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Evaluation of the Plant–Craig stochastic convection scheme in an ensemble forecasting system

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Abstract

The Plant–Craig stochastic convection parameterization (version 2.0) is implemented in the Met Office Regional Ensemble Prediction System (MOGREPS-R) and is assessed in comparison with the standard convection scheme with a simple stochastic element only, from random parameter variation. A set of 34 ensemble forecasts, each with 24 members, is considered, over the month of July 2009. Deterministic and probabilistic measures of the precipitation forecasts are assessed. The Plant–Craig parameterization is found to improve probabilistic forecast measures, particularly the results for lower precipitation thresholds. The impact on deterministic forecasts at the grid scale is neutral, although the Plant–Craig scheme does deliver improvements when forecasts are made over larger areas. The improvements found are greater in conditions of relatively weak synoptic forcing, for which convective precipitation is likely to be less predictable.

1 Introduction

Quantitative precipitation forecasting is recognized as one of the most challenging aspects of numerical weather prediction (Ebert et al., 2003; Montani et al., 2011; Gebhardt et al., 2011). While progress is continually being made in improving the accuracy of single forecasts – through improvements in the model formulation as well as increases in grid resolution – a complementary approach is the use of ensembles in order to obtain an estimate of the uncertainty in the forecast (Buizza et al., 2005, 2007; Montani et al., 2011; Bowler et al., 2008; Thirel et al., 2010; Yang et al., 2012; Zhu, 2005; Abhilash et al., 2013; Roy Bhowmik and Durai, 2008; Clark et al., 2011; Tennant and Beare, 2013). Of course, ensemble forecasting systems themselves remain imperfect, and one of the most important problems is insufficient spread in ensemble forecasts, where the forecast tends to cluster too strongly around rainfall values that turn out to be incorrect.

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eterization can lead to improvements in ensemble forecasts. Of course, the two parameterizations are fundamentally different, quite apart from the stochasticity of the PC scheme, so that it will be impossible to obtain unequivocal proof that the stochasticity is responsible for an improvement in performance. Nonetheless, the default MOGREPS scheme has benefitted from much experience in developing it alongside the Met Office Unified Model (Lean et al., 2008, UM), whereas relatively modest efforts were made here to adapt the PC scheme to the host ensemble system: thus, any improvements that the PC scheme shows over the default scheme are of clear interest.

2 Methods

2.1 The Plant–Craig stochastic convection parameterization

The Plant and Craig (2008) scheme operates, at each model grid point, by reading in the vertical profile from the dynamical core, and calculating what convective response is required to stabilize that profile. It can be considered as a stochastic and spectral generalization of the Kain–Fritsch convection parameterization (Kain and Fritsch, 1990; Kain, 2004), since it adapts the plume model used there and also has a similar formulation for the closure, based on a dilute CAPE. Details of its implementation in an idealized configuration of the UM are given by Keane and Plant (2012); this would be regarded as Version 1.1. The important differences in the implementation for the present study, to produce Version 2.0, are presented here.

The scheme allows for the vertical profile from the dynamical core to be averaged before it is input. This means that the input profile is more representative of the large-scale (assumed quasi-equilibrium) environment, and is less affected by the stochastic perturbations locally induced by the scheme at previous time steps. It was decided in the present study to use different spatial averaging extents over ocean and over land, in order that orographic effects were not too heavily smoothed. The spatial averaging strategy implemented was to use a square of 7×7 grid points over the ocean and

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2.2 Description of MOGREPS

The Met Office Global and Regional Ensemble Prediction System (MOGREPS) has been developed to produce short-range probabilistic weather forecasts (Bowler et al., 2008). It is based on the UM (Davies et al., 2005) with 24 ensemble members, and is comprised of global and regional ensembles. In the present study, the regional ensemble MOGREPS-R was used, with a resolution of 24 km and 38 vertical levels. This covers a North Atlantic and European (NAE) domain, which is shown in Fig. 1. The model was run on a rotated latitude-longitude grid, with real latitude and longitude locations of the north pole and the corners of the domain given in Table 1. The regional ensemble was driven by initial and boundary conditions from the global ensemble, as described by Bowler et al. (2008). The operational system has been upgraded since these tests and so the present study represents a “proof of concept” for a stochastic convection scheme in a full-complexity regional or global ensemble prediction system, rather than a detailed technical recommendation for the latest version of MOGREPS.

Stochastic physics is already included in the regional MOGREPS, in the form of a random parameters scheme, where a number of selected parameters are stochastically perturbed during the forecast run (Bowler et al., 2008). This scheme was retained for the present study, given that the Plant–Craig scheme is intended to account only for the variability in the convective response for a given large-scale state, and as such its design does not conflict with the inclusion of a method to treat parameter uncertainty within other parameterization schemes. The MOGREPS random parameter scheme does introduce variability in parameters that appear within the standard UM convection scheme, which is based on the Gregory and Rowntree (1990) scheme with subsequent developments as described by Martin et al. (2006). No stochastic parameter variation is applied for any of the parameters appearing in the Plant–Craig scheme. Thus, there is no “double counting” of parameterization uncertainty in these tests but rather we are comparing different methods of accounting for convective uncertainties in a framework

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which also includes a simple stochastic treatment of uncertainties in other aspects of the model physics.

