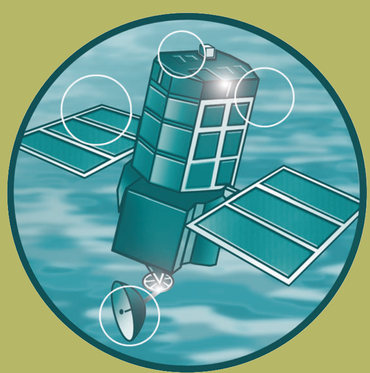
Joint Defra/EA Flood and Coastal Erosion
Risk Management R&D Programme

Extreme event recognition project Phase 2

Development of an extreme rainfall event forecasting system

R&D Project Report FD2208/PR



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Extreme event recognition project phase 2

Project Report

Development & Evaluation of an extreme rainfall event forecasting system

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Work Package 2: Development & Evaluation of an extreme rainfall event forecasting system

1. Aim of the package

The primary aim of the package was to take the conclusions from Phase 1 [1], which identified potentially important parameters associated with Extreme rainfall, and test them in a real-time trial hereafter referred to as the Trial. The purpose of the Trial was to develop a system which would forecast the probability of Extreme rainfall in selected Environment Agency (EA) Catchments and Areas up to 24 hours ahead. The forecasts would be verified using high resolution radar and rain gauge data. It was expected that the Trial would demonstrate the feasibility of predicting extreme conditions probabilistically. In particular, it was hoped that a probability threshold would emerge above which forecasts of the likelihood of an Extreme rainfall event could be useful.

2. User Requirement

The full User Requirement (UR) is provided at Annex A. The UR was agreed with the Project Board in September 2004 in time for the Trial to begin at the end of October and then run continuously for one year to November 2005. Three EA Regions were involved in the Trial: NW England, SW England and Thames. Maps of these Regions showing Areas and Catchments are provided in Appendices 3, 4 and 5. This choice maximised the chances of getting a variety of weather types over a year to thoroughly test the system. Tim Wood (SW Region), Ian Pearse (NW Region) and Alison Pickles were the EA representatives with whom the Trial specification was agreed. Trial outputs were sent by automated e-mail to EA Regional officers and no operational EA staff were involved. This was to avoid confusion and the potential for conflict with operational forecasts. Met Office forecasters at Exeter, Manchester and London also had access to Trial outputs so that they could comment (if they wished) on potential usefulness.

3. The Trial

3.1 Summary of the Trial

The Trial began on 1/11/04 and ended on 31/10/05.

Out of a possible 365 forecasts, 91 were not run. Most of the missed occasions occurred during July, August and part of September when the Trial Coordinator was unexpectedly absent from work. Other missing dates were all due to varying computer system problems. The missing days are tabulated in Table 1. The Table also shows the number of occasions when a “NIL” probability of Extreme rainfall was forecast in each Region. Most NIL forecasts were in THAMES and least in the NW Region. In the NW Region a “NIL” forecast was made on 59% of occasions when a forecast was issued.

Count of forecasts issued in each Region		Nov 04	Dec	Jan 05	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Total number
Dates when forecast not run		08th 16th 23rd	14th 17th 08th 20th	13th 19th 27th 28th 31st*		02nd 08th 09th 10th 11th 16th 22nd 27th 28th	12th 28th	06th 23rd	19th 30th	1st to 26th 28th	3rd to 8th 10th 11th 16th 20th 21st 22nd 26th-31st	1st to 14th 17th 18th	31st	91
Number of days a NIL forecast was issued in each Region	NW	22	19	11	19	13	12	15	15	3	6	9	19	163
	SW	21	20	20	21	15	11	12	19	0	6	11	17	173
	TM	23	25	20	19	16	13	14	18	1	8	11	18	186

Table 1. List of dates when the Trial forecast was not run and the number of occasions when a "NIL" forecast of Extreme Rainfall was issued for each Region (TM=Thames). On the 31st January (marked with an asterisk) the forecast only managed to run for SW Region before it was curtailed by computer problems.

The main technical components of the Trial were

- Data gathering
- Calculating predictor probabilities
- Calculating probability of Extreme rainfall
- Generating outputs

Data gathering was a complicated task involving transfer of NWP model data from 3 different computer systems, including one external to the Met Office at ECMWF, onto a UNIX workstation. The remaining tasks were all done on the UNIX workstation.

The Trial was set up in November 2004 and then ran unchanged up to 19/04/05. Some modifications were introduced after the 19th. The changes introduced a crude predictor of "stationarity" for convective rainfall, revised the Area probability to be the maximum of the Catchment probabilities, added lower and upper thresholds to the text outputs of Extreme rainfall expected in each Catchment and removed unrealistic gaps in duration of frontal rainfall events. The map presentation of Extreme rainfall probability was changed to show full resolution outputs. The Area probability calculation was also revised. Following this change the January 7th (Carlisle flooding) case was re-run and the verification software was altered to use the revised Area probability calculations for all cases prior to the 19th April. On 15th June it was discovered that the file that automatically updates the climatological probability of the orographic rainfall predictors from previous runs had become corrupted (see section 3.4). All affected orographic rainfall cases between 19th April and 15th June were identified and re-run for verification purposes. The dates on which forecasts were re-run were: 23/04/05, 24/04/05, 29/04/05, 30/04/05, 19/05/05, 25/05/05 and 30/05/05. Two other cases were affected, 28/04/05, 23/05/05, however, it was not possible to restore data to re-run these so the cases have been removed from the Trial results (see Table 1). After 15th June the Trial ran unmodified using fixed climatological predictor probabilities.

3.2 Data

NWP data for the Trial originated from three sources; European Centre for Medium Range Weather Forecasts (ECMWF) ensembles, Met Office Mesoscale model (MM) and the Met Office Convection Diagnosis Procedure (CDP). All of these are operational systems. The meteorological data fields used from each of the systems are shown in Table 2.

	ECMWF Ensembles	**Met Office Mesoscale Model**	**Met Office CDP**
Data Time (DT) of forecast	1200 UTC previous day	0600 UTC current day	0600 UTC current day
Data frequency	T+18 → T+60 at 6 hour intervals (51 ensembles)	T+6 → T+36 at 3 hour intervals. (Rainfall accumulations every 15 minutes)	T+6 → T+36 hourly
Data resolution	80 Km	15 Km	15 Km
Data fields/products	Depression tracks (text file of locations) Temperature at 850hPa (T_{850}) Relative Humidity at 850hPa (RH_{850}) 10m wind components CAPE Grid-scale precipitation amounts Convective precipitation amounts	Temperature Relative humidity Pressure Geopotential height Wind speed and direction Vertical gradient of equivalent potential temperature between 900hPa and 600hPa Density weighted vertical wind shear Wet-bulb freezing level Rainfall accumulations at gridpoints Orographic height	Peak rainfall rate in showers at ≥10% probability Peak rainfall rate in showers at ≥70% probability Rainfall accumulations in showers Cloud base probabilities Cloud top probabilities CAPE probabilities

Table 2. List of meteorological data fields used from the Met Office Mesoscale Model (MM), Met Office Convective Diagnosis Procedure (CDP) and the ECMWF global model ensembles. The ECMWF ensemble contains 51 members (forecast runs). from data at 1200UTC the previous day. The MM and CDP runs are from data at 0600 UTC (latest available time). Forecast data were made available every 6 hours

from ECMWF and every 3 hours from the Mesoscale Model (15 minutes for rainfall accumulations). CDP forecast data were available hourly.

All of the data listed in Table 1 were available routinely for operational requirements and were assembled onto a single workstation on each day of the Trial. They were then used to derive meteorological predictors for conditions conducive to Extreme rainfall as per the Phase 1 study.

3.3 Calculation of predictors

In addition to the Phase 1 predictors the Trial also used probabilistic forecasts of “heavy rainfall”. (The definition of “heavy” is explained in section 3.4). This was due to the obvious fact that Extreme rainfall will not happen unless “heavy rainfall” has occurred. Data from the ECMWF ensembles were used to derive predictors relevant to large scale frontal or orographic Extreme rainfall. MM and CDP data were mainly used to diagnose predictors for Extreme convective rainfall on the Met Office Nimrod grid. All predictors had threshold values which were calculated probabilistically on individual model grids. Probabilities derived from ECMWF data were re-projected onto the Met Office Nimrod Grid at 15Km resolution. This was a convenient common grid from which outputs for the EA could be derived. Thus for each predictor threshold, a field of probability of occurrence on a UK National Grid projection at 15Km resolution was produced.

3.3.1 Probability of “heavy” rainfall accumulation over 6 hours (ECMWF data)

This parameter was divided into three classes:
Large Scale, Convective and Total (Large Scale plus Convective).

Probabilities for each class were then the fraction of ECMWF ensemble members exceeding the “heavy rain” threshold at each model gridpoint. Probabilities were re-projected onto the Nimrod grid.

3.3.2 Probability of suitable orographic enhancement conditions for Extreme rainfall (ECMWF data)

There were two classes for this predictor:

Heavy rain and geostrophic wind direction 220-250 degrees with:
(a) Speed 15-25 m/s AND airmass source dewpoint > 14C
or (b) Speed > 25 m/s AND airmass source dewpoint > 14C

The geostrophic wind is the wind blowing at about 600m above ground and is largely unaffected by frictional effects from the surface. Geostrophic wind speed was estimated from the 10m wind by multiplying by a factor of 1.5 if CAPE >300, 2.0 if CAPE 200-300, and 2.5 for CAPE <200 J/Kg. Geostrophic wind direction was assumed to be veered by 20 degrees from the 10m wind.

The airmass source dewpoint was derived by adding 2 degrees to the wet-bulb potential temperature at 850 hPa which was calculated from T_{850} and RH_{850}.

The above calculations were done at all ECMWF gridpoints (around the UK) that had “heavy rain” which was predominantly of the “large scale” type.

Probabilities for each class were then the fraction of ECMWF ensemble members exceeding the threshold at each model gridpoint. Probabilities were re-projected onto the Nimrod grid.

3.3.3 Depression speed probability (ECMWF data)

These were calculated from a text file generated operationally in the Met Office that gives the successive position of each depression centre in all of the ECMWF ensemble members at times throughout the forecast period.

There are three classes for this predictor:

(a) Depression speed less than 5 m/s
(b) Speed 5-9 m/s
(c) Speed 10-19 m/s

Lows at times with speeds greater than or equal to 20 m/s were disregarded.

After the speed calculation within an ensemble member run the low positions for each speed class were projected onto the Nimrod 15 Km grid. The probability of getting a low centre in a particular class at a particular Nimrod pixel was then the percentage of ensemble members in which that pixel was “occupied”.

3.3.4 Large scale CAPE probability (ECMWF data)

Convective Available Potential Energy (CAPE) is a measure (in Joules per Kilogram of air (J/Kg)) of the amount of energy available/released by a rising parcel of air in the unstable part of the atmosphere.

There are three classes for this predictor:

(a) CAPE 1-100 J/Kg
(b) CAPE 101-800 J/Kg
(c) CAPE > 800 J/Kg

Gridpoints with CAPE < 1 J/Kg (i.e. negative or zero) were ignored.

Probabilities for each class were then the fraction of ECMWF ensemble members satisfying the criteria at each model gridpoint. Probabilities were re-projected onto the Nimrod grid.

3.3.5 Probability of Large hail (>15mm diameter) (MM and CDP)

This probability was derived from MM and CDP data directly on the Nimrod 15Km grid. The CDP was used to provide hourly probabilistic information on peak rainfall rates, cloud base, cloud top and CAPE, all of which are important for large hail formation. The MM provided “environmental” conditions of vertical temperature and humidity structures and wind information. Hail size was calculated using Miller’s technique [2] which has been adapted for operational use in the Met Office. After 19th April this predictor was only calculated if the CDP indicated that rainfall accumulations from individual shower clouds would exceed 2.0 mm at a point. This was due to a finding in WP1 which stated that Extreme rainfall was more likely in showers that persisted at a point (stationarity).

3.3.6 Probability of heavy thunderstorms. (MM and CDP)

As in 3.3.5 this predictor was only calculated if the CDP indicated rainfall accumulations from individual shower clouds would exceed 2.0 mm at a point.

In this package a heavy thunderstorm was taken to be a storm with either

(a) Lightning flash rate > 10 flashes/minute or 5Km average rainfall rate > 32 mm/h (with thunder) expected to occur in isolated cells.

(b) Lightning flash rate > 10 flashes/minute or 5Km average rainfall rate > 32 mm/h (with thunder) expected to occur in multiple re-generating cells.

Lightning flash rate was determined from CDP [3] and MM data in a similar way to that done operationally in the Met Office Nimrod system [4]. CDP CAPE and peak rainfall rates were used in the calculation. The distinction between isolated and multiple convective cells was derived using CDP CAPE and MM wind shear information. Probabilities were derived hourly on the Nimrod 15Km grid from the CDP data.

3.3.7 Probability of “localised” heavy rain. (MM)

The purpose of this predictor was to use the Mesoscale model to supplement the larger scale information from ECMWF (3.3.1). This predictor also provided more detailed information in convective situations.

The probabilities were derived hourly on the Nimrod 15Km grid using model verification data to determine the likelihood that heavy rainfall would occur given a particular rainfall accumulation. Essentially a small accumulation would give a low probability and a higher one a higher probability of “heavy rainfall”.

3.4 Derivation of probability of Extreme Rainfall

The probabilities of the predictors listed in section 3.3 occurring at 15Km pixels were linearly interpolated in time to every 15 minutes in the period 1200 to 1200 UTC. The probability of getting Extreme rainfall at each time at each pixel was then derived as follows.

The method is Bayesian [5] and is expressed formally in equation 1.

$$P(R|E) = prior \times P(E|R) / (P(E|R) .P(R) + P(E|R^*).P(R^*)) \quad .... (1)$$

P(R|E) is the probability of getting extreme rainfall **given that** a piece of evidence E occurs. Each piece of evidence is a predictor value (one of 3.3.2, 3.3.3, 3.3.4, 3.3.5, or 3.3.6) that lies within a range of threshold values. Note that the “heavy rainfall” predictor probabilities are used in the next stage.

prior is the climatological probability of getting extreme rainfall. This varies according to month and geographical location (see Appendix 1 for details).

P(E|R) is known as the inverse probability, i.e. the sample probability that a predictor value will occur given that extreme rainfall occurs. These were derived from the 20th century sample for all predictor values. In working out the contribution to extreme rainfall of slow-moving depressions the inverse probability was chosen according to how far a target pixel in a Catchment was from the depression centre and the speed of the low. Therefore, the highest probability for this contribution is chosen taking into account a range of possible aspects and distances from low centres as well as speed. Inverse probabilities are listed in Appendix 2 together with details on how they were calculated.

P(R) is the sample probability of extreme rainfall. (This was derived by counting the number of hours duration of all the extreme events in the 20^{th} Century divided by the number of hours in the century). For orographic events P(R) was 0.0003097 and for non-orographic events 0.0004155 .

P(E|R)* is the sample probability that a predictor value will occur given that extreme rainfall has not occurred.

P(R*) is the sample probability that extreme rainfall will not occur.

Now clearly in the denominator of equation (1) P(E|R) .P(R) is close to zero and P(E|R*).P(R*) is close to P(E) which is the sample (or climatological) probability that a predictor value will occur.

Equation (1) was, therefore, closely approximated by equation (2)

P(R|E) = prior x P(E|R) / P(E) ……. (2)

Climatological sample probabilities for the occurrence of each predictor E_i in the UK at a particular time were derived using historical information and data held in the Met Office.

3.4.1 Climatological probability of slow-moving frontal lows

For slow-moving frontal lows, a year was chosen at random (1999) and the occasions of all slow-moving frontal lows in a target area R of 1500 x 1500 Km centred around Lancaster during 1999 were counted. This would count the number of frontal depressions around the UK and within 450Km of land. The frequencies (probabilities) analysed for three speed categories were:

- Low speed < 5 m/s - P_{low} = 0.025
- Low speed 5-9 m/s - P_{low} = 0.050
- Low speed 10-19 m/s - P_{low} = 0.025

The climatological probability of getting a slow-moving frontal depression at a point in the UK for a particular speed category, at a particular distance and in a certain compass point sector was derived as follows.

Let A = land area of the UK.
Let P_{low} = Probability of getting a slow-moving low at a particular speed somewhere in target area R.
Let R = size of target area.

Then the probability of a point somewhere in R being in the UK is $P_{uk} = A/R$.
The probability of a point somewhere in R being within r kilometres of a slow-moving frontal low is $P_{close} = \pi . r . r / R \times P_{low}$

From the above it follows that the probability of a point being in the UK *and* within r kilometres of a slow-moving frontal low is P_{uk} x P_{close} , and the probability of this point being within a particular 8 point compass sector from the centre of the low is $P(E_i)$ = 0.125 x P_{uk} x P_{close} .

Using A = 244100 sq Km (from the Brittanica Atlas) we can derive the following Table xx of climatological probabilities for slow-moving frontal lows.

Distance from low and speed of low	< 5 m/s	5 – 9 m/s	10 – 19 m/s
≤ 240 Km	0.000027	0.000055	0.000027
241 – 450 Km	0.000069	0.000137	0.000069

Table xx. Climatological probability of getting a slow-moving low moving at a given speed with the low centre at a given distance and 8 point compass direction from a point in the UK at any one time.

3.4.2 Climatological probability of large hail and heavy thunderstorms

These were taken directly from research work undertaken in the Met Office for the prediction of large and damaging hail stones and severe thunderstorms. The research did not distinguish whether the severe storms were from isolated or multiple cell configurations, so it has been assumed here that both occur with equal frequency.

- For large hail $P(E_i)$ = 0.0019
- For heavy thunderstorms with isolated cells - $P(E_i)$ = 0.0115
- For heavy thunderstorms with multiple cells - $P(E_i)$ = 0.0115

3.4.3 Climatological probability of CAPE and orographic enhancement conditions

It was impossible to do direct calculations for the orographic enhancement and CAPE predictors from available data and with the resources given for the project, so initially these were derived from the ECMWF ensemble forecasts by counting the number of times each threshold occurred at all times in the UK area in an ensemble run. These counts were saved from each run and eventually a sufficient sample size was generated to approximate the climatological values over the UK. The following values were used in the Trial from April 2005 (and for a re-run of the Carlisle flooding case of 7/1/05).

- CAPE 1-100 J/Kg - $P(E_i)$ = 0.8
- CAPE 101-800 J/Kg - $P(E_i)$ = 0.1
- CAPE >800 J/Kg - $P(E_i)$ = 0.004

Heavy rain and geostrophic wind direction 220-250 with:

- Speed 15-25 m/s AND airmass source dewpoint > 14C - $P(E_i)$ = 0.00051
- Speed > 25 m/s AND airmass source dewpoint > 14C - $P(E_i)$ = 0.00014

So for each predictor threshold value E_i equation (2) is used to derive $P(R_J|E_i)$ at each 15 km pixel j . If $P(R_J|E_i)$ is then multiplied by $P(E_{iJ})$ i.e. the probability of a predictor value occurring *at* pixel j then we get $P(R)_J$ which is the probability of getting extreme rainfall at pixel j using one predictor theshold.

Thus at each pixel we can build up a vector of probabilities of getting extreme rainfall. In the vector each item is a probability according to a particular predictor threshold. The assumption is made that each item is independent. This is not unreasonable since ECMWF ensemble members offer independent weather evolutions and the predictors derived from the MM and CDP are calculated using separate, unrelated methods.

Therefore, the probability of extreme rainfall at a pixel given all the predictor evidence P(ER) is assumed equal to (*1 - the probability that extreme rainfall doesn't occur with any piece of evidence*). Mathematically this is expressed as

$$P(ER)_J = 1.0 - (P(R_1)_J^* \times P(R_2)_J^* \times \ldots \times P(R_n)_J^*)$$

where $P(R_1)_J^*$ is the probability that extreme rainfall will *not occur* at pixel j using first predictor, etc. Where $P(R_k)_J^* = 1.0 - P(R_k)_J$

Now, $P(ER)_J$ is strictly the probability of extreme rainfall given that "heavy rain" occurs at pixel j since the *priors* are dependent on heavy rain falling. So $P(ER)_J$ is multiplied by the probability of heavy rain falling at pixel j which is taken as the highest probability from the ECMWF and MM rainfall accumulation forecasts (predictors 3.3.1 and 3.3.7).

3.5 Generation of products

The outputs from the process outlined in section 3.4 are probabilities of getting Extreme rainfall at each 15 Km pixel every 15 minutes throughout the forecast period. These outputs were then processed to derive the products specified in the UR. The first step in this process was to establish the likely type of Extreme rainfall.

3.5.1 Establishing Extreme rainfall type

In Phase 1 five types of Extreme rainfall were identified. These are shown in Table 3.

Type	Description
O	Widespread rainfall produced by orographic enhancement.
A	Severe convective events that are triggered by synoptic scale cold frontal forcing or have large hail. This class also includes isolated near stationary clusters and large multi-cells in a strongly sheared environment.
B	Convective events triggered by mesoscale features (e.g. convergence, sea breezes, troughs, upper cold pools, topography or local heating). These events may also have hail but the hail should not be large and damaging or be very prolonged. Some multi-cellular organisation may also be possible but should not be too self-organizing or long lasting.
C	Prolonged frontal (widespread rainfall) events that have little or no convective element.
D	Frontal (widespread rainfall) events that have a significant convective element (embedded instability).

Table 3. Description of types of Extreme rainfall events found during Phase 1.

At each 15 Km pixel with a non-zero value of P(ER) all predictor values were examined and the type of Extreme rainfall was set as follows:

Type (O) if an orographic enhancement predictor threshold probability was the highest and the probability of large scale precipitation was greater than the probability of convective precipitation.

Type (A) if (excluding CAPE probability) probability of heavy thunderstorms with multiple convective cells or large hail probabilities was highest, or if probability of heavy thunderstorms with isolated cells was highest with a non-zero large hail probability.

Type (B) if (excluding CAPE probability) probability of heavy thunderstorms with isolated cells was highest with zero large hail probability.

Type (C) if there was a non-zero probability of a slow-moving depression, “LOW CAPE” probability (see below) and probability of convective rainfall accumulation was less than the probability of large scale rainfall accumulation in the ECMWF ensemble data.

Type (D) if there was a non-zero probability of a slow-moving depression, “HIGH CAPE” probability and non-zero probability of large scale rainfall accumulation *or* the probability of convective rainfall accumulation was greater than a non-zero probability of large scale rainfall accumulation and a non-zero probability of a slow-moving depression in ECMWF ensemble data. The latter was to cater for “thundery rain” in summer. (“LOW CAPE” probability is set when the probability of CAPE in the range 1-100 J/Kg exceeds that for each of the higher threshold ranges and “HIGH CAPE” probability is set when the probability of the lowest threshold (1-100 J/kg) is the lowest of all threshold ranges).

At the end of this procedure each 15 Km pixel would have a probability of Extreme rainfall with the most likely expected type.

3.5.2 Estimating Extreme rainfall amount and duration

The duration of Extreme rainfall at each pixel was determined by looking at the probability and type of Extreme rainfall (Type) at each 15 minute interval throughout the forecast. A particular type is continued from one time to the next if the type remains identical. For convective events the duration is taken to be the time during which the probability is steady or increasing. A convective event is deemed to stop at the time when the probability decreases from that at the previous 15 minute time. A new event could begin at the next 15 minute time which would then continue if the probability increases again in the next time interval. Frontal or orographic events only cease at a pixel when the probability of getting Extreme frontal or orographic rainfall falls below climatology. In reality some events are a mixture of convective, frontal and perhaps orographic. The Carlisle flooding case was an example where all three types were evident. To cater for this the duration of rainfall is extended if the MM indicates a probability of rainfall in the gaps between diagnosed event durations.

An Extreme rainfall amount in millimetres was estimated using linear or log-linear functions of duration (hours) using regression coefficients derived according to type from the study of Extreme rainfall events in the twentieth century.

3.5.3 Catchment and Area forecasts of Extreme Rainfall

These are derived from the 15Km resolution outputs of probability, amount and duration. Each of the three EA Regions is looked at in turn. Each Catchment within a Region is then considered at each 15 minute time. Catchments are identified using coordinates and fractional occupancy of 5Km squares on a UK National Grid projection (same as Nimrod). For a particular time, the probability of getting Extreme Rainfall in the Catchment is taken to be the highest of the probabilities in the 15Km squares intersecting the Catchment. Rainfall amount and duration were calculated using information from the intersecting square with the highest probability. Area forecasts were provided for two 12 hour time periods as per the UR. The probability of getting Extreme Rainfall in an Area was taken to be the highest Catchment probability in the Area during the 12 hour period. The Catchment and Area information were then processed to provide the text message in the format specified in the UR. Note that during the Trial it was agreed that in addition to the specific forecast estimate of Extreme rainfall amount in a Catchment, the fixed lower and upper thresholds of Extreme rainfall (as per Phase 1) for the duration were to be provided in brackets.

3.5.4 Other outputs

Other products produced in the Trial were charts showing the probability of predictors and of the probability of Extreme rainfall over the UK for each hour in the forecast. These were provided for Met Office forecasters and the Trial coordinator. Outputs were viewed on an internal Met Office web site. Examples of these are shown in section 3.7 .

3.6 Objective verification

The purpose of the verification procedure was to objectively examine the performance of the forecast system and to provide information that would inform how useful the probabilities would be if used operationally. Unfortunately, given the rarity of the type of event we are trying to predict (one event likely in the UK every 1.7 years), it was not possible to use established techniques for verifying probability forecasts. For example, use of the Brier score decomposed into components of reliability, uncertainty and resolution [6]. Therefore, the philosophy was adopted to record the spread of the probability forecasts, how close actual rainfall was to an Extreme fall for a range of forecast probabilities and for the Mesoscale model; to measure its own quantitative rainfall forecasts in Catchments whenever a non-zero probability of Extreme Rainfall was predicted. It was expected that this information, together with some subjective assessments would help build up a useful picture of overall Trial performance and enable recommendations to be made on the way forward.

3.6.1 Procedure

Throughout the Trial the text forecasts sent to the EA were saved and these were subsequently processed to obtain the forecast information for the objective verification. MM forecasts of rainfall accumulation were also saved (from March 1st and for the Carlisle flooding case on 7th January). Both the MM and the Trial probability forecasts were compared against 1, 2 or 5Km radar actuals, depending on how far a particular Catchment was from a radar site. The results from the verifications were split into two classes depending on whether the predicted Extreme rainfall in a Region for a particular day was likely to be either entirely orographic/frontal (types O,C,D) or have a convective element in it (types A and B). This was done because the results from WP1 suggested that the predictors were likely to have more skill in orographic/frontal cases than in convective cases. For each Catchment forecast the duration was used to determine the Phase 1 Extreme rainfall accumulation threshold (ET). The radar rainfall accumulations at 1Km resolution inside each Catchment were then divided by ET to obtain the fraction of an Extreme fall. For MM verification, a 15Km resolution radar rainfall accumulation centred on each 1Km pixel was obtained by averaging the radar rainfall in a 15 x15 Km square centred on the 1Km pixels.

