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Rainfall prediction for a flooding event in Ireland caused by the remnants of Hurricane Charley

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Abstract

The high resolution limited area weather prediction model HIRLAM is used to predict 24 h rainfall amounts for a past flooding event in Ireland. The model is run with horizontal resolutions of 55, 28, 13 and 6 km. The effects of increased resolution are studied for the storm cyclone developed from the remnants of Hurricane Charley (25 August 1986), that led to severe flooding in and around Dublin. Special attention is given to the predictions for the catchment of the river Dodder, situated in an orographically complex area south of Dublin. The model is verified using 24 h rainfall totals of 513 Irish stations. For this particular extreme event, increasing the resolution has a beneficial effect on the predictions of the rainfall amounts for both Ireland as a whole and the catchment of the Dodder. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Numerical weather prediction model; Rainfall; Orography; Ireland; Dodder catchment

1. Introduction

Numerical Weather Prediction (NWP) models are increasingly being used in systems for forecasting water levels and discharges of rivers. Especially forecasting of potentially dangerous floods is important, since this may help in anticipating these floods by allowing more time for action. However, the spatial and temporal resolution of NWP models is often too low to allow for accurate precipitation forecasts for the catchment concerned. Moreover, there are uncertainties about the behaviour of the NWP models in extreme situations.

At present, several techniques are available for quantitative precipitation forecasting. For forecasting a few hours ahead (nowcasts), extrapolation of radar and satellite images is the best method (Collier, 1989). For longer term quantitative precipitation forecasting the use of NWP models is the most promising approach. Golding (1998) presented a system that integrates nowcasting techniques with NWP model products for forecasts up to 6 h ahead.

A special version of a NWP model is the Limited Area Model (LAM). A LAM is usually driven by (nested in) a global model. Because a LAM considers only a relatively small area (e.g. Europe) it allows precipitation forecasts with a higher spatial and temporal resolution than the driving model. An alternative approach is the use of a global model with a stretched grid. Such a model has a high resolution over the area of interest and a low resolution over the rest of the globe. In the past two decades, there has been a great progress in development of these models due to the increase in computer power and

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the improvements in the objective analysis, model initialisation, model integration and parameterisation of sub-grid scale processes. The development of the models is stimulated by the need for more accurate regional forecasts in both operational weather forecasting and climate change studies (Kattenberg et al., 1996).

The present horizontal resolution of operational LAMs is usually between 10 and 50 km. In Europe, e.g. the UK Meteorological Office used a model with a resolution of about 15 km operationally over the UK for the past decade (Golding, 1990; Cullen, 1993). Currently they use a horizontal resolution of about 11 km. In the 1980s and 1990s Meteo France used the PERIDOT model at a resolution of 35 km. Currently they use the ALADIN model together with some other European countries. This model is used operationally at resolutions ranging between about 8 and 20 km and is embedded in the global stretched grid model ARPEGE. In Germany the Deutscher Wetterdienst uses a model with a resolution of 14 km. HIRLAM (HIgh Resolution Limited Area Model) is used operationally by the National Weather Services of many European countries with resolutions ranging between 55 km (the Netherlands) and 6 km (Denmark).

Recently, results have been published of experiments with resolutions down to about 5 km. For instance, Lakhtakia et al. (1999) used a nested LAM with 36, 12 and 4 km resolutions to simulate three single-storm events in the NE of the USA and their basin response. Gollvik (1999) studied the effects of horizontal diffusion, resolution and orography on precipitation predictions for Sweden in a LAM with 22, 11 and 5.5 km resolutions. Owing to high computational demands, studies like these are restricted to a limited number of test cases.

In the present study, HIRLAM is used for Ireland to study the effects of increased resolution on rainfall predictions for a past flooding event caused by the remnants of Hurricane Charley (25 August 1986). This event led to severe flooding of the area in and around Dublin. Special attention is therefore given to the forecast for the catchment of the river Dodder (113 km^2), situated in an orographically complex area south of Dublin. Before the Dodder enters the sea it flows through the urban area of Dublin. The work is part of the TELFLOOD project (Bruen, 1999) that aims at the development of methods for forecasting floods in steep mountainous catchments upstream of major urban areas.

The paper is organised as follows. In Section 2, the HIRLAM system is presented, together with the nesting strategy. Also in that section, storm development from the remnants of Hurricane Charley is discussed. Section 3 compares the predicted and observed precipitation amounts for Ireland and the Dodder catchment. The results are discussed in Section 4 and some conclusions are drawn in Section 5.

2. Methodology

In the present section, we first introduce the HIRLAM model with special reference to those aspects relevant for rainfall prediction. To run HIRLAM with high resolutions, successive nesting of models is necessary. This is discussed in Section 2.2. The development of the storm cyclone from the remnants of Hurricane Charley is discussed in Section 2.3.

2.1. HIRLAM

HIRLAM (Gustafsson, 1993) is a limited area model, developed by the meteorological services of Denmark, Finland, Iceland, Ireland, the Netherlands, Norway, Spain, Sweden and France. In this study HIRLAM version 4.7 is used. The standard version of the model covers Europe and the North Atlantic and has a resolution of 55 km with 31 levels. HIRLAM solves the primitive atmospheric equations with the hydrostatic assumption and with the horizontal velocity components, temperature, specific humidity, liquid water and surface pressure as prognostic variables. The vertical coordinate is the terrain following hybrid coordinate system and the horizontal spatial grid is a spherical rotated coordinate system with the equator going through the centre of the integration area. The dynamics are solved with an Eulerian advection scheme using a time step of 240 s for the 55 km grid.

