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DIRECT ASSIMILATION OF RADAR REFLECTIVITY DATA IN THE MET OFFICE CONVECTIVE SCALE FORECAST SYSTEM

Lee D. Hawkness-Smith*, C. Charlton-Perez, and S. Ballard
Met Office, Reading, Berks., United Kingdom

N. Gaussiat
Met Office, Exeter, Devon, United Kingdom

1. INTRODUCTION

A number of operational centres are now routinely running convection permitting atmospheric models for regional Numerical Weather Prediction. The Met Office is currently running a 1.5 km gridlength version of the Unified Model (UM; Davies *et al.* 2005), the UKV, in a domain covering the United Kingdom. The high horizontal resolution of the atmospheric model, and associated high resolution representation of orography, and improved physical parameterizations, allows the model to produce mesoscale and convective features with a high degree of realism. The major challenge for the nowcasting application, i.e. forecasting in the range 0 – 6 hours, is to support the improved realism with improved accuracy by the optimum application of data assimilation.

The operational 1.5 km model runs 8 times per day, with 3-hourly cycling 3D-VAR. Observations assimilated in 3D-VAR include 3 hourly cloud cover, hourly SYNOP reports: screen temperature, relative humidity, wind, pressure and visibility, any available radiosonde ascents, hourly AMDAR, wind profiler, GPS time delay, scatterometer winds, AMVs, and hourly SEVIRI infra-red. In addition, hourly radar-derived surface rain rates are assimilated by latent heat nudging, where model profiles of latent heat release are scaled by the difference between modelled and observed precipitation.

Latent heat nudging has been shown to have a beneficial impact on precipitation forecast skill, particularly during the first three hours where its impact exceeds that of 3DVAR (Dixon *et al.* 2009). Despite recent improvements in resolution and data assimilation, NWP based forecasts for precipitation are still beaten by advection based methods in the first three hours, as shown in *Fig. 1*. Therefore the current Met Office nowcasting system, STEPS, blends information from an advection based scheme and the UK 4 km model.

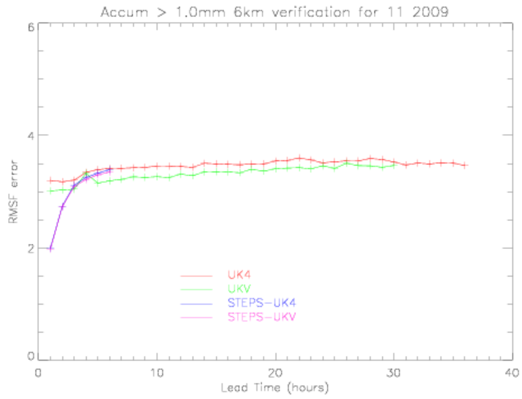

Figure 1. Comparison of NWP forecasts and STEPS (advection) nowcasts of precipitation: RMSF error of 1 hour accumulation > 1mm.

With continued increases in the availability of computer resources and observations, including new data types and more frequent observations, the Met Office has started a project to develop an NWP based nowcasting system. This system is designed to run 6 hour forecasts hourly, for a Southern UK domain, shown in *Fig. 2*, nested within either the UK4 or UKV. It can use 3D-VAR or 4D-VAR data assimilation.

The use of 4D-VAR allows the optimum use of high temporal (5-15 minutes) resolution observations, although at considerably increased cost relative to 3D-VAR due to the requirement to iterate a linearised version of the forecast model.

Novel observations which are being investigated at the Met Office include radar Doppler winds, refractivity, and reflectivity. The assimilation of radar Doppler winds has recently been introduced for the UKV operationally, giving a 1-hour improvement in forecast skill at low rain rates.

