The Met. Office

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Evaluation of Frontiers Forecast Precipitation Accumulation

Final Report

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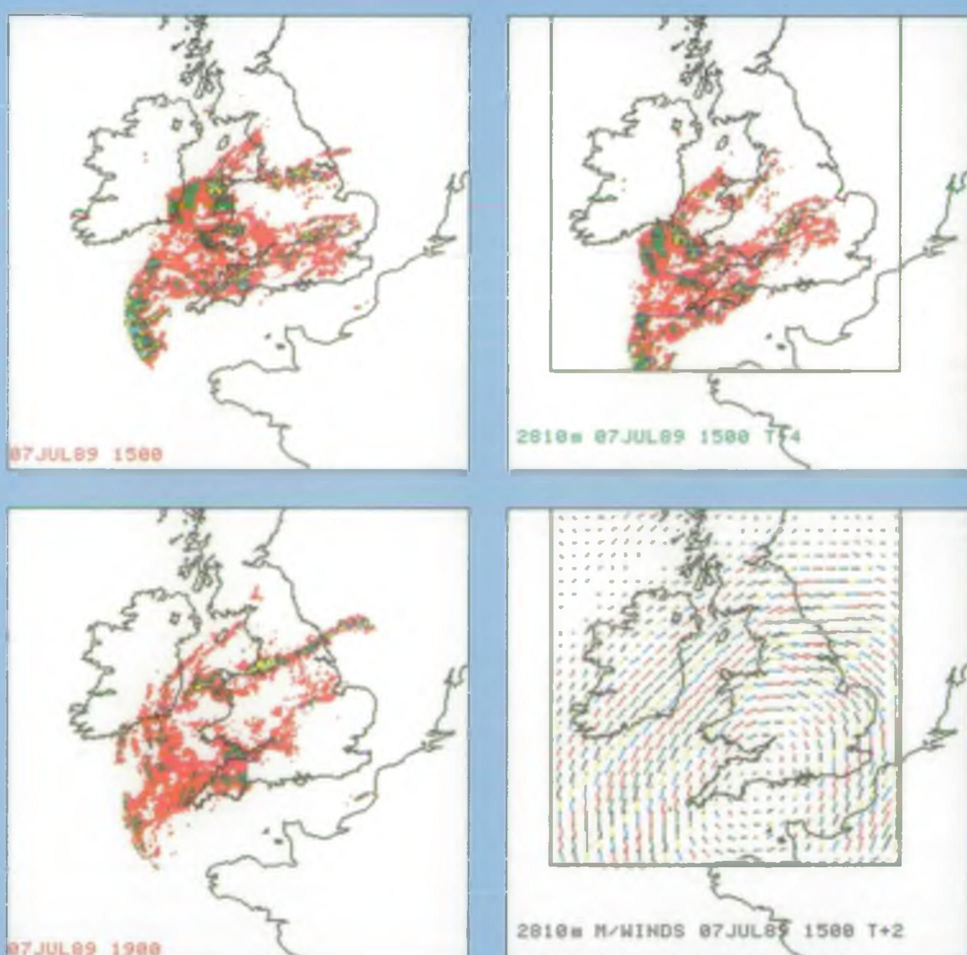

EVALUATION OF FRONTIERS ACCUMULATION FORECASTS IN THE NRA THAMES AND NORTH WEST REGIONS

Final Report of the Joint Met. Office - National Rivers Authority Pilot Operational Service of FRONTIERS forecasts Assessment Group. Covering the period from October 1990 to December 1991

February 1992

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1. Introduction

In March 1990 the Met. Office invited the Thames and North-West Regions of the National Rivers Authority (NRA) to take part in a pilot operational service to receive and assess FRONTIERS rainfall forecasts. Funding was provided by the participants for the work they undertook, although the NRA did contribute an annual amount of £26K for their receipt and use of the forecast data in real-time. The trial period commenced on 1st October 1990 with a duration of one year, later extended to 18 months.

This work has been managed by the steering group given in Annex A (known as POSFFAG), who have compiled this report. The Project was undertaken both to evaluate rainfall forecast accumulations and to evaluate the derived flow forecasts using FRONTIERS forecast rainfall. The Report describes here the analysis undertaken to evaluate FRONTIERS forecast accumulations up to 6 hours ahead using rain-gauges, and an Isolated Event Model for selected catchments in London and the Lee Valley (Figure 1a). Associated work on the use of FRONTIERS data with a transfer function model of the River Irwell catchment north of Manchester (Figure 1b), and investigations of orographic precipitation enhancement over the Chilterns and North Downs, are also outlined.

One motivation for this work has been to assess whether or not the potential financial savings from a 3- hour advance warning of flooding, specified by a joint study undertaken by the National Water Council and the Met. Office in 1983, are likely to be achievable using FRONTIERS forecasts. In the Thames region these savings ranged from £25K per annum (1992 prices) in rural catchments to in excess of £800K per annum, in urban catchments whereas in the North West the savings ranged from less than £1K per annum over coastal areas, to in excess of £170K per annum for steep hilly catchments such as that represented by the Irwell catchment.

2. Background

Research into the quantitative measurement of precipitation using weather radar data began in 1967 as part of the Dee Weather Radar Project (DWRP), a joint Met. Office, Plessey Radar Ltd, Water Industry project. An S-band (later to become C-band) radar was established at Llandegla in North Wales in 1970 and measurements were assessed by comparison with data from a dense rain-gauge network.

The objectives of the DWRP were defined at an early stage as:

1. to investigate the accuracy with which a real precipitation can be measured by radar in a hilly (mountainous) area; and

2. to develop a real-time system for the measurement of areal precipitation in time and space appropriate to the hydrological requirements for water management and river regulation.

At the same time, it was hoped that an examination could be made of ways in which radar might be used to improve short-period quantitative forecasts of precipitation.

By 1974 objective 1 had been achieved and objective 2 was expanded "to explore the potential of real-time hydrological forecasting for river management and control". At this time the project became known as the Dee Weather Radar and Real Time Hydrological Forecasting Project (DWRHP) and a third objective was defined as:

3. starting from a precise knowledge of the present state of the system, reservoir levels, river flows and rainfall in the catchment, to determine the possibility of forecasting the probable state of the system in X hours time for the purpose of flood warning and alleviation, and the control of releases either to mitigate floods or to sustain abstractions.

By the time the Final Report of the DWRHP was published in 1977 (CWPU, 1977) the Project was deemed to have achieved its main objectives, although a number of areas requiring further work were identified. These included the operational use of unmanned weather radar (Llandegla had been a manned site), the installation of radar networks, the study and improvement of short-period precipitation forecasting (only a little work had been done in the DWRP) and the improvement of hydrological models.

This work led directly to the North West Radar Project (NWRP) funded by a consortium comprising the Met. Office, the North West Water Authority, the Water Research Centre, the Central Water Planning Unit and the Ministry of Agriculture, Fisheries and Food (MAFF). An unmanned operational C-band radar was established in 1979 at Hameldon Hill in North West England. Included amongst the objectives (NWRP, 1985) was an assessment of the benefits of the actual radar measurements rather than of precipitation forecasts derived from radar data. Indeed, this work led to a study of the financial benefits from weather radar to flood forecasting throughout England and Wales, which was published by the National Water Council and the Met Office, in 1983 (NWC, 1983).

In parallel with these projects the Met Office initially with the Royal Radar Establishment, see Ball *et al*, 1979, developed software for real-time processing of radar data, and for networking the data from several radars (Taylor and Browning, 1974, Collier, 1980). The radar network steadily expanded throughout the 1980's until the whole of the United Kingdom was within the coverage of at least one radar, albeit at far range for some areas, at the beginning of 1992. Using data from this network, the Met Office developed the FRONTIERS (Forecasting Rain Optimized using New Techniques of Interactively Enhanced Radar and Satellite data) system aimed at providing facilities for real-time quality control, the combination of radar with satellite data and the preparation of quantitative very-short-period forecasts of precipitation. The forecasts so produced were aimed at serving the needs of both meteorologists and hydrologists.

Flood warnings in England and Wales are initiated by the National Rivers Authority under permissive powers derived from Section 1.66 of the Water Resources Act 1991. Dissemination of warnings to the community is undertaken by the police and local authorities under arrangements which vary from place to place. All those involved in flood warning have a clear interest in the quality of the warnings, not least so that resources may be targeted most effectively.

The credibility and utility of flood warnings depend, *inter alia*, upon their perceived reliability, timeliness and accuracy. In this context, reliability is taken to refer to the absence of false warnings. In other words, if a flood warning is issued, the recipient may reasonably anticipate that flooding will occur. Similarly, warnings need to be issued with a lead-time sufficient for the intermediate agencies to pass on warnings and for those at risk to be able to take action to minimize losses. Finally, warnings are most useful if they can specify in some detail, the location, extent and duration of flooding.

It follows that any improvement in any of these three areas is to be welcomed and is worthy of evaluation. FRONTIERS offers the potential to improve timeliness directly and, indirectly to improve both accuracy and reliability. The study by the National Water Council in 1983 of the benefits of national weather radar coverage included a consideration of the beneficial economic impact of FRONTIERS if available to flood forecasters. That situation has now arrived and this report details the assessments made of the potential operational advantages of FRONTIERS for flood forecasters. The work represents the final phase of the assessment of the operational use of weather radar data begun in 1970.

3. The FRONTIERS System

3.1 Introduction

The production of a precipitation forecast from radar and satellite data by the FRONTIERS system is a three-stage process. During a half-hourly cycle, the forecaster applies further quality control to the radar data if necessary (the radar analysis), uses Meteosat satellite data to derive likely areas of precipitation beyond radar range (the satellite analysis) and finally produces a forecast for up to six hours ahead.

The original forecast scheme allows the forecaster to track areas of precipitation and derive their velocity semi-automatically. An extrapolation forecast is then produced by moving the precipitation in a straight line at its recent velocity. To try and account for more complex motion (e.g. curved motion) it is possible to move specified areas of the field with different velocities. However, there is often insufficient time to define enough areas and it is still not possible to represent curved motion properly. After the forecast is computed, the forecaster is permitted to modify each forecast field e.g. delete showers moving from a warm sea to cold land at night. However, there was generally insufficient time to do this on the original system, within the half-hour forecast cycle.

In order to mitigate these problems, a new forecast scheme was developed which uses forecast wind fields at two levels from the UK mesoscale model to produce two advection forecasts based upon the current radar/satellite rainfall field. These automatically include the rotation implied by the wind field and very complex patterns of motion can occur when a circulation centre moves across the UK. Such advection forecasts are not a complete solution because the height of the winds which correlate best with the actual motion of the precipitation may vary across the field. Also, the forecast winds may be in error. Thus the original extrapolation procedure is retained as an option. The new forecast scheme also incorporates the calculation of accumulations over a fifteen minute period.

3.2 Hardware Design and Data Inputs

During the trial, the FRONTIERS system was based upon a VAX 11/750 (upgraded to a VAX 4000 in February 1992). The 11/750 controls two menu display VDUs, whilst two colour monitors showing imagery are driven by RAMTEK display systems linked to the VAX. Three of the monitors are fitted with touch-sensitive screens so that areas of imagery can be delineated or menu options chosen using a finger. The original interactive system is shown on the right hand side of Figure 2.

In order to provide sufficient power to compute the wind-based forecasts it has been necessary to add a DEC VAXstation 3520 with 19 inch colour monitor to the original systems, shown on the left hand side of Figure 2. The menu options on the new workstation have been kept to a minimum, so that FRONTIERS is still mainly operated from the original system. The 11/750s and the VAXstations are connected via an Ethernet/Decnet local area network.

FRONTIERS receives data every fifteen minutes from the UK radars plus Shannon in the Republic of Ireland, although forecasts are only produced from the data on the hour and half-hour. The data from the individual radars are composited into a single image within FRONTIERS. Half-hourly infrared and visible data are also received from the Meteosat geostationary satellite. All data are projected onto the UK National Grid using a 5 x 5 km pixel size.

Products are also extracted from the twice-daily runs of the UK Mesoscale Model. This is a primitive equation non-hydrostatic model employing a 15 km grid, Golding (1990). The forecast products extracted are the wind fields at 1550 m and 3190 m height (approximating to 850 mb and 700 mb) and the instantaneous rainfall rates. The rainfall rate is taken as the model dynamic rate plus the convective rate multiplied by the fraction of convective cloud in a grid square, which is a model variable. The model wind fields are interpolated onto the 5 km FRONTIERS grid, no reprojection being necessary since the model also uses the UK National Grid.

3.3 The Radar Analysis

The first part of the radar analysis involves the removal of corrupt radar data or spurious echoes, whilst the remainder is concerned with improving the estimation of the surface rainfall rates by applying various physically based corrections to the radar data. There is a final overall adjustment to the rainfall rates using the telemetered gauge data received at the radar sites.

The first step of the radar analysis allows data from any radar to be removed if it is hopelessly corrupt. The composite radar field is remade with data from adjacent radars filling in for the missing data where possible.

The forecaster is then allowed to delete spurious echoes, i.e. echoes not arising from precipitation. These generally occur in the presence of a temperature inversion or hydrolapse, which can cause the radar beam to be bent downwards towards the earth's surface more than usual (anomalous propagation), leading to scattering from the surface. Spurious echoes are often identified because they remain stationary or move randomly, while real precipitation moves more systematically. Satellite data and surface observations can also be used to identify areas in which precipitation is expected to be absent.

In order to apply the remaining corrections, the forecaster can define regions in which the same set of physical corrections are applied to the rainfall rates. For example, different regions may contain precipitation of a different depth, one region may be affected by a bright band, etc. First, the empirical range correction applied at the radar sites, which allows for the beam partially overshooting the precipitation, is removed. The forecaster can replace it from a choice of six range corrections, appropriate for shallow, moderate or deep, stratiform precipitation or convective precipitation. The rainfall rate at maximum range is multiplied by a factor which varies from one (deep convection) to eight (shallow stratiform precipitation). The formulation of the range corrections is described in Brown *et al.* (1991).

A substantial increase in rainfall rate can occur in the lowest 1.5 km of the atmosphere over hills and mountains due to the seeder-feeder mechanism, which occurs under conditions of high relative humidity and strong wind speeds at low levels. These conditions produce capping clouds over the hills with substantial liquid water content, leading to growth of pre-existing precipitation by accretion of cloud drops within the capping cloud. Much of this enhancement is missed by the radars because it occurs beneath the radar beam. FRONTIERS contains look-up tables of orographic enhancement, stratified by wind speed and direction and relative humidity. These are increments of rainfall rate (up to about 5 mm h^{-1}) to be added to the radar observed values. Their derivation from daily gauge data is described by Hill (1983). Negative enhancements (i.e. rain shadow effects) are not allowed for. For each radar a table containing the percentage of the enhancement seen by the radar at each pixel has been constructed, based on the assumption that the enhancement occurs over a depth of 1500 m above the local surface, Brown *et al.* (1991).

At present FRONTIERS only allows a simple correction to be made for bright-band effects, the anomalously large rainfall rates, produced by scattering from melting snowflakes just beneath the freezing level. The unrealistic rainfall rates may be capped to a value chosen by the forecaster selected from 2, 4, 6 or 8 mm h^{-1}.

In the final step of the radar analysis, an adjustment factor is applied to each region containing more than one telemetering gauge, using the geometric mean of the radar/gauge ratios, Warner (1991). When forming the radar/gauge ratios, allowance is made for the other corrections applied to the radar data.

3.4 The Satellite Analysis

During the second stage of the cycle, the satellite analysis, a precipitation field is derived from the satellite data, generally based upon correlation with the radar data using the technique of Lovejoy and Austin (1979). Three satellite precipitation fields are derived, using visible data alone, infrared data alone and both together in a two-dimensional correlation table. The satellite precipitation fields are produced automatically, the FRONTIERS forecaster merely has to choose the best. If the correlation technique does not produce an acceptable result, other methods are also available, such as using a predefined table in which, based upon past experience, each satellite class is defined as 'wet' or 'dry'. No rainfall rates are assigned to the satellite-derived field which is displayed in a unique colour. The satellite and radar precipitation fields are carefully merged to produce the base image for the forecast step.

3.5 The Original Forecast Scheme

The original forecast scheme allows the base image to be divided into areas, known as clusters, each of which is assigned a velocity, with which it moves *en masse* in a straight line. The velocities may simply be fed in, e.g. 700 mb wind, but are normally determined from the motion of the radar echoes using semi-automatic techniques. The crudest method asks the forecaster to touch the same feature on two images thirty minutes apart, and the velocity is calculated from the displacement. A better method, known as Lagrangian replay, allows a velocity to be calculated in the same way but from images one or two hours apart. A replay is then performed with the calculated velocity subtracted and fine adjustments made using a joystick until the chosen feature appears stationary, thereby accurately defining its velocity.

An important feature of the forecast in many frontal cases is that the fraction of any orographic enhancement applied in the radar analysis is removed from the base image. As each pixel moves to its new location, the appropriate percentage of the enhancement applying to that pixel is added on. Another feature of the original forecast scheme is that an intensity trend may be specified for each cluster. This decreases the rainfall rates linearly through the forecast period by up to a factor of sixteen or increases them by up to a factor of four. Pixels falling below 0.03 mm h^{-1} are deleted.

After the computation of the cluster forecast, precipitation may be added to or deleted from each of the six individual hourly forecast images, if there is sufficient time.

3.6 Wind-Based Advection Forecast Scheme

Figure 3 shows the relationship between the original scheme and the new wind-based forecasts, together with the data flow between the VAX 11/750 and the new VAXstation 3520. The key to the success of the new scheme lies in the ability of the forecaster to choose which wind field best represents the motion of the precipitation, or to decide that neither is appropriate and use the cluster technique instead. At the end of the radar analysis the quality-controlled radar composite image is passed from the VAX 11/750 to the VAXstation, where it is used to produce two forecast sequences based upon the 850 mb and 700 mb winds. If orographic corrections have been applied, details of these are also passed over, together with the "disenhanced" radar image, which has had removed the fraction of the enhancement which the radars are believed to see. The two forecast sequences are available for inspection by the end of the satellite analysis.

The T+1 to T+6 forecasts may be inspected individually or replayed rapidly in a sequence preceded by the six previous hourly radar actuals. One method of assessing the best forecast is to look for continuity between the motion in the sequence of actuals and the forecast sequence. Another method is to compare the forecast winds, which can be displayed on the VAXstation as shown in Figure 4, with the velocities derived in previous cycles by tracking the radar echoes.

At the end of the satellite analysis the forecaster is invited to select one of the wind-based forecasts, which is recomputed on the VAXstation using the combined radar/ satellite rainfall field. Intensity trends may be applied to delineated areas, as in the cluster forecast technique. As a guide to the selection of the intensity trends, the forecaster can view the mesoscale model precipitation forecasts, which are displayed in a pseudo-radar format on the VAXstation, as single images or in a replay sequence. However, before accepting such guidance, he should examine the accuracy of the model predictions compared to recent radar actuals.

Initial experience with the new scheme showed that on some occasions the wind-based forecasts were only useful for part of the field. For example, post-frontal showers are often tied to the coastal regions of Ireland, where they appear to be generated and decay before moving too far inland. The wind-based forecasts tended to advect them across the UK. Therefore the forecaster has been given the option of delineating areas which will remain stationary, since this appeared to be the best simple option in such cases. This facility has recently been extended to allow the delineated areas to be assigned a specified velocity, as an alternative to remaining stationary. Outside these areas the forecast winds are used.

The forecasters also pointed out that sometimes the pattern of motion produced by the model wind fields was good, but the speed was incorrect at both levels. Therefore the facility has been introduced to apply temporary scale factors to the mesoscale model winds, within designated areas, to change the speed by a factor in the range 0.5 to 2.

If neither wind level gives a reasonable forecast, the forecaster can use the original cluster technique. This option is available even if a wind-based forecast has been selected. After his chosen wind-based forecast has been computed he can still change his mind and ask for the other wind level. He can also choose a wind-based forecast after completing a cluster forecast. However this wastes time and normally his first choice should be the correct one, because he has selected it on the basis of the radar-only forecasts which were viewed at the end of the satellite analysis. After finally accepting his choice of wind-based forecast, the six forecast fields are transferred to the VAX 11/750 where they can be modified individually before dissemination. (If a cluster forecast has been performed they are already on the 11/750.)

3.7 Accumulation Forecasts

The original forecast products were six fields of instantaneous rainfall rates (plus satellite and drawn in rain) at hourly intervals. These were calculated using a one hour timestep, which has also been found to be adequate for the wind-based forecasts. With the addition of the VAXstation, it has been possible to produce accumulations as well. Since one of the principal uses of FRONTIERS forecasts is for hydrological purposes, this is a significant advance. Previously it had been necessary to assume that the rainfall rates in each instantaneous forecast field represented the accumulation over one hour. The computation of the accumulations requires a very short timestep (down to five minutes) in order to avoid jumping over pixels. It takes about eight minutes on the VAXstation 3520 to compute the accumulation forecasts out to six hours.

All the adjustments applied to the instantaneous forecasts, i.e. intensity trends, orographic corrections, are now applied to the accumulations as well. However, the addition of orographic corrections to the accumulations was only introduced in February 1991. Unfortunately it was discovered later that an error in the software meant that the orographic corrections were not being applied to the wind-based forecasts. This was corrected in October 1991.

Forecaster-specified deletions and insertions of rain are also taken into account during the computation of the accumulations. If such alterations have been made, the instantaneous forecasts have to be transferred back to the VAXstation, as shown on Figure 3. Otherwise they can be computed from the base image already resident on the VAXstation.

Although visible and infra-red satellite data have generally been found to contain little information on instantaneous rainfall rates for a specific occasion, useful information has been obtained on accumulations, Bellon and Austin (1986). Therefore the satellite-derived precipitation has been assigned an intensity for the purposes of forming an accumulation. Initially this has been defined as the mean of the average radar rainfall rate in the base image and the climatological average rainfall rate on the western coast of the UK (0.8mmh^{-1}), weighted by the number of radar rainfall pixels and satellite rainfall pixels respectively. Any orographic corrections which have been specified are applied to the satellite-derived rain when forming the accumulations, hence the use of the climatological coastal rate. Precipitation drawn in by the forecaster when modifying the instantaneous forecast fields is treated in the same way as the satellite-derived precipitation. This is a first-guess scheme and will probably require modification in the light of experience.

4. Operational Flood Forecasting

The National Rivers Authority operates a flood warning service throughout ten regions in England and Wales. The objective of the service is to minimize danger to people and reduce financial losses from flooding by providing timely, accurate and reliable warnings of impending river flooding enabling those at risk to take remedial action. The service has three levels of warning, Yellow, Amber and Red, each of which is associated with increasing flood risk. Yellow warnings are indicative that minor flooding of roads and land is likely, up to Red warnings indicating that there is a high probability of serious flooding of property in a particular locality. To be useful warnings need to be issued to the appropriate authorities between 2 and 6 hours before flooding occurs.

4.1 NRA Thames Region

The Thames Region of the NRA operates a flood forecasting and warning service for "main" rivers within the catchment area of the River Thames.

In the upper reaches of river catchments and in the urban area in and around London, rivers can respond to heavy rainfall within a very short time (Figure 5). It is recognized that in such cases a warning target of 2 hours is often not feasible without accurate, quantitative rainfall forecasts. Without such forecasts an effective warning lead-time of thirty minutes to one hour may be the best that can be achieved.

To monitor and forecast floods in fluvial catchments in London and the Lee Valley, the Thames Region has developed a sophisticated system known as CASCADE (a Catchment Assessment System Concerned with the Accurate Dissemination of Effective flood warnings). At its heart lies a VAX 4000 -200 computer which collects data from the weather radar installation at Chenies in Buckinghamshire, a network of 55 rain-gauges and 70 river-level gauges. Heavy Rainfall Warnings and longer term weather forecasts from the London Weather Centre are also received via an integrated telex unit. These data are made available through terminals based within the Flood Warning Centre at Waltham Cross in Hertfordshire and in Flood Duty Officers' homes. This allows a developing flood situation to be monitored at any time of the day or night.

Data from Chenies are received every 5 minutes and may be displayed in either 2 km and 5 km grid format or as sub-catchment totals. Data can be obtained from all of the telemetered rain-gauges and river level stations within 10 minutes. Software allows display of rainfall and river level data in many immediately visible formats. When data become available, displays are automatically updated without user intervention. The outstations are configured to inform the telemetry computer when either critical rainfall rates or river levels are attained. These alarms are either directed to specified terminals or to appropriate telephone numbers, including mobile telephones and pagers, via an Autodialler. In this way the duty officer is very rapidly alerted to a developing flood situation. Menu-driven procedures assist the issue of flood warnings to the police and other external organizations whose details are stored on computer against particular river reaches. Telex and fax messages can be issued automatically from terminals either at home or within the office.

To enhance the accuracy and timeliness of flood warnings several new initiatives have been introduced. A local radar calibration scheme has been developed and run operationally since 1989. Radar images are calibrated on the VAX computer in real-time by reference to rainfall recorded by the network of telemetering rain-gauges. This enables the accuracy of rain-gauge rainfall data to be combined with the spatial characteristics of radar rainfall measurements.

Flood forecasting with catchment models also forms an integral feature of the operational flood warning system. However, the variation in topography, geology and land use throughout the region gives rise to marked contrasts in the hydrological characteristics of different rivers. To accommodate the full range, from smaller flashy urban catchments in and around London, to the larger slower-responding rural catchments, it has been necessary to adopt more than one model, although each is capable of operating with either radar or rain-gauge rainfall estimates (Figure 6).

The use of radar and/or rain-gauge data in isolation limits the maximum warning time to the rainfall-runoff lag of the subcatchment in question. It has already been stated that in the upper reaches of the urban catchments in London, these lag times can be as short as thirty minutes and in such circumstances there is a need for quantitative rainfall forecasts to extend lead times. Until rainfall forecasts of this type become operationally available, any improvement in warning times will only be achieved through closer liaison with the local weather centre or through subjective extrapolation by flood duty staff before and during an event. The system has been designed therefore, to accept rainfall forecast details such as the expected start of the storm,

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It is not surprising, therefore, that Thames Region is keen to implement improved techniques capable of generating reliable and accurate rainfall forecasts in realtime, which in turn will lead to improved flood forecasts. With this in mind, two approaches are being examined in detail:

1. FRONTIERS	making use of data generated by the Met. Office giving forecasts out to 6 hours ahead on a 5 km grid, updated every 30 minutes.
2. LOCAL FORECASTS	a regional radar-based system developed by the Institute of Hydrology providing forecasts up to 2 hours ahead on a 2 km grid, updated every 15 minutes (Moore *et al* 1991).

It is envisaged that both systems will be used in tandem, with the higher-resolution forecasts, which are required particularly for flood warning over the London area, small rural catchments and during convective storms, providing a valuable complement to the national FRONTIERS products. The Institute of Hydrology is evaluating both techniques in a hydrological context and recommendations on operational implementation will be given. In addition Thames Region is assessing the use of FRONTIERS data to ascertain whether such forecasts will enhance flood forecasts and flood warning generally. The results of this work are presented in section 8 of this report.

4.2 NRA North West Region

The North West Region of the NRA operates a flood forecasting and warning service similar to that outlined in the previous section and described by Walsh and Lewsis (1987) and Noonan (1987). In section 9.5 the way in which FRONTIERS forecasts were used by duty flood forecasters is outlined. Radar data from the Hameldon Hill radar are an integral part of this system.

5. Systems Availability

The availability of the FRONTIERS forecasts received by the NRA Thames Region at Waltham Cross is shown in Table 1. The instantaneous forecasts were available 86.5% of the time, at Thames NRA, rather less than the typical net availability of radar actuals. The average percentage of FRONTIERS quality-controlled radar actuals disseminated during this period was around 90%, varying from 85% to 98% on a monthly basis. The lower monthly figures were associated with significant changes to the FRONTIERS software. The additional losses of the instantaneous forecasts can be attributed to telecommunications problems and the lower reliability of the *ad hoc* dissemination software used for the trial. The accumulation forecasts availability averaged over the whole of 1991 was 73.5%. The main reason for the lower availability of the accumulations is that they are produced on the VAXstation 3520, the 11/750 being too slow. The software on the VAXstation 3520 has been only recently developed, and still has a few bugs causing it to crash occasionally. The instantaneous forecasts are then produced by the cluster technique on the 11/750 but no accumulation forecasts can be produced.

Table 1: **FRONTIERS forecast availability at the NRA THAMES Region, Waltham Cross, January to December 1991**

Month	Instantaneous	Accumulations
January	89.6	84.9
February	90.2	62.4
March	87.8	79.9
April	73.0	54.0
May	60.8	50.8
June	89.8	78.3
July	95.2	84.8
August	92.3	84.4
September	93.8	76.3
October	92.8	76.6
November	86.1	73.0
December	86.7	87.2
Year Average	86.5	73.5

6. Current Heavy Rainfall Warning Procedures

Both London and Manchester Weather Centres have been issuing heavy rainfall warnings to their local NRA regions for many years. The forecasters at these Weather Centres use various aids to help them reach a decision on the expected quantities of rain. Both Centres rely on numerical model forecasts as guidance for periods beyond about 6 hours. They also use traditional techniques such as studying the synoptic situation at the surface and upper levels. Continuity of radar rainfall images helps them in the short term (up to about 4 hours). More recently the FRONTIERS forecasts of radar image intensities have been an extra aid in some circumstances. The procedure for heavy rainfall forecasting at Manchester, in more detail, is as follows:

(i) A statistical study of past heavy rainfall events has resulted in a set of rules to predict such occurrences. A series of flow charts, is in use and runs to 9 pages. Briefly, the NRA Northwest Region is split into 15 areas (figure 16) for which heavy rainfall warnings are required. Areas north of the Mersey are unlikely to receive critical amounts of rainfall unless the airflow is from the west or south-west and is moist up to 600mb. South of the Mersey, the warning areas are in a rain shadow for west or south-west winds and north-west winds are usually required. These southern catchments are also susceptible to summer thunder storms moving north from the Midlands. Together with these general rules, the movement of fronts, waves and depressions and the stability of the air mass are taken into account.

(ii) The forecaster makes an ongoing appraisal of the forecast synoptic situation, in this he is assisted by guidance from the Central Forecasting Office. Particular regard is taken of frontal positions. He is aware of situations that are favourable for producing large rainfall totals (from (i)).

(iii) Using the forecasting aids previously mentioned (flow charts, radar, FRONTIERS, latest synoptic information, model guidance, Central Forecast Office guidance) the forecaster will estimate quantities of rain to be expected in the 15 areas of NRA North-west. If necessary, warnings will be issued.

(iv) At around 1700 each day a forecast of rainfall totals is passed over the telephone to the NRA duty officer. It acts as a preliminary alert that a warning may be issued during the following 24 hours.

One outcome of the project was that procedures for preparing heavy rainfall forecasts at the London Weather Centre were improved in the latter half of the study period such that forecasts were made for smaller areas of the NRA Thames Region rather than just for SE England.

its duration, peak intensity and total depth. This information is fed into one of several pre-defined rainfall profiles which is in turn used to generate a flow forecast at a point of interest. In practice, it has been found that the rainfall forecasts supplied by the local weather centre have not been reliable enough to be used quantitatively in catchment models and the procedure has not been used operationally.

It is not surprising, therefore, that Thames Region is keen to implement improved techniques capable of generating reliable and accurate rainfall forecasts in realtime, which in turn will lead to improved flood forecasts. With this in mind, two approaches are being examined in detail:

1. FRONTIERS	making use of data generated by the Met. Office giving forecasts out to 6 hours ahead on a 5 km grid, updated every 30 minutes.
2. LOCAL FORECASTS	a regional radar-based system developed by the Institute of Hydrology providing forecasts up to 2 hours ahead on a 2 km grid, updated every 15 minutes (Moore *et al* 1991).

It is envisaged that both systems will be used in tandem, with the higher-resolution forecasts, which are required particularly for flood warning over the London area, small rural catchments and during convective storms, providing a valuable complement to the national FRONTIERS products. The Institute of Hydrology is evaluating both techniques in a hydrological context and recommendations on operational implementation will be given. In addition Thames Region is assessing the use of FRONTIERS data to ascertain whether such forecasts will enhance flood forecasts and flood warning generally. The results of this work are presented in section 8 of this report.

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7. Met Office Assessment of FRONTIERS Forecasts

7.1 Basic Evaluation Strategy

This report concentrates on the evaluation of the FRONTIERS accumulation forecasts, introduced as a new product at the start of the POSFFAG project trial year. Online comparisons of the instantaneous forecasts with radar actuals have been made since the beginning of 1990. These are used in this report to evaluate the accuracy with which the instantaneous forecasts correctly predict the location of rain areas.

Forecast accumulations are evaluated by comparison with raingauge data, rather than radar integrations, because the latter can be subject to significant errors due to bright-band effects and growth beneath the radar beam. Use of raingauge data as ground truth is not without its problems. The gauges used in the study are of tipping bucket design, each tip representing 0.2 mm. This will lead to quantisation errors in comparisons with accumulation forecasts, which are stored in increments of 1/32 mmh^{-1}. There is also a representativeness problem because the gauges sample at a point and the accumulations are averages over 5 x 5 km pixels. Kitchen and Blackall (1992) found that the spatial representativeness effect for convective rain produced a root mean square error in log (accumulation/gauge) for hourly accumulations of around 0.34, for a 5 x 5 km pixel with the gauge at the median distance from the centre of the pixel (ie 1.2 km). This was reduced to 0.19 if hourly values less than 0.5 mmh^{-1} were excluded. It should also be less for frontal rain, although the root mean square error has not been obtained directly in this case. Despite these problems the errors involved in comparison with gauges are thought to be less than those involved with radar data. Also, hydrologists generally consider gauges to represent the "ground truth" rather than radar data. Finally, it should be noted that in most of the evaluations the quantisation and representativeness errors will be mitigated because comparisons are performed for areas containing several gauges.

Different evaluation strategies have been used for the NW and Thames regions. Because Manchester Weather Centre (MWC) make quantitative forecasts of accumulations over specific catchments, evaluation for the North West has concentrated on comparing the MWC and FRONTIERS forecasts accumulations. The forecasts provided by London Weather Centre (LWC) for the Thames area are less specific, especially with regards to area, which makes them difficult to compare with FRONTIERS. However, the density of gauges is higher in the Greater London area than in the NW. Therefore evaluation in this area has concentrated on examining the accuracy as a function of catchment size and accumulation period.

7.2 Definition of Statistics for Rain-gauge Comparisons

Many statistics are available and more than one is required to describe fully the performance of the forecasts. Considerations which have influenced the choice include the ability to compare with previous published work, ease of interpretation and possibility of performing tests of significance. In equations (1) to (5), F_i, G_i, represent forecast and gauge accumulations, either individual values or catchment averages. When individual gauges are used they are compared with the co-located 5 x 5 km forecast value. When considering catchments, the arithmetic mean gauge value has been used as an estimate of the catchment average. The corresponding forecast value is taken as the arithmetic mean of the pixels within the catchment. At the boundaries of catchments, pixels are included in the catchment with which they have the greatest overlap. The full pixel value is used in these cases, i.e. we have not apportioned a fraction of the value to each catchment overlain by a pixel.

The simplest statistics used are the bias (B) and the mean absolute error (MAE).

$$B = 1/N \sum_{i=1}^{N} (F_i - G_i) \tag{1}$$

$$MAE = 1/N \sum_{i=1}^{N} |(F_i - G_i)| \tag{2}$$

They have the advantage of being in understandable units eg mm and can deal with zero F_i ,G_i , values. However their value is likely to be correlated with the magnitude of the F_i and G_i values, so they need to be put into perspective by comparison with the actual gauge values. Following CWPU (1977) and Bellon and Austin (1984) we consider :-

$$AD = 100/N \sum_{i=1}^{N} |F_i - G_i| / \bar{G} \tag{3}$$

Bellon and Austin (1984) refer to this as the mean absolute deviation, abbreviated to AD. The MAE is expressed as a percentage of the observed accumulation. The precise definition of F_i, G_i, and G is not totally clear in Bellon and Austin. Since this is dependent upon the evaluation strategy, which is not the same in the NW and Thames areas, Fi and Gi will be defined in the appropriate later sections.

The bias may also be expressed as a percentage, in a similar way to AD.

$$BP = 100/N \sum_{i=1}^{N} (F_i - G_i) / \bar{G} \tag{4}$$

Besides the advantage of AD already noted, it is also easy to understand. It has the disadvantage of not coping fully with zero gauge values, individual gauge values can be zero but not G. Another disadvantage of this statistic is that it is not likely to be normally distributed, because for $F_i = G_i$, AD = 0 but its range is 0 to ∞. Furthermore it does not give equal weight to forecast overestimates and underestimates, since if $G_i >> F_i$, AD ——> 100, but if $F_i >> G_i$, AD is unbounded in its upper value. Similar comments apply to BP.

The final statistic used is the root mean square difference in log10 F_i, G_i, (RMSL).

$$\text{RMSL} = \left\{1/N \sum_{i=1}^{N} (\log F_i - \log G_i)^2\right\}^{1/2}$$
$$= \left\{1/N \sum_{i=1}^{N} \left(\log \frac{F_i}{G_i}\right)^2\right\}^{1/2} \quad (5)$$

The advantage of RMSL is that it is likely to be more normally distributed than AD because RMSL = 0 if $F_i = G_i$ and has a possible range of $\pm\infty$. It also treats $F_i >> G_i$ the same as $F_i << G_i$. Equal weight is given to all values, ie $F_i = 0.4$, $G_i = 0.2$ makes the same contribution to RMSL as $F_i = 40$, $G_i = 20$. This might not be an advantage, since the frequency of rainfall rates decreases rapidly with increasing rate, RMSL might be dominated by large fractional errors in small accumulations. Although numerical values of RMSL are not so open to interpretation as MAE, AD, it has been used widely in radar/gauge comparisons, which gives some sort of baseline for the forecast/ gauge comparisons.

The biggest problem with RMSL is that it does not admit the use of zero values. To overcome this problem, Moore *et al* (1991) at the Institute of Hydrology has introduced a modified form by adding 1mm to each F_i and G_i value inserted into equation (5). This has the advantage of allowing zero F_i and G_i values, besides reducing the weight given to F_i, G_i values <<1. All F_i, G_i >>1 are still given equal weight. This statistic has been included to allow comparison with results from the IH precipitation nowcasting system.

7.3 Results from the North West Area

The FRONTIERS accumulation forecasts are compared with the heavy rainfall warnings issued by MWC, produced using the technique described in section 6. The catchments for which warnings are issued are shown in Figure 1b. The warning criteria are:-

Type	Warning Criteria	Catchments
A	30-40mm or more in 6-12 hours	1-10
B	15mm or more in 6 hours	11-14
C	10mm or more in 6 hours	15

The occasions analysed were those when either MWC issued a heavy rain warning or when FRONTIERS forecasts exceeded the warning limits in one or more catchments. The latter cases were included because FRONTIERS might have achieved a high probability of detection, at the expense of a high false alarm rate, by issuing too many warnings. When the MWC warning was for a twelve hour period, two consecutive six-hour FRONTIERS accumulations were added together. Occasionally the MWC warning was for a period between six and twelve hours. Then the appropriate number of hours of accumulation from the second FRONTIERS forecast were added to the six-hour accumulation from the first. Table 2 gives details of the warnings issued by MWC. It can be seen that the lead times of the forecasts issued by MWC varied from about six hours to minus four hours (i.e. four hours into the event). Because of the limited period of the FRONTIERS forecasts we have not followed the MWC lead times. All the FRONTIERS forecasts evaluated used as initial data that from the start of the warning period in Table 2 (and of course six hours later if it was necessary to form an accumulation over more than six hours). Only forecasts up to the end of October 1991 have been included in the evaluation exercise.

