMWF in particular: stochastic parametrisation of sub-gridscale processes. Why is stochastic parametrisation of potential importance? Three possible reasons are listed below.

Firstly, stochastic parametrisation can potentially lead to a more complete representation of model uncertainty in ensemble prediction systems, compared with more conventional (eg multi-model) approaches. In ensemble prediction, we try to estimate the forecast probability distribution given the relevant uncertainties in both initial conditions and model equations - a complete representation of model uncertainty is therefore essential if the forecast probability distributions are to be considered reliable.

The second reason for considering stochastic parametrisation is that it can potentially lead to a reduction of systematic error through a noise-induced drift effect. As a simple example of this, imagine a ball bearing in a one-dimensional skewed potential well. If the ball bearing is forced with (say) Gaussian noise, the most likely position of the ball bearing will be offset from the minimum of the well, in the direction of the well’s smaller slope. That is, there will be a systematic shift in the mean position of the ball bearing when it is stochastically forced.

The third reason for considering stochastic parametrisation is not one that is directly relevant to weather prediction, but is important, for example, for detection/attribution studies of climate change. In trying to attribute observed climate change to, for example, anthropogenic forcing factors, it is necessary to have an estimate of internal climate variability. Such estimates are made from long integrations of climate models in which the external forcing factors are kept fixed. Clearly stochastic parametrisation could have an impact on such estimates of internal climate variability.

Indirect evidence for the need to represent model uncertainty in ensemble prediction systems can be found in medium-range ensemble prediction, where ensemble dispersion towards the end of the medium range is typically smaller than forecast error (Buizza et al, 2005). Such underdispersion is even larger in the extended range (Palmer et al, 2005).

More direct evidence of the need to represent model uncertainty in ensemble prediction systems can be found by integrating a cloud resolving model, treated as “truth”, and performing coarse-grained budgets of temperature and momentum - the coarse-graining dimension being consistent with the grid box of a typical global climate or weather prediction model. Such analyses (Shutts and Palmer, 2004) reveal substantial errors in the parametrised sub-grid tendency of temperature, compared with the “true” sub-grid tendency of temperature. Typically, the parametrisation error increases monotonically with the parametrisation tendency itself.

There are alternative and reasonably well-established methodologies for representing model error. For example, the multi-model method has been well established in seasonal climate forecasting (Palmer et al, 2004), and perturbed-parameter ensembles have been used in climate-change prediction (Murphy et al, 2004:

Stainforth et al, 2005). However, both of these techniques assume implicitly that the basic paradigm, within which present-day climate models are formulated, is fundamentally correct. This paradigm assumes that the known partial differential equations of climate can be projected on some suitable Galerkin basis, and that the effect of unresolved scales can be given by a deterministic bulk-formula representation of the mean effect of some ensemble of sub-grid processes.

On the other hand, observations indicate (eg Nastrom and Gage, 1985) that the energy associated with unresolved features in the global circulations is dominated by near grid-scale circulations - it is the effect of these grid-scale circulations that needs primarily to be considered in schemes which purport to represent model uncertainty in ensemble prediction systems.

One simple way of representing the fact that the near grid scales cannot be represented by a simple bulk formula, is to generalise the parameterisation methodology to include some form of stochastic noise. This leads to a radically different paradigm for a climate model; no longer would a parametrisation represent the mean of some supposed soup of sub-grid processes, it would represent a specific realisation of the near and sub-gridscale.

ECMWF has run its ensemble prediction system for the medium and extended range with a simple stochastic parametrisation since 1999 (Buizza et al, 1999: Palmer 2001). In this scheme, the stochastic tendency was formed by multiplying a simple stochastic process over a uniform distribution by the (deterministic) parametrised tendency. This multiplicative-noise formulation is consistent with the results from coarse-grained budget studies from cloud-resolving models, as discussed above. Results have shown that even this simple parametrisation leads to a clear improvement in probabilistic medium-range scores (Buizza et al, 1999).

A different (Cellular Automaton Stochastic Backscatter; CASB) approach to stochastic parametrisation has been developed by Shutts (2005). In this approach the level of dissipation associated with conventional parametrisations (notably convection, orography and numerical diffusion) is calculated and a fraction (typically 10%) is backscattered onto the model grid. The scales onto which this energy is backscattered are determined by a simple cellular automaton model - which essentially plays the role of a stochastic number generator.

Recently Jung et al (2005) examined the capability of the CASB scheme to reduce the systematic error of northern midlatitude flow. A circulation regime analysis was performed. It was found that the systematic error of the deterministic version of the model could be interpreted in terms of over-population of the dominant circulation regimes, and an under-population of the sub-dominant regimes: by contrast the regime structures were well simulated by the deterministic model (in comparison with ERA-40) consistent with the paradigm of Molteni and Ti baldi (1990). With the stochastic backscatter scheme, the model continued to simulate the structure of the circulation regimes well, but now, in addition, the population frequencies were also much better simulated - thus leading to a reduction in systematic error.

