ASSIMILATION OF PRECIPITATION IN THE MET OFFICE MESOSCALE MODEL

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Abstract

The Met Office introduced the assimilation of radar-derived rainfall data into its operational mesoscale model in April 1996. Here we report on subsequent developments, including impact studies to measure the benefit of rainfall assimilation and sensitivity of forecasts to the temporal frequency of the rainfall data. It is found that on a monthly timescale, impact from the rainfall assimilation can be detected at a forecast range of 12 hours in some months, and an exceptional impact was found after 15 hours in one case. Increasing the frequency of rainfall data from 3-hourly to hourly improves the first 6 hours of the forecast. A physically based radar quality estimate has been introduced into the assimilation scheme. The quality estimate takes account of lower accuracy in derived surface rain rate when the beam is above the freezing level. Its adoption will ease the path to introduction of new European radars into the assimilation.

1 Introduction

An accurate description of the hydrological cycle is vital for short-period forecasting with regional operational Numerical Weather Prediction (NWP) models. To improve prediction of near-surface weather elements, it is important that models are initialised with the best possible description of the current atmospheric state. Precipitation and evaporation are key processes, yet it is not easy to assimilate data into models to influence them. Rainfall rate is not a prognostic variable in most NWP models, which makes assimilation of rainfall data more difficult than, say, the assimilation of wind data. A direct approach of updating model variables is not possible. Instead, techniques have focused on indirect methods of adjusting temperature and moisture in NWP models so that the rainfall diagnosed more closely matches that observed. The method adopted at the Met Office is known as Latent Heat Nudging (LHN), and is explained in detail (along with a review of other techniques) by Jones and Macpherson (1997).

The basic idea behind LHN is that since relatively little moisture is stored in clouds, the precipitation rate is proportional to the vertically integrated condensation (latent heating) rate. Also, latent heating is important for the development and forcing of precipitating systems, so if the correct latent heating can be supplied to the model, the forecast will improve. Latent heating acts as a source term in the thermodynamic equation influencing the adjustment of the vertical velocity. If we know (or can specify) the vertical structure of latent heating, then we can scale its vertical integral by the ratio of observed precipitation rate to model precipitation rate, and then add a temperature increment to the model consistent with this scaling. One can also add moisture increments to try and produce saturation in raining areas.

The Met Office runs an operational Mesoscale Model (MES) of gridlength 12km and 38 vertical levels. For the moisture component of LHN, we rely on the Moisture Observation Pre-processing System (MOPS), which blends satellite imagery and surface cloud reports with radar imagery to produce a 3-dimensional cloud analysis for assimilation by the MES (Macpherson et al., 1996). The cloud fraction data are converted into humidity increments through a relationship derived from the model cloud scheme. In the cloud analysis, both visible and infrared imagery along with surface reports are used to define the total cloud cover. Cloud top heights are assigned by comparing cloud top temperatures from infrared imagery with model temperature profiles and with a conceptual model of low cloud decks. Care is taken to try and prevent the model from assimilating thin cirrus which has been mistakenly assigned to lower levels, where it can generate spurious convection. Cloud thickness is adjusted to be consistent with areas of significant rain detected by radar.

For the temperature part of LHN, we rely on surface precipitation rate estimates at 15km resolution supplied by the radar analysis step of the 'Nimrod' nowcasting system (Golding, 1998). The data have been through anaprop removal, bright band correction and orographic enhancement. The vertical structure of latent heating rates is taken from the model's latest estimated heating distribution, and the scaling by precipitation rates is applied, as described above. If the model is producing no rain where rain is observed, then a search is conducted around that grid-point to find a point where the model is raining, and the heating profile from that point is used to calculate increments at the point where it is desired to introduce rain.

As reported by Jones and Macpherson (1997), LHN was tested in a pre-operational trial on 14 cases covering a variety of precipitation situations. The scheme was found on average to improve precipitation forecasts in the first 6-9 hours of the forecast, with little impact beyond that time. Frontal cases showed more beneficial impact than convective cases.

