



# CEH-GEAR: 1 km resolution daily and monthly areal rainfall estimates for the UK for hydrological and other applications

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**Abstract.** The Centre for Ecology & Hydrology – Gridded Estimates of Areal Rainfall (CEH-GEAR) data set was developed to provide reliable 1 km gridded estimates of daily and monthly rainfall for Great Britain (GB) and Northern Ireland (NI) (together with approximately 3500 km<sup>2</sup> of catchment in the Republic of Ireland) from 1890 onwards. The data set was primarily required to support hydrological modelling.

The rainfall estimates are derived from the Met Office collated historical weather observations for the UK which include a national database of rain gauge observations. The natural neighbour interpolation methodology, including a normalisation step based on average annual rainfall (AAR), was used to generate the daily and monthly rainfall grids. To derive the monthly estimates, rainfall totals from monthly and daily (when complete month available) rain gauges were used in order to obtain maximum information from the rain gauge network. The daily grids were adjusted so that the monthly grids are fully consistent with the daily grids. The CEH-GEAR data set was developed according to the guidance provided by the British Standards Institution.

The CEH-GEAR data set contains 1 km grids of daily and monthly rainfall estimates for GB and NI for the period 1890–2012. For each day and month, CEH-GEAR includes a secondary grid of distance to the nearest operational rain gauge. This may be used as an indicator of the quality of the estimates. When this distance is greater than 100 km, the estimates are not calculated due to high uncertainty.

CEH-GEAR is available from doi:10.5285/5dc179dc-f692-49ba-9326-a6893a503f6e and is free of charge for commercial and non-commercial use subject to licensing terms and conditions.

## 1 Introduction

Estimates of areal daily or monthly rainfall over extended periods are often required for hydrological purposes such as catchment management of water resources (e.g. Young et al., 2003), catchment modelling (e.g. Bell et al., 2013; Young et al., 2006), peak flow estimation (e.g. Prosdocimi et al., 2014) and groundwater recharge (e.g. Sorensen et al., 2014). More widely, they are required by a variety of disciplines, for example to model or explain processes such as the atmospheric deposition of nitrogen in geosciences (Dore et al., 2012) and

the relationship between rainfall and cholera in epidemiology (Eisenberg et al., 2013).

In the UK, point measurements of daily and monthly rainfall data have been collected using standardised storage rain gauges since the late 19th century (Burt, 2010; Eden, 2009). Here rainfall is defined as total precipitation which is the sum of liquid precipitation plus the liquid equivalent of any solid precipitation (UK Meteorological Office, 2014) and is in accordance with the British Standards Institution (BS 7843-4:2012, 2011b), the UK convention for areal rainfall calculations. The UK network of rain gauges grew from around 450 in 1860 to approximately 3500 by 1900 and peaked at around

6250 in 1974 (Eden, 2009). By 2009, data were recorded at 3285 sites (Burt, 2010). While the current national rain gauge network is dense in global terms, the resulting rainfall information is limited to a set of discrete points in space and time. Practical considerations, such as those relating to the suitability of sites and the cost of maintaining the network, mean that there is considerable spatial variation in the density of the network. Nevertheless, interpolation techniques can then be used to provide rainfall estimates across a continuous area based on the rainfall data collected.

The Met Office has developed a method for generating 5 km grids of daily, monthly and annual estimates of rainfall for the UK from 1961 onwards (Perry and Hollis, 2005; Perry et al., 2009). However, for hydrological purposes there are often requirements for finer spatial resolutions to model river flows accurately at a catchment level (Bell et al., 2013; Cole and Moore, 2008; Young et al., 2006), as well as longer time series to allow assessment of hydrological change (in particular daily data prior to 1961 when computer-held rain gauge data are less prevalent). Spatial rainfall fields, represented as daily 1 km grids, are required for the estimation of catchment average rainfall time series for input into generalised rainfall–runoff models. As the optimisation of parameters of any model will tend to compensate for measurement error within both the input data and the calibration flow data, it is essential that the methods used for estimating rainfall data are accurate and consistent in approach for both calibration and subsequent application.