HIRLAM contains a comprehensive physics parameterisation package for vertical diffusion (turbulence), radiation, condensation and precipitation, and surface processes (land–air and sea–air interaction). For the parameterisation of the convective and moisture processes the STRACO (Soft TRAnsition COndensation) scheme developed by Sass et al. (1999) is used. In this scheme the changes in the vertical structure of temperature and humidity are determined from specified functions as outlined by Kuo (1974). Because the latter scheme considers a closure based on moisture convergence at surface level only, it was modified in such way that the origin of convection could be at any level of the model. The cloud cover in STRACO is computed at every model layer and a distinction is made between convective and stratiform clouds. A gradual (soft) transition between the convective and stratiform regime is a novel feature of the scheme and this leads to smooth accumulated precipitation fields.

In HIRLAM, the onset of precipitation in layer-clouds takes place as soon as the water vapour content exceeds the saturation point. After taking into account the effect of latent heat on temperature, and thus on the saturation point, the net water loading that results from the condensation process will transform to precipitation according to the cloud physics scheme of Sundqvist et al. (1989).

The vertical diffusion scheme in HIRLAM is a parameterisation of the vertical fluxes of momentum, sensible heat and moisture, caused by turbulence in the atmospheric boundary layer (Louis, 1979). In this scheme the vertical fluxes are based on local gradients of the forecast variables. In unstable conditions the fluxes are modified with non-local terms. These terms account for the transfer of heat, moisture and momentum at the top of the atmospheric boundary layer (Holtslag and Boville, 1993).

All versions of the model grid use the same physics. This approach reduces imbalances at the boundaries of the nested models. On the other hand, the scale dependency of the physical parameterisations is neglected, which may not be realistic in models with horizontal resolutions smaller than 10 km where, e.g. non-hydrostatic effects become important.

In this study we focus on the effects of increased model resolution only. Extreme rainfall events mostly develop mesoscale organisation or involve a complex interaction between convection and topography. Both processes are sensitive to model resolution. The rainfall predictions in this study are not real forecasts because the model runs are made after the occurrence of the event.

2.2. Nesting strategy

Experiments are carried out using HIRLAM with horizontal resolutions of 55, 28, 13 and 6 km. As shown in Fig. 1, each model grid is centred at Ireland. The size of the grid is chosen such that in all four models the number of grid cells in the x- and y-direction equals 114 and 100, respectively. The purpose of nesting is simply to zoom in on a certain area with a higher resolution than the driving model. The difference between the resolution of the driving and the nested model should not be too large to prevent instabilities and to minimise errors. These errors are associated with the quality of the forecast of the driving model and the spatial and temporal interpolation from that model. To prevent the large differences between the driving and nested model, the process of nesting is repeated (multiple nesting) up to tree times in this study. Successive nesting may reduce unrealistic waves that develop at the interface of the driving and nested models and propagate into the inner domain.

The 55 km model itself is driven by the ECMWF (European Centre for Medium range Weather Forecasting) model (alien nesting). This implies that the lateral boundary conditions are taken from the ECMWF analysis (ECMWF, 1997). The update frequency of the boundary fields is 6 h. At intermediate times the boundary values are interpolated linearly. The initial field is obtained by HIRLAM itself from the observations using an Optimal Interpolation analysis scheme (Gustafsson, 1993). Subsequently, the 28 km model is nested in the 55 km model (single nesting), the 13 km model in the 28 km model (double nesting) and 6 km model in the 13 km model (triple nesting). All models use the initial fields from the 55 km model and the boundary fields from the model where it is nested in. With exception of the 55 km model, the update frequency of the boundary fields is 3 h.

It is important to note that none of the embedded models have their own analysis cycle and receive initial information from the coarse mesh model (55 km) by interpolation. Therefore, no mesoscale structures (5–30 km) will be present in the initial fields.

Prior to the prediction of each model, an implicit normal mode initialisation with four vertical modes

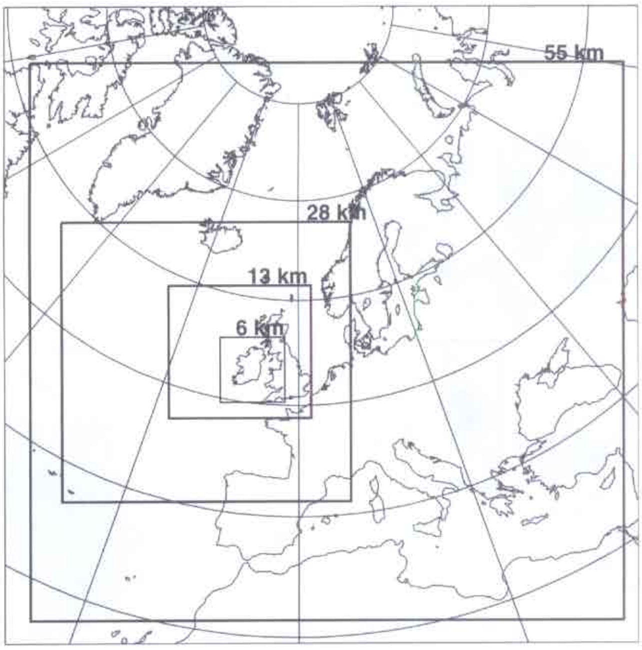

Fig. 1. Situation of the 55, 28, 13 and 6 km HIRLAM grids.

using adiabatic model tendencies and two iterations is made. The prediction runs from 0600 UTC to 0900 UTC the next day. To reduce unbalances and spin-up problems, the first three hours of the 27 h integration are not taken into account. This means that the +03 h prediction is subtracted from the +27 h to obtain 24 h rainfall totals. In this way the rainfall predictions also correspond to the observations, which are available as 24 h accumulation sums between 0900 UTC and 0900 UTC.

In the lateral boundary zone of the model domain the prognostic variables are relaxed towards the output of the coarse scale model using the Davies scheme (Davies, 1976). McDonald and Haugen (1992) found that a cosine profile as relaxation function minimised false reflections adequately and also transferred the external forcing to the inner area. A disadvantage of this method is that there is no distinction between in and outflow. Information from the coarse mesh model is fed into the fine mesh model but there is no feedback. Another well-known problem is that mass is not conserved, because mass computed from the boundary integral is not equal to mass from the area integral (McDonald 1998a).