The forecasts using the Plant–Craig scheme were obtained by rerunning the regional version of MOGREPS, with the standard convection scheme replaced by the Plant–Craig scheme, and driven by initial and boundary conditions taken from the same archived data that were used for the operational forecasts. These are compared with the forecasts produced operationally during the corresponding period, so that the only difference between the two sets of forecasts is in the convection parameterization scheme. The study used the UM at version 7.3. The model timestep was 7.5 min, within which the convection scheme was called twice.

2.3 Time period investigated

The time period investigated was from 10–30 July 2009. This length of time was chosen as being sufficient to obtain statistically meaningful results, but without requiring a more lengthy experiment that would only be justified by a more mature system. The particular month was chosen partly for convenience and partly as a period that subjectively had experienced plentiful convective rain over the UK, therefore providing a good test of a convective parameterization scheme.

Experimental forecasts with the Plant–Craig scheme were generated twice daily (at 06:00 and 18:00 UTC) for comparison with the operational forecast which was taken from the archive. On some days the archive forecast was missing and so no experimental forecast was generated. In total 34 forecasts were generated, with start times shown in Table 2.

2.4 Verification

A detailed verification was carried out against Nimrod radar rainfall data (Harrison et al., 2000; Smith et al., 2006). This observational data set is only available over the UK (as shown in Fig. 1), and so most of the verification in the following focuses on this region.

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The forecasts were assessed on the basis of 6 hourly rainfall accumulations, every 6 h, for lead times from 0 to 54 h.

2.4.1 Fractions skill score

This score (denoted FSS) was developed by Roberts and Lean (2008), and was used by Kober et al. (2015) to assess the quality of deterministic forecasts produced using the Plant–Craig scheme for two case studies. Note that we use the term “deterministic”, in this manuscript, to refer to forecasts providing a single quantity (for example, a single-member forecast, or the ensemble mean), and “probabilistic” to refer to forecasts providing a probabilistic distribution (or, at the very least, a deterministic forecast, with, in addition, an assessment of its uncertainty). The FSS is determined, at a given grid point X , by comparing the fractions of observed, O , and forecast, F , grid points exceeding a specific rainfall threshold, within a specific spatial window centred at X . Here we define:

$$\text{FSS} = 1 - \frac{\langle (F - O)^2 \rangle}{\langle F^2 \rangle + \langle O^2 \rangle} \quad (1)$$

where the angled brackets $\langle \dots \rangle$ indicate averages over the grid points X for which observations are available, and also over the different forecast initialization times. The score is positively oriented, and ranges between 0 and 1.

2.4.2 Brier scores

In order to determine whether or not the variability introduced by the Plant–Craig scheme is added where it is most needed, the Brier skill score (Wilks, 2006) was applied to both forecast sets, using the same observational data, to assess the respective quality of the probabilistic forecasts. The Brier score is a threshold-based probabilistic verification score, and is given by the mean difference between the forecast probability of exceeding a given threshold (this probability is here simply taken to be the fraction

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that the proportion of ensemble variability arising from the use of the stochastic scheme (as against that arising from variations in the initial and boundary conditions) depends on the strength of the large-scale forcing, as measured by the large-scale vorticity maximum. In particular, the stronger the large-scale forcing, the lower the proportion of the variability that comes from the stochastic scheme.

Kober et al. (2015) investigated two of the case studies further, by verifying forecasts using the Plant–Craig scheme and using a non-stochastic convection scheme. They found that the improvement in forecast quality from using the Plant–Craig scheme was significantly higher for the more weakly-forced of the two cases, since the additional grid-scale variability introduced by the stochastic scheme is more important.

As part of the present study, we extend the work of Kober et al. (2015) by separating our verification period into dates for which the synoptic forcing is relatively weak or strong. We then compare any improvement in the forecasts using the Plant–Craig scheme, over those using the Gregory–Rowntree scheme, for the two sets of forecasts, to assess over an extended period whether the benefit of using a stochastic scheme is indeed greater when the synoptic forcing is weaker.

The separation into weakly- and strongly-forced cases was carried out a posteriori to the event based on surface analysis charts. The aim here is not to develop an adaptive forecasting system, but rather to develop understanding of the behaviour of the Plant–Craig scheme. Nonetheless, the results may also be interpreted as providing evidence that such a system may be feasible if the strength of the synoptic forcing could be predicted in advance (using, for example, the convective adjustment time scale as discussed by Keil et al., 2014). The period was divided into 12 h sections, centred on 00:00 or 12:00 UTC, and a surface analysis chart valid at the respective centre-time was used to determine whether to categorize the section as weakly- or strongly-forced. The 00:00 UTC analyses were taken from Wetterzentrale (2009) and the 12:00 UTC analyses from Eden (2009).

The separation was conducted by assigning periods with discernible cyclonic and/or frontal activity over or close to the UK as strongly-forced and the rest as weakly-forced,

thresholds, while with upscaling this becomes less dependent on threshold, as was seen in Figs. 2 and 3.

PC generally performs better than GR for weakly-forced cases, and worse for strongly-forced cases. While both schemes benefit from upscaling the score, this benefit is greater for PC. The results agree well with those of Kober et al. (2015) for two example cases, where the Plant–Craig scheme benefits more from the upscaling than the non-stochastic scheme, and performs relatively better for the weakly-forced than for the strongly-forced case. Note that the upscaling required for the Plant–Craig scheme to show better results is a function of number of grid boxes and rather independent of the actual physical scale – the PC scheme works on the scale of the grid box, whatever that may be, and the key is to average over a sufficient number of calls to the scheme.