The aim of this paper is to outline the development of the Centre for Ecology & Hydrology – Gridded Estimates of Areal Rainfall (CEH-GEAR) data set, a 1 km daily and monthly rainfall data set for Great Britain (GB) and Northern Ireland (NI) (together with approximately 3500 km<sup>2</sup> of catchment in the Republic of Ireland) for the period 1890–2012. A description of the data (Sect. 2) used to generate this data set is presented followed by the rainfall interpolation method (Sect. 3). Quality control of the daily rainfall data is described (Sect. 4) and validation results of the gridded rainfall estimates presented using an independent rain gauge network over Scotland (Sect. 5). Finally, some recommendations are provided regarding the use and limitations of this data set.

## 2 Data

### 2.1 Rain gauge rainfall observations

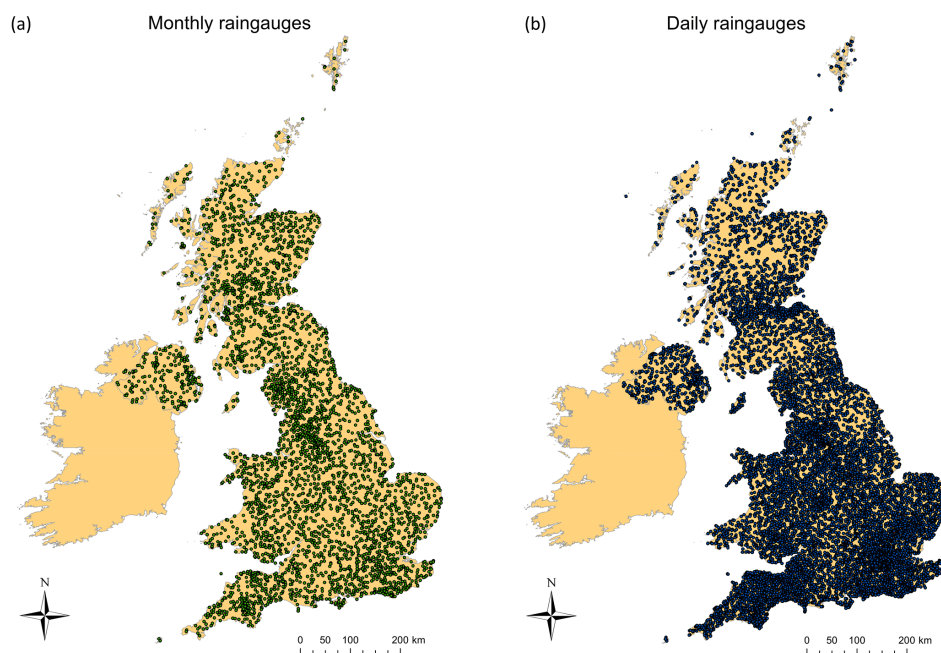
The aim of the CEH-GEAR data set is to produce temporally consistent areal rainfall data for as long a period as possible. This data set makes use of the Met Office collated historical weather observations for the UK, specifically the daily and monthly rainfall accumulations (liquid precipitation plus the liquid equivalent of any solid precipitation; UK Meteorological Office, 2012) from a national network of rain gauges (UK Meteorological Office, 2014). These rainfall data are col-

lected by a range of organisations from an irregularly spaced and constantly evolving network of manual and automated rain gauges (Eden, 2009). For the period 1961–2000, there is an average of one rainfall station per 49 km<sup>2</sup> (4400 stations) (Perry and Hollis, 2005), with the peak density occurring in 1974. While the UK rain gauge network expanded rapidly during the late 19th and early 20th century, only a limited proportion of the pre-1961 data is currently available in digital form. The national database contains records of rainfall accumulations over a range of durations, however this paper will focus on daily and monthly accumulations from both manual and automated rain gauges. Maps of all daily and monthly rain gauges used to generate the CEH-GEAR data set are presented in Fig. 1.