It is very unrealistic to expect a model with a grid-point spacing of 15Km to forecast rainfall accumulations up to 30 hours ahead in Catchments with an average size of 293 square kilometres in the NW, SW and Thames Regions. With this in mind it was decided to adopt the following procedure to verify MM rainfall accumulations.

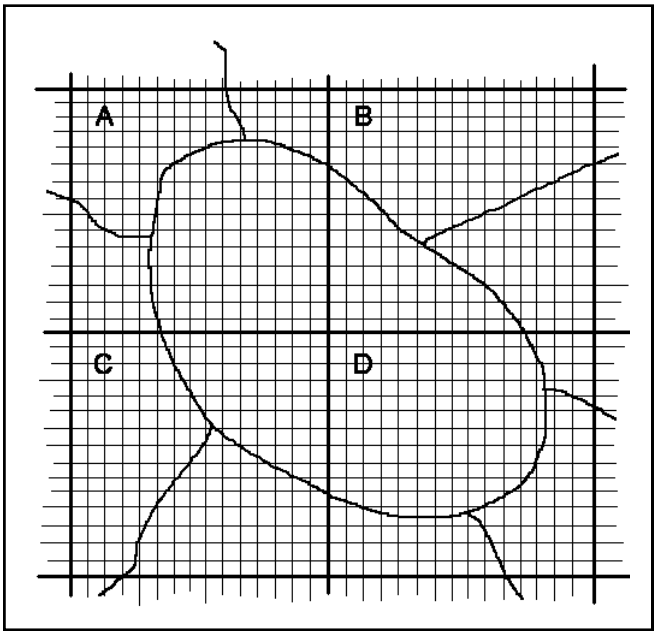


Figure 1. Schematic showing an irregular shaped Catchment, with four 15Km squares A, B, C and D divided into 1Km pixels.

Referring to the typical schematic Catchment shown in Figure 1; the MM rainfall accumulation forecast for the predicted duration of Extreme rainfall in the Catchment is taken to be the maximum model forecast in squares A, B, C and D, all of which intercept the Catchment. The verifying radar rainfall accumulations are taken to be the maximum 1Km and 15Km values in the Catchment. Verifying maximum model value against maximum radar value slightly mitigates the problem that Catchment sizes are small compared to the Mesoscale model resolution.

3.6.2 Results

3.6.2.1 Mesoscale Model (MM) verification

The results are shown in Table 4.

Mesoscale Model performance in Catchments												
	Entirely frontal/orographic cases						Other cases (mixed or convective)					
	15Km radar			1km radar			15Km radar			1km radar		
Duration (hours)	No. of fcs	Mean	Std. Dev.	No. of fcs	Mean	Std. Dev.	No. of fcs	Mean	Std. Dev.	No. of fcs	Mean	Std. Dev.
<1	0	-	-	0	-	-	883	0.1	1.1	883	-0.6	2.3
1-2	0	-	-	0	-	-	2253	0.2	1.8	2253	-1.1	3.8
2-3	0	-	-	0	-	-	1486	0.7	3.5	1486	-0.6	4.4
3-6	153	-2.2	7.5	153	-5.3	11.5	1236	0.4	2.8	1236	-1.6	5.2
6-12	253	-0.8	7.4	253	-6.0	14.2	178	1.4	3.3	178	-0.3	4.0
12-18	211	5.1	7.0	211	0.9	9.6	87	-1.2	4.6	87	-4.7	7.5
18-24	294	13.8	21.4	294	5.6	24.6	50	-6.7	19.9	50	-23.0	30.5

Table 4. Performance of MM forecasts in all Catchments from November 2004 to October 2005 where a non-zero probability of Extreme Rainfall was predicted. Extreme Rainfall forecasts arising from orographic or frontal rainfall with a slow-moving depression are distinguished from the rest. The maximum model rainfall forecast accumulation in a Catchment was compared with the maximum observed 15Km and 1Km resolution accumulations using radar data. The number of forecasts

in seven Extreme Rainfall duration categories with mean and standard deviation of departures from radar accumulations in millimetres are indicated.

The results unsurprisingly show that the MM performed better against 15Km average radar data than 1Km radar data. Generally the MM performance verified this way was excellent. The mean errors are generally very small except for the 12-18 and 18-24 hour duration events where in frontal/orographic (FO) cases the bias is positive and negative for the other types. It is useful to compare the model performance statistics with those for the radar data which are shown in Table 5.

Statistics of actual maximum observed radar rainfall in Catchments when Extreme Rainfall has been predicted								
Entirely frontal/orographic cases					Other cases			
	15Km radar		1km radar		15Km radar		1km radar	
Duration (hours)	Average (mms)	Max. (mms)	Average (mms)	Max. (mms)	Average (mms)	Max. (mms)	Average (mms)	Max. (mms)
<1	0	0	0	0	0.4	7	1.1	35
1-2	0	0	0	0	1.0	12	2.3	37
2-3	0	0	0	0	1.7	18	3.0	29
3-6	5.0	30	8.1	50	2.2	19	4.3	45
6-12	7.1	47	12.3	110	3.6	16	5.3	19
12-18	7.7	29	11.9	48	8.7	25	12.2	43
18-24	13.2	59	21.4	82	48.5	126	64.8	158

Table 5. Statistics of actual maximum observed radar rainfall in Catchments where a probability of Extreme Rainfall was predicted. Entirely orographic or frontal rainfall situations are distinguished from the rest. The average and maximum values of maximum radar rainfall accumulations in Catchments at 1Km and 15Km resolutions are shown for seven duration categories.

Looking at the 18-24 hour duration, the bias for the FO cases is 13.8 mm which is higher than the corresponding 15Km average actual radar rainfall value of 13.2 mm. Also at 12-18 hour duration the model bias was 5.2 mm compared to an actual average of 7.7 mm. Therefore, we can say that there is a tendency for the MM to predict significantly too much rain in long duration FO cases.

3.6.2.2 Catchment forecasts

The frequency of probability forecasts in ten percent ranges are shown in Tables 6 and 7.

Probability (%) / Duration (hours)	<1h	1-2	2-3	3-6	6-12	12-18	18-24	Rounded fraction of total (%)
1-10	0	0	0	117	246	209	146	71
11-20	0	0	0	0	5	29	30	6
21-30	0	0	0	25	23	15	46	11
31-40	0	0	0	11	14	2	25	5
41-50	0	0	0	0	19	1	27	5
51-60	0	0	0	0	4	0	14	2
61-70	0	0	0	0	0	0	3	>0
71-80	0	0	0	0	0	0	5	>0
81-90	0	0	0	0	0	0	0	0
91-100	0	0	0	0	0	0	0	0
Total	0	0	0	153	311	256	296	100

Table 6. Frequency of Extreme Rainfall probability forecasts in a range of probability/duration (hours) classes. Forecasts are from all Catchments in the period November 2004 to October 2005 where a probability of Extreme Rainfall from either a slow-moving frontal depression or orographic enhancement was predicted.

Probability (%) / Duration (hours)	<1h	1-2	2-3	3-6	6-12	12-18	18-24	Rounded fraction of total (%)
1-10	998	2762	1946	1034	121	56	66	88
11-20	31	114	104	225	23	5	4	6
21-30	9	15	20	95	38	33	6	3
31-40	0	3	7	30	0	7	0	1
41-50	0	12	0	9	0	4	0	>0
51-60	0	0	0	0	4	0	1	>0
61-70	0	0	0	0	0	0	3	>0
71-80	3	2	0	5	0	0	0	>0
81-90	0	0	0	0	0	0	0	0
91-100	0	0	0	0	0	0	0	0
Total	1038	2908	2077	1398	186	105	80	100

Table 7. Frequency of Extreme Rainfall probability forecasts in a range of probability/duration (hours) classes. Forecasts are from all Catchments in the period November 2004 to October 2005 *excluding* those where a probability of Extreme Rainfall from either a slow-moving frontal depression or orographic enhancement was predicted.

There were 1016 non-zero Catchment probability forecasts of Extreme rainfall for FO events and 7792 for the rest. This was out of proportion with the observed 20th Century frequency of occurrence of 42% for FO events over the entire UK. It was felt that there were too many non-zero probability forecasts of Extreme convective rainfall. In the FO cases 0.71 of probability forecasts were in the range 1-10% as opposed to 0.88 in the non-FO set. Probabilities with values >20% occurred in 0.23 of FO events and in 0.06 of the rest. This demonstrates a higher level of confidence (albeit at low probability) in predicting rarer and spatially larger FO events as opposed to the rest (mainly convective events).

3.6.2.3 Area forecasts

The probability forecasts in EA Areas (max of Catchment forecasts in Area) were verified against 1/2/5 Km resolution radar rainfall data (see Tables 8 and 9). The radar accumulations were divided by the Phase 1 Extreme rainfall threshold for the event duration. This ratio R provided a measure of “how close” an actual event was to becoming an Extreme event. The maximum radar accumulation in an Area was used for the verification. Using this measure, R for the Carlisle case came out at 104% in the north Area of NW Region. The results showed that in the FO events there was a signal that R increased with increasing forecast probability, this was not the case with the convective events. This shows that the forecast probabilities were more useful for FO type events. This was especially the case for forecast probabilities over 10%. Given also that the majority of convective forecast probabilities were less than 10% it would appear that 10% could be a threshold above which a “heads up” could be issued for a possible Extreme event in an EA Area? In this context it is interesting to note that the Area probability forecast for Cornwall for the Boscastle storm was 11%.

Number of 12 hourly Area probability forecasts of Extreme Rainfall according to 1Km radar rainfall accumulations for orographic and frontal cases										
	Area probability forecast category (%)									
Max. radar accumulation fraction of Extreme Rainfall in Area (%)	NIL	1-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90
NIL	157	4	0	0	0	0	0	0	0	0
1-10	1	49	3	2	0	0	0	0	0	0
11-20	0	18	3	2	2	2	0	0	0	0
21-30	0	11	3	2	3	3	0	0	1	0
31-40	0	4	2	2	0	1	1	0	0	0
41-50	0	5	2	1	1	0	0	1	0	0
51-60	0	1	1	0	1	0	0	0	0	0
61-70	0	0	0	0	0	0	0	0	0	0
71-80	0	0	0	0	0	0	0	0	0	0
81-90	0	1	0	0	0	0	0	0	0	0
91-100	0	0	0	0	0	0	0	0	0	0
101-110	0	0	0	0	0	0	0	0	0	0
Average (%)	NIL	14	25	23	29	23	35	45	25	0

Table 8. Table showing number of 12 hourly Area probability forecasts categorised according to maximum fraction of 1, 2 or 5Km radar rainfall accumulation to Extreme rainfall accumulation in an Area. Forecasts are from the period November 2004 to October 2005 for cases in a Region which are entirely orographic or frontal associated with a slow-moving depression.

Number of 12 hourly Area probability forecasts of Extreme Rainfall according to 1Km radar rainfall accumulations for cases excluding orographic and frontal										
	Area probability forecast category (%)									
Max.radar accumulation fraction of Extreme Rainfall in Area (%)	NIL	1-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90
NIL	4115	37	1	0	0	0	0	0	0	0
1-10	1	338	29	16	5	5	1	0	1	0
11-20	0	72	16	5	2	1	0	1	1	0
21-30	0	21	6	2	1	0	0	0	0	0
31-40	0	10	1	0	0	0	0	0	0	0
41-50	0	4	0	2	0	0	0	0	0	0
51-60	0	1	1	0	1	0	0	0	0	0
61-70	0	1	0	0	0	0	0	0	0	0
71-80	0	1	0	0	0	0	0	0	0	0
81-90	0	0	0	0	0	0	0	0	0	0
91-100	0	0	0	0	0	0	0	0	0	0
101-110	0	1	0	0	0	0	0	0	0	0
Average (%)	NIL	8	12	12	15	7	5	15	10	0

Table 9. Table showing number of 12 hourly Area probability forecasts categorised according to maximum fraction of 1, 2 or 5Km radar rainfall accumulation to Extreme rainfall accumulation in an Area. Forecasts are from the period November 2004 to October 2005 for all cases *excluding* those which are orographic or frontal associated with a slow-moving depression.

3.6.2.3 Frontal and orographic cases

In order to look at these in a little more detail a subjective assessment was made on how good each FO case, for which a non-zero probability of Extreme rainfall was predicted, was in reality to the archetypal frontal or orographic system that gave Extreme rainfall in the Phase 1 study. The criteria for the subjective assessments are shown in Table 10.

	Good (G)	Moderate (M)	Poor (P)
Frontal	Low moving with a speed less than 20 m/s and less than 450 Km away from a Region. Low moves such that Region is always in the NW quadrant relative to the low centre.	Low moving with a speed less than 20 m/s and less than 450 Km away from a Region. Low moves such that Region is always north of the low centre.	Region is to the south of the low centre or the low is further than 450Km away from the Region or it is moving at a speed greater than 20 m/s.
Orographic	High pressure over Spain or Bay of Biscay, long fetch greater than 1450 Km from a west-southwest or southwest direction with a geostrophic wind speed > 15 m/s.	Only one of the "good" criteria missing.	At least two of the "good" criteria missing.

Table 10. Criteria used to assess the goodness of fit of each FO case to the Phase 1 conceptual model. Assessment was based on actual synoptic charts.

Each case was then compared with the highest Trial probability forecast of Extreme Rainfall in each Region, the highest observed radar rainfall fraction of an Extreme fall, and the highest MM rainfall accumulation fraction of an Extreme fall. The results are shown in Tables 11 and 12.

Analysis of Frontal cases in each Region				
NW	**Max. forecast probability of Extreme rainfall in Region (%)**	**Max. 1Km actual radar accumulation fraction of an extreme total (%)**	**Max. Mesoscale Model forecast accumulation fraction of an extreme total (%)**	**Fit of reality to Phase 1 model (Good, Moderate, Poor)**
20050330	37	23	6	G
20050414	23	14	11	G
20050429	2	38	9	P
20050524	9	11	2	P
20050623	4	13	7	P
20050624	4	11	1	P
20050628	22	35	26	M
20050727	37	59	19	M
20051011	3	50	65	M (in part)
20051020	2	12	9	M
SW	**Max. forecast probability of Extreme rainfall in Region (%)**	**Max. 1Km actual radar accumulation fraction of an extreme total (%)**	**Max. Mesoscale Model forecast accumulation fraction of an extreme total (%)**	**Fit of reality to Phase 1 model (Good, Moderate, Poor)**
20050122	3	27	N/A	P
20050329	14	35	26	G
20050330	32	15	3	M
20050513	13	23	26	M
20050515	6	7	2	P
20050623	8	53	4	M
20050624	2	8	1	P
20050628	50	36	12	M (in part)
20050727	73	49	149	M
THAMES	**Max. forecast probability of Extreme rainfall in Region (%)**	**Max. 1Km actual radar accumulation fraction of an extreme total (%)**	**Max. Mesoscale Model forecast accumulation fraction of an extreme total (%)**	**Fit of reality to Phase 1 model (Good, Moderate, Poor)**
20050413	7	5	3	P
20050513	2	1	5	P
20050623	7	41	3	M
20050624	6	9	1	P
20050628	31	33	20	M (in part)
20050727	37	47	36	M
20051021	2	2	<1	P

Table 11. List of cases (data time day) in each EA Region which were entirely frontal and associated with a slow-moving depression. The analysis shows the maximum forecast probability of Extreme Rainfall in each Region, the maximum 1Km radar accumulation fraction of an extreme fall, the maximum Mesoscale Model forecast accumulation fraction of an extreme total and a subjective assessment of how well each case fits in with the Phase 1 conceptual model.

Analysis of cases in each Region which were entirely orographic				
NW	**Max. forecast probability of Extreme rainfall in Region (%)**	**Max. 1Km actual radar accumulation fraction of an extreme total (%)**	**Max. Mesoscale Model forecast accumulation fraction of an extreme total (%)**	**Fit of reality to Phase 1 model (Good, Moderate, Poor)**
20050109	2	42	N/A	M
20050525	2	9	18	P
20050601	13	54	23	M
20050602	2	14	8	P
20050823	1	38	27	P
20050929	1	7	7	P
20051010	2	16	19	P
20051023	6	87	30	P
SW	**Max. forecast probability of Extreme rainfall in Region (%)**	**Max. 1Km actual radar accumulation fraction of an extreme total (%)**	**Max. Mesoscale Model forecast accumulation fraction of an extreme total (%)**	**Fit of reality to Phase 1 model (Good, Moderate, Poor)**
20050107	2	5	1	G
20050211	3	13	N/A	P
20050518	4	11	2	P
20051023	3	3	N/A	P
THAMES	**Max. forecast probability of Extreme rainfall in Region (%)**	**Max. 1Km actual radar accumulation fraction of an extreme total (%)**	**Max. Mesoscale Model forecast accumulation fraction of an extreme total (%)**	**Fit of reality to Phase 1 model (Good, Moderate, Poor)**
20050211	5	5	N/A	P
20050930	1	5	4	P
20051012	2	1	1	P
20051023	7	13	18	M

Table 12. List of cases (data time day) in each EA Region which were entirely orographic. The analysis shows the maximum forecast probability of Extreme Rainfall in each Region, the maximum 1Km radar accumulation fraction of an extreme fall, the maximum Mesoscale Model forecast accumulation fraction of an extreme total and a subjective assessment of how well each case fits in with the Phase 1 conceptual model.

The conclusion was that in the Frontal category, the Good and Moderate cases (58% of total) gave higher forecast probabilities from the Trial system and higher rainfall totals from the Mesoscale model than in the Poor cases. This is very encouraging since it is evidence that the method of calculating predictors in the Trial was sound. For the orographic cases, 75% were assessed as having a poor fit to the conceptual model, for varied reasons. All of the poor cases had low probabilities of Extreme rainfall. However, only one case, 01/06/05 which was assessed as “moderate” had an Extreme rainfall probability greater than 10%. In the other “moderate” cases and also in the one “good” case, the probability of heavy rain was predicted to be low in the Region.

3.7 Case studies

The following case studies have been chosen either because Extreme rainfall occurred or to illustrate some of the points already made in the report and to demonstrate the use of the predictors for Extreme rainfall. The date listed for the cases is the data time (DT) day, that is, the first day of a 24 hour period.

3.7.1 DT 07/01/05 (Carlisle flooding; Extreme rainfall case)

This case was a mixture of frontal, orographic and convective types and was the only Extreme event that occurred during the Trial. The synoptic developments are shown in Figures 2a, 2b, 2c and 2d. At 1200 UTC on the 7th (Figure 2a) there was a waving cold front over the Borders extending west into Northern Ireland. South of this front a very warm and moist tropical maritime west-southwesterly airstream prevailed providing good conditions for orographic enhancement of rainfall.

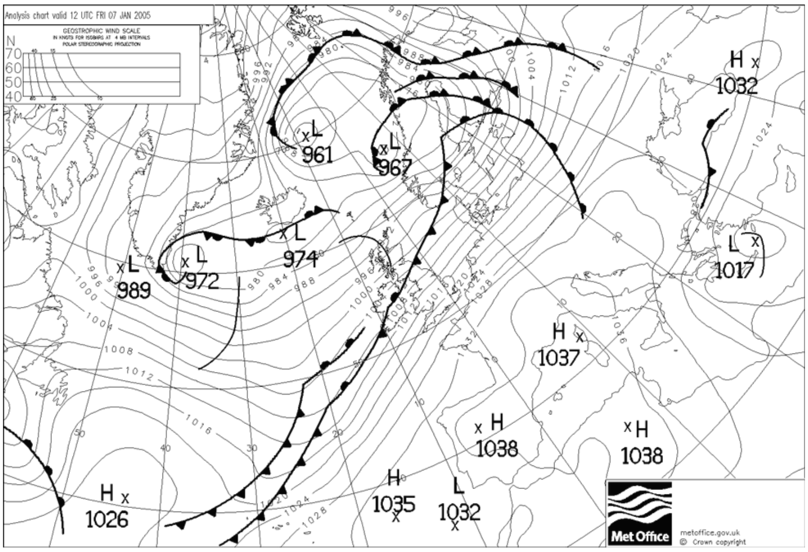


Figure 2a. Synoptic chart showing mean sea level pressure and fronts for 1200 UTC 07/01/05.

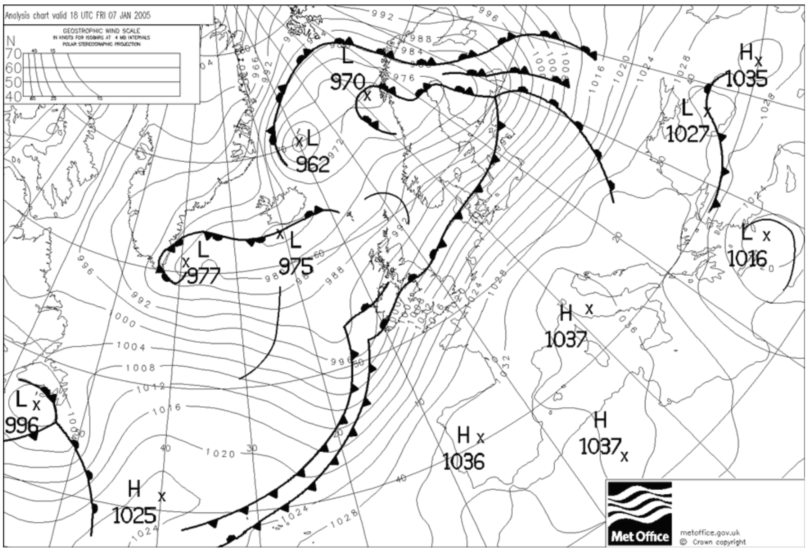


Figure 2b. Synoptic chart showing mean sea level pressure and fronts for 1800 UTC 07/01/05.

By 1800 UTC (Figure 2b) the front had moved a little further south into the North Area of NW Region and the strong west-southwest flow still persisted to the south. However, a low was deepening just to the west of Ireland. By 0000 UTC on the 8th (Figure 2c), the low was moving into Northern Ireland as a deepening feature with some strengthening of the airflow over the NW Region. Soon after midnight the cold front came through the Region signalling a change of weather type.

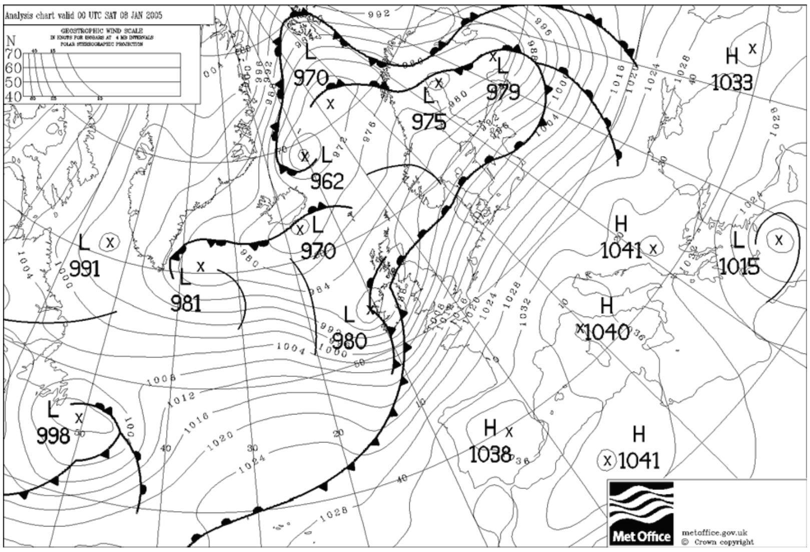


Figure 2c. Synoptic chart showing mean sea level pressure and fronts for 0000 UTC 08/01/05.

Six hours later at 0600 UTC (Figure 2d) the low had deepened rapidly into an intense feature over southern Scotland. A deep and unstable convective airmass now covered the NW Region with a core of very strong north-westerly winds moving into the Irish Sea.

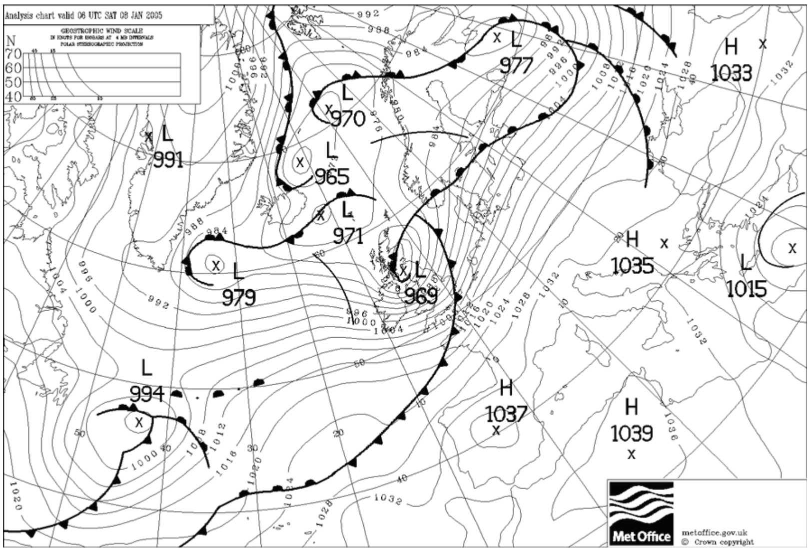


Figure 2d. Synoptic chart showing mean sea level pressure and fronts for 0600 UTC 08/01/05.

During the morning of the 8th the low moved away into the North Sea leaving the NW Region in a typical polar maritime north-westerly airstream.

The Extreme Rainfall forecast system predicted the change of weather type around 0000 GMT on the 8th very well. The type of Extreme Rainfall is shown in Figure 3.