The dynamics of the nested models are adapted slightly by modifying the time step and the horizontal diffusion for smaller grid lengths. The choice of the time step is checked with the dimensionless Courant number and the correct amount of horizontal diffusion is derived by scaling (McDonald, 1998b).

Orography plays an important role in this study. For all model grids, the topography is derived from the GTOPO30 data set (USGS, 1996). This data set is distributed by the US Geological Survey and is freely available from the internet. The heights are based on a digital elevation model with a grid spacing of 1/120° (about 1 km). Fig. 2 shows the elevations for the 6 km grid for both Ireland and the catchment of the Dodder.

2.3. Cyclone Ex Charley 25 August 1986

Hurricane Charley first appeared as a tropical storm off the South Carolina coast (USA) on the 15th of August 1986. On the 17th it was classified as a hurricane and wind speeds up to 33 m/s were reported. Charley's strength began to decline while coming across the North Atlantic. By the 22nd of August, Charley was an ordinary depression. On 23rd,

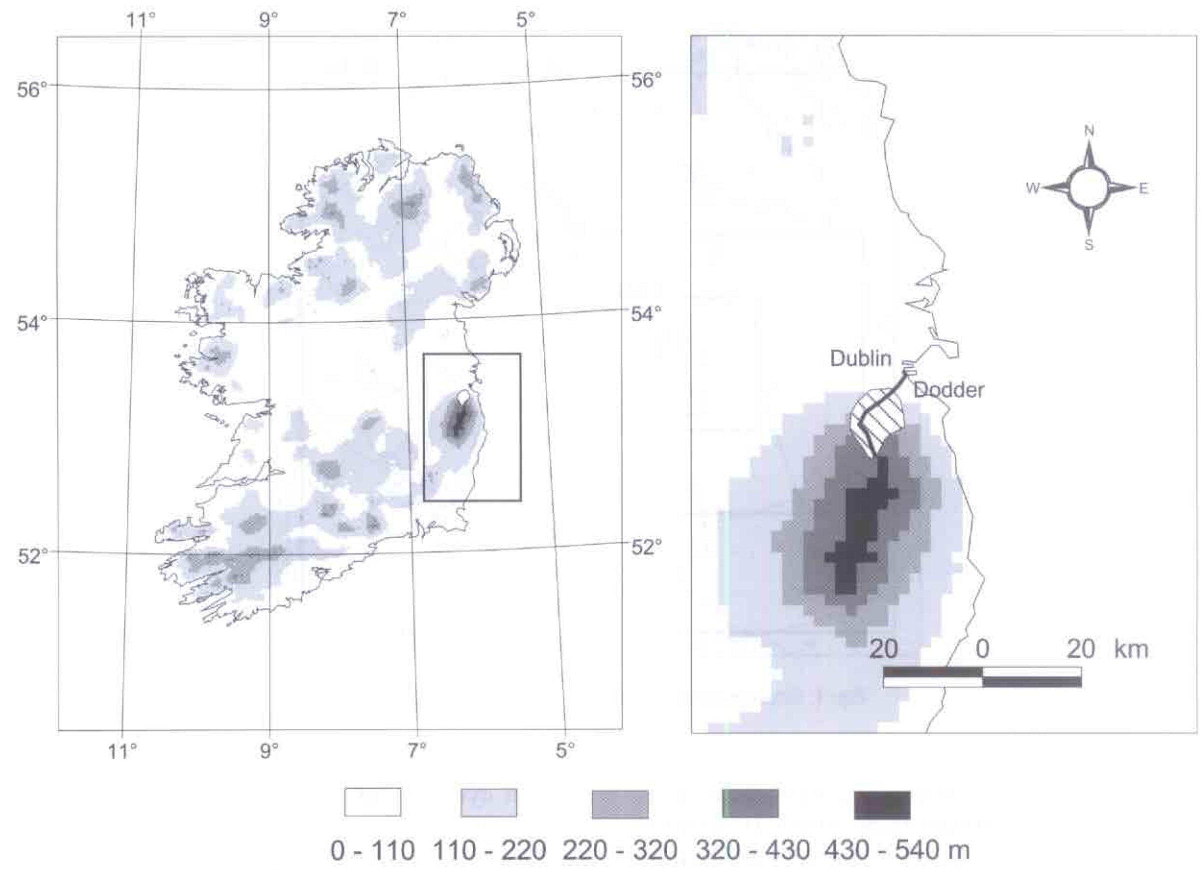

Fig. 2. Elevations in the 6 km grid for Ireland (left) and the area around Dublin (right) with the catchment of the Dodder (hatched area).

however, rapid baroclinic development began to occur, resulting in the formation of an extratropical cyclone by midday on the 24th. On the 25th the centre of this cyclone was positioned 550 kilometres South-west of Ireland and was moving North-eastwards and deepening. About noon the centre was just south of Ireland near the Cork coast while it was raining steadily all over the country, with the exception of the extreme north.

By midnight the centre had just reached St. David's Head in Wales with a surface pressure of 983 hPa (see Fig. 3). Near the catchment a wind speed of 15 m/s was reported (interpolated from measurements by HIRLAM). The ex cyclone continued to move eastwards and started to fill up. The weather system caused an East to Northeast flow over Ireland. The advected moist air interacted strongly with the Wicklow Mountains south of Dublin and resulted in a pronounced orographic enhancement of rainfall in the river catchments there.

During the storm a number of small rivers, mainly the Dodder (Fig. 2) and the Dargle, which drain the east side of the Dublin mountains, flowed through the Dublin and Bray urban areas and burst their banks. As a result, a number of lives were lost, over 400 houses were flooded, some with up to 2.5 m of water, and 35 commercial premises were inundated. The total insurance claims amounted to about EUR32 million.