Three events have been omitted from the analysis when FRONTIERS underforecast significant accumulations, because each case was found to be due to a software problem in FRONTIERS. These were 10th October 1990, 2300-0800, 28th December 1990, 1000-1600 and 1st January 1991, 1200-0000. Four other forecasts have been omitted from the scatter plots and statistics, where FRONTIERS produced unrealistic totals because of corrupt radar data not removed in the FRONTIERS radar analysis. These are 19 July 1991, 1130 (F = 50mm, G = 0mm), 29 August 1991, 2300 (F = 32mm, G = 0mm), 11 October 1991, 2100 (F = 75mm, G = 0mm), 30 October 1991, 0900, (F = 30mm, G = 0.2mm). These cases are included in Table 2. Cases where there may have been problems with the radar data of a meteorological origin are retained.

Table 2: Heavy rainfall warnings issued by Manchester Weather Centre

DATE	ISSUED	F/C PERIOD	CATCHMENTS	LEAD TIME	FORECAST
30 Sep 90	0300GMT	0300-0900	15	NIL	10-15mm in 6h
02 Oct 90	1430GMT	2000-0200	11-15 inc	5h30min	15mm in 6h
02 Oct 90	1515GMT	1515-0315	2,4,6,7	NIL	30mm in 12h
04 Oct 90 05 Oct 90	1845GMT	 0000-1200	1,3,5,6 7,9	5h15min	30mm in 12h
05 Oct 90	2050GMT		1,3,5,7,9	5h	50mm in 9h
06 Oct 90		0200-1100	11-14		13-20mm in 9h
10 Oct 90 11 Oct 90	2230GMT	 2300-0800	1,3,5 6,7	30min	30-40mm in 9h
15 Oct 90	0315GMT	0400-1000	1-6 inc	45min	40-60mm in 6h
18 Oct 90	0130GMT	0600-1000	11,13,14	4h30min	20mm in 4h
25 Oct 90 26 Oct 90	2050GMT	2100-0300	11-15	NIL	15mm in 6h
16 Nov 90	1230GMT	1300-1900	2-4 inc,6,7,9	30min	30mm in 6h
19 Nov 90	1700GMT	1700-2300	11-14 inc	NIL	15mm in 6h
06 Dec 90	1655GMT		11-13 inc	10h	15mm in 6h
07 Dec 90		0300-0900	15		10mm in 6h
11 Dec 90	1600GMT	1600-2200	1-10 inc	NIL	>30mm in 6h
11 Dec 90			11-15inc		15mm in 6h
22 Dec 90	0900GMT	0900-2100	3-7 inc	NIL	>30mm in 12h
22 Dec 90 23 Dec 90	2143GMT	 0300-1200	1-7 inc	5h15min	>30mm in 9h
28 Dec 90	1400GMT	1000-1600	1-10 inc	-4h	>30mm in 6h
31 Dec 90	0855GMT	1000-1600	11-13 inc	1h	15mm in 6h
01 Jan 91	0945GMT	1200-2400	1-10 inc	2h15min	30mm in 12 h
01 Jan 91		1500-2100	11-14 inc	5h15min	15mm in 6h
01 Jan 91		1500-2100	15	5h15min	10-15mm in 6h
05 Jan 91 06 Jan 91	2301GMT	 0000-0600	 11,12,13	 1h	 15mm in 6h
08 Jan 91	1100GMT	1300-1900	11-15 inc	2h	15mm in 6h
09 Jan 91	1700GMT	1600-2200	11-15 inc	-1h	10-20mm in 6h
18 Jan 91	1730GMT	1600-2200	1-10 inc	-1h30min	30mm in 6h
15 Feb 91 15 Feb 91	0230GMT	0200-2100	1-7 inc	-30min	>10mm rain in 18h + thaw
21 Feb 91	1215GMT	1100-1700	4,7,8	-1h15min	>30mm in 6h
21 Feb 91			11-14 inc		15-25mm in 6h
21 Feb 91			15		>10mm in 6h
22 Feb 91	0810GMT	1400-0200	3,4,5,6,7	5h50min	35mm in 12h
23 Feb 91			1,2,8,9,10		25mm in 12h
23 Feb 91		1400-2000	11,13,14		15mm in 6h

Table 2: Heavy rainfall warnings issued by Manchester Weather Centre

DATE	ISSUED	F/C PERIOD	CATCHMENTS	LEAD TIME	FORECAST
04 Mar 91	0730GMT	0800-1800	1-10 inc	30min	>30mm in 10h
04 Mar 91	1040GMT	1200-1800	11-15 inc	1h20min	10-15mm in 6h
04 Mar 91	1835GMT	1900-0000	1-10 inc	30min	30mm in 5h
07 Mar 91	0745GMT	0900-1500	1-15 inc	1h15min	10-15mm in 6h
18 Mar 91	0800GMT	1400-0200	3,5,6,7,9	6h	40mm in 12h
19 Mar 91		1400-2000	11-14 inc	6h	15mm in 6h
19 Mar 91	0115GMT	0100-1300	3,4,5,6,7	-15min	30mm in 12h
19 Mar 91	1530GMT	1500-1900	10,11,13	-30min	15mm in 4h
01 Apr 91	0600GMT	0600-1800	1-10 inc	NIL	>30mm in 11h
01 Apr 91		1200-1800	11-14 inc	6h	15mm in 6h
01 Apr 91		1200-1800	15	6h	10mm in 6h
01 Apr 91	1615GMT	1800-0600	3,5,6,7,8	1h45min	30mm in 12h
29 Apr 91	0245GMT	0800-1400	11-15 inc	5h15min	10-15mm in 6h
27 Jun 91	1350GMT	1400-1900	11,13,14	10min	15mm in 5h
02 Jul 91	0955GMT	1200-1800	11-14 inc	2h5min	15mm in 6h
02 Jul 91		1200-0600	1-10 inc	2h5min	30mm in 18h
02 Jul 91		1200-0600	15	2h5min	10mm in 18h
06 Jul 91	0545GMT	0600-1100	12,13,14,15	15min	15mm in 5h
11 Jul 91	0825GMT	1000-1600	11-15 inc	1h35min	15mm in 6h
18 Jul 91	0500GMT	0600-0800	15	1h	10mm in 2h
30 Jul 91	1945GMT	0200-0800	11-15 inc	NIL	20mm in 6h
09 Aug 91	0720GMT	0800-1400	11-14 inc	40min	15mm in 6h
09 Aug 91		0800-1400	15	40min	10mm in 6h
21 Sep 91	1740GMT	1800-0200	1-7 inc	20min	30mm in 8h
21 Sep 91		1800-0200	8-14 inc	20min	15mm in 8h
26 Sep 91	0710GMT	0700-1000	11,13	-10min	15mm in 3h
04 Oct 91	2145GMT	0000-0900	1-9 inc	3h15min	30mm in 9h
31 Oct 91	0525GMT	0600-1800	1-10 inc	35min	25mm in 12h
31 Oct 91		0600-1800	11-14 inc	35min	15mm in 12h
31 Oct 91	1535GMT	1500-2100	11-15 inc	-35min	30mm in 6h
10 Nov 91	1600GMT	1600-0200	1-10 inc	NIL	30mm in 9h
10 Nov 91		1600-0200	11-14 inc	NIL	20mm in 9h
12 Nov 91	1430GMT	1500-2100	1-9 inc	30min	30mm in 6h
19 Dec 91	0430GMT	0430-1030	5-10 inc	NIL	30mm in 6h
21 Dec 91	0400GMT	0400-1000	1-7 inc	NIL	30mm in 6h
21 Dec 91	1155GMT	1200-1800	11-14 inc	5min	15mm in 6h
21 Dec 91	1950GMT	2000-0800	7,9,11,13,14	10min	30mm in 12h
23 Dec 91	0655GMT	0700-1200	1-10 inc	5min	30mm in 5h
23 Dec 91		0700-1200	11-14 inc	5min	15mm in 5h

During the evaluation, persistence forecasts were also prepared for each case. These assume that the initial rainfall rate in each pixel persists for the entire accumulation period. (In fact, rather than use the initial instantaneous rainfall-rate field, for convenience, the initial fifteen-minute accumulation was multiplied by the appropriate number, e.g. 24 for a six hour accumulation). The FRONTIERS forecasters sometimes decide that the best option is to leave the initial field stationary. This may be the best tactic with convection tied to topographic features or stationary fronts, at least with regards to the instantaneous forecasts. Thus sometimes the FRONTIERS forecasts and persistence forecasts are identical.

About eighteen gauges were used initially. However during the project other data from other gauges became available and the total rose to about eighty. The earlier cases were reworked using the extra data. The number of gauges per catchment varied from one to thirteen, averaging five per catchment.

It was not possible to form representative average values in many of the catchments because there were too few gauges. Therefore the FRONTIERS forecasts were compared to the average of the totals from the gauges located in the catchments for which warnings were issued, rather than on a catchment by catchment basis. The FRONTIERS forecast accumulations were also averaged over the same catchments, using every pixel value, not just those collocated with gauges. Figure 7 shows the results for the Manchester Weather Centre forecasts, which are really lower bounds not actual forecast values. It can be seen that the forecast lower bounds often greatly exceed the gauge values and there is a strong bias towards overestimating the accumulations. However the general correlation between the forecast lower bound and the gauge values is better than for FRONTIERS. It is also important to note that during the trial period MWC issued heavy rainfall warnings for all events exceeding the warning criteria as recorded by the gauges. This was not true for FRONTIERS.

One possibility considered during the analysis was whether the MWC technique appeared to be overestimating because it actually predicted the maximum value in a catchment rather than the average. Figure 8 shows the same MWC forecasts as in Figure 7 plotted against the maximum gauge value drawn from all the gauges in the catchments for which warnings were issued. It can be seen that although the forecast overestimation is reduced it is still significant.

Figure 9 shows that the results for FRONTIERS for the occasions when either MWC issued a warning (filled circles) or FRONTIERS would have issued a warning but MWC did not (open circles). The results for the occasions when MWC issued a warning are scattered about the 1:1 line, but with less correlation apparent than for the Weather Centre forecasts. There is a tendency for FRONTIERS to underestimate the larger accumulations observed. One reason may be that the option to apply orographic enhancements to the accumulations was only introduced at the end of the evaluation period. Orographic enhancement is believed to be an important factor in many of the NW catchments.

It can be seen from Figure 9 that when the FRONTIERS forecasts exceeded the warning criteria, they were generally large overestimates. Many of these forecasts were persistence forecasts as can be seen by comparing Figures 9 and 10, i.e. the forecaster left the rain stationary. In most cases (70%) the warning criteria were only exceeded in one catchment, where a small area of intense rain was present in the initial field. In reality this either decayed or moved into other catchments. Whilst the use of stationary forecasts can sometimes give the best indication of the instantaneous field for the next few hours ahead, it is not surprising that this strategy causes problems for the accumulations and some modification to the accumulation procedure appears necessary for these cases. The FRONTIERS warning cases which were not persistence forecasts generally involved the use of small velocities. Figure 10 shows the results for persistence for both the MWC warnings (filled circles) and FRONTIERS warning cases (open circles). It can be seen that for the MWC warning cases, many of the points lie away from the 1:1 line, whilst for the FRONTIERS warnings a few points have moved closer.

The fact that the large FRONTIERS accumulation values are localised is illustrated by Figure 11 which shows the results for the catchments for which warnings were not issued, for both the MWC and FRONTIERS warning cases. It can be seen that in the cases when FRONTIERS issued a warning the average value in the non-warning catchments was much closer to the gauge value. Figure 12 shows the results for persistence in the non-warning catchments. For the MWC warning cases the difference between the FRONTIERS and persistence seem less than for the warning catchments. There is little difference for the FRONTIERS warning cases, because in the majority of these FRONTIERS used persistence and in many of the other cases the rain was very slow moving.

The results presented so far suggest that forecast accuracy improves as the area over which the accumulations are averaged is increased. One reason why in the FRONTIERS warning cases, the results in the non-warning catchments are so much better is probably that often all the catchments but one are non-warning catchments. To confirm this, the FRONTIERS accumulations have been averaged over all catchments and compared with the average value of all the gauges, for both MWC and FRONTIERS warning cases. The result are shown in Figure 13, which should be compared with Figure 9. A definite improvement is noticeable, although some poor forecasts remain. These have been investigated and are discussed in the next section. The equivalent results for persistence are shown in Figure 14. There is not such a marked difference between the FRONTIERS forecasts and persistence as in the case of the warning catchments i.e. comparing Figures 9 and 10, although there are more outliers from the 1:1 line in the case of persistence and several more points on the x axis.

Twenty-one of the worst FRONTIERS forecasts cases have been investigated. Three of these have been discarded because they were caused by software problems. The rest have been divided into two classes, FRONTIERS significantly overestimates and FRONTIERS significantly underestimates, relative to the gauges. There are only two cases in the latter category. In one of these the overall pattern of the forecast was good on the larger scale, but the detail on the scale of the NW catchments was wrong. In the other case a wind-based forecast was applied to a stationary front.

The results of the analysis for cases where FRONTIERS overestimated are shown in Table 3.

Table 3: **Analysis of Significant FRONTIERS Overestimates**

Main Problem	Number
Persistence was used, generally good on larger scale, but wrong in detail	5
FRONTIERS advected the ppt. Forecast good on large scale, but wrong on scale of catchments	3
The actual ppt. field decayed, FRONTIERS did not decay it.	3
Bright band or intense convective cell in base field.	3
Undeleted severe anaprop or high-intensity corrupt radar data	4
Cluster forecast used wrong velocity	1

Although the cases of undeleted anaprop etc. are disappointing, they only represent about 1 in 3500 of the forecast sequences scanned.

An example of a forecast which was quite good on the broad scale but wrong in detail is shown in Figure 15 for 1st July 1991, 1400 GMT. FRONTIERS forecast a six-hour accumulation of 23 mm in catchment 10 whilst the gauge average was 8 mm (13 mm gauge maximum). Figure 15a shows the six forecasts of instantaneous rainfall rate with the verifying radar actual underneath (reduced to 10 km resolution). The radar actual includes satellite-diagnosed rain in pink. The other colours represent different radar rainfall rates, red being the lightest and yellow the heaviest. There were various areas of convective rain circulating around a weak low centred over the Irish Sea at this time. The FRONTIERS forecaster used the 3190 m model wind, but with a stationary area defined over part of NW England, the whole of Wales and SW England. It can be seen from Figure 15a that this strategy has produced a good forecast on the broad scale out to T+3, except for the area of rain over Southern Ireland, which has been moved too far eastwards. Also, on the broad scale, the stationary area of echoes over the NW in the forecast still verifies quite well at T+6. Thus the forecaster appears to have done a very good job in this difficult situation.

Figure 15b shows details of the six forecasts of instantaneous rainfall rate for the NW catchments, together with the T+0 radar field (labelled MRADCM). It can be seen that the echoes in the south have been left stationary whilst the rest move NE. Figure 15c shows the verifying radar actuals. Comparing Figures 15b and 15c it can be seen that on the scale of the entire NW area the forecasts give a good impression of the general distribution of the precipitation. However on the scale of individual catchments there are some large discrepancies. For example at T+1 there is insufficient precipitation forecast in catchment 13. Figure 13d shows the hourly accumulations and the six-hour accumulation. It can be seen how small intense cells in the initial radar field have led to large localised accumulations where the precipitation is left stationary. As noted earlier, some alteration to the accumulation calculation appears necessary for stationary forecasts.

The results illustrated in Figure 7 - 14 are summarised in terms of the statistics defined in equations (1) to (5) in Table 4. In evaluating equations (3) and (4), G is the average value over all events. All cases where F or G equal zero have been excluded from all the statistics, although this is only strictly necessary for RMSL. Table 4 illustrates the large positive bias (overestimate) of the MWC and FRONTIERS warnings and the tendency for FRONTIERS to underestimate in the case of MWC warnings.

Table 4. Summary of statistics for NW area.

	MAE (mm)	BIAS (mm)	AD (%)	BIAS (%)	RMSL
MWC warnings (gauge average)	15.16	15.08	252.80	251.43	0.78
MWC warnings (gauge maximum)	12.00	11.90	130.76	129.67	0.67
FRONTIERS, MWC warning cases	3.59	−1.90	54.04	−28.57	0.37
FRONTIERS, warning cases	14.98	14.88	324.74	322.74	0.73
FRONTIERS, all cases (warning catchments)	7.70	4.82	142.62	89.25	0.56
Persistence, all cases (warning catchments)	8.27	4.74	153.22	87.74	0.56
FRONTIERS, all cases (non-warning catchments)	1.86	0.57	72.36	22.26	0.45
Persistence, all cases (non-warning catchments)	1.72	−0.13	66.82	−4.92	0.42
FRONTIERS, all cases (over all catchments)	2.57	0.26	55.88	5.61	0.40
Persistence, all cases (over all catchments)	3.23	0.72	70.15	15.66	0.42

FRONTIERS beats persistence, although sometimes only by a small margin, except for the non-warning catchments. Two factors may be relevant to this result. Firstly, because zeroes are excluded some of the cases where persistence did much worse than FRONTIERS are excluded (see the number of points on the x axis in Figures 10, 12, 14). Secondly, the nature of the warning criteria for the NW favours occasions when precipitation persists for many hours, in order to accumulate such a large amount. Because the FRONTIERS forecasts made at the start of the MWC warning period have been used, in many cases there will be precipitation in the catchments at T+0 which persists through the warning period. It will be difficult to beat persistence by a significant margin on these occasions.

7.4 Evaluation in the Thames Area

The evaluation is based upon data from about 55 gauges supplied by the Thames Region of the NRA. During the evaluation period some gauge sites were discontinued and others were opened. The positions of the gauges *circa* spring 1991 are shown in Figure 16. It can be seen that the gauge density was up to one per 50 km^2. The gauges were of the tipping bucket type, one tip corresponding to 0.2 mm. The gauge data were received in the form of 15 minute accumulations. The high spatial and temporal resolution of the gauge data meant that it was possible to examine the accuracy of the results as a function of accumulation period and catchment size. However the current report only contains results for comparisons with individual gauges and for 15 x 15 km catchments. Results for 15 x 45 km and 30 x 30 km catchments have been produced but do not in general show the increase in accuracy with catchment size apparent in the NW results. However, there are other anomalous features within the results, indicating that further checks on their accuracy are required before publication.

A key consideration was whether to use real NRA catchments or make up hypothetical catchments. The latter were used for two reasons:-

(i) examination of the positions of NRA gauges relative to the catchments indicates that most of the catchments contain one to three gauges (some contain none) because the gauge spacing tends to increase with catchment size. Artificial catchments can be positioned to maximize the number of gauges contained therein.

(ii) the actual catchments do not coincide exactly with the 5 km FRONTIERS pixels or 15 km mesoscale model grid boxes.

The 15 x 15km catchments finally chosen are shown in Figure 16. Two of the catchments are in areas affected by orographic enhancement. This was a deliberate choice, in order to determine the beneficial effects of the orographic corrections in FRONTIERS on the forecasts, if any. The orographic corrections were not added to the accumulation calculation until February 1991. Unfortunately an error in the software meant that they were not applied to accumulations based upon advection with mesoscale model winds until October 1991. There might still have been a difference between the orographic and non-orographic catchments because of enhancement detected by the gauges, which was not in the forecast accumulations. However, no obvious difference was discernible between the results for the orographic and non-orographic catchments. One reason is probably that there are not sufficient cases, because of the dry trial-period, to detect a moderate orographic signal above the natural scatter of the results. Therefore in the current analysis the results for all catchments are averaged together.

Results were also produced for individual gauges which were compared with the co-located 5 x 5km pixel. In the context of the above analysis, this can be considered a 25 km catchment average. It can be seen from Figure 16 that many of the gauges are positioned towards the edge of the colligated pixel, which will increase the representativeness error, as shown by Kitchen and Blackall (1992).

The problem of how to deal with zeroes was not a significant issue in the evaluations for the NW area, because the long accumulation period meant that few zeroes occurred. There was also less emphasis on formal statistical evaluation. Besides the problem that some of the statistics do not admit zeroes, there arises the scientific issue as to whether a double zero ie both forecast and observed, should be considered a perfect quantitative score. Also, whether a forecast or observed finite value should be taken as the error when the other is zero. There is limited discussion of this issue in previous studies. Bellon and Austin (1984) insisted that both the forecast and corresponding catchment average should exceed 0.1mm, before being admitted to the evaluation procedure. Einfalt et al (1989), evaluating 15 minute ahead forecasts over a 25 km^2 catchment, insisted that the observed catchment average was equivalent to at least 1mm h^{-1}, in order to be hydrologically significant rainfall. They do not appear to have placed a restriction on the forecast value.

The criterion that the forecast and corresponding gauge or catchment average value must equal at least 0.2 mm has been used here unless stated otherwise. A lower limit was not possible for comparisons with individual gauges and the same limit was then applied to catchment averages. Thus the question is addressed – if rain was forecast and observed in an area, how accurately was the amount forecast. If zeroes are admitted, it is not clear how much of the error is caused by incorrectly forecast rainfall rate and how much by incorrect location of the forecast rain area. The latter is an important source of error and has been quantified by on-line comparison of the 6 hourly instantaneous forecasts with the quality-controlled radar data, the results of which are presented later. Results are also presented for the IH version of the RMSL which admits double zeroes.

7.5 Results for Individual Gauges

The statistics for the comparisons with the individual gauges are summarized in Table 5, which shows the percentage bias, percentage absolute deviation, RMSL and RMSL+1mm, as a function of forecast lead-time and accumulation period. Because there was some random scatter in the 15-minute accumulation results, these have been averaged over each hour to introduce some smoothing and also facilitate comparison with the 1-hour accumulation results. In evaluating equations (1) to (5), F_i, G_i, are individual gauge values for one forecast sequence and G is the average gauge value for that sequence. Thus Table 5 shows the average value of the individual statistics for each forecast sequence.

Table 5 Statistics for Comparisons with Individual Gauges

	T+1	T+2	T+3	T+4	T+5	T+6
BIAS(%)						
15 mins	+11	+22	+30	+23	+31	+51
1 hour	+4	+15	+4	+3	+25	+63
3 hours			+8			+7
AD(%)						
15 mins	57	64	71	68	75	89
1 hour	65	81	78	86	107	131
3 hours			67			89
RMSL						
15 mins	0.27	0.28	0.29	0.30	0.30	0.29
1 hour	0.34	0.40	0.42	0.47	0.50	0.47
3 hours			0.38			0.53
RMSL +1mm						
15 mins	0.08	0.10	0.11	0.11	0.11	0.11
1 hour	0.15	0.20	0.22	0.23	0.25	0.24
3 hours			0.30			0.37

Table 5 shows a general positive bias (FRONTIERS exceeds gauges) which increases through the forecast period but decreases with accumulation period. The reason for the decrease with accumulation period has not been confirmed. It may be partly a consequence of the imposed lower limit of 0.2 mm, necessitated by the 0.2 mm gauge quantization. This has resulted in exclusion of many forecasts in the range greater than zero but less than 0.2 mm. These would all produce a negative contribution to the bias. The proportion of forecasts in this range decreases as the accumulation period increases, hence the effect of their exclusion on the average bias decreases. Results mentioned later cast some doubt on this explanation however. Further analysis is required to determine whether there are real meteorological reasons for that bias to be a function of accumulation period.

Statistics were produced for different accumulation periods because, as pointed out by Bellon and Austin (1984), it seems reasonable to suppose that increased accuracy will result from a longer accumulation period, as short periods of underestimation and overestimation offset each other. Such an increase in accuracy is not very apparent in Table 5. One hour accumulations appear less accurate than 15-minute ones, especially in terms of RMSL. The 3-hour accumulations are rather more accurate than the 1-hour accumulations in terms of *AD*, but only comparable in terms of RMSL. This suggests that the larger accumulations are more accurate over a 3-hour period but the smaller ones are not, since *AD* is most influenced by larger values. (The statistics for the 3-hour accumulations should be compared with the average of the T+1, T+2, T+3 values for the other periods.)

It is possible that the apparent relatively good accuracy of the 15-minute accumulations is also an artifact of the limited gauge resolution. A gauge and forecast lower limit of 0.05 mm is necessary for the 15-minute accumulations, to be comparable with a 0.2 mm limit for the one hour accumulations. Because the distribution of accumulations is biased towards lower numbers at 15 minutes than 1 hour, given a gauge value of 0.2 mm say, there is much less chance of obtaining a spuriously large value for a 15 -minute accumulation than for a one hour accumulation. Only 6% of the 15-minute gauge values exceeded 0.8 mm but 45% of the hourly gauge totals exceeded this value. Results presented in the next section do not support this explanation however.

The root mean square values of log rainfall accumulation with 1 mm added to the gauge and forecast values are shown at the bottom of Table 5. Zero gauge and forecast values are included in this case. The values are smaller for 15-minute accumulations, because 1 mm is larger relative to these.

7.6 Results for 15 × 15 km Catchments

The statistics for the 15 ×15km catchments are shown in Table 6. In evaluating equations (1) to (5), F_i, G_i, are individual catchment averages for one forecast sequence and $G = G_i$. This is more severe than summing $F_i - G_i$ over all forecast sequences and then dividing by the average of G_i over all forecast sequences, because small G_i values can produce large *AD* values for relatively insignificant events.

Table 6 Statistics for the 15 ×15 km Catchments

	T+1	T+2	T+3	T+4	T+5	T+6
BIAS(%)						
15 mins	+7	+9	+27	+31	+53	+37
1 hour	–2	–7	+4	+19	+16	+5
3 hours			–16			–16
AD(%)						
15 mins	43	44	51	60	73	64
1 hour	48	43	52	69	71	65
3 hours			37			53
RMSL						
15 mins	0.17	0.18	0.20	0.20	0.20	0.21
1 hour	0.21	0.21	0.24	0.24	0.31	0.30
3 hours			0.20			0.30

The *AD* and bias for the 15 x15 km catchments are plotted in Figure 17, together with the values for the comparisons with individual gauges. Table 6 and Figure 17 show than the catchment average accumulations are more accurate that the comparisons with individual gauges, in terms of both *AD* and *RMSL*. The biases have tended to become less positive except for the 15-minute accumulations. The 15-minute accumulations are still the most accurate.

Plotted on Figure 17 are the *AD* values from Bellon and Austin (1984) arising from comparisons with individual gauges and for a 600 km catchment. It can be seen that the FRONTIERS results are comparable to T+2 and rather better at T+3. The FRONTIERS results for catchment averages are significantly better at T+2 and T+3. To check that FRONTIERS has not scored better because we have imposed a higher lower limit, the results for the catchments have been reworked with a lower limit of 0.1 mm, the same as Bellon and Austin. Figure 17 shows that the FRONTIERS *AD* values are only slightly higher using the lower limit.

Although not reproduced here, the results for 15-minute accumulations using a lower limit of 0.1mm are only marginally different in bias or *AD*, in contradiction of the explanation of the variation of bias with accumulation period offered in the previous section. Further work is required to explain this.

Bellon and Austin point out that to put the forecast statistics into perspective one should consider the values obtained comparing radar actuals with gauges. They quote a value of *AD* = 30% for comparisons with individual gauges reducing to 24% for catchment averages, both figures applying to 4 hour accumulations. This compares with *AD* = 67% for a 3-hour accumulation (T+0 to T+3) for individual gauges and 37% for the catchments. In evaluations of FRONTIERS radar actuals RMSL values typically in the range 0.25 to 0.4 are found.

7.7 On-line Comparisons with Radar Data

On-line evaluation of the FRONTIERS forecasts of instantaneous rainfall rate have been undertaken since late 1989. Six forecast sequences are evaluated per day by comparison with the FRONTIERS quality-controlled radar actuals. The evaluation is limited to areas within about 150 km of the radars to avoid problems with the radar failing to detect rain.

The assessment is done mainly on a rain no-rain basis, i.e. the location of the rain is assessed, not its intensity. The four statistics used are the Critical Success Index (CSI), the Hansen and Kuiper Skill Score (HK), Probability of Detection (POD) and False Alarm Rate (FAR). All four are calculated from a 2 x 2 contingency table of forecast vs actual counts:-

		FORECAST	
		WET	DRY
OBSERVED	WET	A	B
	DRY	C	D

CSI = A/(A+B+C)

HK = A/(A+B) – C/(C+D)

POD = A/(A+B)

FAR = C/(A+C)

The CSI is the most severe score because it gives no credit for correct forecasts of dry pixels, which are generally in the majority. The HK score does give credit for this. The POD and FAR, although easier to understand have to be considered together because a high POD could be achieved by forecasting precipitation nearly everywhere, but this would result in a high FAR. The range of the HK score is –1 to +1, +1 being a perfect forecast and –1 a perfect anti-forecast. A forecast with no skill scores 0 on average. The range of the other scores is 0 to 1, with 1 being a perfect forecast. However forecasts with no skill score slightly more than zero on average.

Because evaluating the instantaneous forecast position on a 5 km scale is an extremely severe criterion, it was decided to relax it by including as a success any forecast wet pixel with an adjacent verifying wet pixel, i.e. the wet forecast was correct if it was wet within five kilometres. Dry forecasts were only verified by the collocated verification pixel. Forecasts were verified including and excluding satellite-diagnosed precipitation but only radar data was used for verification. The results excluding the satellite-diagnosed precipitation (not shown here) were consistently worse than those including it, indicating the benefit of the FRONTIERS satellite analysis.

A persistence forecast has also been evaluated in each case, i.e. the initial precipitation field is used at all forecast lead times.

The results for FRONTIERS and persistence at T+1 and T+3 hours are shown in Figure 18a, 18b respectively, from January 1990 to October 1991. It can be seen that at both lead times the FRONTIERS results have improved, in terms of CSI and HK, relative to persistence. At T+1 FRONTIERS beat persistence throughout the period but the gap between them noticeably widened during 1991. At T+3 the gap is narrower and FRONTIERS only started to beat persistence consistently during 1991. The improvement in FRONTIERS sets in most noticeably at the beginning of 1991, especially at T+3. This suggests that it is most likely a consequence of the introduction of the new forecast scheme in October 1990. The lag is probably due to initial software problems and the time taken for the forecasters to learn to use the scheme to its best advantage. Also further improvements to the forecast scheme were made in February 1991, in particular to allow the forecaster to keep delineated areas stationary and use the winds for advection in the remaining area, which hopefully contributed to the performance during 1991. Figure 18 also shows that the improvement indicated by CSI and HK is almost entirely due to an increase in POD, no obvious trend being discernible in FAR.

As an illustration of the severity of the scores, Figure 19 shows an example of a forecast at T+1 and T+2 with the verifying radar pictures underneath. The satellite-derived precipitation is shown brown in the forecast sequence, which also has written on the CSI value. (In comparing forecasts and actuals the limits of radar coverage must be taken into account). Although the showers over Ireland have been incorrectly advected eastwards, the band of precipitation over England and Wales has been handled quite well, although the CSI has fallen to 0.286 by T+2.

8. Assessment of Radar and FRONTIERS-derived flow forecasts

8.1 NRA Thames Region

8.1.1 Methodology

The NRA Thames Region have carried out a detailed evaluation of the FRONTIERS product over the trial period to ascertain whether such forecasts will enhance flood forecasting and flood warning generally. To enable this to be carried out the Met. Office agreed to supply the following data types from the FRONTIERS system to the NRA:

1. "Type 1" data at eight intensity levels. These consist of hourly instantaneous forecast images out to 6 hours ahead (T + 6). Data are transmitted every 30 minutes and cover the whole of England and Wales on a 5 km grid. In addition, the current network FRONTIERS actual image is transmitted with every forecast sequence (T + 0).

2. "Type 2" data at 208 intensity levels. These consist of 15-minute accumulations out to 6 hours ahead on a 5 km grid, updated every 30 minutes. For the purposes of the pilot study, type 2 data covers only the Thames and North West Regions (Figure 1). Data are transmitted to the Thames Region at Waltham Cross via a BT private wire from Bracknell at 2400 baud. A process (FRCAPT), running permanently on a VAX 4000-200 computer, captures all transmitted data. FRCAPT carries out basic format checking and selection before valid data are passed to another process, FRSORT, which carries out further checking and translation into display formats. This software also archives the data and sets event flags to inform other processes that new data are available. This dual mechanism allows data capture and processing to be carried out simultaneously without data loss.

All valid data received are archived initially on-line. The quantity of data involved requires storage in a compressed format. On-line archiving is limited to the last 30 days and selected events, with all information copied to an off-line archiving system after 30 days.

FRONTIERS data, whether instantaneous or accumulations, are also placed in display files which are continually overwritten as new data are received. User-driven software, invoked using simple commands, will allow these data to be displayed on Tektronix colour graphics terminals making use of the Tektronix Plot 10 Graphics Library. Display terminals are available in the Flood Warning Centre, Waltham Cross and at Flood Duty Officers' homes.

(i) Instantaneous Data Displays

The 6 hourly forecast images and the FRONTIERS actual image from the latest transmission are always available for display using the commands:-

FRI n – forecast images (where n equals the forecast time, 1 to 6 hours).

FRN – actual image

The format of the displays is illustrated in Figure 20a - 20c and includes the following information:-

(a) the time the forecast was made,

(b) the time the forecast is applicable for,

(c) the data that are available for immediate display for other times,

(d) whether the forecast has been generated automatically or by operator intervention,

(e) whether the forecast has been generated by using 1550 m or 3190 m level winds from the Met. Office Mesoscale model or by using a cluster forecast,

(f) whether the forecast sequence is identical or shows variation. Historic data may also be displayed using a menu system invoked by using a simple command.

(ii) Accumulation Data Displays

Three types of display are available initially,

(a) Thames Region display - which allows accumulation data for each 5 km. grid square across the Region to be shown for any time interval ranging from 15 minutes to 6 hours ahead for a given transmission (Figure 21).

(b) London sub-catchment display - 5 km grid accumulations are averaged over the principal sub-catchments covering London. The time interval will be user defined ranging from 15 minutes to 6 hours ahead for a given transmission (Figure 22).

(c) Lee sub-catchment display - similar to (b) above but for principal subcatchments in the Lee area.

Historic data may also be displayed for each type listed above.

(iii) Flood Forecasting Model Input and Output

In addition to the displays described in (i) and (ii) above, FRONTIERS accumulation data have been made available for input to flood forecasting models. Initially, FRONTIERS data are used to run the Isolated Event Model (IEM) which is a rainfall/runoff, non-linear storage model currently used for flood forecasting in London and the Lee Valley (Haggett et al 1991). The model is being used to evaluate FRONTIERS forecasts in three river catchments of varying size and land-use;

Silk Stream at Colindeep Lane - small urban catchment (29 km^2)

Beverley Brook at Wimbledon Common - medium urban catchment (43.5km^2)

Roding at Loughton - large rural catchment (269km^2)

Accumulation data are averaged over the 5 km grid squares that make up each of the river catchments listed above; three covering the Silk Stream, five covering the Beverley Brook and twenty two covering the Roding. At a simple level, subcatchment rainfall averages from FRONTIERS are compared with observed data including rain-gauge point measurements and subcatchment data generated from uncalibrated radar measurements at Chenies (Figure 23). However a more detailed analysis has been undertaken using the IEM. Examples of the IEM output are shown in Figures 24-26.

The analysis followed the fixed origin, variable lead-time approach to enable comparisons to be made between the accuracy of rainfall forecasts with different lead times. For each event, this initially involved compiling a rainfall profile of all one hour ahead forecasts (T + 1) and using this information to generate corresponding flow forecasts for each gauging station. The procedure was then repeated for all other forecast lead times, comparing the resultant error statistics at each stage (Figures 24-26).

A number of error statistics were used in the analysis, but the Root Mean Square Error (RMSE) formed the basis for comparison between modelled and observed flows and may be defines as;

$$RMSE = \left\{ 1/N \sum_{i=1}^{N} \left(\frac{F_i}{G_i} \right)^2 \right\}^{½}$$

where, F_i is the forecast flow in cumecs

G_i is the gauged flow in cumecs and

N is the total number of flow values

In addition to flow forecasts generated from FRONTIERS data, forecasts were also produced from observed rainfall, both rain-gauge and radar subcatchment, for each event. This enabled inherent model errors to be determined and provided a yardstick for assessing the performance of the FRONTIERS forecasts.

It should be noted that the IEM was calibrated using subcatchment information from Chenies, generated from uncalibrated 2 km instantaneous data. Six events were used to calibrate the model at Colindeep Lane, three at Wimbledon Common and four at Loughton. All the events used to calibrate the IEM can be classified as "high flow" events none of which were used in the assessment of FRONTIERS forecasts.

(iv) Event Selection

FRONTIERS accumulation data became available in October 1990. Due to the poor availability of data, it was decided to select periods for analysis from the beginning of 1991. Initially, events were selected for study as they occurred and because very few significant rainfall amounts were recorded during the first part of the project, those chosen tended to be very small. Also, sequences with a high percentage of missing data were accepted because events for analysis were so limited.

Towards the end of the project it was decided to re-analyse the data so far selected to check for events which could be added to the analysis and to introduce a consistent selection criteria for each catchment.

Due to the nature of the Roding catchment and to the fact that for the whole of 1991 the soil moisture deficit had been high, only relatively large rainfall events caused any response in the river. It was decided to identify all events which had caused a river flow of 3 cumecs or more, which is in fact only one seventh of the 1 in 2 year river flow for the Roding at Loughton. The eight events selected on this basis were then examined in more detail to ascertain whether enough data were available to make the analysis worthwhile.

Due to the problem of missing data, it was often necessary to interpolate missing FRONTIERS data with information from other transmissions. On occasions the degree of data loss made this difficult and the decision was made to replace missing information with an estimate of rainfall for a particular time made by weather radar. Obviously replacement of too high a proportion of data in this way will tend to bias the results and make any comparisons invalid, it also fails to mirror what can be undertaken in the operational environment. It was therefore decided to accept only events where at least 80% of each data type were available (rain-gauge, radar and FRONTIERS forecasts at all lead times). Of the eight events identified for Loughton only four met this criterion and were used in the assessment of FRONTIERS forecasts based on the average RMSE over all suitable events.

In the urban catchments of the Beverley Brook and Silk Stream, many more events were identifiable because both catchments tend to respond to even the smallest rainfall event. For each of these catchments, the 20 events which produced the highest recorded flows in 1991 were chosen and data availability was checked as for Loughton. Of the 20 largest events selected for Wimbledon Common on the Beverley Brook, 8 were found to be suitable. One of these (18/11/91) was later rejected due to a marked overestimation of rainfall by the Chenies radar, making comparisons impossible.

At Colindeep Lane on the Silk Stream, only 5 of the 20 largest events identified met the criteria set for FRONTIERS forecast assessment.

8.1.2 Results

(i) Silk Stream at Colindeep Lane

Tables 7 (a) - (d) give values of root mean square error (RMSE) for the 20 largest events at Colindeep Lane occurring in 1991. Where no RMSE value is given, this indicates that inadequate FRONTIERS forecast data are available to make any valid assessment. Figures 27 (a) - (d) show the RMSE's generated for the 20 events for lead times between 1 and 6 hours ahead in graphical form. There is a wide variation between events ranging from a general increase in errors as the lead time increases for events 2, 9 and 15 to rather erratic changes with lead time for events 1, 18 and 20.