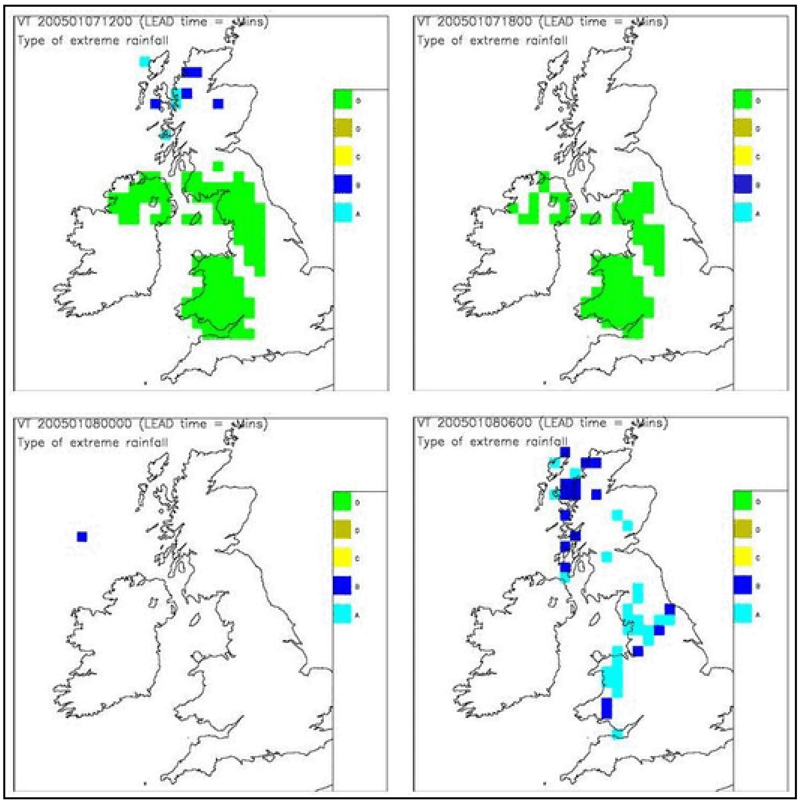


Figure 3. Meteorological type of predicted Extreme rainfall. Green is orographic. Blue is convective and yellow is slow-moving frontal. The times are for 07/01/05 1200 UTC (top left), 07/01/05 1800 UTC (top right), 08/01/05 0000 UTC (bottom left) and 08/01/05 0600 UTC (bottom right).

The orographic Type of rainfall was well predicted at 1200 and 1800 UTC (tending to die out from the north). The 0000 UTC chart shows very little activity as the airflow backed and the fast moving cold front approached. However, some Extreme convective rainfall was predicted after then as demonstrated at 0600 UTC. The forecast probabilities of getting Extreme rainfall are shown in Figure 4.

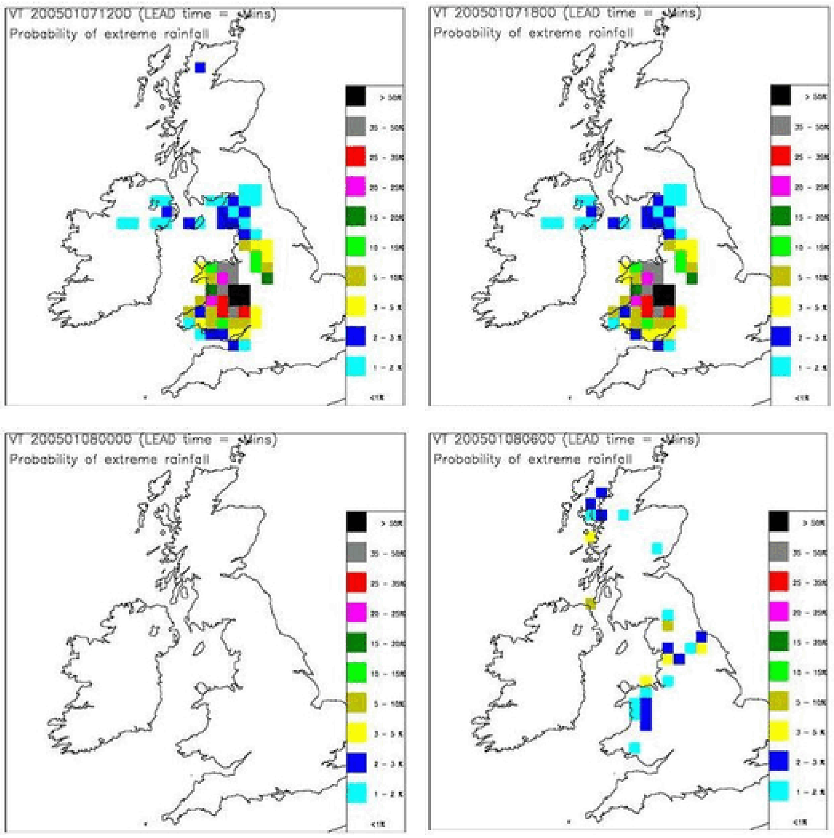


Figure 4. Forecast probabilities (%) of getting Extreme Rainfall somewhere over the British Isles for 1200 and 1800 UTC on 07/01/05 (top row) and 0000 and 0600 UTC on 08/01/05 (bottom row).

The forecast probabilities gave a strong signal (>10%) for Extreme orographic rain over Wales and the southern part of NW Region up to 0000 UTC on the 8th with a much weaker signal in the northern half. At 0600 UTC there are low probabilities of Extreme convective rainfall scattered over the NW Region. The orographic rainfall predictors are shown in Figure 5 which shows the charts for 1200 UTC on the 7th and 0000 UTC on the 8th.

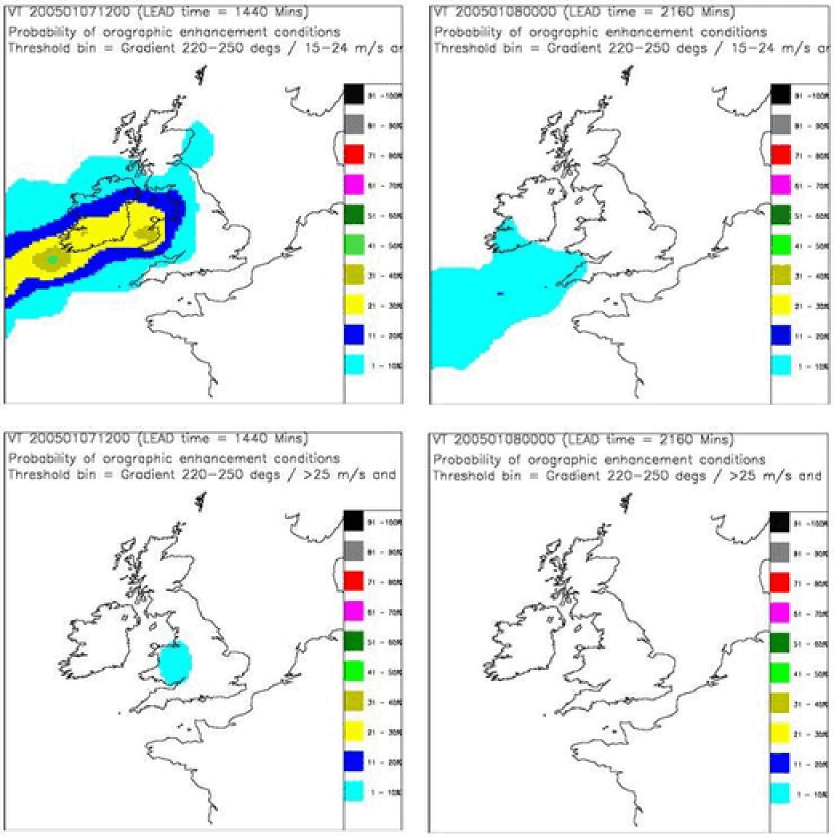


Figure 5. Probability of getting suitable orographic enhancement conditions for Extreme rainfall. The top row (1200 UTC 07/01/05 and 0000 UTC 08/01/05) shows the probability of getting a geostrophic wind direction between 220-250 degrees with a speed 15-24 m/s from air with a source dewpoint greater than 14 deg C. The bottom row shows the likelihood with geostrophic wind speeds greater than 25 m/s (more severe conditions).

The charts shown in Figure 5 were derived from ECMWF ensemble data. At 1200 UTC there was a low to moderate chance of suitable orographic enhancement conditions with the emphasis clearly over Wales. By 0000 UTC on the 8th the probability had decreased considerably and retreated south-westwards. The above is consistent with the predicted probabilities of Extreme rainfall shown in Figure 4, noting the low probability of getting strong enhancement conditions over Wales at 1200 UTC.

Another important contributor to the overall Extreme rainfall probability is the MM forecast of rainfall accumulation. The forecast probabilities of getting “heavy rainfall” from the MM are shown in Figure 6.

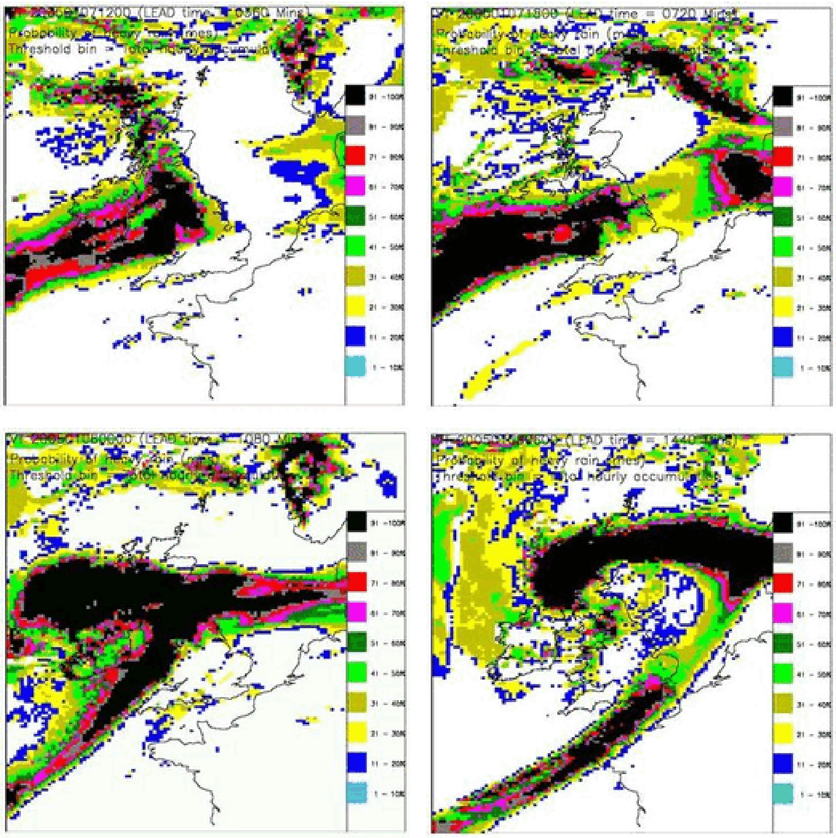


Figure 6. Probability of "heavy rainfall" at 1200 UTC 07/01/05, 1800 UTC 07/01/05, 0000 UTC 08/01/05 and 0600 UTC 08/01/05 (top left to bottom right) from Mesoscale model forecasts.

At 1200 UTC the model shows a broad band of heavy rain south of the waving cold front extending from southern Ireland eastwards into Wales and northern England. This band fits in well with the Extreme orographic enhancement conditions shown in the leftmost column of Figure 5. By 1800 UTC the model again shows heavy orographic rain over Wales but the band over northern England is weakening and emphasis is being switched to the cold front coming into southwest Ireland. By midnight the cold front is clearly marked as a band of high probability of "heavy rain" in the Irish Sea. Note that by this time the orographic signal over Wales and northern England has disappeared. By 0600 UTC on the 8th the model had developed a curl of high heavy rainfall probability wrapping around the deep low over southern Scotland. Also by this time the model had developed a high probability region of heavy showers over NW England in the polar air.

The Area forecasts and the corresponding largest fractions of the Phase 1 Extreme Rainfall threshold observed by radar are shown in Table 13.

Area	Forecast probability (%)	Largest fraction of the Extreme Rainfall threshold observed by radar (%)
North	4	104
Central	7	73
South	14	94

Table 13. NW Region Area forecasts of the probability of getting Extreme Rainfall somewhere in each Area. The largest fraction of the Phase 1 Extreme Rainfall threshold observed by radar in the Area is shown in the last column.

The Table shows that all areas of NW Region had very heavy rainfall observed by radar with an Extreme fall in the North Area. Unfortunately it was only the South Area that had a forecast probability greater than 10%. This was a “near-miss”. In the ECMWF ensembles used to calculate the orographic enhancement conditions the front was slightly further south thus cutting off the supply of warm moist air early in the forecast.

Catchment probability forecasts in North Area (where Carlisle is located) have been reproduced in Table 14. The Extreme rainfall forecast in Lower Eden Catchment was “NIL”, which was good as that Catchment is relatively low-lying. However, all other Catchments were forecast to get 152mm during the 24 hour period. Three Catchments; Derwent, Greta and Ehen all collected an Extreme rainfall (according to the radar data) during the forecast period. It is interesting that the forecast probability of Extreme rainfall was the highest in these Catchments but still very low overall. Although the forecast probability of Extreme rainfall is zero at 0000 UTC on the 8th (Figure 4), the MM was still showing a high probability of “heavy rainfall” in the North Area (Figure 6) and so the duration of Extreme rainfall was extended (in fact to the end of the forecast period).

Catchment	Forecast period	Prob(%)	Amount (mm)	Radar actual (mm)
Esk/Irthing	07/1200 – 08/1200	2	152	50
Lower Eden	NIL	-	-	-
Wampool/Ellen	07/1200 – 08/1200	2	152	63
Petteril/Caldew	07/1200 – 08/1200	2	152	88
Middle Eden	07/1200 – 081200	2	152	70
Derwent	07/1200 – 081200	4	152	158 (Honister 142.0)
Greta/St Johns	07/1200 – 081200	4	152	158
Lowther/Eamont	07/1200 – 081200	2	152	135
Upper Eden	07/1200 – 081200	2	152	102
Ehen/Calder	07/1200 – 081200	4	152	158
Duddon	07/1200 – 081200	2	152	129
Brathay/Rothay	07/1200 – 081200	2	152	126
Kent/Bela	07/1200 – 081200	3	152	127

Table 14. NW Region Catchment forecasts for North Area. Table shows probability and amount of Extreme rainfall. The largest rainfall observed by radar in the Catchment is shown in the last column. Honister rain gauge total is shown for the Derwent catchment.

The rainfall from Honister rain gauge in Derwent seemed to summarise the events of the 7th/8th January 2005 quite nicely. Hourly and 12 hour period totals are shown in Table 15. Hourly rainfall accumulations diminished after 2300 on the 7th as the orographic enhancement weakened. The cold front passage is indistinguishable from the deep convection which seemed to peak in the period 0600-0700 UTC. The 24 hour accumulation fell short of the Phase 1 Extreme rainfall threshold. However, the 0900 7th to 0900 8th rainfall accumulation at this gauge was 164.4 mm which did exceed the Extreme rainfall threshold of 152 mm for a 24 hour fall.

Honister hourly rain gauge totals (mm) ending at hour specified from 1300 UTC 07/01/05 to 1200 UTC 08/01/05													
Time	13	14	15	16	17	18	19	20	21	22	23	00	Total
Rainfall	7.2	6.6	6.2	9.4	11.6	7.4	7.2	16.0	16.0	9.6	7.6	7.4	112.2
Time	01	02	03	04	05	06	07	08	09	10	11	12	Total
rainfall	3.6	2.2	2.2	0.8	0.0	1.8	9.4	4.4	5.0	0.0	0.2	0.2	29.8

Table 15. Hourly rainfall totals from the Honister (Derwent) rain gauge (courtesy of the EA) from 1300 UTC 07/01/05 to 1200 UTC 08/01/05. The total for each 12 hour period is shown.

Generally the performance of the Trial in this case was disappointing, particularly as this was the only recorded Extreme rainfall during the year. However, it was very encouraging that high Extreme rainfall probabilities were predicted over Wales close (on a National scale) to NW Region. This implies that an improved ensemble forecast of synoptic conditions could have given an excellent result in NW Region.

3.7.2 DT 30/03/05

This was a good example of a frontal system associated with a slow moving low giving Type C rainfall. The synoptic charts for this case are shown in Figures 7 and 8. There was a slow-moving low over SE England with an old occlusion further north giving a persistent band of rain moving slowly southwards. The radar image for 1830 UTC (Figure 9) shows that the heaviest rain at that time was over Wales and the north Midlands.

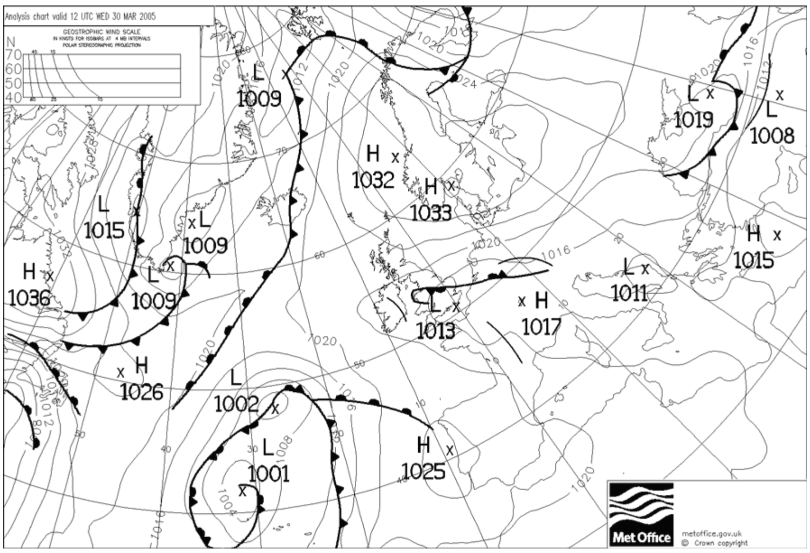


Figure 7. Synoptic chart showing mean sea level pressure and fronts for 1200 UTC 30/03/05.

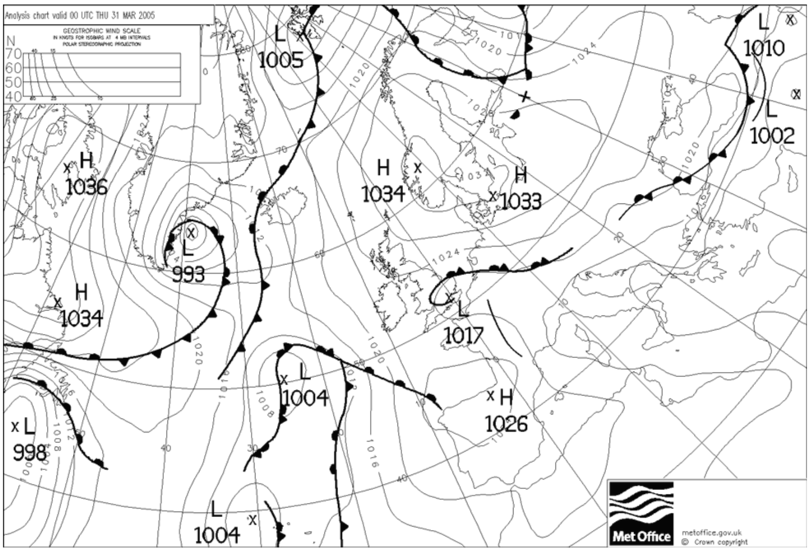


Figure 8. Synoptic chart showing mean sea level pressure and fronts for 0000 UTC 31/03/05.

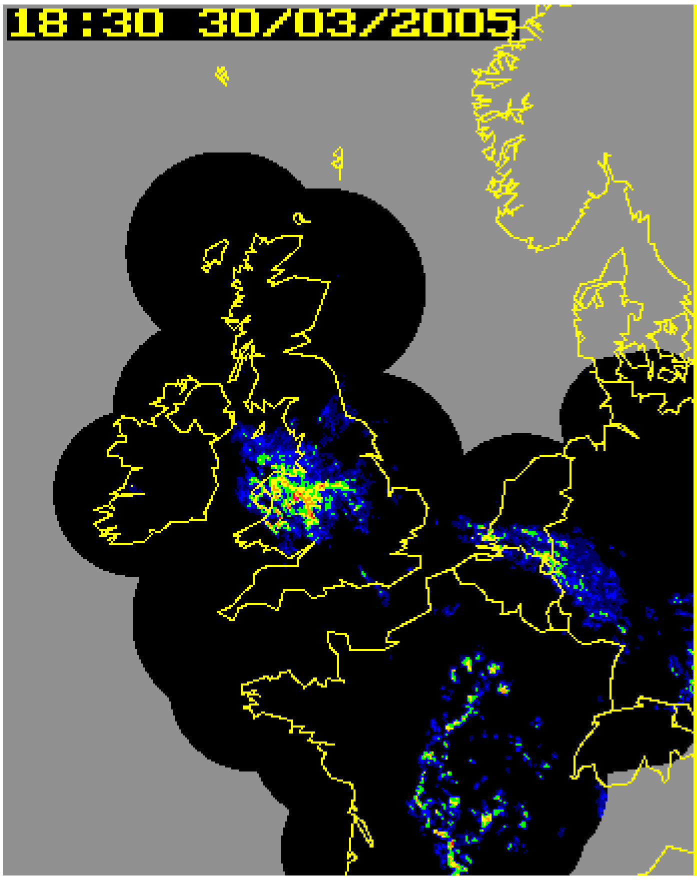


Figure 9. Radar rainfall at 1830 UTC 30/03/05.

In the Trial forecast the highest probability of Extreme rainfall (>50%), all of Type C, was centred over the west Midlands at 1800 UTC (Figure 10). This was consistent with the MM and ECMWF ensemble guidance of where the probability of “heavy rain” was greatest (Figures 12 and 13).

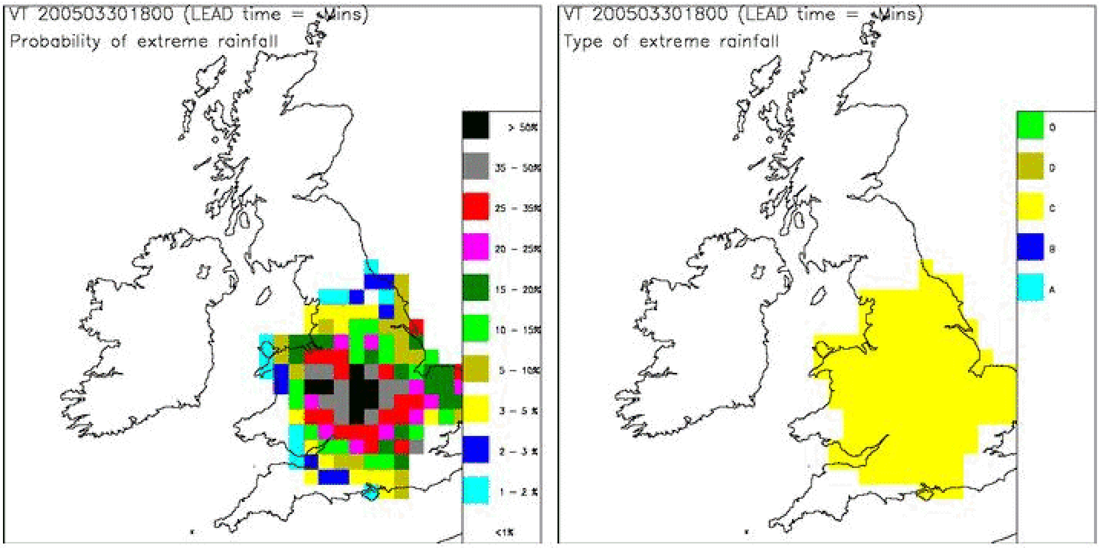


Figure 10. Trial forecast probabilities of Extreme Rainfall and associated synoptic Type at 1800 UTC 30/03/05.

The highest probabilities of Extreme rainfall are also in a sector that is northwest of a slow-moving depression which had a forecast probability of occurrence of 21-30% for a speed < 5 m/s in the Dover straits at 1200 UTC decreasing to circa 10% by 1800 UTC, see Figure 11. This sector has the highest inverse probability given Extreme rainfall (Table 9 in Appendix 2).

Type C was justified since the probability of CAPE being released was low in the ECMWF ensembles in which most of the rain was large scale frontal precipitation. Even though the front was slow-moving there was not enough rain for an Extreme fall. The case was, after all, at the end of March and no Extreme Rainfall cases in March and April have been found to date. However, time of year was not used as a predictor in order not to preclude Extreme rainfall in March or April.

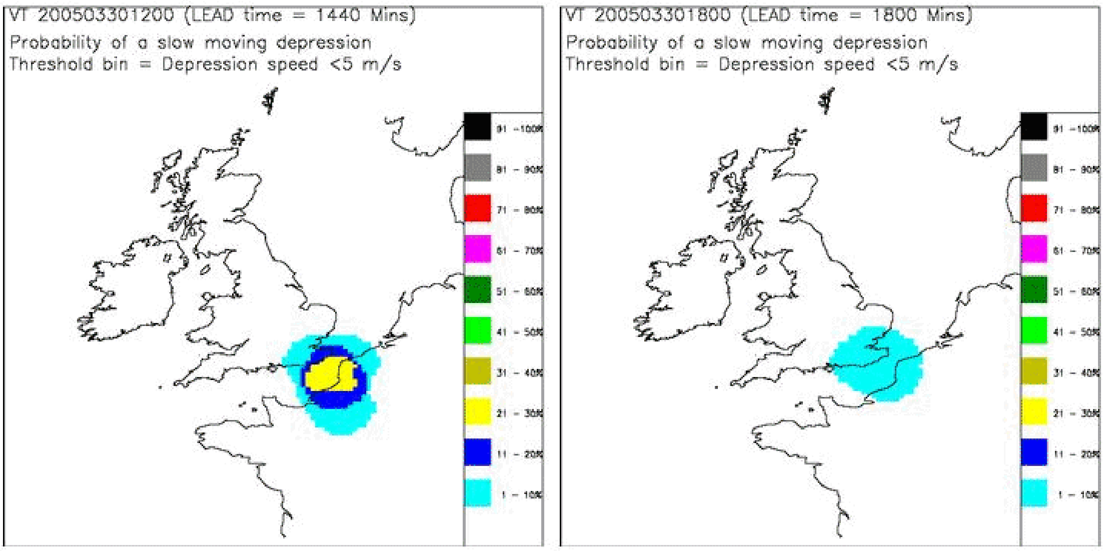


Figure 11. Trial forecast probability of a slow-moving depression moving at less than 5 m/s.

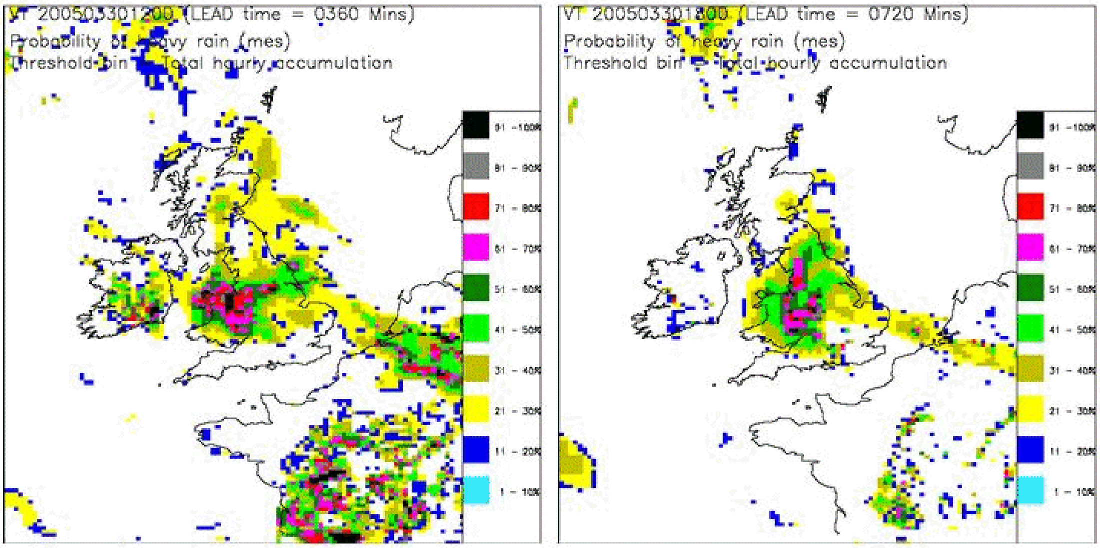


Figure 12. Mesoscale probability forecast of "heavy rain" at 1200 and 1800 UTC 30/03/05.