3. Results

In the present section, we present the results of the 55, 28, 13 and 6 km models. We first compare the predicted synoptic situation with the observed

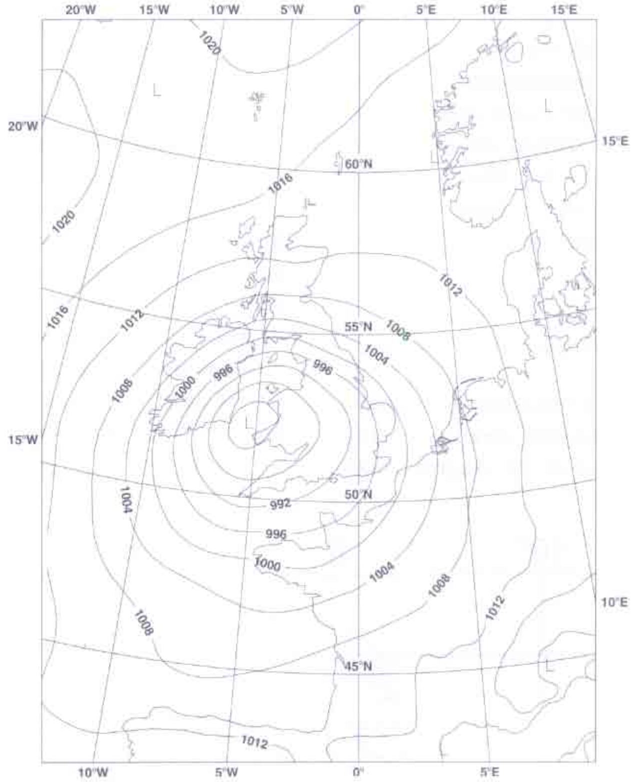

Fig. 3. Analysis of mean sea level pressure at 26 August 0000 UTC 1986.

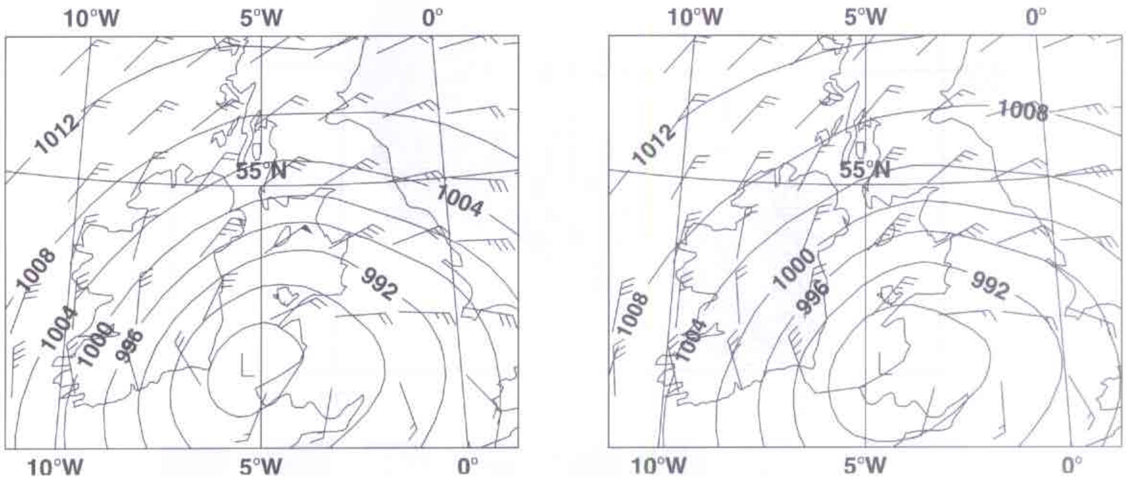

Fig. 4. Analysed (left) and predicted (right) mean sea level pressure (hPa) and wind speed (m/s) and direction at 10 m, valid at 26 August 0000 UTC 1986. The contour interval of the pressure field is 4 hPa. Wind speed en direction is represented by flags where one full barb corresponds to 5 m/s; a solid pennant represents 25 m/s.

situation. Thereafter, we compare the predicted spatial rainfall distributions with the observed distribution, followed by a direct comparison of station predictions and observations. The visual comparisons and verification scores in this section are helpful to mutually compare the models for this particular extreme event. Because only one extreme event is considered, no conclusions can be drawn on the adequacy of a particular model.

3.1. Verification of the synoptic situation

Fig. 4 compares the analysed (measurements interpolated by HIRLAM) and predicted mean sea level pressure and wind speed valid at 26 August 0000 UTC, which is 9 h before the end of the prediction period. The analysis is a combination of observations and a previous prediction and represents the state of the atmosphere on the model grid.

Fig. 4 shows that the location of the low centre and the other large-scale features of the pressure pattern are rather well reproduced by the model. There are, however, some differences. For instance, the analysed and predicted core pressures are 983 and 985 hPa, respectively. Because of this overestimation the depression is not deep enough, resulting in an underestimation of the wind speeds by the model. At the East Coast of Ireland near the catchment, e.g. the predicted and analysed wind speeds are 12.5 and 15 m/s, respectively, combined with a small deviation