2 Extended impact studies

LHN was introduced operationally in April 1996. It was later established (Wilson, personal communication) that the precipitation skill of the MES for 1996 was substantially better than for 1995 and 1994, especially in the first 6 hours of the forecast, but to a lesser extent at later forecast times too. The Equitable Threat Score (ETS) is a measure of skill relative to a random forecast. For 6-hourly accumulations exceeding 1mm (measured against rain gauges) between t+0 and t+6, the ETS increased from 33% in 1995 to 38% in 1996.

To examine the contribution of LHN to such improvements, some extended periods of parallel assimilation without LHN were undertaken in 1997. While confirming the general findings of the pre-operational trial, this study revealed an example of a longer lasting forecast impact from LHN (Figure 1), this time at t+15 hours. The situation involved a rainband which formed near the south of the model domain and moved slowly northwards as it developed, so the signal from initial conditions was not swept out of the domain as quickly as with a more rapidly moving system in a westerly flow. The run with rainfall assimilation gives a significantly better depiction of the rainfall pattern.

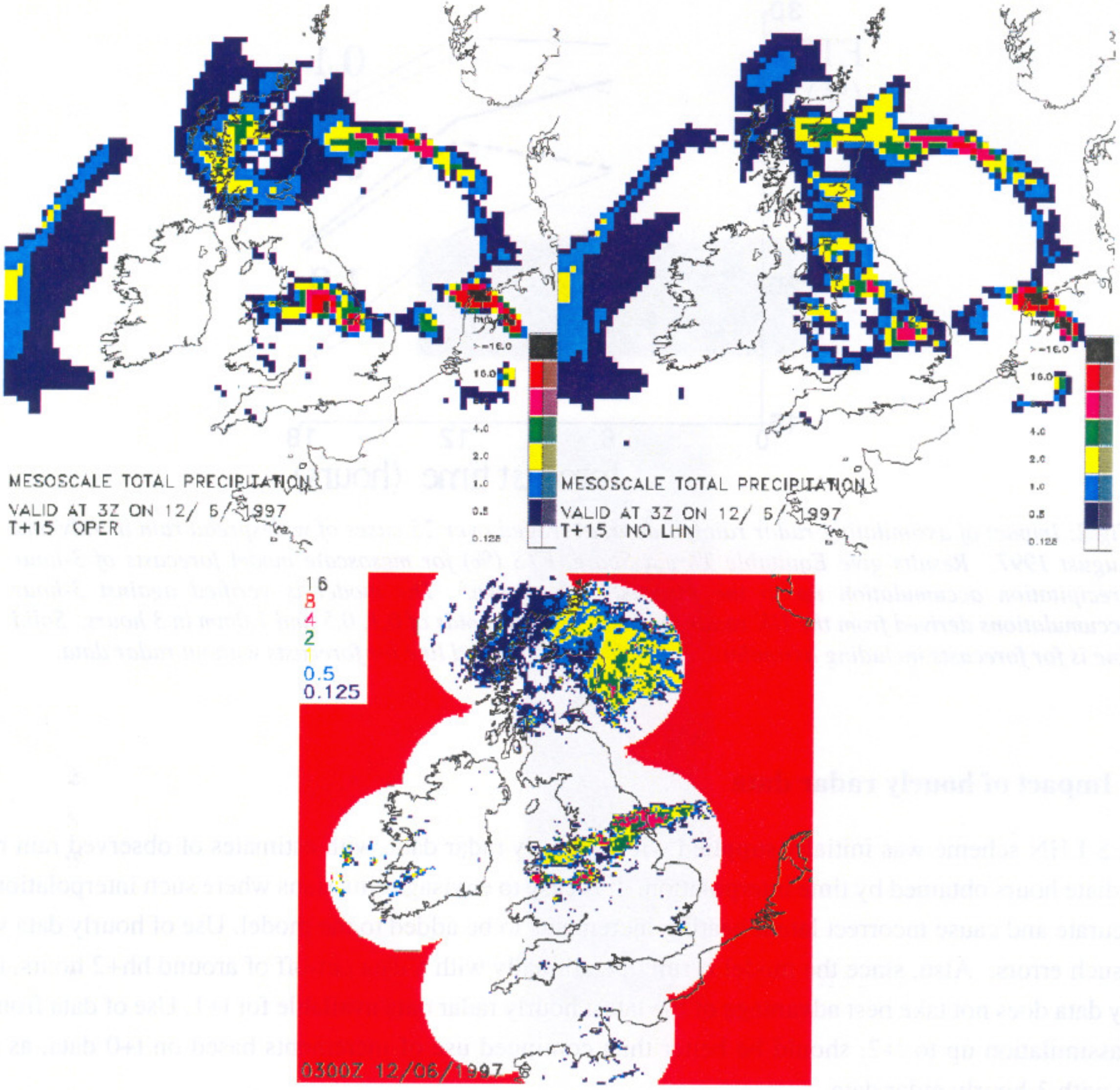

Fig 1: An unusually long lasting forecast impact of radar rain rate assimilation in the Met Office mesoscale model. Bottom frame shows radar picture for 03 UTC on 12th June 1997, with northward moving rainband over central England. Top left frame shows operational precipitation rate forecast at t+15 hours. Top right frame is from a run with NO assimilation of radar data.