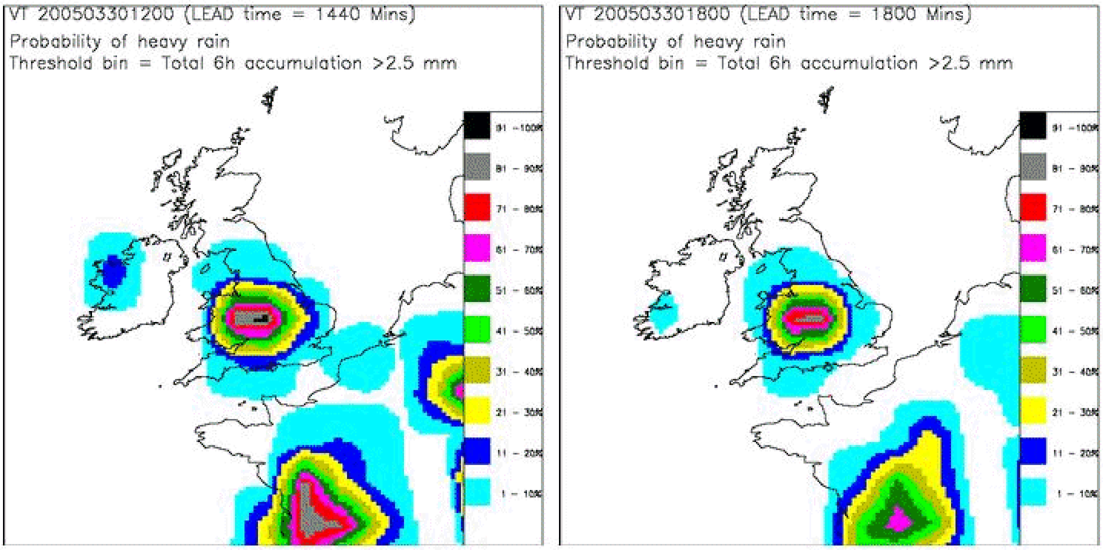


Figure 13. Probability of getting "heavy rain" from ECMWF ensemble data at 1200 and 1800 UTC 30/03/05

Table 15 shows the forecast probability of extreme rainfall in each Area of NW and SW Regions. It is pleasing that the three highest forecast probabilities coincided with the three highest fractions of an Extreme fall observed by radar.

NW Region	**Forecast probability of Extreme rainfall in Area (%)**	**Max.fraction of Extreme fall observed by radar (%)**
North	2	1
Central	20	15
South	37	23
SW Region		
Cornwall	NIL	N/A
Devon	3	2
North Wessex	32	15

South Wessex	14	2

Table 15. Highest forecast probability of extreme rainfall in each Area of NW and SW Regions and the corresponding highest fraction of an extreme fall observed by radar.

3.7.3 DT 14/04/05

This is another good example of a slow-moving frontal case, this time it is a mixture of Types C and D. At 0000 UTC on 15th April (Figure 14) there was a slow-moving low over East Anglia with frontal system over northern England. By 0600 UTC (Figure 15) the low had become complex and had moved south but with the frontal system remaining stationary over northern England.

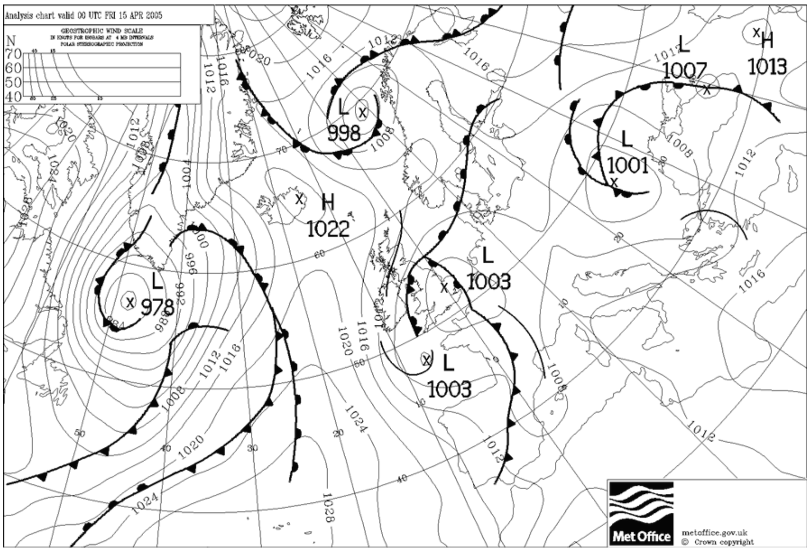


Figure 14. Synoptic chart showing mean sea level pressure and fronts for 0000 UTC 15/04/05.

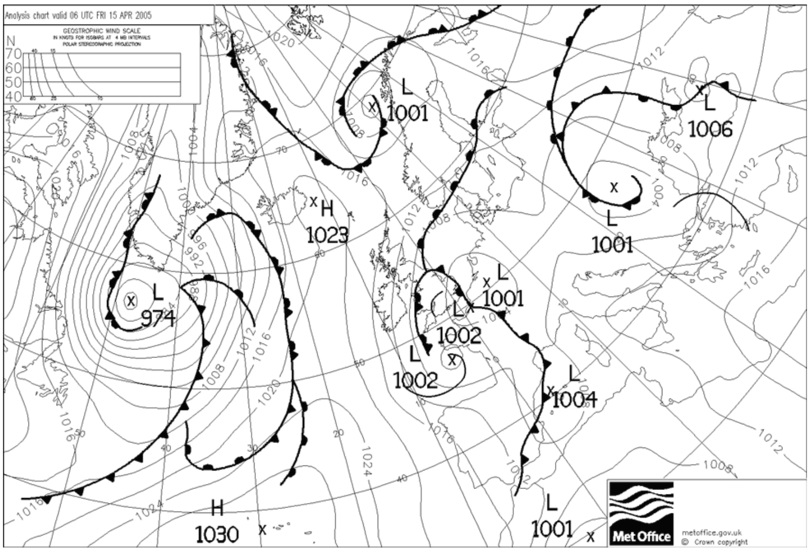


Figure 15. Synoptic chart showing mean sea level pressure and fronts for 0600 UTC 15/04/05.

The forecast probability of Extreme rainfall and Type for 0600 UTC 15/04/05 are shown in Figure 16. Relatively high probabilities are indicated over NE England but in

NW Region they are in the range 5-23%. The Type in NW Region was forecast to be mainly C with some Type D in the west of the Region.

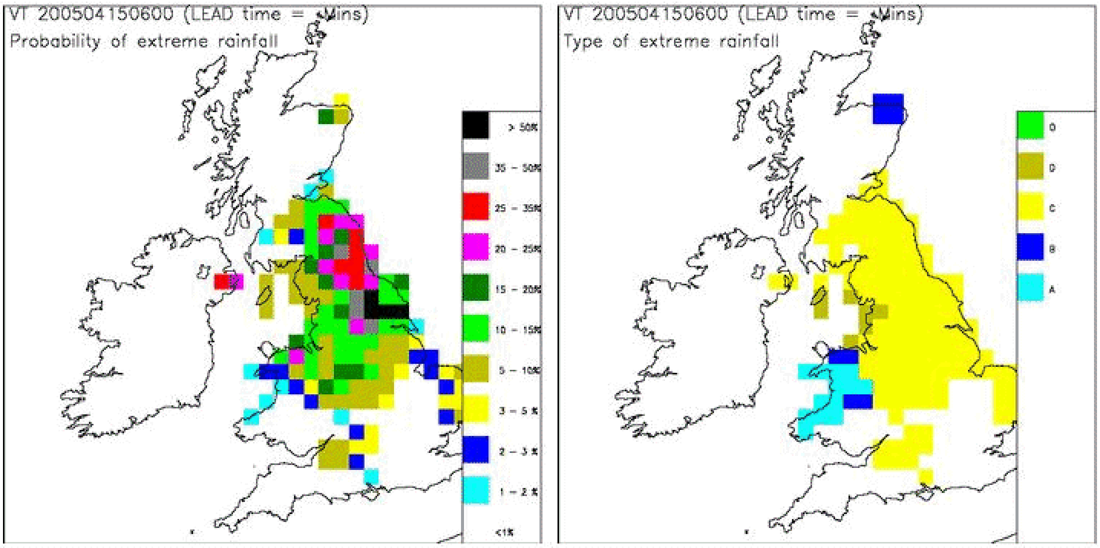


Figure 16. Forecast probability of Extreme rainfall and Type of rainfall at 0600 UTC 15/04/05.

The forecast probability of “heavy rain” from the Mesoscale model is shown in Figure 17. This chart picks out the slow moving frontal system over northern England very well. The highest probabilities of “heavy rain” are shown over NE England coinciding with a cluster of high forecast probabilities of extreme rainfall. The line of higher probabilities of extreme rainfall just north of Hull are a result of that area being closer to the slow-moving depression to the south (Figure 18). This depression was predicted to be slightly too far north by the ensembles.

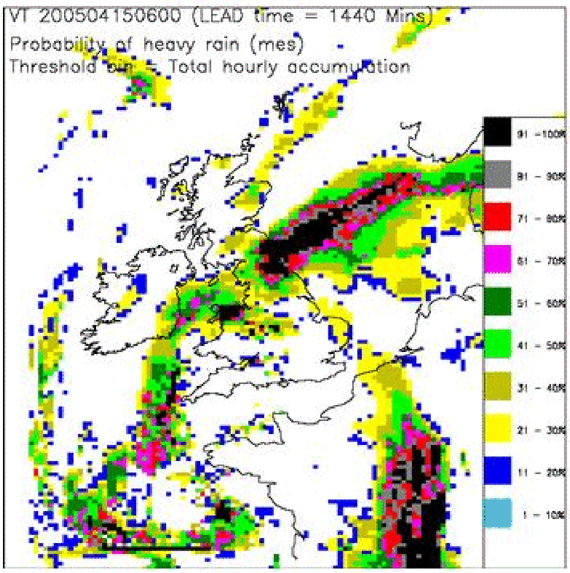


Figure 17. Mesoscale model forecast of the probability of “heavy rain” for 0600 UTC 15/04/05.

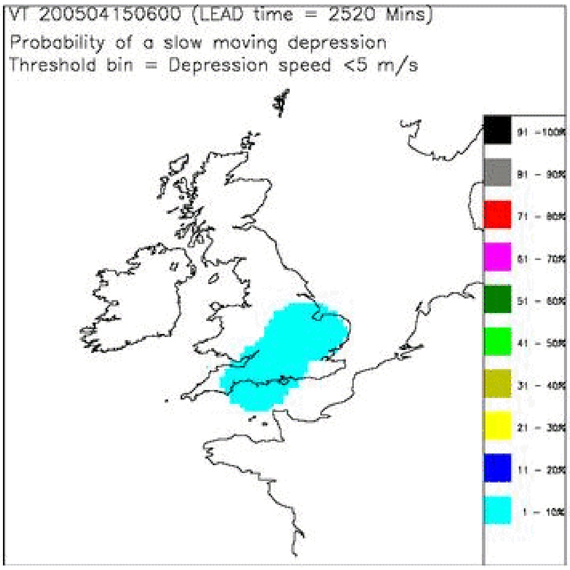


Figure 18. Probability of getting a slow moving depression at a speed less than 5 m/s at 0600 UTC 15/04/05.

The probability of getting CAPE in the range 100-800 J/Kg from ECMWF ensembles is shown in Figure 19. Relatively high values are indicated in the west of NW region, giving a forecast Type D of Extreme rainfall.

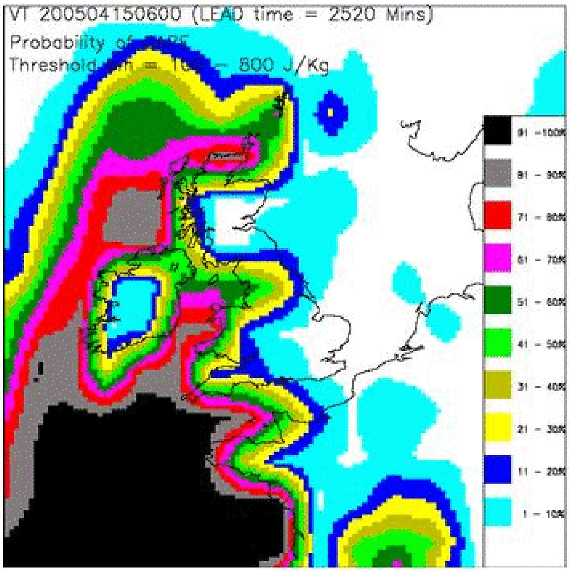


Figure 19. Forecast probability of CAPE in the range 100-800 J/Kg from ECMWF ensembles at 0600 UTC 15/04/05.

The radar image for 0015 UTC on the 15^{th} shown in Figure 20 indicates the position of the front and some heavy rain in NE England. However, generally the rainband was quite fragmented and remained so. The largest radar fraction of an Extreme total was 14% (22mm) in Lowther Catchment and the highest forecast Mesoscale model rainfall accumulation fraction was 11%.

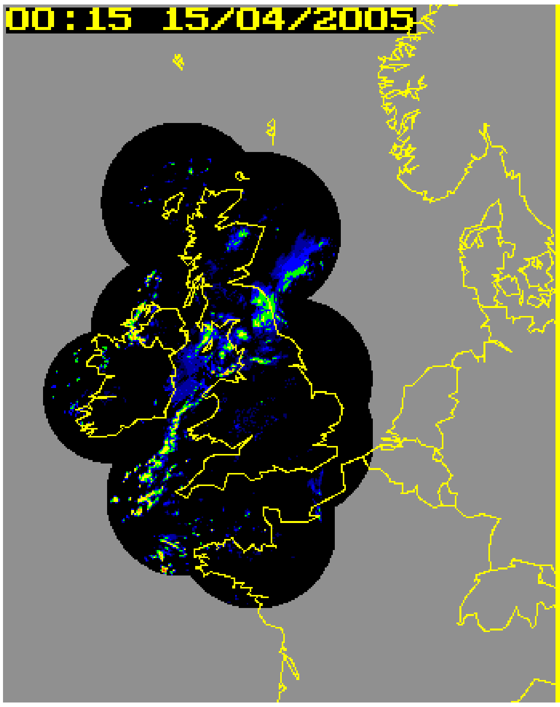


Figure 20. Radar rainfall rate for 0015 UTC 15/04/05.

3.7.4 DT 03/05/05

This case focuses on Thames Region and is an example of an over-prediction of Type A Extreme convective rainfall.

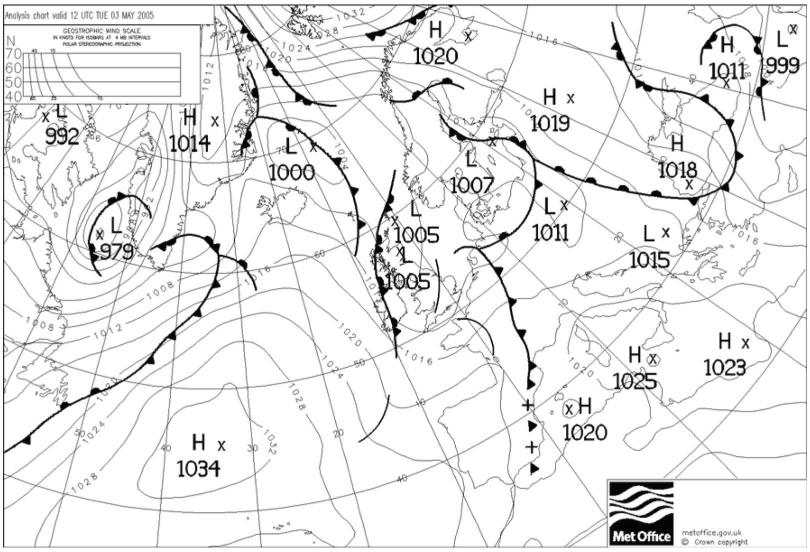


Figure 21. Synoptic chart showing mean sea level pressure and fronts for 1200 UTC 03/05/05.

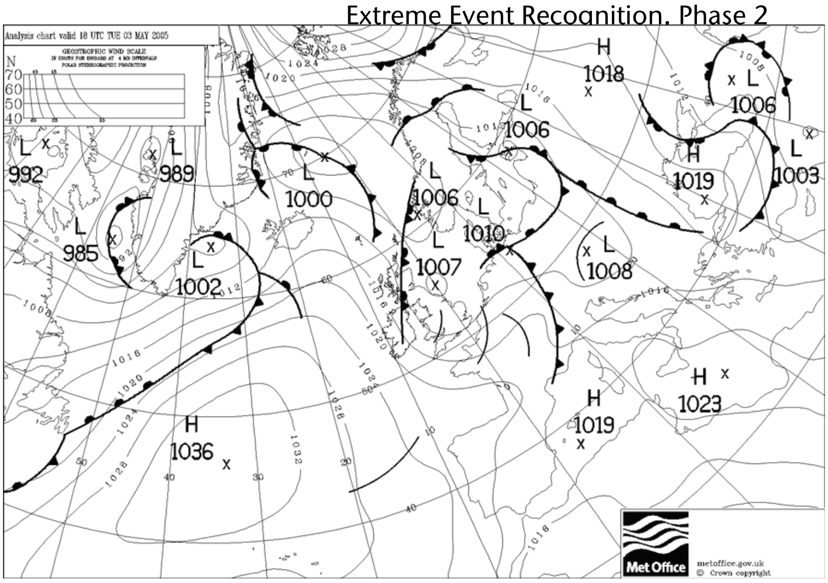


Figure 22. Synoptic chart showing mean sea level pressure and fronts for 1800 UTC 03/05/05.

The synoptic situation shown in Figures 21 and 22 was conducive to scattered thunderstorm generation with a slow-moving area of low pressure over the UK and troughs (short thick lines on chart) highlighting active areas of instability. The potential for strong convective development is shown in Figure 23 which shows the forecast probability of getting

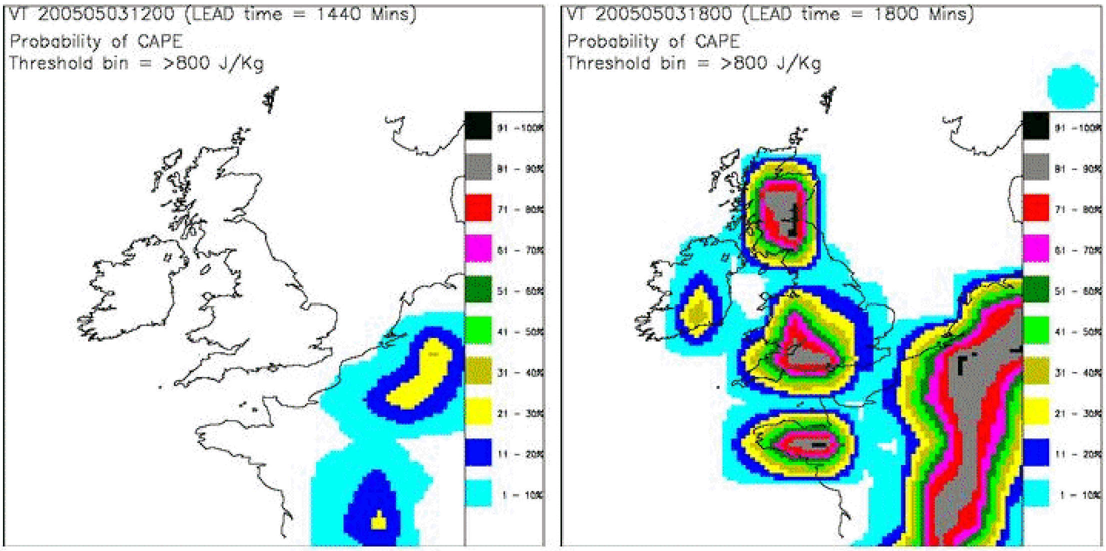


Figure 23. ECMWF ensemble forecast probability of getting CAPE with values greater than 800 J/Kg at 1200 UTC and 1800 UTC 03/05/05.

Very high values of CAPE (>800 J/Kg) from the ECMWF ensemble forecasts. At 1800 a high probability was forecast over SE Scotland and over the West Country. The MM forecast probability of "heavy rain" reflected the situation showing numerous clusters of high probability at 1200 but by 1800 had tended to focus activity over eastern Scotland and parts of southern Britain (Figure 24).

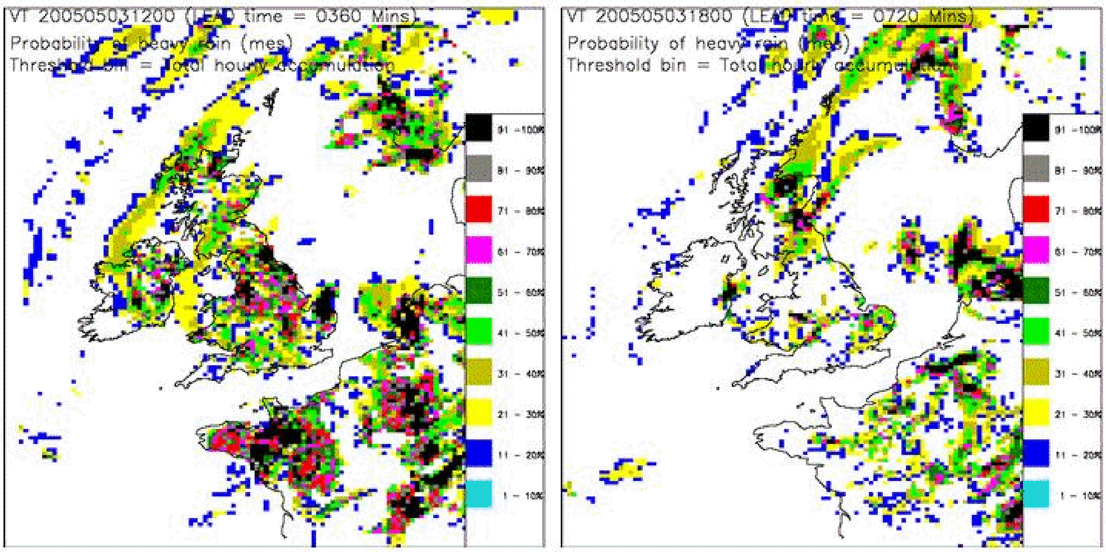


Figure 24. Mesoscale model forecast of the probability of "heavy rain" for 1200 and 1800 UTC 03/05/05.

Complementing the MM forecast the output from the CDP (Figure 25) showing the probability of getting heavy thunderstorms and multiple cell convection gave an indication of potentially severe activity in southern England, northern England and Scotland, but tending to diminish during the afternoon.

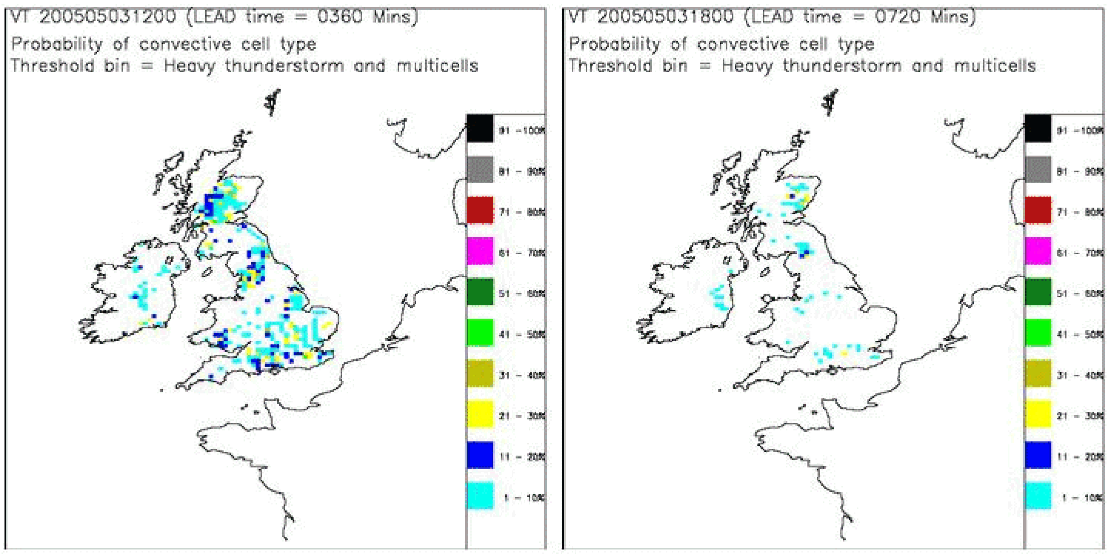


Figure 25. CDP forecast of the probability of heavy thunderstorms with multiple convective cells at 1200 and 1800 UTC 03/05/05.

There was very little probability of isolated convective cells with heavy thunderstorms from the CDP.

Putting all the information together the probability of getting Extreme rainfall due to convective activity at 1700 UTC is shown in Figure 26.

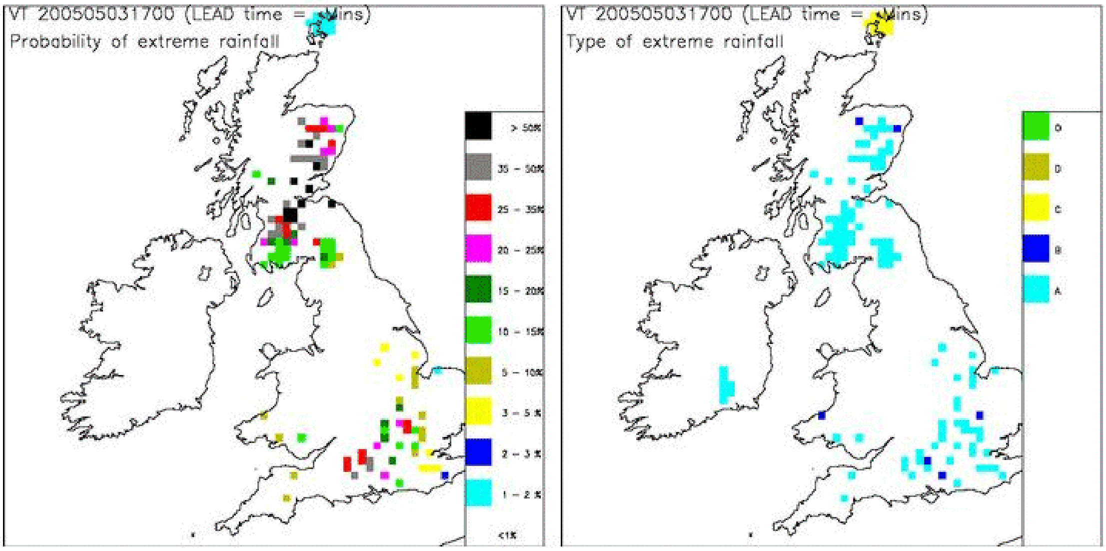


Figure 26. Forecast probability of Extreme rainfall and Type of rainfall at 1700 UTC 03/05/05.