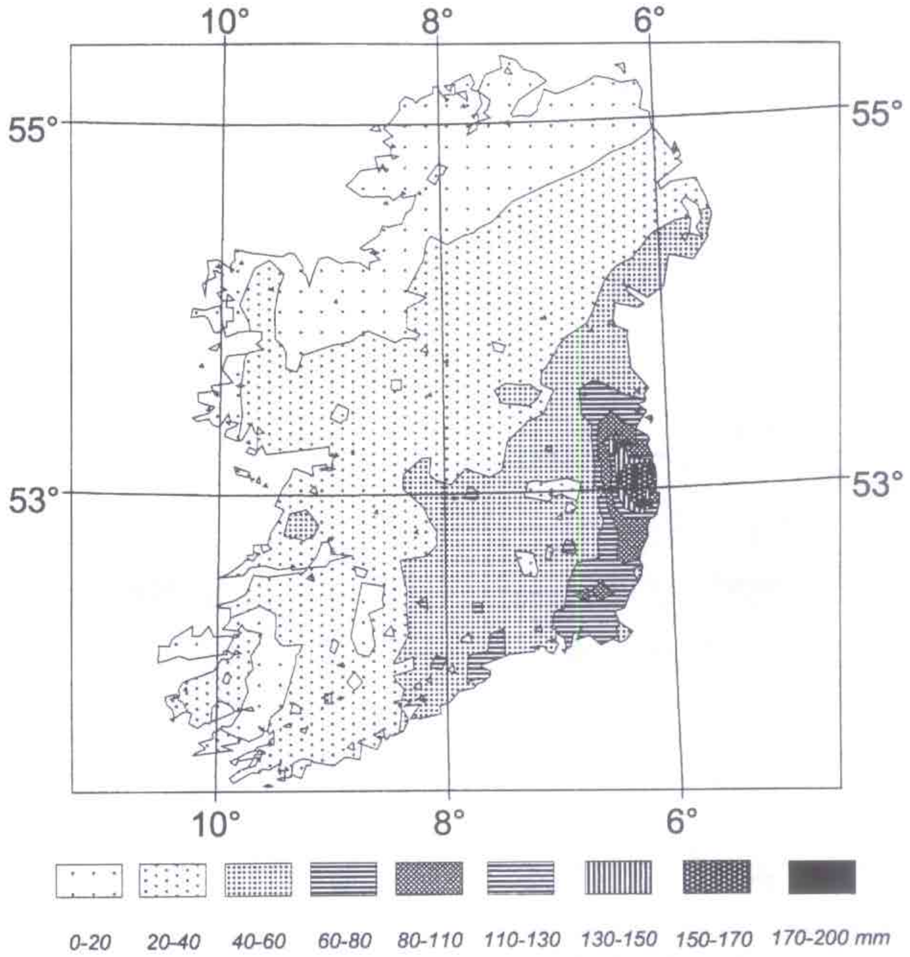

Fig. 5. Spatial distribution of the observed 24 h rainfall amounts of 513 Irish stations measured at 26 August 0900 UTC 1986.

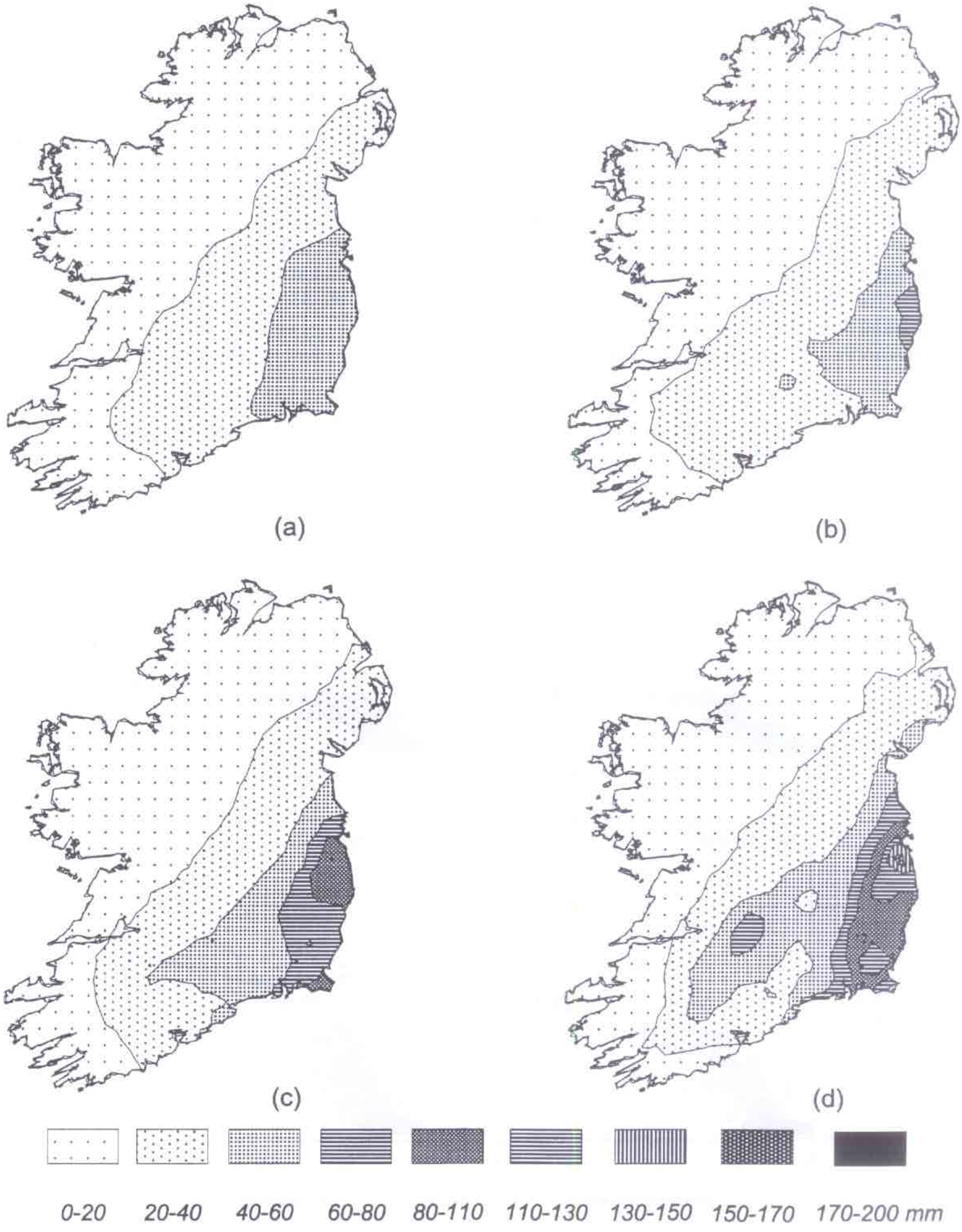

Fig. 6. Spatial distributions of the predicted 24 h rainfall amounts accumulated between 25 August 0900 UTC and 26 August 0900 UTC 1986: (a) 55 km model; (b) 28 km model; 13 km model; and (4) 6 km model.

in wind direction. The analysed wind comes from Northeast and the predicted wind originates from a more northerly direction.