TABLE 7a: RMSE for events at Colindeep Lane using FRONTIERS Forecasts

	Forecast Lead Time (hrs)					
EVENTS	1	2	3	4	5	6
1. 01/01/91	0.93	1.89	3.94	0.69	0.76	0.84
2. 02/01/91	-	0.56	0.63	-	0.67	0.71
3. 08/01/91	-	-	-	-	-	-
4. 09/01/91	-	-	-	-	-	-
5. 10/01/91	-	-	0.37	0.48	0.47	0.49
6. 11/01/91	-	-	-	-	0.54	0.51

TABLE 7b: RMSE for events at Colindeep Lane using FRONTIERS Forecasts

	Forecast Lead Time (hrs)					
EVENTS	1	2	3	4	5	6
7. 18/01/91	0.85	-	1.09	0.61	1.59	2.92
8. 29/04/91	-	-	-	-	-	-
9. 14/06/91	0.49	0.82	1.03	1.05	1.07	1.10
10. 23/06/91	-	-	1.12	0.70	2.15	2.16
11. 24/06/91	0.57	1.02	-	0.88	-	-
12. 25/06/91	0.67	1.15	1.10	1.49	1.52	-

Table 7c: RMSE for events at Colindeep Lane using FRONTIERS Forecasts

	Forecast lead time (hrs)					
EVENTS	1	2	3	4	5	6
13. 26/06/91	2.68	-	2.20	2.34	2.26	2.77
14. 27/06/91	2.83	2.35	2.76	3.22	3.04	2.53
15. 02/07/91	0.83	1.18	1.40	1.79	-	2.32
16. 30/07/91	1.49	2.58	-	-	2.58	-
17. 22/09/91	1.33	0.85	0.93	-	-	-
18. 26/09/91	2.54	5.84	5.81	2.30	2.65	2.87

Table 7d: RMSE for events at Colindeep Lane using FRONTIERS Forecasts

	Forecast lead time (hrs)					
EVENTS	1	2	3	4	5	6
19. 01/11/91	0.46	0.54	-	-	-	-
20. 18/11/91	3.13	3.77	1.33	1.47	1.42	1.44

Of the 20 highest flow events occurring in 1991 at Colindeep Lane, one reached mid-sensor level which is considered to be about a 1 in 5 year event, and 3 others reached low-sensor level, equivalent to about 1 in 2 year event. The largest event, which occurred on 30 July 1991 produced a flow of 11.6 Cumecs, but was not used in the average analysis because of the significant amount of missing FRONTIERS forecast data. Only 2 of the 3 low-sensor events could be used for the same reason. Three of the other smaller events were found to be acceptable for use in the analysis giving a total of 5 suitable events. Figure 28 shows the average RMSE for these 5 events for all the forecast time steps. The lowest errors were generated for the T+4 and T+6 forecasts, followed by the T+5, the T+1 and the T+2, with the T+3 forecast generating the highest RMSE of 2.97. The raingauge data (Harrow Weald) gave a slightly higher RMSE than most of the FRONTIERS forecasts except those for T+2 and T+3 hours ahead. The radar subcatchment data gave the lowest RMSE overall (1.32).

(ii) Beverley Brook at Wimbledon Common

Tables 8 (a) - (d) show the RMSE's generated for the 20 largest events at Wimbledon Common occurring in 1991, again where no value is given this indicates that insufficient FRONTIERS data are available. Figures 29 (a) - (d) show the RMSEs generated for the 20 events for lead times between 1 and 6 hours ahead. As with Colindeep Lane, there is a large variation of results for each event. Events 13 and 15 show a general upward trend with increasing lead time, whilst events 2, 3, 8, 9 and 12 show a general upward trend with a little deviation.

TABLE 8a:RMSE for events at Wimbledon Common using FRONTIERS Forecasts

	Forecast lead time (hrs)					
EVENTS	1	2	3	4	5	6
1. 08/01/91	-	-	-	1.49	-	0.61
2. 10/01/91	0.56	0.66	0.72	0.66	0.74	0.94
3. 18/01/91	-	0.54	0.97	0.94	1.61	4.09
4. 04/04/91	1.32	0.53	0.63	1.04	2.12	0.93
5. 06/04/91	1.33	0.62	0.74	0.86	3.12	3.04
6. 18/04/91	-	-	-	-	-	-

TABLE 8b: RMSE for events at Wimbledon Common using FRONTIERS Forecasts

	Forecast Lead Time (hrs)					
EVENTS	1	2	3	4	5	6
7. 29/04/91	3.12	4.25	4.07	-	-	-
8. 14/06/91	0.55	0.51	0.52	0.77	0.99	1.00
9. 23/06/91	-	-	0.89	1.21	1.02	1.44
10. 24/06/91	0.77	0.99	-	-	-	-
11. 26/06/91	1.33	1.44	1.27	1.16	-	1.60
12. 27/06/91	2.06	2.81	3.03	3.08	3.07	3.09

TABLE 8c: RMSE for events at Wimbledon Common using FRONTIERS Forecasts

	Forecast Lead Time (hrs)					
EVENTS	1	2	3	4	5	6
13. 02/07/91	2.51	4.09	4.12	-	-	6.10
14. 03/07/91	2.05	-	2.34	3.59	-	-
15. 22/09/91	0.64	0.90	1.00	1.05	-	-
16. 26/09/91	1.22	1.92	3.46	1.81	1.81	1.75
17. 28/09/91	-	-	-	-	-	-
18. 29/10/91	1.71	2.19	2.81	0.95	1.69	2.51

TABLE 8d: RMSE for events at Wimbledon Common using FRONTIERS Forecasts

	Forecast Lead Time (hrs)					
EVENTS	1	2	3	4	5	6
19. 02/11/91	0.82	1.23	1.75	1.26	-	-
20. 18/11/91	5.69	1.88	2.40	2.81	2.78	2.53

The other events show maxima and minima at various lead times. Only one of the 20 highest flow events occurring in 1991 at Wimbledon Common reached the low-sensor level (approx 1 in 2 year event). This was on 2 July, but could not be used in the assessment because of the high proportion of missing data for forecasts at 4 hours and 5 hours ahead. Only 7 of the other 19 events could be used in the analysis. RMSEs averaged over these 7 events are presented in Figure 30 which illustrates that the lowest errors are associated with the T+1 forecast and the highest with the T+5 forecast. It is interesting to note that most of the FRONTIERS forecasts over the 7 events out-perform both of the rain-gauges used in the assessment. Hogsmill rain-gauge gave an average RMSE of 1.68 and Cheam one of 2.44, compared with the average RMSE of 1.25 for the one hour ahead FRONTIERS forecast. However, the observed Chenies subcatchment data gave the lowest RMSE overall (0.89) as was found in the analysis for Colindeep Lane.

(iii) River Roding at Loughton

Tables 9 (a)-(b) show the RMSEs generated for the 8 largest events which were recorded at Loughton in 1991. Figure 31 presents the RMSEs for the 8 events in a graphical form. Once again, there is a large variation in RMSE between events. Events 1, 3, 4, 6 and 8 give a fairly constant RMSE over all lead times for which data are available, but Event 5 is rather more erratic with a max. at T+3 and a min. at T+6.

TABLE 9a: RMSE for events at Loughton using FRONTIERS Forecasts

	Forecast Lead Time (hrs)					
EVENTS	1	2	3	4	5	6
1. 02/01/91	-	0.87	0.96	1.57	1.02	1.04
2. 09/01/91	-	-	-	-	-	-
3. 15/02/91	4.40	4.50	4.52	-	-	-
4. 21/02/91	1.74	1.65	1.75	1.70	1.94	1.94
5. 05/03/91	1.89	2.11	3.22	2.71	0.54	0.43
6. 16/03/91	3.46	3.14	3.34	3.26	3.03	3.49

TABLE 9b: RMSE for events at Loughton using FRONTIERS Forecasts

	Forecast Lead Time (hrs)					
EVENTS	1	2	3	4	5	6
7. 29/04/91	-	-	-	-	-	-
8. 27/06/91	1.21	0.64	0.70	1.01	0.85	0.68

None of the flow events occurring in 1991 at Loughton approached low-sensor level which is set at 21 cumecs. The highest flow achieved during 1991 was 11.4 cumecs on 9 January. Unfortunately, data for this event were not sufficient for it to be used in the analysis of FRONTIERS forecasts. In fact, only four of the eight events could be used due to the large amount of missing data in the others. Figure 32 shows the average RMSE over these four events for all forecast time steps. The lowest errors were generated for the T+5 forecast while the highest errors occurred for a lead time of 3 hours. In contrast with the results from the two urban catchments the radar subcatchment rainfall data performed far worse than the FRONTIERS forecasts at all lead times with a RMSE of 2.77 as opposed to 2.08 for the T+1 forecast. This is thought to be due to the effects of bright band causing the radar to over-estimate rainfall intensity quite severely. Both rain-gauges (Epping and Thornwood) produced results comparable with FRONTIERS forecasts.

8.1.3 Conclusions

1. The conclusions which can be drawn from the results of this study are limited by the fact that very few significant rainfall events occurred throughout the duration of the project. The study was also troubled by a large amount of missing data (see Conclusions and Recommendations below) which prevented some of the larger events which did occur from being used in the analysis. Only events with at least 80% of data available by volume were used. The majority of the events used can be classed as "low flow" events. Two of the events at Colindeep Lane have a return period of about 2 years, but none of the events at Wimbledon Common or Loughton reached a 1 in 2 year level. This means that it is not safe to assume that the FRONTIERS forecast performance statistics found for the events studied will be representative of the larger events in which the NRA is most interested.

2. Results show wide variations in FRONTIERS forecast performance between events for all three catchments studies. Therefore the average root mean square error statistics presented should be treated with caution as they tend to mask these differences. It must also be emphasized that the fixed-origin variable lead-time approach used in these off-line analyses of FRONTIERS forecast performance cannot be mirrored operationally. The intention of this project was to compare the forecasts for different lead times to see whether there was a marked decrease in forecast accuracy with increasing lead time. This might have suggested that it was not possible to rely quantitatively on forecasts beyond a certain lead time. However, results so far have not been conclusive in demonstrating a relationship between forecast accuracy and lead time.

3. Radar subcatchment data from Chenies radar were used to provide a comparison with the performance of the FRONTIERS forecasts. These radar data were found to produce lower root mean square errors than the FRONTIERS forecasts or the rain-gauge data in both of the two urban catchments studied. However, in the rural catchment of the River Roding, the radar subcatchment data produced the highest RMSE averaged over all events. This is felt to be due to the effects of bright band, the Roding catchment being about 60 km from the radar site, a common distance for bright band effects to occur.

4. Despite the limitations described above, it can be said that FRONTIERS forecasts perform well on average for all lead times. The forecasts consistently perform as well as or better than actual rainfall data from rain-gauges, which is particularly impressive for the small urban catchments which were analysed. The Silk Stream catchment at Colindeep Lane for instance, incorporates only three of the 5 km grid squares over which FRONTIERS forecast data are calculated and for a national rainfall forecasting system like FRONTIERS to perform as well as it has is very encouraging. It forms a good basis on which to build and improve.

5. The analysis has shown that the reliability and accuracy of FRONTIERS forecasts is variable. During the period of trial it has not been fully demonstrated that FRONTIERS can improve the NRA's flood forecasting capabilities but nonetheless results are promising. Above all, FRONTIERS is able to generate rainfall forecasts in real-time automatically and it should be said that even in its present form, it out-performs the rather subjective attempts that are made at the moment to forecast rainfall quantitatively, a process which can take up valuable time during a flood event.

8.2 NRA North West Region

As part of the strategy to improve the capability of the flood warning service, especially in areas of data accessability and improved forecasting NRA North West Region contracted Salford University Water Resources/Radar Group to develop and apply transfer function models for flow forecasting in a number of catchments for the NW Region of the NRA. In addition, with the real possibility of accurate rainfall forecasts being available to produce timely forecasts in fast-response catchments, the NRA North West Region and Met. Office jointly funded a PhD student, David Viner to undertake a study of the hydrological utilization of FRONTIERS data using a Transfer Function Model (TFM) (Annex B).

The study looked at the River Irwell catchment, in the South Pennines which, arising in elevated moorland contributed to a major flood risk zone in the residential and industrial areas of Salford. Forecasting for the main catchment of 558 km^2 and a tributary of 186 km^2 (River Roch) were subject to detailed study. One aspect of the study was concerned with assessing the flow forecasting accuracy of the developed TFM models using the forecast rainfall from the FRONTIERS system.

Two series of models were used in the study – one with models calibrated by using the locally calibrated (on - site with rain-gauge information) radar rainfall estimates from Hameldon ('At site'), the other using the FRONTIERS modified network radar rainfall ('Actuals').

In each case the forecasts were compared with perfect foresight of the rainfall (derived from the FRONTIERS Actuals) for up to 6 hours ahead.

Figure 36 shows the Average Root Mean Square Error (RMSE) of flow as a function of forecast lead-time derived from eight events for the at-site Radar calibrated model, and three events for the FRONTIERS calibrated model. In both instances flows derived from FRONTIERS forecast rainfall input are out performed by flow forecasts using perfect foresight, though it is only at 5 and 6 hours ahead that the difference increases markedly for both rainfall scenarios. The FRONTIERS model is out-performed by the at-site model for both scenarios, this is probably due to more events being used in verification thus giving a larger data set for producing the averaged parameters during the calibration process. For further details see Viner *et al* (1991).

Although this study used only a limited set of FRONTIERS forecasts, with events up to June 1991, and changes were made to the FRONTIERS forecasting methodology during the period of this project, it is felt that useful feedback was obtained to aid in the development of the quantitative use of FRONTIERS forecasts. For the larger catchment the average RMSE of flow for the two models suggest that FRONTIERS forecasts are reasonably comparable to perfect foresight of rainfall up to at least 4 hours ahead. However, the need to improve the modelling of the decay or growth of the rainfall system and the storm velocity were apparent from some of the events.

9. Qualitative assessment of FRONTIERS forecasts

9.1 Method at Manchester Weather Centre (MWC)

Senior forecasters at MWC were asked to give a subjective assessment of FRONTIERS performance. This was done by completing a standard list of 10 questions at the end of each 12-hour shift. Between July and November 1991 there were 150 periods of 12 hours in which precipitation was forecast by FRONTIERS. The whole of England and Wales and adjacent sea areas were evaluated, though the most critical scrutiny was applied to the Manchester area of responsibility. About half of the forecasts were considered to give good guidance that enhanced other advice available to the forecaster.

9.2 Occasions of good advice

Occasions of good advice often related to situations in which:

(a) a front is moving steadily, with a mass of precipitation echoes. In this case for the 6 hours of a forecast, FRONTIERS usually gives good guidance. FRONTIERS is usually quicker than the outstation forecaster to change the velocity of fronts. This may be because the forecaster is too busy to notice the change in the conventional radar display patterns.

(b) there are discrete dynamic rain echoes associated with upper troughs, ahead of fronts, in cold pools or enhanced shower activity in troughs. When the forecaster considered that such conditions would persist for more than 6 hours, then FRONTIERS guidance was useful in showing him where the rain would be during that period.

(c) extrapolating is carried out for areas of rain using the upper winds. However, there are a sufficient number of exceptions to cause the prudent forecaster to check whether recent radar displays confirm the FRONTIERS forecast trends. However, in general most senior forecasters now feel confident in their knowledge of when FRONTIERS will be giving good advice.

Further quantitative verification needs to be done before it can be ascertained that FRONTIERS is more accurate than conventional forecasting techniques at predicting the actual amount of rain that falls over a limited area in the forecast period for all meteorological situations.

9.3 Occasions of misleading advice

Occasions of misleading advice were categorized as follows:

(a) If a front consisted of disjointed or separate echoes, then on some occasions, FRONTIERS would have been more successful moving the echoes with the upper winds. Frontal velocities were used instead, and this resulted in poor advice.
(b) Most showery days were treated with inconsistent techniques that sometimes varied between successive 6-hourly runs. Some forecasts used persistence (zero movement), others did not dissipate showers with time or did not decay them crossing the Pennines and Welsh Hills. Most showers only have a life cycle around 2 hours and should not be persisted for longer – apart from orographic enhancement or in association with troughs.

(c) Some rain echoes were moved with a vector that was unrelated to recent movement or upper winds. During some of these events consecutive FRONTIERS runs moved the echoes in different directions.

(d) The effect of the rain shadow from the Welsh Hills is not allowed for directly during a FRONTIERS forecast. In fairness to the operators there were some occasions when a shadow effect was expected but did not occur. It is difficult to formulate a rule that would apply in every case and further work on this problem would be beneficial.

9.4 Assessments at London Weather Centre (LWC)

The forecasters at LWC became much less sceptical of the FRONTIERS forecasts as the project proceeded. A log of events and forecasters comments was kept, the following being an example taken from the log in December 1991:-

5th Dec. 1900 Dealt with a few showers near eastern East Anglia quite well.

17th Dec. 0700 Reasonable guidance as echoes moved across southern England.

17th Dec. 2230 32 mm h^{-1} over a large area on radar actual to NW of London. FRONTIERS has discounted this and shows 4 mm h^{-1} and this solution preferred. No SFLOCs (lightning flash measurement) in the area. Contacted NRA and said that rate may well be 4 mm h^{-1} but total accumulation not expected to reach warning criteria. Discussed situation and no warning issued.

26th Dec. 0200 Has been advecting a band of rain southwards into the London area all evening; the rain should become more fragmented with time. No rain from that particular band reached London.

The improvement in the perception of usefulness was attributed to a combination of more technical reliability, quicker response to faults reported and, not least, to a generally perceived improvement on the guidance given. The fact that "doubtful" guidance can often be recognized, whereas situations similar to occasions remembered from past experience as having provided good guidance can be trusted more implicitly

9.5 Assessments at NRA NW Region

Advantage was taken of the existing communications links with Met. Office Bracknell to receive a display of the FRONTIERS forecast pictures, with a view to, an albeit subjective assessment of the forecasts by the flood warning team and duty officers. Although not able to use the forecasts quantitatively (see section 8.2) it was felt that forecasts of which catchments were likely to be at risk from heavy rainfall would improve the overall forecasting performance and give greater confidence in extending existing forecasts.

Forecasts were displayed in the Flood Forecasting Room and were also available on home terminals (towards the end of the trial), along with local (Hameldon Hill) and network radar data.

Data availability appeared to be quite reasonable (although no actual statistics were available) and a log book was kept. The scarcity of serious events in the period meant that there was less need for forecasts, and these comments were necessarily limited, but it also tended to highlight the negative aspects of where forecasts were not helping. However the reports helped to identify weather situations where analysis by Met. Office allowed improvements to be made to the forecasting methodology for example orographic enhancement.

Two recent events, 21 December and 5 January, where there was serious flooding of property in East Lancashire and Manchester areas indicate where the FRONTIERS forecasts concurrently help and confuse. Weather systems coming in from the West (usual) were forecast quite well whilst still moving. However storms with flooding potential tend to move into the area, slow down and hover, eventually gradually decaying. Unfortunately these aspects are not well forecasted currently and the forecasts led to some confusion and lack of usefulness during the events. Further work needs to be carried out to improve performance in these situations.

10 Quantitative benefits of FRONTIERS forecasts for flood forecasting

It is generally accepted that the benefits of a flood warning system are related to the extent to which effective action can be taken after a flood warning to reduce losses arising from flooding. The reduction in losses that may be achievable is, in turn, related to the lead time the system provides. To a degree, the longer the lead time, the greater the opportunity to limit the danger. It has been estimated that lead times greater than 4 hours are not accompanied by great increases in damage reduction. The lead time is taken not to include time needed for issue and dissemination of warnings, which typically can vary from half an hour to one and a half hours depending upon circumstances. It also excludes that time related to preparation of a forecast prior to the issue of a warning. In other words, about 6 hours prior warning of potential flood producing conditions is optimal. Given the uncertainties generally associated with both rainfall and flow forecasting, an increase in lead time is very often associated with a reduction in reliability and accuracy.

It is against this background that FRONTIERS offers potentially attractive opportunities to improve rainfall forecasting in terms of both spatial and temporal occurrence. This, in turn, encourages greater confidence in flow forecasts enabling flood warnings to be given with more notice and greater detail of the extent and duration of flooding.

It was with these possible advantages in mind that the 1983 study on national weather radar coverage by the then National Water Council, examined the potential benefits of radar rainfall measurement both with and without FRONTIERS. The figures were up-dated by Collinge in 1989, and have been updated to 1992 prices using inflation figures from 1983 in Figures 33 and 34. Figure 35 shows the actual benefits due solely to FRONTIERS forecasts rather than radar measurements plus forecasts. The added benefit of FRONTIERS over and above instantaneous weather radar displays, is now assessed at £2.9M p.a. excluding reductions in traffic dislocation. This is the value of most interest to the NRA but if traffic dislocation is included, the relative benefit of FRONTIERS is likely to be at least double. The figures assume FRONTIERS data available across England and Wales at a level of reliability which is unspecified, although at a level of accuracy comparable to that measured in this study.

In order to assess further the benefits of FRONTIERS, it is necessary to estimate the annual losses due to river flooding in England and Wales. Unfortunately, the data are inadequate, but in a recent study, Mott McDonald Consultants Ltd. estimated the average annual fluvial flood damage in England and Wales as £75M. The figure is derived from the annual average damage per 'house' in the flood plains and the total number of house equivalents in all flood plains nationally. The house equivalent includes both commercial and industrial premises as well as agricultural land. It has to be said that there is a degree of speculation in the total flood damage estimate which is an extrapolation of data collected in the Thames Region of the NRA. Nevertheless, it appears to have some substance when compared with detailed data collected for a single event. The flooding in Maidenhead in February 1990 caused damage estimated at £380,000 in the 39 houses flooded above damp proof course level and over £0.5M in total. Although the event attracted considerable media attention, it was not remarkable hydrologically having a return period of about 1 in 5 years. The same event also, of course, affected a number of other locations within the Thames Region although detail and damage costs are not available. There appears to be an urgent need to collect these data nationally, since assumptions about flood damage underlie a range of investment decisions.

In this context the £2.9M p.a. damage saving attribution to FRONTIERS represents about 3.9% - a fairly modest claim. The great difficulty will be to demonstrate it given the other changes that will influence flood warning arrangements at the same time as FRONTIERS becomes generally available, the variability in the weather year on year and the possibility that there may be gradual climatic change taking place.

11 Orographic rainfall over the Chilterns and North Downs

Orographic rainfall, generated by the Bergeron seeder-feeder mechanism, can dominate the spatial distribution of frontal rainfall accumulations in mountainous areas and, in favourable conditions, is significant because growth of precipitation within a few hundred metres of the surface causes significant errors in radar estimates of surface rainfall in conditions where rainfall accumulations are likely to be generally high. It should also be noted that persistent, small-scale orographic patterns in rainfall can also render measurements from gauge networks unrepresentative. Corrections are made in FRONTIERS for that part of the enhancement which arises beneath the radar beam by assuming that the spatial distribution of the enhancement is related to the climatological distribution via three factors; wind-speed, relative humidity and wind direction (Hill, 1983). The orographic rainfall rate profile is approximated by a single 'universal' profile which is taken to be representative of all conditions in which significant growth occurs. The profile used assumes approximately linear growth starting at 1500 m above the ground (see Brown *et al*, 1991).

These correction procedures were developed from observations over 400 m hills in South Wales and the method has not previously been verified for the smaller scale topography in SE England. Combining the radar and gauge data which were available during the POSFFAG trial enabled the horizontal and vertical distribution of orographic rainfall to be studied and the impact upon radar estimates of surface rainfall to be assessed. Full details of the work may be found in Kitchen and Blackall (1992). Six periods of wintertime frontal rainfall were selected for detailed study (Table 10). Gauge data from the NRA Thames and Met. Office networks, along with

a few private gauges were able to resolve horizontal variations in the accumulations. In all cases, gauge data showed a clear orographic pattern with a band of minimum accumulation along the Thames valley and larger accumulations over the higher ground (see Fig 37), The ridges of typical height 150 m produced enhancements of up to 2 mm h^{-1} in conditions favourable for the operation of the seeder-feeder mechanism (strong, moist low-level wind and pre-existing background rainfall). In Case 4, rainfall accumulation over the hills was several times that in the Thames valley.
Some of the variations in enhancement over the N. Downs were explained by the component of the surface wind blowing normal to the ridge and the background or 'seeder' rainfall rate. These factors accounted for about half the case-to-case variance in the mean enhancement recorded by gauges on the ridge. In contrast, Hill *et al* (1981) reported that enhancement over S Wales hills depended strongly upon the windspeed at 600m. The low-level origin of the enhancement in the present cases may explain this difference (see below).

In Bergeron's original experiments, the average maximum enhancement during periods when the rainfall distribution was dominated by the seeder-feeder mechanism was 0.9 mm h^{-1} over a 60m hill. The average for the 150 m ridge in the present cases was 1.4 mm h^{-1}. This may be compared with an average of 2.7 mm h^{-1} for the 8 cases of enhancement over the Glamorgan Hills detailed in Hill *et al* (1981).

The results confirmed that orographic corrections are essential to the radar analysis if serious underestimation of rainfall is to be avoided, even over SE England. The corrections added to the radar measurements in FRONTIERS were shown to be of the right order and have the potential for improving the radar analysis if applied correctly. In general the observed enhancements were slightly larger than the corrections and the case-to-case variations were not as anticipated.

Vertical cross-sections of radar and gauge data showed that the orographic growth occurred in the kilometre above the hills. In one case (number 4 in Table 10) all the growth arose within the lowest few hundred metres within precipitation of total depth of only 1.5 km. The radar overshot most of the precipitation even at ranges of a few tens of kilometres and detected hardly any of the orographic enhancement. In such cases, the assumed universal growth profile is clearly not a good model. However on average, the profile was shown to result in improved radar rainfall estimates.

Table 10 : Summary of the orographic rainfall case study periods

Case No.	Date	Period UTC	Rain from	Typical accumulations (mm) Thames Valley	Chilterns	N. Downs
1	1.2.90	1700-2200	warm front/sector	2-6	9	13
2	7.2.90	0300-0800	ahead of warm front	4-7	12	13
3	7.2.90	0800-1400	warm sector	3-5	8	10
4	26.2.90	0300-0500	warm sector	0-0.5	1.5	2
5	8.1.91	1100-1600	ahead of warm front	1-2	6	8
6	8.1.91	1700-1900	warm sector	1-2	4	3

12. Conclusions and Recommendations

If the year of the FRONTIERS trial was kind to those living in the flood plains, it proved problematic for those evaluating the product as well as the water companies of Southern and Eastern England. In short, the year 1991 was unusually dry with the average rainfall in the Thames region about 86% of standard average and in North West Region 73%. It was characterised by very few flow events that gave rise to significant river flows of the scale for which flood forecasting models have been calibrated. Also, as the first year in which FRONTIERS data have been available outside of the Meteorological Office, the service has developed as a result of feedback. Nevertheless, the following conclusions and recommendations have been derived from the studies reported here:

1. Relative to the only comparable quantitative rainfall forecasts issued manually from Manchester Weather Centre, FRONTIERS was less reliable at issuing warnings, but its quantitative estimates were generally closer to ground truth than the manually produced forecasts.

2. The accuracy of FRONTIERS forecast accumulations tends to improve with increasing catchment size. There is less evidence that accuracy improves with increasing accumulation period, but such an effect may be masked by limited gauge resolution.

3. There is a significant problem with slow-moving or stationary forecasts, which can give good guidance on the scale of the UK, but produce large errors in a few individual catchments.

4. The accuracy of the forecast accumulations is comparable with or better than studies published previously.

5. Routine evaluation of forecasts of instantaneous rainfall rate, compared to radar actuals, since January 1990, indicates an improvement in accuracy since the beginning of 1991. Subjective assessment at London and Manchester Weather Centres confirms an improvement during the trial period.

6. During the trial, FRONTIERS generated rainfall forecasts in real-time outperformed the objective methods otherwise available to flood forecasters. On average, FRONTIERS based forecasts outperformed those based on rain-gauge data. However, there was a wide and apparently random variation between events which makes it as yet unsuitable for reliable operational use. FRONTIERS only outperformed radar based forecasts when bright-band effects were present.

7. The experience gained by flood forecasters during this trial enabled the forecasts to be interpreted with growing skills, but difficulty remains distinguishing between realistic and unrealistic forecasts. For this reason and the current unsatisfactory availability, it is considered that this option is not yet suitable for general operational use in flood forecasting. Despite these reservations, in the Thames and North West Regions, FRONTIERS has proved a useful adjunct to the other tools available to flood forecasts.

8. The format of FRONTIERS is broadly similar to that of other weather radar data and utilizes similar communications links. This makes assimilation of the data with existing monitoring systems relatively straightforward, given the availability of suitable skills.

9. Presently FRONTIERS offers considerable advantages for flood forecasting generally, but particularly, for small catchments with short lead-times.

10. Subjective evaluation indicates:

(a) inconsistent appreciation of techniques, especially in convective cases, e.g. swapping from a stationary forecast to model winds.

(b) showers were not decayed as often as they should have been, probably because the forecaster had insufficient time.

(c) there were also problems with rain-shadow effects, which are not dealt with in FRONTIERS.

(d) precipitation hanging back over hills, which FRONTIERS advected.

11. The project has been greatly troubled by the large amount of missing FRONTIERS forecast data. Study of some potential events was hampered by a lack of data. The average availability of instantaneous FRONTIERS forecast data in 1991 was 86.5%, and of FRONTIERS accumulations, 73.5%. Data availability in excess of 95% during events which may lead to flooding is required if the data are to be relied upon operationally.

12. The first action for the future is to continue the trial for at least a further 12 months on a basis similar to the joint study which is the subject of this report. This will allow more rainfall (and flood) events to be assessed and for both Met. Office forecaster and flood forecaster to develop experience and confidence in the product.

13. An extension of the trial will allow the Meteorological Office to take steps to improve FRONTIERS both by further research and operational enhancement as a result of its use. Specific improvements are proposed as follows:

(a) Improving the availability of data.

(b) Improving the treatment of showers and thunderstorms to allow for their development, decay and movement.

(c) Investigate the feasibility of applying negative orographic corrections to deal with rain-shadow effects

(d) A strategy needs to be devised to handle better accumulation calculations for slow moving or stationary weather systems.

(e) Investigating further the extent to which bright-band effects can be mitigated by appropriate correction procedures.

(f) Investigating further the integration of the mesoscale model and FRONTIERS including use of the model precipitation fields on occasions.

(g) Investigating whether or not some of the current procedures in FRONTIERS can be fully automated.

14. At the same time, and separate from the evaluation, the NRA should seek to establish a national database of fluvial flood damage details. This will provide a firmer basis on which to assess the benefits derived not only from FRONTIERS but also other techniques and technologies aimed at improving the Authority's flood warning service. In time, this should greatly enhance the quality of flood defence investment decisions.

15. An assessment of FRONTIERS forecasts and the Local Forecasting System operated by Thames Region is currently being undertaken by the Institute of Hydrology under contract to the NRA. The project is looking at how both systems perform when used as input to the hydrological models currently used operationally by the Thames Region. The results of this study should be taken into account by the NRA when considering the provision of operational flow forecasting.

16. Opportunities for joint research between the Met. Office and the NRA to improve the techniques discussed in this report should be investigated.

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NRA North West Regional Duty Officers.

NRA Thames Region Duty Officers.

FRONTIERS forecasters.

Met. Office Operational Forecasters at London and Manchester Weather Centres.

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ANNEX A

Membership of the POSFFAG
(Pilot Operational Service of FRONTIERS Forecasts Assessment Group)

National Rivers Authority

P F Borrows	-	Thames Region (Reading)
C M Haggett	-	Thames Region (Waltham Cross)
J M Knowles	-	North West Region
R Hatton	-	South West Region

Met. Office

C G Collier	-	Project Officer, METSTAR Consultants, Bracknell (Chairman)
R Brown	-	Head, FRONTIERS Development, (OB), Bracknell
S N Wass	-	Manchester Weather Centre
J M Merson	-	London Weather Centre
Mary Clarke	-	Commercial Services (Secretary)
Barbara Richardson		Commercial Services

ANNEX B

Flow Forecasting Models

Isolated Event Model (IEM 4)

This is a four parameter, non-linear conceptual rainfall/runoff model, well suited to flow forecasting.

Structure

The model has two principle components: volume reduction and shape transformation.

Reduction of total rainfall to effective rainfall is explicitly modelled by defining a rainfall runoff relation derived empirically from two parameters and the soil moisture deficit.

Shape transformation is achieved by introducing a time delay (another of the 4 parameters - DEL) and by a non-linear reservoir defined by a routing coefficient - the fourth parameter.

The model also employs updating features with initial conditions being modified according to observed records as the event progresses.

$ROP = PERC.e^{-PERI.\,SMD}$

$S = AC * Q^n$

ROP	=	rainfall runoff relation	PERC	4-parameters
SMD	=	soil moisture deficit	PERI	
S	=	storage in mm	DEL	
Q	=	output discharge in mm/h	AC	
n	=	reservoir's exponent		

Calibration

The model is used with gauged data and its 4 parameters optimised using the Rozenbrock algorithm, iteratively refining them given defined limits (based upon minimisation of the integral square error). This optimisation process may be carried out with a single or a complete series of rainfall events, and is currently used with radar and rain-gauge inputs.

Forecasting

The model is used with optimised parameters and a forecast rainfall input to give a predicted flow response.

Any forecast profile may be used. The rainfall profile may be wholly made up of forecast data or, for running during an event, a combination of observed data (rain-gauge/radar subcatchment) and forecast values. Similarly observed and forecast elements of the flow profile are merged to give a single hydrograph.

Transfer Function Models

The transfer function is a simple, linear model capable of producing multi-step forecasts. As a rainfall-runoff model it uses past rainfall and past flow to forecast flow, in the form:-

$$y_t = a_1 y_t + a_2 y_{t-2} + \ldots + a_p y_{t-p} + b_1 u_{t-1} + b_2 u_{t-2} + \ldots + b_9 u_{t-9}$$

past flow past rainfall

Where y = flow forecast; y = flow; u = total rainfall; a, b = parameters; t = time

Forecasting more time steps ahead is achieved by using forecast flows and rainfall in the model.

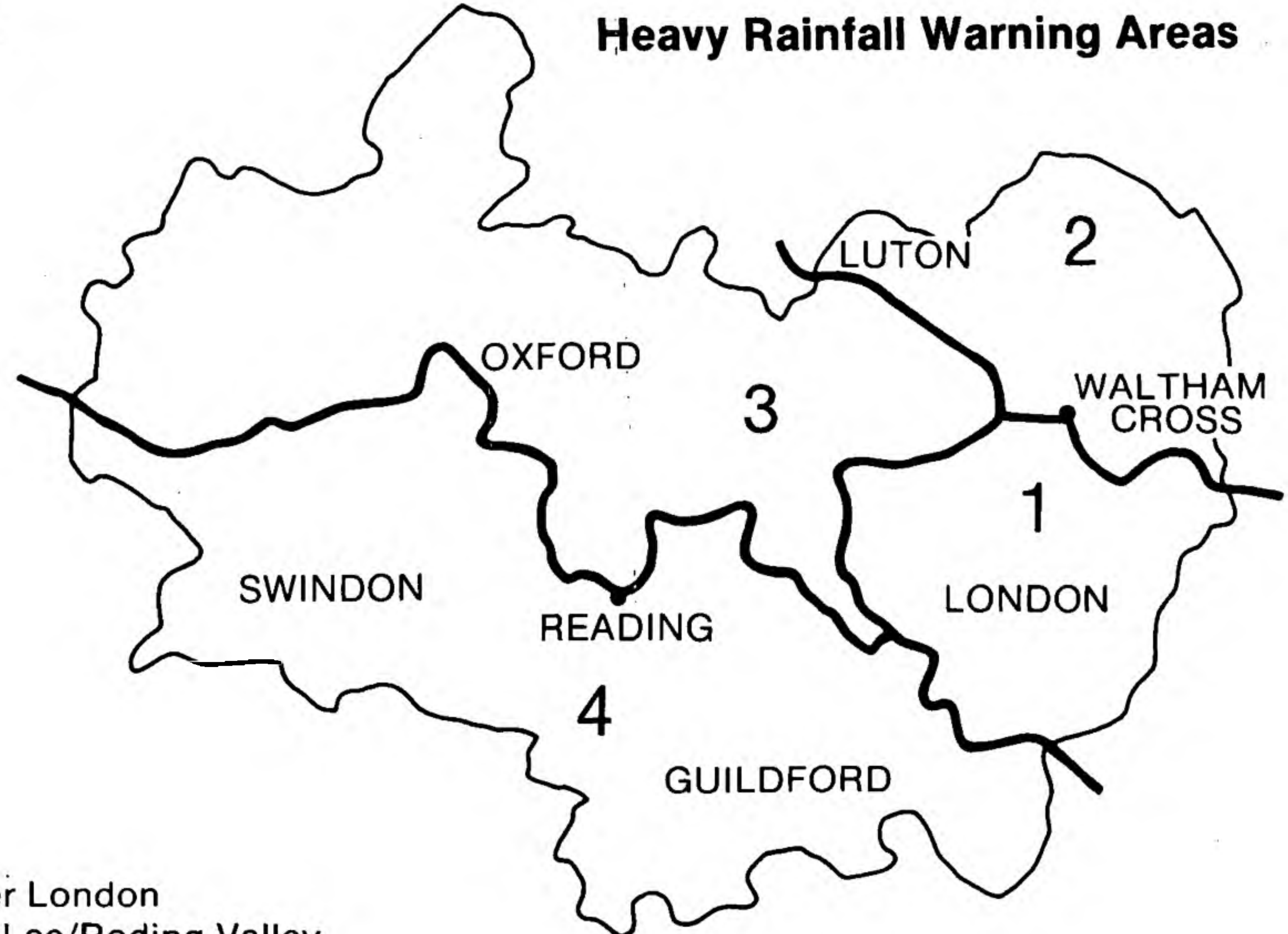
The impulse of the transfer function is defined as the response due to unit input. This is analogous to the traditional unit hydrograph, which is the direct runoff due to unit effective rainfall. However, the transfer function offers a number of advantages over the unit hydrograph, especially for real-time forecasting. The use of past flow in addition to past rainfall in the transfer function produces a model with fewer parameters than the equivalent unit hydrograph. During an event the real-time input of measured flows into the model provides a self correction to the forecasts which is not available with the unit hydrograph.

The transfer function is capable of accepting total rainfall as an input, which is advantageous when considering the difficulties in establishing effective rainfall, particularly during an event. The model has an associated percentage runoff which can be adjusted in real-time by scaling the rainfall parameters. The scaling factor is updated according to the one-step ahead forecast errors.

Model derivation involves choosing the appropriate number of parameters and their values. The optimum number of parameters will be the lowest which produces a good model. An algorithm such as the recursive least squares estimator can be used to estimate the model parameters.

