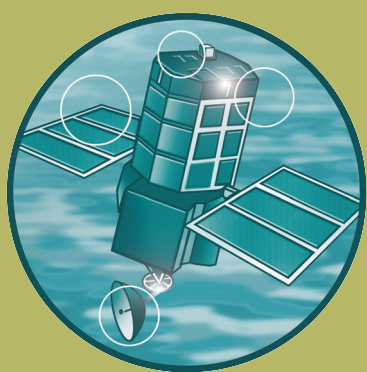


Extreme event recognition project Phase 2

Evaluation of a vorticity indicator for extreme events

R&D Project Report FD2208/PR



Joint Defra/EA Flood and Coastal Erosion Risk
Management R&D Programme

Project title: Evaluation of a vorticity
indicator for extreme events

R&D Project Report FD2208/PR

Produced: 15 November 2005

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Statement of use

This project report informs the final project outputs of **FD2208** and thus should be viewed as supporting material to the outcomes in the final technical report.

Dissemination status: Released internally and to the public domain

Keywords: vorticity, extreme rainfall, data assimilation, stochastic modelling

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www.defra.gov.uk/environ/fcd

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Executive summary

Numerical Weather Prediction (NWP) models having grid lengths of a few kilometres are now coming into operational use in some countries. Forecasts of heavy rainfall provided by these models appear to offer significant improvements to the detail of forecast rainfall. These models also offer the possibility of providing indicators of convective development derived from model parameter fields.

This study has investigated one parameter, the vorticity tipping term, which has previously shown some promise in this respect. However, it has been found that unless model output is available with a resolution of around 1 km or better then this parameter does not provide any useful information, although at these high resolutions the field of vorticity tipping term might indicate the level of uncertainty to be expected in forecasts.

Drawing upon on-going work on the assimilation of data into the variational analysis scheme of the Met Office Unified Model, it is demonstrated that there is considerable potential to improve forecasts of wind and rain. Radar data contain information at scales commensurate with the model grid lengths now being introduced operationally. This presents research challenges as grid lengths of a few kilometres are too large to represent the cloud scale directly, and therefore effective parameterisation of cloud processes on the mesoscale is still required.

It is clear that high resolution numerical forecasts will continue to have error characteristics that will vary between different types of events. We discuss one approach to dealing with the error characteristics in hydrological models using a stochastic formulation.

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1. Background

Hand et al (2004) discuss the occurrence of extreme rainfalls in the United Kingdom having durations from minutes to days. This work was carried out under contract to Defra Extreme Event Recognition Phase I (Ref: ?). However, forecasting such rainfall events, particularly those associated with convective clouds presents major challenges. Thunderstorms have horizontal dimensions of 5-10 km causing rainfall intensity to vary widely over short distances and time scales.

The present work was carried out at the University of Salford under contract to Defra through the Met Office (Ref: Annex A to PB/B3959). This work concentrated on the identification of extreme convective events based on an analysis of vorticity as recorded in a published paper (Sleigh and Collier, 2004). The basis of the proposed technique is the recognition of developing symmetry, and then asymmetry, in the field of the tipping term in the vorticity equation. Work carried out in this project followed a recommendation made in the Extreme Event Recognition Phase I Project as articulated in the Subcontract for Defra Contract Ref: CSA 6511/FD2208 as follows:

- Identification of test cases for which Doppler data (Chilbolton or the new SE radar, if available) and mesoscale model data are available and assemble the required data.
- For one selected case, obtain Met Office data from a finer resolution version of the mesoscale model that is expected to come into operational use in 2005.
- Develop and implement code to calculate diagnostics.
- Evaluate the performance of the technique on the selected case studies for each of the data sources.
- If deemed worthwhile assist the Met Office in adding this predictor to the real-time trial in Work Package 2 using just mesoscale model data.
- Assess results from the trial, prepare report and submit scientific paper.

These aims have been largely achieved. It was decided at an early stage of the Project that it was not worthwhile implementing the vorticity indicator within the real-time trial. The justification for this decision is evident in the following discussion of the case studies. It also became evident that alternative approaches to forecasting extreme flood events may offer more chance of ultimate success. These will also be discussed in this report. Data from the new SE radar were not available during this project.

2. The NWP model vorticity tipping term as a measure of forecast uncertainty

2.1 Indicating likely convective development

The rate of change of the vertical component of absolute vorticity (a measure of rotation) in the atmosphere is a function of four processes:

1. Tipping of horizontal vorticity into the vertical by gradients in vertical velocity;
2. Vertical compression of vertical vorticity by horizontal divergence effects;
3. Generation of vertical vorticity by solenoidal effects due to barotropy in the atmosphere;
4. Frictional effects.

The tipping term of the vorticity equation (T) has usually been ignored in dynamical meteorology. In synoptic scale situations hydrostatic balance is usually assumed, meaning that vertical velocities, and thus the tipping term, are considered negligible. However, in the case of strong vertical convection, vertical velocities can have magnitudes of order a few tens of metres per second. Hydrostatic balance thus breaks down, and the tipping term becomes important in the vorticity equation being of comparable magnitude to the divergence term. It is on these scales in mesoscale, and more importantly, cloud scale situations, that the lack of high resolution wind measurements required to accurately determine the tipping term becomes the limiting factor.

The tipping term in the vorticity equation is derived from,

$$T = - (dw/dx \cdot dv/dz - dw/dy \cdot du/dz)$$

where u and v are the components of the horizontal wind speed.

Davies-Jones (1984) presented a simple, physical model of how the rotation associated with convective supercell updraughts is generated. The model represented a three dimensional region of the atmosphere using a stack of flat, horizontal surfaces. Note that, because potential temperature, θ , is a conserved quantity, such material surfaces are also isentropic surfaces, and shall be called such hereafter. Horizontal vorticity was introduced, and, although the horizontal vortex lines were not strictly material lines, they were considered to be so in the model. Making this approximation required the assumption that the solenoid generation of horizontal vorticity, which would serve to divert the vortex lines, was negligible. Consequently, the vortex lines remained in their original isentropic surfaces. In this initial pre-storm state, the vertical vorticity was zero everywhere.