3.2. Comparison of spatial rainfall distributions for Hurricane Charley

Fig. 5 presents the spatial distribution of the observed 24 h rainfall sums (513 stations) for Ireland during Hurricane Charley, measured on 26 August at 0900 UTC. The figure shows a gradual increase in rainfall amounts from the Northwest to the Southeast, with the maximum amounts located near the Wicklow Mountains. In the North there is an area with rainfall amounts less than 10 mm.

The spatial distributions of the 24 h rainfall predictions of the 55, 28, 13 and 6 km models are compared in Fig. 6. In accordance with the observations in Fig. 5, all models show a gradual increase in rainfall amounts from the Northwest to the Southeast. The reproduction of spatial details improves with increasing model resolution, especially above the Wicklow Mountains. The maximum predicted rainfall amounts above these mountains are 44, 53, 102 and 131 mm produced by the 55, 28, 13 and 6 km models, respectively. Those maximums are all well below the observed maximum of 200 mm.

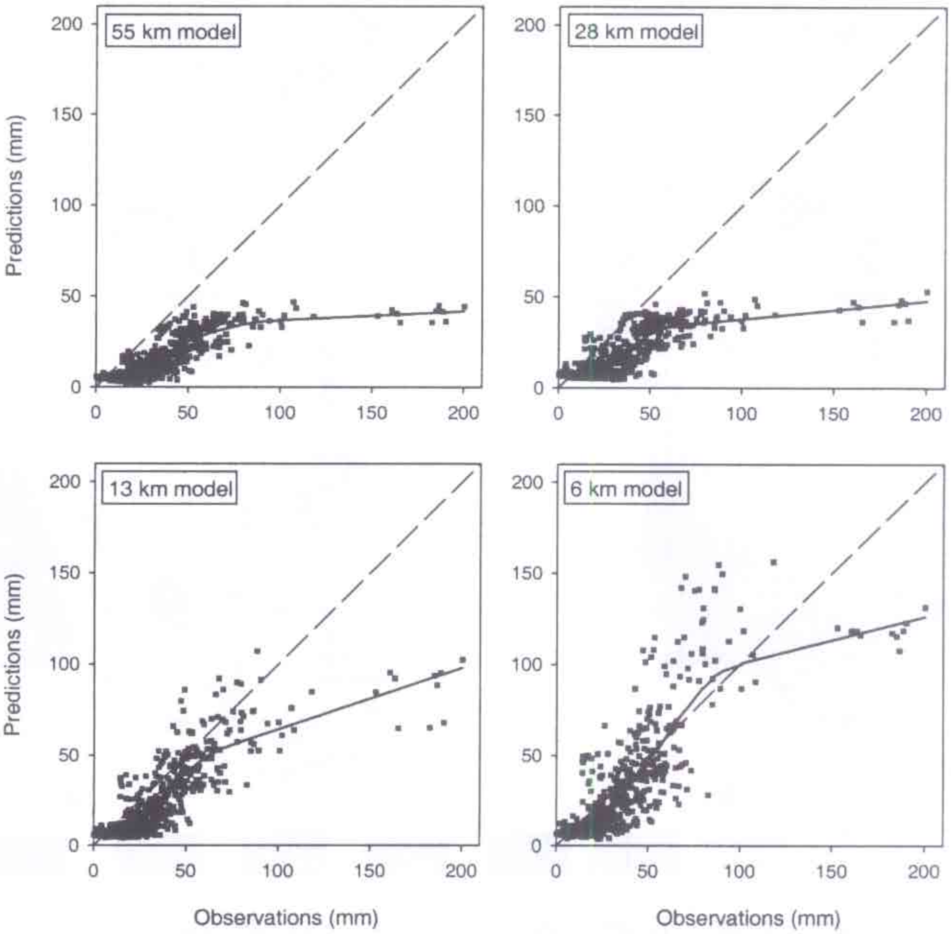

Fig. 7. Comparison between the observed 24 h rainfall amounts of 513 Irish stations and the predicted amounts (interpolated to these stations), accumulated between 25 August 0900 UTC and 26 August 0900 UTC 1986, together with a smoothed average.

Table 1
Bias, root mean squared error (RMSE) and root mean square factor of the models for Hurricane Charley. The arithmetic mean of the 513 rainfall stations equals 37.1 mm

Model	Bias (mm)	RMSE (mm)	RMSF
55 km	−21.0	29.6	0.43
28 km	−17.8	27.6	0.55
13 km	−10.6	19.8	0.67
6 km	−3.5	20.2	0.79

3.3. Direct comparisons with station observations for Hurricane Charley

3.3.1. Verification for Ireland

Verification of rainfall amounts is difficult because model rainfall amounts are represented as mean amounts over grid squares while observations are taken at specific geographical locations. Model predictions can, however, be interpolated to the observation locations. Especially for low-resolution models this may lead to representativeness problems. Here we applied a two-dimensional linear interpolation method to obtain station precipitation.

Fig. 7 shows that the predictive power of the 55 and 28 km models is inferior to the other two models. Especially the large underprediction of rainfall amounts in the 55 and 28 km models is striking. This was also anticipated from the comparison of Figs. 5 and 6.