Figure 1a

NRA THAMES REGION
Heavy Rainfall Warning Areas



(1) Greater London
(2) Upper Lee/Roding Valley
(3) Thames Valley North
(4) Thames Valley South

● Flood Warning Centres
Rainfall Warning areas

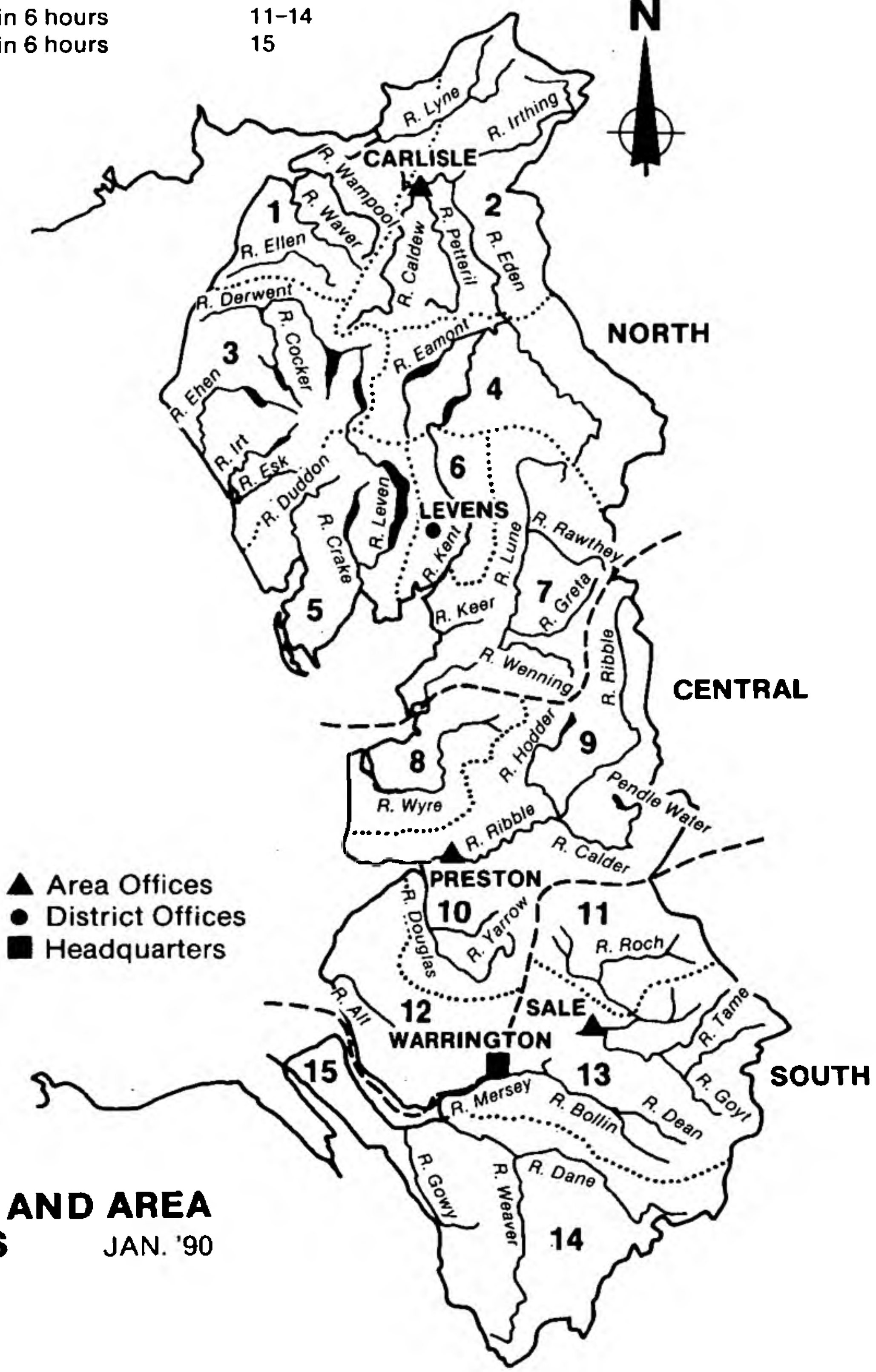
A. Thunderstorms with rainfall intensities exceeding 10 mm/hr AND total rainfall amounting to 10 mm or more.

B. Frontal storms with rainfall intensities exceeding 4 mm/hr AND total rainfall amounting to 20 mm or more in the summer months, and 15 mm.

NATIONAL RIVERS AUTHORITY — NORTH WEST
FLOOD WARNING

TYPE	WARNING CRITERIA	CATCHMENTS
A	30–40 mm or more in 6–12 hours	1–10
B	15 mm or more in 6 hours	11–14
C	10 mm or more in 6 hours	15

1. South Solway
2. Lower Eden
3. West Lakes
4. Upper Eden
5. South Lakes
6. Kent
7. Lune
8. Wyre
9. Ribble
10. Douglas
11. Irwell
12. West Lancs
13. Mersey
14. Weaver
15. Wirral



CATCHMENT AND AREA BOUNDARIES JAN. '90

Figure 1b

Figure 2

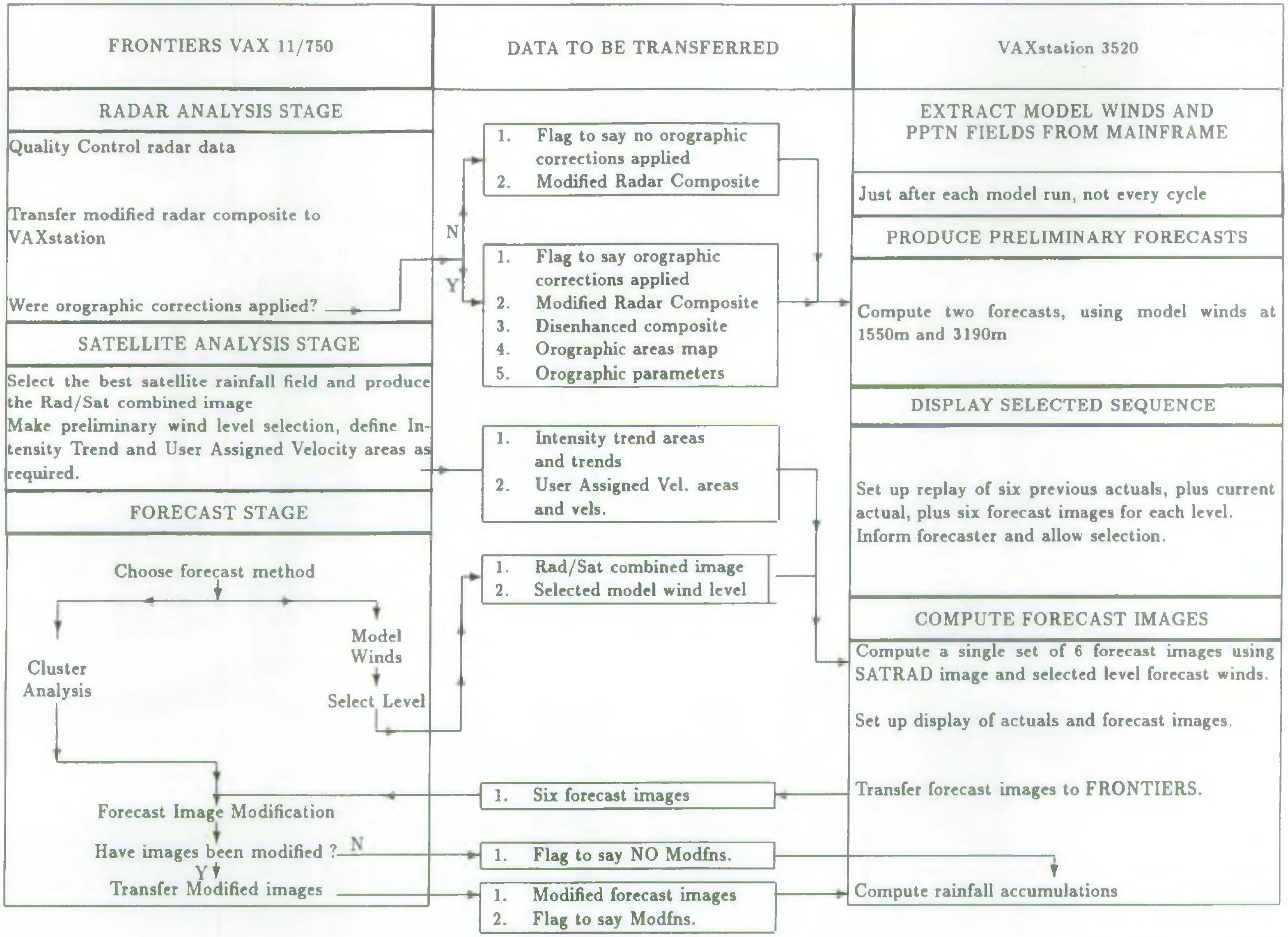


Fig. 3 Outline of the structure of the new Forecast Stage, showing the data to be transferred between the FRONTIERS VAX 11/750 and the VAXstation 3520 at each stage of the FRONTIERS cycle, and the main tasks to be performed on the VAXstation.


RAIN FORECAST USING MESOSCALE WINDS
T+0 ACTUAL 1430
1550m Mesoscale wind forecast + SAT data
850mb/1550m
700mb/3190m
? mb/?m
DISPLAYING MODEL WIND FIELD
1550m M/WINDS 07JAN91 0000 T+15
AUXILIARY DISPLAY
MIDNIGHT (0000) OR MIDDAY (1200) RUN? : 0000
LEVEL (1550 or 3190)? : 1550
T+? (04-18) : 15
Display another at same level (Y/N)? :

Figure 4

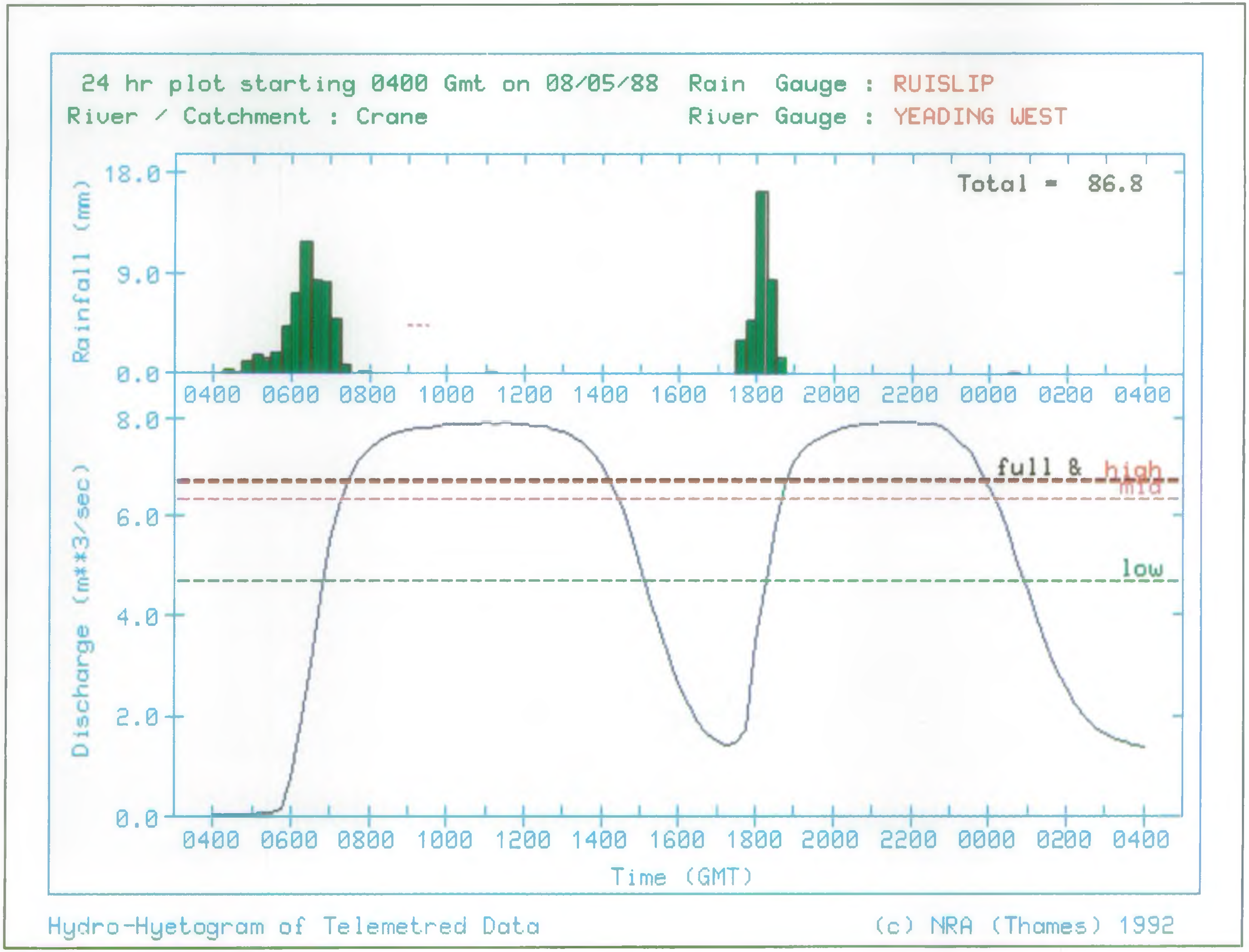

24 hr plot starting 0400 Gmt on 08/05/88
Rain Gauge : RUISLIP
River / Catchment : Crane
River Gauge : YEADING WEST
Rainfall (mm)
18.0
9.0
0.0
Total = 86.8
0400 0600 0800 1000 1200 1400 1600 1800 2000 2200 0000 0200 0400
Discharge (m**3/sec)
8.0
6.0
4.0
2.0
0.0
full & high
mid
low
0400 0600 0800 1000 1200 1400 1600 1800 2000 2200 0000 0200 0400
Time (GMT)
Hydro-Hyetogram of Telemetred Data
(c) NRA (Thames) 1992

Figure 5

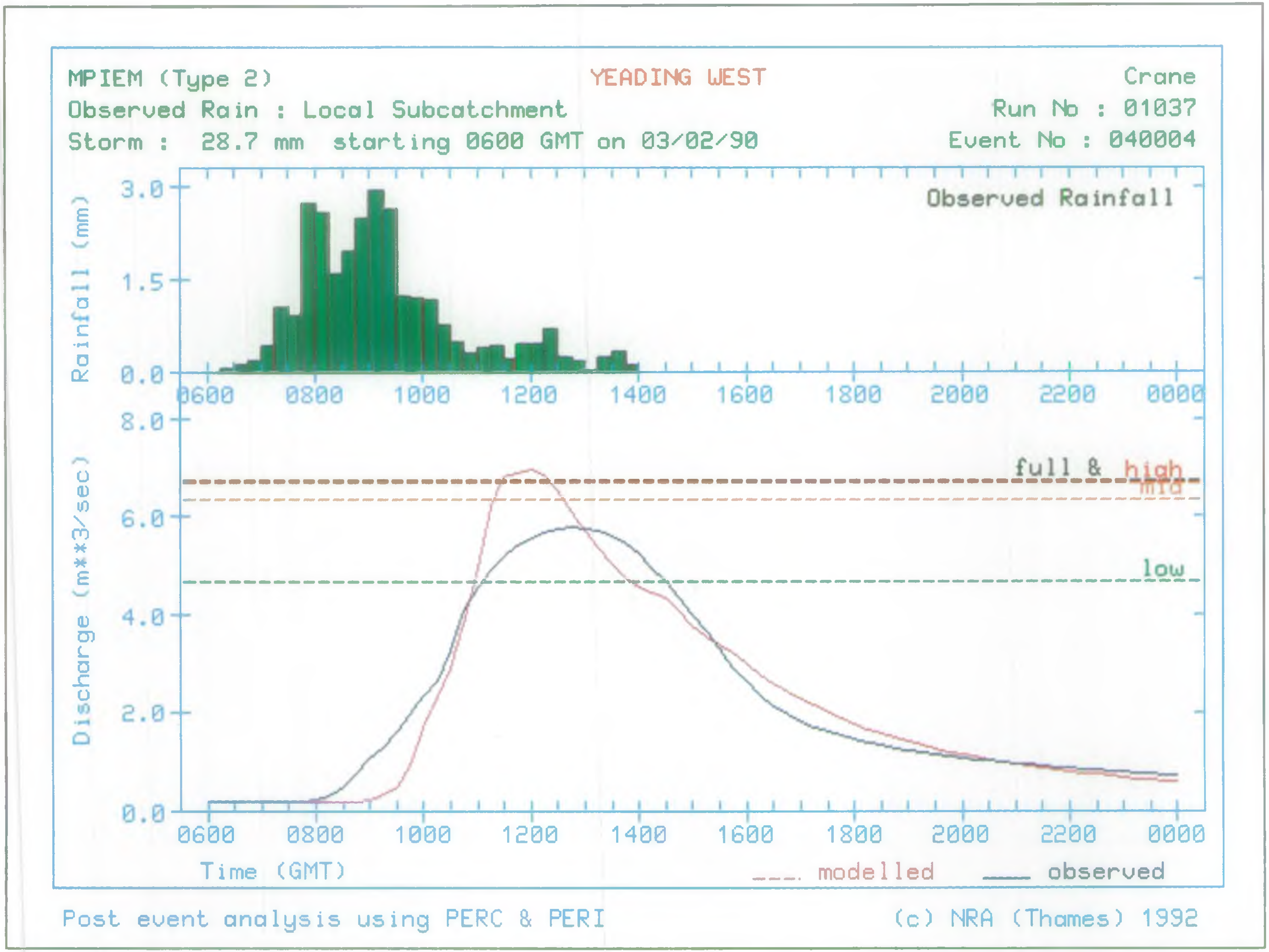
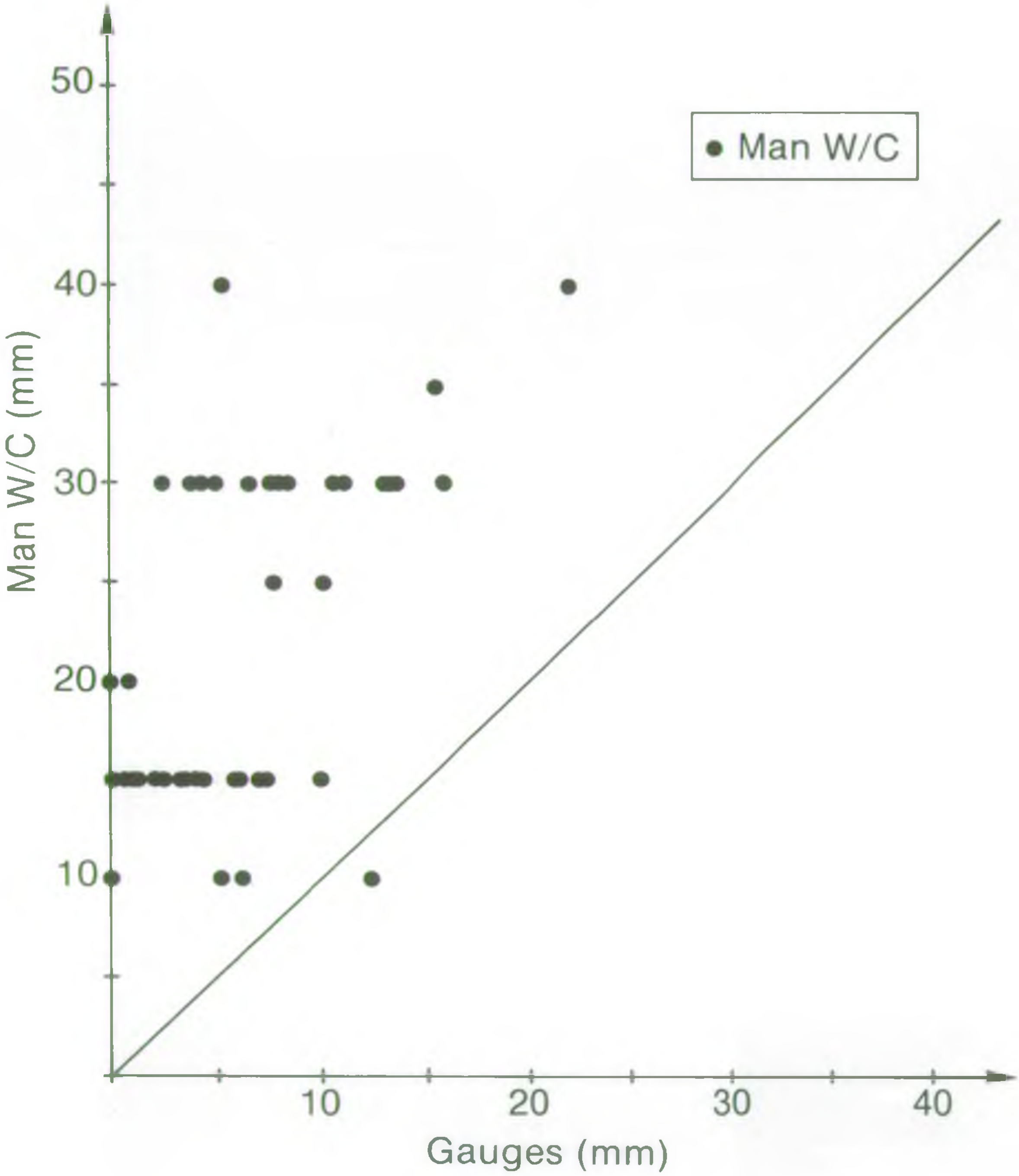
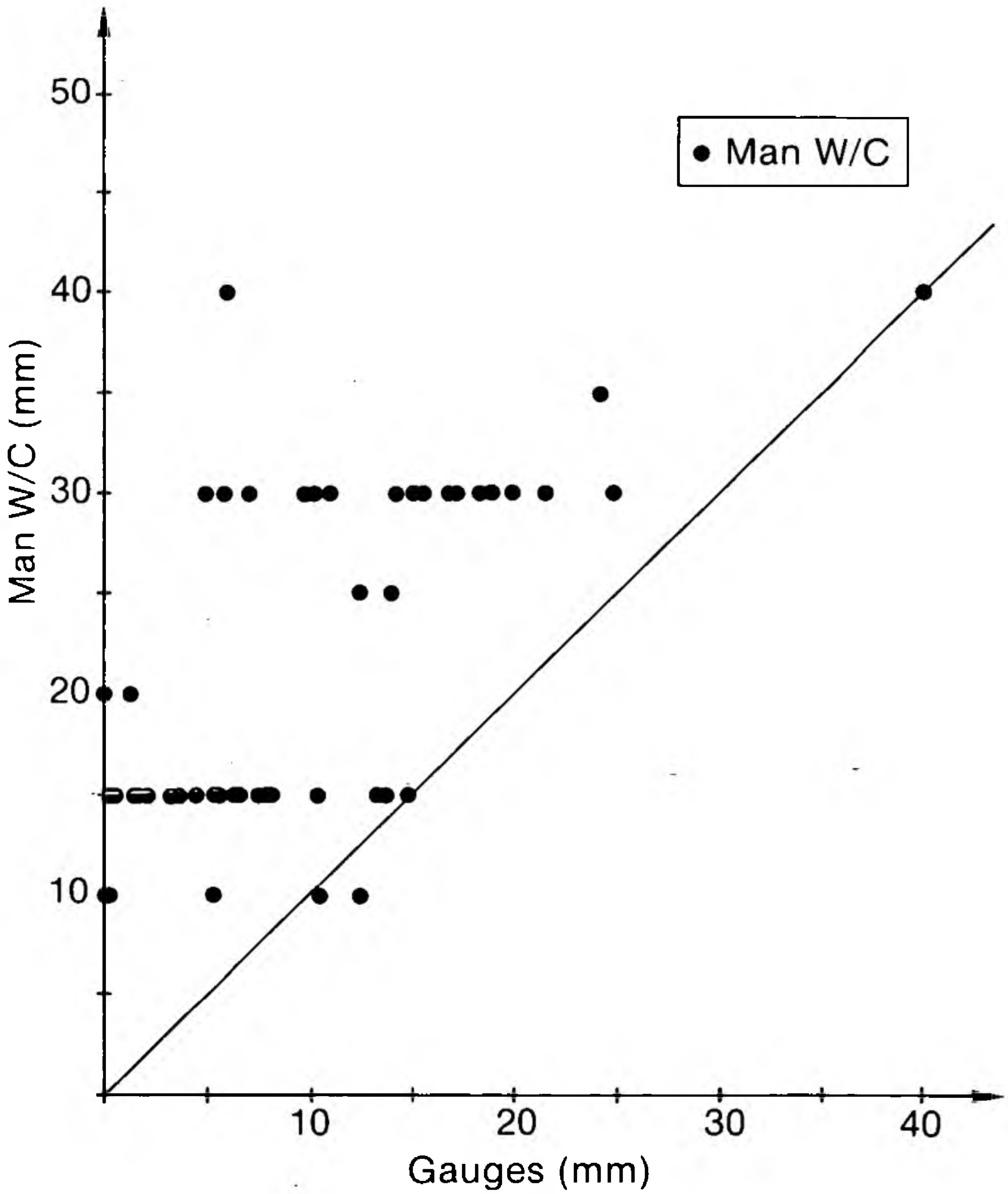

MPIEM (Type 2)
YEADING WEST
Crane
Observed Rain : Local Subcatchment
Run No : 01037
Storm : 28.7 mm starting 0600 GMT on 03/02/90
Event No : 040004
Observed Rainfall
Rainfall (mm)
3.0
1.5
0.0
0600 0800 1000 1200 1400 1600 1800 2000 2200 0000
8.0
6.0
4.0
2.0
0.0
Discharge (m**3/sec)
full & high
mid
low
0600 0800 1000 1200 1400 1600 1800 2000 2200 0000
Time (GMT)
modelled
observed
Post event analysis using PERC & PERI
(c) NRA (Thames) 1992

Figure 6



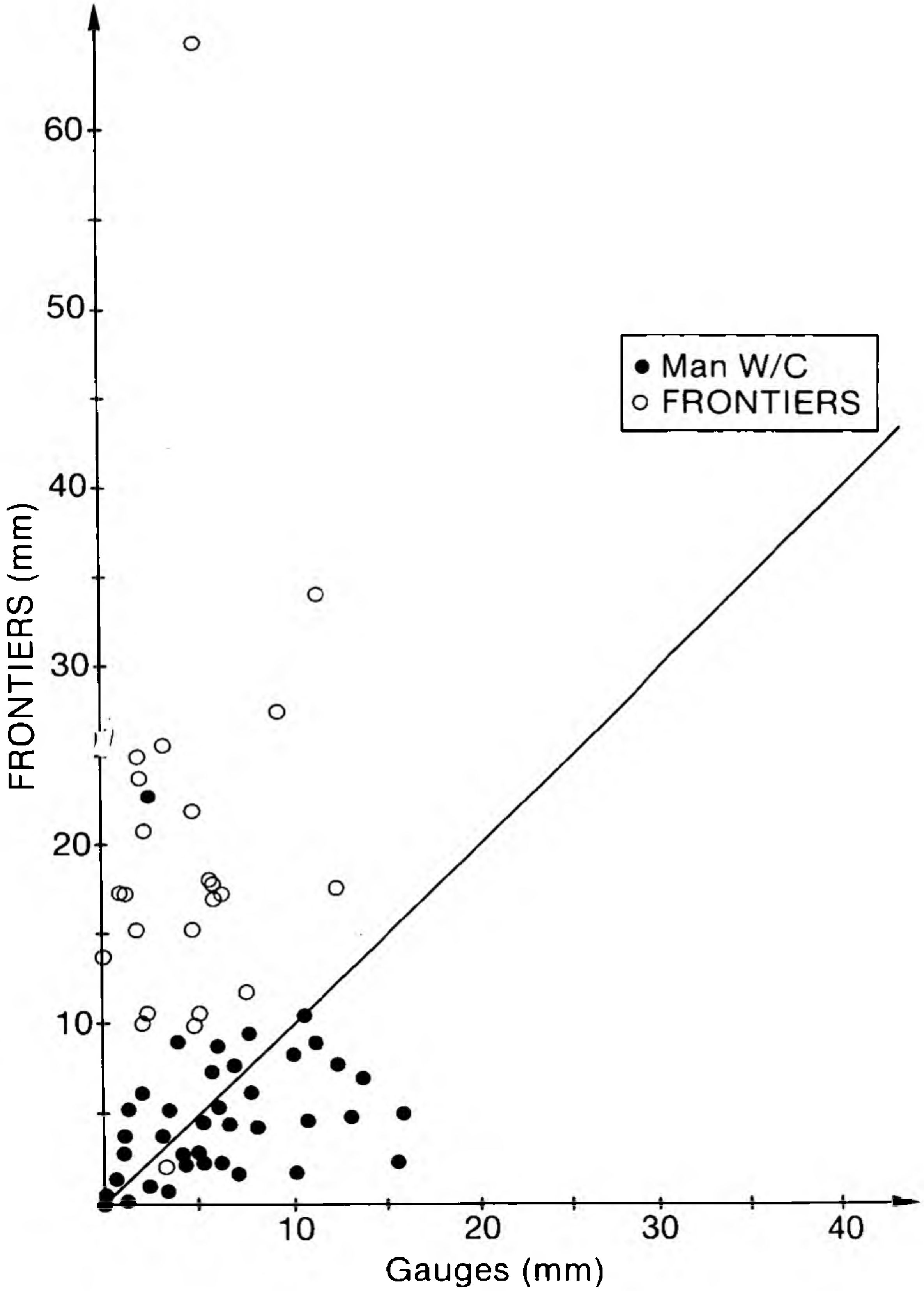
Manchester Weather Centre warning vs rain-gauge average

Figure 7



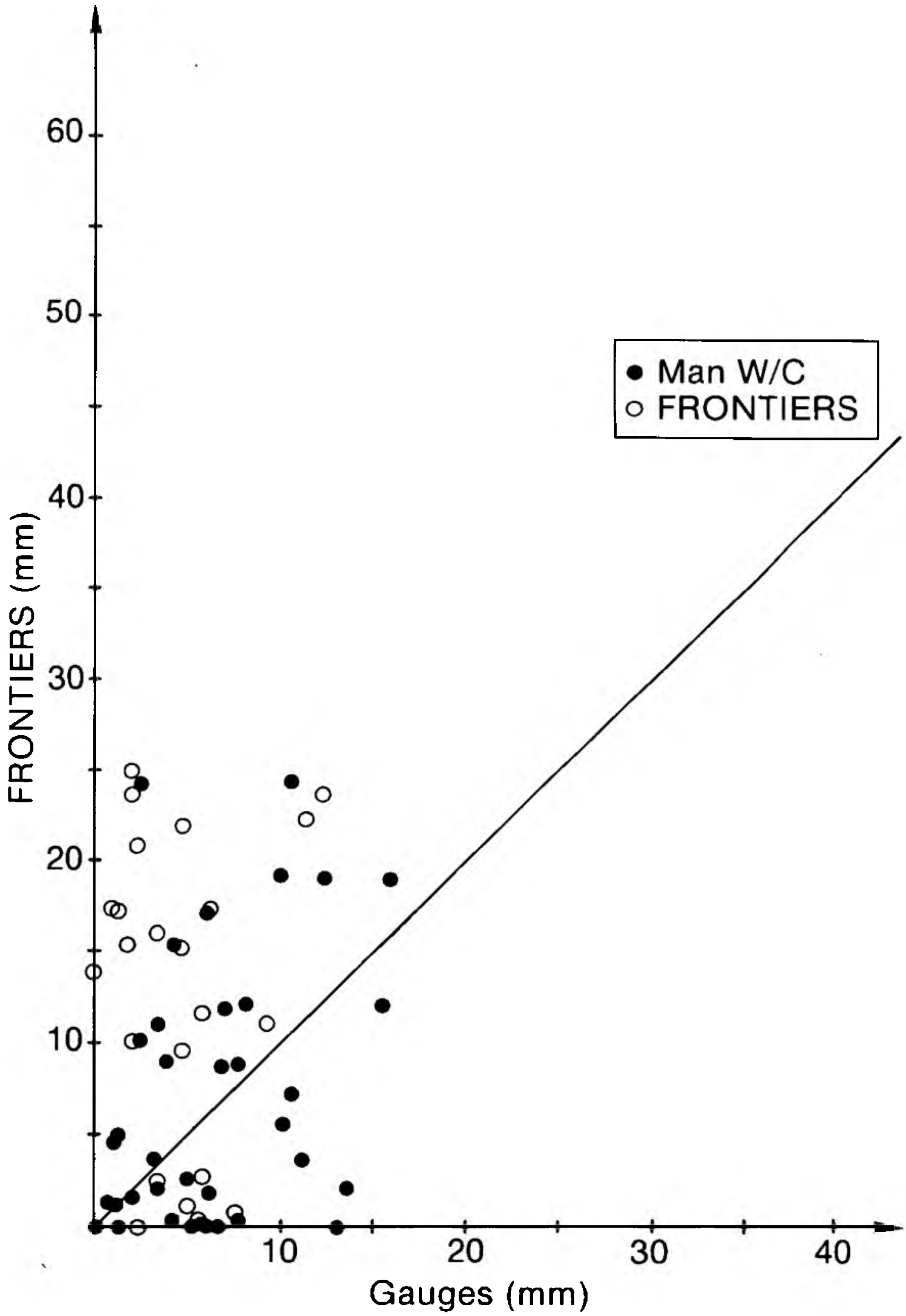
Manchester Weather Centre warning vs rain-gauge maximum

Figure 8



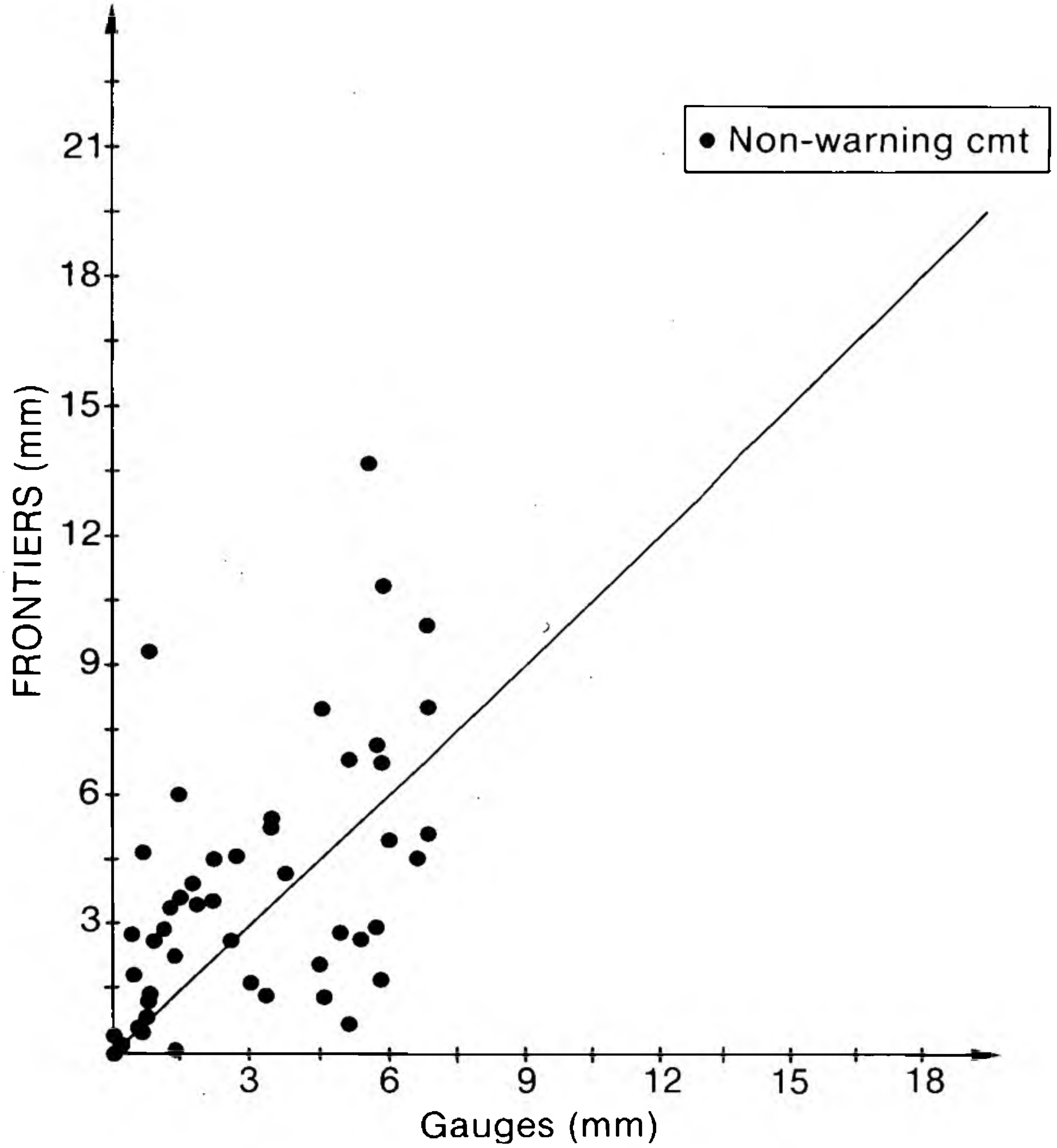
FRONTIERS accumulation F/C vs rain-gauge average (MWC and FRONTIERS warnings)

Figure 9



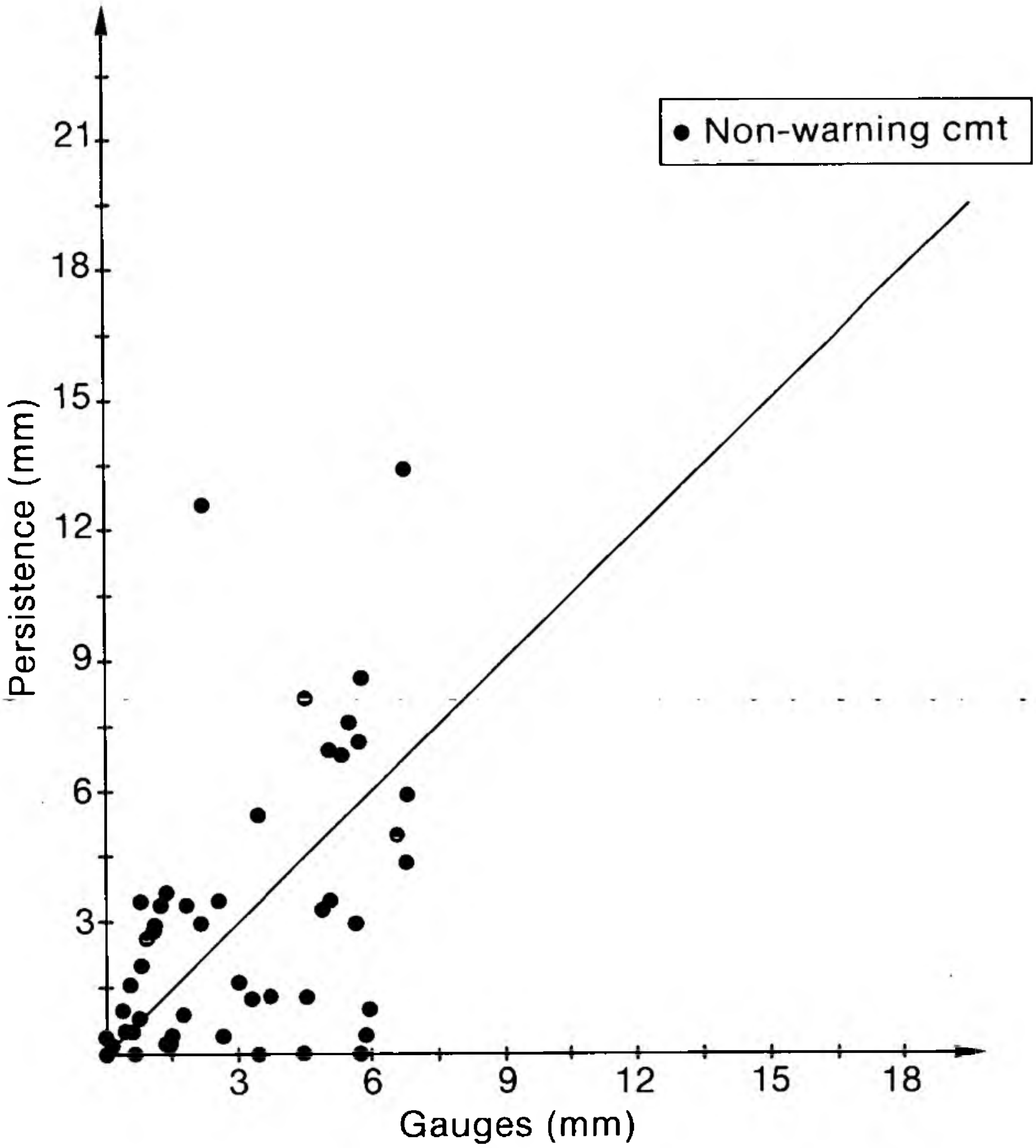
Persistence accumulation F/C vs rain-gauge average (MWC and FRONTIERS warnings)