* *Corresponding author address:* Lee D. Hawkness-Smith, Met Office, Meteorology Building, University of Reading, Reading, Berks, RG6 6BB, United Kingdom; e-mail: lee.hawkness-smith@metoffice.gov.uk

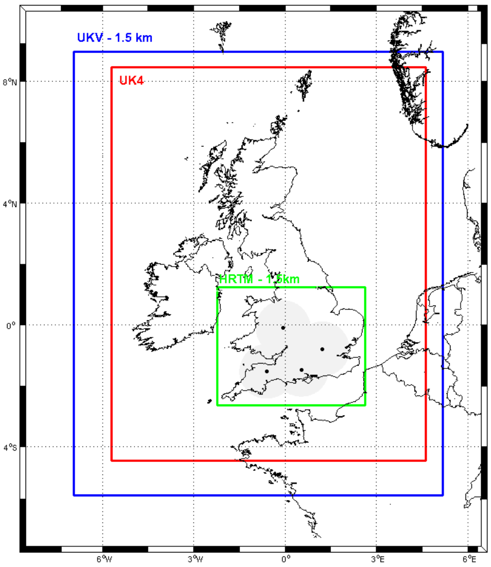

Figure 2. Model domain of Southern UK nowcasting demonstration project, nested within UK4 / UKV model. The four Doppler capable radars in the Southern UK domain are shown by the black dots.

This paper discusses research into the assimilation of radar reflectivity at the Met Office. The UK Weather Radar Network is shown in *Fig. 3*. Whilst latent heat nudging of radar-derived surface rain rates is beneficial for precipitation forecasts, and may be difficult to beat by variational assimilation methods due to the ability of latent heat nudging to add or remove precipitation in the model, there are advantages to using radar reflectivity data within the variational assimilation system. Variational assimilation does not require the assumption of latent heat nudging that latent heat release occurs in same column as precipitation. The use of all observations together in a common framework should alleviate sub-optimal interactions and allow the consistent use of complementary information. A further advantage of 4D-VAR is that it evolves the background error covariances.

2. APPROACHES TO RADAR REFLECTIVITY ASSIMILATION

The Met Office is pursuing two approaches to the assimilation of radar reflectivity data: the indirect approach, where radar reflectivity and model background data are used in 1D-VAR to produce relative humidity and temperature profiles, which could be assimilated in 3D-VAR or 4D-VAR, and the direct approach, where a forward model is used to assimilate reflectivity observations within 4D-VAR.

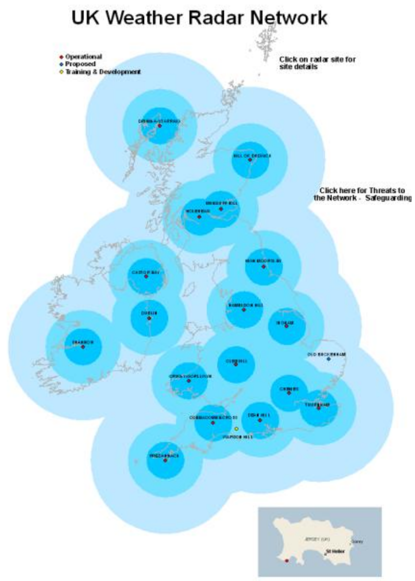

Figure 3. UK Weather Radar Network

The first step in developing a system for the assimilation of novel observations is monitoring the observations against the model background, to ensure that the observations are of sufficient quality, and the fit between the observations and the model is good enough, to fulfil the assumptions of the data assimilation method being used. For 3D-VAR and 4D-VAR, that means that the observations should be unbiased, and that the minimisation problem is only weakly non-linear. The radar data must therefore be processed to remove artefacts such as clutter and anomalous propagation, and the observations selected for assimilation must be sufficiently close to the model background to allow the assumption of approximate linearity to hold.

The Met Office has implemented a Radar Quality Management System (RDQMS) to address issues of radar data quality and reliability, which impact not only on data assimilation, but also hydrological applications (Georgiou *et al.* 2011).

Fig. 4 illustrates the radar data processing chain. Data preprocessing is performed on the RADARNET server, which passes data to the Observation Processing System (OPS). Preprocessing includes options to average in range and azimuth, to recalibrate, to measure the noise level for each averaged ray and perform noise subtraction, and to set flags for clutter, partial beam blockage and speckle. The data is encoded in NetCDF and Grib2 files with all the quality control information and metadata.

The OPS performs quality checks using the model background for all observations ingested into the Met Office data assimilation system. The observations are filtered using quality control flags. A forward model is used within OPS which simulates reflectivity using the rain and ice water content from the UM. A simple correction is made for beam bending and earth curvature; attenuation and beam integration are not currently accounted for but will be included in future versions of OPS. Superobbing can be performed on either a polar or the model grid, and there is an option to Poisson thin the data. Thinning the data before assimilation is important not only to reduce the data volume and reduce the cost of VAR, but also as assimilating observations which are closer than the observation error correlation lengthscale may be detrimental to the analysis.