Two clusters of relatively high probability are evident; one over central southern England in Thames, Southern and SW Regions and a larger cluster in SE Scotland. The radar rainfall at 1800 UTC is shown in Figure 27.

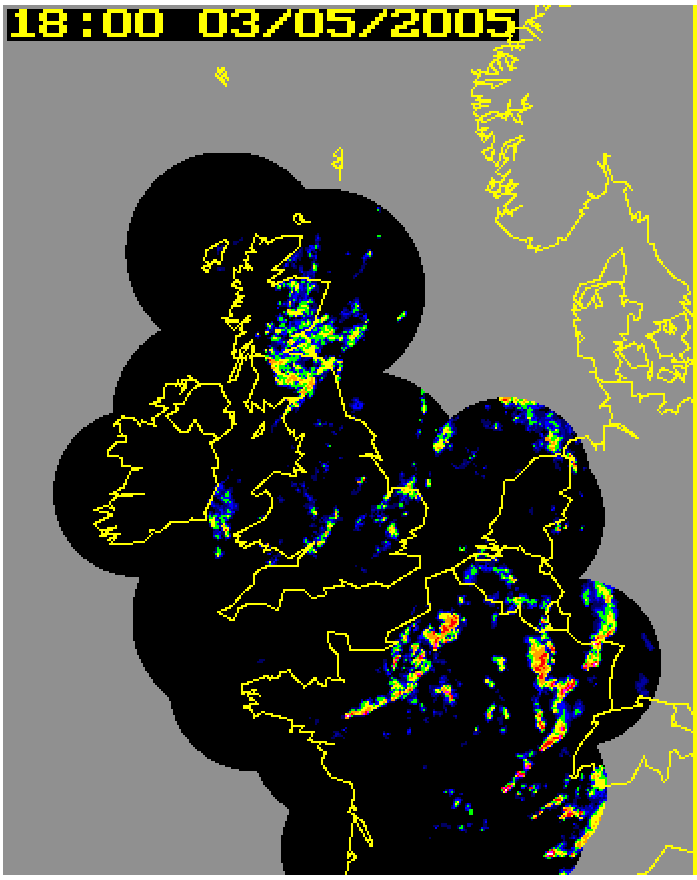


Figure 27. Radar rainfall rate for 1800 UTC 03/05/05.

Most activity was over SE Scotland with a few showers over East Anglia and a line of showers extending northeast from Bristol. None of these were thundery, however, there were some thunderstorms over northern England during the afternoon. In Thames Region the highest forecast probability of extreme rainfall in an Area was 30% and the highest observed radar rainfall fraction of an extreme fall was 11%. It is interesting to note that the Mesoscale model captured the line of showers extending north-eastwards from Bristol very well.

3.7.5 DT 21/05/05

This convective case is another Type A example. The synoptic charts for 1200 and 1800 UTC 21/05/05 are shown in Figures 28 and 29.

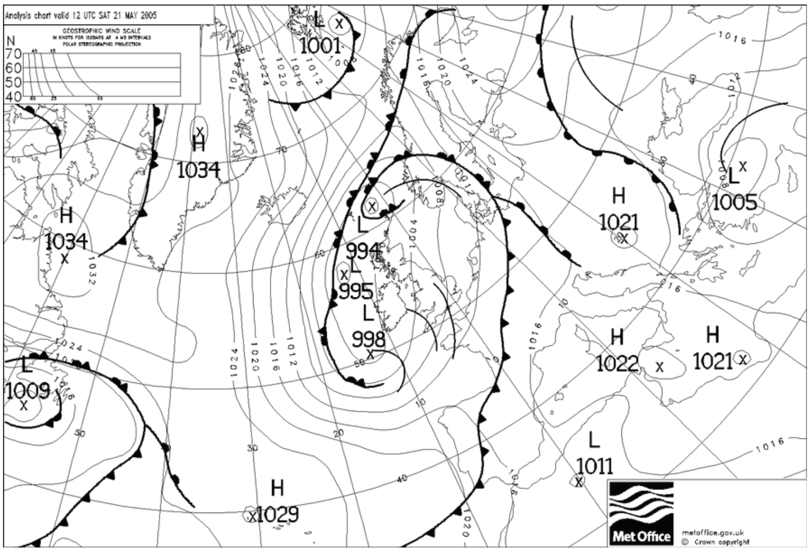


Figure 28. Synoptic chart showing mean sea level pressure and fronts for 1200 UTC 21/05/05.

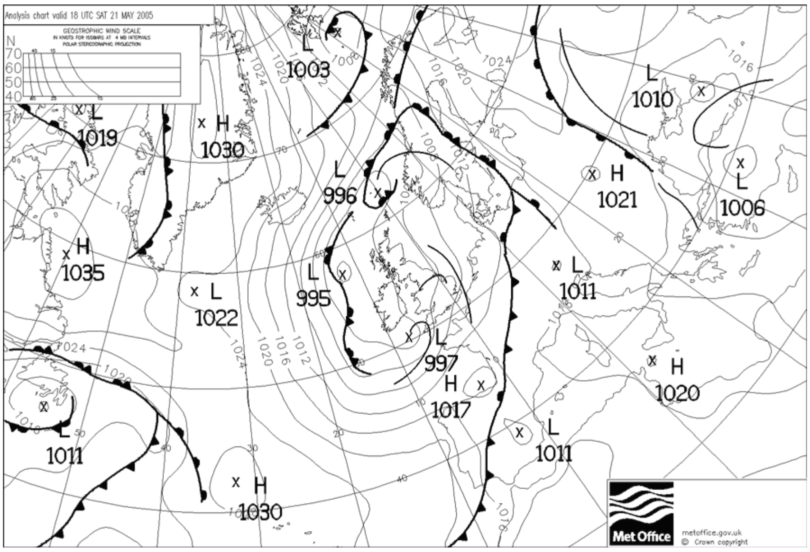


Figure 29. Synoptic chart showing mean sea level pressure and fronts for 1800 UTC 21/05/05.

Again we have a complex area of low pressure over the British Isles with troughs swinging around the centres indicating areas of deeper instability. The Mesoscale model forecast probabilities of “heavy rain” at 1200 and 1800 UTC (Figure 30) shows a large cluster of high probability at 1200 UTC over southern England and an organised band coming into SW England at 1800 UTC. This was most likely associated with the trough shown in the synoptic analysis for that time. So the model forecast was good synoptically.

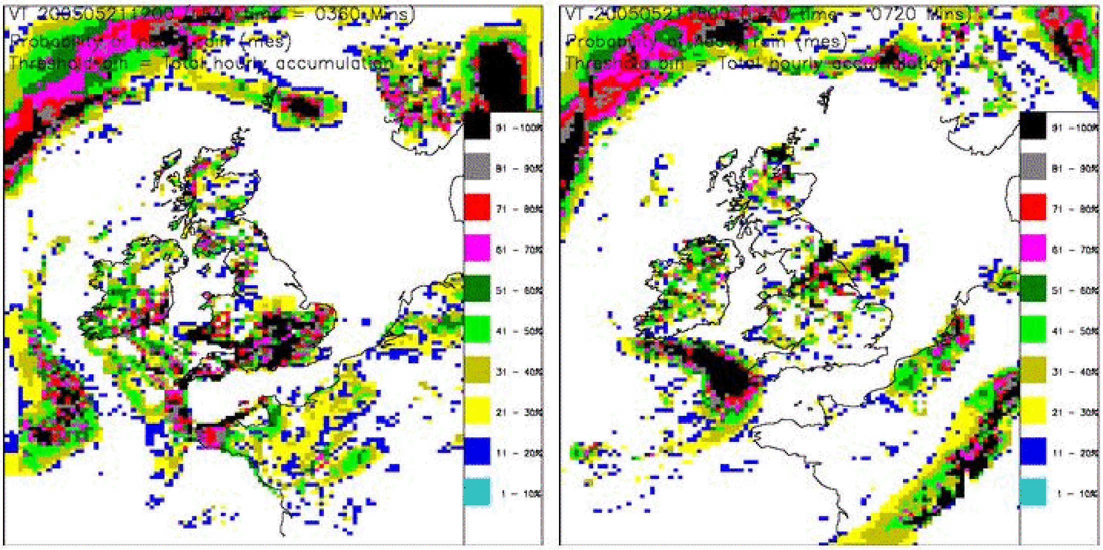


Figure 31. Mesoscale model forecast of the probability of “heavy rain” for 1200 and 1800 UTC 21/05/05.

The CAPE charts from the ECMWF ensembles shown in Figures 31 and 32 indicate relative high probabilities of CAPE in the range 100-800 J/Kg spreading eastwards during the afternoon with peak values > 800 J/Kg expected over eastern parts of SW England and SE Wales by 1800 UTC (Figure 32).

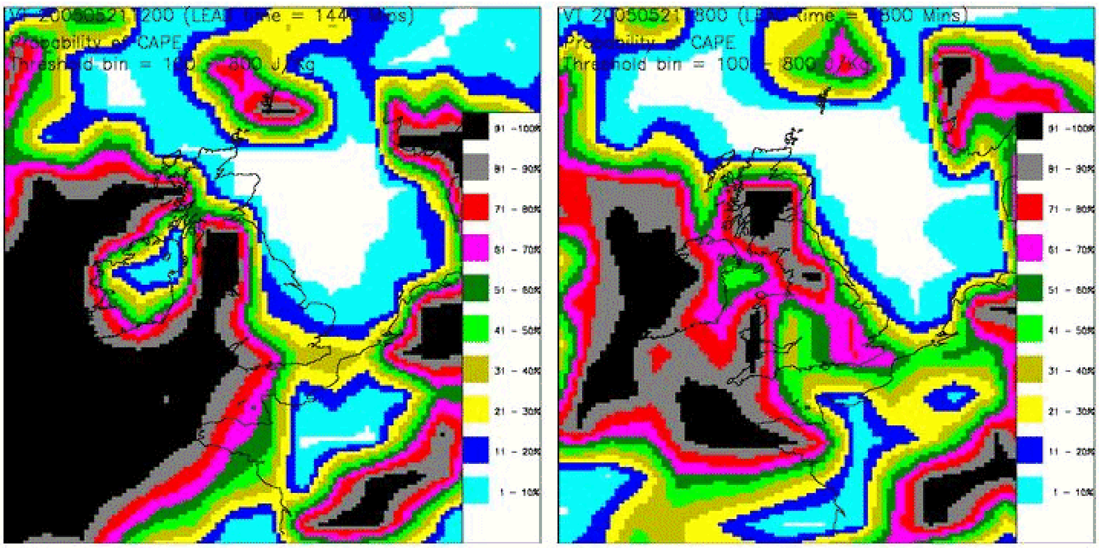


Figure 32. ECMWF ensemble forecast probability of getting CAPE with values in the range 100 - 800 J/Kg at 1200 UTC and 1800 UTC 21/05/05.

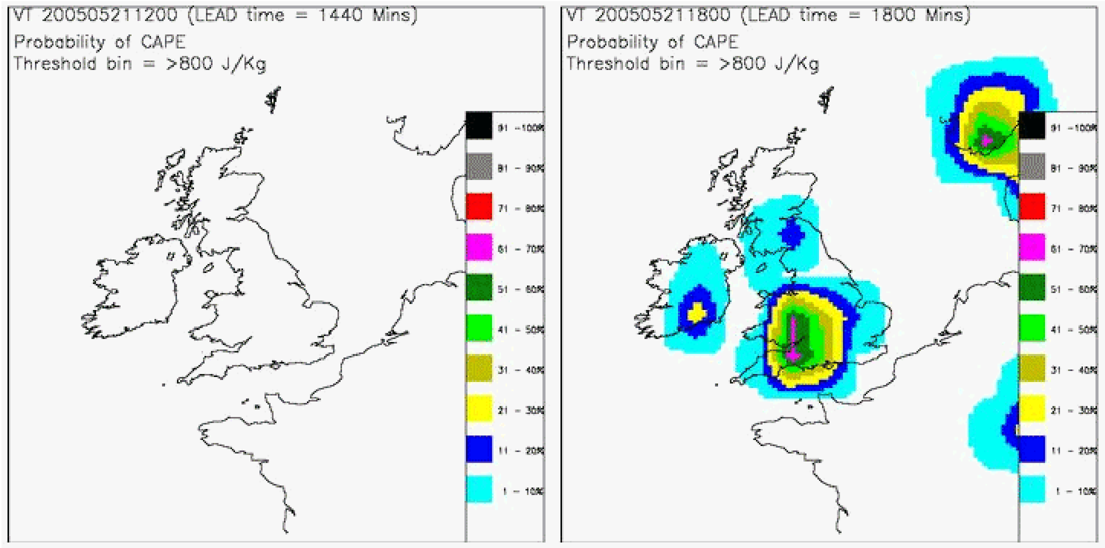


Figure 32. ECMWF ensemble forecast probability of getting CAPE with values greater than 800 J/Kg at 1200 UTC and 1800 UTC 21/05/05.

The CDP outputs shown in Figure 33 indicate a 20-40% probability of heavy thunderstorms with multiple cell convection at 1200 UTC over the Midlands and SE Wales decreasing during the afternoon.

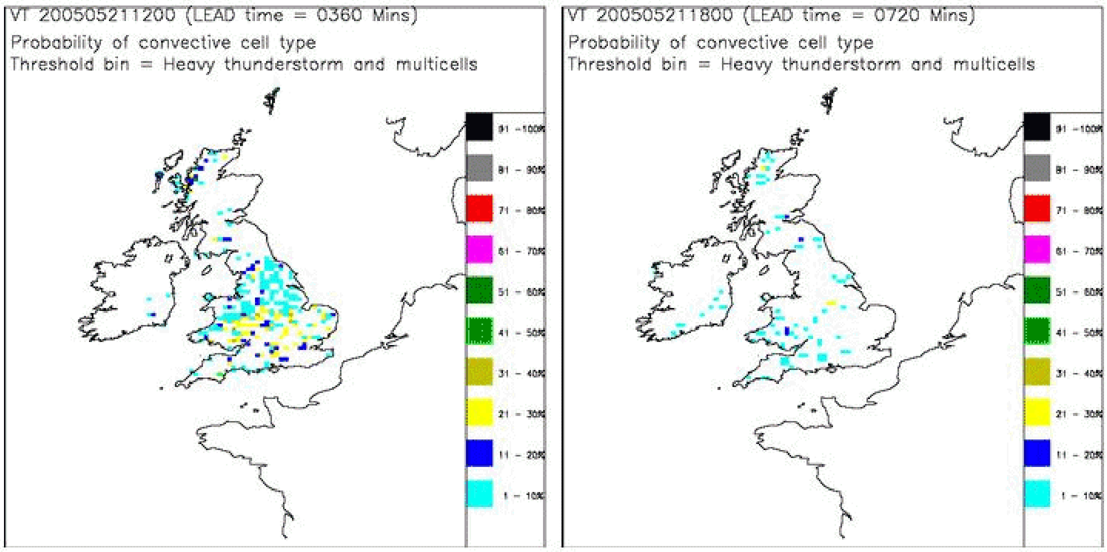


Figure 33. CDP forecast of the probability of heavy thunderstorms with multiple convective cells at 1200 and 1800 UTC 21/05/05.

The locations of thunderstorms during the afternoon from the Met Office ATD thunderstorm detection system [7] are shown in Figure 34.

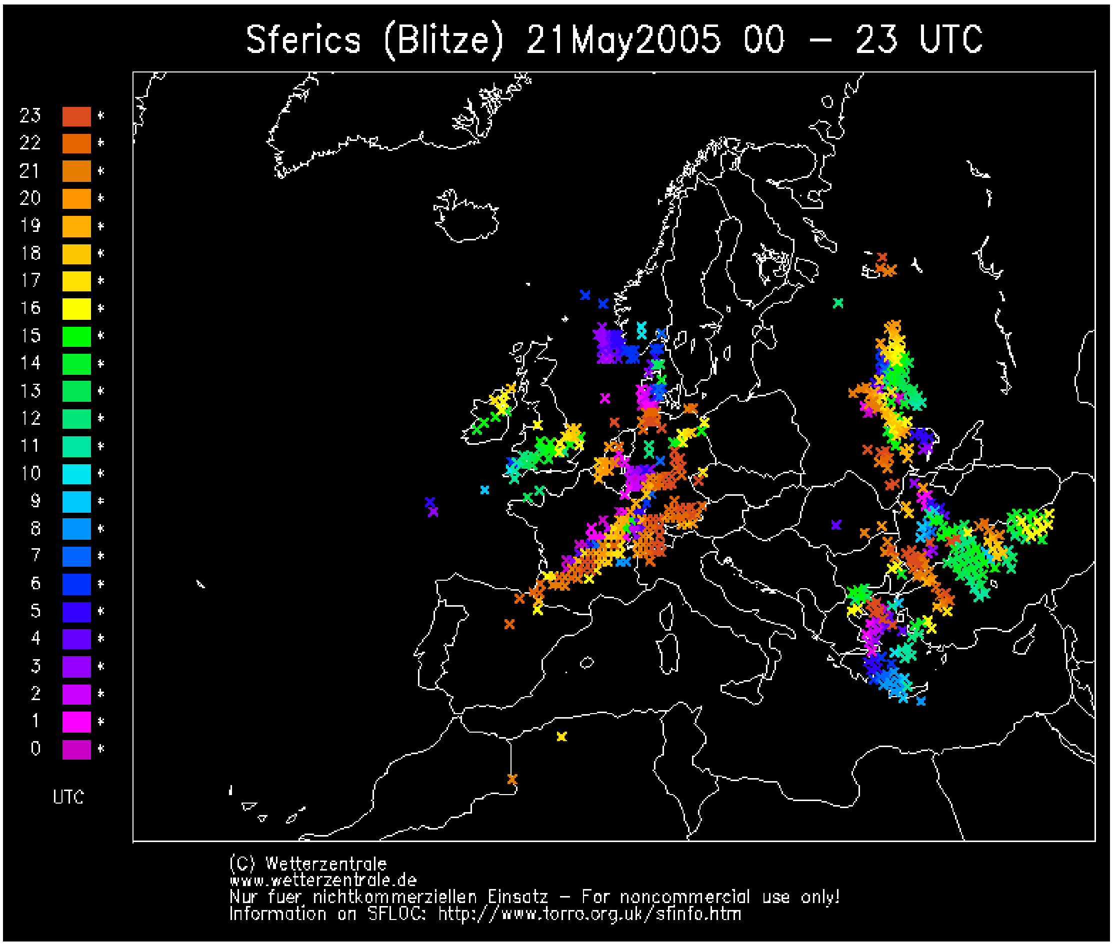


Figure 34. Map showing temporal (colour coded) and geographical (marked with an 'X') distribution of thunderstorms on 21/05/05 from the Met Office ATD thunderstorm detection system.
(From http://www.wetterzentrale.de/topkarten/tkbeoblar.htm)

Most of the thunderstorms on the 21st were in a line from SW England to East Anglia. The storms were heavy and triggered in the morning in SW England, reaching the south Midlands by 1400 and then into East Anglia by late afternoon. The radar rainfall images during the afternoon are shown in Figure 35.

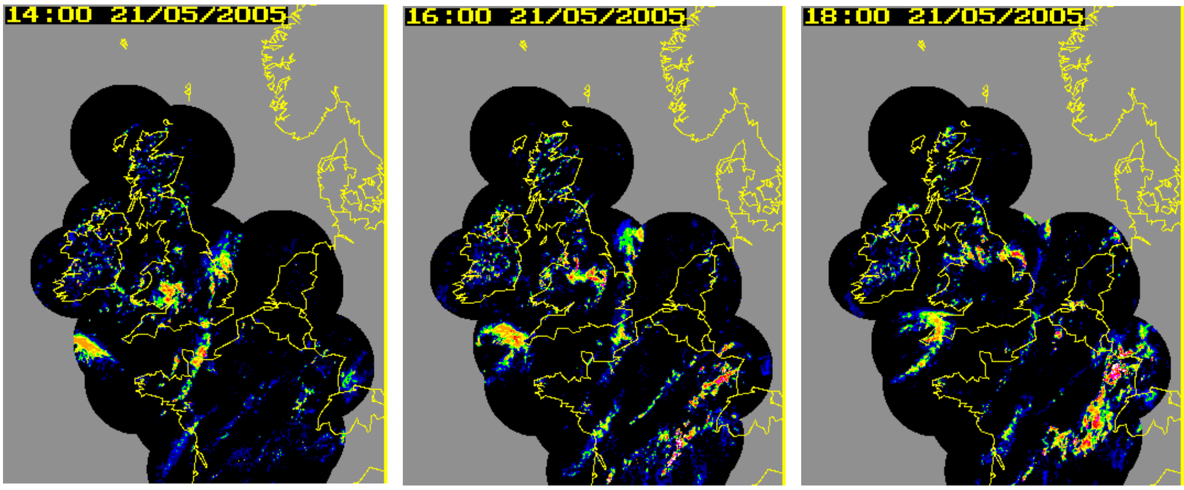


Figure 35. Radar rainfall images for 1400, 1600 and 1800 UTC 21/05/05.

The radar rainfall maps clearly show the areas of thunderstorms and heavy rain over SE Wales at 1400 and by 1600 this had moved northeast into the north Midlands and then further northeast by 1800. During the afternoon a curl of heavy rain was moving into SW England associated with the trough evident in the Mesoscale model output and on the synoptic chart at 1800 UTC.

The probability of Extreme rainfall for 1400 UTC is shown in Figure 36.

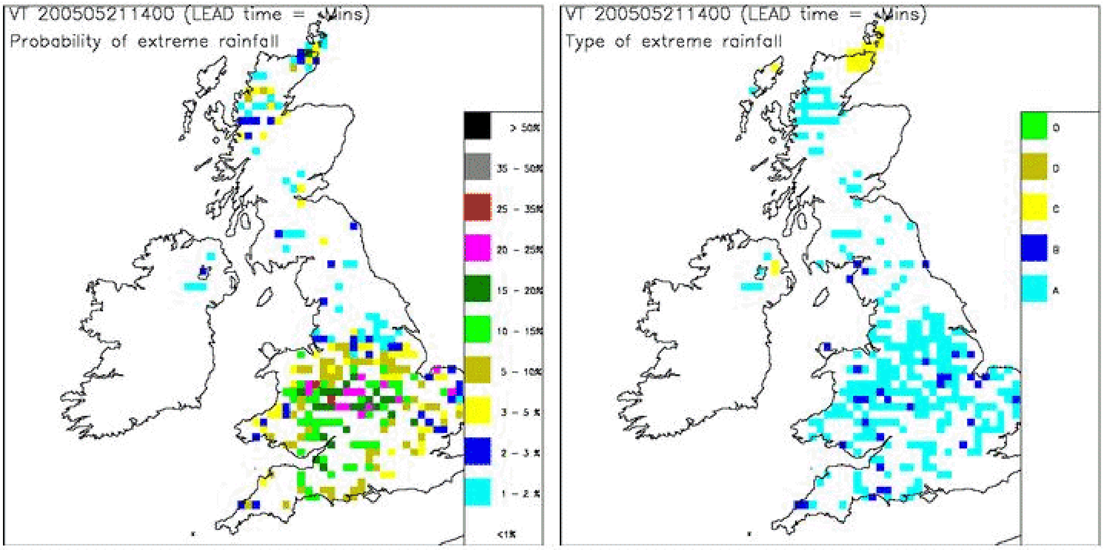


Figure 36. Forecast probability of Extreme rainfall and Type of rainfall at 1400 UTC 21/05/05.

This forecast was quite good with a cluster of probabilities in the range 15-25% in the Midlands with two pixels indicating 25-35% further east. The highest forecast probability of Extreme rainfall in SW Region during the afternoon was 29% and the highest observed fraction of an extreme fall was 41%. The Mesoscale model gave a maximum fraction of 7%. So the Trial forecast gave an improved indication of the likelihood of severe conditions. In Thames Region the highest forecast probability of Extreme rainfall was 41% with a maximum observed fraction of 19%. The maximum fraction from the Mesoscale model was 6%.

3.7.6 DT 28/06/05

This is another example of frontal rainfall of Type D which was assessed as a moderately good (in part) example of the Phase 1 conceptual model. The synoptic analyses for this case are shown in Figures 37, 38 and 39. These charts show a complex and slow-moving area of low pressure to the south of Ireland with a frontal system moving slowly north over England. At 0000 UTC on the 29th a new low formed over Kent.

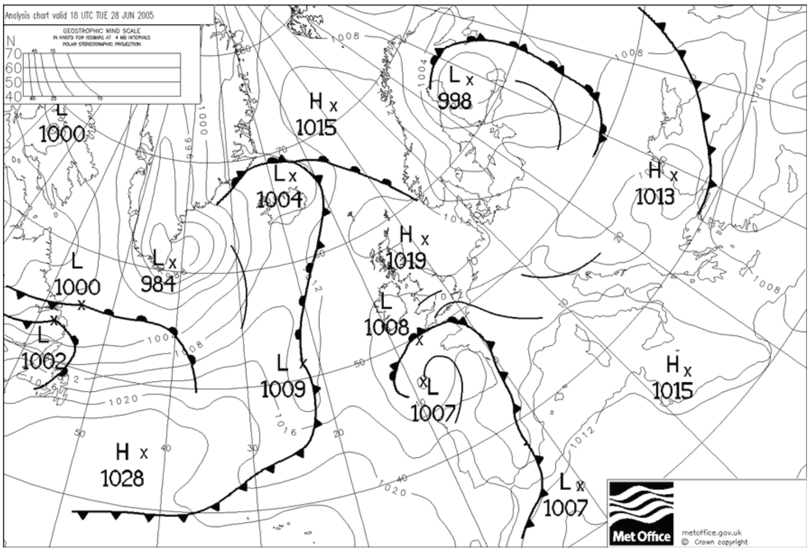


Figure 37. Synoptic chart showing mean sea level pressure and fronts for 1800 UTC 28/06/05.