Figure 10



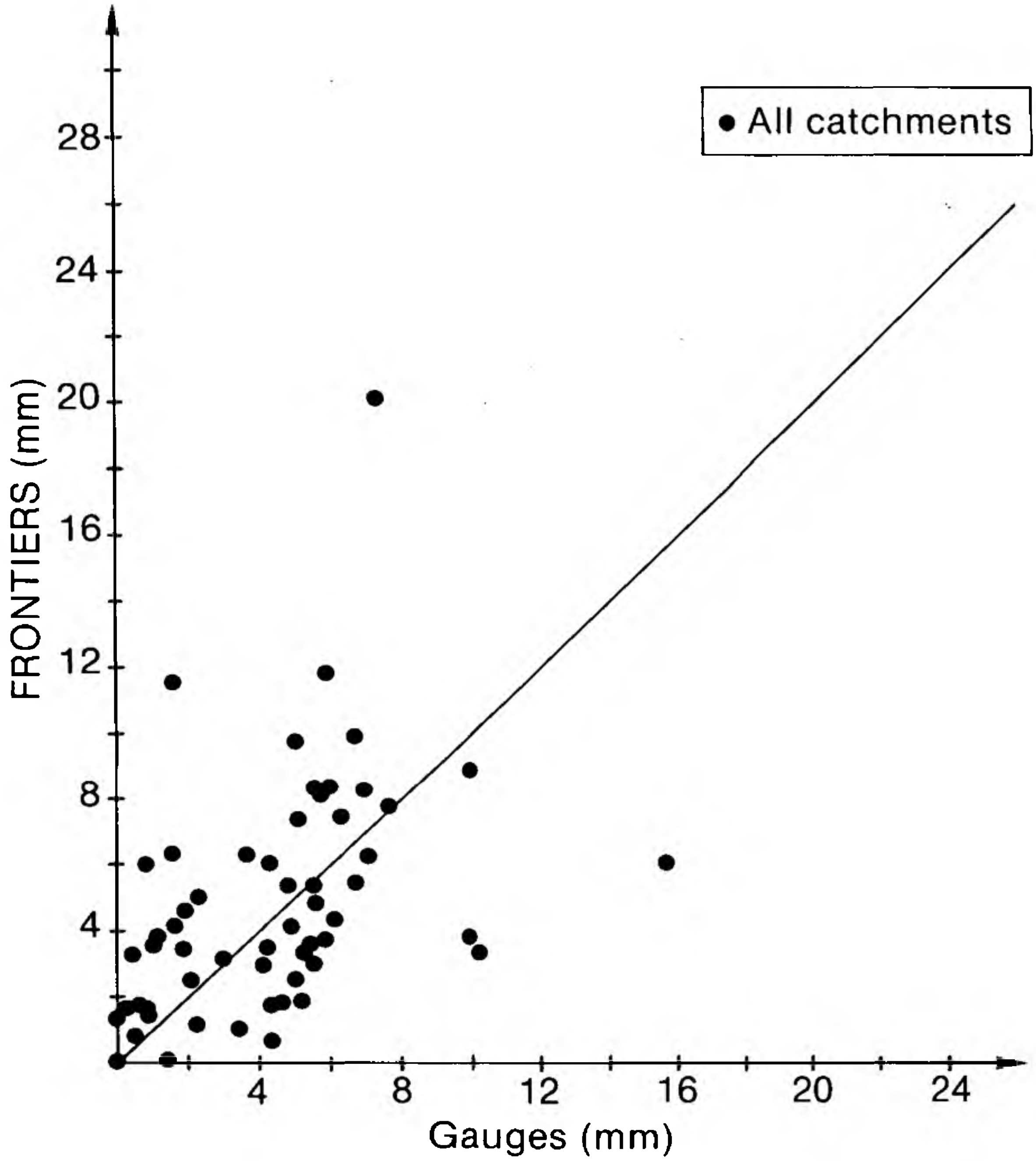
FRONTIERS accumulation F/C vs rain-gauge average for the non-warning catchments (all cases)

Figure 11



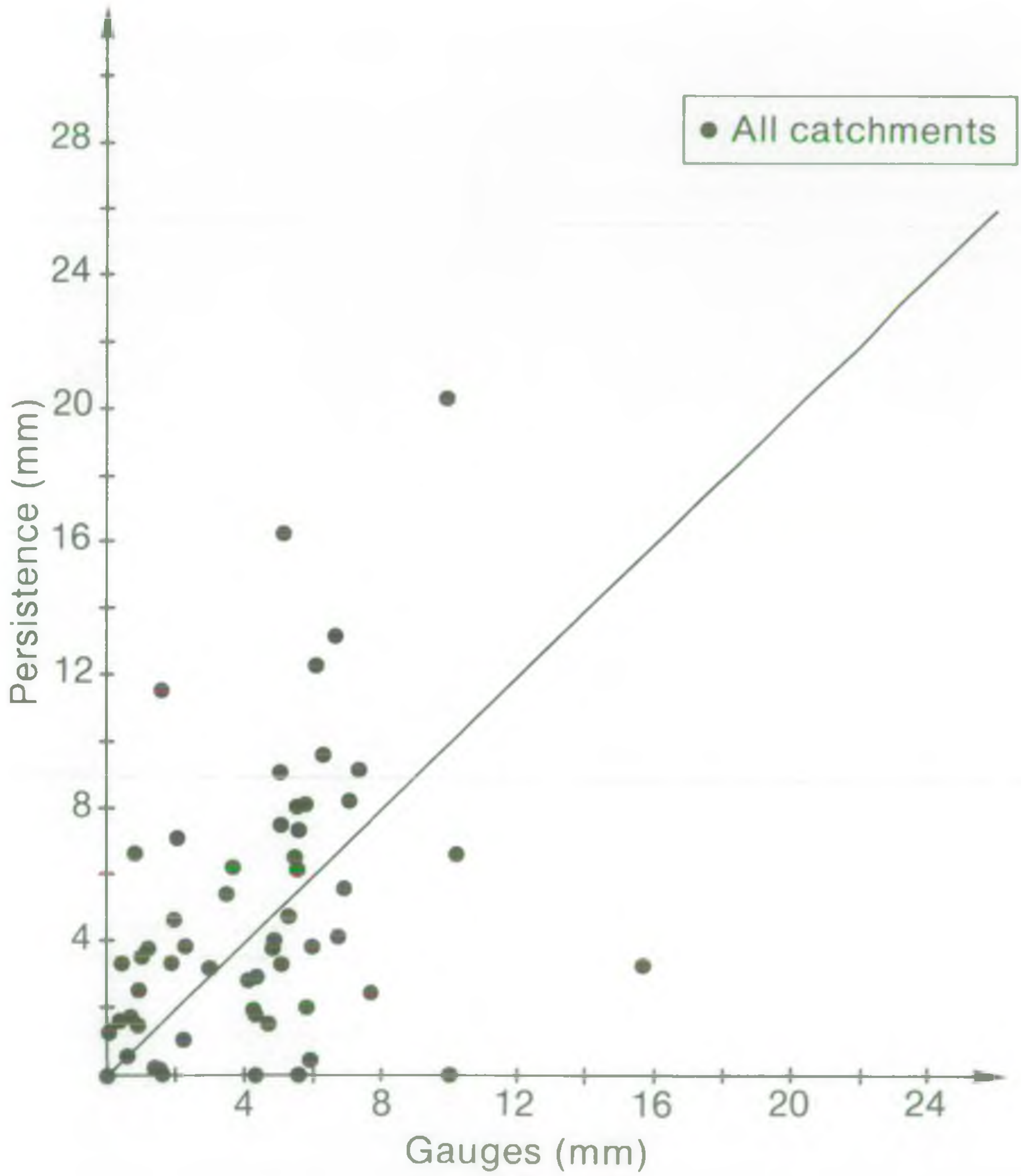
Persistence accumulation F/C vs rain-gauge average for the non-warning catchments (all cases)

Figure 12



FRONTIERS accumulation F/C vs rain-gauge average (all cases)

Figure 13



FRONTIERS persistence F/C vs rain-gauge average (all cases)

Figure 14

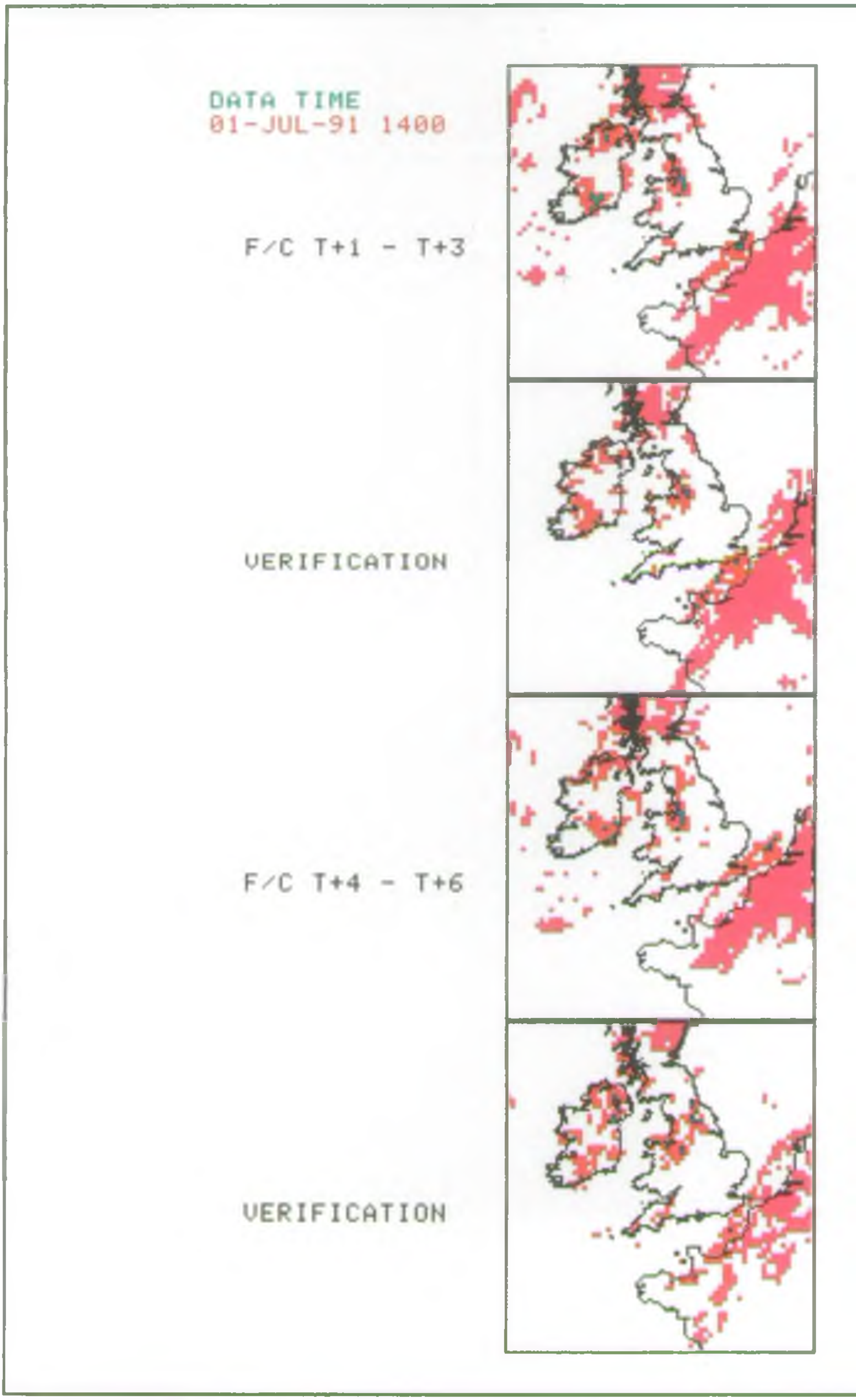
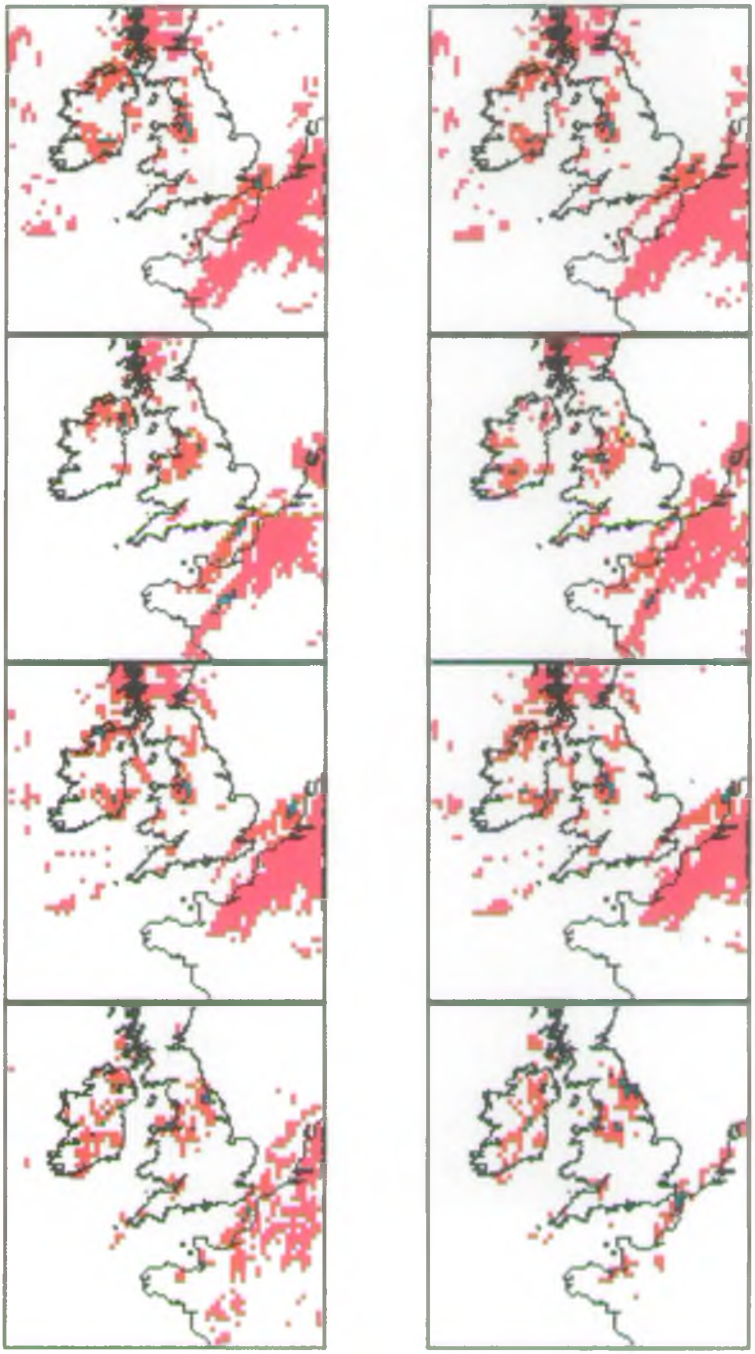

DATA TIME
01-JUL-91 1400
F/C T+1 - T+3
VERIFICATION
F/C T+4 - T+6
VERIFICATION

Figure 15a



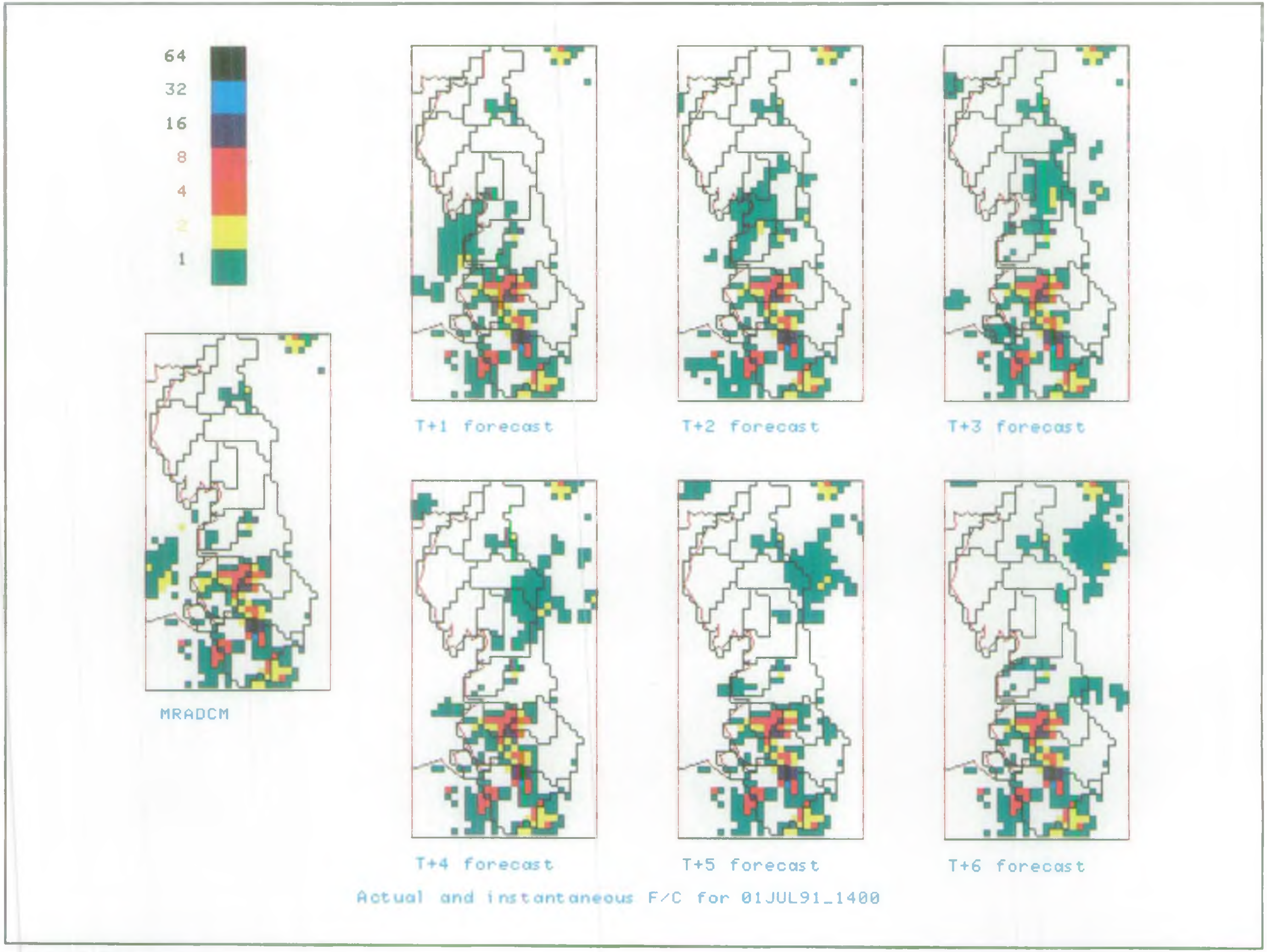

64
32
16
8
4
2
1
MRADCM
T+1 forecast
T+2 forecast
T+3 forecast
T+4 forecast
T+5 forecast
T+6 forecast
Actual and instantaneous F/C for 01JUL91_1400

Figure 15b

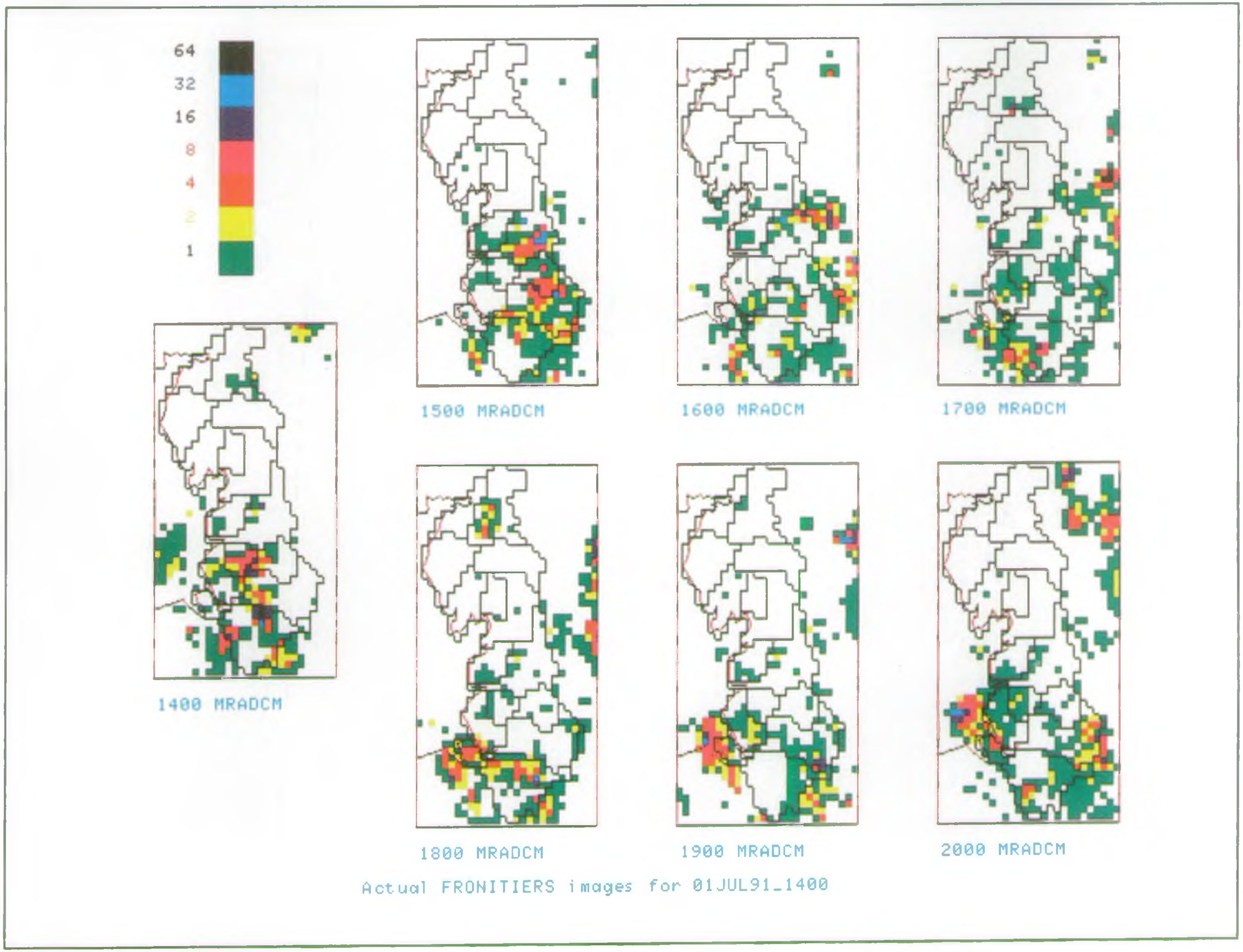

64
32
16
8
4
2
1
1500 MRADCM
1600 MRADCM
1700 MRADCM
1400 MRADCM
1800 MRADCM
1900 MRADCM
2000 MRADCM
Actual FRONITIERS images for 01JUL91_1400

Figure 15c

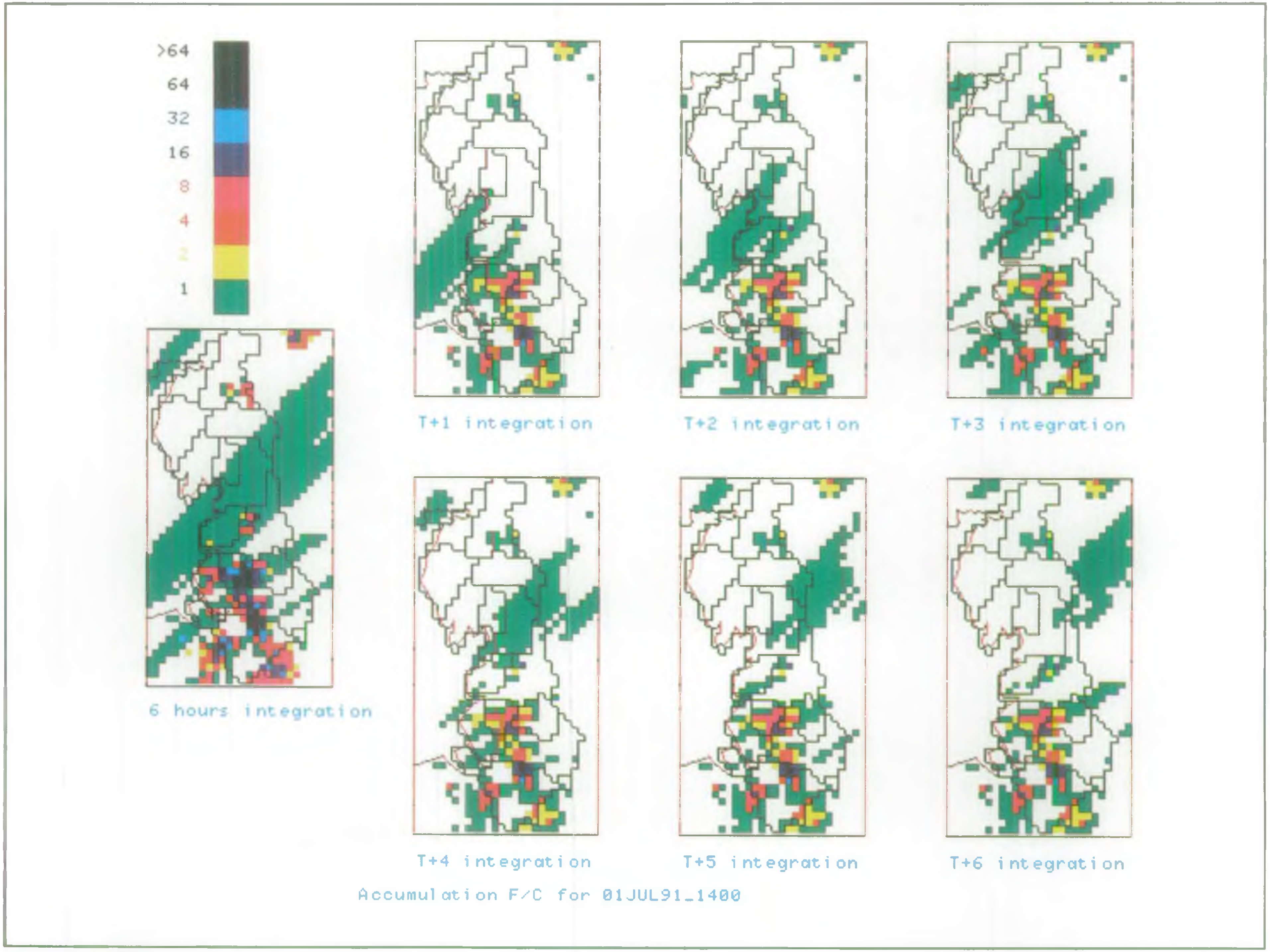
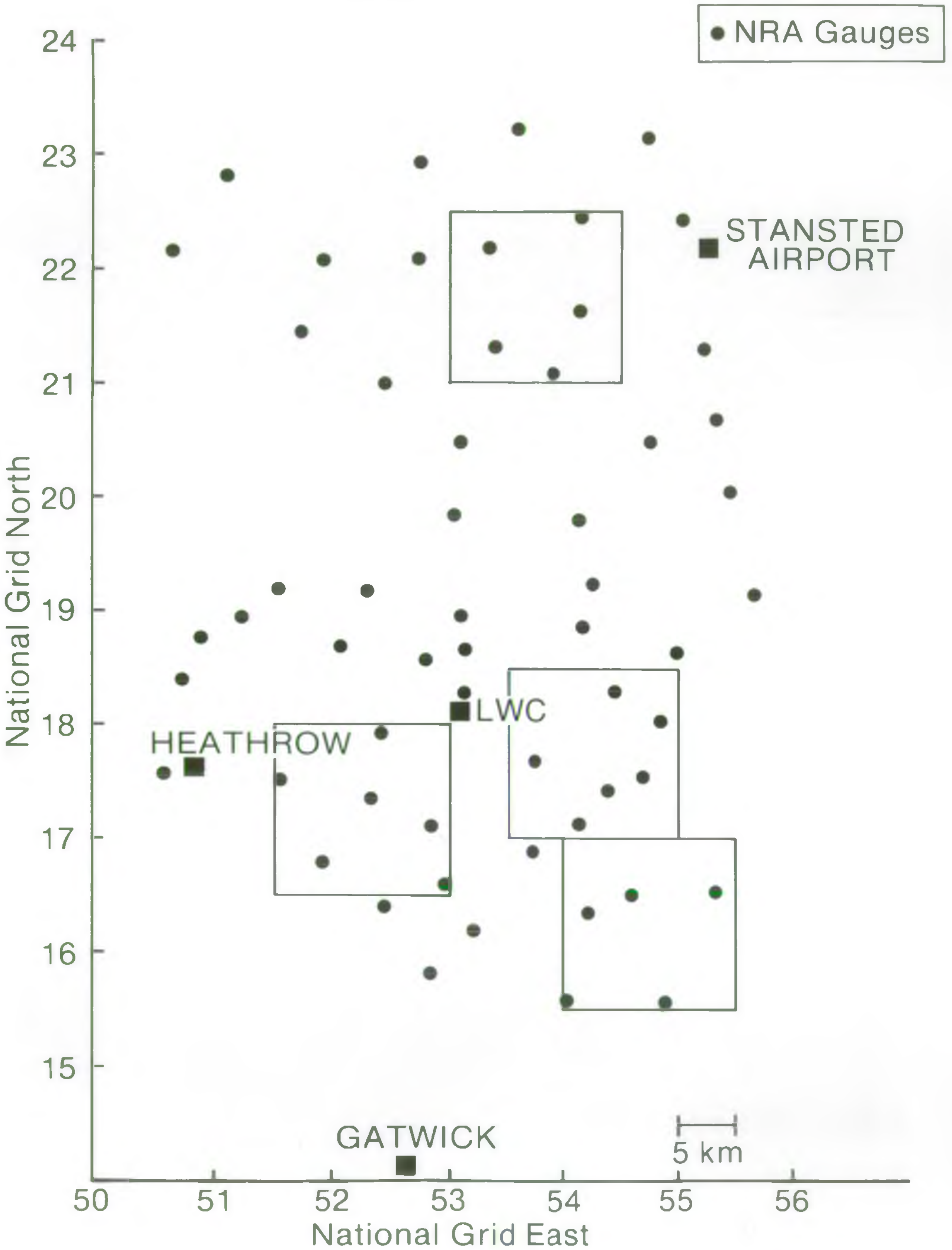

>64
64
32
16
8
4
2
1
6 hours integration
T+1 integration
T+2 integration
T+3 integration
T+4 integration
T+5 integration
T+6 integration
Accumulation F/C for 01JUL91_1400

Figure 15d



Pseudo Catchments used in the assessment of FRONTIERS forecasts for the NRA Thames Region. Rain-gauge locations are shown as dots.

Figure 16

The absolute deviation and bias of FRONTIERS forecasts as a function of forecast lead time.