Moreover, it is clear that the upscaling is more beneficial to the PC scheme (relative to the GR scheme) for the weakly-forced cases than for the strongly-forced cases. The interpretation is that the PC scheme provides a better statistical description of small-scale, weakly-forced convection than a non-stochastic scheme. This will not provide any improvement to the FSS evaluated at the grid scale, since the convection is placed randomly, but it does improve the FSS when it is evaluated over a neighbourhood of grid points, so that it becomes a more statistical evaluation of the quality of the scheme.

3.2 Brier score

The quality of the probabilistic forecasts is assessed using Brier skill scores, plotted in Fig. 5. While neither scheme has skill for high thresholds, PC performs substantially better for medium and low thresholds, for all lead times. In particular, PC has skill in predicting whether or not rain will occur (zero threshold), while GR does not. Further analysis shows that this is also the case for thresholds between 0 and 0.05 (not shown).

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3.2.1 Separation into weakly- and strongly-forced cases

Figure 6 shows the Brier skill scores as a function of threshold, separated into strongly- and weakly-forced cases. The forecasts are improved using PC for both sets of cases, and the difference is considerably greater for weakly-forced cases, where GR has almost no skill. This can be interpreted in terms of the fact that small-scale variability is relatively more important for the weakly-forced cases, and ensemble members using the Plant–Craig scheme differ from each other more than for the strongly-forced cases, where initial and boundary condition variability is relatively more important (Groenemeijer and Craig, 2012). Our result is similar to what was found by Kober et al. (2015), where the Plant–Craig scheme was found to perform better than a non-stochastic scheme for a weakly-forced case, and at low thresholds, but worse than the non-stochastic Tiedtke (1989) scheme for a strongly-forced case.

3.3 Ensemble added value (EAV)

The EAV is plotted in Fig. 7. The PC scheme performs substantially better for this score across lead times, and the improvement is of a similar magnitude to that of the Brier score. This suggests that the improvement in the probabilistic forecast from using PC comes from the stochasticity of the scheme, since the EAV is measured against individual forecasts from the same ensemble and should, therefore, be “normalized” against differences in the underlying convection scheme which are not related to the stochasticity. The interpretation here is that while structural differences between two convection schemes will lead to differences in the quality of the ensemble forecasts, this will mainly be due to differences in the quality of individual members of the ensemble. The stochastic character of the PC scheme may or may not improve the quality of the individual members, but it is primarily designed to improve the quality of the ensemble as a whole.

Note that the ensemble forecasts using the GR scheme also have a positive EAV, representing the value added by the multiple initial and boundary conditions provided

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by the global model, and by the stochasticity coming from the random parameters scheme. Since these factors are also present in the ensemble forecasts using the PC scheme, it can be interpreted that the fractional difference between the two EAVs represents the value added by the stochastic character of the PC scheme as a fraction of the value added by all the ensemble generation techniques in MOGREPS.

Ben Bouallègue (2015) suggests that the resolution component of a skill score represents a more fundamental assessment of its quality than the reliability, as the latter can be reduced to zero by applying statistical calibration to the forecast. Therefore, because the EAV is based on the resolution component of the quantile score, the fact that the PC scheme improves this quantity provides some evidence that it improves the forecast beyond what could be achieved by a simple statistical calibration or downscaling of the forecast.

3.4 General climatology

Although Nimrod radar observations were only available over a restricted part of the forecast domain, it is also of interest to compare the forecasts over the whole domain. Figure 8 shows the convective fraction (that is, the amount of rainfall which came from the convection scheme divided by the total amount of rain from the convection scheme and grid-scale precipitation). Both schemes produce more convective rain over land, and the difference between the fractions over land and sea is in proportion to the fraction over the whole domain; the fractions are fairly constant with forecast lead time. As discussed in Sect. 2.1, the convective fraction is much lower for PC than for GR, suggesting that adjusting parameters to increase this fraction would further increase the PC influence on the forecast (for example, Groenemeijer and Craig, 2012, used a reduced closure time scale to increase the activity of the PC scheme), although it is important to reiterate that there is no correct value for the convective fraction.

The ensemble spread is shown as a function of lead time in Fig. 9, over the whole domain and separately over land and over ocean. Both schemes produce more spread over land, but the difference between PC and GR is also much greater over land. This

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This shows that, while the improvements demonstrated in this Section hold for other areas outside the UK, this has come at a cost to the quality of the forecast for some of the other variables. An important advantage of using a stochastic convection scheme, over a statistical downscaling procedure, is its feedback on the rest of the model, and it is important that this feedback is of benefit. The recent analysis by Selz and Craig (2015a) is very encouraging in this regard, demonstrating the processes of upscale error growth from convective uncertainties can be well reproduced by the PC scheme, in good agreement with the behaviour of large-domain simulations in which the convection is simulated explicitly Selz and Craig (2015b).

4 Conclusions

A physically-based stochastic scheme for the parameterization of deep convection has been evaluated by comparing probabilistic rainfall forecasts produced using the scheme in an operational ensemble system with those from the same ensemble system with its standard deep convection parameterization. The impact of using a stochastic scheme on deterministic forecasts is broadly neutral, although there is some improvement when larger areas are assessed. This is relevant to applications such as hydrology, where rainfall over an area larger than a grid box can be more relevant than rainfall on the grid box scale.