Forecasts from the impact trial were also verified objectively against 3-hourly accumulations derived from radar based analyses, with Equitable Threat Score (ETS) as the measure. These experiments revealed that on a monthly timescale, impact from LHN can be detected objectively up to t+12 in some months, with a very marked benefit in the first 6 hours, while in other months LHN may give only a neutral signal. Figure 2 shows results for a period in July/August 1997 when LHN of radar data gave significant benefit. The improvements in ETS are appreciable relative to those noted in annual means for this score. By contrast, results for a period covering June 1997 (not shown) were close to neutral.

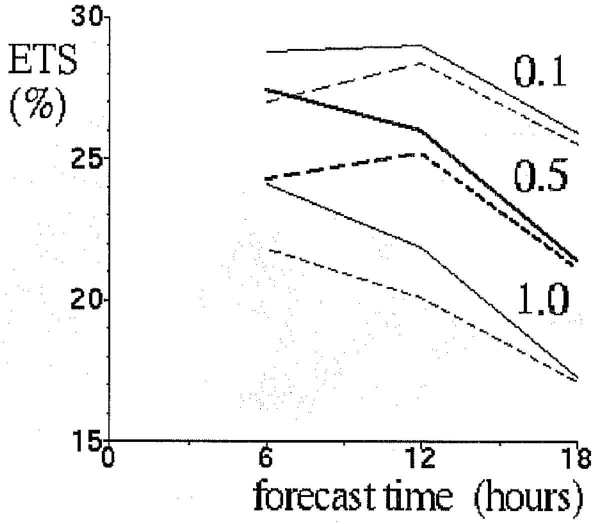

Fig 2: Impact of assimilating radar rainfall data, averaged over 25 cases of widespread rain in July and August 1997. Results give Equitable Threat Score, ETS (%) for mesoscale model forecasts of 3-hour precipitation accumulation up to the forecast time shown. The model is verified against 3-hour accumulations derived from the UK radar network, for thresholds of 0.1, 0.5 and 1.0mm in 3 hours. Solid line is for forecasts including assimilation of radar data, dashed line for forecasts without radar data.

3 Impact of hourly radar data

The MES LHN scheme was initially supplied with 3-hourly radar data, with estimates of observed rain rate at intermediate hours obtained by time interpolation. It is easy to envisage situations where such interpolation may be inaccurate and cause incorrect latent heating increments to be added to the model. Use of hourly data would reduce such errors. Also, since the model is run operationally with a data cut-off of around hh+2 hours, use of 3-hourly data does not take best advantage of the latest hourly radar data available for t+1. Use of data from t+1, during assimilation up to t+2, should be better than continued use of increments based on t+0 data, as is the practice with 3-hourly radar data.