When a vertical deformation of the isentropic surface was introduced, which represented the upward displacement associated with a convective updraught, the vortex lines became tilted and vertical vorticity was induced. The stream-wise component of the horizontal vorticity served to generate anticlockwise vertical vorticity on the near side of the peak vertical velocity and clockwise vorticity on the far side (when looking in the direction of the storm inflow vector). In a zone of uniform horizontal vorticity, and given an isentropic updraught, the regions of opposing rotation generated by each component of the tipping term should be of equal size and magnitude. However, even given an isentropic updraught the likelihood is that the convergence in the inflow region and divergence in the low-level outflow region of a thunderstorm will serve to modify the horizontal vorticity field. This will be exacerbated by the strengthening of the horizontal vorticity by horizontal stretching of the air parcels, and by solenoid

effects. The manifestation of the weakening inflow to the cell is therefore expected to be increasing asymmetry in the tipping term couplet field.

Sleigh and Collier (2004) confirmed that when the positive / negative couplets in the field were symmetric convective development was likely to follow in a short time. When the couplets in the field were asymmetric the convective downdraft killed off the updraft and decay ensued. The appropriate level for evaluating this effect was found to be around the top of the atmospheric boundary layer in the region where air was being entrained into the convective cloud.

2.2 Case studies

The data used by Sleigh and Collier (2004) were obtained during the spring in Australia. In what follows we carry out the same analysis in the UK using 1 km grid length Met Office NWP output derived for a case of line convection and a case of convective cell generation over the same area. In the latter case, known as the Boscastle storm, a flash flood occurred.

The first case on 1 July 2003 is an example of an active cold front moving from the north west across the Chilbolton radar site located in central southern England. The frontal position was indicated by a line of heavy rainfall producing convective cells reaching altitudes of around 8 km orientated south west to north east. The main band of cells was preceded by lighter rainfall from shallower cells capped at an altitude of 3 km as shown by the Chilbolton radar in Figure 1.

Comparison with 94 GHz cloud radar

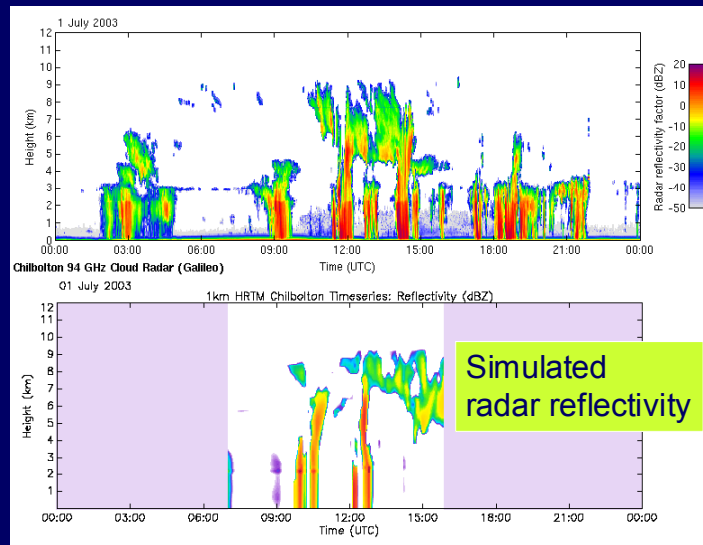


Figure 1: Comparison of the simulated radar reflectivity derived from the 1 km UM compared to the 94 GHz Chilbolton cloud radar image on 1 July 2003

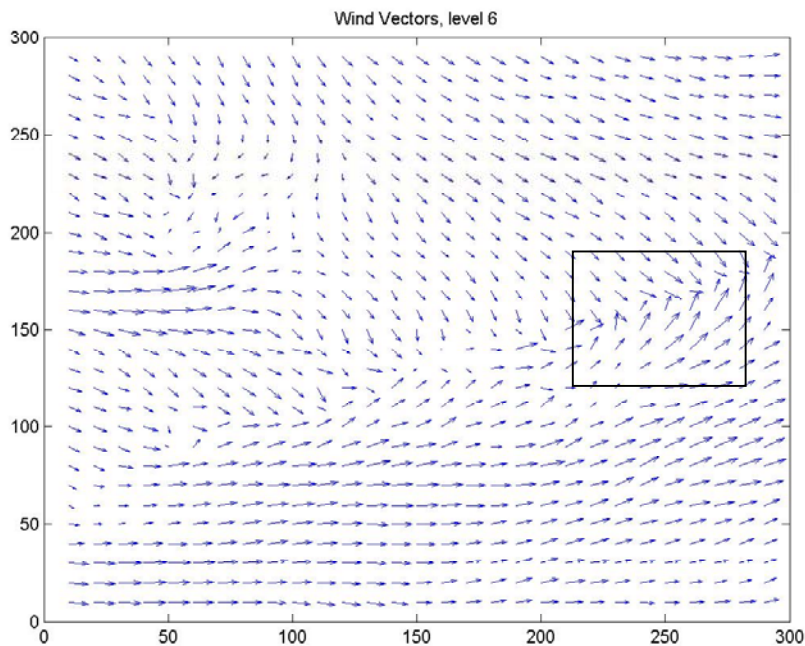


Figure 2: Horizontal wind field from 1 km resolution UM on 1 July 2003 at 1215 UTC

Figure 1 shows a comparison between the 1 km numerical simulations of radar reflectivity and the actual 94 GHz cloud radar measurements at Chilbolton. Note the success of the numerical simulations in reproducing the convective rainfall. Figure 2 shows the horizontal wind field from the Met Office 1 km Unified Model (UM) at 1215 UTC on 1 July 2003. The rectangle shows the area

over which the vorticity tipping term has been evaluated. Figure 3 shows the NWP model-generated vorticity tipping term field for the case of the mobile active cold front (line convection) over central southern England on 1 July 2003 shown in Figure 1.