Table 1 and Fig. 8 show some relevant summary statistics. The Root Mean Square Factor (RMSF) in Table 1 is defined by:

$$\mathrm{RMSF} = \exp\left\{\frac{1}{N}\sum_{i=1}^{N}\ln\left(\frac{F_i}{G_i}\right)^2\right\} \tag{1}$$

where F_i are the forecast values, G_i the observations and N the number of stations. To prevent taking the log of zero, rainfall amounts equal to zero (occurring only once here) are set to 0.1 mm. As discussed by Golding (1998), the RMSF can be interpreted as giving scale to the multiplicative error, i.e. $F = G \times \mathrm{RMSF}$ or $F = G/\mathrm{RMSF}$, while the more common Root Mean Squared Error (RMSE) is giving scale to the additive error, i.e. $F = G \pm \mathrm{RMSE}$. For rainfall amounts, the RMSF is found to provide more information than the RMSE. The closer the RMSF is to

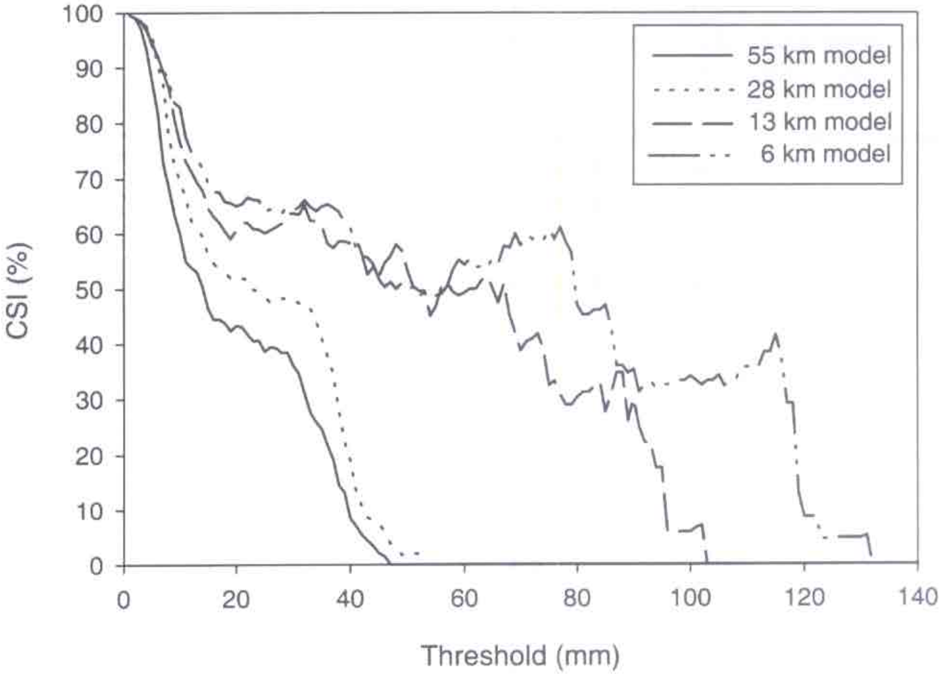

Fig. 8. Critical Success Index (CSI) for thresholds ranging between 1 and 140 mm.

one, the better the forecast. The Critical Success Index (CSI) for different thresholds is defined as the number of stations for which both the observed and predicted rainfall amounts are above the threshold, divided by the total number occasions on which that event was predicted and/or observed.

In terms of bias and RMSF, Table 1 shows a clear improvement of the results with increasing model resolution. The RMSE, however, suggests that the results of the 55 and 28 km are comparable and worse than the results for the 13 and 6 km models. The RMSE of the 13 and 6 km model are also comparable with the 13 km model performing even slightly better than the 6 km model.

The differences in performance of the models are further illustrated by the CSI in Fig. 8. The figure shows a comparable performance of 55 and 28 km models, with the latter model performing somewhat better. Above a threshold of about 50 mm, the CSI of these models becomes zero because for stations with observed rainfall amounts larger than 50 mm the models always predict amounts smaller than 50 mm. The performance of the 13 and 6 km models is clearly better than that of the two lower resolution models. Up to thresholds of about 60 mm the performance of the 6 km model is slightly better than that of the 13 km. However, for thresholds greater than 60 mm the 6 km model outperforms the 13 km model.

3.3.2. Verification for the catchment of the Dodder

Because of the severe flooding in and around Dublin, we now zoom in to the catchment of the Dodder and examine the rainfall results for that area. The Dodder has its source in a steep mountainous area at an altitude of 743 m a.m.s.l. and then flows through a number of reservoirs and a flat urban coastal plain before entering the sea near Dublin. The catchment can be considered as an orographically complex area.

Table 2 compares the observed and predicted rainfall amounts of 10 stations in or near the catchment of the Dodder. The table shows a large underprediction of the observed mean rainfall amounts for the 55 and 28 km models. For the 13 km model this underprediction is much smaller and for the 6 km model there is even a slight overprediction of the observed mean rainfall amounts.

Table 2 shows that the observed rainfall varies significantly on the relatively small scale of the Dodder catchment (113 km^2). It should be noted that none of the models is able to predict this variation. Especially in this orographically complex area, rainfall is a local phenomenon and large variations in rainfall amounts may be expected at relatively short range (tens of meters). Therefore, interpolation of mean rainfall amounts over grid squares to station precipitation is not realistic, even for the 6 km model. It is also known that large measurement errors may occur in mountainous areas due to local wind effects.