The Plant–Craig scheme has been shown to have a positive impact on probabilistic forecasts for light and medium rainfall, while neither scheme is able to skillfully forecast heavy rainfall. The impact of the scheme is greater for weakly-forced cases, where subgrid-scale variability is more important. Keil et al. (2014) studied a convection-permitting ensemble without stochastic physics, and found that deterministic forecast skill was poorer during weak than during strong forcing conditions. They developed a convective adjustment time-scale to measure the strength of the forcing conditions. This quantity can be calculated from model variables and could therefore be used in advance to determine how predictable the convective response will be for a given

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forecast. This could potentially be useful in an adaptive ensemble system using two convection parameterizations (see, for example, Marsigli et al., 2005), one of which is stochastic and is better suited to providing an estimate of the uncertainty in weaker forcing cases.

Although the Plant–Craig scheme clearly produces improved probabilistic forecasts, it is not certain whether this is due to its stochasticity, or to different underlying assumptions between it and the standard convection scheme. In order to make a clean distinction, further studies could be performed in which the performance of the Plant–Craig scheme is compared against its own non-stochastic counterpart, which can be constructed by using the full cloud distribution and appropriately normalizing, instead of sampling randomly from it (cf. Keane et al., 2014). Nonetheless, the results from applying the recently-developed ensemble added value metric do provide some relevant information for this question. This metric aims to assess the quality of the ensemble in relation to the underlying member forecasts, and the Plant–Craig scheme has been shown to increase it. This indicates that the stochastic aspect of the scheme can increase the value added to a forecast by using an ensemble, since other aspects of the scheme would be expected (broadly) to affect the performance of the ensemble as a whole, and of the individual members, equally.

The results of this study justify further work to investigate the impact of the Plant–Craig scheme on ensemble forecasts. Since the version of MOGREPS used in this study has been superseded, it is not feasible to carry out more a more detailed investigation beyond the proof-of-concept carried out in the present study. Interestingly, the resolution used in this study is now becoming more widely used in global ensemble forecasting, and so future work could involve implementing the scheme in a global NWP system, for example the global version of MOGREPS. This would enable assessments to be made as to whether the scheme provides benefits for the representation of tropical convection, in addition to those aspects of mid-latitude convection that were demonstrated here.

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Code availability

The source code for the Plant–Craig parameterization, as it was used in this study, can be made available on request, by contacting r.s.plant@reading.ac.uk.

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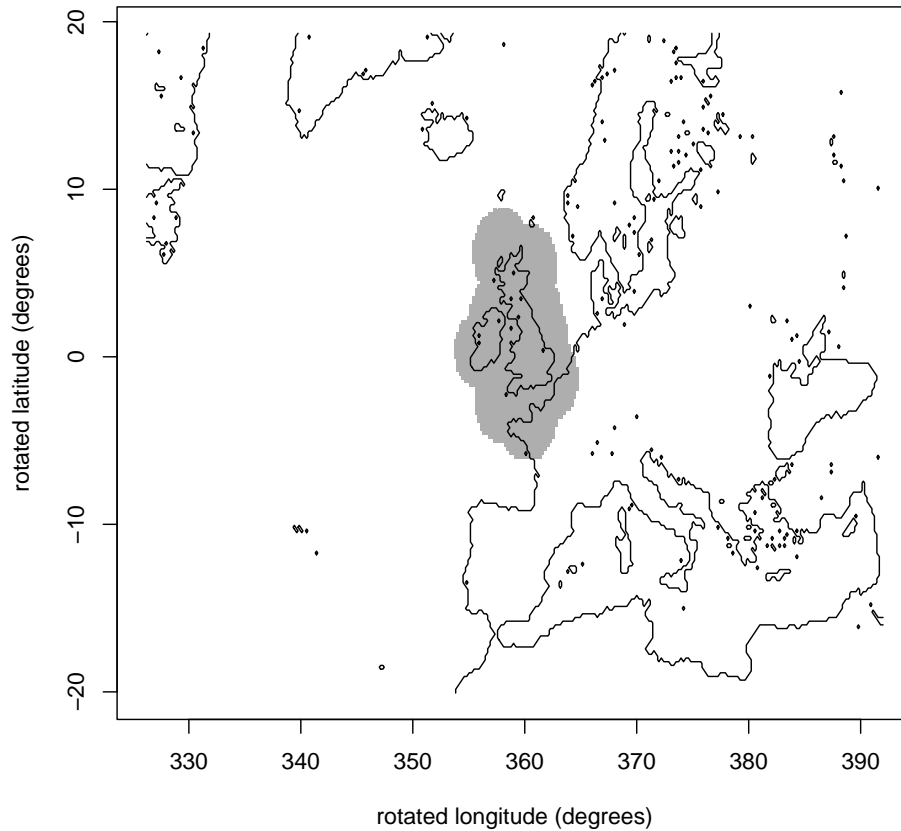


Figure 1. An outline of the MOPREPS NAE domain, with its rotated latitude-longitude grid. The contours are for reference, and are derived from the dataset used in the present study to separate the domain into land and ocean areas. The grey shading shows the region for which radar-derived precipitation data were available.