The graph in Fig. 2 shows the evolution of the daily and monthly rain gauge network used to derive the rainfall grids in the 1890–2012 period. The maps in Fig. 3 reveal the spatial distribution of the daily rain gauge network at different times. These two figures highlight the significant differences in the network density before and after 1961, an important consideration for potential users of the data set as it affects the quality of the resulting rainfall estimates. Due to the uneven geographic development of UK precipitation monitoring, some regions have reasonable rain gauge coverage even in the early 20th century (London area, Somerset, West Midlands), whereas some others have very poor gauge density (Scotland, South Central England, Wales, Cornwall and Devon, East and North of England, East Midlands). As a result, caution is required when using CEH-GEAR data before 1961, as the quality of the data will be highly variable temporally and spatially.

Depending on the intended use of the data set, different tolerances in relation to the underlying gauge density may be appropriate. The CEH-GEAR rainfall grids are supplied together with minimum distance grids, which provide information regarding the distance to the closest gauge used to calculate rainfall at each grid cell. Users are very strongly advised to make use of the minimum distance grids, especially for data before 1961, to be able to assess the suitability of the data for their individual applications. More detail on the effect of the network density on the accuracy of the rainfall estimates is given in Sect. 5.

When developing and using spatially aggregated rainfall data based on rain gauge observations, it is important to consider the uncertainties in the source measurements. Extensive international trials have shown that the main sources of error in rain gauge measurement include those due to adhesion of water to the gauge surface, in- and out-splash, wetting and evaporation. However, the largest source of error is caused by the wind around the rain gauge, leading to a systematic underestimation of the rainfall amount (Rodda and Dixon, 2012). Indeed, long-term trials have shown that, for the UK standard Met Office Mk2 rain gauge (British Standards Institute, 2011a), these errors lead to significant systematic undercatches of around 5 % in the estimation of average annual



**Figure 1.** Maps of daily rain gauges used to derive the CEH-GEAR data set: (a) monthly rain gauges and (b) daily rain gauges.

rainfall (AAR), a figure that can rise to 16 % in highly exposed areas (Rodda and Smith, 1986). While alterations to the sitting of gauges, for example by locating rims at ground level, can reduce undercatch, this is not systematically done within the UK. The high spatial and temporal variation in the degree of underestimation means that data held in the national archive cannot be routinely corrected for undercatch.

The magnitude of errors in rainfall fields derived from point measurements is mainly a function of the local density of the rain gauge network. The meteorological forcing is also important: errors are likely to be smaller for frontal rainfall than for thunderstorms or localised showers associated with warm sector weather.

## 2.2 Standard period average annual rainfall (SAAR)

The distribution of rain gauges across the UK is not uniform. Many stations are situated in locations of easy access, and often near population centres which tend to be lower in altitude and therefore dryer (British Standards Institute, 2011b). Thus, to avoid a downward bias in the gridded rainfall estimates, there is a need to normalise the rain gauge rainfall totals before interpolation, and the most suitable available variable for this is AAR.

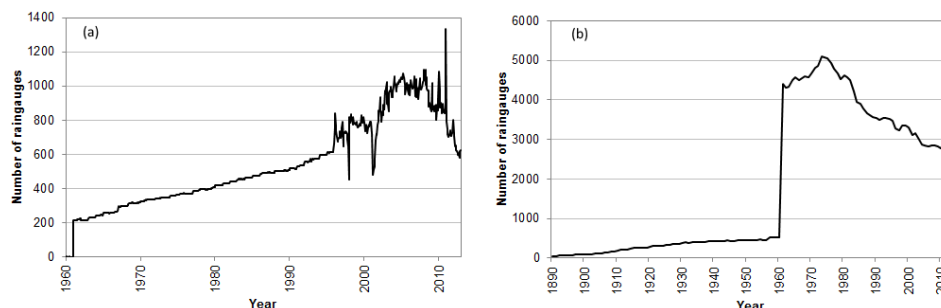
The version used for GB was the Met Office 1 km grid for the 1961–1990 standard period (SAAR 61–90). This was developed by Spackman (1993) by deriving grid point values of AAR values for a 10 km grid using monthly data from approximately 13 100 rain gauges. These values were gridded at a 1 km resolution using a bicubic spline interpolation procedure.

For NI, the Met Éireann 1 km grid of 1961–1990 long-term average rainfall was used (Walsh, 2012b). This data set, which covers the whole of Ireland, has been derived from rain gauge observations, using regression analysis (Walsh, 2012a).