In order to investigate whether or not the tipping term evaluated over coarser resolution contains useful information, the field shown in Figure 3 has been averaged over the grid squares in the rectangle shown in Figure 2. The arrangement of the grid squares for the averaging at point A in Figure 3 is shown in Figure 4. The modulus of the maximum tipping term ratio in the vicinity of point 'A' has been plotted as a function of the grid resolution in Figure 5. The ratio decreases rapidly from a resolution of 1 km to 6 km. It would seem from this analysis that the tipping term might only be useful if a model has a grid length of 1 km or less.

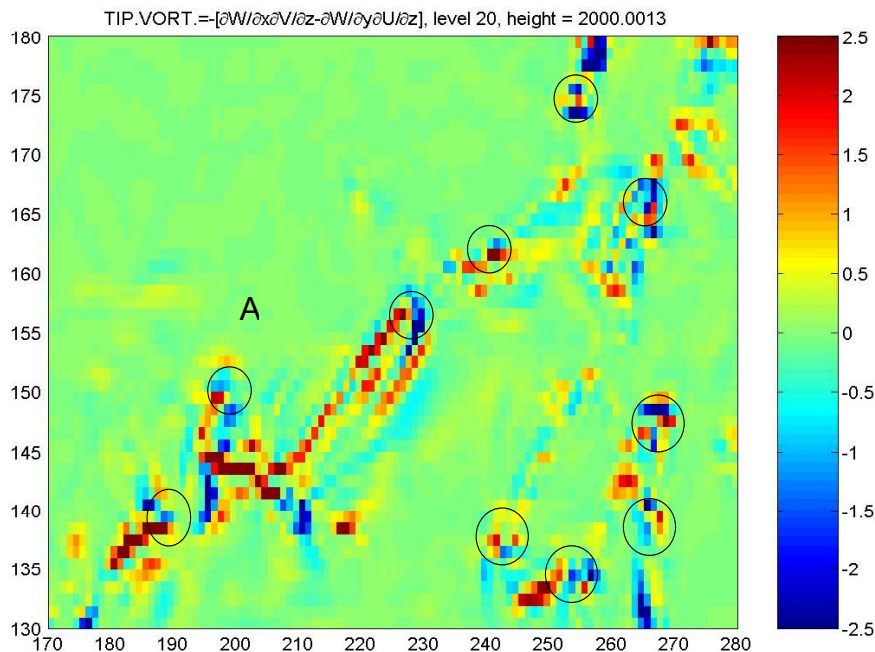


Figure 3: Vorticity tipping term field ($\text{sec}^{-2} \times 10^5$) derived from the 1 km resolution UM 1 July 2003 at an altitude of 2000 m