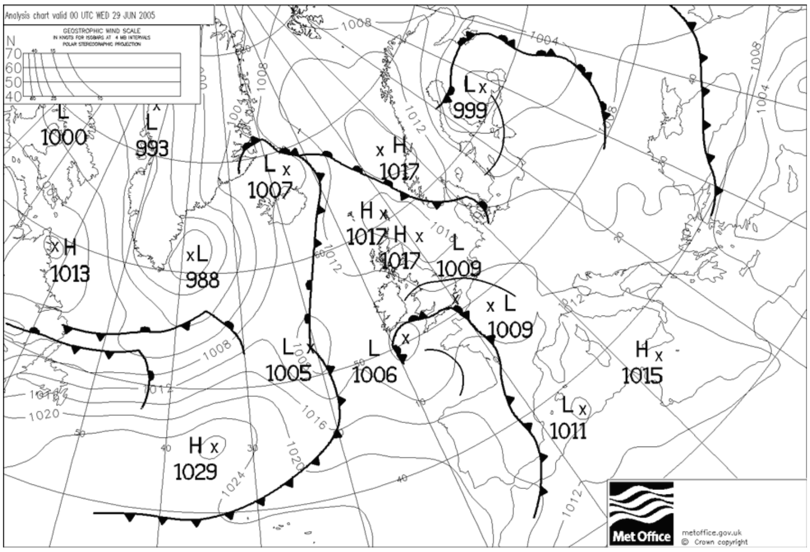


Figure 38. Synoptic chart showing mean sea level pressure and fronts for 0000 UTC 29/06/05.

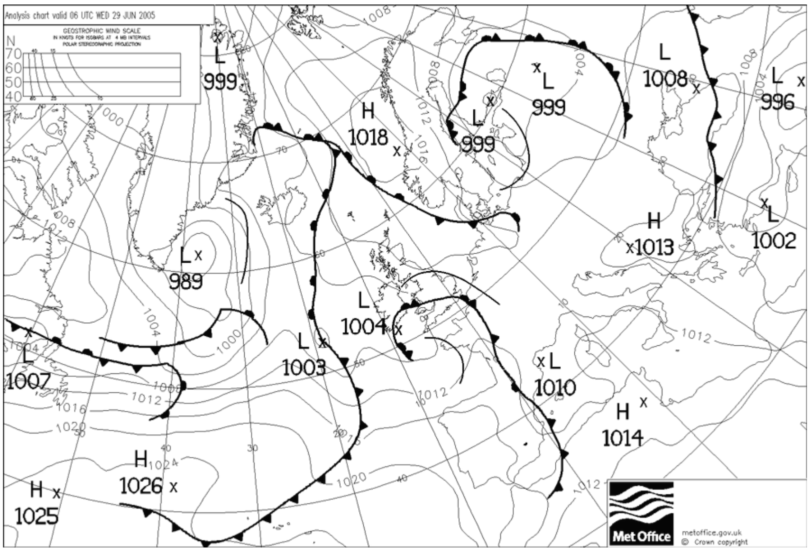


Figure 39. Synoptic chart showing mean sea level pressure and fronts for 0600 UTC 29/06/05.

The corresponding forecasts of the probability of “heavy rain” from the Mesoscale model are shown in Figures 40 and 41. These clearly show high probabilities of “heavy rain” moving north and a cluster of high probability moving northeast over Thames Region.

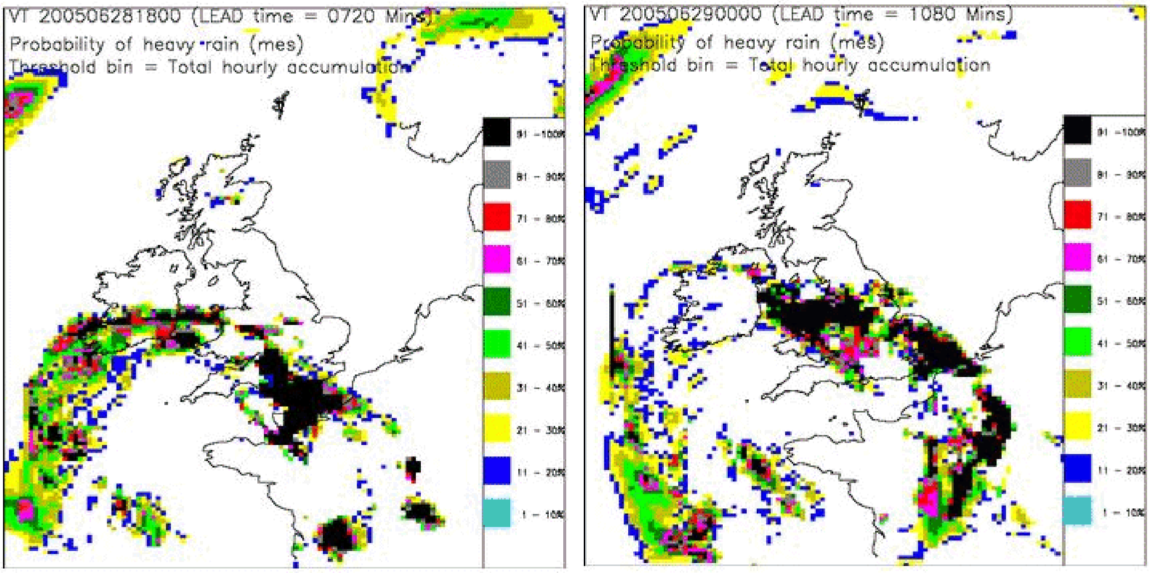


Figure 40. Mesoscale model forecast of the probability of “heavy rain” for 1800 UTC 28/06/05 and 0000 UTC 29/06/05.

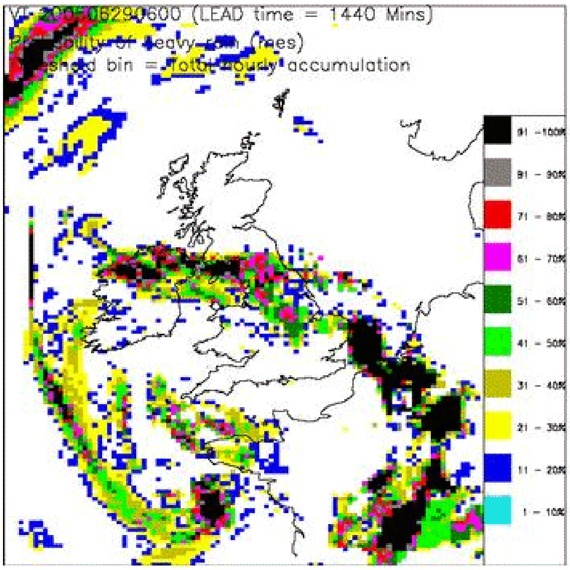


Figure 41. Mesoscale model forecast of the probability of “heavy rain” for 0600 UTC 29/06/05.

The radar rainfall images (Figure 42) show that rainfall rates were high (16-32 mm/h in many places) during the evening of the 28th. The rain also moved quite quickly north-eastwards over England.

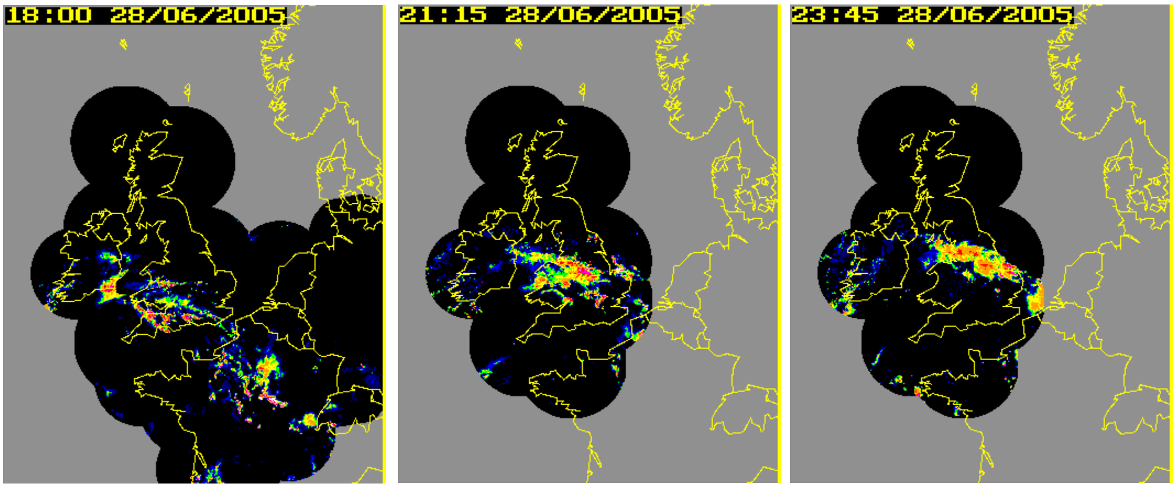


Figure 42. Radar rainfall images for 1800, 2115 and 2345 UTC 21/05/05.

The forecast probability of Extreme rainfall with Type at 2300 is shown in Figure 43. The probabilities are arranged in a line associated with the front moving northeast and tied to a band of rain in the MM to the southwest of the main band. Unfortunately this had dissipated somewhat earlier in the evening. The Extreme rainfall probabilities diminished with increasing distance from the forecast position of the centre of the slow moving depression whose probabilities of occurrence for one speed category are shown in Figure 44.

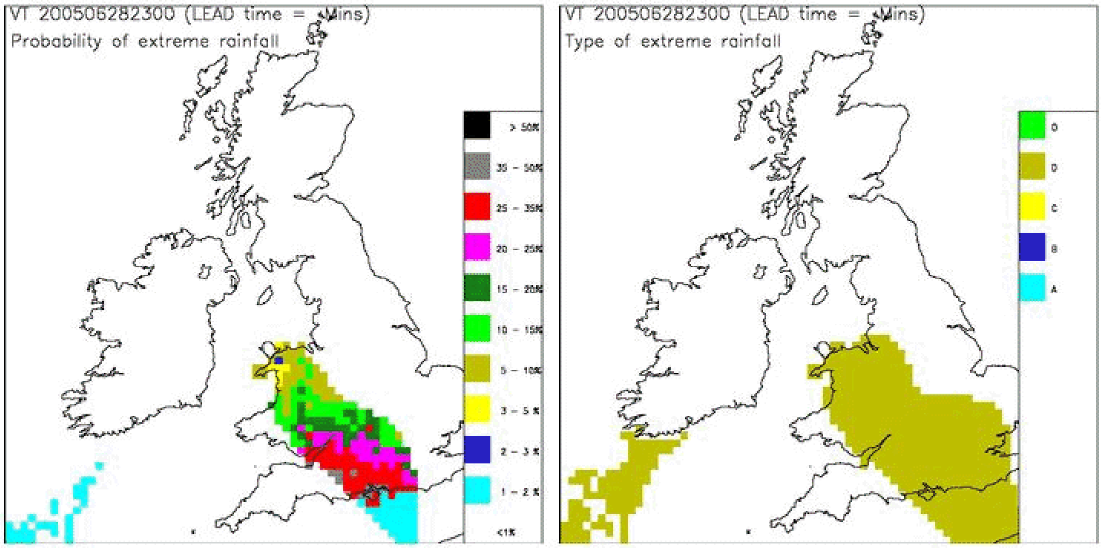


Figure 43. Forecast probability of Extreme rainfall and Type of rainfall at 2300 UTC 28/06/05.

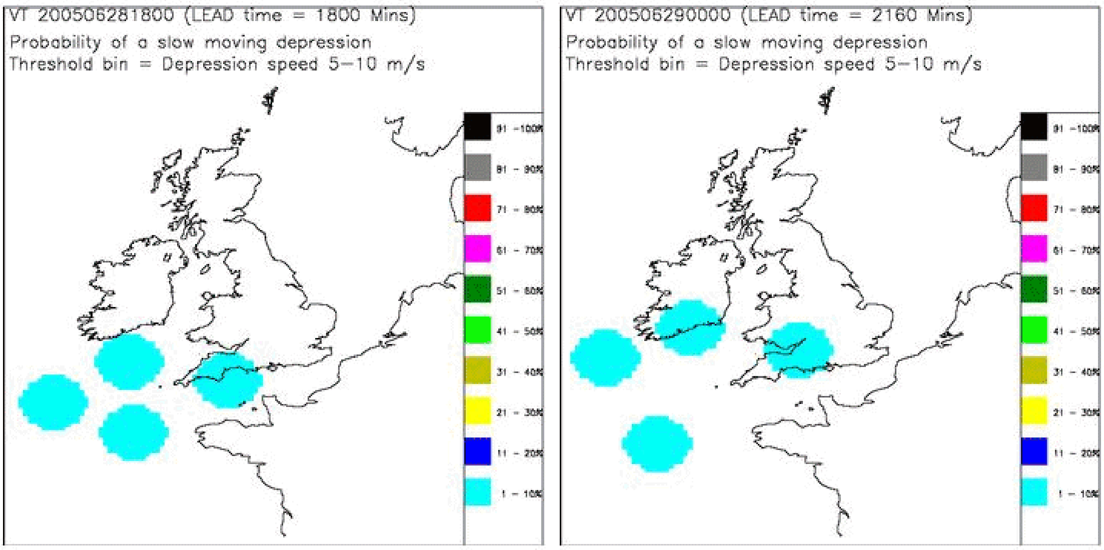


Figure 44. Probability of getting a slow moving depression at a speed of 5-10 m/s at 1800 UTC 28/06/05 and 0000 UTC 29/06/05

In SW Region the highest forecast probability of extreme rainfall was 50% and the highest fraction of an extreme fall measured by radar in the Region was 36%. The highest fraction forecast by the MM was 12%.

3.7.7 DT 27/07/05

The final case example from the Trial is another frontal one (Type D) classed as moderate in its fit to the Phase 1 conceptual model. In this case the MM directly predicted an extreme fall which was overdone and incorrect. The synoptic charts for this case are shown in Figures 45, 46 and 47.

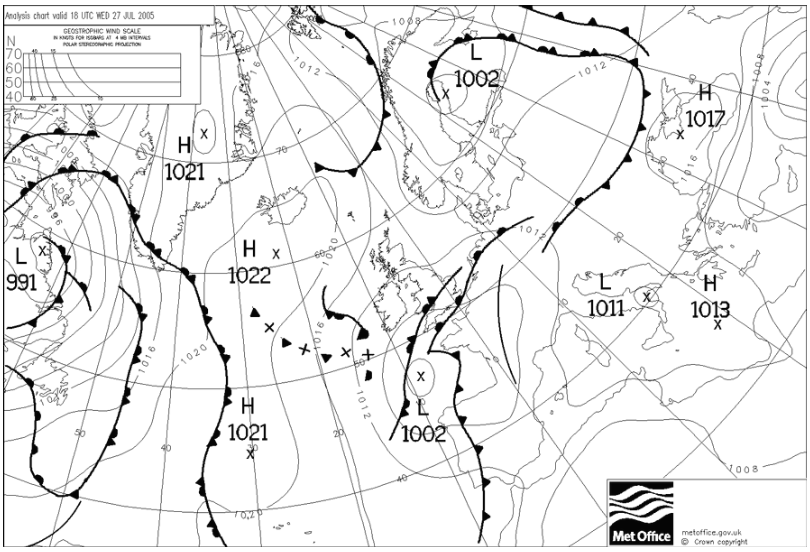


Figure 45. Synoptic chart showing mean sea level pressure and fronts for 1800 UTC 27/07/05.

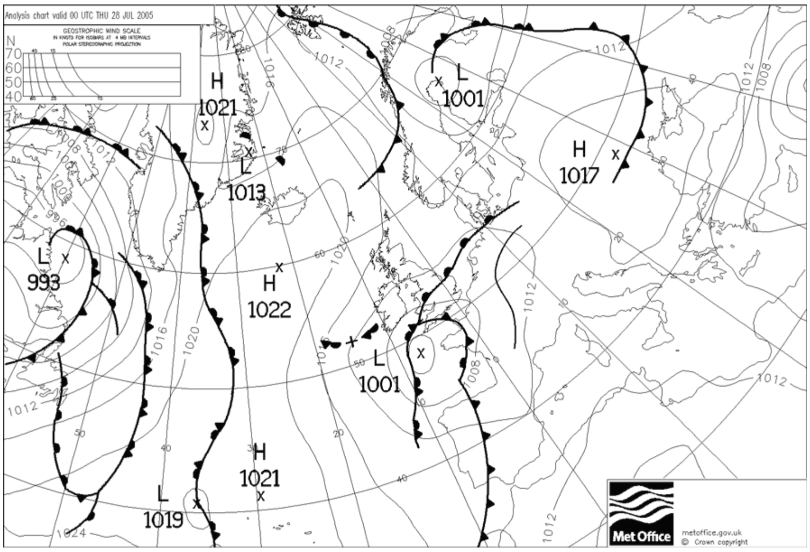


Figure 46. Synoptic chart showing mean sea level pressure and fronts for 0000 UTC 28/07/05.

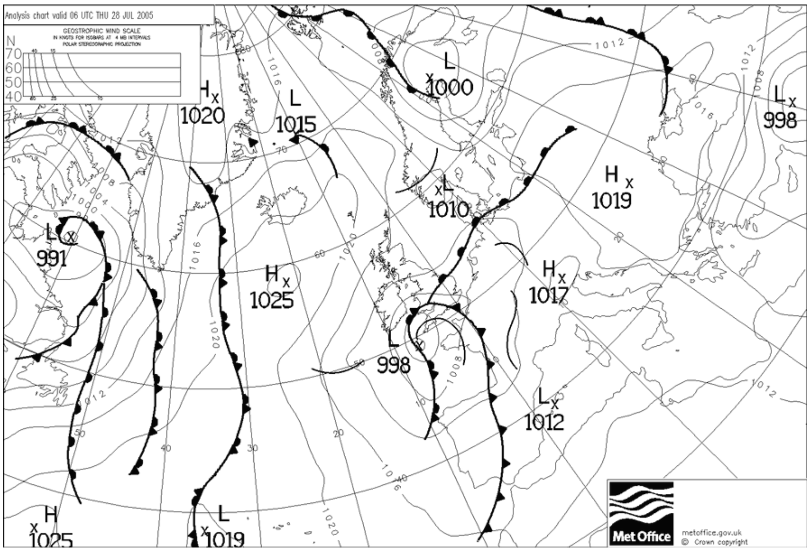


Figure 47. Synoptic chart showing mean sea level pressure and fronts for 0600 UTC 27/07/05.

The charts show a depression moving north to the west of SW England with associated frontal systems crossing the SW Region during the period. The accumulated 24 hour precipitation total from the Mesoscale model is shown in Figure 48.

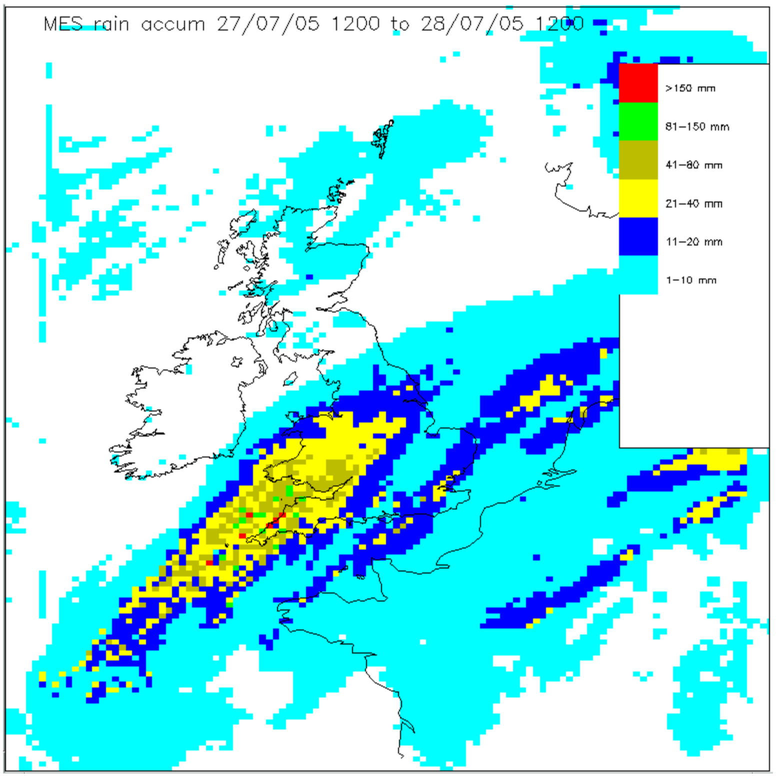


Figure 48. Accumulated forecast precipitation total from the Mesoscale model for the period 1200 UTC 27/07/05 to 1200 UTC 28/07/05.

This chart shows that the model was predicting an Extreme rainfall (>150mm) on the north coast of Cornwall and over the sea to the west in the 24 hour period. There was certainly heavy rainfall during the time as indicated in the radar rainfall pictures shown in Figure 49.

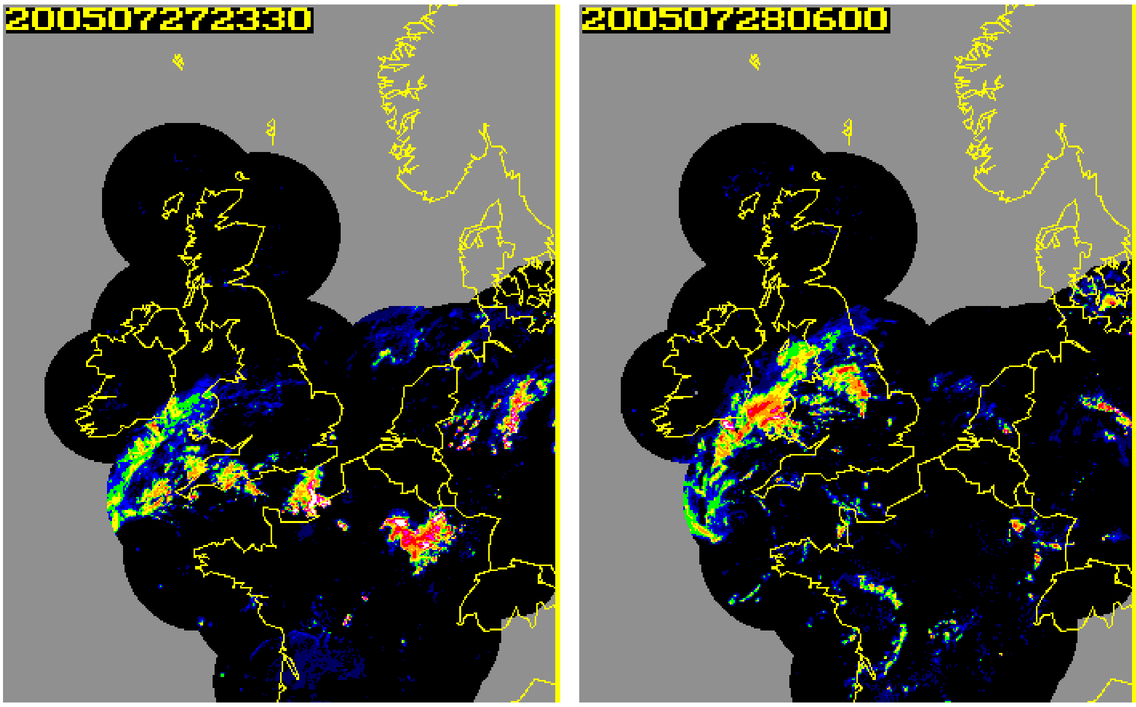


Figure 49. Radar rainfall images for 2330 UTC 27/07/05 and 0600 UTC 28/07/05.

During the evening of the 27th clusters of heavy rainfall moved westwards over SW Region but by 0600 UTC on 28th most of the heavy rainfall was out over the Irish Sea. The highest 24 hour radar rainfall total was 75mm in the Tavy, Plym and Dart Catchments (49% of an Extreme 24 hour fall). There were no reports of an Extreme fall from the gauge network. The highest forecast probability of an extreme fall in the Trial outputs was 73% in the Lower and Upper rivers and Brue Catchments. The largest model rainfall accumulation was 226 mm in Camel Catchment (149% of an Extreme fall).

3.7.8 DT 16/08/04 (Boscastle)

During the Trial the Boscastle flooding case was run to see the impact and the results are presented below. The synoptic chart for 1200 UTC 16/08/04 is shown in Figure 50. Once again troughs are evident showing regions of greater instability. During the afternoon, heavy rainfall (184 mm in 5 hours) brought very serious flash flooding to Boscastle on the north Cornish coast [8].

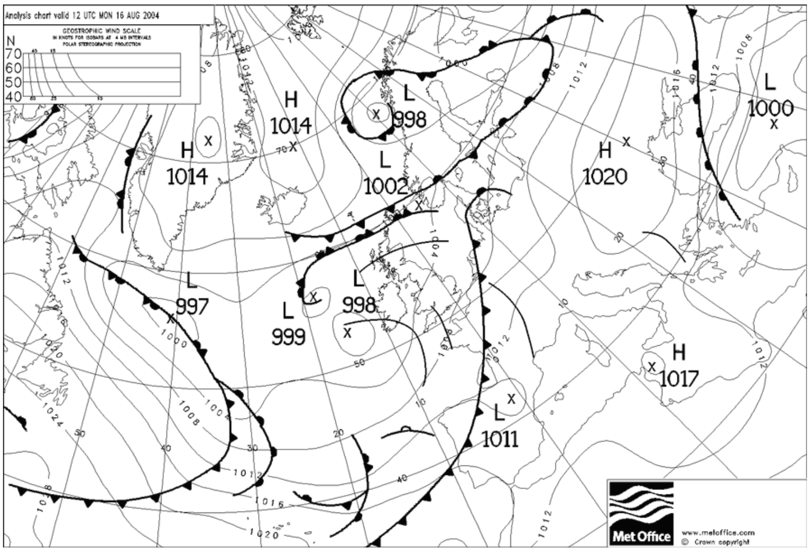


Figure 50. Synoptic chart showing mean sea level pressure and fronts for 1200 UTC 16/08/04.

The Extreme rainfall probability forecasts for 1400 and 1500 UTC are shown in Figure 51.

