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Issues with high-resolution NWP

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Introduction

The Met Office is developing high-resolution NWP along two closely related paths. The first is directed at short range forecasting, where we expect most benefit in the 12-36 h timeframe. The second is directed at nowcasting, meaning frequently-updated (generally hourly) 0-6 h forecasts.

Both are based on the Met Office Unified Model (MetUM, Davies et al 2005) running at horizontal resolution high enough to permit the development of (poorly resolved) deep convection (1.5 km) but the different applications lead to different emphases; it is essential that the nowcasting system produces an accurate small-scale forecast at extremely short range, especially of rainfall. Thus, we aspire to represent major convective cells or at least clusters of them reasonably faithfully (in location and intensity) at T+1 hour. (This is a pragmatic aspiration, based on the idea that the T+1 forecast will probably reach users not long before the verifying radar observations are available together with the experience that ‘traditional’ nowcasting systems based on extrapolation of the movement of existing cells have some skill at T+1). Nowcasting thus has a very strong emphasis on data assimilation, especially the assimilation of high-resolution data.

Forecasting individual convective storms in the 12-36 time frame is not a realistic aspiration at present (if at all). The forecast model provides a non-linear downscaling of coarser resolution information in the initial and lateral-boundary conditions. This downscaling contains information of deterministic value when the larger-scales are sufficiently accurate and there is significant forcing from well-characterised high-resolution inputs such as orography and surface characteristics. We have a number of examples of significant flooding events involving orographic enhancement being forecast much better by a high-resolution model. For example, Roberts *et al.*, 2009, in a case study of the Carlisle Flood, show that a 1 km version of the MetUM coupled to a catchment model forecast river flows 12 h or more ahead at least as accurately as driving the same model with observed rainfall.

Even when the deterministic skill is small, the downscaling still provides statistically useful information. A very good example is the penetration of showers inland in the winter; a long-standing feature of the MetUM at lower (e.g. 12 km) resolution with parametrized convection is that showers die out rapidly at the coast. In practice, such showers often penetrate some distance (e.g. 50-100 km) inland, often bringing significant snow and often with some intensification at the coast due to roughness-induced coastal convergence. A high-resolution model may provide very valuable information about the region at risk from heavy snow in spite of information about individual showers being purely statistical.

The emphasis in the 12-36 h time frame is therefore less on assimilation of high-resolution data and more on the faithful incorporation of larger scale information and the interpretation of output to make full use of the available information without being mislead by detail.

At present, available computer power has forced a choice between the short-range and nowcasting applications. The former is has been implemented as an operational system (‘UKV’) to support services such as the Extreme Rainfall Alert service. The nowcasting system remains a research activity; while DA techniques are being developed, it has been implemented on a small domain within the UK model covering southern England, in order to incorporate the cluster of Doppler radars and the Future Upper Air Network Demonstration (FUND) sites available in this area.

UKV Model Configuration

Current Status

The new ‘UKV’ model has 0.0135° (approximately 1.5 km) horizontal resolution over the UK with variable resolution stretching to 4 km away from UK. See Figure 1 for the domain. It has 744 x 928 gridpoints (622 x 810 in the inner 1.5 km area) and 70 levels. It will eventually replace the UK 4 km and small 1.5 km ‘on-demand’ models. It runs with a 50 s timestep, currently 4 runs per day to T+36. Lateral boundaries come from the 12 km NAE every half hour; its start time is staggered 3 hours from the NAE to enable it to run with up-to-date lateral boundary conditions in a timely manner. The initial state comes from 3DVAR+Latent Heat Nudging.

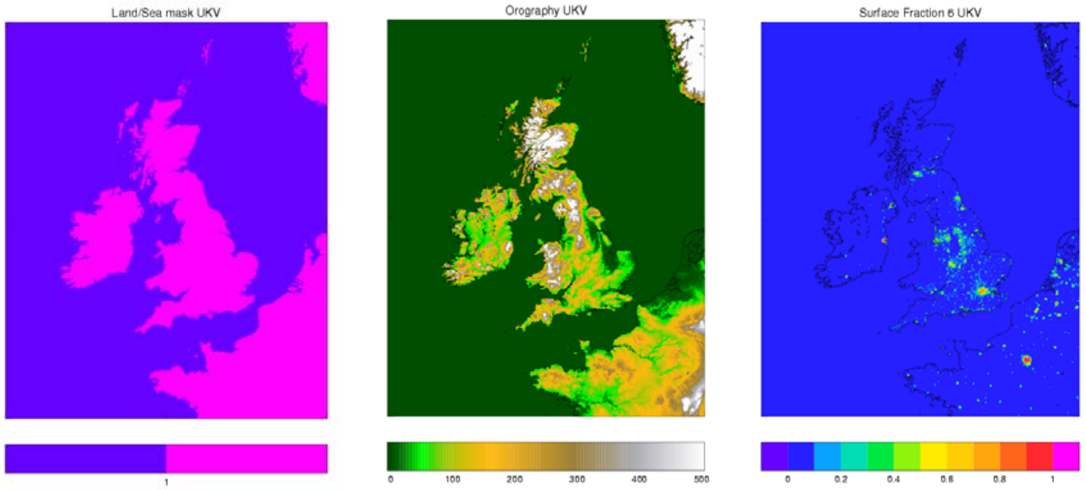

Figure 1 Land/sea mask, orography and urban land-use fraction from the 'UKV' 1.5 km variable resolution model.

Issues

Vertical and horizontal mixing

In general, the UM has proven capable of producing very useful forecasts at convective scale; however, throughout its development it has been evident that the characteristics of the convection which develops is quite sensitive to the treatment of mixing in the model. Convection triggering remains an issue. In practice, the issue turns out often to be of secondary importance, because mesoscale forcing (e.g. convergence lines) dominates, but in weakly forced circumstances (e.g. ‘airmass convection’) the development of convection depends very much on the model. This is a common finding for a variety of models, and a model inter-comparison is being designed within the SRNWP framework to study the problem in more depth.

Considering the development of deep convection from a convective boundary layer, both horizontal and vertical mixing are important for different reasons. Vertical mixing controls the depth of the boundary layer but also entrainment from above. It therefore tends to control initiation. Horizontal mixing controls the horizontal scales which develop through instability.