To assess the magnitude of these potential benefits, a parallel assimilation experiment was run for several periods between August and October 1998, with the operational run as control, receiving 3-hourly data, and the trial supplied with hourly data. Again, precipitation forecasts were verified objectively by comparing 3-hourly accumulations against radar based analyses, with Equitable Threat Score (ETS) as the measure of skill. Subjective assessment of precipitation fields was also carried out.

As anticipated, the impact of hourly data was mainly seen in the first 6 hours of the forecast (Figure 3). For a threshold of 1mm/3hours, the ETS for the period t+3-t+6 was 29.8% for the control and 31.2% for the trial, averaged over 70 forecasts. The benefit at lower thresholds was smaller, and the signal at t+12 and t+18 was very marginally detrimental. Overall, the objective precipitation scores represent a worthwhile improvement from hourly data.

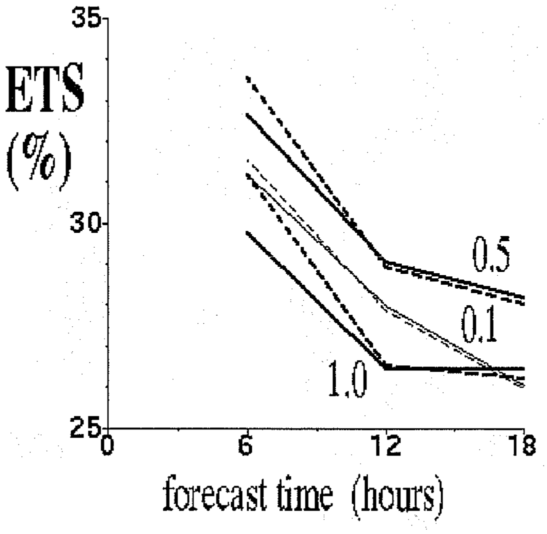

Fig 3 : Impact of increasing the frequency of radar data supplied to the mesoscale assimilation from 3-hourly to hourly, averaged over 70 forecasts of widespread rain in the period August-October 1998. Results give Equitable Threat Score, ETS (%) for mesoscale model forecasts of 3-hour precipitation accumulation up to the forecast time shown. The model is verified against 3-hour accumulations derived from the UK radar network, for thresholds of 0.1, 0.5 and 1.0mm in 3 hours. Solid line is for forecasts with assimilation of 3-hourly data, dashed line for forecasts with assimilation of hourly radar data.

Occasionally significant impacts were noted subjectively, of which Figure 4 is one of the clearest examples. The trial forecast has a better structure and intensity in the rain area over northern England. It also has less heavy rain over the Irish Sea than the operational run, where the radar shows none. Operational use of hourly data began in May 1999.

4 Radar Quality Estimate

The initial treatment of the error characteristics of radar based surface precipitation rate estimates was very simple. Relative to the model, we assumed the radar data to be of high quality within 100km of the nearest radar and of diminishing quality out to maximum range around 200km. One weakness of the implementation of this idea was that we assumed a fixed radar network, whereas at any one analysis time, one or more radars may not have been contributing to the composite. This meant that some of the data assumed to be coming from a nearby radar may actually have come from a radar further away, and the LHN scheme may have given too much weight to the longer range data. A real-time assessment of data quality was required.

More fundamentally, surface precipitation rate estimates are found to be less accurate when the radar beam is above the freezing level. This is primarily due to the difficulty in extrapolating the observed reflectivity above the freezing level to the reflectivity that would be observed at ground level, which in turn is used to determine the precipitation rate at the ground. Therefore, it is desirable to have a quality measure which takes account of radar beam geometry and freezing level height. This has now been developed within the radar analysis step of the Nimrod nowcasting system, as reported by Gibson et al.(2000).