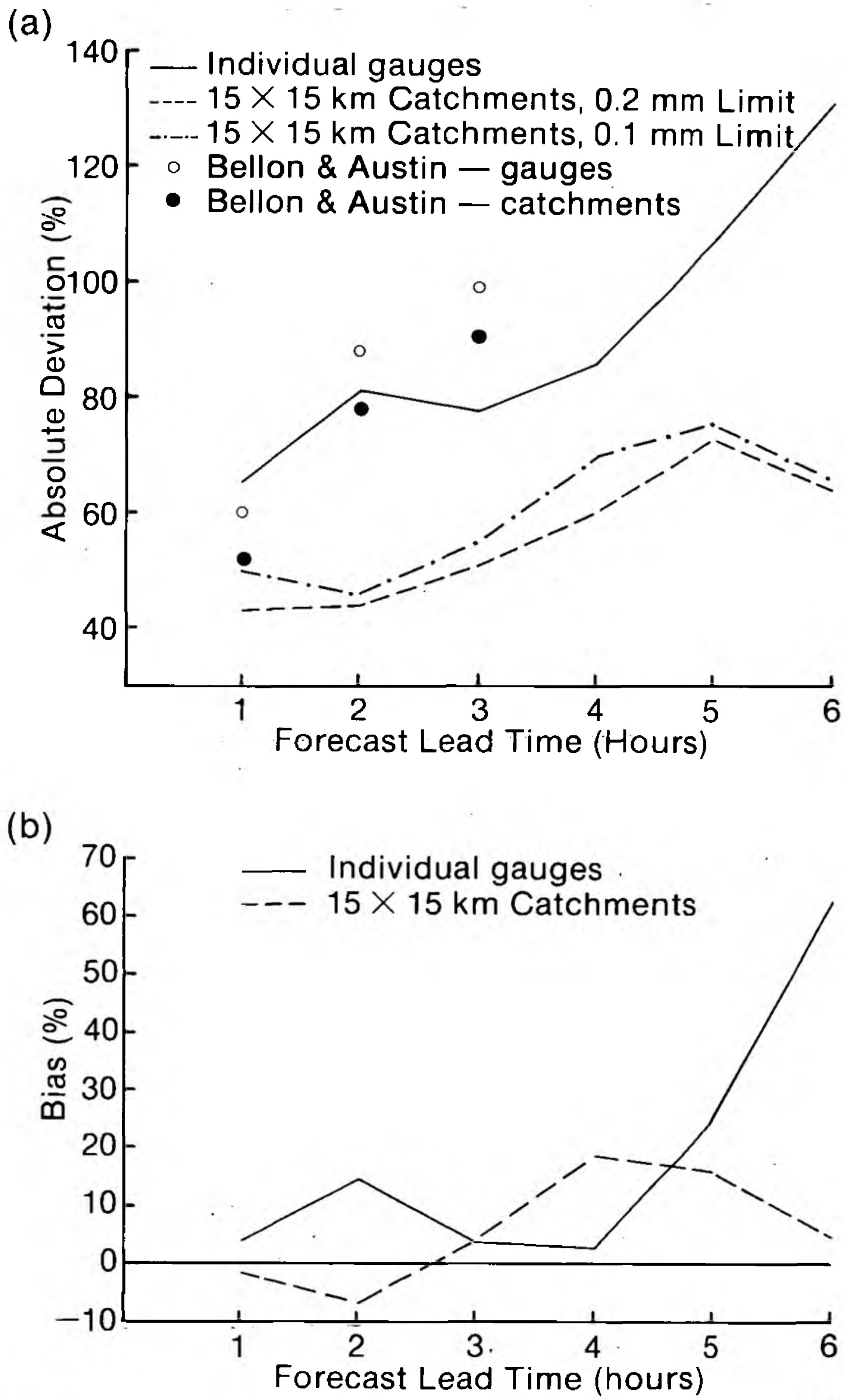


Figure 17

Instantaneous Forecasts Assessment T+1 All cases

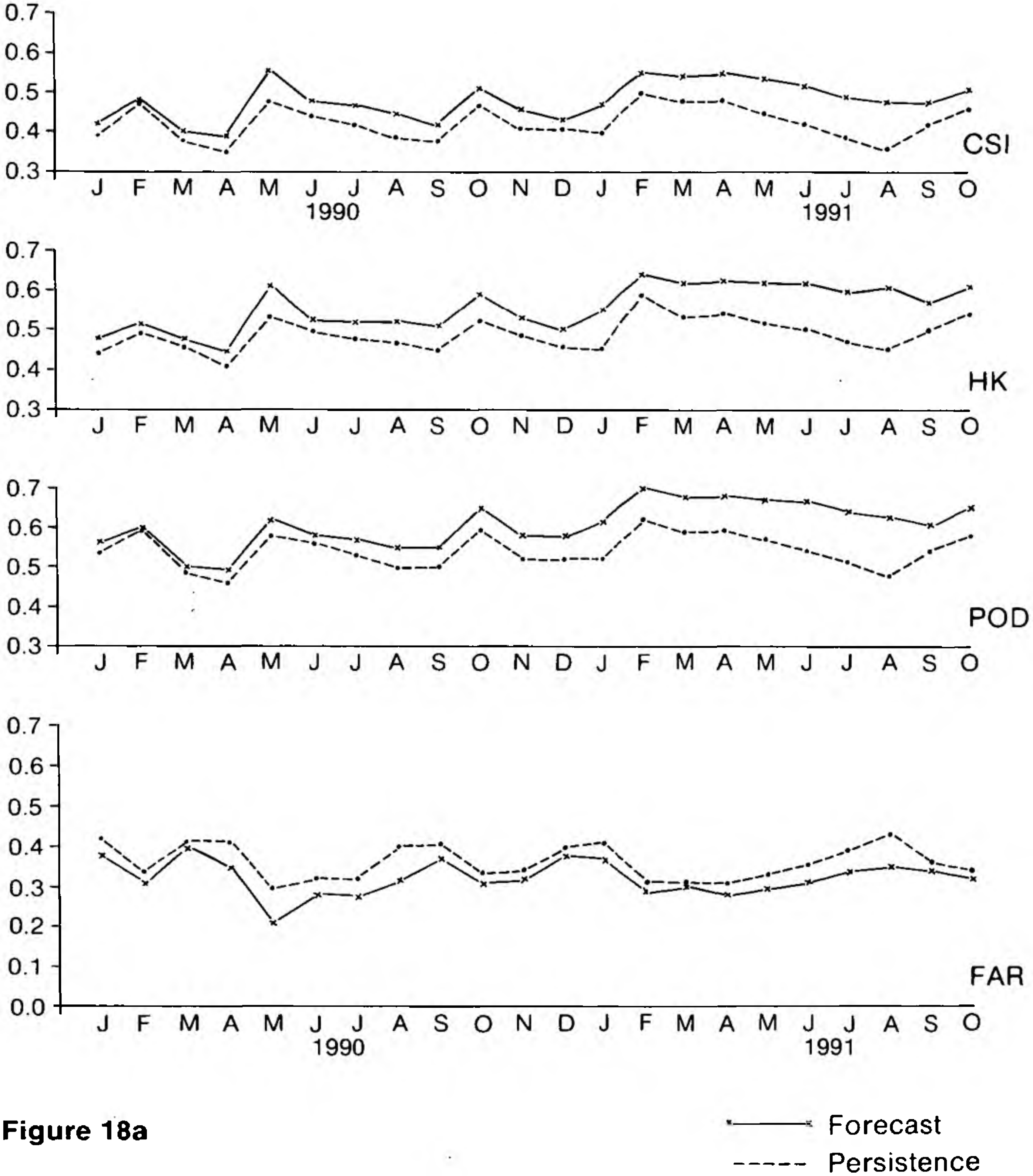


Figure 18a

Instantaneous Forecasts Assessment T+3 All cases

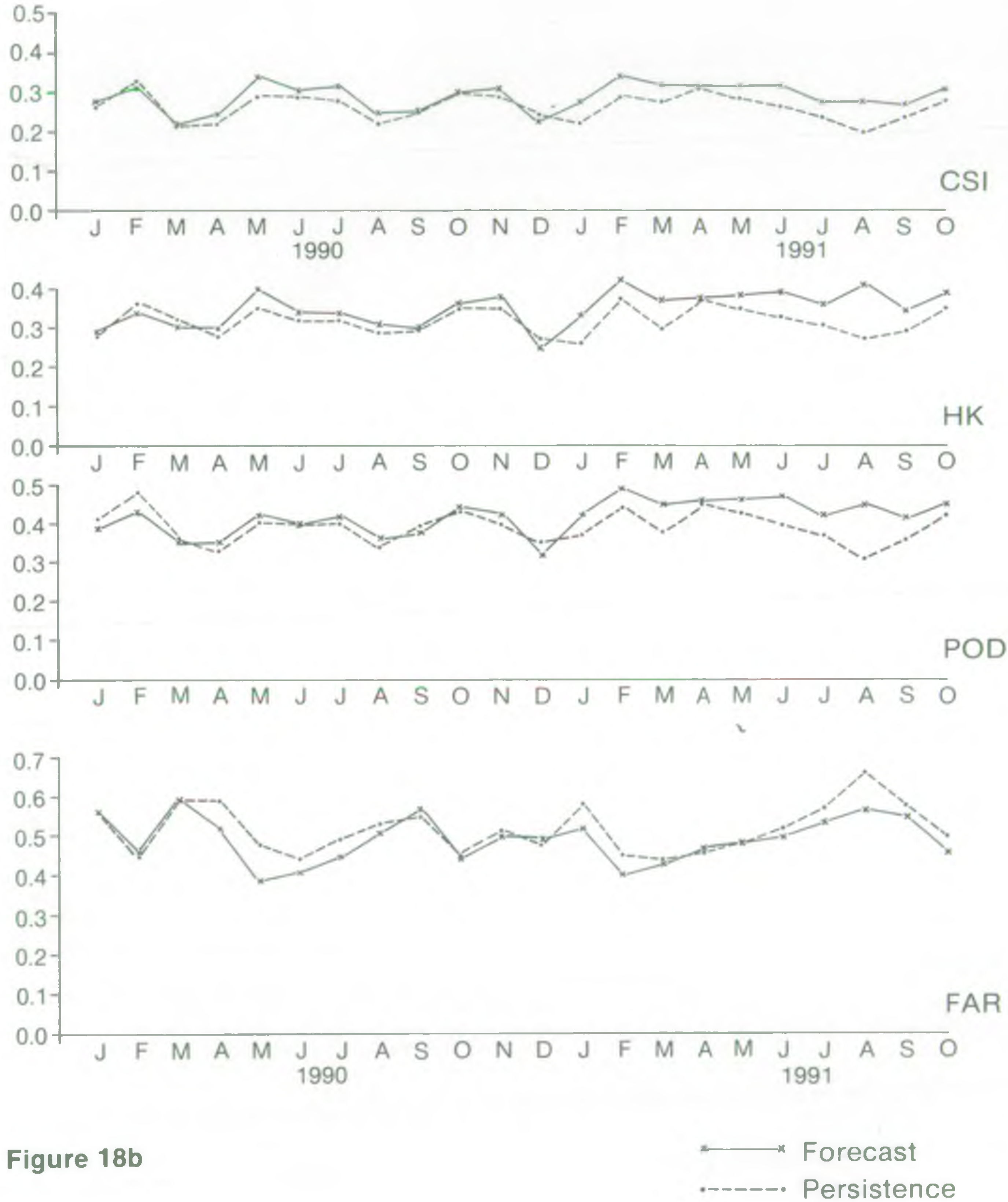


Figure 18b

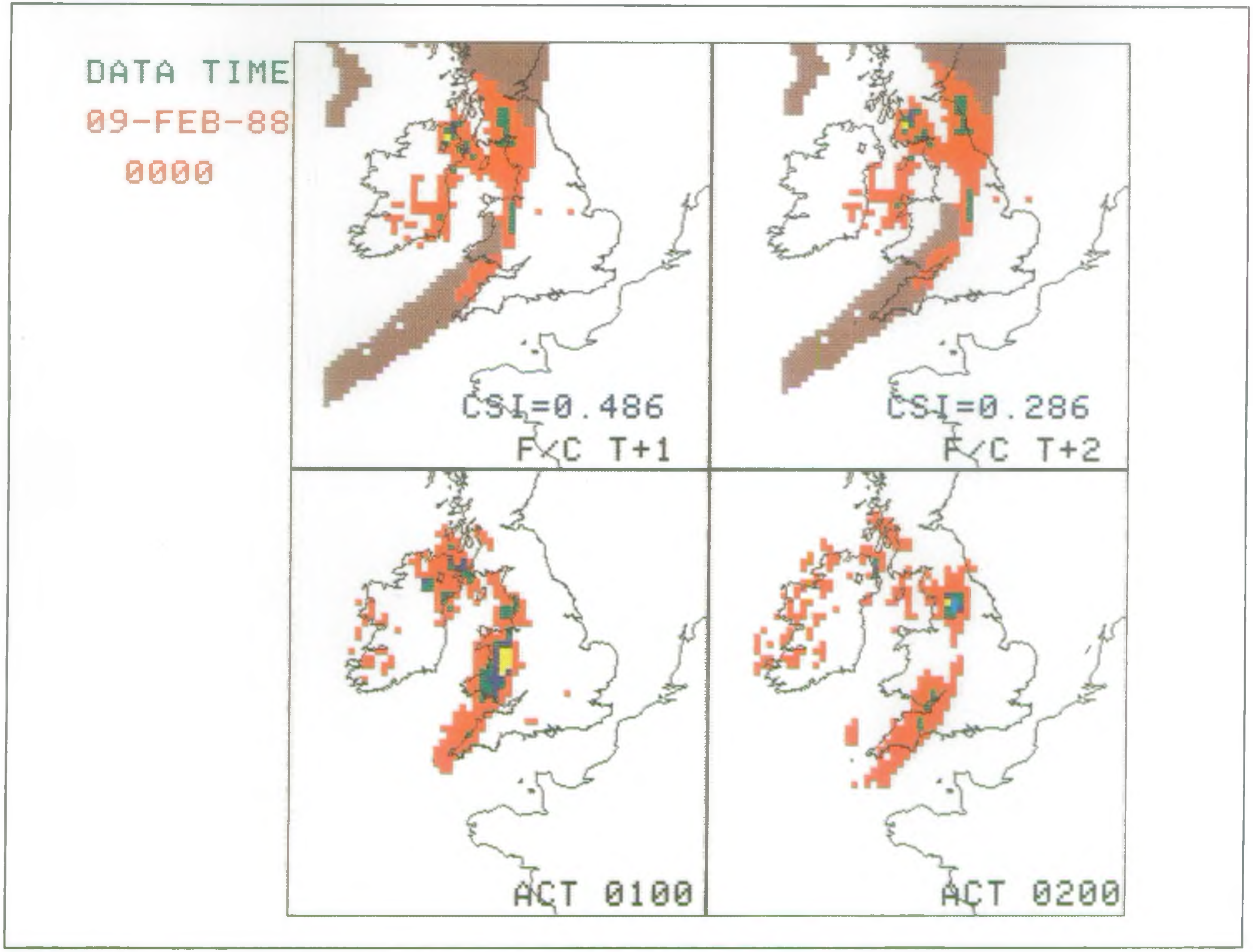


Figure 19 Example of instantaneous FRONTIERS forecasts

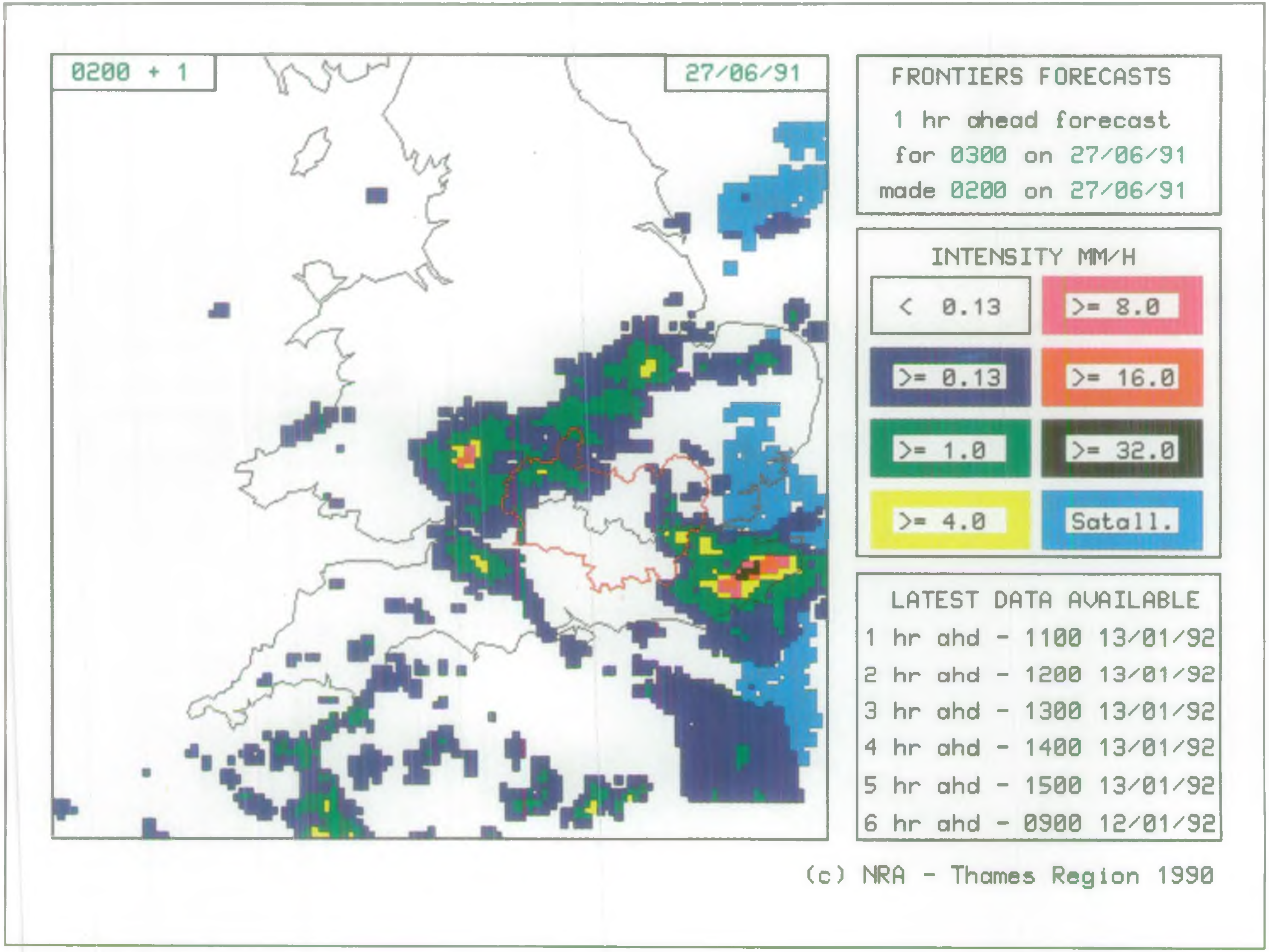

0200 + 1
27/06/91
FRONTIERS FORECASTS
1 hr ahead forecast
for 0300 on 27/06/91
made 0200 on 27/06/91
INTENSITY MM/H
< 0.13
>= 8.0
>= 0.13
>= 16.0
>= 1.0
>= 32.0
>= 4.0
Satall.
LATEST DATA AVAILABLE
1 hr ahd - 1100 13/01/92
2 hr ahd - 1200 13/01/92
3 hr ahd - 1300 13/01/92
4 hr ahd - 1400 13/01/92
5 hr ahd - 1500 13/01/92
6 hr ahd - 0900 12/01/92
(c) NRA - Thames Region 1990

Figure 20a

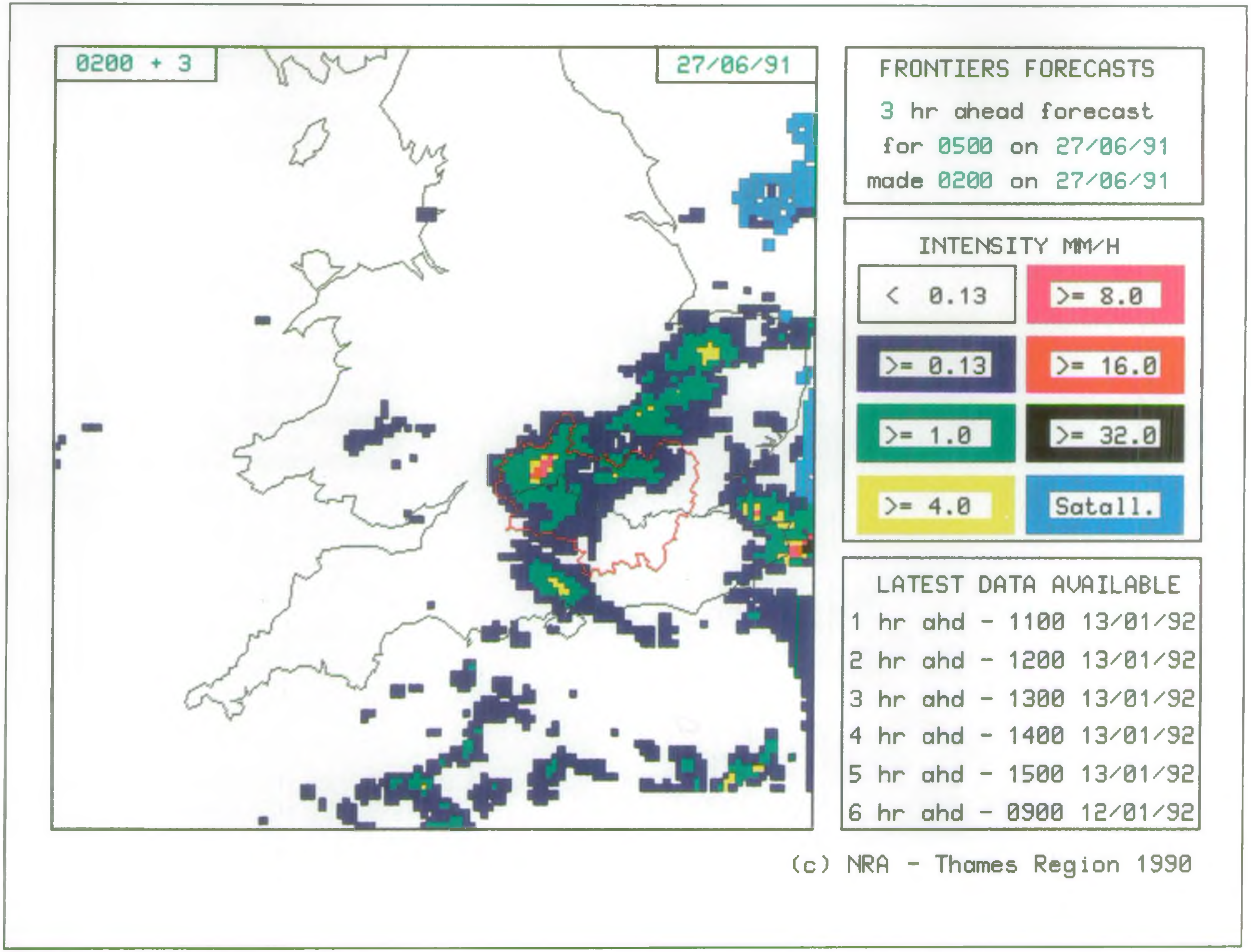
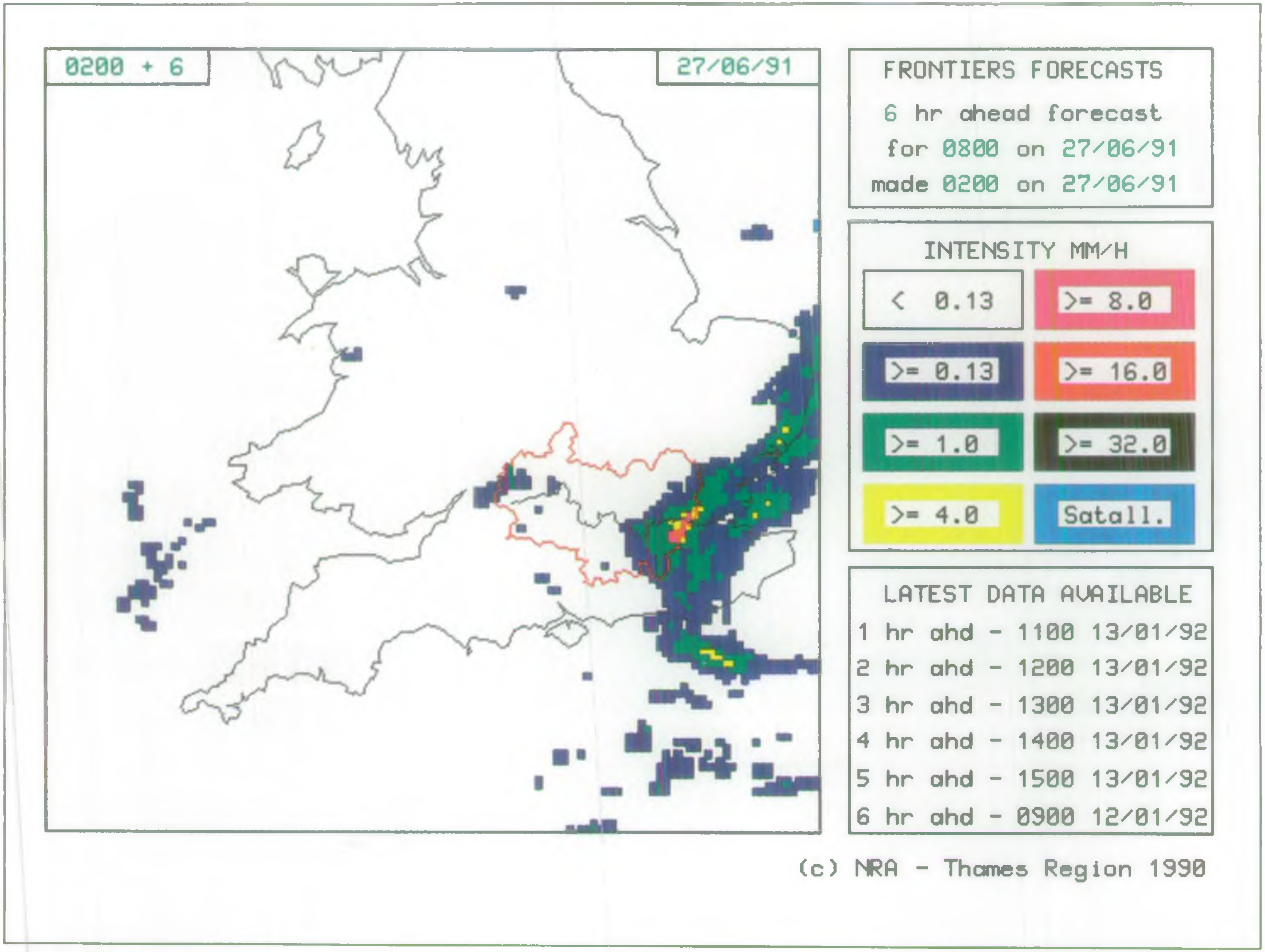
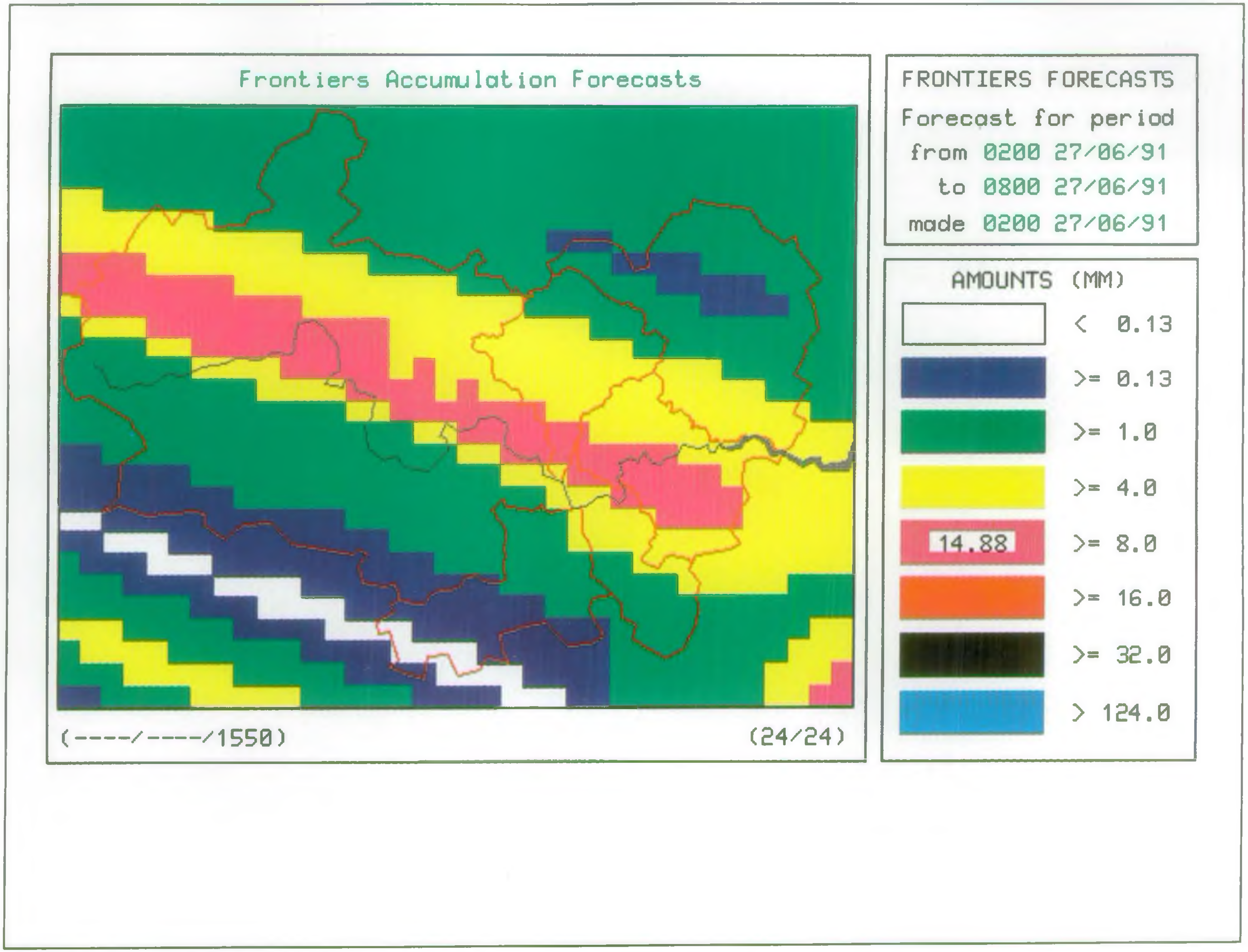

0200 + 3
27/06/91
FRONTIERS FORECASTS
3 hr ahead forecast
for 0500 on 27/06/91
made 0200 on 27/06/91
INTENSITY MM/H
< 0.13
>= 8.0
>= 0.13
>= 16.0
>= 1.0
>= 32.0
>= 4.0
Satell.
LATEST DATA AVAILABLE
1 hr ahd - 1100 13/01/92
2 hr ahd - 1200 13/01/92
3 hr ahd - 1300 13/01/92
4 hr ahd - 1400 13/01/92
5 hr ahd - 1500 13/01/92
6 hr ahd - 0900 12/01/92
(c) NRA - Thames Region 1990

Figure 20b



0200 + 6
27/06/91
FRONTIERS FORECASTS
6 hr ahead forecast
for 0800 on 27/06/91
made 0200 on 27/06/91
INTENSITY MM/H
< 0.13
>= 8.0
>= 0.13
>= 16.0
>= 1.0
>= 32.0
>= 4.0
Satall.
LATEST DATA AVAILABLE
1 hr ahd - 1100 13/01/92
2 hr ahd - 1200 13/01/92
3 hr ahd - 1300 13/01/92
4 hr ahd - 1400 13/01/92
5 hr ahd - 1500 13/01/92
6 hr ahd - 0900 12/01/92
(c) NRA - Thames Region 1990

Figure 20c



Frontiers Accumulation Forecasts
(----/----/1550)
(24/24)
FRONTIERS FORECASTS
Forecast for period
from 0200 27/06/91
to 0800 27/06/91
made 0200 27/06/91
AMOUNTS (MM)
< 0.13
>= 0.13
>= 1.0
>= 4.0
14.88
>= 8.0
>= 16.0
>= 32.0
> 124.0

Figure 21

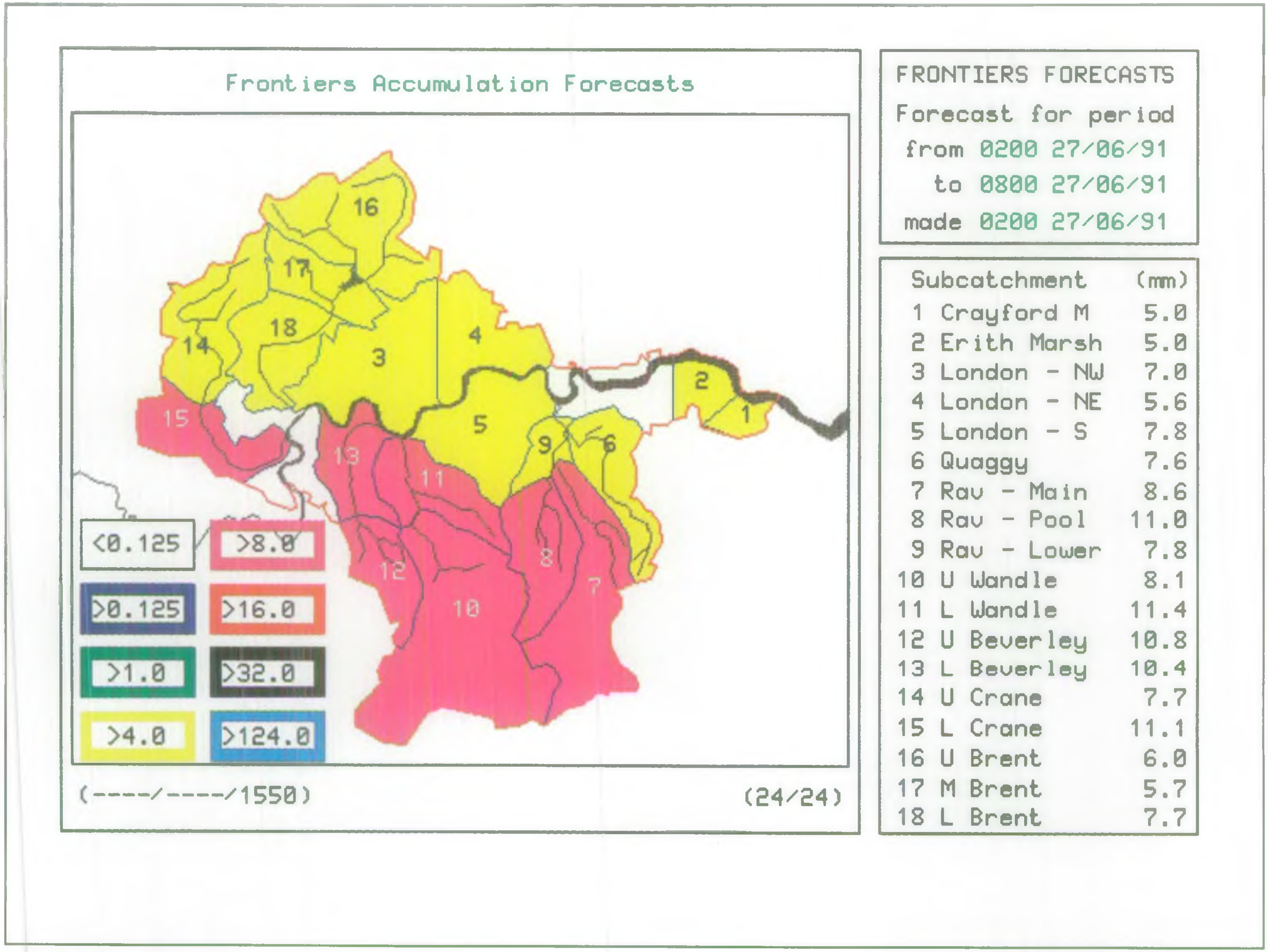

Frontiers Accumulation Forecasts
16
17
18
14
3
4
15
5
2
1
9
6
13
11
12
10
8
7
<0.125
>8.0
>0.125
>16.0
>1.0
>32.0
>4.0
>124.0
(----/----/1550)
(24/24)
FRONTIERS FORECASTS
Forecast for period
from 0200 27/06/91
to 0800 27/06/91
made 0200 27/06/91
Subcatchment (mm)
1 Crayford M 5.0
2 Erith Marsh 5.0
3 London - NW 7.0
4 London - NE 5.6
5 London - S 7.8
6 Quaggy 7.6
7 Rav - Main 8.6
8 Rav - Pool 11.0
9 Rav - Lower 7.8
10 U Wandle 8.1
11 L Wandle 11.4
12 U Beverley 10.8
13 L Beverley 10.4
14 U Crane 7.7
15 L Crane 11.1
16 U Brent 6.0
17 M Brent 5.7
18 L Brent 7.7

Figure 22

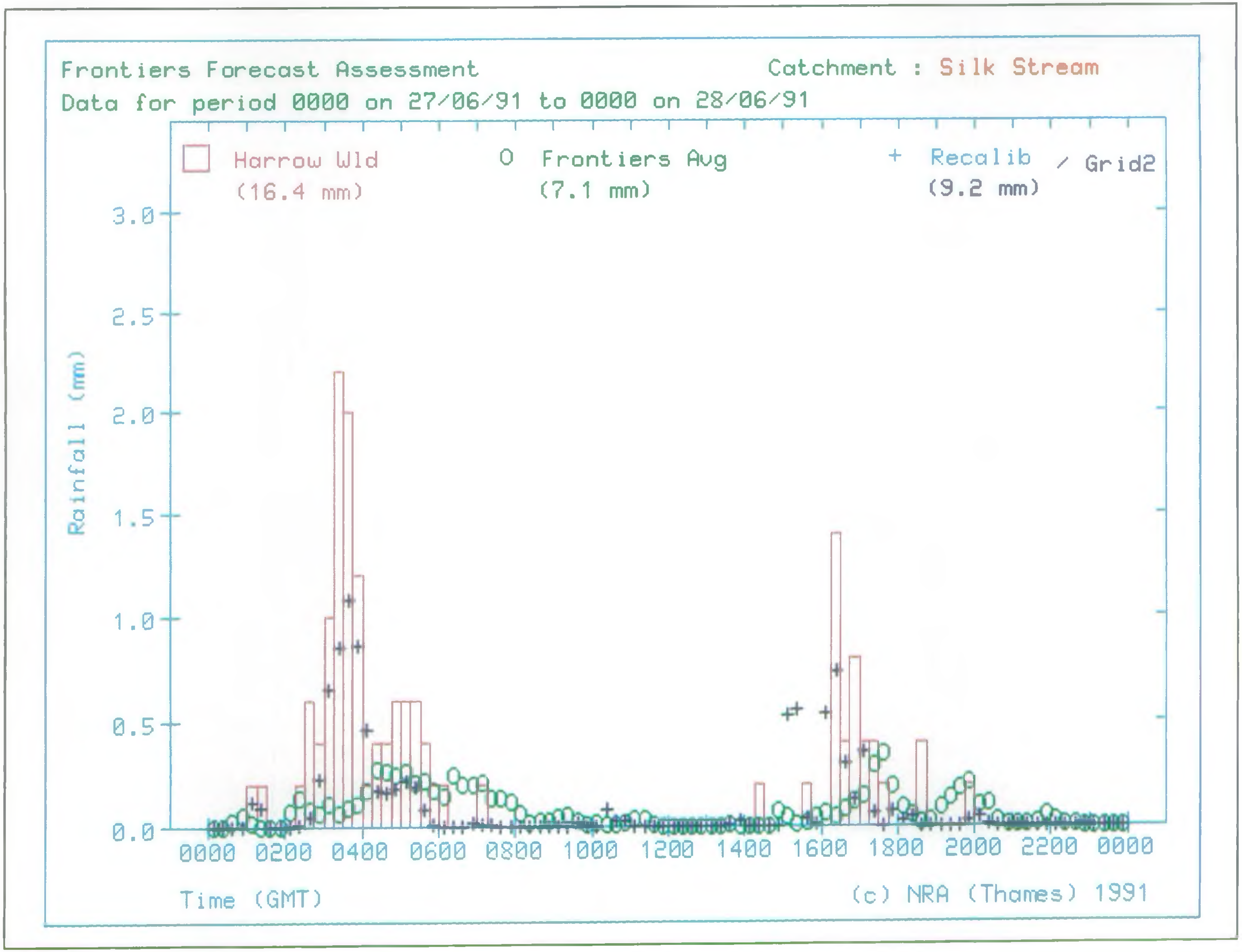

Frontiers Forecast Assessment
Catchment : Silk Stream
Data for period 0000 on 27/06/91 to 0000 on 28/06/91
Harrow Wld
(16.4 mm)
O Frontiers Avg
(7.1 mm)
+ Recalib / Grid2
(9.2 mm)
Rainfall (mm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0000 0200 0400 0600 0800 1000 1200 1400 1600 1800 2000 2200 0000
Time (GMT)
(c) NRA (Thames) 1991

Figure 23

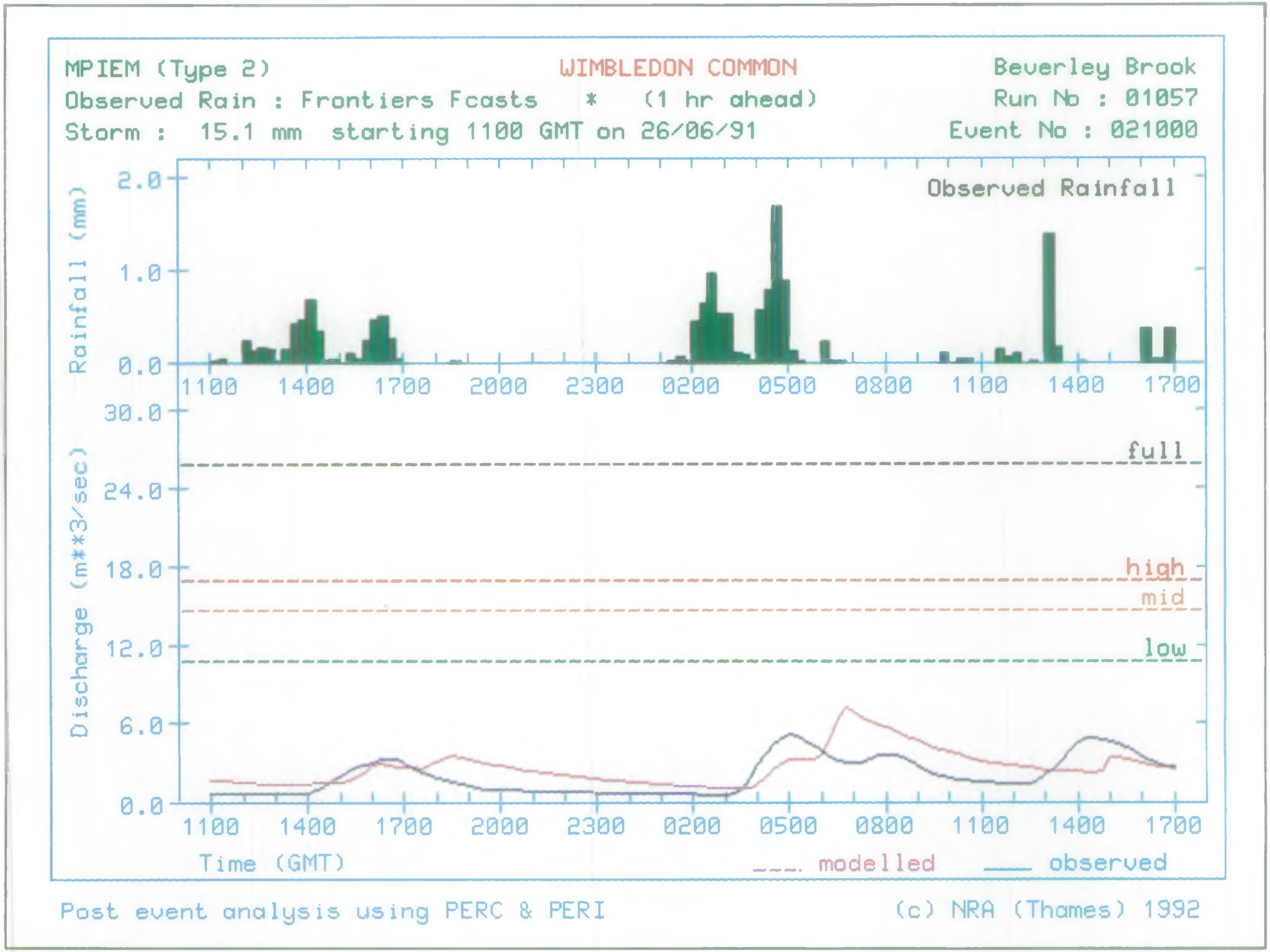
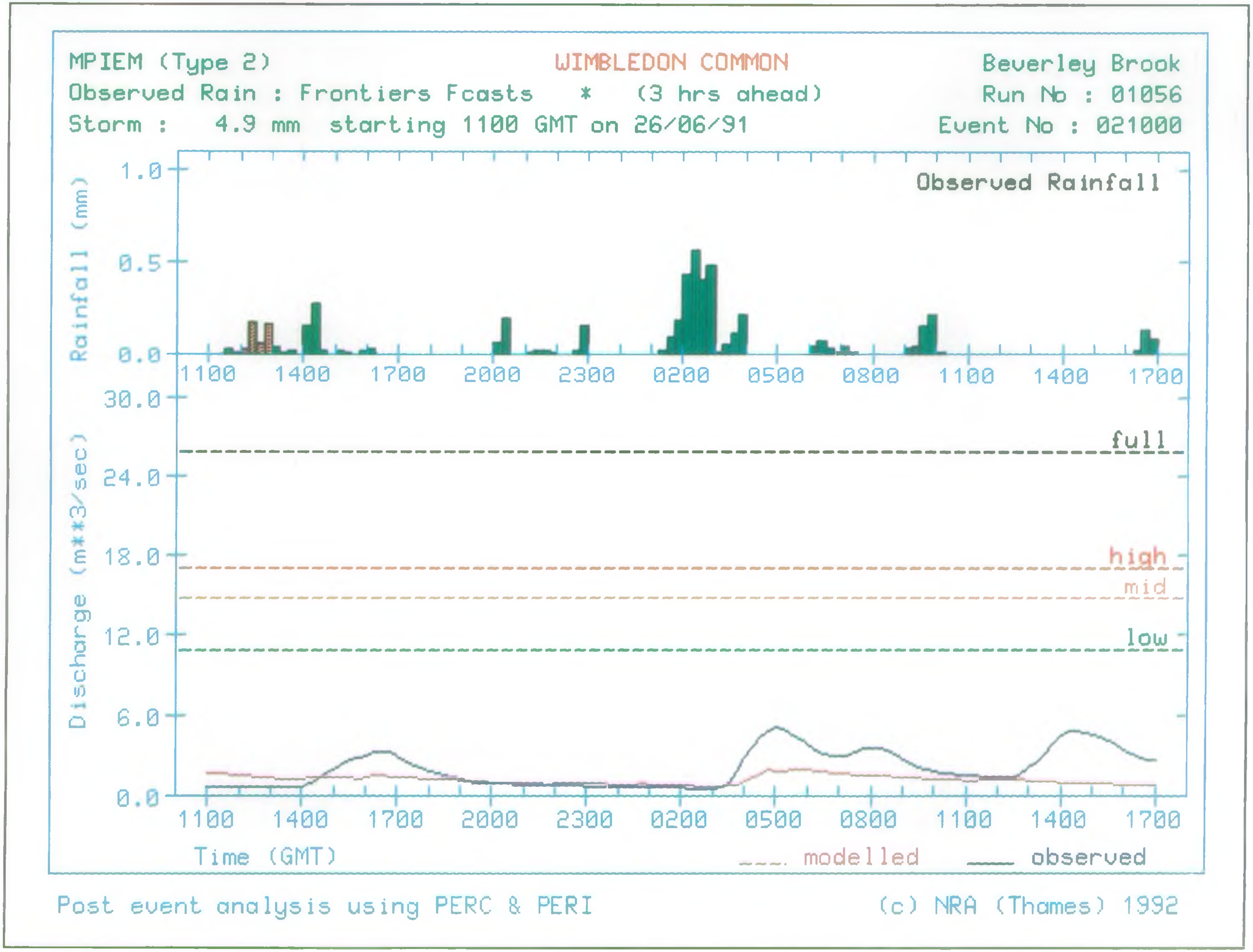