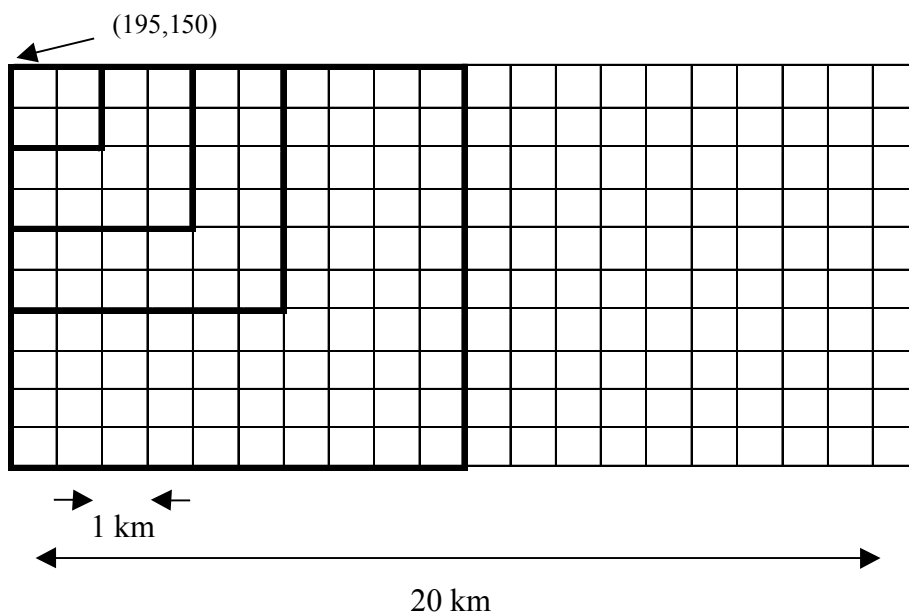


Figure 4: Arrangement of grid squares over which the tipping term is evaluated

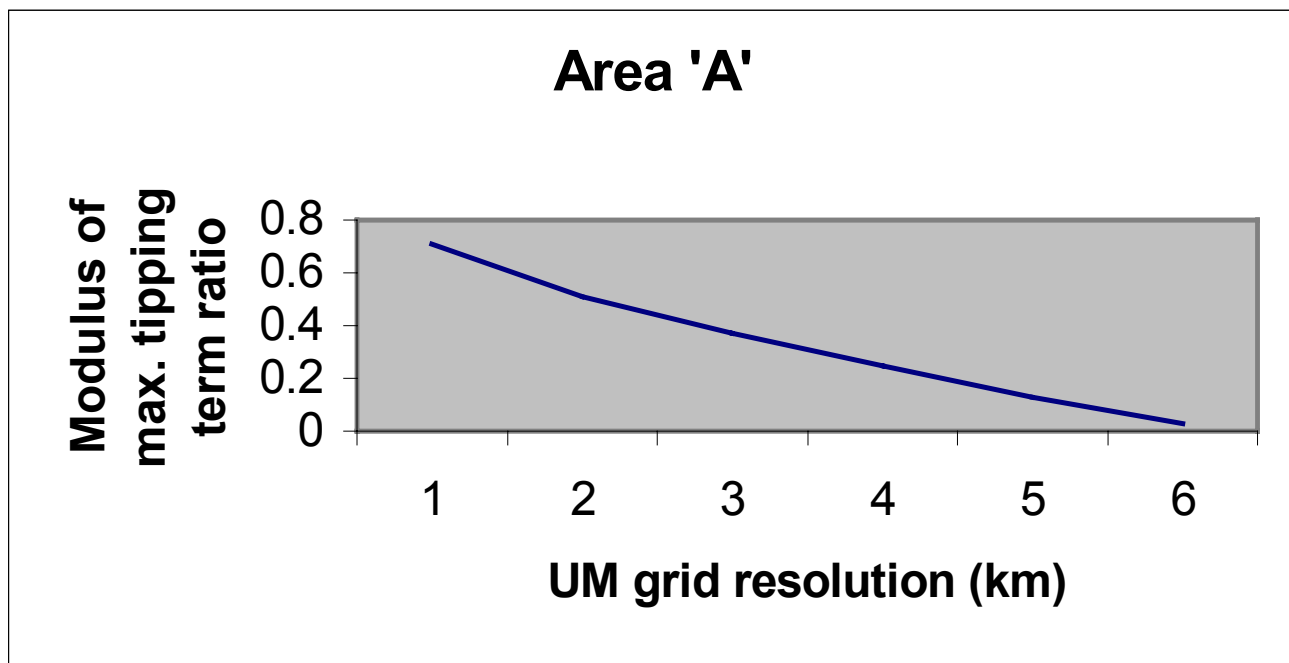


Figure 5: Average values of the couplet ratio in the vicinity of area A (Fig. 3) as a function of grid resolution over which they are evaluated

The second case is the Boscastle storm case on 16 August 2004. A detailed description of this event producing very substantial convective rainfall over the north Devon and Cornwall coasts has been provided by Golding et al (2005). Figure 6 is the field of the tipping term evaluated for the case of convective cells

developing more or less in situ over south west England. Vorticity couplets are evident in the vicinity of Boscastle (north Cornwall) – symmetric (A), and over the north Devon coast – asymmetric (B). Couplet A is only very locally symmetric having values of about $\pm 0.003 \text{ sec}^{-2}$. Couplet B is very asymmetric having locally maximum positive and negative values of about 0.008 sec^{-2} and -0.004 sec^{-2} respectively. Examination of the model output at different heights in this case indicated that above the level shown 1215 m (close to the top of the boundary layer) the symmetric couplet (A) becomes more asymmetric then weakens and vanishes. Below the level shown the symmetric couplet quickly weakens and vanishes. The couplets shown over south Wales (top of image) reflect the valleys in the underlying orography. They become stronger below the level shown and weaker above, and are not relevant to the convective development. It is clear that the vorticity tipping term couplet indication of convective development must be taken in the limited region close to the top of the boundary layer

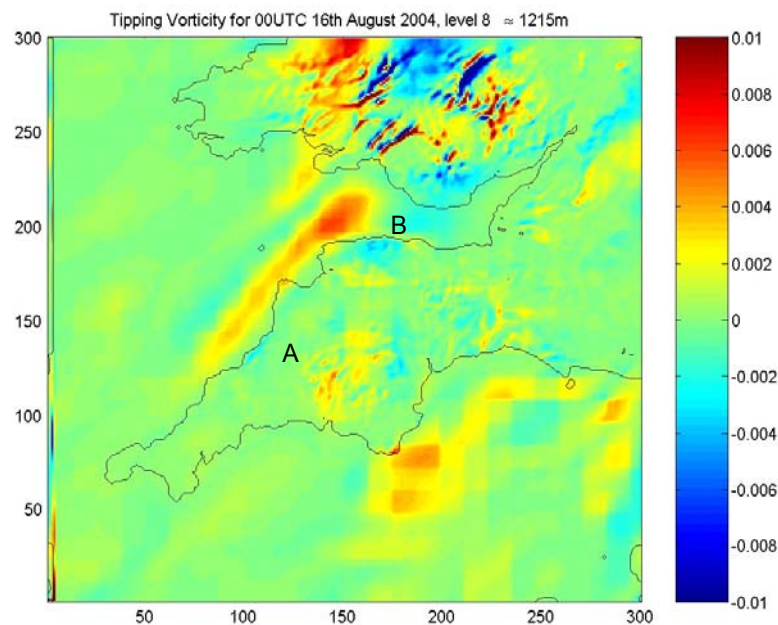


Figure 6: Tipping term field evaluated from 1 km grid NWP data at 0000 UTC on 16 August 2004 (sec^{-2})

In both the forecast cases shown in Figures 3 and 6 convective development did subsequently occur. However in Figure 6 the development only occurred in the region of north Cornwall where there is a weak symmetric couplet (A) not over north Devon (see Figure 6) where there is a strong asymmetric couplet (B). Figure 7a shows the subsequent model forecast rainfall. Interestingly whilst significant rain was forecast to fall over the Boscastle area which did indeed occur (Figure 7b), consistent with convective development associated with the weak symmetric tipping term couplet (A), much less rain fell over North Devon

associated with the lack of convective development indicated by the asymmetric vorticity tipping term couplet (B) in Figure 6.

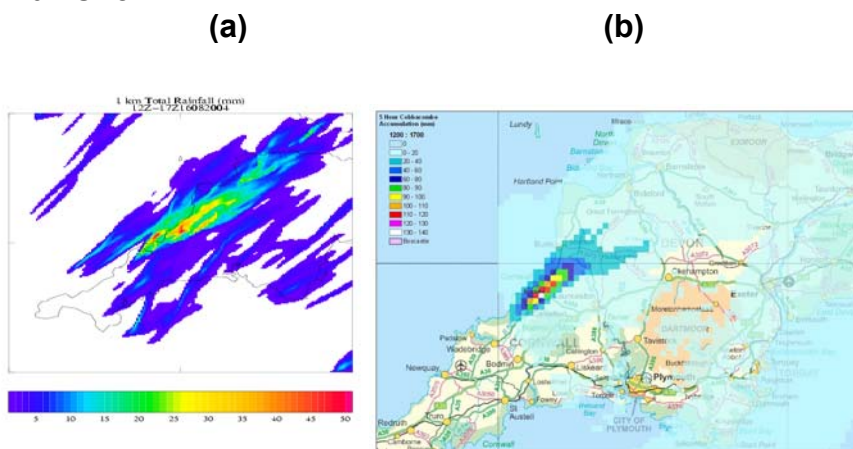
The question arises as to why the model predicted a very large amount of rainfall over North Cornwall when the tipping term couplet was only weakly symmetric as shown in Figure 6. After all the model dynamics should have behaved in a way consistent with the vorticity couplet theory if that theory is correct. However one may speculate that the vorticity field is indicative of cloud scale processes occurring on a scale less than the model can resolve in this case a length scale of around 3 km.