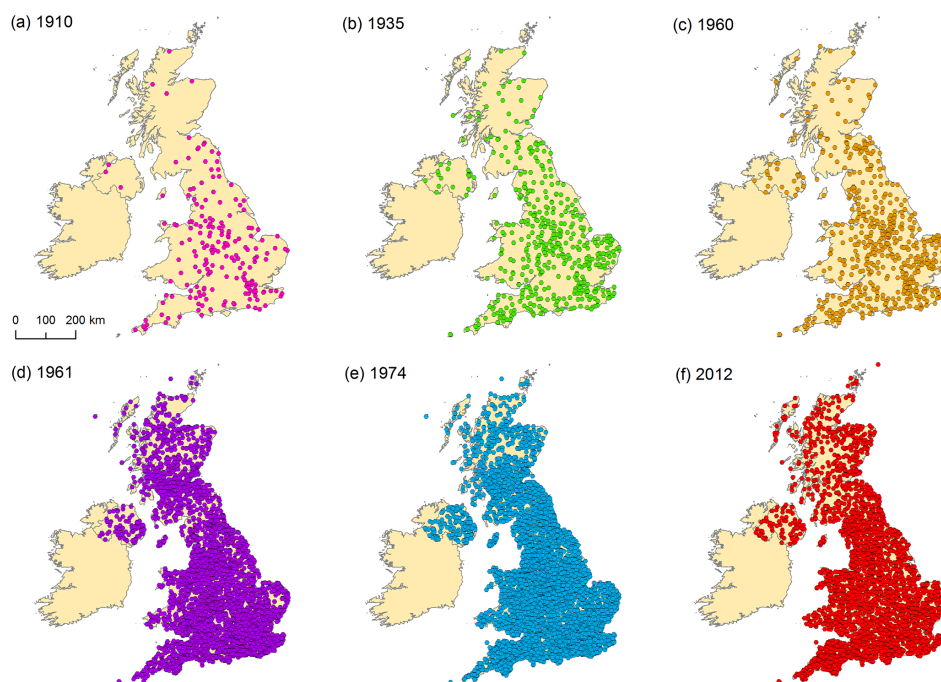
## 2.3 Weather radar rainfall estimates

Over recent decades, weather radars have played an increasingly important role in areal rainfall estimation, particularly in real-time applications. Weather radars can give good qualitative estimates of rainfall across extensive areas at fine spatial and temporal resolutions (e.g. 1 km and 5 min resolution for the UK), and data are usually available within minutes of the observation time. As a consequence, a major use is for flood forecasting where radar can detect the location, extent and evolution of convective storms that rain gauge networks rarely sample well, if at all. The UK weather radar network has only been operational since 1985, when it was launched with just four radars (Kitchen and Illingworth, 2011). Since its inception there have been many changes to radar processing that have improved the quality of rainfall estimates, and the UK network coverage has now expanded to 15 radars (Kitchen and Illingworth, 2011).

However, rain gauges still provide more accurate quantitative rainfall estimates at a particular point and are the only option for generating long-term time series of areal rainfall. Whilst merging radar and rain gauge information to form historical daily or monthly totals has the potential to provide improved areal rainfall estimates, radar data have not been used in the production of the current version of CEH-GEAR. This



**Figure 2.** Evolution of number of rain gauges in the UK within the network used to derive CEH-GEAR rainfall grids for (a) monthly rain gauges (1960 to 2012, prior to 1961 only one monthly rain gauge) and (b) daily rain gauges (1890 to 2012).



**Figure 3.** Maps of daily rain gauges used to derive CEH-GEAR rainfall grids on 1 January (a) 1910, (b) 1935, (c) 1960, (d) 1961, (e) 1974 and (f) 2012.

is in part due to the comparatively short duration available for the radar rainfall estimates ( $\sim 30$  years) compared to the rain-gauge-based observations. It was therefore considered that CEH-GEAR would have greater temporal consistency if it was based solely on rain gauge data.