We have adopted a philosophy of retaining, where possible, the existing MetUM BL scheme (Lock *et al.*, 2000), as this should still be appropriate at 1.5 km grid length. The intention has been to use the local part of this scheme outside the BL, but this has only

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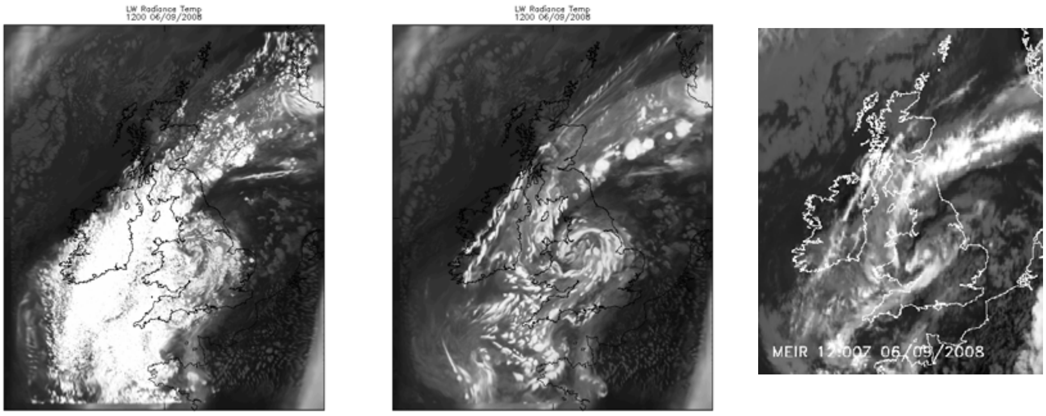
been fully possible from version 7.3 of the MetUM. Apart from its role in development of deep convection, the importance of vertical mixing at upper levels was highlighted during the testing phase of UKV; initial implementation did not include vertical mixing above about 3 km. As a result, instabilities occurred at the top of extensive areas of frontal cirrus in areas with strong radiative cooling. This has largely been cured by allowing the local mixing scheme to operate at these levels, but there remains a tendency to develop occasional unrealistic ‘convective’ circulations at cloud top (Figure 2). It seems likely that the local scheme is unable to provide enough entrainment of warm air at cloud top (often tropopause level) in much the same way that local schemes do not treat stratocumulus layers well; a non-local scheme very similar to the ‘decoupled stratocumulus’ scheme already present may be needed.



a) b) c)

Figure 2 a) and b) Broad-band IR radiance temperature derived from he total outgoing long-wave radiation in the UKV configuration; a) shows the impact of cloud-top instability a run without vertical mixing at upper levels, b) the same with local vertical mixing applied. c) shows (narrow-band) IR image from MSG. Images are for 1200 UTC, 06/09/2008 (the ‘Morpeth flood’).

A ‘2D-Smagorinsky-Lilly’ scheme has been implemented for horizontal mixing. (The Smagorinsky-Lilly scheme is also available in 3D for use at higher resolution). This seems to perform better than the fixed ∇^4 mixing used previously, primarily because much of the time it does much less mixing. It is recognised, however, this is very much an area of pragmatic tuning. Over the next year, once the UKV model is fully operational, we plan more extensive diagnostic studies in order to gain insight into model behaviour, especially through the triggering and development of convection.

At resolutions around 1 km, it is evident that not all of the turbulent energy will be (or should be) contained within the boundary-layer scheme. We are investigating use of stochastic backscatter of some form, following the results of Weinbrecht and Mason, 2008, but this work is at a very early stage.

Microphysics

The MetUM microphysics has been extended to (optionally) include prognostic rain, ice, snow and graupel, but is currently being run with prognostic rain, a single combined ice and snow prognostic and no graupel. The main justification for this is that no forecast benefit has been found over the UK for running with a more complex scheme. (Benefit of prognostic rain **has** been found, primarily in orographically enhanced rain but also in increasing the lifetime of convective cells). Furthermore, it is possible that with more prognostics, interactions between mixing and microphysics may become more important.

Issues with sharp land-sea contrast in drizzle have already been noted in forecaster feedback. This is a well-known problem due to the assumptions made regarding fixed land and sea aerosol concentrations in the warm autoconversion scheme. Coupling to an aerosol variable will certainly ameliorate this effect cosmetically but will be approached cautiously. There may be a related issue regarding warm rain in convective clouds, and knock-on effect on glaciation, but this has yet to be demonstrated.

It should be noted that, as part of the CASCADE project, problems with conservation of hydrometeor species have been found. This arises because the Priestley algorithm, which may be used to enforce conservation, does not always converge. The long-term solution to this problem will be available in ENDGAME with the SLICE conservative advection scheme, but in the meantime extensions to the Priestley algorithm and other solutions are being considered. A secondary problem arises because the Priestley algorithm has not been implemented for boundary-forced limited area models; this will be rectified shortly. Nevertheless, non-conservation has not been found to be such a problem in the UK model, perhaps because convection is usually much less energetic than in the CASCADE cases.

Other Parametrization Issues

A number of parametrization issues remain which are not felt to be of high priority but may have some influence on forecast performance. Most are related to possible improvements to surface forcing.

First, we are currently running with no unresolved orographic drag scheme. It is reasonable to suppose that the existing orographic roughness scheme (preferably, the distributed drag version of it) is appropriate even at 1.5 km, but with current estimates of parameters it does very little and we are currently running without it. The small contribution may result from inadequate orography data. A careful analysis of the optimal orographic filtering and provision of suitable unresolved orography parameters is needed, preferably using better data than the 100 m DTED data we currently use.

Second, we currently use the off-line MOSES-based analysis of soil moisture. As well as needing upgrading to use better soil parameters, there are some concerns that the lack of horizontal transport in this system may compromise accuracy at high resolution. We are considering options regarding coupling to a more 3D hydrology model.

Similarly, we currently use the OSTIA sea surface temperature analysis, held fixed during a forecast, no surface currents and the Charnock formula for sea surface roughness. The possibility exists to couple (one or two-way) to wave and ocean models. We are currently considering available options and timescales given the likely future development path of the ocean forecasting systems.

Data Assimilation

Current Status

The current model system uses variational data assimilation system (Lorenc et al 2000, Rawlins et al 2007) including latent heat and moisture nudging (Macpherson et al 1996, Jones and Macpherson 1997, Dixon et al 2009). The 1.5km resolution forecast system producing 36 hour forecasts will be using 3D-Var. It will initially be using 3-hourly cycling essentially the same as the UK 4 km system. Some benefit has been shown in the prototype nowcasting system using higher time frequency data in the nudging schemes and 1-hourly cycling, so this will be trialled in the near future.