2.3 Conclusion

We must conclude from the analyses of both the cases discussed in section 2.2 that for forecast models having grid lengths of a few kilometres the vorticity tipping term is not a reliable indicator of convective development. The Met Office has introduced in 2005 an operational forecast model using a 4 km grid. Figure 5 suggests that this grid resolution may be approaching the grid size which could be useful for the tipping term technique.

Figures 3 and 6 were evaluated using 1 km grid NWP outputs, and certainly tipping term couplets can be seen in the fields. Nevertheless, the best way of using this information remains unclear. A more appropriate way to that discussed above of improving forecasts of extreme convective rainfall may be the direct assimilation of radar data into high resolution numerical forecast models, and the assimilation of NWP forecasts into hydrological models using measures of uncertainty related to the tipping term couplets. We discuss these approaches next.

Figure 7: Illustrating (a) model rainfall forecast using the 1 km UM 1200-1700 UTC over the West Country 16 August 2004 (from Golding et al, 2005), and (b) the Cobacombe 5 hour radar rainfall 1200-1700 UTC. Rainfall shown in mm



3. High resolution Numerical Weather Prediction (NWP)

3.1 Introduction

Until recently NWP models used to make forecasts of rainfall operated with grid lengths of around 12 km or larger. Consequently convective cloud scale processes had to be represented by parameterisation schemes comprising representations of the entrainment of air into cloud, condensation as air rises and the processes associated with the formation of rain and the evaporation of rain drops as they fall to earth. Such schemes have been effective on scales of two to two and a half times the model grid length or greater (greater than 25 km). However, there is little hope of forecasting reliably the initiation and subsequent development of individual clouds and heavy localised rainfall.

Increased computer power previously available only to researchers is now enabling the operational introduction of high resolution (a few kilometres) NWP models (Lean and Clark, 2003). During 2005 the UK Met Office has introduced such a model using a 4 km grid length. At these spatial scales operational numerical calculations are approaching those made using research Large Eddy Simulation (LES) models of individual clouds. LES models using grid lengths of a few hundred metres do not need to parameterise cloud processes explicitly as the necessary physics is included in the model equations albeit subject to errors in the representation of atmospheric turbulence, gravity waves etc. Unfortunately grid lengths of a few kilometres lie between these different approaches. Consequently operational high resolution models may, or may not, provide rainfall forecasts which are spatially and temporally accurate. The forecast outcome will depend upon the model initial conditions and how well they represent cloud dynamics.

Weather radar, and to some extent high resolution satellite imagery, are the only operational observing systems providing data on the spatial and temporal scales of convective cloud systems. High resolution satellite imagery is presently only available during daylight hours every fifteen minutes (HRVIS from the current Eumetsat geostationary satellite).

These data offer the prospect of enabling high resolution NWP models to be initialised at scales appropriate to convective cloud systems. However, the way in which NWP models are initialised is not straightforward as different types of input data must be balanced against each other so that an accurate representation of the atmosphere is provided. This involves complex mathematical procedures such as Four Dimensional Variational Analysis (4D-Var) (for a review see Rihan et al, 2005a). Work is on-going in this area in several countries.

It is well known that small errors in the initial description of the atmospheric state from which NWP models are integrated forward in time grow exponentially into much larger errors (Lorenz, 1969). Hence if an ensemble of forecasts is produced by varying the model initial conditions it is possible to associate a

measure of uncertainty with the forecasts (see for example Stensrud and Fritsch, 1994; Stensrud et al, 2000). This approach has led to improvements in the accuracy of general weather forecasts at medium (greater than 24 hours ahead) range lead times (Tracton and Kalnay, 1993) and at short (less than 24 hours ahead) lead times (Du et al, 1997). However, difficulties remain in pinpointing rapid development over small areas, and it must be emphasized that only the use of carefully constructed initial state perturbations enable quantitative measures of uncertainty to be obtained from such ensembles.

NWP models generate a wide range of forecast output fields of geophysical parameters (for example wind velocity, temperature, humidity). To this output may also be added fields closely associated with atmospheric thermodynamic and dynamic structure (for example instability indices, vorticity). This information offers the opportunity to place measures of uncertainty with forecasts using the insight provided by combinations of particular parameters.

This idea is not new. Wind and temperature fields at the jet stream level have been interpreted by forecasters using Sutcliffe development theory (Peterssen, 1956), and fields of Potential Vorticity (PV) (Hoskins et al., 2000) providing reliable diagnostic tools. However, what is not clear is whether this type of approach, the use of model fields to improve forecasts, provides anything useful at high resolutions. There may be more chance of improving forecasts of floods if measures of uncertainty, derived from high resolution NWP outputs, are assimilated into hydrological models developed explicitly to use this information. In what follows we note one approach to improving NWP forecasts which may reduce uncertainty in these forecasts namely the assimilation of radar data.

3.2. Assimilation of radar data into high resolution numerical forecast models

NWP is considered as an initial boundary value problem i.e. given an estimate of the present state of the atmosphere, the model simulates (forecasts) its evolution. Hence specification of proper initial conditions and boundary conditions is essential in order to have a well-posed problem and subsequently a good forecast model. This is the goal of data assimilation schemes.