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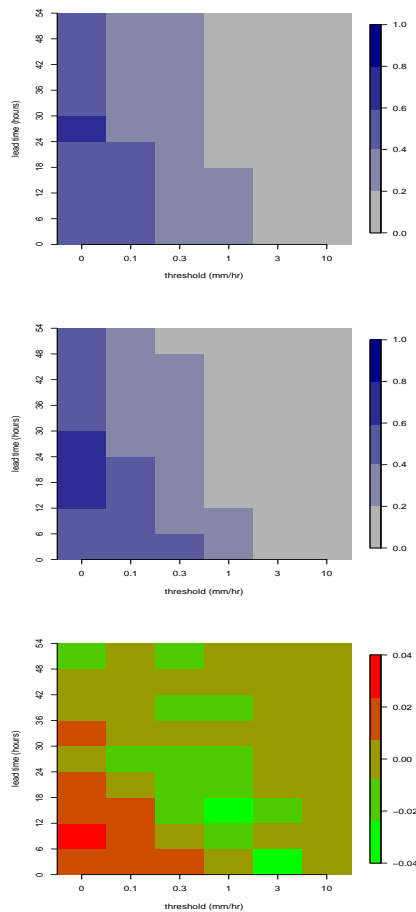


Figure 2. Fractions skill score computed for grid-scale data for the Gregory–Rowntree scheme (top), the Plant–Craig scheme (centre) and the difference between the two schemes (bottom).

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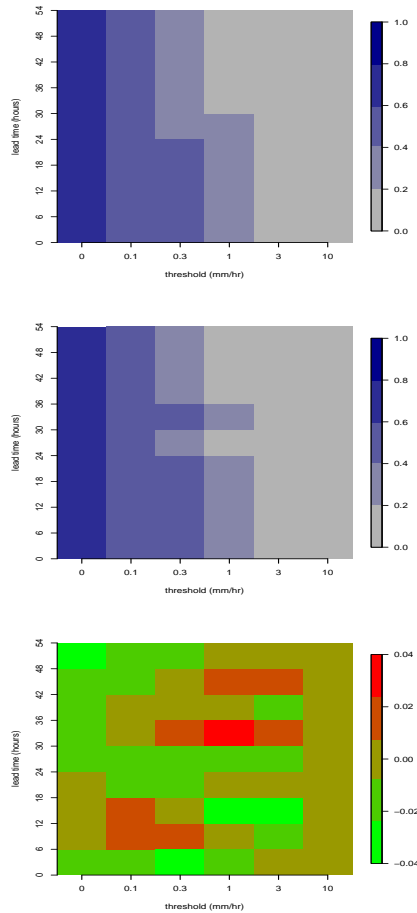


Figure 3. Fractions skill score for the Gregory–Rowntree scheme (top), the Plant–Craig scheme (centre) and the difference between the two schemes (bottom). The neighbourhood area is $(120 \text{ km})^2$, corresponding to the central grid box and two grid boxes in each direction.

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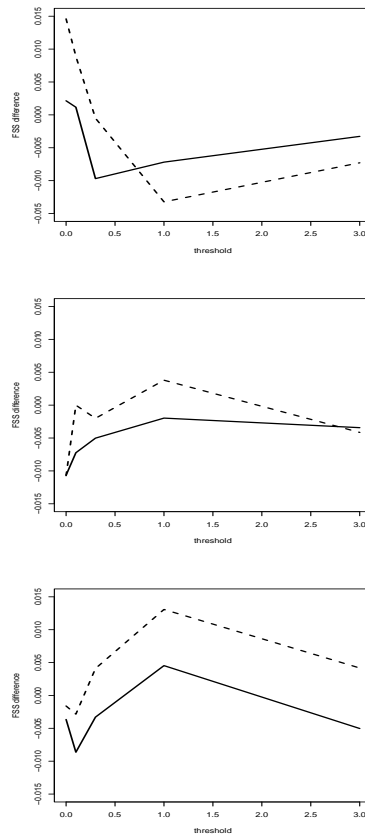


Figure 4. Fractions skill score for the Plant–Craig scheme, minus that for the Gregory–Rowntree scheme, for strongly forced cases (full lines) and weakly forced cases (dashed lines), with no averaging (top), with a neighbourhood area of two grid boxes in each direction (centre) and with a neighbourhood area of four grid boxes in each direction (bottom). The score shown is the average over all lead times.

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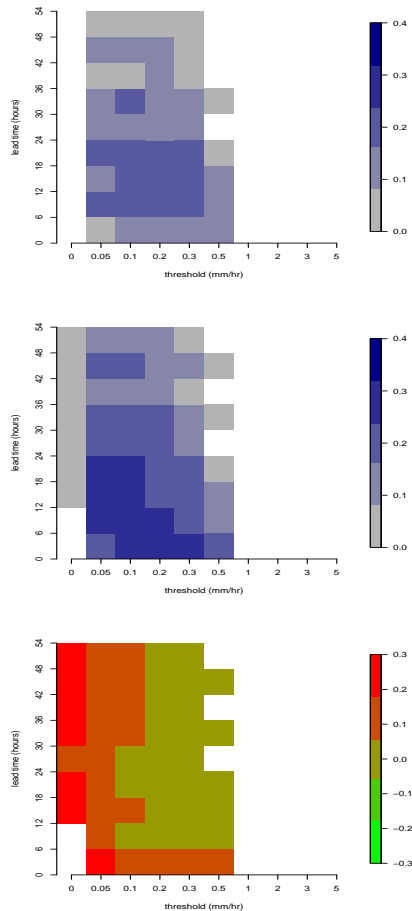
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Figure 5. Brier skill score for the Gregory–Rowntree scheme (top), the Plant–Craig scheme (centre) and the difference between the two schemes (bottom). For the difference plot, instances where both skill scores are lower than zero are not plotted.