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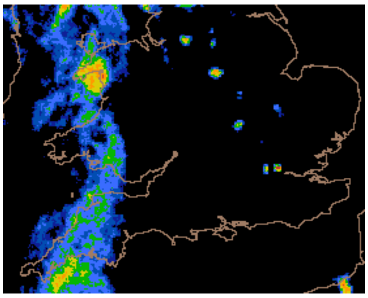
In parallel a prototype NWP nowcasting system is being developed to produce hourly 7 hour forecasts for southern England, also at 1.5km resolution. These forecasts need to be produced rapidly and to match the observations as closely as possible in the early hours of the forecast. They present a considerable challenge for data assimilation. An hourly 3D-VAR analysis and forecast system has been run over a limited number of cases of summer rain and convection using conventional data. Research and development is under way to investigate use of 4D-VAR assimilation and to exploit novel observations in both 3D-VAR and 4D-VAR such as radar Doppler winds, radar reflectivity, surface rain rates, satellite imagery data, ceilometer, cloud radar and radiometer data as well as more frequent conventional observations. Research is proceeding to investigate the background errors, balances and control variables required for use in convective scale data assimilation.

Progress with 4D-VAR

Currently the nowcasting forecasts are produced from the UK Post-Processing system (UKPP) at 2 km resolution using STEPS extrapolation forecasts (Bowler et al 2007) in first few hours merged with down-scaled 4 km resolution NWP forecasts at later times. It is useful to use this as a standard against which to judge the success of a nowcasting NWP system. As an example, Figure 3 shows UKPP forecasts valid at 21UTC 3rd June 2007 at range 3 , 2 and 1 hours compared with the radar derived surface rain rates. At T+3 the UKPP forecast mainly comes from the UK 4km NWP forecast which tends to produce convective cells at too large a scale and not enough light banded convection as can be seen in the forecast of the band of convection in the east. At T+2 the STEPS scheme has produce the line of convection in the east but it is too narrow presumably due to convergence by the advection scheme used. By T+1 a reasonable forecast has been produced.

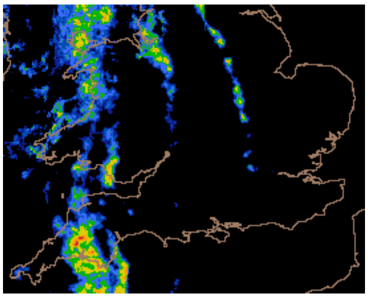
Eventually we plan to incorporate assimilation of radar data of various types directly into 4D-VAR. However, a first step is to ensure that 4D-VAR works properly at convective scales. With this objective we have implemented a system using 4D-VAR over a 1 hour time window using conventional observations, retaining the nudging of 15 min radar derived rain rates and hourly humidity derived from 3D cloud cover analyses of rainfall rates and moisture. Figure 4 shows the 1.5 km NWP forecasts for this case valid at 21 UTC on 3rd June 2007. The NWP forecasts improve at shorter lead times due to benefit of data assimilation, in particular latent heat nudging of surface precipitation rates. In comparison with the UKPP forecasts the 1.5km NWP forecast has a better representation of the rain band in the east at both T+3 and T+2. The representation of the rain in the SW of England is poorer than from UKPP. However for the first case compared with UKPP and without optimization of the data assimilation scheme and exploitation of more frequent conventional observations this is a very promising result.

T+3



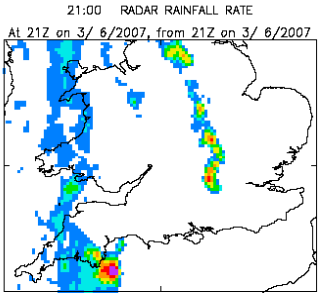
T+1

T+2



T+0

Radar



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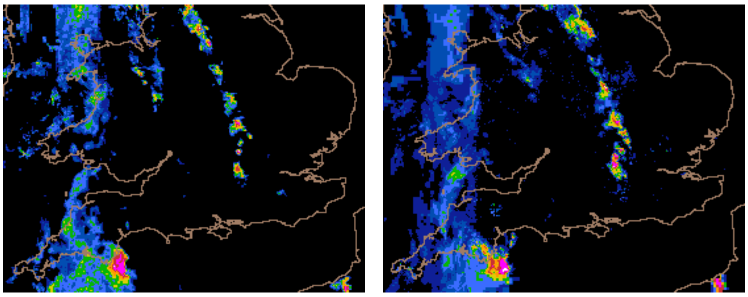
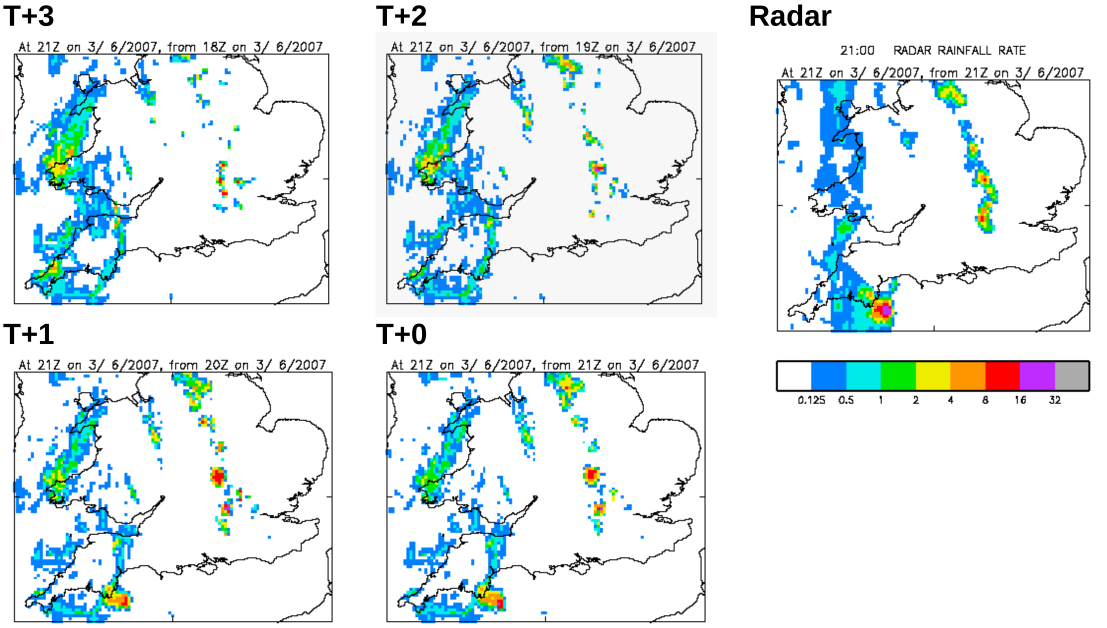


Figure 3 UKPP forecasts of surface rain rate valid at 21UTC 3/6/2007. T+0 is the UKPP analysis, which uses information in addition to the radar.