MPIEM (Type 2)
WIMBLEDON COMMON
Beverley Brook
Observed Rain : Frontiers Fcasts * (1 hr ahead)
Run No : 01057
Storm : 15.1 mm starting 1100 GMT on 26/06/91
Event No : 021000
Observed Rainfall
Rainfall (mm)
2.0
1.0
0.0
1100 1400 1700 2000 2300 0200 0500 0800 1100 1400 1700
Discharge (m**3/sec)
30.0
24.0
18.0
12.0
6.0
0.0
full
high
mid
low
Time (GMT)
modelled
observed
Post event analysis using PERC & PERI
(c) NRA (Thames) 1992

Figure 24



MPIEM (Type 2)
WIMBLEDON COMMON
Beverley Brook
Observed Rain : Frontiers Fcasts * (3 hrs ahead)
Run No : 01056
Storm : 4.9 mm starting 1100 GMT on 26/06/91
Event No : 021000
Observed Rainfall
Rainfall (mm)
1.0
0.5
0.0
1100 1400 1700 2000 2300 0200 0500 0800 1100 1400 1700
Discharge (m**3/sec)
30.0
24.0
18.0
12.0
6.0
0.0
full
high
mid
low
1100 1400 1700 2000 2300 0200 0500 0800 1100 1400 1700
Time (GMT)
modelled
observed
Post event analysis using PERC & PERI
(c) NRA (Thames) 1992

Figure 25

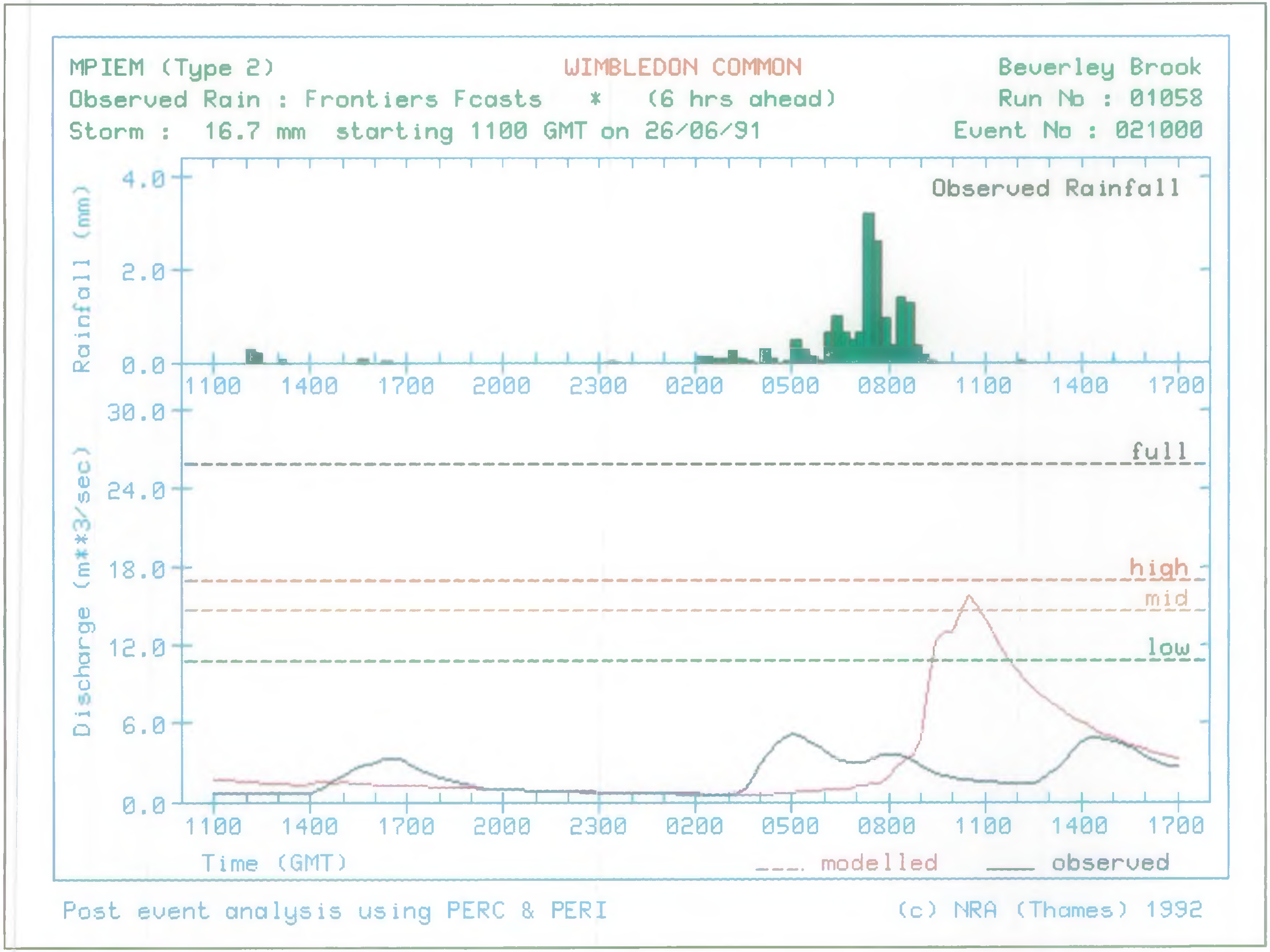

MPIEM (Type 2)
WIMBLEDON COMMON
Beverley Brook
Observed Rain : Frontiers Fcasts * (6 hrs ahead)
Run No : 01058
Storm : 16.7 mm starting 1100 GMT on 26/06/91
Event No : 021000
Rainfall (mm)
4.0
2.0
0.0
Observed Rainfall
1100 1400 1700 2000 2300 0200 0500 0800 1100 1400 1700
Discharge (m**3/sec)
30.0
24.0
18.0
12.0
6.0
0.0
full
high
mid
low
Time (GMT)
modelled
observed
Post event analysis using PERC & PERI
(c) NRA (Thames) 1992

Figure 26

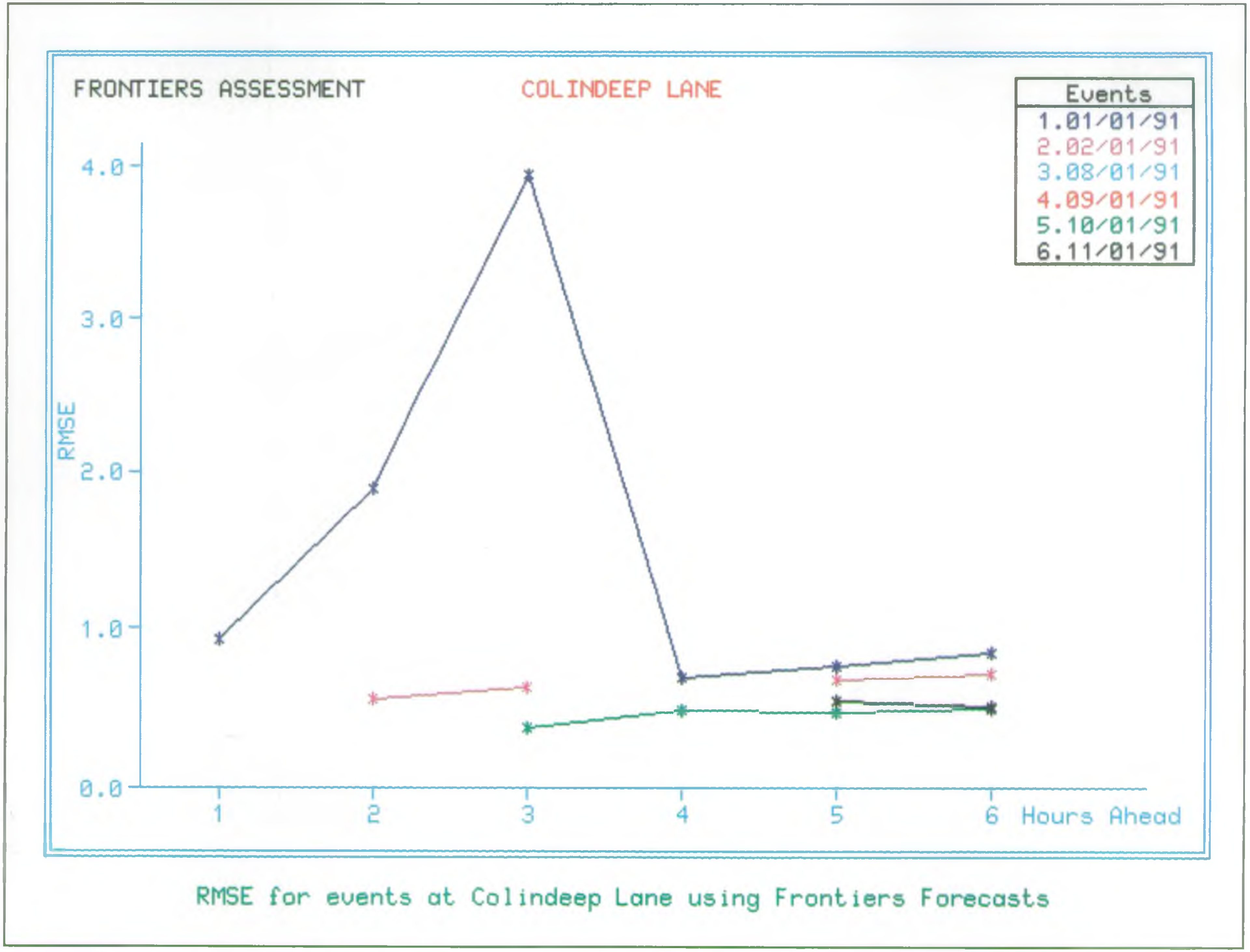
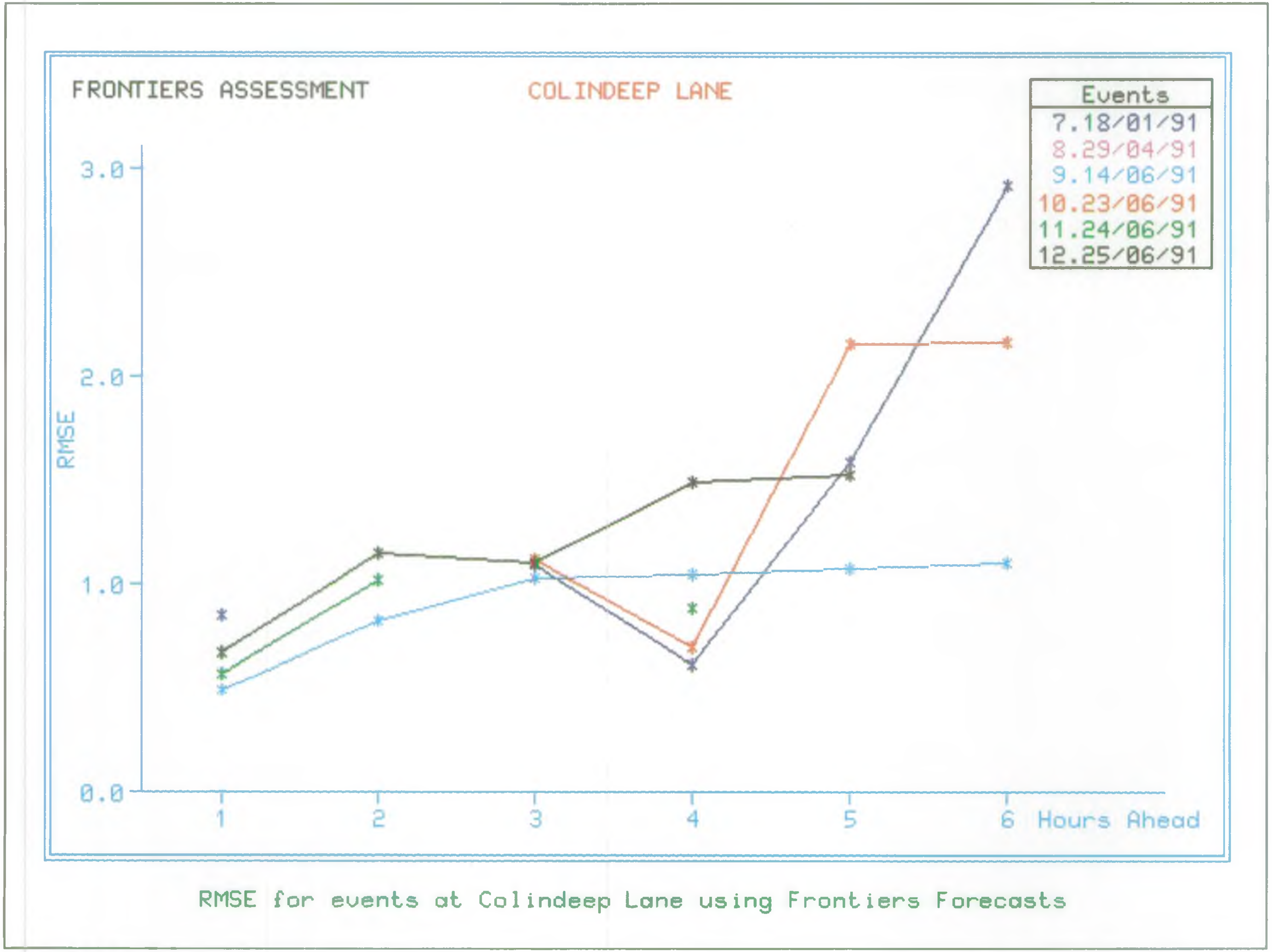
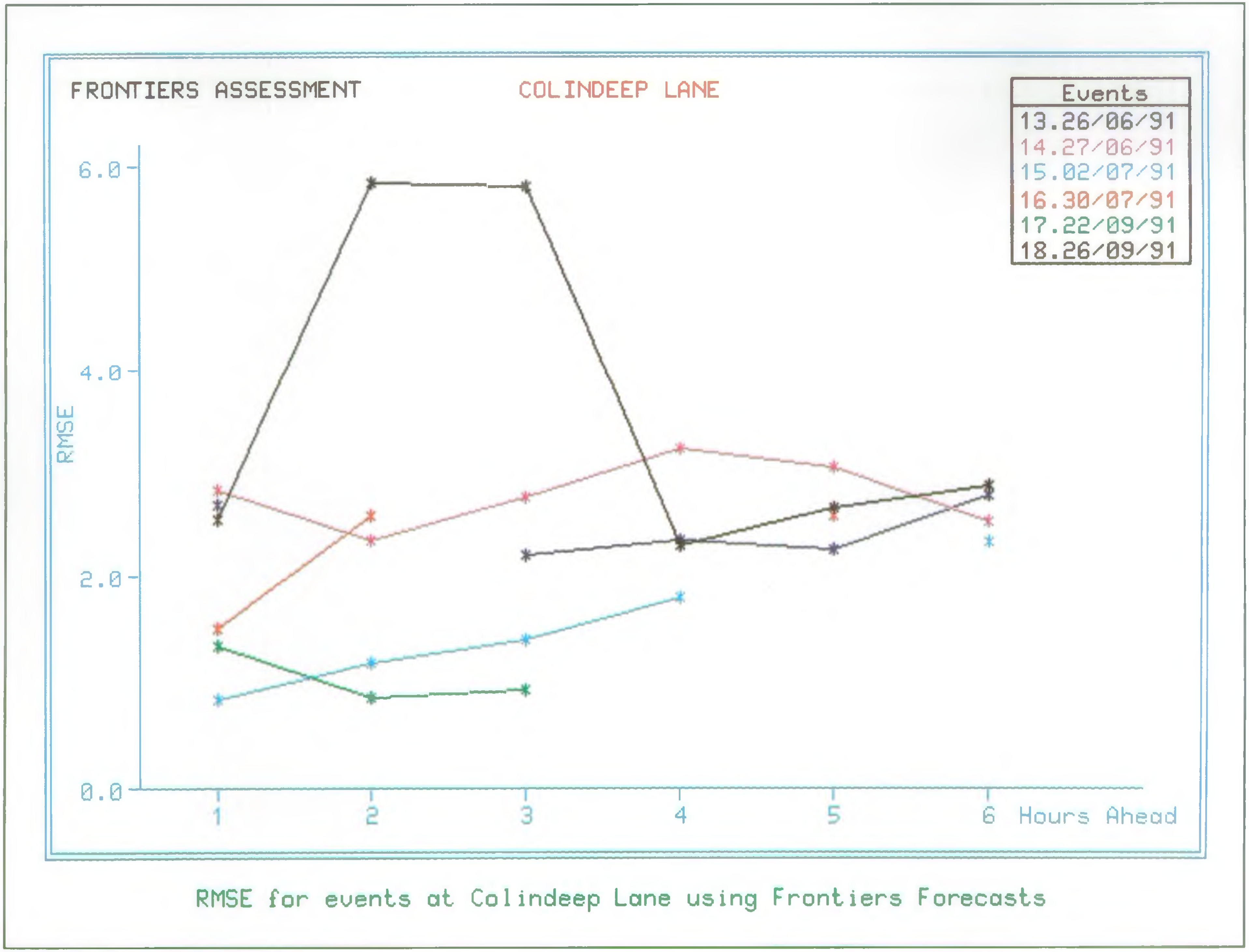

FRONTIERS ASSESSMENT
COLINDEEP LANE
Events
1.01/01/91
2.02/01/91
3.08/01/91
4.09/01/91
5.10/01/91
6.11/01/91
RMSE
4.0
3.0
2.0
1.0
0.0
1
2
3
4
5
6
Hours Ahead
RMSE for events at Colindeep Lane using Frontiers Forecasts

Figure 27a



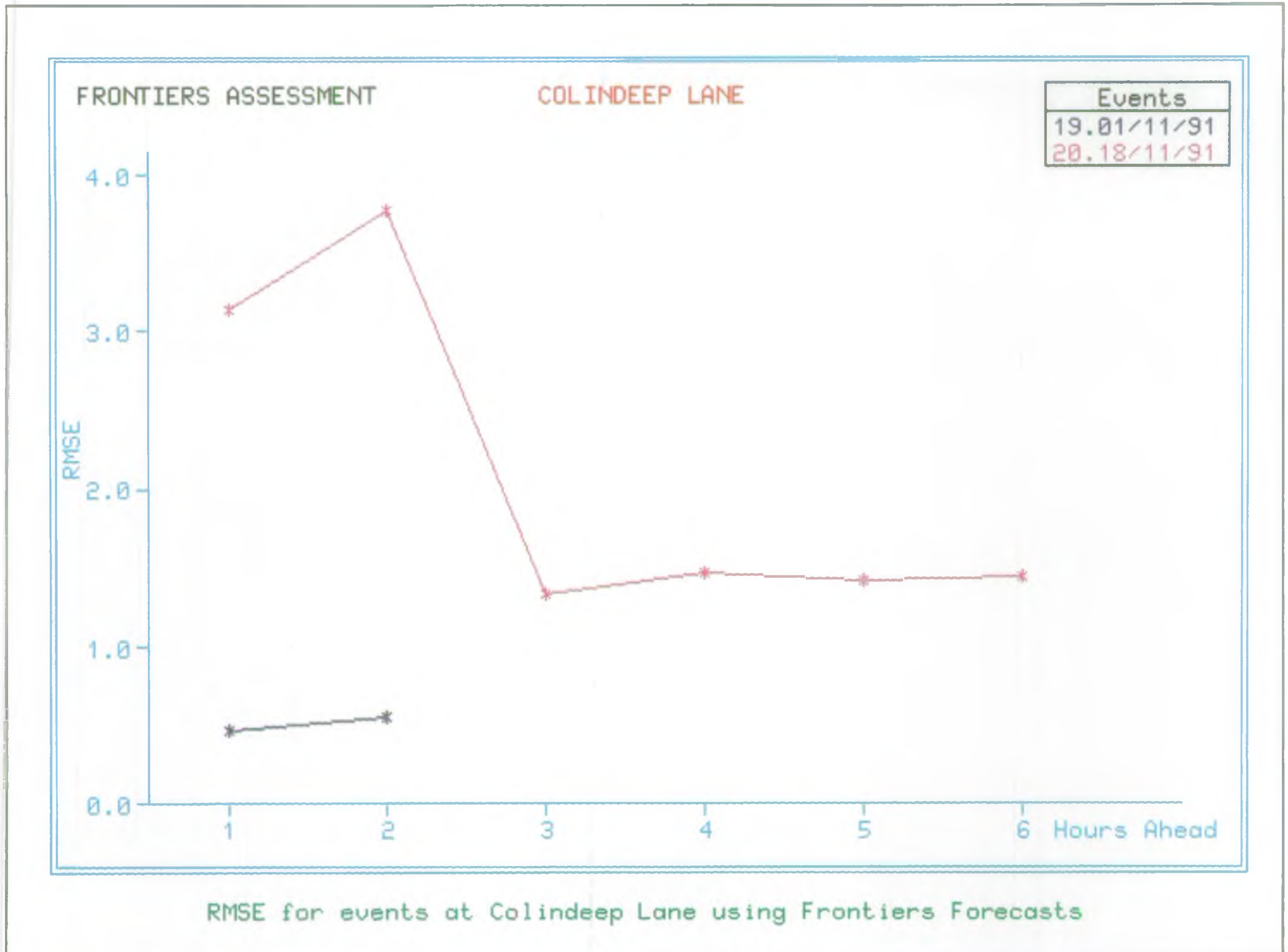
FRONTIERS ASSESSMENT
COLINDEEP LANE
Events
7.18/01/91
8.29/04/91
9.14/06/91
10.23/06/91
11.24/06/91
12.25/06/91
RMSE
3.0
2.0
1.0
0.0
1
2
3
4
5
6
Hours Ahead
RMSE for events at Colindeep Lane using Frontiers Forecasts

Figure 27b



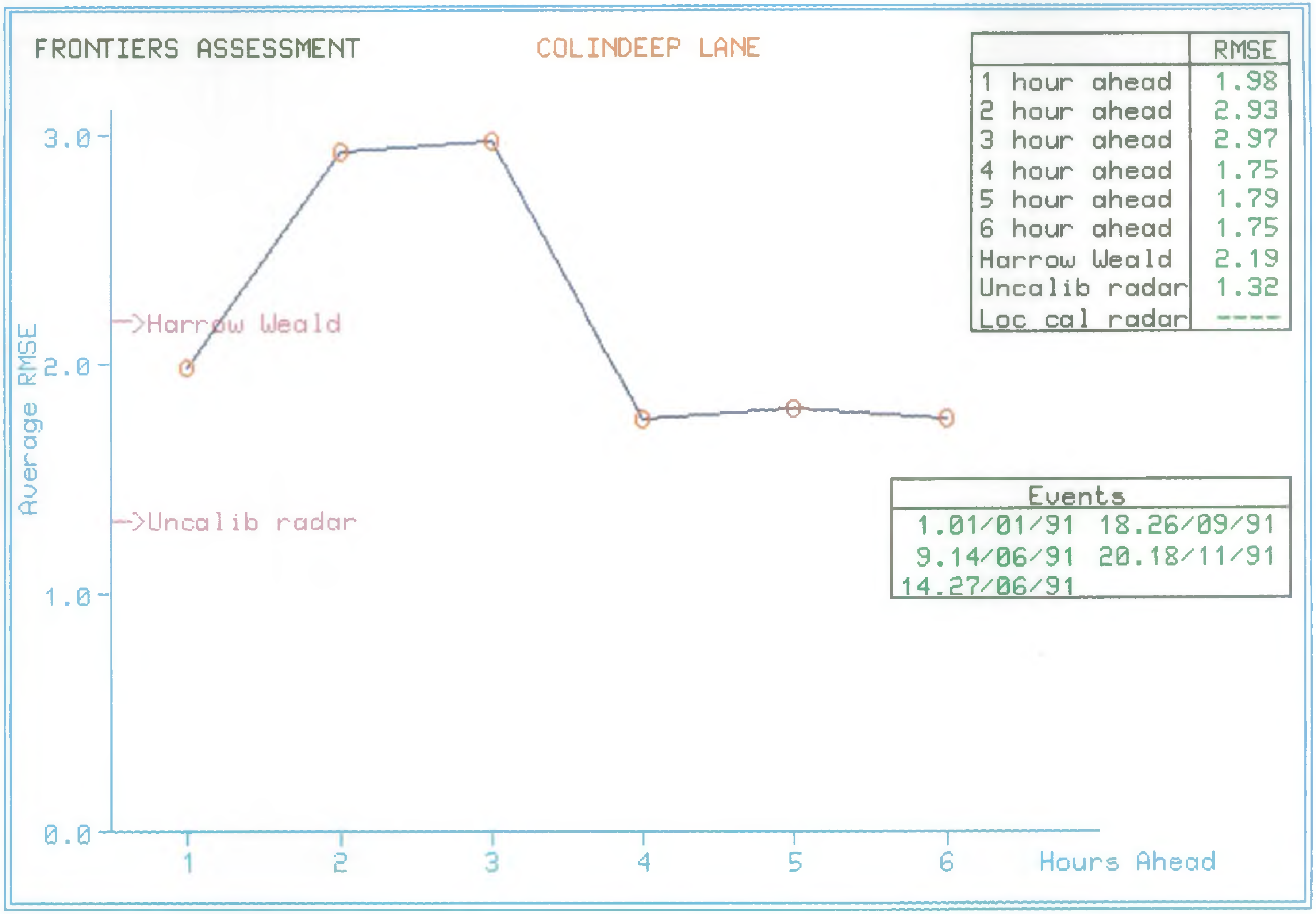
FRONTIERS ASSESSMENT
COLINDEEP LANE
Events
13.26/06/91
14.27/06/91
15.02/07/91
16.30/07/91
17.22/09/91
18.26/09/91
6.0
4.0
2.0
0.0
RMSE
1
2
3
4
5
6
Hours Ahead
RMSE for events at Colindeep Lane using Frontiers Forecasts

Figure 27c



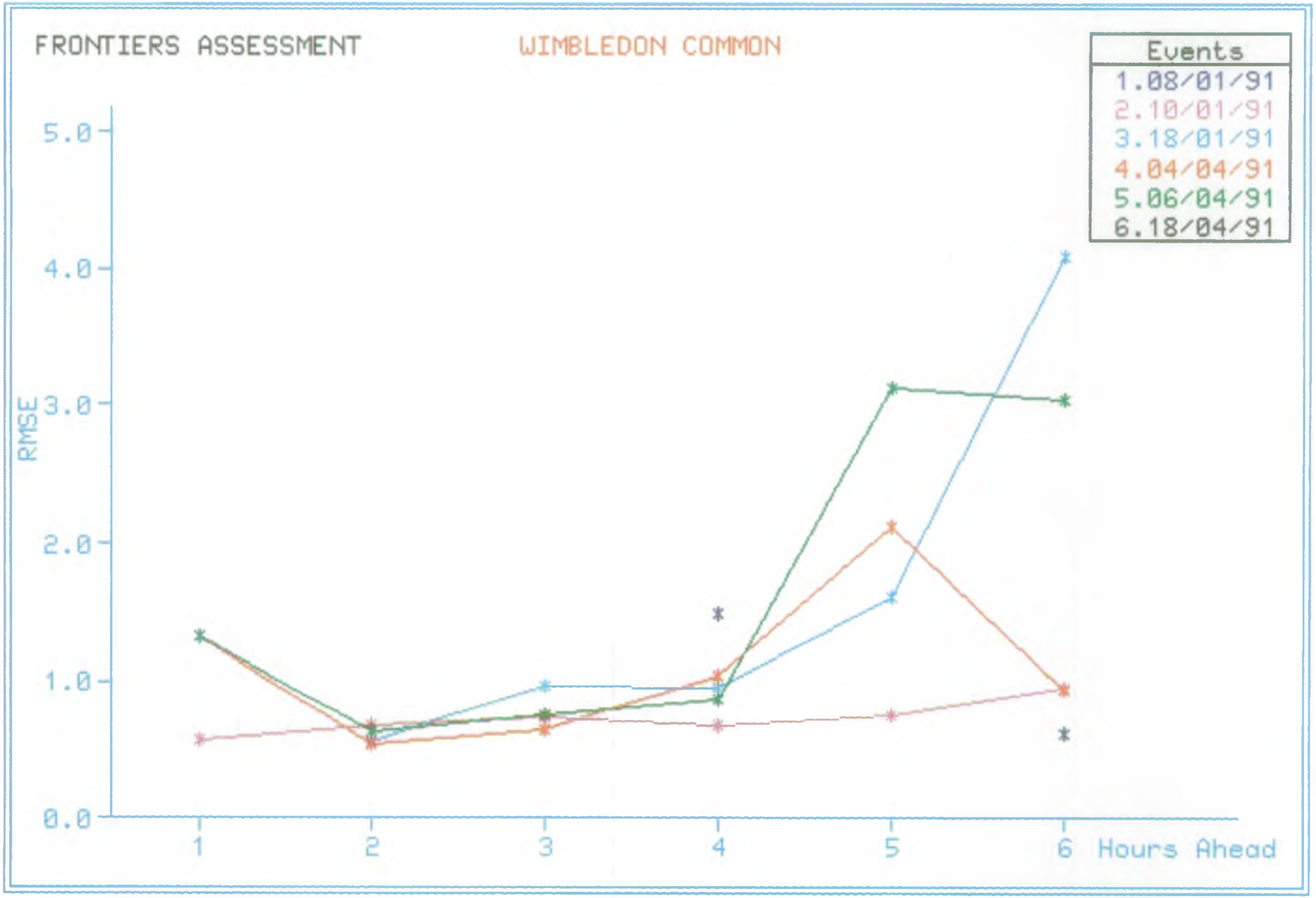
FRONTIERS ASSESSMENT
COLINDEEP LANE
Events
19.01/11/91
20.18/11/91
4.0
3.0
2.0
1.0
0.0
RMSE
1
2
3
4
5
6
Hours Ahead
RMSE for events at Colindeep Lane using Frontiers Forecasts

Figure 27d



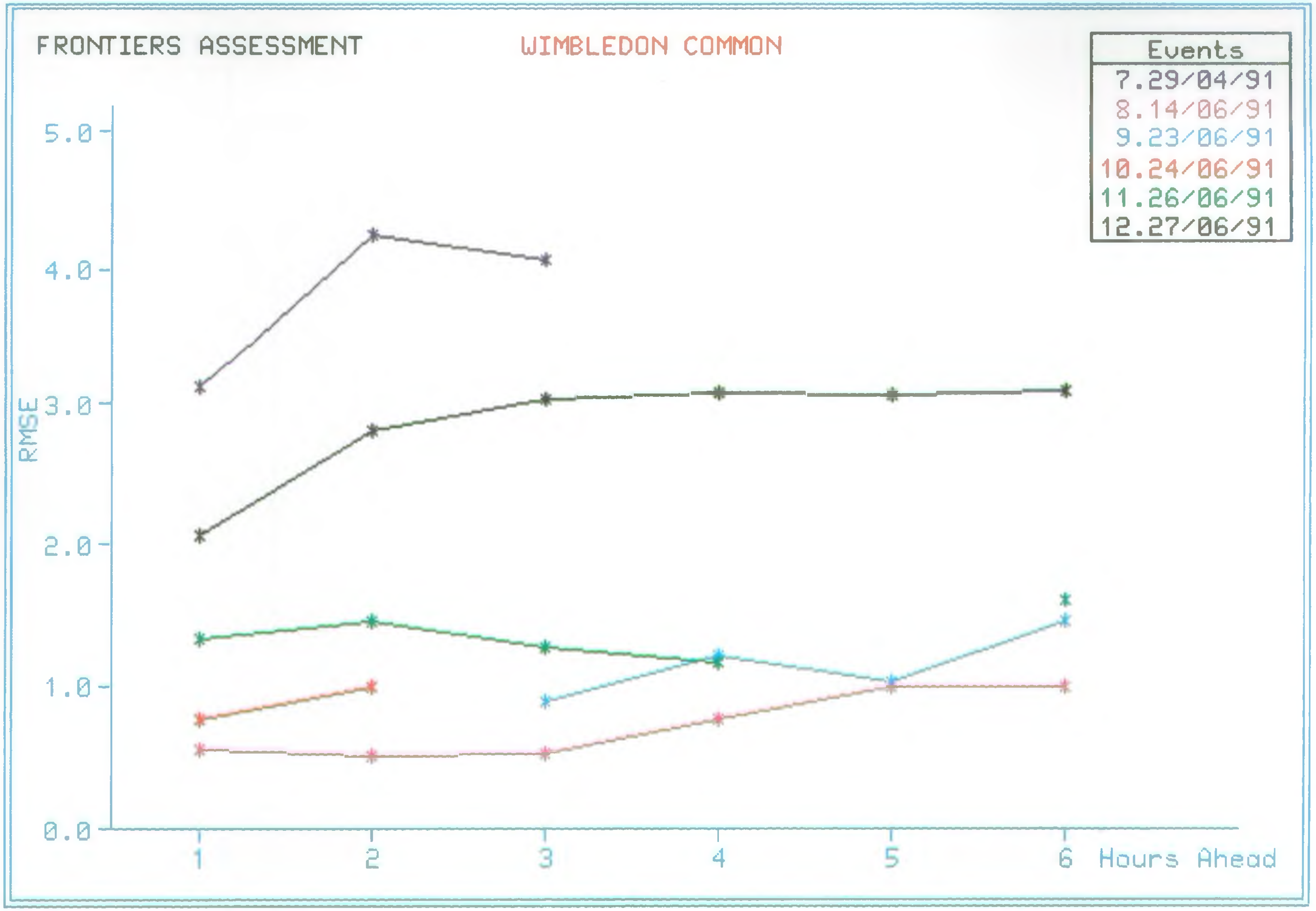
Average flow RMSE for 5 events at Colindeep Lane using Frontiers Forecasts

Figure 28



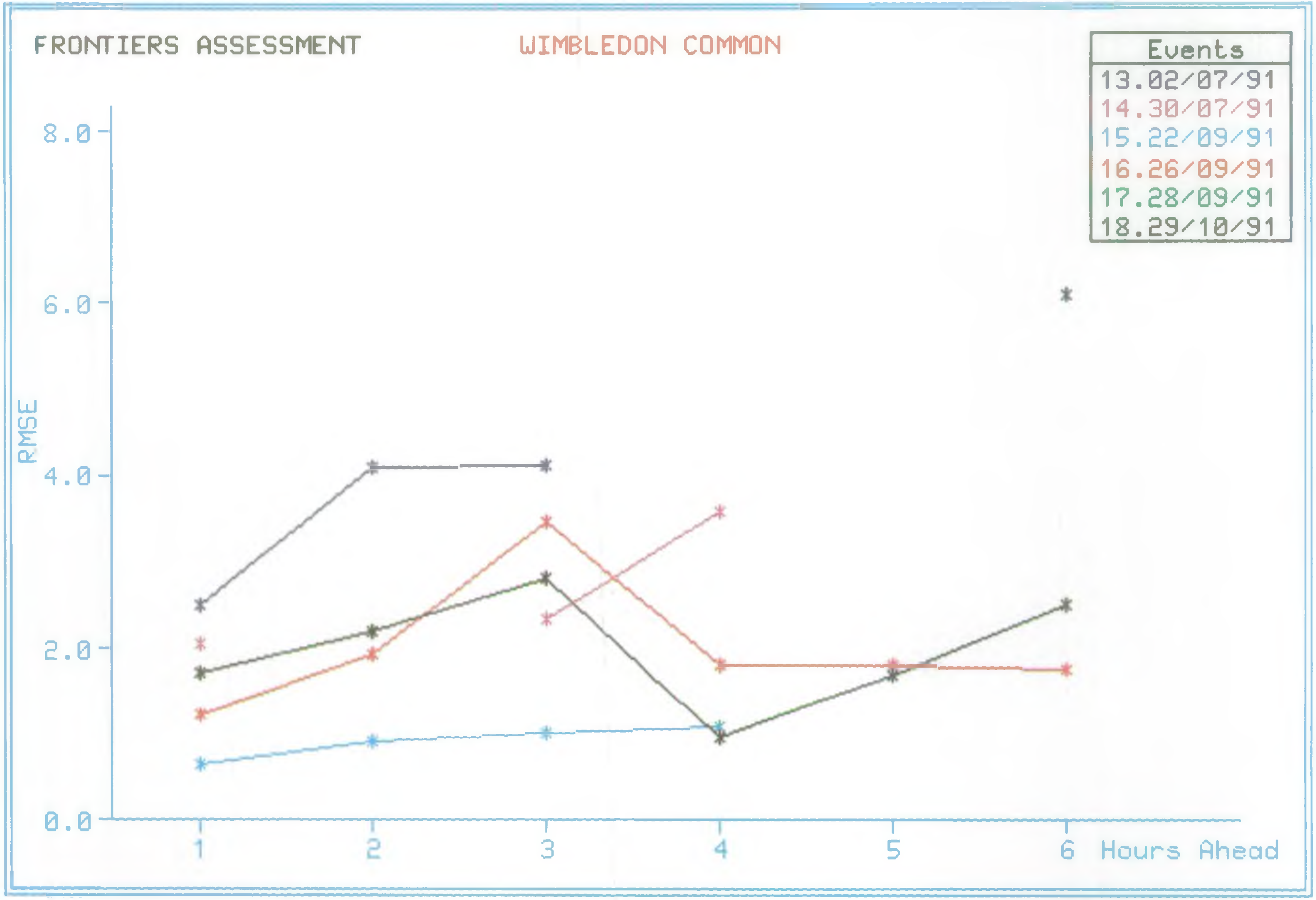
RMSE for events at Wimbledon Common using Frontiers Forecasts