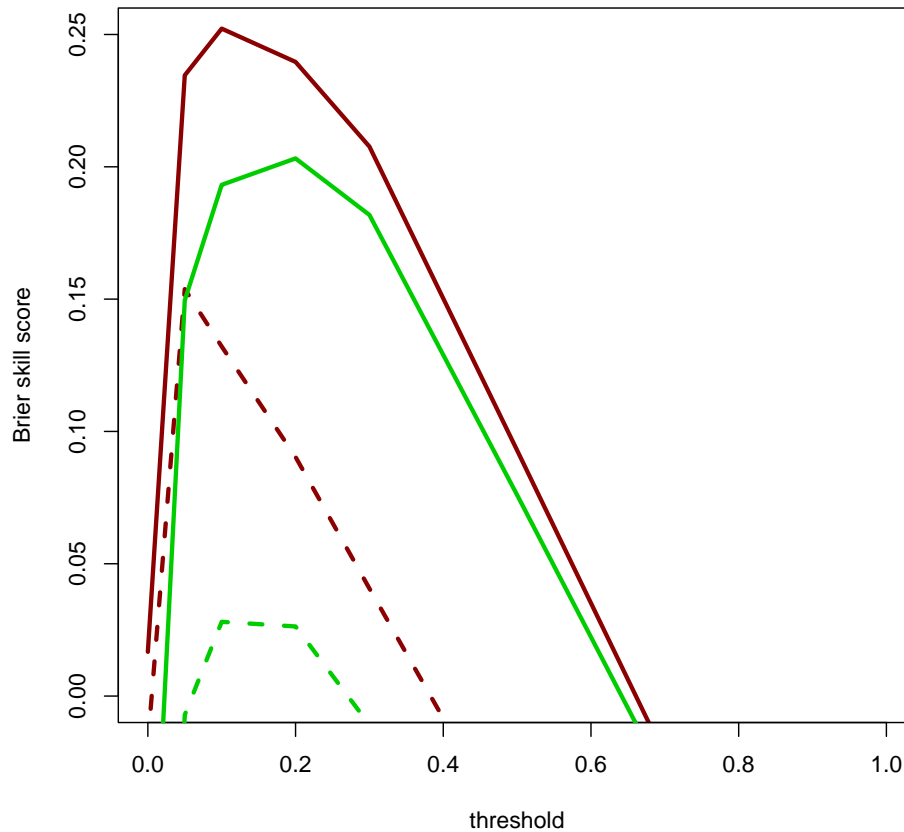


Figure 6. Brier skill score for the Gregory–Rowntree scheme (green lines) and the Plant–Craig scheme (red lines), averaged over all lead times, for cases with strong forcing (full lines) and weak forcing (dashed lines), as a function of threshold. The axes have been chosen to focus on where the skill score is above zero.

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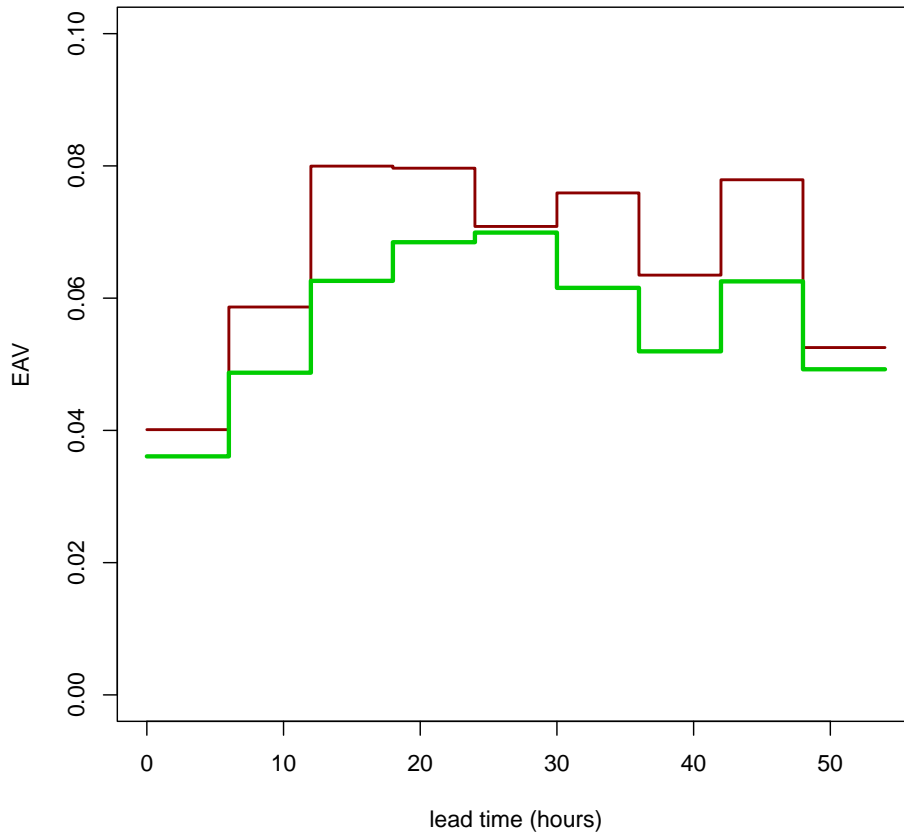


Figure 7. Ensemble added value (EAV) for the Gregory–Rowntree scheme (green line) and the Plant–Craig scheme (red line) as a function of forecast lead time.