In future direct assimilation of the radar derived surface precipitation rates within 4D-Var will be investigated as well as direct assimilation of the radar reflectivity or indirect assimilation of radar reflectivity through derived temperature and humidity increments derived from external 2D-Var along radar beam and for multiple beam elevations along same azimuth.

Radar radial Doppler winds

Weather radar potentially provides a high resolution source of wind data from the Doppler returns from hydrometeors and insects. Four radars currently produce Doppler winds operationally every 5 minutes within the UK when there is precipitation. Code has been developed to allow their processing, quality control, monitoring, super-obbing and data assimilation and experiments are just starting to investigate their impact on forecasts using 3D-VAR. Reading University are undertaking work to look at potential for use of winds derived from insect returns in fine weather. Radar returns only give radial winds i.e. in the direction of the radar beam rather than 3D wind components so the additional information in areas of overlapping radars (dual Doppler) may increase impact of winds in those locations. Once evaluated for use in 3D-Var (and, hopefully, incorporation into the UKV 3D-VAR system) we shall investigate use in 4D-VAR.



T+3 **T+2** **Radar**

T+1 **T+0**

Figure 4 4D-Var Assimilation with latent heat nudging of radar derived surface rain rates.

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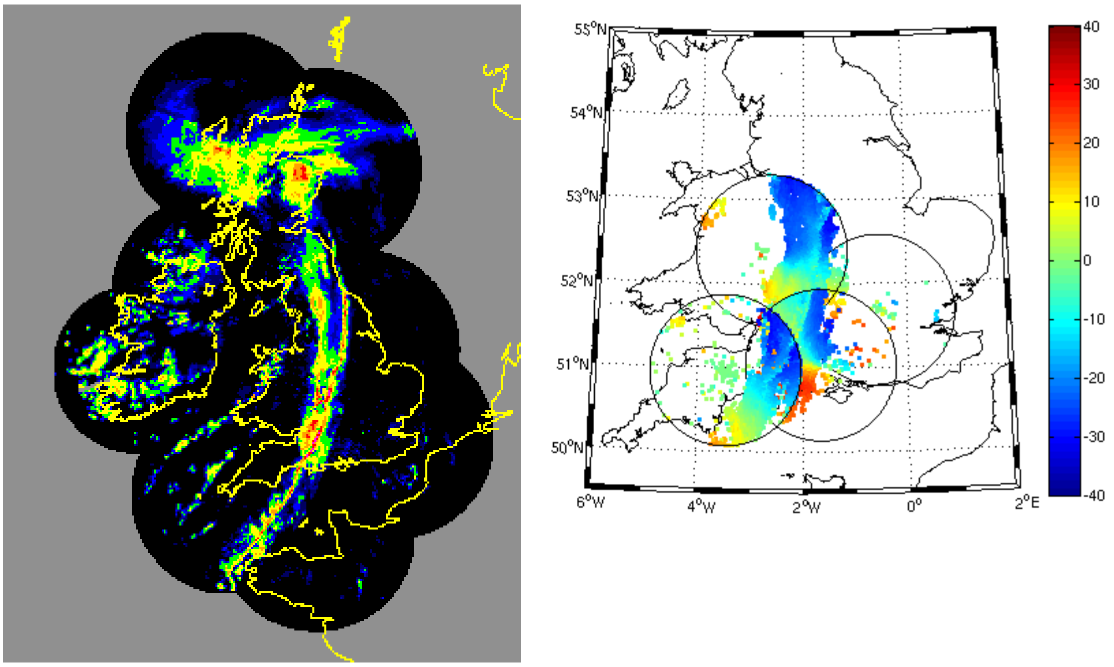

a) b)

Figure 5 Example of radar radial Doppler wind coverage over the UK on 8th January 2008 a) Radar derived surface rain rates 08/01/08 21UTC b) Radar radial Doppler winds m/s towards radar.

Issues

Data assimilation strategy

Our current strategy is based upon the premise that, in order to make effective use of observations such as radar reflectivity and satellite imagery, which tell us most about cloud and precipitation, and high time frequency observations (see below) the model dynamics must take an active role in the assimilation process. This occurs weakly through the nudging schemes, but the use of a variational scheme together with nudging of some variables raises consistency issues. Our current strategy is to implement and evaluate 4D-VAR including direct assimilation of radar and imagery. As shown above, initial experiments using just conventional observations are encouraging, but the performance and cost of a full system is not yet known. If sufficiently good performance can be demonstrated then we would anticipate that the system would become affordable as computing costs fall.

It is possible that 4D-VAR may not provide the best (or sufficiently good) performance. As a longer-term project we are collaborating with NCEO (primarily at the University of Reading) developing ensemble-based techniques.

Exploitation of novel and more time frequent observations

Current operational Met Office data assimilation systems such as the UK 4km 3D-Var system use hourly conventional observations. Geostationary satellite data, e.g. SEVIRI available every 15mins, is only just starting to be exploited with inclusion of upper air clear radiances and work has started to exploit clear surface and cloudy radiances.

More frequent conventional observations are potentially available for use in the 1.5 km hourly nowcasting NWP system. These include GPS water vapour, wind profiler winds and reflectivity, AMDAR temperatures and winds and surface observations. Work is also underway to define a potential future upper air network based on ground-based remote sensing. This could involve additional sites for current observing systems or exploit

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novel observations with high temporal and spatial coverage such as ceilometer (lidar), cloud radar and radiometer data.

These high time-frequency data sources could potentially be used in 4D-Var with a 1-hour time-window. As shown in Figure 6 and Figure 7 these high time frequency data contain fine-scale detail. It is tempting to think of this high time frequency data as providing information about spatial structure advecting over a site (as has been implicitly done in the interpretation of Figure 7), but the impact of this extra data on forecasts has yet to be demonstrated.