As models are introduced operationally with grid lengths of a few kilometres, input data having comparable or better resolutions become increasingly important in the assimilation process. Radar data offer information on atmospheric humidity, rainfall and radial winds, all of which impact the dynamics and the microphysics of the model atmosphere. Complex mathematical schemes based on variational analysis are being developed to enable quite different types of data to be combined to provide models with initial fields (for a review see Rihan et al (2005a). NERC sponsored work at the University of Salford in collaboration with the Met Office at Reading is on-going to assimilate Doppler radial winds from the Chilbolton S-band radar in central southern England into the Met Office Unified Model (UM).

Rihan et al (2005b) describe encouraging progress so far, although much more needs to be done, particularly with data from the operational network of C-band radars. Significant impact on forecast wind fields has been demonstrated as shown in Figure 8 for a case of widespread convective showers. Figure 9 shows the impact on forecast rainfall which is not as dramatic although still evident for individual showers in the vicinity of the radar. It is clear that considerable potential exists in the assimilation of information that radar can provide. However, considerable uncertainty will remain in the forecasts, and, if hydrologists are to use the forecasts, then hydrological models must be formulated to deal with this uncertainty.

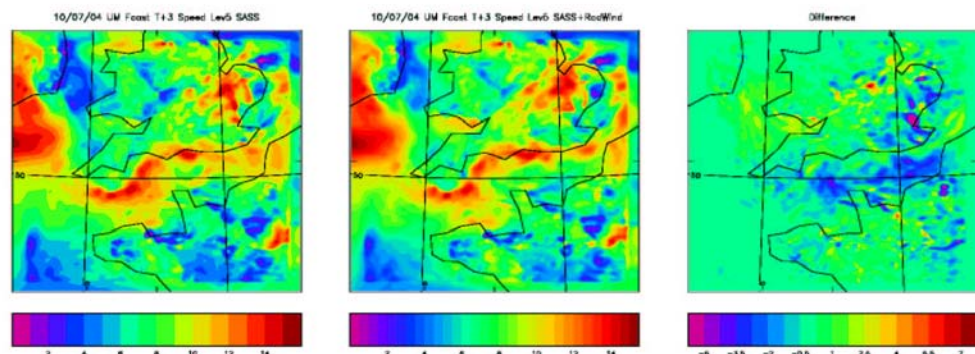


Figure 8: Impact of Doppler radial winds on the model wind speed forecasts made at 1200 UTC on 10 July 2004 for three hours ahead. Left hand panel without Doppler radar radial winds, middle panels with radial winds, and right hand panel the difference

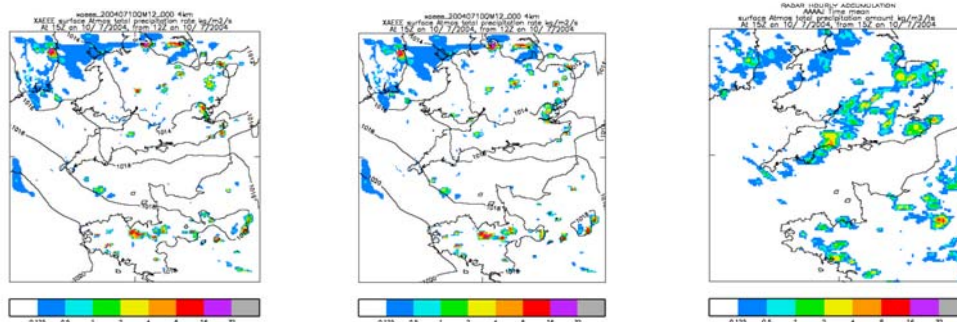


Figure 9: Impact of Doppler radial winds on the model rainfall field forecasts made at 1200 UTC on 10 July 2004 for three hours ahead. Left hand panel without Doppler radar radial winds, middle panel with radial winds, and right hand panel radar network image at the forecast verification time 1500 UTC

4. Stochastic hydrological modelling

4.1 Background

Forecasting floods associated with these events requires the use of hydrological models of river catchments which may have a range of different structures. The models may be either *lumped* taking no account of the spatial variability of model parameters or inputs over the catchment, or *distributed* accounting for variability of parameters and inputs throughout the catchment. Hybrid models between these two approaches are developed using sub-catchment structures.

In addition, the model may be physics-based in which all the physical laws governing the dynamics of the system are specified (known as a *white box* model), or be based purely upon past system behaviour and input and output observations (a *black box* model). So-called *grey box* models use a combination of aspects of both approaches.

The final decision of which model structure to employ in an operational flood forecasting system will depend upon the nature of the available input rainfall fields and forecasts and the model parameters together with whether deterministic or stochastic outputs are to be produced. Increasingly it is recognised that uncertainties exist in input values and model parameters and therefore reliable deterministic forecasts are not possible. Stochastic measures of uncertainty are an essential component of flow forecasts.

Numerical forecasts of rainfall present exciting opportunities for flood forecasting, but also present significant challenges. In this section we discuss current developments in such forecasting, and how they might be improved. The availability of measures of uncertainty that can be associated with

numerical rainfall forecasts can be used within stochastic hydrological model formulations which are discussed next.

4.2. A Stochastic hydrological model structure

The potential of combining several types of rainfall measurements has been recognised by Grum et al (2002) and others. This may be achieved by constructing a numerical representation of the rainfall field and how it changes with time (referred to as the rainfall plane by Grum et al, 2002) and a numerical model of the hydrological system using a stochastic state-space approach as follows for which the rainfall field provides the input. All measured data are considered to be different ways of looking at the same quantity. The state of the rain plane and the hydrological system is updated using new observations by weighting each observation between what the model has predicted using data at an earlier time and the current observations. The weighting is done, using a Kalman filter, based upon the respective uncertainties of the predictions and observations previously defined.

A simple model predicts the rainfall intensities one time step ahead for each pixel of the rain plane, and is based on the notion that the rainfall in a particular pixel, $X_{i,j}$ at time step $t-1$ will probably be like that at time-step t . Therefore at every time-step the rainfall model predicts the rainfall intensity based upon knowledge from the previous time-step. This is achieved by weighting a pixel's own current value with those of its immediate neighbour pixels. A damping coefficient is introduced with a value of just under 1.0 to provide an exponential decay of the intensity.