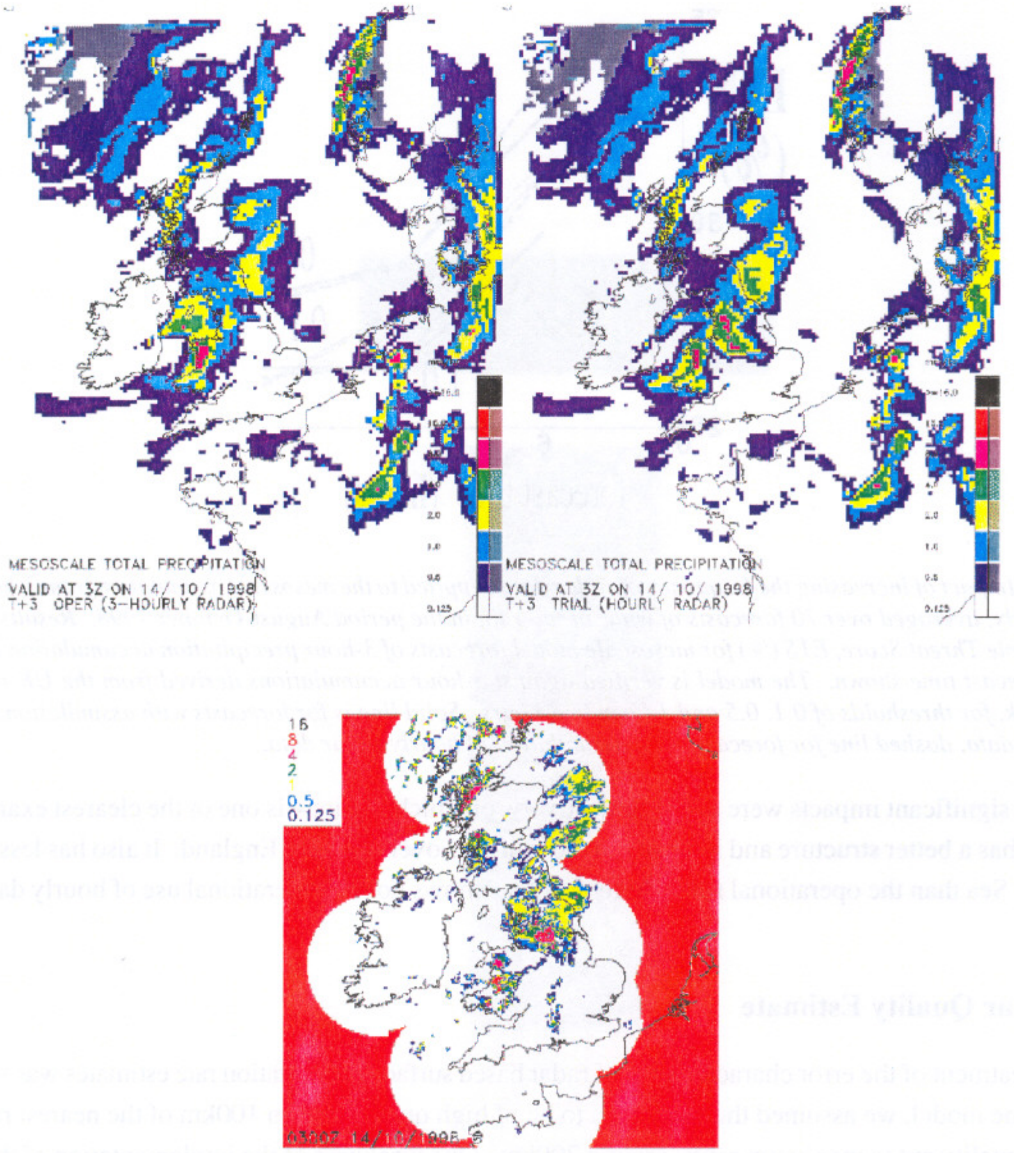

Fig 4: Impact of hourly radar data on a 3-hour forecast of precipitation rate valid at 03 UTC, 14th October 1998. Top left frame is the operational forecast at the time, assimilating 3-hourly radar data. Top right frame is from a run assimilating hourly radar data. Bottom frame is a verifying radar picture.

In more detail, the weighting factor, W, in the original MES LHN assimilation was given by:

$$W = W_0 \, (R - d)/(R - 100) \qquad d > 100\text{km}$$

$$W = W \qquad d \leq 100\text{km} \qquad (1)$$

where W_0 is a constant (currently 10), R is the maximum range of the radar, and d is the radar-pixel distance, both in km. W gives the relative weight of the radar precipitation rate to the model precipitation rate when calculating the analysed precipitation rate, towards which the model is forced during LHN.