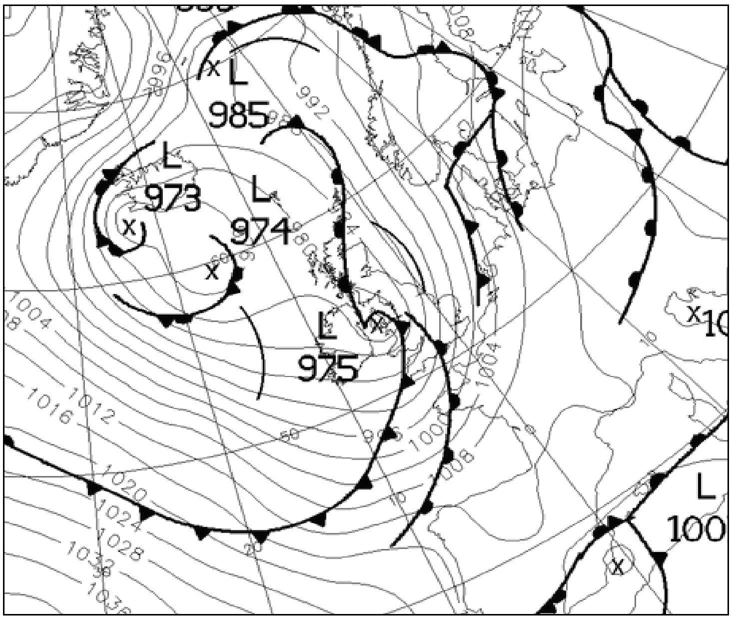
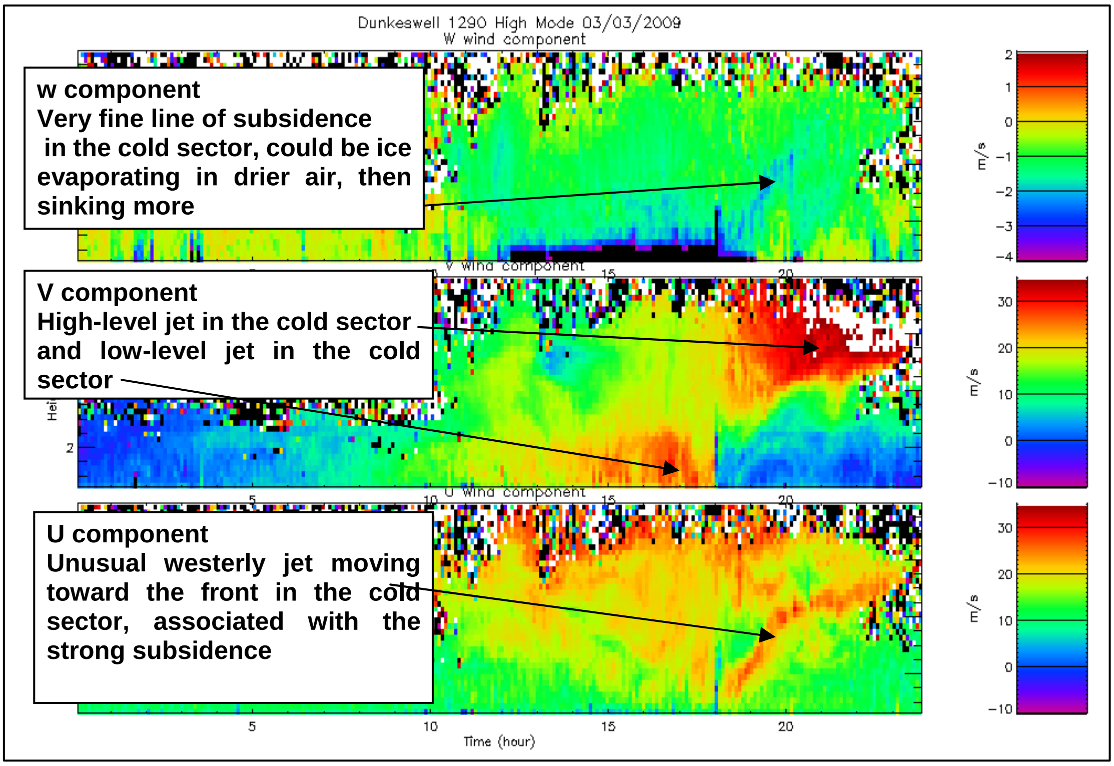


Figure 6 3 March 2009 Northern part of cold front near UK moves with us = 19, vs = 19 ms^{-1} . Triangle shows location of wind profiler at Dunkeswell providing 15min observations.



w component
Very fine line of subsidence in the cold sector, could be ice evaporating in drier air, then sinking more

V component
High-level jet in the cold sector and low-level jet in the cold sector

U component
Unusual westerly jet moving toward the front in the cold sector, associated with the strong subsidence

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Figure 7 Wind profiler at Dunkeswell shows fine scale detail. The vertical scale extends to 8 km.

If the value of high time-frequency data cane be demonstrated, we have the practical issue of data timeliness to address. Data that are already used for nowcasting (i.e. radar and satellite imagery) already have rapid data paths, with radar available about 5 minutes after data time. However, some data types are slower, e.g. GPS is currently available about 90 minutes after data time, and some, such as high time frequency (10 minute) surface data have yet to be delivered.

Verification and Applications

As stated above, the emphasis in the 12-36 h time frame is on the faithful incorporation of larger scale information and the interpretation of output to make full use of the available information without being misled by detail. Different synoptic conditions lead to different levels of predictability. Experience is leading to more firm ideas that forecasts are more likely to be accurate in some situations than others. Broadly, we can divide situations into two extremes:

1. Situations with strong surface influence leading to a high degree of predictability, in which case the (non-linear) downscaling is likely to be directly useful irrespective of data assimilation.
2. Situations driven by internal organisation in which growth of small scale errors leads to a low level of predictability so that only a statistical interpretation of model forecasts is likely to be useful beyond the nowcasting range.

These ideas are becoming more objective, especially for convective rainfall. The role of mesoscale convergence lines in triggering convection is well known. Ideas have been developed regarding the role of convective inhibition (CIN) in controlling predictability (Done et al, 2006) and the Convective Storms Initiation Project (CSIP) provided excellent examples which have been analysed in detail (e.g. IOP1/18). The role of gravity waves in ‘upstream’ triggering of convection and hence predictability has been proposed as a mechanism controlling predictability (Hohenegger et al. 2006) while the interaction of gravity waves with CIN has been shown to contribute to downstream triggering of convection (Morcrette et al, 2006) and hence organisation. Thus, there is scope for a great deal of research into the quantitative assessment of predictability. In the mean time, forecasters will need both training and experience in judging the likely reliability of a forecast.

These concepts apply both to the use and verification of convective-scale forecasts. At present, ideas are relatively crude, based upon the idea that a forecast has a characteristic scale above which it has some deterministic accuracy and below which forecasts are better treated statistically. We have turned this into a verification methodology (Roberts and Lean, 2008) which has been adopted by a number of other groups. The approach can be viewed in two ways; for a given forecast, either what is the smallest scale at which a given skill is achieved or what is the skill at a given reference scale?