A simple rainfall-runoff model is also constructed using two series linear reservoirs running parallel to each other, one to represent the fast and the other to represent the slow flows through the system. The proportion of water flowing into the slow reservoir series is exponentially inversely proportional to the volume of water present in the reservoirs. At any given moment, the state of the runoff system is defined by the volume of water present in each of the reservoirs.

To apply the Kalman filter a prediction is needed not only of the state variables themselves, but also a prediction of their variances. The model also serves to calculate the propagation of the state's covariance matrix.

4.3. Preliminary experiments using a stochastic hydrological model

The stochastic state-space hydrological modelling approach to flow forecasting discussed in section 4.2 requires knowledge of the likely errors in the observations or NWP forecasts of rainfall used as input. These errors may vary as an event unfolds, and the vorticity tipping term indicator may be one way of suggesting the reliability of NWP forecast input.

To illustrate how a stochastic model responds to changes in the uncertainty in the input data, such a model has been implemented for the River Croal, a tributary of the River Irwell in North West England (Robbins and Collier, 2005). Figure 10 shows the flow predictions made using different errors associated with raingauge and radar rainfall inputs for both a deterministic and stochastic hydrological model. Note that the stochastic model reduces the errors in the output flow forecasts. Further work is needed to investigate the performance using NWP inputs.

4.4 The tipping term as a measure of forecast uncertainty

In section 2 we discussed whether or not the symmetry in the tipping term couplet could indicate likely convective development. Whilst there was some indication that this might be useful if high resolution grid (1 km) NWP output is available, the practicality and reliability of this approach remains unclear. An alternative approach might be to use this information to indicate uncertainty in the numerical forecasts. For example, vorticity couplets indicate rapid convective development and decay, situations for which numerical forecasts might or might not be reliable.

A measure of uncertainty could be associated with the symmetry in the forecast vorticity fields. Such a measure of uncertainty could then be used as one input to a stochastic hydrological model. In the case of the Boscastle storm the NWP generated good forecasts of the rainfall (Figure 7). The presence of symmetric (A) and asymmetric (B) tipping term couplets (Figure 6) may suggest that the forecasts of rainfall amount and distribution in these locations are reliable being due to convective development (A) and weakening (B). Resources were not available in this study to investigate how this information might be used in a stochastic model.

5. Conclusions

It is clear that the vorticity tipping term is not a useful indicator of convective development unless the numerical forecast model has a grid resolution of around 1 km or less. However, it may be possible to use this parameter at this resolution as a measure of the likely uncertainty in forecasts of extreme precipitation which might then be used within a stochastic hydrological modelling framework as outlined in this study.

A promising approach for improving forecasts of extreme rainfall events is found to be the assimilation of parameters from Doppler radars. If the data assimilation work is to lead to improved forecasts of extreme events it is concluded that stochastic hydrological modelling approaches will also need to be investigated further to ensure that the error characteristics of numerical rainfall forecasts are dealt with appropriately. In this project we have dealt with a number of issues that are of major importance and require analysis to confirm the promise that has been indicated.

In summary, the original aims of the Project have been achieved. However, the rather limited conclusion regarding the probable lack of utility of the use of the absolute value of the vorticity tipping term on its own has led to consideration of the question of how best to assimilate Doppler radar data. In addition the possibility has been raised of using measures of uncertainty in NWP forecasts, perhaps derived from the tipping term information, in a stochastic hydrological modelling framework.

6. Recommendations

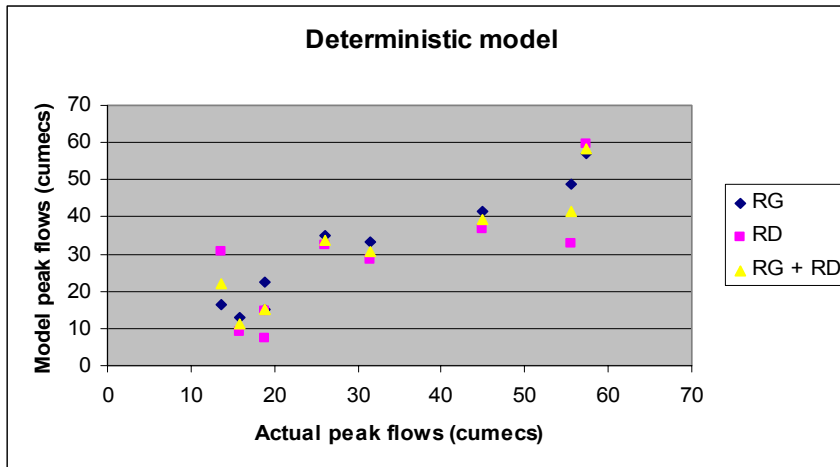
It is likely that a grid length of 1 to 1.5 km may be used for the Met Office operational model within about five years. Therefore we recommend that the use of the vorticity tipping term couplet as an indicator of convective development should be re-visited when such model output is available routinely.