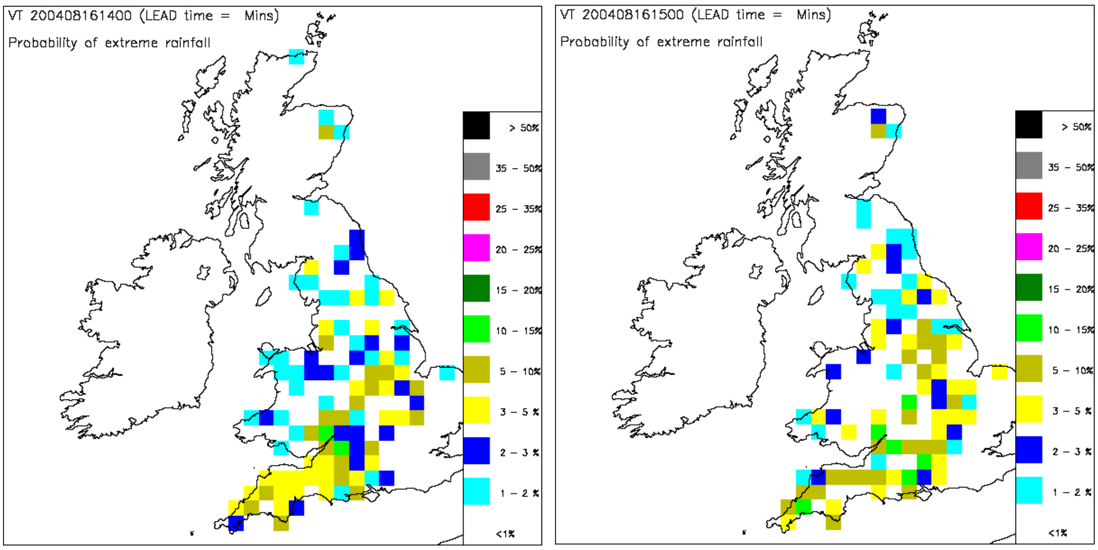


Figure 51. Forecast probability of Extreme rainfall at 1400 UTC 16/08/04 and 1500 UTC 16/08/04.

The 1400 UTC forecast shows a line of 5-10% probability down the spine of Cornwall and at 1500 UTC there is a 10-15% probability covering part of the Camel, Mid-Tamar, Par, Fowey, Pol and Lynher Catchments. This was the highest probability in Devon and Cornwall at the time, albeit low. Unfortunately on a National scale Boscastle does not stand out with other instances of 10-15% probability of Extreme rainfall in other parts of England. The MM had high probabilities of “heavy rainfall” over Devon and Cornwall (Figure 52). This was associated with a high forecast probability of CAPE in the range 100-800 J/kg (Figure 53) which compared well with an observed value at 1200 UTC of circa 200 J/Kg at Camborne in Cornwall. The forecast from the CDP (not shown) indicated a chance of heavy thunderstorms with multiple convective cells in a line over North Cornwall, however, similar probabilities were predicted elsewhere too.

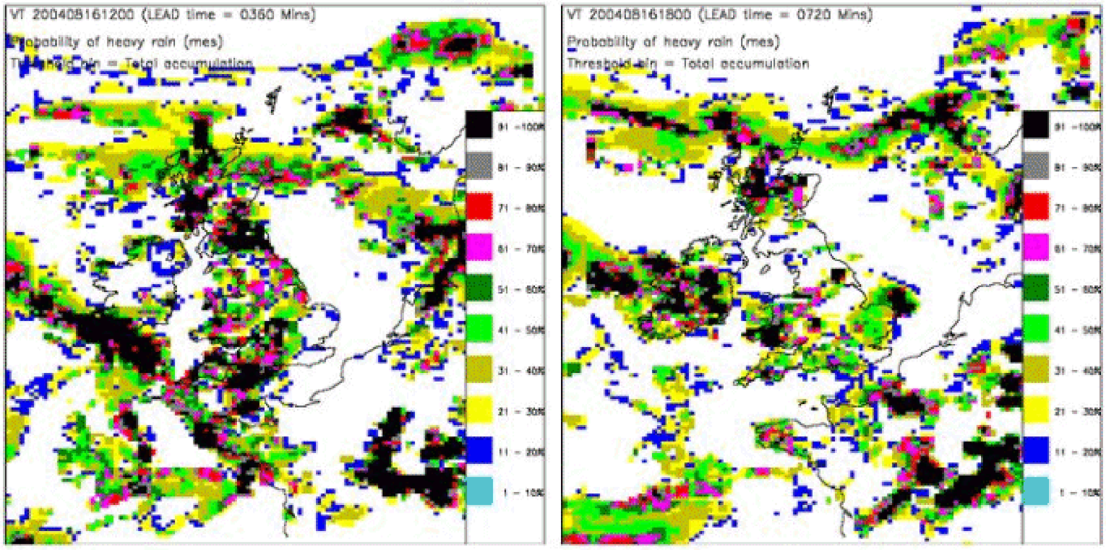


Figure 52. Mesoscale model forecast of the probability of "heavy rain" for 1200 and 1800 UTC 16/08/04.

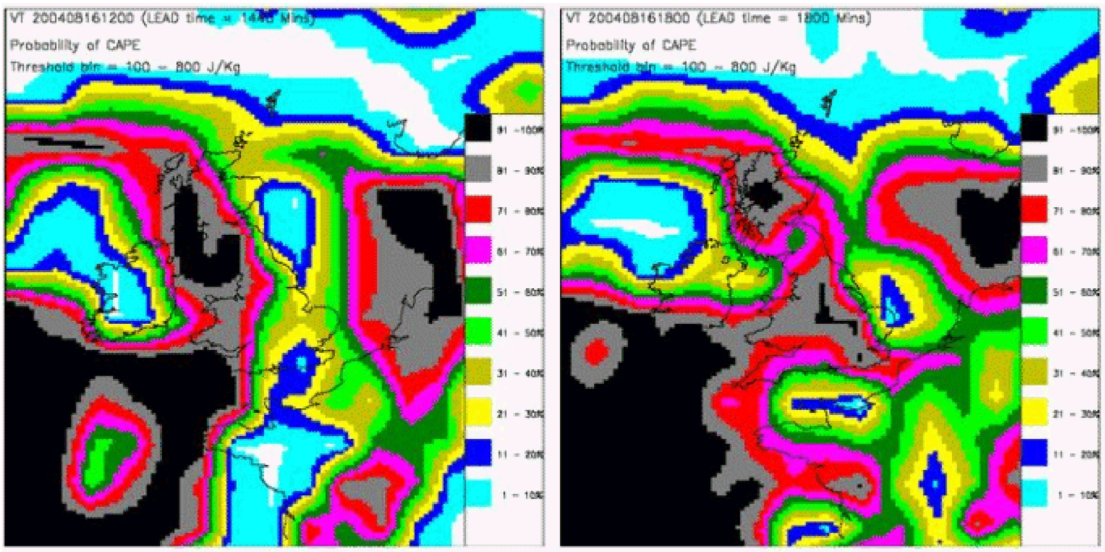


Figure 53. ECMWF ensemble forecast probability of getting CAPE with values in the range 100-800 J/Kg at 1200 UTC and 1800 UTC 16/08/04.

A reasonable indication was given of the likelihood of an Extreme rainfall event in North Cornwall during the afternoon of 16/08/04, unfortunately similar indications were also given for other parts of the UK and there was nothing in the Trial outputs to say that Boscastle or even Cornwall were more likely than anywhere else to see Extreme rainfall during the afternoon of 16/08/04.

3.8 User Feedback

Comments from the EA users were collated by Tim Wood and Adrian Wynn. A summary of their conclusions follows.

For operational use any forecast needs to provide information which is both targeted and accurate. On receipt of a flood warning the two immediate questions are "when?" and "how deep?" If confident answers can be given to these, then appropriate action can and probably will be taken.

The Trial endeavoured to achieve a targeted area by the use of the EA's Flood Watch areas. These are based on catchment groups and some are comparatively small. Accuracy was trialled using a measure of probability.

The Trial results were not sent to the operational forecasting and monitoring duty officers but instead to nominated specialists in the regional flood forecasting teams. An attempt was made to use the results to prompt increased monitoring and model runs. An example of the output is shown in Annex A.

In the event the view was that unfortunately the product was not yet fit for use operationally. This was mainly because it was perceived that the probabilities were over-forecast, given that no extreme events occurred. For example, during the period 01/11/04 to 23/02/05 in SW region 30 forecasts were received within the 1-9% probability band with no extreme events recorded.

The presentation and concept of the probabilistic information was not intuitive to a non expert user. A probability of 10% within the Trial is significant whereas users would normally look for a probability of 40 to 50 % before taking action.

The following user suggestions are made:

(i) Try taking the figures from the extreme events that we know about and presenting the probability from the forecast relative to those figures.

(ii) Reduce the forecasts to a simple yes/ no switch which could appear as a check box in the daily weather forecast. The extreme event forecast would then be received and evaluated by the Met Office forecaster and expert knowledge applied.

(iii) Another alternative would be to hold back the extreme event forecast until a certain threshold of confidence was crossed eg 40%. Then issue the forecast as a warning after a Met Office forecaster has quality checked the output.

(iv) Given the limited skill, it would be more realistic and achievable at the present time to aim for forecasts at an Area/ County scale. We can work towards refinement and a finer mesh at a later stage.

(v) There is no doubt that the work should be continued. EA users are supportive of using a simple tool to enable increased awareness and the need to enhance forecasting and monitoring.

(vi) The technical recommendations at Section 5 of the report are supported and should be taken forward.

4. Conclusions

- The Trial has been successful despite only one Extreme rainfall event occurring during the Trial (Carlisle flooding, 07/01/05). Met Office forecasters thought that trying to forecast for Catchments was very ambitious and that the Area (County) scale would have been more appropriate. The Met Office Manchester forecasters were disappointed with the Carlisle case saying that the predicted probabilities could not distinguish that event from others forecast during the Trial with similar probabilities. However, they praised the useful guidance from the MM on that day, which alerted them to the possibility of heavy rainfall (but not Extreme rainfall).

- The Extreme rainfall forecast for Carlisle was a near-miss. The case clearly indicated the potential usefulness of orographic predictors provided that their location was accurate and that actual rainfall was entirely orographic. If the orographic enhancement predictors had been over the Lake District then the MM forecast of very heavy rainfall would have been supplemented by a high probability that an Extreme fall could occur.

- The objective verification gave a weak signal that the Trial performed best in FO cases giving a larger spread of forecast probabilities. However, the FO case studies (3.7.2, 3.7.3, 3.7.6, 3.7.7) showed that the predictors led to an over-prediction of the probability of extreme rainfall based on actual rainfall observed in the Trial Regions and radar imagery. This was a common feature in the FO cases. (*Note that Carlisle was not an FO case*). However, all the FO cases subjectively classified as a poor fit to the Phase 1 conceptual model (Tables 11 and 12) correctly gave low (<10%) forecast probabilities of Extreme rainfall. This indicated some skill in the ability of the predictors to spot a potential severe event.

- Mesoscale model rainfall accumulation forecasts were demonstrably very good at the Catchment scale when maximum model rainfall accumulations in a Catchment were verified against maximum radar rainfall accumulations. However, in the FO cases there was a clear signal for significant over-prediction of amounts when durations exceeded 12 hours, for example 27/07/05 case (section 3.7.7).

- The objective and subjective assessments of Trial performance in convective cases showed that Extreme rainfall probabilities (albeit low) were predicted too frequently and over too large an area. For example, in the Boscastle case, Extreme rainfall was predicted at 10-15% probability in many parts of southern England. The inclusion of a crude stationarity predictor from the CDP was not successful and it is clear that the Trial probabilities were picking out areas of potentially heavy convective rainfall as opposed to Extreme rainfall. The predictors used in the Trial were unable to adequately distinguish areas of potentially Extreme convective rainfall from the rest.

- The objective verifications lead to the tentative conclusion that using the techniques used in the Trial forecast probabilities above 10% would at least indicate a potential for some very heavy rainfall. However, it is thought that that threshold would likely change with a different set of predictors or methodology.

- The Bayesian probability system required some ingenuity in setting prior and inverse probabilities and the corruption of the file containing climatological probabilities of predictors during the Trial led to absurd probabilities being output. This indicated sensitivity of the overall system to the priors, inverse and climatological probabilities. There is also still an issue with independence of predictors and it is not clear that the procedure adopted in the Trial was the best way to combine information from combinations of predictors.

- The derivation of predictors and their probability of exceeding important threshold values were satisfactory but could be improved. The method chosen in the Trial made best use of available operational outputs. However, several assumptions were made, for example, in determining airmass source dew point for the orographic predictors. The large scale predictors also suffered from the relatively coarse resolution of the ECMWF global model ensemble data.

5. Recommendations

Given the potential consequences of the events under study, it is important that this work should continue. Taking account of the objective and subjective results of the trial, and of the user feedback, we recommend that the following further research be carried out:

- Develop a prototype 24-hour probabilistic extreme rainfall warning system for EA Areas for frontal/orographic events. The recently developed Met Office short range ensemble and high resolution UK model should be used to develop and provide improved predictors, utilising the extended historical results from WP1.

- Develop automated monitoring of the frequently updated output from the new Met Office high resolution UK model post-processing suite, which incorporates radar data and the STEPS nowcasting algorithms, to identify evolving weather situations (especially convective) from an extreme rainfall point of view. Provide frequent short term forecasts of the probability of extreme rainfall in EA rapid response catchments for 0-6 hours ahead. This work should be complementary to activity within the EA to develop a warnings capability against the threat to human life in such catchments.

In both cases, EA and Met Office forecasters should be fully involved in the evaluation. However, if implemented, operational output of the systems should initially be orientated towards prompting the Met Office forecaster to consider issuing a Heavy Rainfall Warning to the EA. It is noted, in this context, that it is proposed to issue Heavy Rainfall Warnings only when the probability of an extreme event exceeds 20%. It is suggested that this should be reviewed after the new research has been trialled.

6. Acronyms and units

ATD	Arrival Time Difference (lightning detection system)
CAPE	Convectively available potential energy
CD	Compact disc
CDP	Convection Diagnosis Procedure (Met Office)
DT	Data Time
EA	Environment Agency
ECMWF	European Centre for Medium Range Weather Forecasts
ER	Extreme Rainfall
ET	Extreme Rainfall accumulation threshold (function of duration)
FO	Frontal or orographic events
hPa	Hecto-pascals (unit of pressure) (1 hPa = 1 millibar)
HP	Hewlett Packard
J/Kg	Joules per kilogram
Km	Kilometres
MASS	Met Office archiving system
m/s	Metres per second
MM	Mesoscale Model (Met Office)
Nimrod	Met Office very short range weather forecasting system (0-6h ahead)
NWP	Numerical Weather Prediction
Ops	Operations
R	Fraction of an Extreme rainfall
RH_{850}	Relative humidity at a height with a pressure of 850 hPa
T_{850}	Temperature at a height with a pressure of 850 hPa
TM	Thames flood warning Region
UNIX	A computer operating system
UR	User Requirement
UTC	Coordinated Universal Time (Greenwich mean time)
UK	United Kingdom
WP1	Work Package 1

7. References

1. Defra R&D Project Report FD2201 – Extreme Rainfall and Flood Event Recognition.

2. Miller, R.C., 1972: Notes on analysis and severe storm forecasting procedures of the Air Force Global Weather Center. AWS Technical report 200 (Rev), Headquarters, Air Weather Service, Scott AFB, IL, 106pp.

3. Hand, W.H., 2002: The Met Office Convection Diagnosis Scheme. Meteorol. Appl. **9**, pp69-83

4. Golding, B.W., 1998: Nimrod: a system for generating automated very short range forecasts. Meteorol. Appl., **5**, pp1-16.

5. Bayes, T., 1764: An Essay Toward Solving a Problem in the Doctrine of Chances. Philosophical Transactions of the Royal Society of London, 370-418.

6. Hsu, W., and Murphy, A.H., 1986: The attributes diagram. A geometrical framework for assessing the quality of probability forecasts. Int. Journal of Forecasting, ***2***, pp285-293.

7. Lee, A.C.L., 1986: An Operational system for the remote location of Lightning Flashes using a VLF arrival time difference technique. J.of Atmospheric and Ocean. Tech. **3**, pp630-642.

8. Golding, B.W., Clark, P. and May, B., 2005: The Boscastle flood: meteorological analysis of the conditions leading to flooding on 16 August 2004. Weather. **60**, pp230-235.

Annex A

User Requirement for the real-time trial

1. Aims of the trial

The trial will be known as the Probabilistic Extreme Rainfall Forecasting Trial and will be managed by the trial coordinator – Will Hand (Met Office).

The key aim will be to test the accuracy and usefulness of the probabilistic extreme rainfall forecast system which has been designed to provide early warnings of the possibility of extreme rainfall up to 24 hours ahead.

The trial will improve the Environment Agency's understanding of probability forecasts and how they may best be used in the future. Met Office forecasters will be exposed to the outputs and will be able to critically assess their value in rainfall prediction.

The trial will also provide the opportunity of a test-bed for new ideas concerned with forecasting extreme rainfall.

2. Daily running of the trial

The trial is scheduled to run from the end of October 2004 to November 2005. This long period will hopefully capture either a range of extreme event scenarios or sufficient "near-misses" to test the system.

A forecast will be produced once per day issued at around 1030 GMT covering a 24 hour period from 1200 GMT. The forecast will be based on ECMWF ensemble data and Met Office forecasts from the Mesoscale model and CDP (Convection Diagnosis Procedure).

The forecast will run on a Met Office HP UNIX server (FP0100) controlled by a master script running under 'cron'. ECMWF ensemble data will be routed to FP0100 and Mesoscale model and CDP forecasts will be obtained from Nimrod.

All outputs and dissemination will be handled automatically but the trial will be monitored each working day by the trial coordinator.

3. Recipients of trial outputs

Detailed forecasts will be prepared for the SW, NW and Thames EA regions divided into EA areas. Forecasts will be provided for each of the new flood watch catchments due to go operational in the EA in 2005. These forecasts will be text based and will be sent by e-mail to weather.services@environment-agency.gov.uk . Three emails will be sent each day. The subject line will be one of "Probabilistic Extreme Rainfall Forecasting Trial <dd/mm/yy> data for SW/NW/THAMES" and the body will contain a text file (forecast) as an attachment. Each e-mail will then be auto-forwarded by a rule set up by the account owner in the EA to the appropriate Regional Flood Warning Officer. Duty flood warning officers will not routinely see the extreme rainfall forecasts. This procedure will be tested before the trial starts and the EA representatives on the Project Board will ensure that all involved parties in the EA are clear as to the aims and conduct of the trial.

The text forecasts will be put onto an internal Met Office web site for inspection by Met Office forecasters at Cardiff, Exeter, London and Manchester. The web site will also contain graphical outputs of the probability of extreme rainfall and the expected type (orographic, frontal etc) over the whole of the UK. The predictors which underpin the forecast will also be available covering the full Nimrod forecast domain. Notes describing the forecasting system will be written for forecasters and made available on the web site before the trial starts. Instructions for forecasters explaining the aim of the trial and how they are to monitor it will be prepared before the trial begins by the trial coordinator with assistance and advice from the Forecasting Service Managers. The instructions will then be issued to the forecasters at the Ops Centre and the relevant Civil Centres. The non-operational nature of the trial will be emphasised.

4. Trial outputs

The text forecast file will be headed (e.g. for SW Region) as

Extreme Rainfall Forecast for SW Region issued at 1030 GMT <dd/mm/yy>

The Area probability forecasts will then follow. If these are not all 'NIL' then the catchment forecast will follow. All unaffected catchments will be listed first and then affected catchments in chronological order according to expected start of an extreme rainfall event e.g.

Cornwall

Area Extreme Event Rainfall Probability Forecast.

Probability of getting extreme rainfall somewhere in the Area sometime during the following time periods is:

23/08/05 1200 – 2345 GMT 41%
24/08/05 0000 – 1145 GMT NIL

Catchment Extreme Event Rainfall Probability Forecast.

(Probability of getting extreme rainfall somewhere in each catchment)

Camel - NIL
Fowey - NIL
Upper Tamar – NIL

Mid Tamar 177 mm 23/08/05 1600 to 23/08/05 2245 GMT Confidence= 7 %
Teign 88 mm 23/08/05 1800 to 23/08/05 2000 GMT Confidence= 16 %

….

Devon

In the event of equal start times then the longest lasting event will be printed first. No events with a confidence level below 1% will be tabulated. [***Note*** *that during the Trial it was agreed that in addition to the specific forecast estimate of Extreme rainfall amount in a Catchment, the fixed lower and upper thresholds of Extreme rainfall for the duration were to be provided in square brackets.*]

The graphical forecast on the internal Met Office website will show the probability of getting extreme rainfall somewhere in a 30 Km square provided it is greater than or equal to 1%. Squares will be coloured according the probability value. The meteorological type of extreme rainfall will also be indicated irrespective of probability.

5. Forecast assessment and verification

Forecast verification will be an important activity during and after the trial. It is expected that both objective verification and subjective assessments will be performed.

During the trial high resolution radar accumulation data (derived from the merged 1km rain rate data) will be gathered from Nimrod and a subset of these files saved to disk and dumped to CD. The subset will be a limited area covering the trial regions. The aim will be to compare maximum accumulations with the catchment point probability forecasts of extreme rainfall over the period of the trial according to a verification plan which is scheduled to be in place by December 2004. If extreme rainfall occurs on a particular occasion or there is a “near-miss”, then the EA will gather rain gauge data so that the case can then be studied in more detail. All of the catchment based text forecasts will be saved to disk and dumped to CD. Model data will not be saved but procedures will be in place to restore the data from MASS and other archives as efficiently as possibly.

Subjective assessments will concentrate on the potential usefulness of the forecasts and, in particular, deciding at which probability threshold any action would or should have been taken had the system been operational. The Met Office forecasters will be able to comment on whether the extreme rainfall forecasts would have influenced their operational forecasts. The subjective assessments will be carried out regularly but not necessarily daily and regular feedback to the trial coordinator will be provided by the Met Office Service Managers and the EA Regional flood forecasters. Feedback from the EA is required at least once every three months once the trial is working satisfactorily.

Extreme rainfall cases and “near-misses” will be studied in more detail after the event, possibly re-running forecasts to test out new ideas.

6. Changes to the trial

During the trial any bugs in the computer code will be corrected by the trial coordinator and all parties informed. Any science changes will be tested on saved cases and if they improve forecasts, or demonstrate the potential to improve forecasts, they will be implemented by the trial coordinator. All changes will be recorded and forecast recipients will be informed. Any necessary changes to the schedule due to computer system changes or other reasons will be agreed beforehand with forecast recipients.

7. Report on the trial

Towards the end of the trial period verification data and assessments will be gathered and synthesised into a report on the overall performance of the forecasting system. Cases studies of extreme rainfall and “near-misses” will be written up and an assessment will be made of how well the trial met its aims and how successful it was. The report will also record suggested strategies for any future development and incorporation into operational systems, in particular what should be forecast and how the forecasts could best be disseminated and used. The report will be written by the trial coordinator but with significant inputs from the EA project board representatives and the Met Office Service and account managers.

Appendix 1

Estimation of prior probabilities

Using the historical study data from Phase 1 we can estimate the climatological probability of experiencing an Extreme Rainfall event somewhere in the UK in any hour chosen at random. This was done by dividing the sum of durations of all Extreme events (in hours) by the number of hours in 100 years. The two probabilities for orographic and non-orographic Extreme rainfall types were calculated as:

$P(ER)_{orog} = 0.0003097$
$P(ER)_{non\text{-}orog} = 0.0004155$

Although we could have used these prior values directly in the prediction system, it was sensible to make use of the fact that “heavy rainfall” by definition always occurs in an Extreme rainfall event. Therefore if we divide the climatological probabilities by the probability of getting “heavy rain” then we will introduce seasonal and geographical variation into the priors. The historical study demonstrated such a dependency in the Extreme events. The meaning of “heavy rain” is arbitrary, however, a sensible choice would be a threshold value which has high variability in time and space and for which data are available over a long period. It also needs to be a value which NWP can predict over the full range of probabilities. A rainfall accumulation of 10 mm/day was chosen for the heavy rain threshold. The Met Office has gridded 5km average number of such occasions in the UK for each month using data from 1961-1990.

Examples for January and July are shown in Figures 1 and 2 respectively.

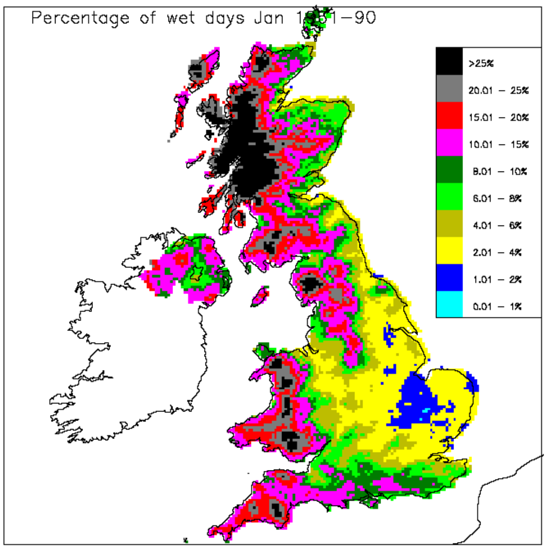


Figure 1. Average percentage frequency frequency of wet days (>10 mm) in January.

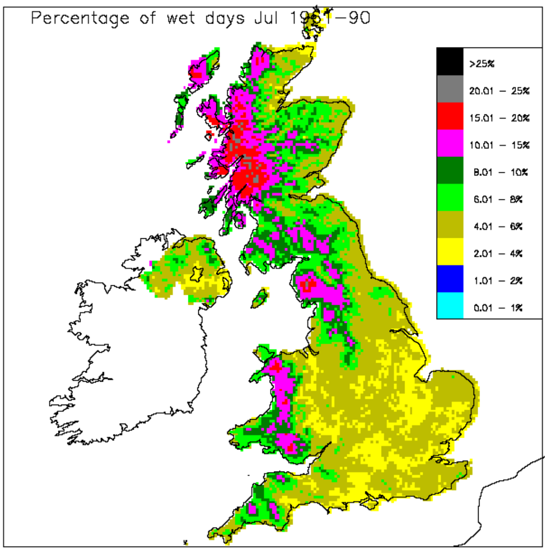


Figure 2. Average percentage of wet days (>10 mm) in July.

Clearly during the year most heavy rainfall is over high ground in the west and north. However, southern coastal regions in winter collect more heavy rain than during the summer. Over eastern England heavy showers during summer increase in frequency from relatively low values in winter.

Since Extreme orographic rainfall is restricted to high ground directly exposed to the southwest quadrant the priors were set to zero at places which are not exposed to the southwest.

The effect this has on the priors for both orographic and non-orographic events is illustrated in figures 3 to 6. Note that the figures show the climatological probability of extreme rainfall *given that heavy rain (at a rate of >10 mm/day) occurs*.

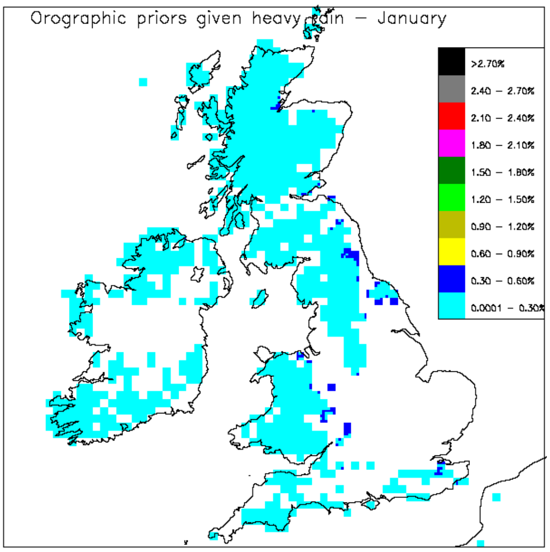


Figure 3. Priors for orographic Extreme rain given heavy rain in January.