The approach has demonstrated that different situations can have very different skilful scales though, helpfully, there is strong correlation in time of the skilful scale. It would clearly be very valuable to have some measure of the skilful scale at forecast time to aid use and interpretation of the forecast. There is clearly a very strong relationship between this and forecast error covariances and their case-to-case variability, but we are only beginning to explore this relationship. It is likely that ensemble methods can help with this problem once they become affordable. In the meantime, we have adopted a pragmatic approach of using a (forecast lead time-dependent) skilful scale

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representative of the mean over a number of situations as the basis for generating ‘pseudo-ensembles’ and hence some measure of probability of given events based upon the ‘deterministic’ forecast.

Figure 8 shows a 22-28 hour forecast of the probability of exceeding 50 mm at *at least* one location within 32x32 km squares in the 6-hour period ending 13.00 UTC on the 17th July 2009. Serious flooding was reported in northeast England on this day. The product is currently routinely generated from the UK 4 km model using the neighbourhood and fuzzy sampling method developed at JCMM for a single forecast, with forecast probabilities combined using a time-lag ensemble. Similar products will be produced using the UKV model once operational.

The neighbourhood code has been incorporated into the National Severe Weather Warning code framework and is used to produce 'first-guess' probabilities of exceeding 'extreme' (1 in 30 year) rainfall events for the Extreme Rainfall Alerts (ERA) service provided by the Environment Agency/Met Office Flood Forecasting Centre.

The neighbourhood method uses a larger neighbourhood, i.e. increasing area of uncertainty with increasing forecast length. Verification of rainfall events in summer 2008 gave suitable values of spatial uncertainty of just a few kilometres in each direction for forecasts of a few hours (but with 5 ensemble members), 36 km for 27 hours (3 members) and 100 km (1 member) for 36 hours. When combined in a lagged ensemble, the spatial uncertainty applied to each ensemble member depends on forecast length for that member. This approach has certainly made a valuable contribution to the ERA service; however, issues remain regarding the fine tuning of the probability generation mechanism and its verification, given that it is directed to extreme and hence rare events.

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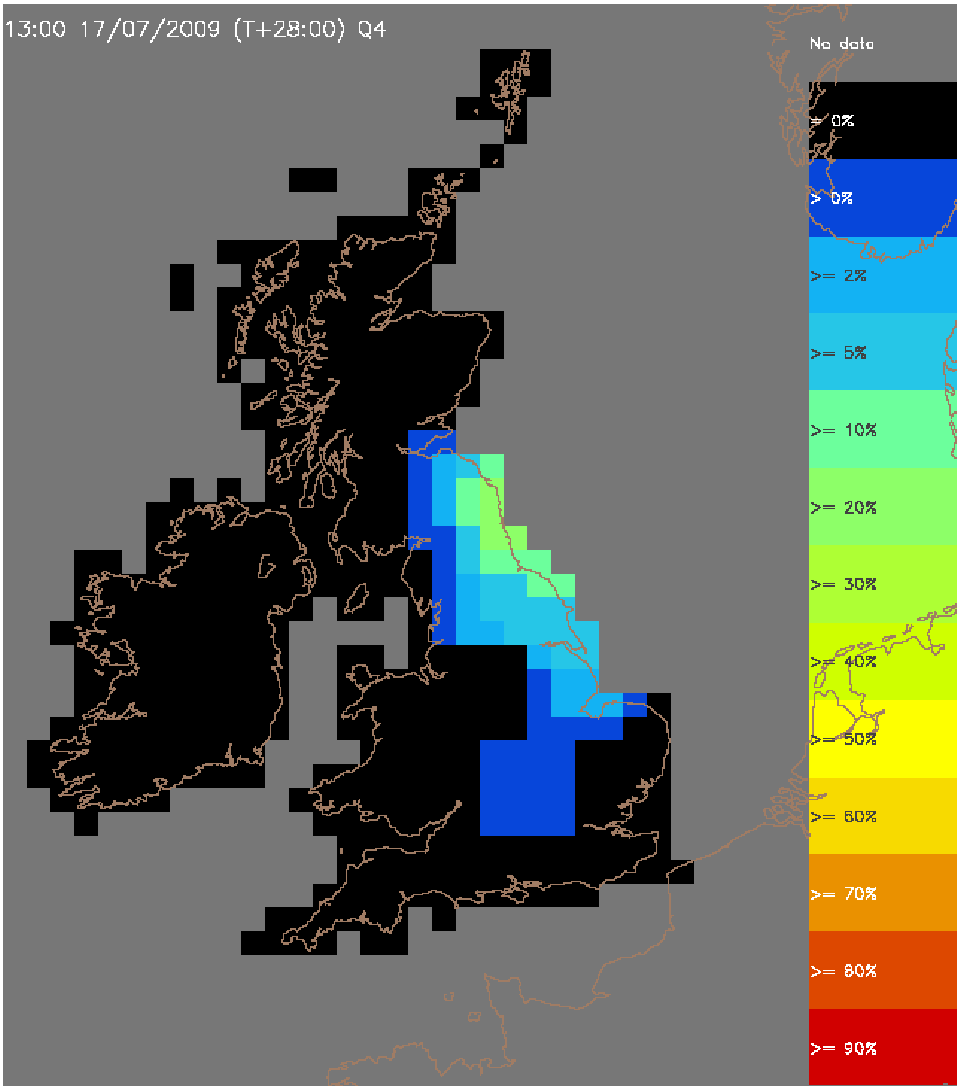

Figure 8 A 22-28 hour forecast of the probability of exceeding 50 mm at *at least* one location within 32x32 km squares in the 6-hour period ending 13.00 UTC on the 17th July 2009.

Ensembles

The lagged ensemble approach used above has proven useful at convective scales as, in many critical cases, small scale predictability is as important in producing divergence between forecasts as changes in the larger scales. However, the ensemble size is small and it is difficult to address case-to-case variability of predictability. Both issues can be can be addressed, in principle, through more traditional ensemble techniques. We have made the decision (as recommended by MOSAC) that any convective-scale ensemble modelling should be at the same resolution as our 'deterministic' forecast because of the likely biases introduced by a reduction in resolution. Thus, an ensemble-based scheme will be expensive. Nevertheless, we feel that there may be benefits from using even a small ensemble (perhaps combined with lagged ensembles).