The new quality measure, introduced in September 2000, is given by:

$$W = W_0\alpha \qquad h < h_{fl}$$

$$W = W_0\,\alpha\left(1-\frac{(h-h_{fl})}{4}\right) \qquad h_{fl} < h < (h_{fl} + 4\ \mathrm{km})$$

$$W = 0 \qquad h \geq h_{fl} + 4\ \mathrm{km} \qquad (2)$$

where W_0 is a constant, h is the beam height, h_{fl} is the height above the freezing level and α is a factor depending on range R that further reduces the weighting beyond 150 km, given by:

$$\alpha = 1 \qquad R < 150\ \mathrm{km}$$

$$\alpha = 1-\left(\frac{R-150}{60}\right) \qquad 150 < R \leq 210\ \mathrm{km}. \qquad (3)$$

Equations (2) and (3) essentially say that the radar data quality should decrease once the beam is above the freezing level, falling to zero when the beam is more than 4 km above the freezing level. This should be a reasonable measure of radar quality, since once the beam height is higher than 4km above the freezing level it is difficult to reliably extrapolate to a rainrate at the ground. The factor α means that the data quality also falls off once the range is greater than 150km from the radar. This takes into account the effects of increasing beam width at longer range, which leads to a reduction in data quality.

For a winter case with relatively low freezing level, the new quality estimate produces a weights field like Figure 5(a), while a summer case is simulated by a field for constant freezing level of 3500m in Figure 5(b). The weights produced by equations (1) are in Figure 5(c). Note the difference between Figures 5(a) and 5(c) in NW Scotland where the freezing level is low for the winter case.

One qualification of the above formulae is applied, in that we ensure for wet observations, $W \geq 1$. This means we still give significant weight to a wet observation near the edge of the radar area, which could be important if the model were dry there.

To test the new quality estimate, a continuous assimilation 'parallel' to the operational system was run for 3 weeks. The signal was very close to neutral, but the new quality estimate was adopted for its better scientific principles. The lack of significant impact may be due in part to the relative simplicity of the LHN technique, in which it is found that errors in the observed rain position are more detrimental for assimilation than errors in observed rain intensity. In future, however, as rainfall assimilation schemes improve, we can expect a greater sensitivity to observation error estimates.

Fig 5(a): The weights field (W/W_0) *from equations (2) and (3) for a winter case. Light shading for* $(W/W_0)=1$, *dark shading for* $(W/W_0)<1$

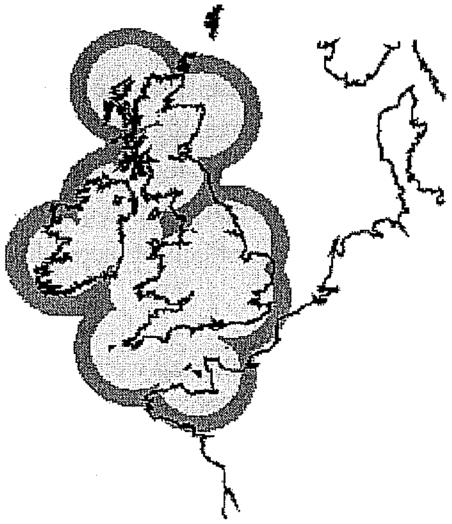

Fig 5(b): As Fig. 5(a) for a summer case with uniform freezing level height of 3500m.