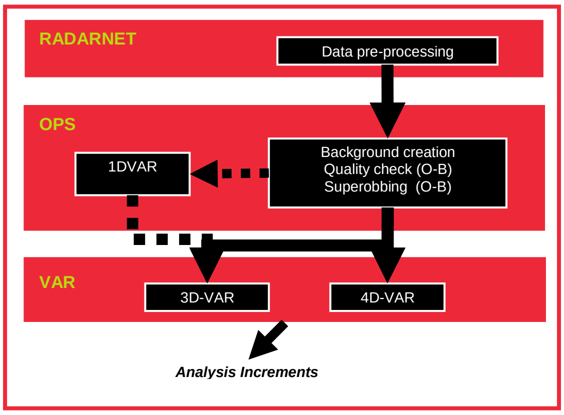

Figure 4. Radar data processing chain

The 1D-VAR retrievals of humidity and temperature profiles are also performed within OPS. Quality checked and superobbed observations are provided with columns of model variables at observation locations to VAR for assimilation. VAR provides increments to the UM.

3. DEVELOPMENTS TO 4D-VAR

The Met Office 4D-VAR system (Rawlins *et al*. 2007) has an incremental formulation, where the UM is used to provide the background, and a simplified, linear model, the perturbation forecast (PF) model, is iterated during the minimisation procedure to provide updated values of the model guess fields through the assimilation time window. Following each run of the PF model, its adjoint, which is used to calculate gradients for the minimisation, is run backwards through time. The model variables are transformed into control variables which should be uncorrelated. The control variables used in the Met Office VAR system are velocity potential, stream function, unbalanced pressure and a humidity variable which represents total water.

Implementing assimilation of radar reflectivity within the VAR system has involved the introduction of a reflectivity operator, and a linearisation of the operator and its adjoint, and enhancements to the PF model to include a rainrate model field, from which reflectivity is calculated. The reflectivity operator has the form:

$$Z\ [\mathrm{mm}^6\ \mathrm{m}^{-3}] = Z_R + Z_I \qquad (1)$$

where the rain component is given by:

$$Z_R = 181R^{7/4.67} \qquad (2)$$

where R is the model rainrate in mm hr^{-1} interpolated to the observation location, and the ice component is given by:

$$Z_I = 10^{0.035(T-273.15)+3.2}\ q_I^{1.67} \qquad (3)$$

where q_I is the model ice water content in kg kg^{-1} and T is the model temperature in K interpolated to the observation location. The VAR system includes a cloud incrementing operator, by which q_I is related to total water, which could be used in the assimilation procedure, alternatively the PF model could be developed to explicitly account for ice, or the ice term could be used purely for the UM background, with increments to total water calculated via the rainrate term.

When developing the PF model, a balance must be maintained between increasing physical realism, whilst avoiding unnecessary complexity which would make the system more non-linear and hence cause problems in minimisation. This is particularly challenging for cloud and precipitation microphysics which are inherently non-linear.

The current representation of the rainrate field in the PF model is as a diagnostic variable which is calculated from the condensed water increment in an autoconversion term. A set fraction of condensed water is autoconverted into precipitation during a model timestep. There is no attempt to represent evaporation, which could potentially lead to negative water contents in the linear framework. Improvements to this representation are currently being researched, and tested using linearisation tests, where the PF model increments are compared to UM increments.

A limitation of this approach is that where there is no rain in the model background, there is no gradient with respect to rain in the 4D-VAR cost function, and hence no means by which to introduce rain. Where there are large differences between the model and observations, the observations will have to be rejected to avoid the introduction of strong non-linearity. Thus misplacement of convective systems in the model with respect to the observations may be particularly challenging. Where observations can be assimilated, however, the model error covariances should allow the information to spread, and assimilating radar reflectivity observations in combination with the full set of standard observations should provide complementary information, constraining the analysis.

The oral presentation will highlight cases where the current operational system has failed to accurately represent precipitation features, and where reflectivity assimilation may have been beneficial for the forecast.

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