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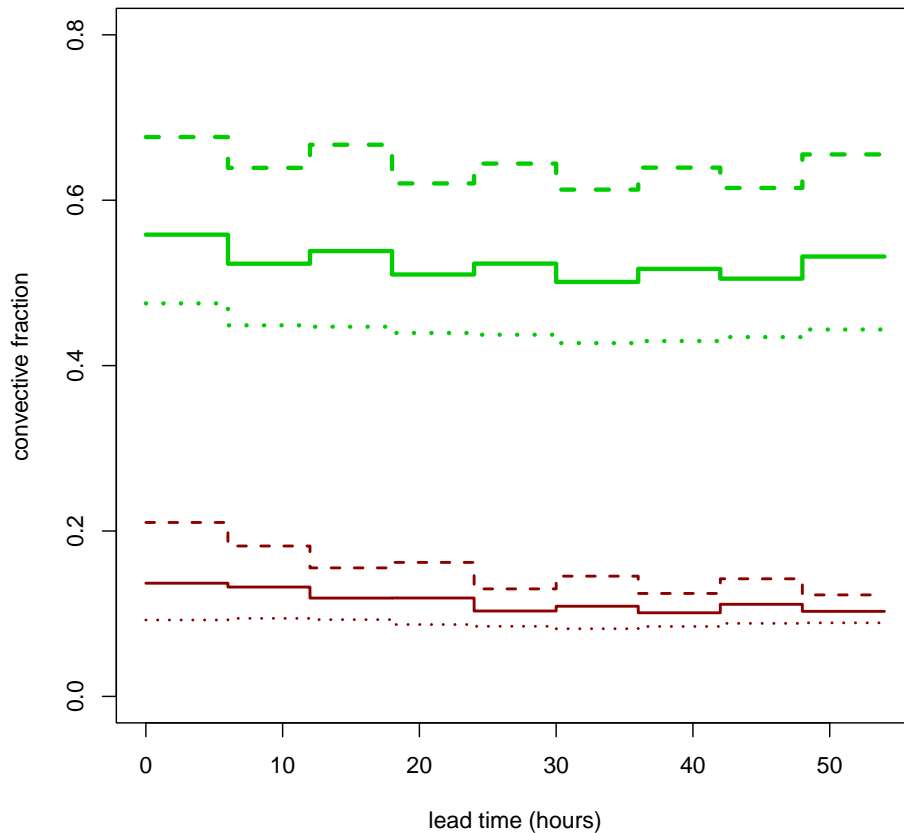


Figure 8. Convective fraction as a function of forecast lead time, for the Gregory–Rowntree scheme (green lines) and the Plant–Craig scheme (red lines), over land (dashed lines), over ocean (dotted lines) and in total (full lines), for the full NAE domain.

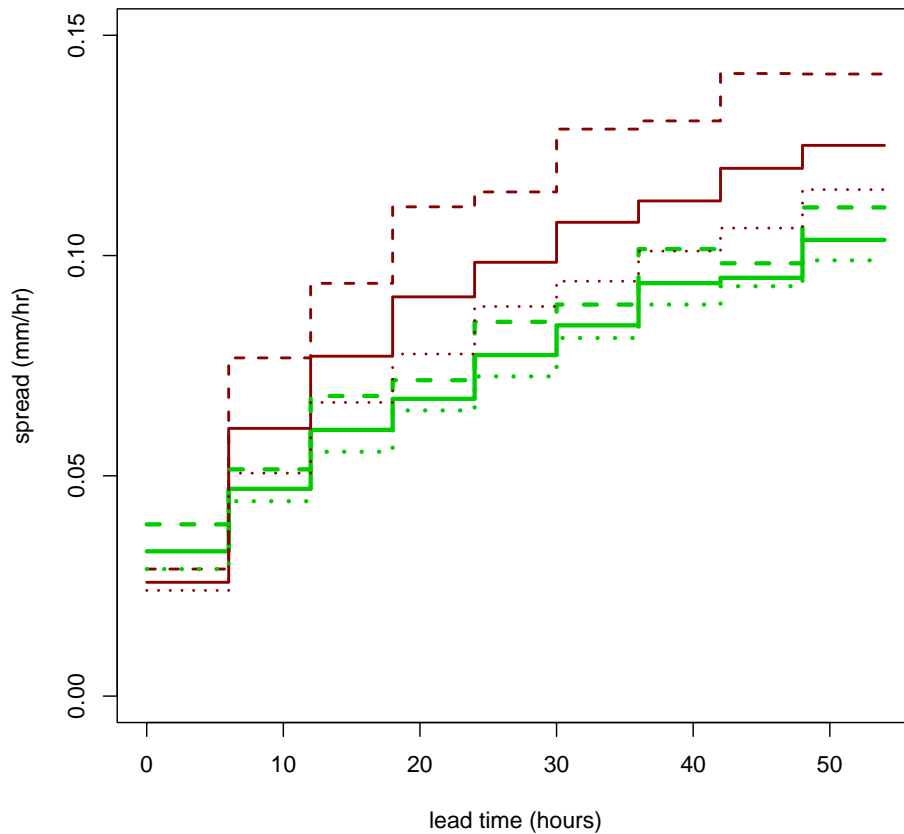


Figure 9. Ensemble spread as a function of forecast lead time, for the Gregory–Rowntree scheme (green lines) and the Plant–Craig scheme (red lines), over land (dashed lines), over ocean (dotted lines) and in total (full lines), for the full NAE domain.