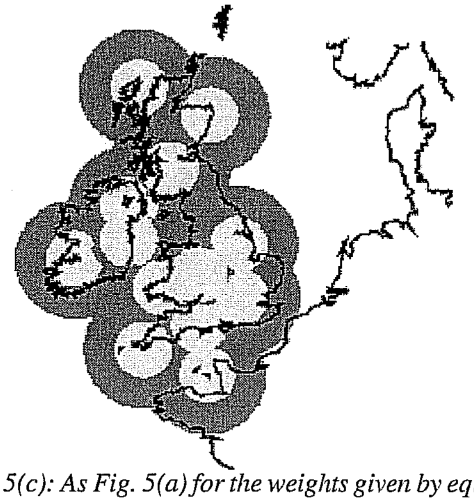

Fig 5(c): As Fig. 5(a) for the weights given by equations 1, for which $(W/W_0)=1$ *up to a range of 100km from each radar.*

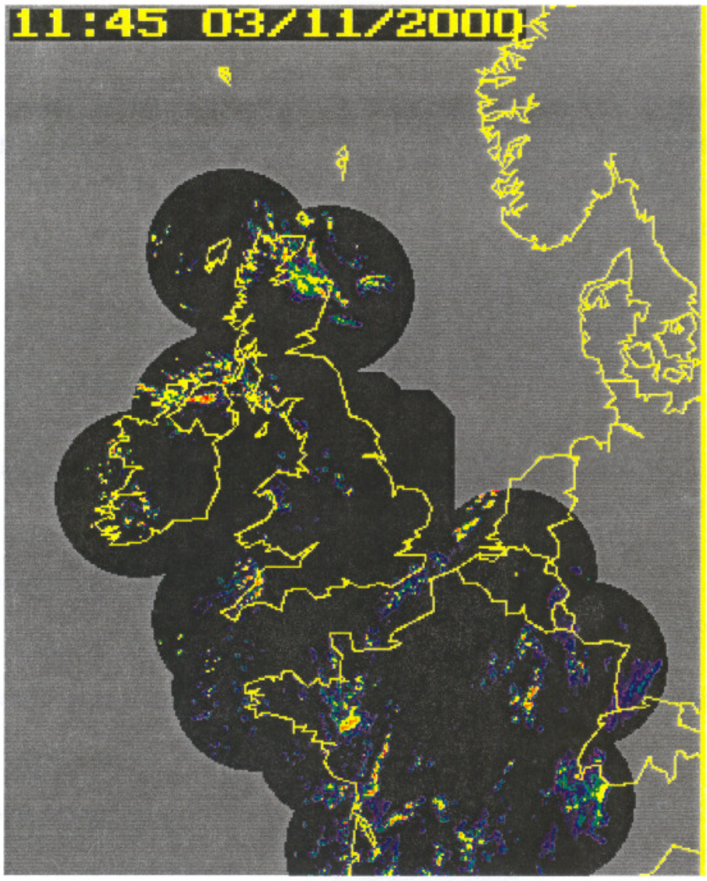

Fig 6: Expanded area of radar coverage due to be implemented operationally in early 2001.

5 Further Developments

Examples of significant impact such as Figure 1 provide encouragement to extend the coverage of radar data, especially to the south. Continental radar data to supplement the UK network could be helpful in forecasts with southerly, or south-easterly flow. In summer 1998, the model southern boundary was extended to ~44°N and in late 1999 work began on integrating radar data from Belgium and France into the UK radar composite for data assimilation by the MES. Early in 2001, it is intended to expand the coverage to that shown in Figure 6 (compare with Figure 5). Data from the Netherlands are also due for inclusion. This work has been stimulated by collaborative work within the COST-717 Action entitled: 'Use of Radar Observations in Hydrological and NWP Models' (Rossa, 2000), especially its Working Group 3 (Macpherson, 2000).

In October 1999, the Met Office introduced a 3-dimensional variational (3D-VAR) assimilation scheme into the MES. At present the 3D-VAR scheme does not treat the cloud or rainfall data, for which nudging and LHN are retained. The procedure followed is to analyse 'conventional' observations by 3D-VAR, and produce a set of analysis increment fields. These are then added gradually to the model by the so-called Incremental Analysis Update (IAU) technique (Bloom et al., 1996) during an integration from t-2 hours in which moisture nudging and LHN are also performed up to t+2. This rather empirical combination has proved acceptable in terms of its overall impact on short-period rainfall forecasts, but it is planned to integrate the cloud and rainfall assimilation increasingly within the variational assimilation scheme.

Acknowledgements

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