Experience suggests that at T+24 errors are dominated by mesoscale structure (largely inherited from the lateral boundary conditions), so our strategy is to run a small ensemble (e.g. 6 members) driven from MOGREPS-R lateral boundary conditions. Clearly, there are a number of issues, including:

1. What initial state to use? We are currently 'spinning-up' from MOGREPS-R forecasts but several alternatives are possible.
2. How to sample suitable MOGREPS-R members to drive the ensemble?

3. How to turn the small ensemble into useful probabilities? Can the pseudo-ensemble technique be improved taking into account ensemble spread?
4. Is there a need for stochastic physics?

A project is in its early stages to investigate these issues; at present a single case study has been run using all MOGREP-R members in order first to establish that the UKV model can be run successfully using LBCs from a 24 km resolution model and second to begin to look at clustering and post-processing methods. This case study is instructive in illustrating the issues that we face.

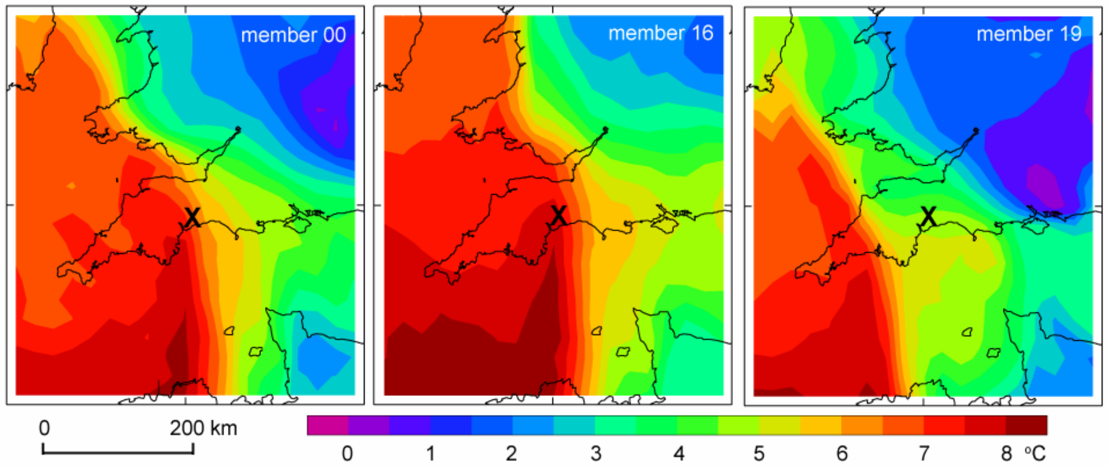

Figure 9 Wet-bulb potential temperature at 950 hPa at 00 UTC 30/10/08 from 3 MOGREPS-R members (24 km) run from 06 UTC on 29/10/08. The 'X' marks the location of Ottery-St-Mary where a severe thunderstorm / hailstorm in the early hours of the 30th produced serious flooding.

Figure 9 shows illustrates the degree of variation of mesoscale structure between MOGREPS-R members in an 18 h forecast. The members were produced by taking the global MOGREPS ensemble members (90 km) from 00 UTC, finding the differences from the global ensemble control forecast at 07 UTC (i.e. 7-hour forecasts) and feeding these differences into the operational North Atlantic European (NAE) forecast from 06 UTC over the period 06 to 09 UTC using the Incremental Analysis Update (IAU). All this was done on the 24 km MOGREPS-R grid.

The Figure shows significant differences in the position and shape of a warm front in relation to Ottery in these members, but also shows that the basic meteorological situation was the same in them all. Figure 10 shows the difference in frontal structure between two of these members. The surface warm fronts are based on the warm edge of the 950 hPa wet-bulb potential temperature gradient. In addition there was an upper-level cold/humidity front that overran the warm fronts. This is largely based on 600 hPa wet-bulb potential temperature and relative humidity. The grey shading marks where there was (relatively weak, less than 1 C) potential instability between 950 and 700 hPa, which occurred in the warmer air behind the warm front, beneath the lower wet-bulb potential temperature air aloft behind the upper front and ahead of weakly defined surface cold fronts. The surface cold fronts are dashed because they are weakly defined and difficult to place. It is possible that the UKV will show multiple cold fronts, but this is yet to be analysed.

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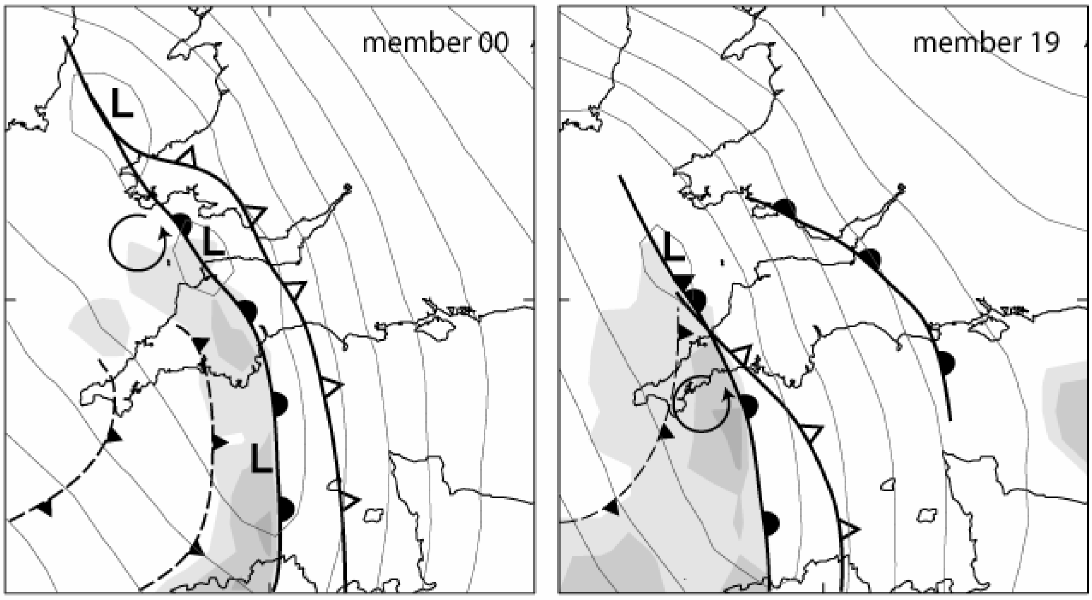

Figure 10 Frontal analysis at 00 UTC 30/10/08 from two of the MOGREPS 24 km members shown in Figure 9

UKV runs have been performed starting from each of the MOGREPS-R forecasts at 12 UTC (with MOGREPS-R starting at 06 UTC). Results from the three members illustrated above are shown in Figure 11. The highest value of all (96 mm) was in member 19. Member 00 is shown because it is the control forecast, and gave ~55 mm over the sea. Member 16 gave ~55 mm over the sea, but close to Ottery. The final frame is an attempt to summarise information about possible high accumulations using all members; it shows some clusters of high accumulations over the sea but mainly along the coast and a short distance inland, suggesting interaction between the warmer sea and coastal topography.

