Representing model error in the Met Office convection permitting ensemble prediction system

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Recently, many weather centres have developed ensembles at the convective-scale to provide detailed forecasts over regions of particular interest. While these high resolution models are able to provide very realistic looking forecasts, there continue to be cases where the observed weather has not been captured by the ensemble, and a common complaint of forecasters is that the ensemble is over-confident, with the members too similar. This lack of spread, typical of ensemble prediction systems, is at least partly attributed to uncertainty arising from the model itself.

At the Met Office, we routinely run a limited-domain convection-resolving ensemble prediction system (EPS) over the British Isles, known as MOGREPS-UK. The ensemble consists of twelve members (one control and eleven perturbed) and is run out to T+36, every 6 hours, four times a day. It is widely recognises that a successful EPS should represent all forms of uncertainty in the forecast, namely, uncertainty arising from (i) the initial conditions, (ii) the boundary conditions, and (iii) the model physics (Buizza *et al.* 1999). MOGREPS-UK is nested in the Met Office global ensemble, with initial and boundary conditions directly downscaled from the corresponding global ensemble members (since March 2016, each ensemble member is initialised by re-centering over the UKV analysis, as described in Tennant, 2015). The question then remains of how best to represent model uncertainty in MOGREPS-UK.

When it comes to representing model uncertainty at the convective scale, a natural starting point it to use one of the established stochastic physics schemes used at global and meso-scales. It is not as straightforward as simply choosing one such scheme and implementing it, as different physical processes dominate at the convective scale and any such scheme will first need to be adapted to the relevant small-scale processes. Determining the nature of the model uncertainty is also not straight forward – ideally, we would have a full evaluation of the type and extent of model uncertainty and could match our choice of stochastic physics scheme appropriately. In the absence of such an evaluation, we rely on the experience of forecasters and parametrization modellers to identify key areas in the model that are either inherently uncertain or known to be inadequately represented.

One stochastic physics approach used in the Met Office global EPS is the Random Parameter (RP) scheme (Bowler *et al.* 2008). The RP scheme perturbs a set of parameters from relevant parametrizations and varies them stochastically throughout the forecast. Like the Stochastically Perturbed Physics Tendency (SPPT) schemes (*e.g.* Buizza *et al.* 1999; Charron *et al.* 2010), the RP scheme is used to represent the knowledge uncertainty in the physics parametrizations. The RP scheme has the advantage over SPPT that it targets known areas of uncertainty within the parametrizations, it produces physically realistic tendencies, is conceptually simple and cheap to implement. The limitations of the scheme are that it needs regular updates as physics parametrizations are changed and developed, and the choice of parameters and their ranges can be subjective. Historically, the RP scheme has shown only a modest impact on spread and skill and there is a question over the most appropriate way to evolve the parameters through time. We chose this approach over the SPPT scheme as, while the SPPT scheme has the potential to increase the spread of the ensemble, it is applied in a general way to the atmospheric variables, and not linked to any particular physical processes or physical understanding.

To make the RP scheme suitable for the convective scale of MOGREPS-UK, we have revised the RP algorithm to make it easily adaptable to different spatial and temporal resolutions. In the original RP scheme as used in the global ensemble, the parameters are updated every 3 hours with shocks up to a third of the parameter range. For MOGREPS-UK, we use the revised algorithm and the parameters are updated more frequently (every 5 minutes) with smaller perturbations so that the parameters take a smoother, more slowly varying path throughout the forecast. We apply the revised algorithm to a set of parameters in MOGREPS-UK chosen to represent uncertainty in the parametrizations relevant to the convective-scale UK forecast. These parameters are from the boundary layer and micro-physics parametrizations and cover processes including cloud formation, rain rate, turbulent mixing, entrainment at the boundary layer top and near-surface droplet settling.

Fog forecasting is of particular interest to the UK forecast - accurately predicting the timing, location and extent of fog can be challenging, and the implications of getting the forecast wrong can cause major problems, particularly in the aviation industry. One of the reasons that fog is so difficult to forecast, is that it depends on local scales that may be inherently uncertain and poorly observed. The forecast of fog is affected by many of the parameters used in the revised RP scheme. Two of the new parameters have been chosen to explicitly address the uncertainty in fog formation. The first is related to droplet settling and fog dissipation and is a parameter to which fog formation in the model is known to be particularly sensitive (Wilkinson *et al.* 2013). The second is related to the contribution of wind shear to entrainment at the BL top and addresses a known issue in the model where fog is erroneously lifted into stratocumulus (see discussion in Price *et al.* 2015).

To assess the impact of the revised RP scheme on MOGREPS-UK, we consider fog case studies and the objective verification statistics of two separate month-long trial periods covering winter and summer. In each case, a reference ensemble (straight downscaler, no stochastic physics) was compared with the RP ensemble (as the reference ensemble plus the revised RP scheme). The case study results show that the revised RP scheme in MOGREPS-UK increases the variability in the forecast of fog while producing physically realistic forecasts. This increase in variability results in a reduction of over-confident probabilities of fog and therefore a more useful probabilistic forecast. The case studies also show the encouraging results that the revised RP scheme enables the ensemble to capture observed fog events otherwise missed by the forecast.

For both the winter and summer trials, the RP ensemble shows a small increase in spread for surface temperature and 10m wind compared with the reference ensemble. Probabilistic scores show an overall improvement in ensemble skill for visibility and surface temperature. Positive results were also seen for cloud base height and fog, however statistical tests (using the non-parametrix Wilcoxon test for paired data as described in Hamill 1999) indicate that these last two results are not statistically significant – we hypothesise that this is because there are too few fog and low cloud cases in a month and that a better test would be to run the ensemble over a series (30+days) of interesting fog case studies.

Overall, we have found the revised RP scheme to have a positive impact on MOGREPS-UK with particular benefit to fog forecasting. The scheme has been running operationally in MOGREPS-UK since March 2016. Currently, work is undergoing at the Met Office to extend the RP scheme to parameters in the land-surface scheme, and Warren Tennant (Met Office) is trialling a spatially varying version of the RP scheme in the global ensemble. In parallel to the work described here, Adrian Lock (Met Office) has developed a scheme to stochastically perturb potential temperature in the lower part of the boundary layer in conditionally unstable regimes. This scheme has a positive effect on the initiation of convection and is currently being run operationally at the Met Office in both the single high resolution model (UKV) and MOGREPS-UK. Refinements to the BL perturbations are also underway and there are plans to apply these perturbations to other variables in the boundary layer (Adrian Lock and Carol Haliwell Met Office, and Peter Clark, University of Reading).

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