For flood forecasting purposes the timing of rainfall is of interest. Fig. 9 compares the predicted half-hour rainfall amounts with the observed amounts for Glenasmole DCWW (situated in the centre of the

Table 2
Observed and predicted rainfall amounts in mm of 10 stations in and near the Dodder catchment during the Hurricane Charley (25 August 1986)

Station	Observation	Model			
		55 km	28 km	13 km	6 km
Dublin airport	72.2	34.5	34.3	62.2	91.7
Glenasmole DCWW	165.3	35.6	36.4	64.9	116.0
Casement aerodrome	89.3	33.0	32.6	52.7	86.8
Glenasmole Castlekelly	190.2	36.1	37.3	67.9	122.8
Glenasmole (Supt's lodge)	182.5	35.6	36.5	65.2	117.0
Ballyboden	100.1	36.4	36.7	68.2	130.4
Tibradden (Larch hill)	75.3	37.2	38.1	74.1	140.5
Rathcoole-Saggart	100.8	33.0	32.9	52.7	86.8
Rathfarnham	86.0	37.3	37.8	74.2	141.5
Dundrum	86.3	37.4	37.5	74.6	140.8
Mean	114.8	35.6	36.0	65.7	117.4

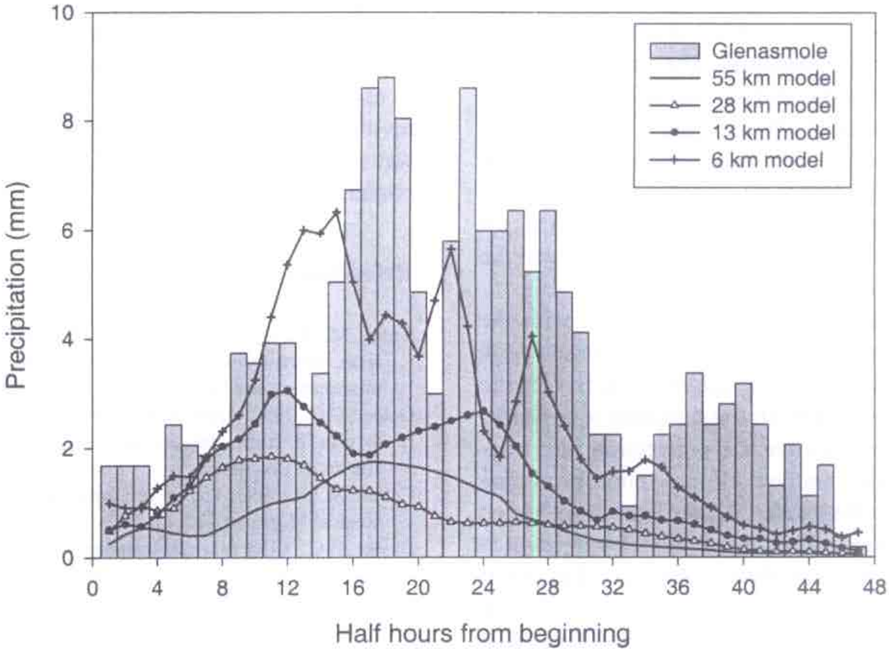

Fig. 9. Predicted and observed half-hour rainfall amounts for Glenasmole DCWW between 25 August 0900 UTC and 26 August 0900 UTC 1986. The observed values for Glenasmole DCWW are derived from a recording rain gage at Casement Aerodrome by scaling with the observed 24 h rainfall amounts (Table 2) of these stations.

catchment). The figure shows that, despite a small timing error, the 13 and 6 km model are able to represent some of the temporal details of the observed values. For this particular event, the 28 km model differs most from the observed rainfall pattern.

4. Discussion

For the particular extreme event studied in this paper, the positive effect of enhancing the horizontal model resolution of HIRLAM is obvious. The 6 km model has the best performance, especially for the mountainous catchment of the Dodder. Nevertheless, even the 6 km model could not predict the variability of the rainfall amounts across the Dodder catchment. The model resolutions are still much too coarse to represent the small-scale effects of the mountains. The difference in performance of the models can probably best be explained by the better representation of the orography in the higher resolution models, combined with the particular synoptic situation for the event.

In contrast to the present study, other studies (Nielsen-Gammon and Strack, 1999; Lakhtakia et al., 1999; Gollvik, 1999; Xiaoding et al., 1997) showed that positive effects of resolution enhancement do not always occur. This suggests that the effects of resolution enhancement may be dependent on the events being studied.

It seems that results mainly improve due to the better-resolved orography for finer model grids. Additionally, the better-represented physics also contributes, but there is a certain limit. In the convective parameterisation scheme, it is assumed that convection occurs so rapidly that it evolves and dies on the time scale identical with the time step applied in the parameterisation of the physical processes in the model. The time step in high-resolution models becomes small for numerical stability reasons and is only a small fraction of the lifetime of a convection cell. For model grids of 6 km or less, the short time scale of the parameterised convection is therefore a severe limitation.

Although numerical forecasting of precipitation has a large intrinsic uncertainty, models are still being improved. For instance, the English and French models have their own analysis system and do not just run from interpolated data. The English analysis system has been deliberately set up to try to improve precipitation forecasts (Wright and Golding, 1990; Macpherson et al., 1996; Jones and Macpherson, 1997), mainly by a better representation of the initial moisture distribution. Adaptation of HIRLAM for these developments could have further improved the rainfall predictions in this paper.

Convective processes are parameterised with the hydrostatic assumption. At a model resolution high enough to resolve the most significant scales of the convection (say <10 km) this assumption is no longer valid. Models that resolve the convection in a non-hydrostatic model framework are now becoming operational (e.g. Deutscher Wetterdienst and Meteo France). However, when these models are run at high resolution, it is not always clear to what extent they converge to a particular solution. A lot of questions in this field are still to be answered (Kuo et al., 1997; Weisman et al., 1997). Besides worrying about improvements in the parameterisation schemes, it is just as important to ensure that synoptic forcing of the large scale model and high resolution initial conditions, the initial moisture distribution and surface characteristics are correct.

5. Conclusions

In this paper we presented a case study of the impact of increasing horizontal resolution of an NWP model on the accuracy of rainfall predictions. Because only one specific extreme event was considered, general conclusions cannot be drawn from this study. For the event studied, it was demonstrated that increasing horizontal model resolution has a beneficial effect on the rainfall predictions for both Ireland as a whole and the catchment of the Dodder. We conclude that for this particular case, refining the model grid pays off for the prediction of rainfall mainly because of orographic enhancement.

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