None of the ensemble members produced high accumulations over to Ottery, though there are clusters close by. This clearly illustrates two points;

1. The ensemble gave a very good indication of the threat of an extreme event along fairly long (~100 km) but well-defined stretch of coast.
2. Some form of post-processing (‘dressing’) is still required to produce useful probabilities from this information. It is unlikely that the ‘gaps’ in the final panel in Figure 11 arise from anything other than sampling error, which must be adequately addressed.

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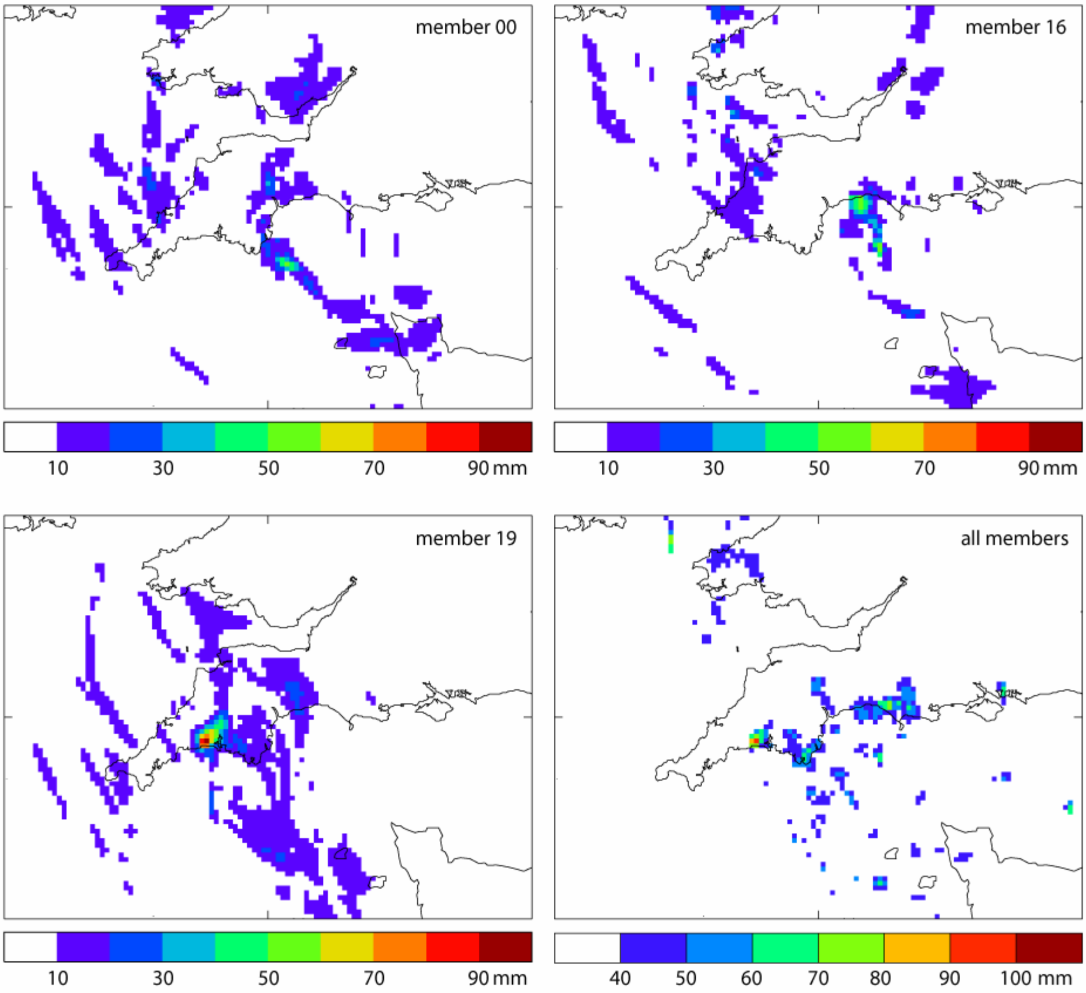

Figure 11 First 3 panels: the highest 6-hour accumulation that occurred in selected members from the UKV ensemble between 18 UTC 29/10/08 and 08 UTC 30/10/08. The pixels are 4.5 x 4.5 km rather than 1.5 x 1.5 km to give better visibility. Each 4.5 km pixel has taken the highest value from its nine 1.5 km pixels. The final panel shows the highest 6-hour accumulations that occurred over all members (each pixel shows its highest value). Most of the high accumulation activity occurred along the coast (within 70 km of Ottery) - presumably where topographical effects and a warmer boundary layer both had an influence.

Summary

1.5 km resolution NWP is showing considerable promise in very short range prediction of convection over the UK. Nevertheless, we must regard ourselves as just starting out in a new field and many challenges lie ahead. This paper has identified the following immediate issues, though no-doubt others will arise as we make progress.

- The character of deep convection in the model depends sensitively on the treatment of mixing, especially in weakly forced conditions and outside the boundary-layer.
- We have yet to evaluate the use of stochastic backscatter or improvements to its formulation.
- How complex does our microphysics scheme need to be? In particular, how do we best make use of aerosol information in the warm rain process.
- Issues have arisen with conservation of microphysical and tracer species by the advection scheme.

- We need to understand the need for more detailed surface representation in general, including coupling to 3D soil moisture and ocean and wave models.
- The strategy for DA, especially for nowcasting, needs regular review as we make progress with 4D-VAR.
- 4D-Var performance, though so far encouraging, is unknown when new data types are incorporated. Cost may become a major issue.
- Ability to benefit from high time-resolution data has to be evaluated.
- Timeliness of data is an issue for nowcasting.
- Much progress has been made on verification but further work is required.
- Application of km-scale modelling is a major issue. We need to manage expectations and, in particular, ensure that the finest detail is not taken too seriously. We need to understand more what scales are reliable in different circumstances and why, if possible predicting these parameters with the forecast
- In the short-term, we need to improve and tune 'neighbourhood' pseudo-ensemble approach.
- We need to understand how to make best use of small ensembles.

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