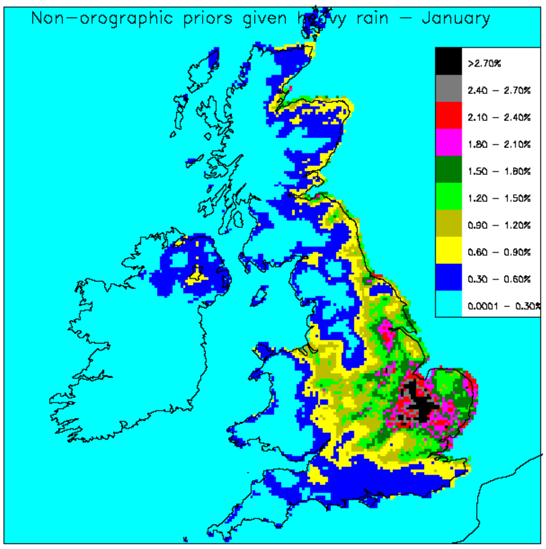


Figure 4. Priors for non-orographic Extreme rain given heavy rain in January.

In Figure 3 all high ground directly exposed to the SW is picked out. Since heavy rainfall is relatively common in these areas in January the priors, that is the probability of getting Extreme rainfall whenever heavy rain occurs is low. This should be compared with the non-orographic Extreme rainfall priors shown in Figure 4. Highest values are in eastern England where the frequency of heavy rainfall is lowest. What we are saying here is that given heavy rainfall, climatologically there is higher risk of that rainfall event turning Extreme in the east than in the west.

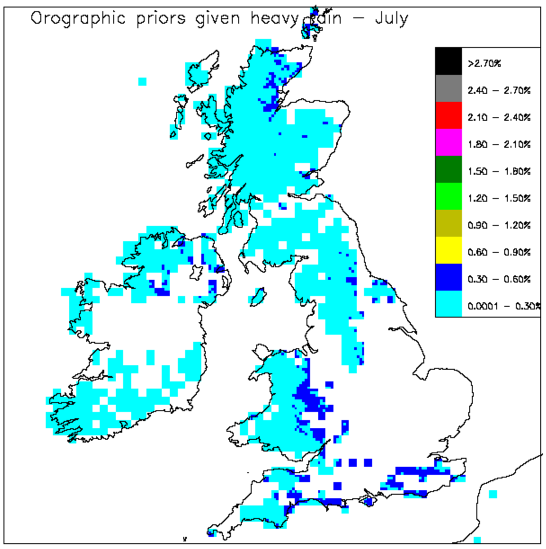


Figure 5. Priors for orographic extreme rain given heavy rain in July.

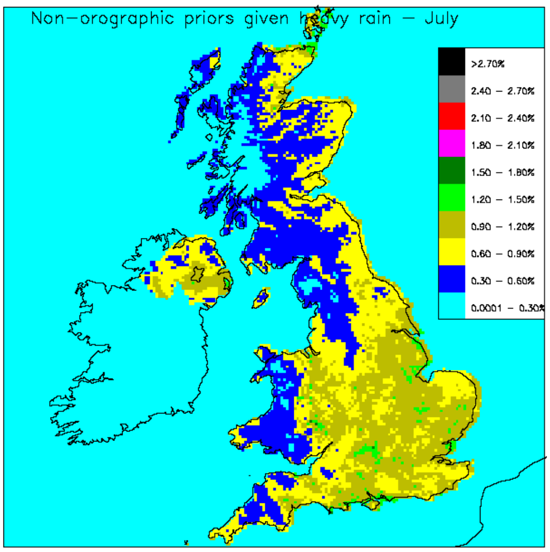


Figure 6. Priors for non-orographic extreme rain given heavy rain in July.

In July orographic rainfall is less common in the south and to the east of main high ground and so the priors are higher. Also, due to the higher incidence of thunderstorms in July, the distribution over England is more uniform than in January.

Appendix 2

Estimation of “inverse” probabilities P(E|R)

All of the historical cases in the twentieth century were looked at and a table of predictor values was completed. The analysis is shown in Table 1.

List of cases and key predictor values								
	Cases	CAPE category	Orog enh. Cat.	Multicell category	Depression speed	Closeness to depression	Event rel. to dep.	Large hail ?
	(Type A)							
Reading	09/06/10	N/A	0	N/A	nil	nil		Y
Kensington	16/06/17	N/A	0	2	nil	nil		Y
Brymore	19/08/24	N/A	0	1	nil	nil		Y
Cranwell	11/07/32	N/A	0	2	nil	nil		Y
Bath	25/06/35	N/A	0	2	3	100	NE	Y
Torquay	04/08/38	3	0	2	1	250	NE	Y
Newcastle	22/06/41	2	0	1	nil	nil		no
Ferriby	14/09/43	2	0	2	nil	nil		Y
March	15/07/49	5	0	1	1	350	E	no
Bradford	11/06/56	6	0	2	nil	nil		no
Cornwall	08/06/57	6	0	1	nil	nil		Y
Kent	05/09/58	6	0	2	nil	nil		Y
Norfolk	11/07/59	1	0	2	nil	nil		Y
Horncastle	07/10/60	1	0	2	2	240	N	no
Norfolk	06/06/63	4	0	2	nil	nil		Y
London	14/08/75	5	0	2	nil	nil		no
Sevenoaks	25/06/80	4	0	1	nil	nil		Y
Halifax	19/05/89	5	0	2	nil	nil		no
N. Weald	10/06/93	3	0	1	nil	nil		no
	(Type B)							
Ilkley	12/07/00	N/A	0	N/A	1	300	N	no
Maidenhead	12/07/01	N/A	0	N/A	nil	nil		no
Croydon	30/05/03	N/A	0	N/A	1	250	E	no
Louth	29/05/20	N/A	0	2	1	30	SE	no
Fleet	26/09/33	N/A	0	1	1	450	N	no
Kent	22/07/34	N/A	0	1	nil	nil		no
Wisley	16/07/47	1	0	1	1	120	NW	no
Eskdalemuir	26/06/53	4	0	2	nil	nil		no
Derbyshire	05/08/57	5	0	1	nil	nil		no
Bolton	18/07/64	3	0	1	nil	nil		no
Lancs	08/08/67	5	0	1	1	360	NE	no
Pershore	11/06/70	5	0	2	nil	nil		no
Wisbech	27/06/70	1	0	1	nil	nil		no
Norwich	01/08/73	5	0	2	nil	nil		no

Antrim	01/08/80		2	0		1		nil		nil		no	
Cheshire	05/08/81		N/A	0		1		nil		nil		no	
	(Type C)												
Norwich	26/08/12		N/A	0		0		1		30	W	no	
Inverness	26/09/15		N/A	0		0		1		190	W	no	
N. Yorks	22/07/30		N/A	0		0		1		30	NW	no	
Tweed	12/08/48		0	0		0		2		400	NW	no	
Co. Down	31/10/68		0	0		0		1		450	NE	no	
Kent	20/09/73		1	0		0		3		55	NW	no	
E. Anglia	31/08/94		0	0		0		2		160	NW	no	
	(Type D)												
Portland	21/10/08		N/A	0		N/A		1		80	E	no	
Bruton	28/06/17		N/A	0		N/A		3		180	N	no	
Boston	08/08/31		N/A	0		1		2		200	N	no	
Boston	15/07/37		5	0		2		3		160	N	no	
Lynmouth	15/08/52		6	0		2		1		40	NW	no	
Martinstown	18/07/55		4	0		1		2		350	N	no	
Bristol	10/07/68		1	0		2		4		190	N	no	
Kent	15/09/68		2	0		1		1		10	N	no	
	(Type O)												
Blaenau	28/06/28		0	2		0		nil		nil		no	
Rhondda	11/11/29		0	1		0		nil		nil		no	
SW to Lakes	03/11/31		0	1		0		nil		nil		no	
Princetown	23/11/46		0	1		0		nil		nil		no	
Loch Quoich	18/12/54		0	1		0		nil		nil		no	
Glen Etive	17/12/66		0	1		0		nil		nil		no	
N. Wales	09/11/73		0	2		0		nil		nil		no	
Loch Sloy	17/01/74		0	1		0		nil		nil		no	
W. Highland	05/02/89		0	2		0		nil		nil		no	
Loch Sloy	10/12/94		0	1		0		nil		nil		no	

Table 1. List of historical cases and category bin for each predictor. Cases have been split into types (A), (B), (C), (D) and orographic (O) as per the historical study in Phase 1. Predictor categories are as follows (note N/A means that there were insufficient data to calculate a value):
CAPE – 0 is ≤ 0; 1 is 1-100; 2 is 101-200; 3 is 201-400; 4 is 401-800; 5 is 801-1600; 6 is >1600 J/Kg.
Orogographic enhancement – 0 is no factor; 1 is wind direction 210-250 degrees, speed ≥ 25 m/s and dewpoint > 14C; 2 is wind direction 210-250 degrees, speed ≥ 15 m/s and dewpoint > 14C.
Multicell – 0 is no heavy thunderstorms , 1 = isolated cells, 2 = multi-cells .
Depression speed – 'nil' indicates no depression closer than 450 Km;
1 is < 5 m/s; 2 is 5-9 m/s; 3 is 10-19 m/s; 4 is ≥ 20 m/s.
Closeness to depression – 'nil' is > 450 Km; rest are closest approach value to event.
Event relative to depression – Eight point compass bearing of event location from depression centre at closest approach.

Large hail – 'Y' = large hail (>15mm) recorded, 'no' = no large hail recorded.

From the results it is clear that the orographic cases comprise a separate sub-sample, since when Extreme orographic rainfall occurs, it is only the orographic predictors that have values. Conversely the orographic predictors have zero values whenever other types of Extreme rainfall occur. For the derivation of inverse probabilities the orographic enhancement predictors were taken as a sample of 10 and the others were a sample of 50 reduced by the number of occasions that a predictor could not be estimated (N/A).

1. CAPE

Sample size is 32.

Table 2 shows the frequency of CAPE classes for all types of extreme rainfall (except orographic) and for frontal and convective types only.

	≤ 0	1-100	101-200	201-400	401-800	801-1600	> 1600 J/Kg
All types	3	6	4	3	4	8	4
Frontal	3	2	1	0	1	1	1
Convective	0	4	3	3	3	7	3

Table 2. Frequency of CAPE classes for extreme rainfall types

For the frontal types the distribution of positive CAPE is uniform, whereas for convective types it is biased to higher values. Using the frontal distribution, four CAPE classes were identified to derive inverse probabilities which are shown in Table 3. The classes were chosen so as to provide equal frequencies in positive CAPE classes for frontal extreme rainfall.

CAPE class (J/Kg)	Inverse probability P(CAPE | non-orographic Extreme rainfall)
1-100	0.187
101-800	0.344
> 800	0.375

Table 3. Inverse probabilities according to CAPE class

2. Orographic enhancement

Sample size is 10
Two classes were chosen here shown in Table 4.

Orographic enhancement class	Inverse probability P(Orog. Enh. | orographic Extreme rainfall)
Surface wind direction 210-250 degrees Airmass source dewpoint > 14.0 deg C Geostrophic wind speed ≥ 25 m/s	0.7
Surface wind direction 210-250 degrees Airmass source dewpoint > 14.0 deg C Geostrophic wind speed 15 - 24 m/s	0.3

Table 4. Inverse probabilities for orographic enhancement classes.

3. Multi-cell category

Sample size is 44.
These are shown in Table 5. Note that seven frontal Type C cases had no convective cells with heavy thunderstorms.

Multi-cell category	Inverse probability P(Multi-cells | non-orographic extreme rainfall)
Isolated cells and heavy thunderstorms	0.409
Multi-cells and heavy thunderstorms	0.432

Table 5. Inverse probabilities for multi-cell classes.

4. Depression speed, 'closeness' to depression and aspect of event location to depression

Sample size is 50.

To facilitate probability estimation, frequencies of closeness as a function of speed were tabulated as shown in Table 6.

Closeness of event to depression (Km)	Speed of depression (m/s)			
	≤ 5	5-9	10-19	≥ 20
421 – 450	2	0	0	0
361 – 420	0	1	0	0
301 – 360	2	1	0	0
241 – 300	3	0	0	0
181 – 240	1	2	0	1
121 – 180	0	1	2	0
61 – 120	2	0	1	0
≤ 60	5	0	1	0

Table 6. Frequency table of closeness of extreme events to depressions within 450 Km as a function of depression speed.

This analysis suggested 6 closeness/speed classes could be clustered together. These are labelled A-F in Table 7.

Closeness of event to depression (Km)	Speed of depression (m/s)		
	≤ 5	5-9	10-19
421 – 450	D	E	F
361 – 420	D	E	F
301 – 360	D	E	F
241 – 300	D	E	F
181 – 240	A	B	C
121 – 180	A	B	C
61 – 120	A	B	C
≤ 60	A	B	C

Table 7. Clusters of closeness versus depression speed frequencies.

The next step was to determine how each cluster related to the aspect of the Extreme events to the depression centre at closest approach. The results are shown in Table 8 which relates closeness/speed clusters to 8 point compass directions of aspect.

Speed/closeness cluster	Aspect of event to depression centre at closest approach							
	N	NW	W	SW	S	SE	E	NE
A	1	3	2	0	0	1	1	0
B	2	1	0	0	0	0	0	0
C	2	1	0	0	0	0	0	1
D	2	0	0	0	0	0	2	3
E	1	1	0	0	0	0	0	0
F	0	0	0	0	0	0	0	0

Table 8. Aspect of event to depression centre at closest approach as a function of speed of depression and distance from depression cluster.

Table 8 shows that no extreme events occurred within 450 Km to the south or southwest of a depression. However, 9 events occurred to the north. The frequencies have been converted to inverse probabilities and are given in Table 9.

Depression speed/event closeness category	Cluster	Aspect of event to depression centre at closest approach							
		N	NW	W	SW	S	SE	E	NE
< 5 m/s & ≤ 240 Km	A	0.02	0.06	0.04	0	0	0.02	0.02	0
5-9 m/s & ≤ 240 Km	B	0.04	0.02	0	0	0	0	0	0
10-19 m/s & ≤ 240 km	C	0.04	0.02	0	0	0	0	0	0.02
< 5 m/s & 241-450 Km	D	0.04	0	0	0	0	0	0.04	0.06
5-9 m/s & 241-450 Km	E	0.02	0.02	0	0	0	0	0	0
10-19 m/s & 241-450 Km	F	0	0	0	0	0	0	0	0

Table 9. Inverse probabilities as a function of aspect of event to depression centre at closest approach, depression speed and closest distance to an event of extreme rainfall.

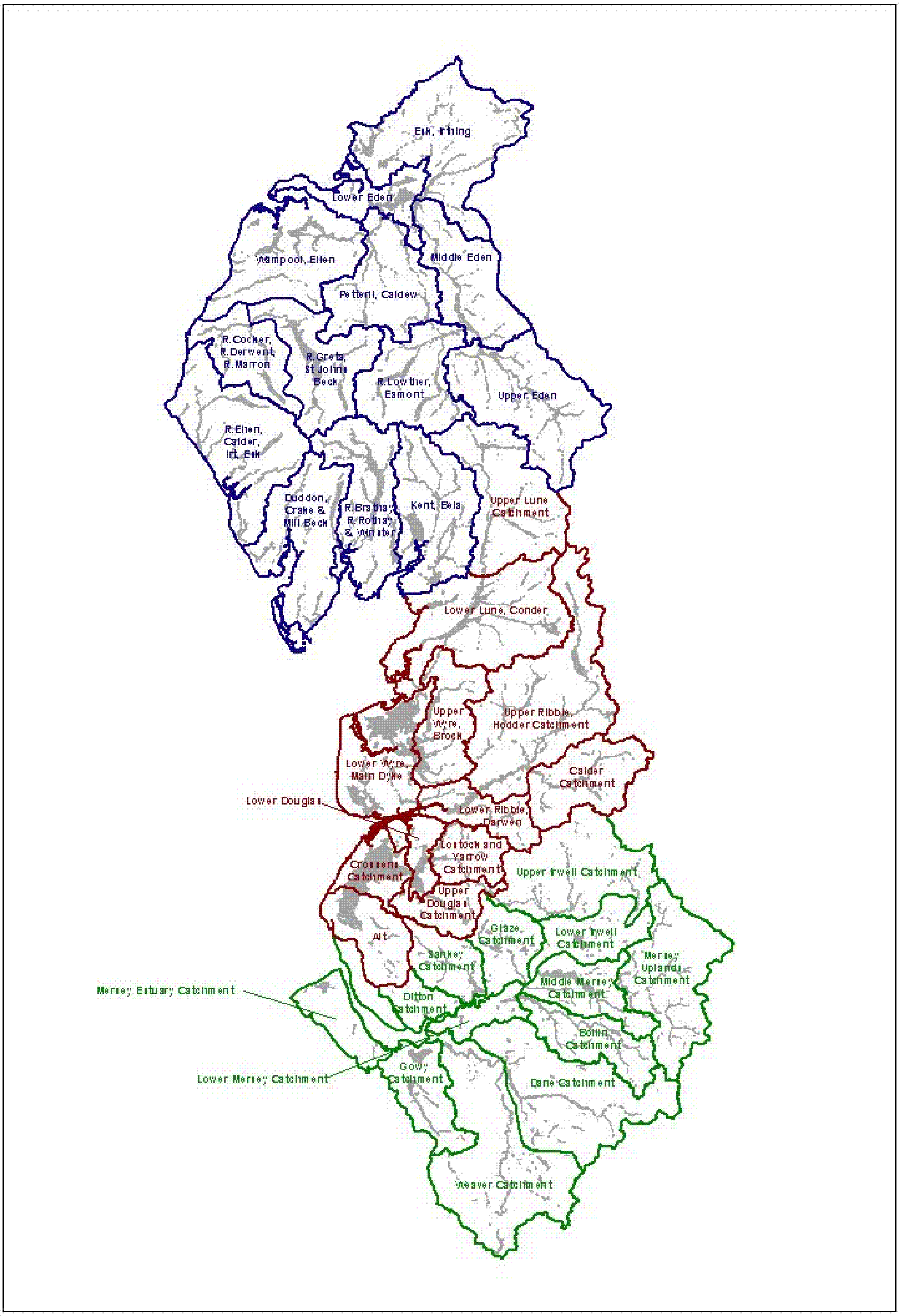
5. Large hail

Sample size is 50.

Large hail is defined as hailstones with a diameter greater than or equal to 15mm. The inverse probability of getting large hail given non-orographic extreme rainfall is 0.24 .

Appendix 3

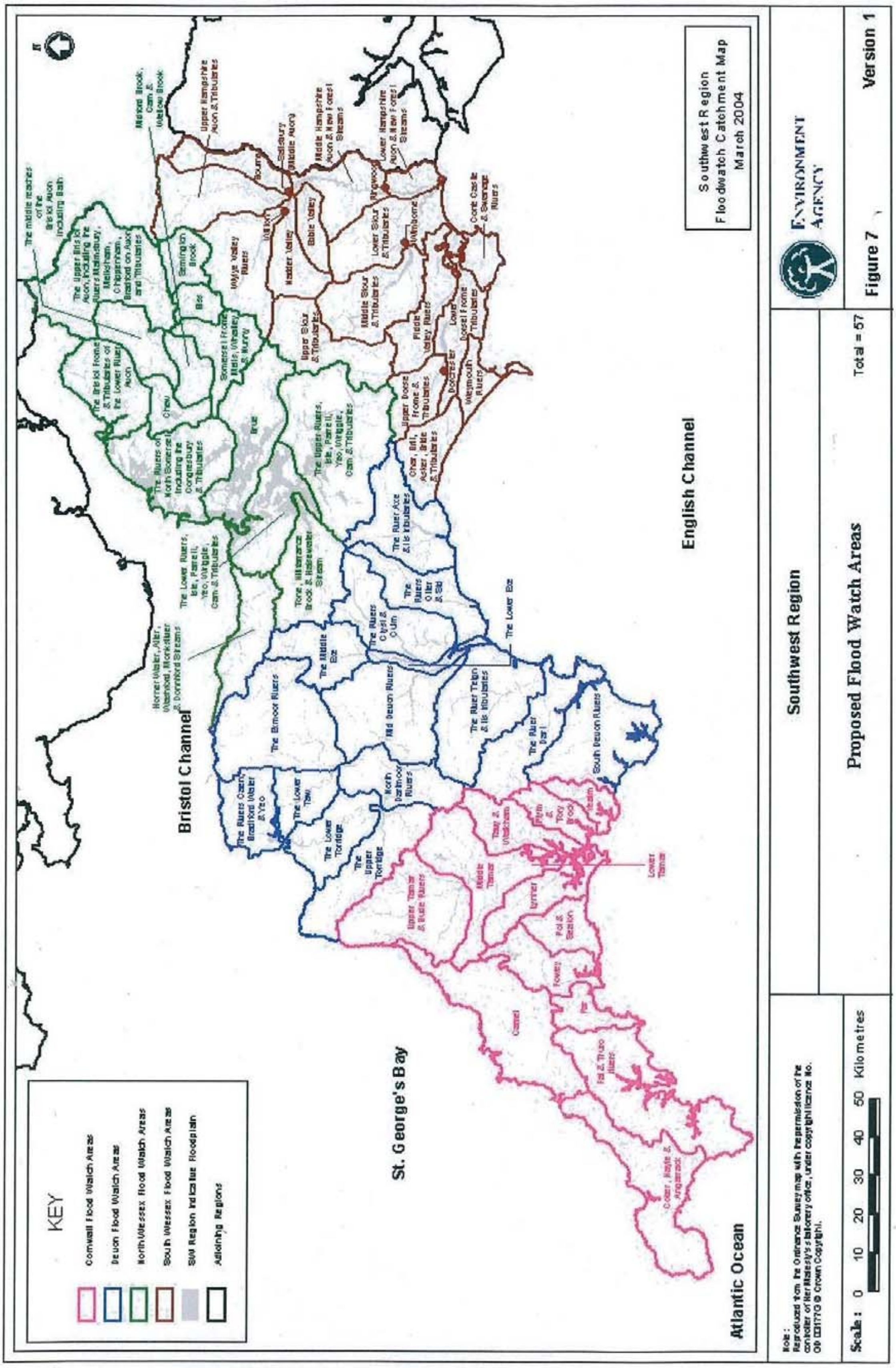
<u>NW Region, Areas and "Floodwatch" Catchments</u>



NW Region showing North Area (blue), Central Area (red) and South Area (green) with "Floodwatch" Catchments.

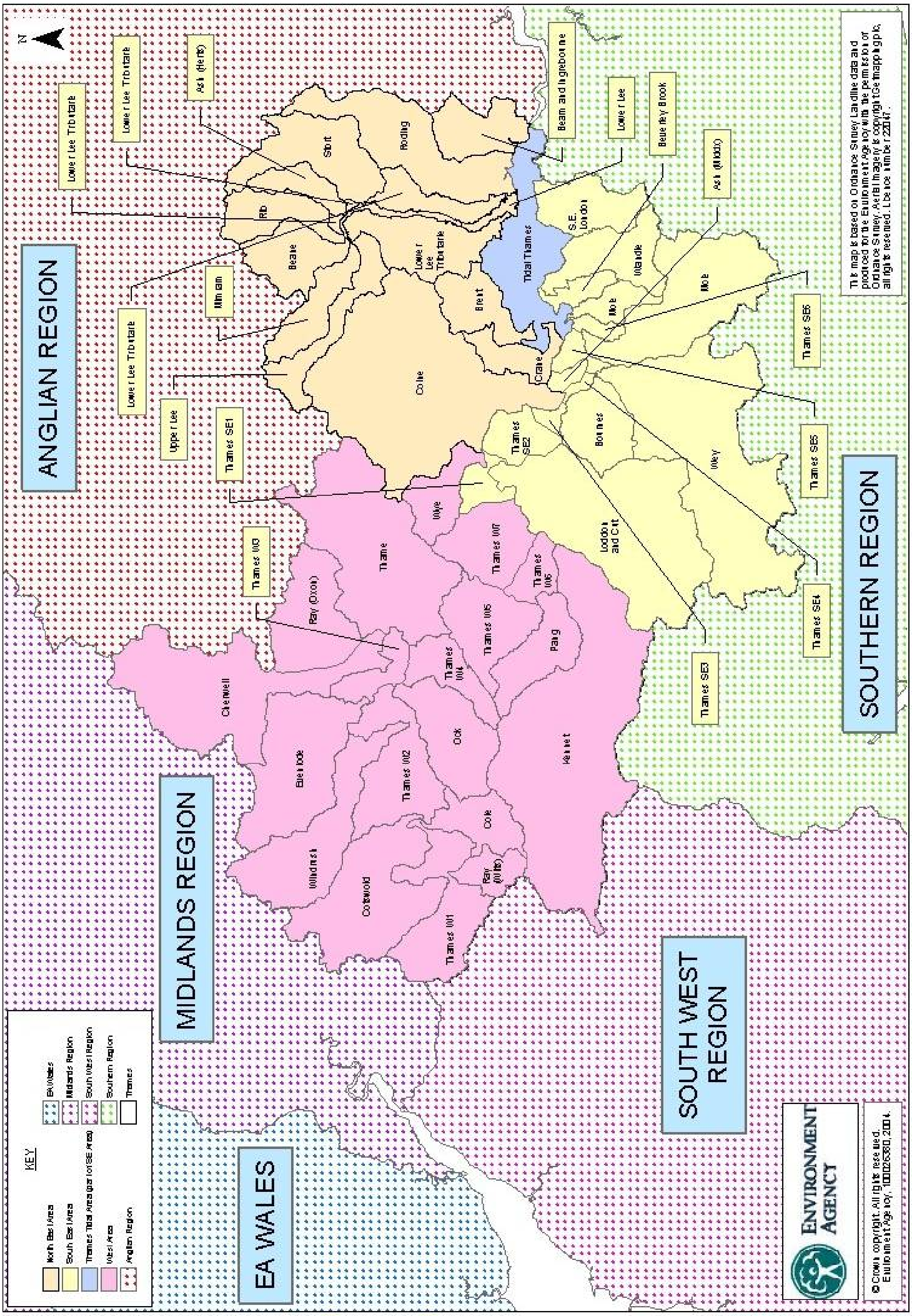
Appendix 4

<u>SW Region, Areas and “Floodwatch” Catchments</u>



Appendix 5

Thames Region, Areas and “Floodwatch” Catchments



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