The notion of using a cellular automaton model to simulate near gridscale motions has been proposed earlier (Palmer, 1997, 2001). In principle, it is easy for cellular automaton models to simulate not only stochastic processes, but also coherent eg soliton or wave-like processes. On this basis Berner and Palmer (2005) have proposed a multi-scale cellular automaton model to represent both individual tropical convective plumes and their organisation by convectively-coupled wave modes. It is possible that a solution to the long-standing problem of representing the Madden-Julian oscillation in climate models, in ways which do not damage the time-mean climatology of the model, can be found, using such simplified stochastic-dynamic models.

In this way, the notion of stochastic parametrisation can be generalised to stochastic-dynamic parametrisation in which both stochastic and coherent dynamical processes can be modelled by simplified (and hence computationally simple) nonlinear schemes (Palmer et al, 2005). This raises interesting metaphysical questions as to what constitutes a set of “legitimate rules” for parametrising subgridscales.

References

Berner J. and Palmer T.N., 2005: Parametrizing the coherent structures of organised convection using a cellular automaton. This volume.

Buizza, R., M.J. Miller and T.N.Palmer, 1999: Stochastic simulation of model uncertainties in the ECMWF ensemble prediction system. *Q.J.Meteorol.Soc.*, **125**, 2887-2908.

Jung, T., T.N.Palmer and G.J.Shutts, 2005: Influence of a new stochastic physics scheme on weather regimes in the North Pacific region. *Geophys. Res. Letters*, submitted.

Nastrom, G.D. and Gage, K.S., 1985: A climatology of atmospheric wavenumber spectra of wind and temperature observed by commercial aircraft. *J. Atmos.Sci.*, **42**, 950-960.

Molteni, F. and S.Tibaldi, 1990: Regimes in the wintertime circulation over the northern extratropics, II: Consequences for dynamical predictability. *Quart. J. Roy. Meteor. Soc.*, **116**, 1263-1288.

Murphy, J.M., Sexton, D.M.H., Barnett, D.N., Jones G.S., Webb, M.J. et al, 2004: Quantifying Uncertainties in climate change using a large ensemble of global climate model predictions. *Nature*, **430**, 768-72.

Palmer, T.N., 1997: On parametrizing scales that are only somewhat smaller than the smallest resolved scales, with application to convection and orography. *ECMWF workshop proceedings: New Insights and Approaches to Convective Parametrization*.

Palmer, T.N., 2001: A nonlinear dynamical perspective on model error: a proposal for nonlocal stochastic-dynamic parametrisation in weather and climate prediction models. *Q.J.R.Meteorol.Soc.*, **127**, 685-708.

Palmer, T.N., A. Alessandri, U.Andersen, P.Canteloube, M.Davey, P.Délécluse, M.Dequé, E. Díez, F.J. Doblas-Reyes, H.Feddersen, R. Graham. S.Gualdi, J.-F.Guérémy, R.Hagedorn, M.Hoshen, N.Keenlyside, M.Latif, A.Lazar, E.Maisonnave, V.Marletto, A.P.Morse, B.Orfila, P.Rogel, J.-M.Terres, M.C.Thomson, 2004: Development of a European Multi-Model Ensemble System for Seasonal to Inter-Annual Prediction. *Bull. Amer. Meteor.Soc.*, **85**, 853-872.

Palmer, T.N., G.J.Shutts, R. Hagedorn, F.J.Doblas-Reyes, T. Jung and M. Leutbecher, 2005: Representing model uncertainty in weather and climate prediction. *Annual. Rev. Earth Planet Sci.*, Volume **33**, 163-93.

Shutts, G., 2005: A stochastic kinetic energy backscatter algorithm for use in ensemble prediction systems. *Quart. J. Roy. Met.Soc.* To appear.

Shutts, G. and T.N.Palmer, 2004: The use of high-resolution numerical simulations of tropical circulation to calibrate stochastic physics schemes. *Proceedings of ECMWF workshop on intra-seasonal variability.* ECMWF.

Stainforth, D.A., T. Aina, C.Christensen, M.Collins, D.J.Frame, J.A.Kettleborough, S.Knight, A.Martin, J.Murphy, C.Piani, D.Sexton, L.A.Smith, R.A.Spicer, A.J.Thorpe, M.R.Allen. Uncertainty in Predictions of the Climate Response to Rising Levels of Greenhouse Gases, 2005: *Nature*, **433**, 403-406.