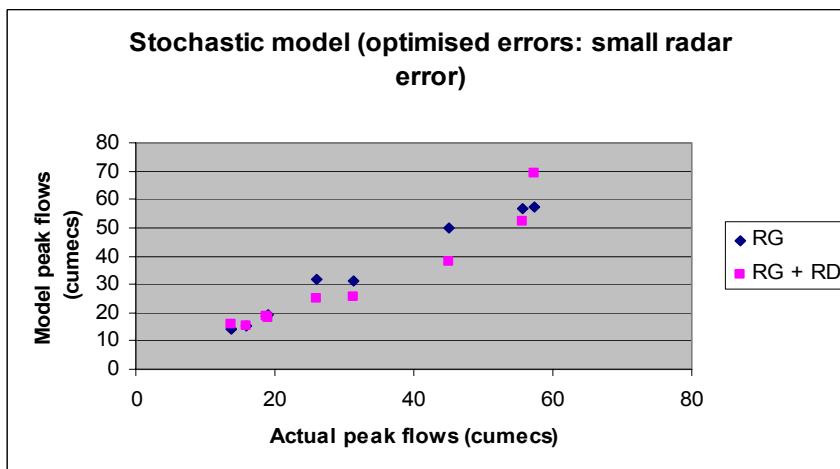
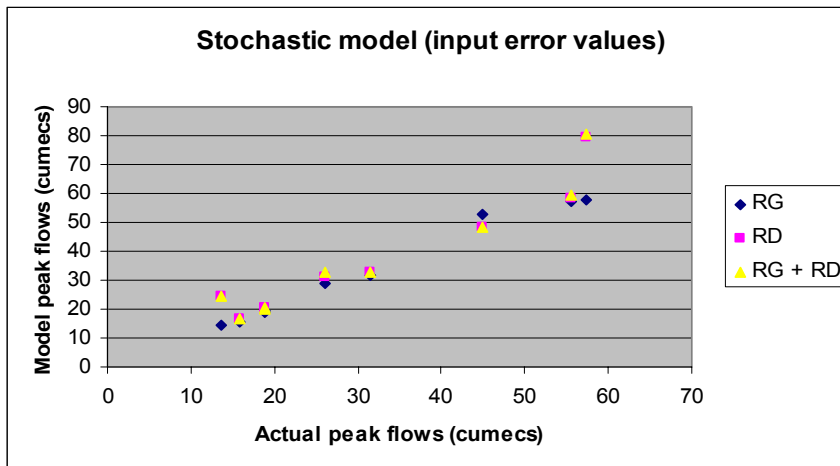
Only a limited amount of work on the assimilation of radar data has been carried out in the UK, and it is recommended that further work be undertaken to investigate the impact of the assimilation of radar reflectivity, humidity information derived from radar (refractivity) and radial winds.

Since forecasts of flows from extreme events are likely to be significantly influenced by errors in rainfall, forecast inputs and hydrological model formulation errors it is recommended that stochastic approaches to model development are investigated further. Such work should involve the use of a range of techniques including Ensemble Kalman filters, Bayesian statistics and fuzzy measures of model evaluation.

Figure 10

Performance of a deterministic model of the River Croal compared with a stochastic model using different combinations of input errors: RG – raingauge; RD – radar; RG + RD – raingauge and radar.





7. Acknowledgement

This work was part funded by the Natural Environment Research Council (NERC) through the Universities Weather Research Network (UWERN) part of the NERC Centre for Atmospheric Research (NCAS). The provision of the NWP model output and radar data by the Met Office is acknowledged.

8. References

Davies-Jones, R. (1984) "Sreamwise vorticity: the origin of up-draft rotation in supercell storms", *J. Atmos. Sci.*, **41**, 2991-3006

Du, J., Mullen, S.L. and Sanders, F. (1997) "Short-range ensemble forecasting of quantitative precipitation", *Mon. Wea. Rev.*, **125**, 2427-2459

Golding, B., Clark, P. and May, B. (2005) "The Boscastle flood: Meteorological analysis of the conditions leading to flooding on 16 August 2004", *Weather*, **60**, 230-235

- Grum, M., Harremoes, P. and Linde, J. J. (2002) "Assimilating a multitude of rainfall and runoff data using a stochastic state-space modelling approach", 91 Conference on Urban Drainage, Portland, Oregon
- Hand, W.H., Fox, N.I. and Collier, C.G. (2004) "A study of twentieth-century extreme rainfall events in the United Kingdom with implications for forecasting", *Meteor. Apps.*, **11**, 15-31
- Hoskins, B.J., Buizza, R. and Badger, J. (2000) "The nature of singular vector growth and structure", *Quart. J. R. Met. Soc.*, **126**, 1565-1580
- Lean, H.W. and Clark, P.A. (2003) "The effects of changing resolution on mesoscale modelling of line convection and slantwise circulation in FASTEX IOP16", *Quart. J.R. Met. Soc.*, **129**, 2255-2278
- Lorenz, E.N. (1969) "The predictability of a flow which possesses many scales of motion", *Tellus*, **21**, 289-307
- May, B., Clark, P., Cooper, A., Forbes, R., Golding, B., Hand, W., Lean, H., Pierce, C., Roberts, N. and Smith, R. (2005) "Flooding at Boscastle, Cornwall on 16 August 2004 – A study of Met Office Forecasting Systems", Forecasting Research Technical Report No 429, Met Office, Exeter
- Petterssen, S. (1956) *Weather Analysis and Forecasting Volume 1 Motion and Motion Systems*, 2nd Edition, McGraw-Hill, New York / London, 428pp
- Rihan, F.A., Collier, C.G. and Roulstone, I. (2005a) "Four-dimensional variational data assimilation for Doppler radar wind data", *J. Comp. App. Math.*, **176**, 15-34
- Rihan, F.A., Collier, C.G., Ballard, S.P. and Swarbrick, S.J. (2005b) "Assimilation of Doppler radial winds into a 3D-Var system: Errors and impact of radial velocities on the variational analysis and model forecasts" submitted to *Quart. J.R. Met. Soc.*
- Robbins, G.L. and Collier, C.G. (2005) "Assessing error in hydrological and hydraulic model output flows", *Atmos. Sci. Letters*, **6**, 47-53
- Stensrud, D.J. and Fritsch, J.M. (1994) "Mesoscale convective systems in weakly forced large-scale environments. Part III: Numerical simulations and implications for operational forecasting", *Mon. Wea. Rev.*, **122**, 2084-2104
- Stensrud, D.J., Bao, J.W. and Warner, T.T. (2000) "Using initial condition and model physics perturbations in short-range ensemble simulations of mesoscale convective systems", *Mon. Wea. Rev.*, **128**, 2077-2107
- Sleigh, M.W. and Collier, C.G. (2004) "An investigation of the tipping term as a prognostic tool in short-range thunderstorm forecasting", *Atmos. Res.*, **69**, 185-198

Tracton, M.S. and Kalnay, E. (1993) "Operational ensemble prediction at the National Meteorological Center: Practical aspects", *Wea. Forecasting*, **8**, 378-398

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