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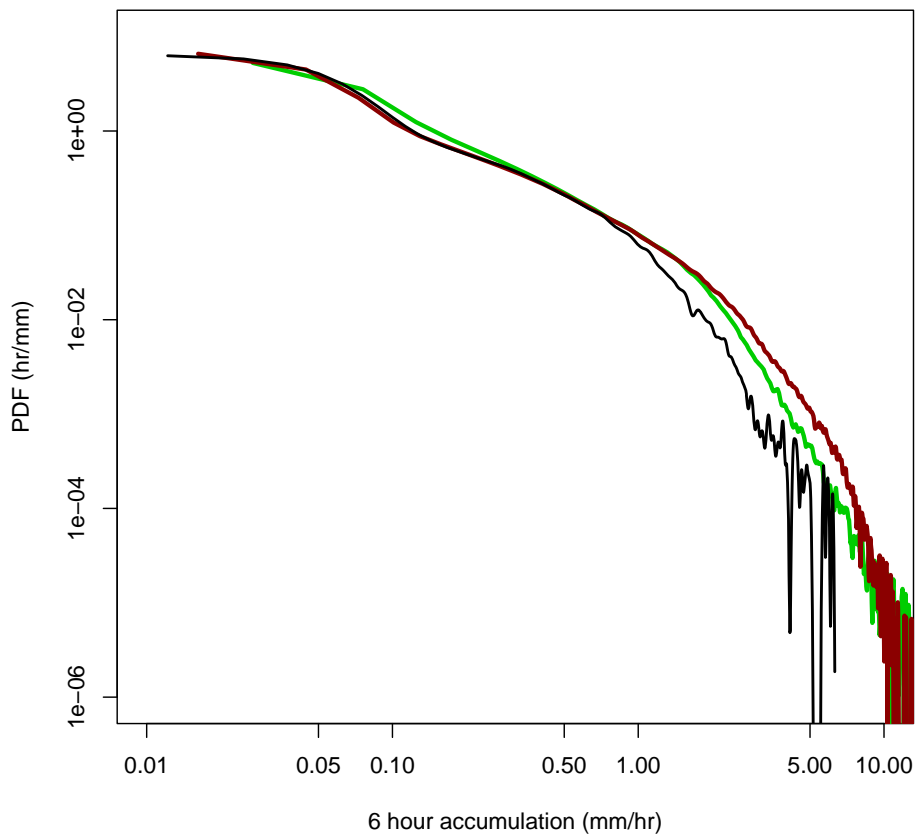


Figure 10. Density plots for accumulated rainfall for the period of 30 to 36 h lead time, over the UK part of the domain, for forecasts with the Gregory–Rowntree scheme (green line), the Plant–Craig scheme (red line) and observations (black line).

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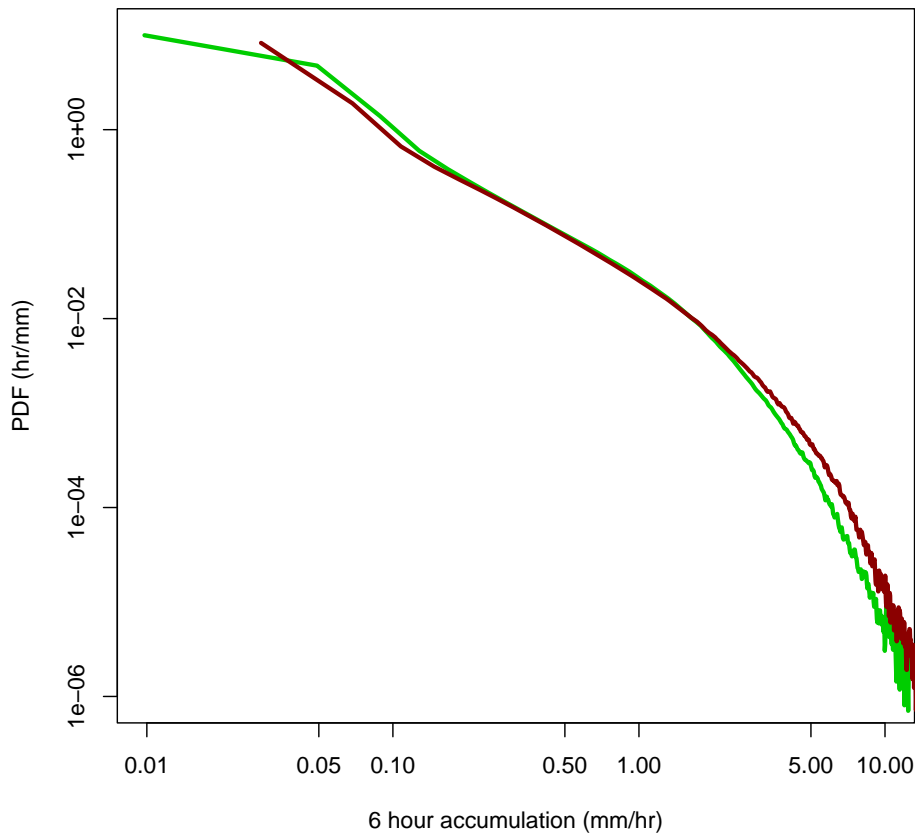


Figure 11. Density plots for accumulated rainfall for the period of 30 to 36 h lead time, over the entire NAE domain, for forecasts with the Gregory–Rowntree scheme (green line) and the Plant–Craig scheme (red line) over ocean.

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