Figure 29a



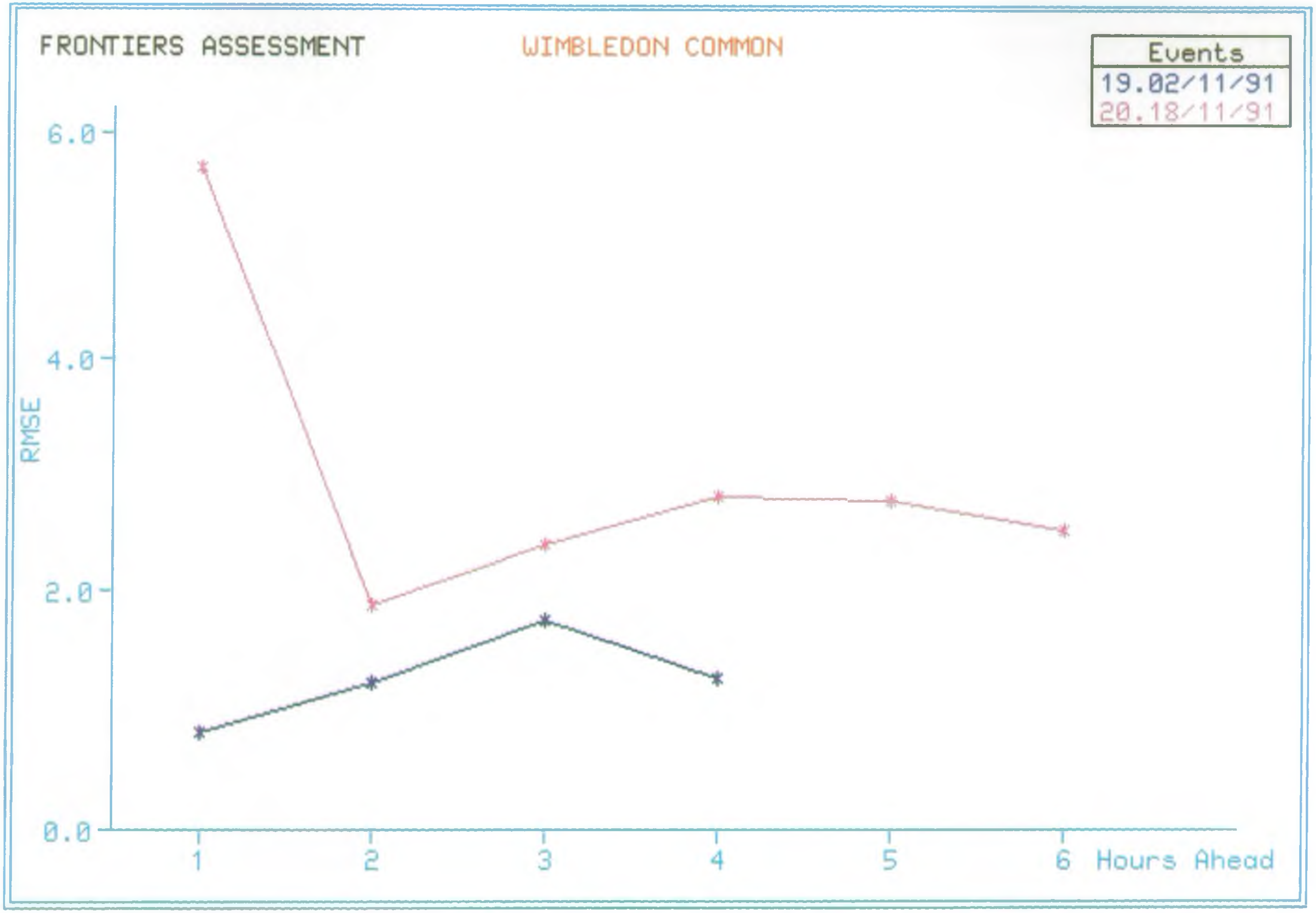
RMSE for events at Wimbledon Common using Frontiers Forecasts

Figure 29b



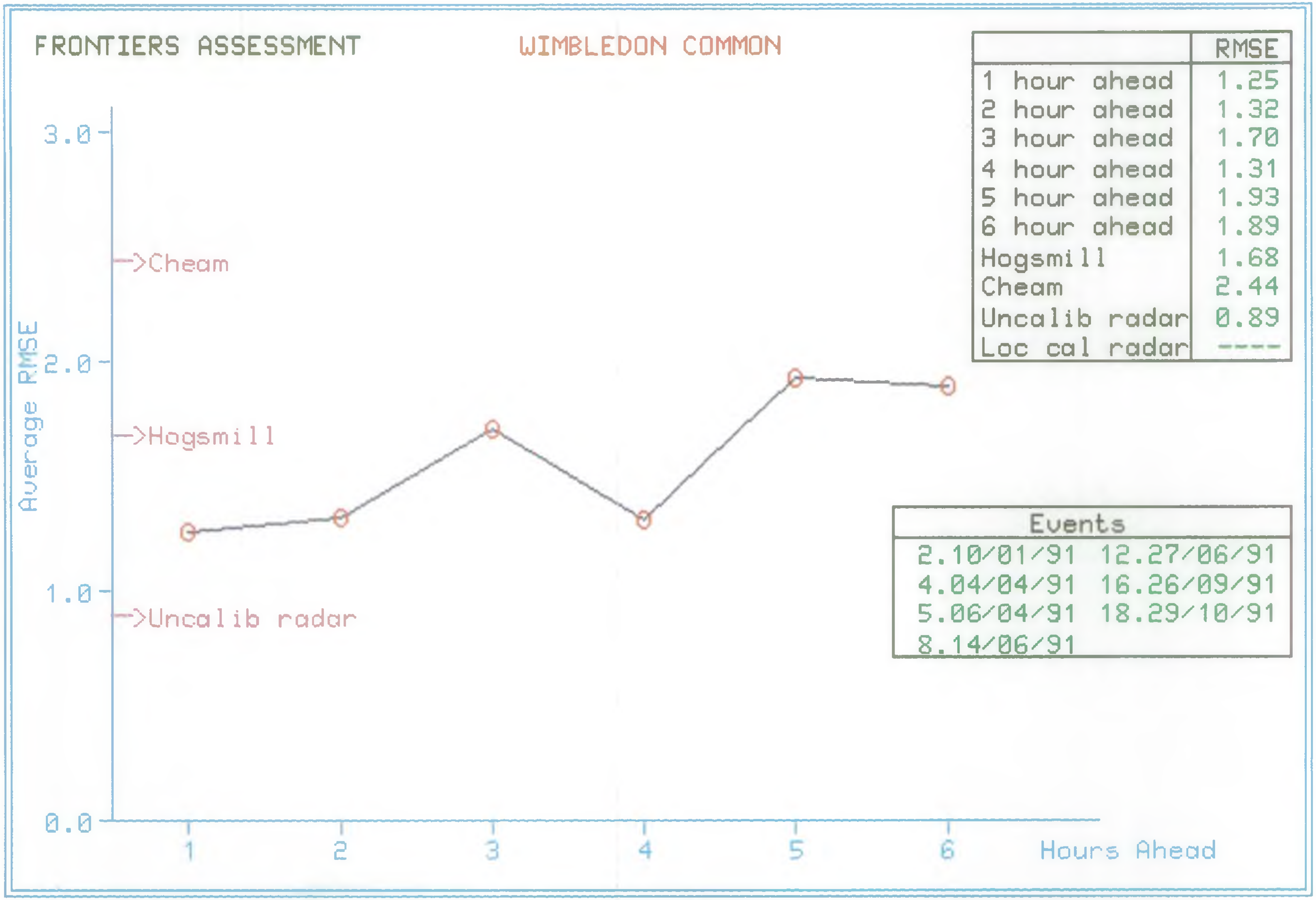
RMSE for events at Wimbledon Common using Frontiers Forecasts

Figure 29c



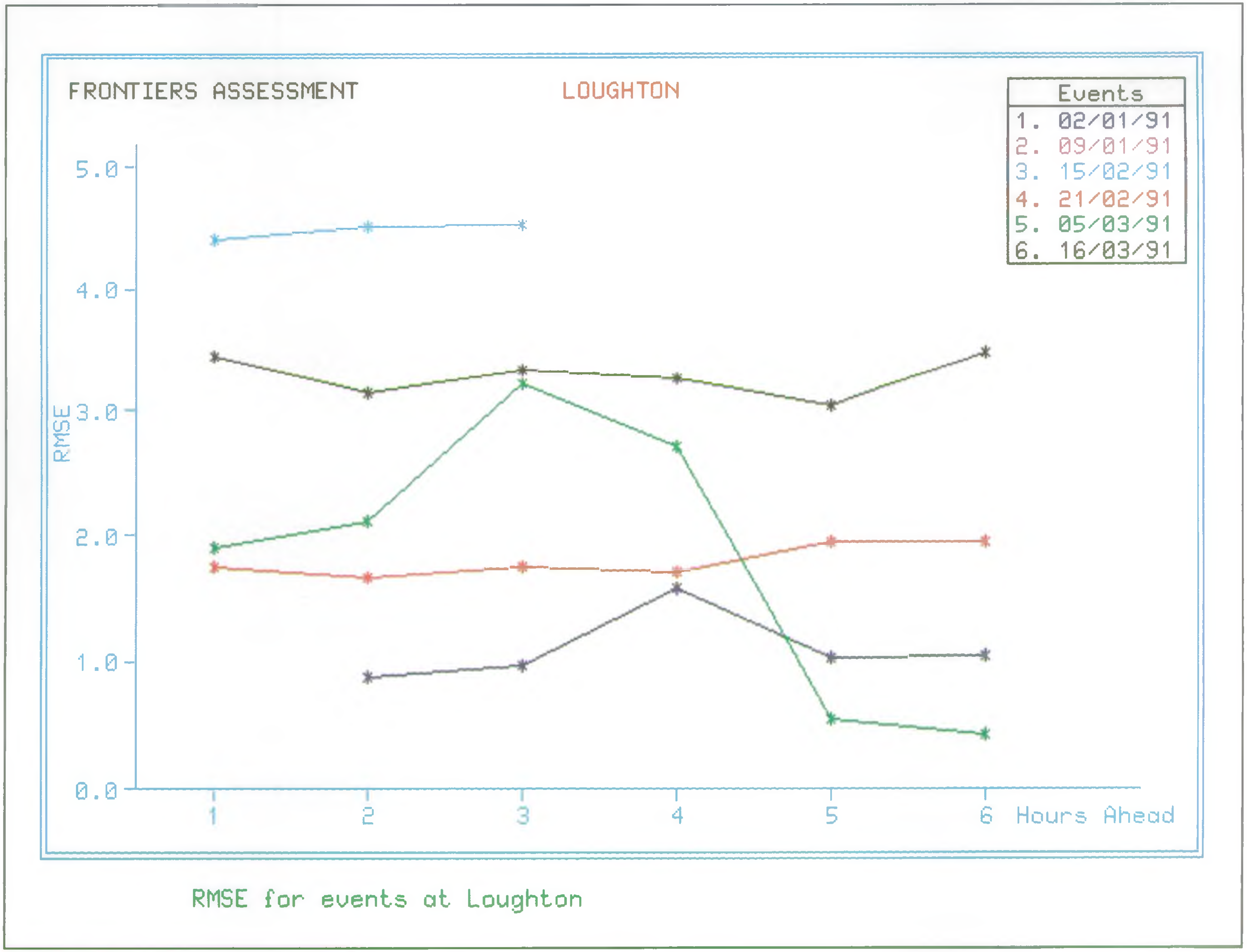
RMSE for events at Wimbledon Common using Frontiers Forecasts

Figure 29d



Average flow RMSE for 7 events at Wimbledon Common using Frontiers Forecasts

Figure 30



FRONTIERS ASSESSMENT
LOUGHTON
Events
1. 02/01/91
2. 09/01/91
3. 15/02/91
4. 21/02/91
5. 05/03/91
6. 16/03/91
RMSE
5.0
4.0
3.0
2.0
1.0
0.0
1
2
3
4
5
6
Hours Ahead
RMSE for events at Loughton

Figure 31a

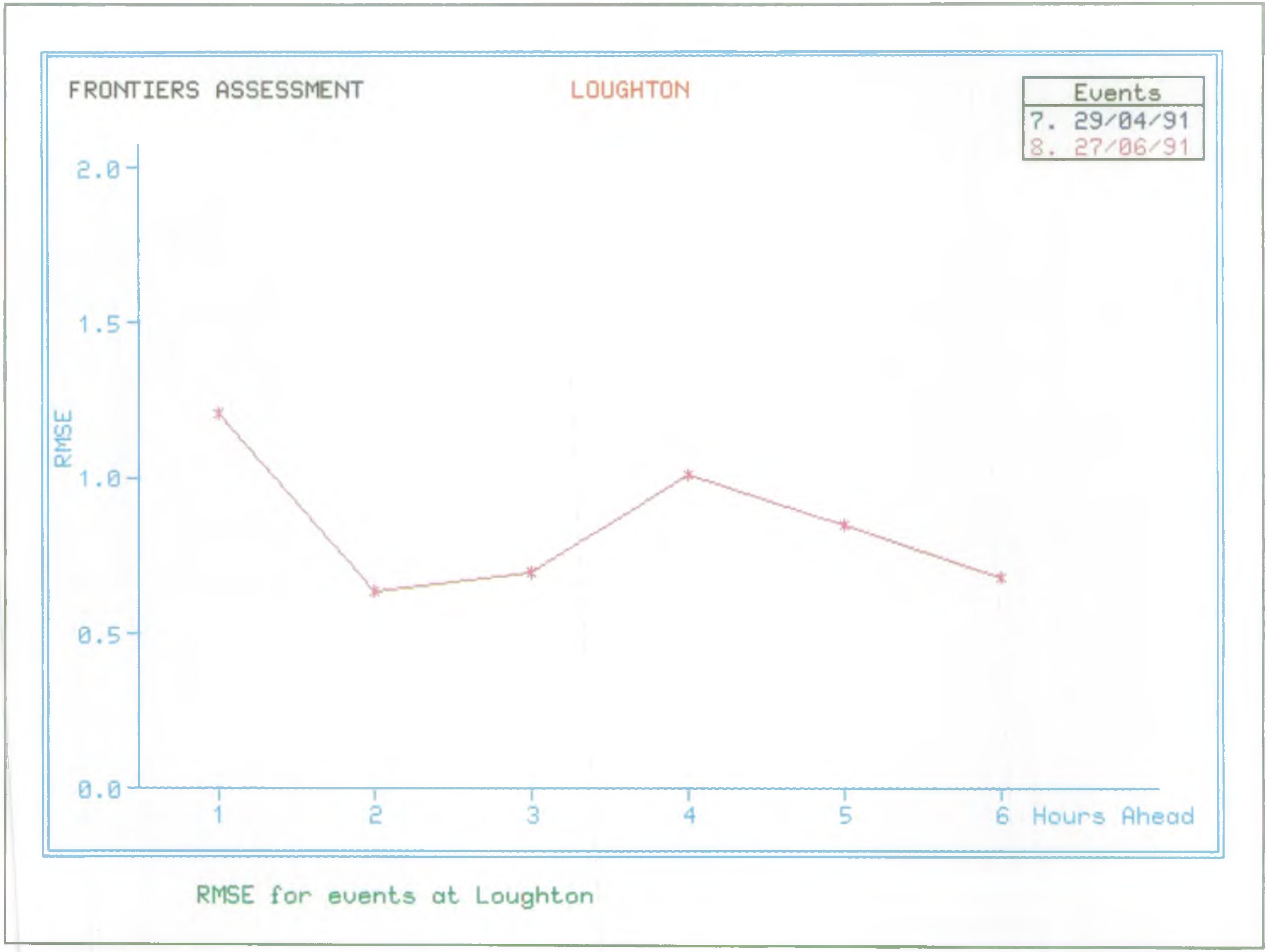

FRONTIERS ASSESSMENT
LOUGHTON
Events
7. 29/04/91
8. 27/06/91
2.0
1.5
1.0
0.5
0.0
RMSE
1
2
3
4
5
6
Hours Ahead
RMSE for events at Loughton

Figure 31b

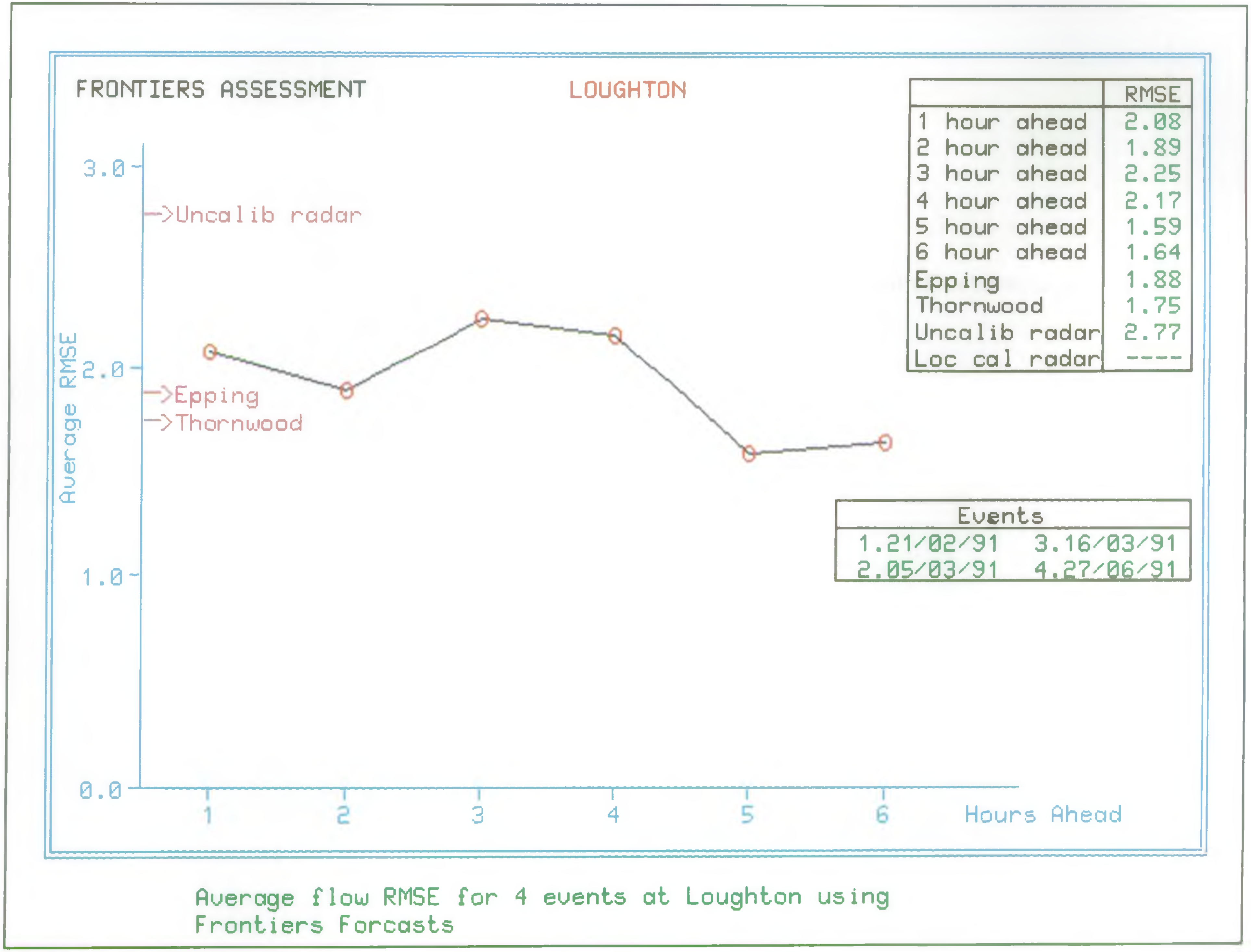
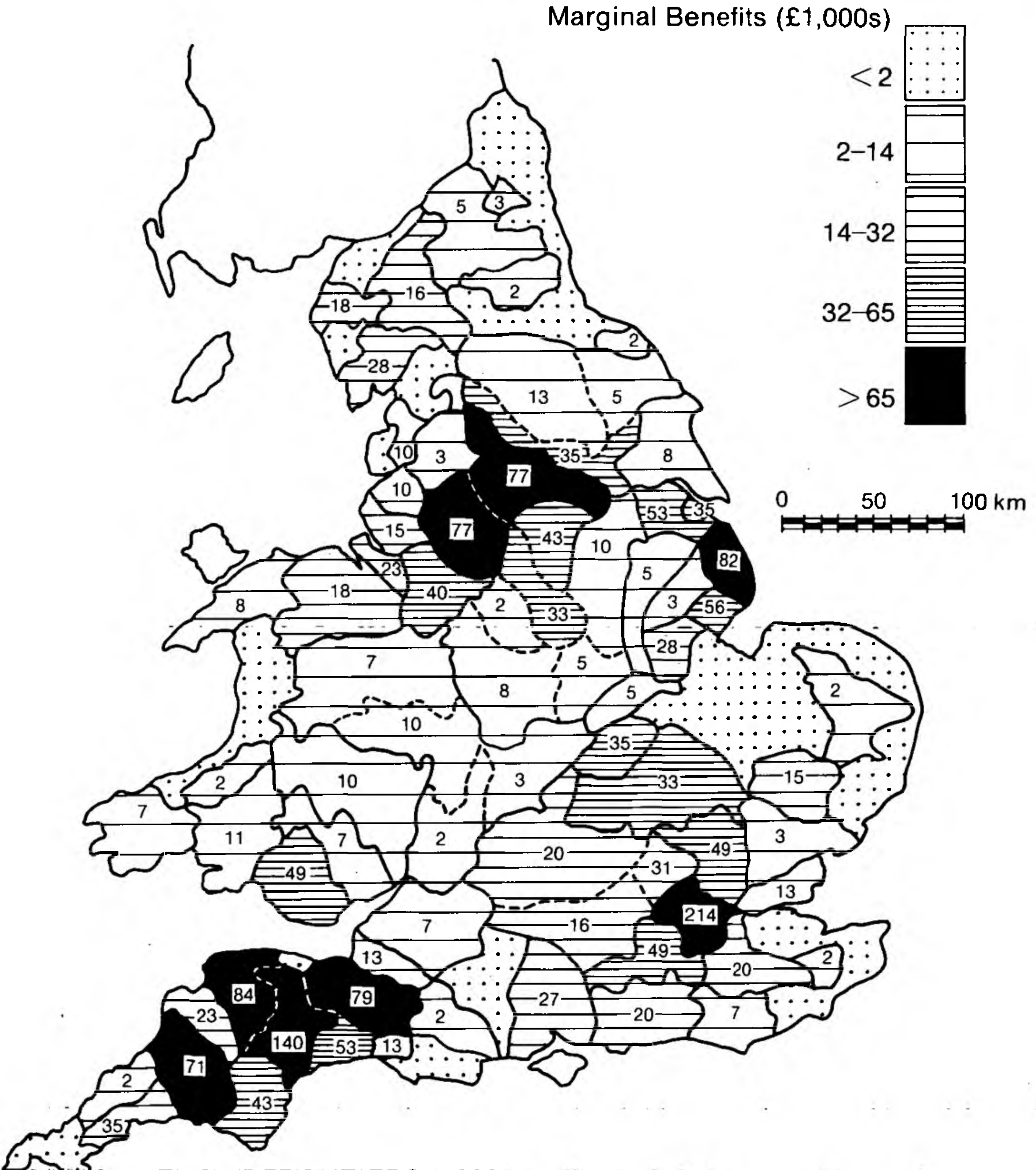

FRONTIERS ASSESSMENT
LOUGHTON
RMSE
1 hour ahead 2.08
2 hour ahead 1.89
3 hour ahead 2.25
4 hour ahead 2.17
5 hour ahead 1.59
6 hour ahead 1.64
Epping 1.88
Thornwood 1.75
Uncalib radar 2.77
Loc cal radar ----
3.0
2.0
1.0
0.0
Average RMSE
->Uncalib radar
->Epping
->Thornwood
Events
1.21/02/91 3.16/03/91
2.05/03/91 4.27/06/91
1
2
3
4
5
6
Hours Ahead
Average flow RMSE for 4 events at Loughton using
Frontiers Forcasts

Figure 32

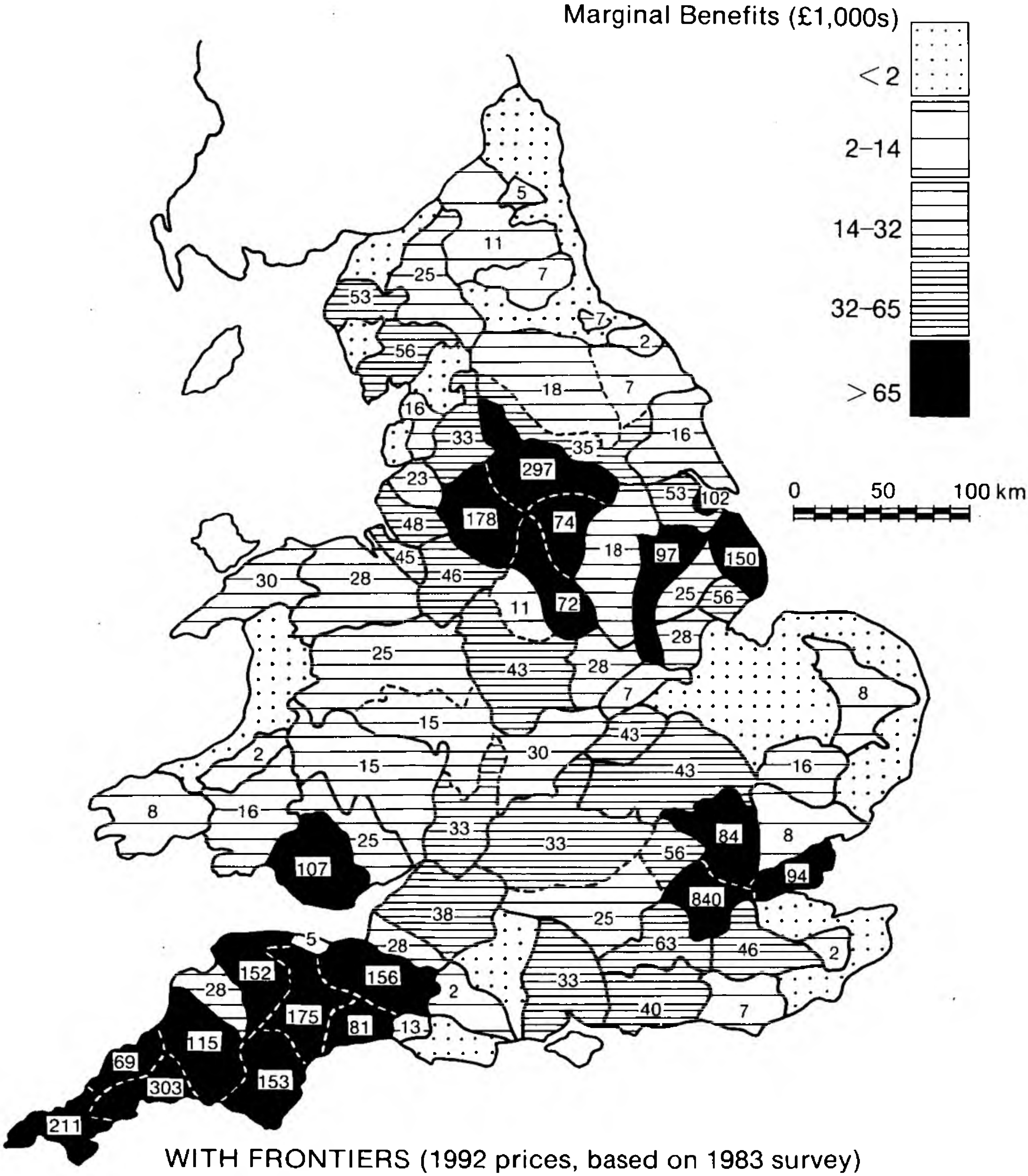
Relative marginal benefits (£1,000s) attributable to the use of radar in flood warning.



WITHOUT FRONTIERS (1992 prices, based on 1983 survey)

Figure 33

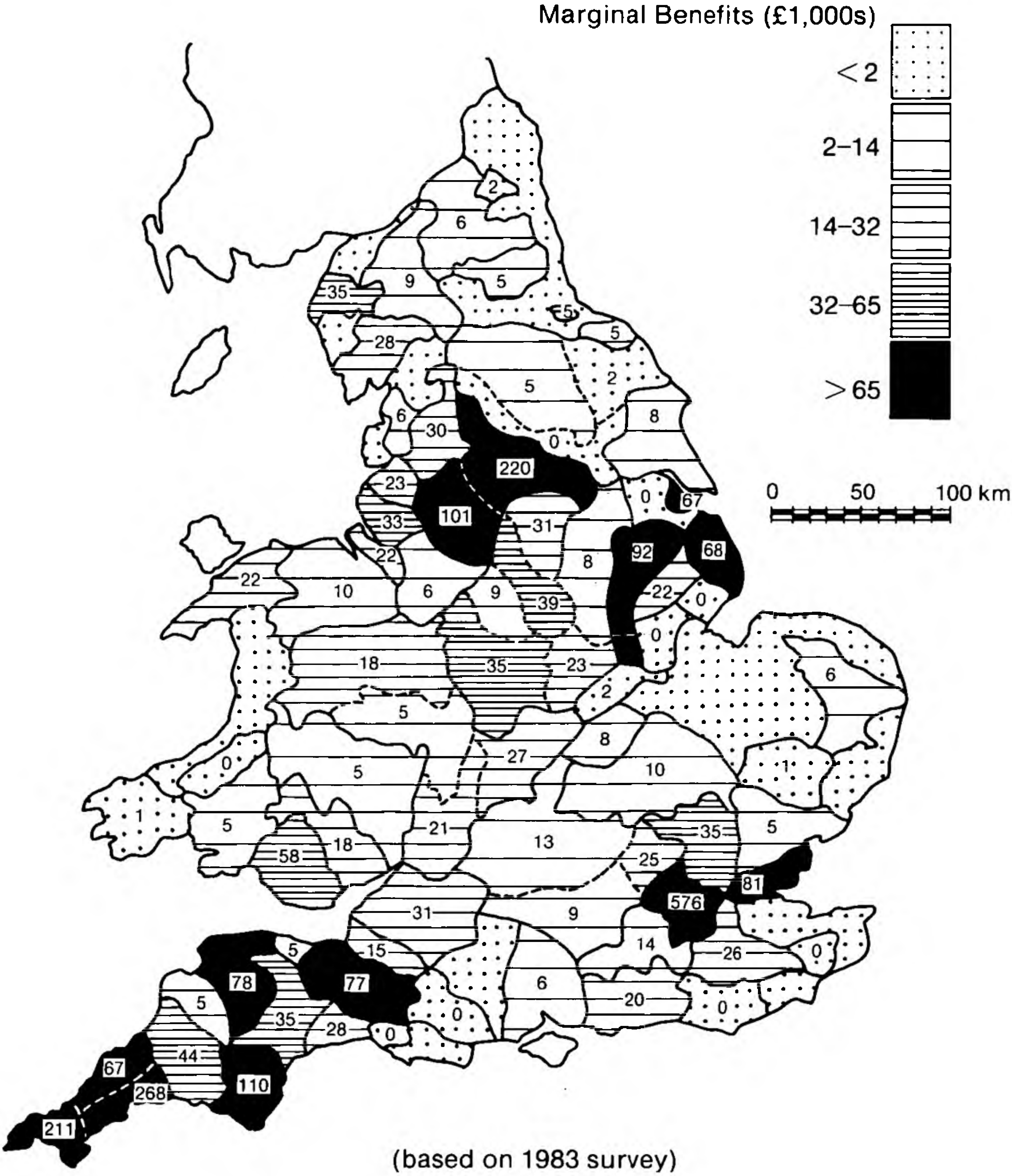
Relative marginal benefits (£1,000s) attributable to the use of radar in flood warning.



WITH FRONTIERS (1992 prices, based on 1983 survey)

Figure 34

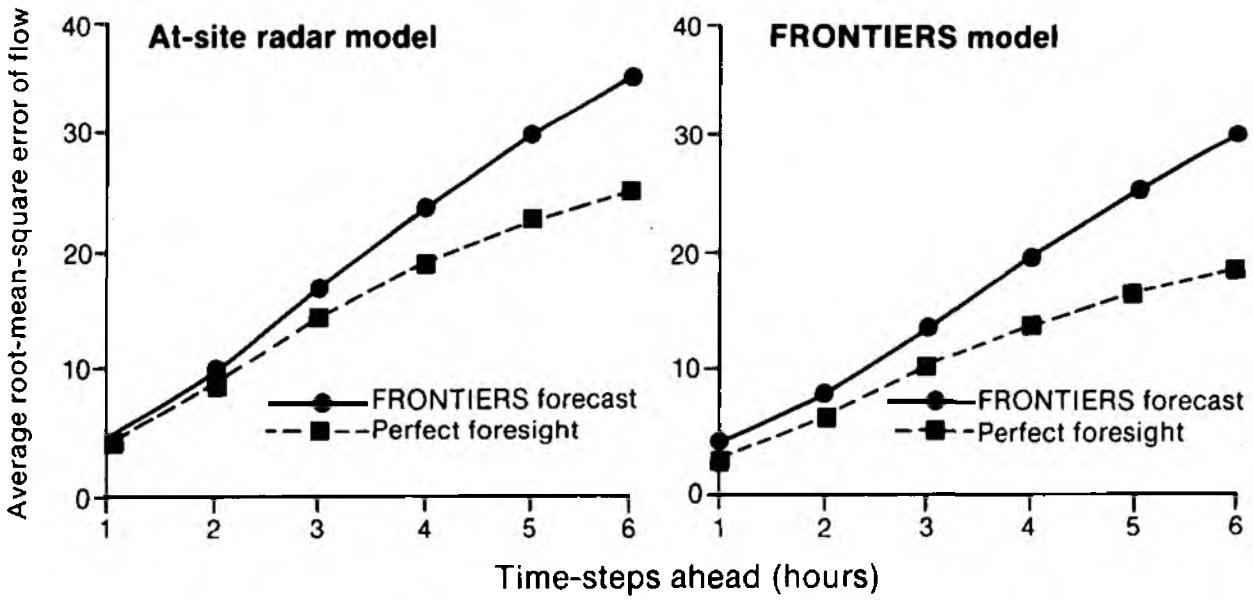
Relative marginal benefits (£1,000s) attributable to the use of FRONTIERS in flood warning.



(based on 1983 survey)

Figure 35

Figure 36 Comparison of the average RMSE of FRONTIERS and perfect foresight of rainfall flow forecasts for the at-sight radar model and the FRONTIERS derived model for Manchester Racecourse.



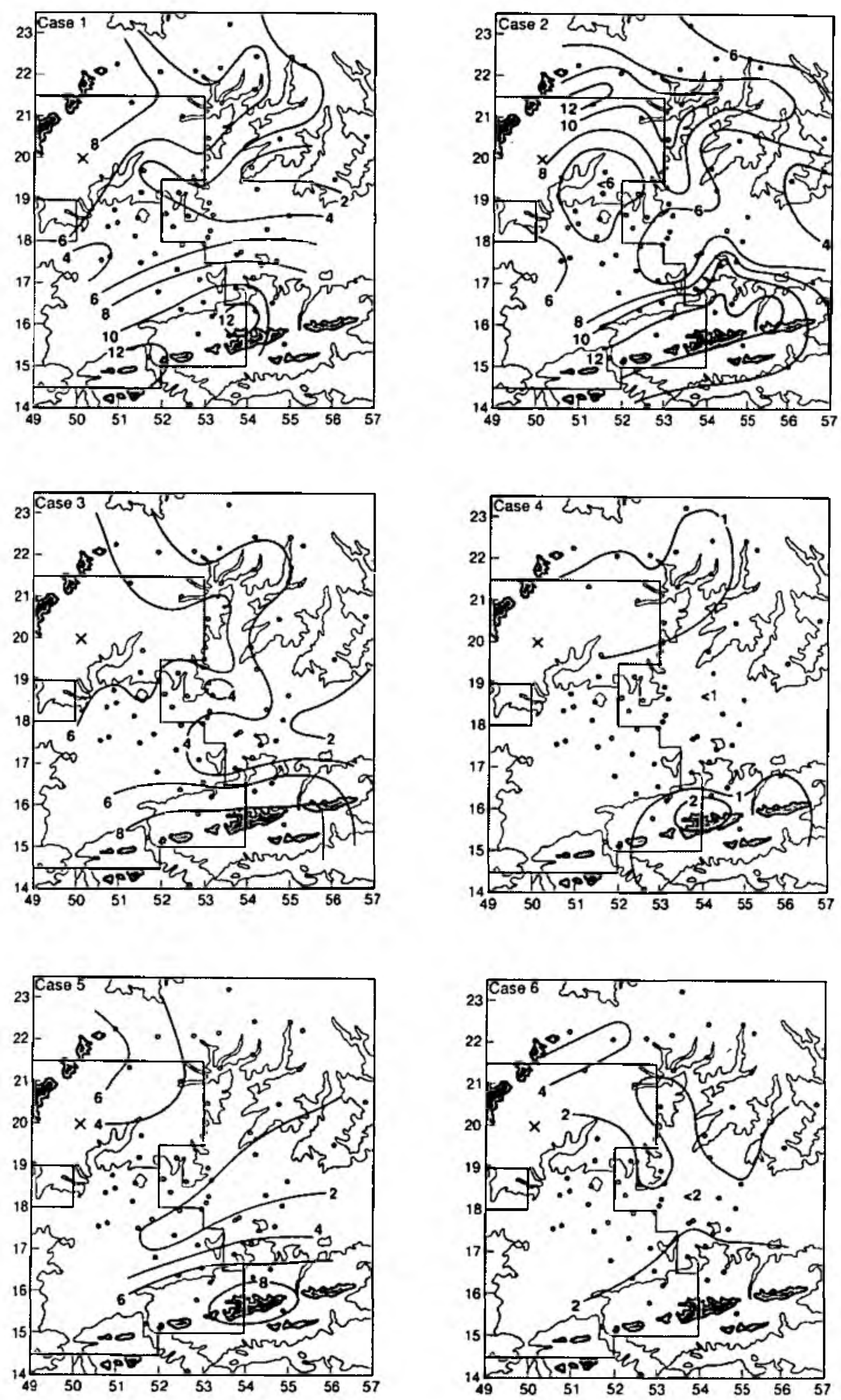


Figure 37