### 3 Areal rainfall estimation procedure

#### 3.1 Introduction

Areal rainfall methods seek to represent the spatial distribution of rainfall over a catchment, a region or even a country. Within CEH-GEAR, a grid interval of 1 km was chosen as this aligns to the resolution of the available SAAR grids used for normalisation and because there are few locations in the

UK where the rain gauge density is sufficient to justify a finer resolution.

There are many spatial interpolation methods available; however, they all have specific features and therefore are not suitable to all environmental data sets (Li and Heap, 2008, 2011). There are four principal categories of procedures for estimating the rainfall at each grid point. Although all of the procedures may be applied directly to the gauged values, it is generally recommended that they are applied to values that have been normalised by SAAR (British Standards Institute, 2011b), as discussed in Sect. 2.2.

The first category is termed the domain method, where each operational rain gauge is considered to represent a contiguous area of the surrounding surface (referred to as domain), and each grid point in that domain is allocated the



rainfall recorded at the rain gauge. Domains are most commonly defined on the basis of proximity, and this kind of estimation of point values is known as nearest neighbour interpolation. This is the basis of the well-established Thiessen procedure for areal rainfall estimation (Thiessen, 1911). A serious drawback with this type of approach is the presence of discontinuities at the edges of domains; this is of particular concern when using the grid to estimate areal rainfall in small catchments with an area of a similar spatial resolution as the rain gauge domains.

The second category involves the fitting of a mathematical surface to the observations from a selection of local gauges. An example of an interpolation method that falls in this category is splines (Mitasova and Mitas, 1993). The two main drawbacks of this approach are the risk of unjustifiable or unrealistic extrapolation, and sensitivity to the selection procedure: discontinuities can arise where a gauge with a particularly low or high observation drops in or out of the local selection.

The third category involves the fitting of a mathematical surface to the observations from all gauges, and computing the value at every grid point from this surface. This also presents the risk of unjustifiable or unrealistic extrapolation, and is computationally impractical for the large area and number of rain gauges applicable to CEH-GEAR.

Within the fourth category, rainfall ( $\bar{R}_t$ ) at a time  $t$ , is estimated as a weighted average of the rainfall observations from a selection of local gauges:

$$\bar{R}_t = \sum_{i=1}^n w_i r_{i,t}, \quad (1)$$

where  $n$  is the number of gauges,  $w_i$  is the weight applied to rain gauge  $i$  ( $w_i \in [0; 1]$ ) and  $r_{i,t}$  is the observed rainfall depth from rain gauge  $i$  at time  $t$ .

The British Standards Institute “Guide to the acquisition and management of meteorological precipitation data” (British Standards Institute, 2011b) recommends a set of such interpolation techniques, including the triangular planes method (Jones, 1983), the natural neighbour interpolation, also called Voronoi interpolation (Gold, 1989; Ledoux and Gold, 2005; Sibson, 1981), and the inverse distance weighting (IDW) method. The latter has been widely used for decades (Shepard, 1968) and is present in most GIS packages, but has the drawbacks of being adversely influenced by uneven spatial distribution of gauges and giving too much weight to distant gauges, and therefore is sensitive to distant outliers. Another method suitable for interpolating rain gauge observations is kriging, which is a geostatistical method and uses the spatial correlation between gauge observations to determine how gauges should be weighted. The great advantage of kriging is that, together with the predicted values, it provides some measure of the uncertainty in the predictions. For a more complete comparison of interpolation functions for spatial data, the reader is referred to Watson (1992). The

natural neighbour method was selected for CEH-GEAR as it produces smooth rainfall surfaces without the boundary discontinuities that occur between adjacent polygons in the Thiessen polygon method, and, it is relatively simple to implement.

### 3.2 CEH-GEAR interpolation method

A schematic of the interpolation methodology used to derive daily and monthly 1 km grids for the UK is presented in Fig. 4. The grids are generated using the natural neighbour interpolation methodology, including a normalisation step based on AAR. Note that the derivation of the daily grids involves two stages: an initial estimate from daily gauges alone, followed by multiplication by a correction grid to give consistency with monthly grids that have been derived from all available gauged data – daily and monthly. This is discussed further in Sect. 3.3.

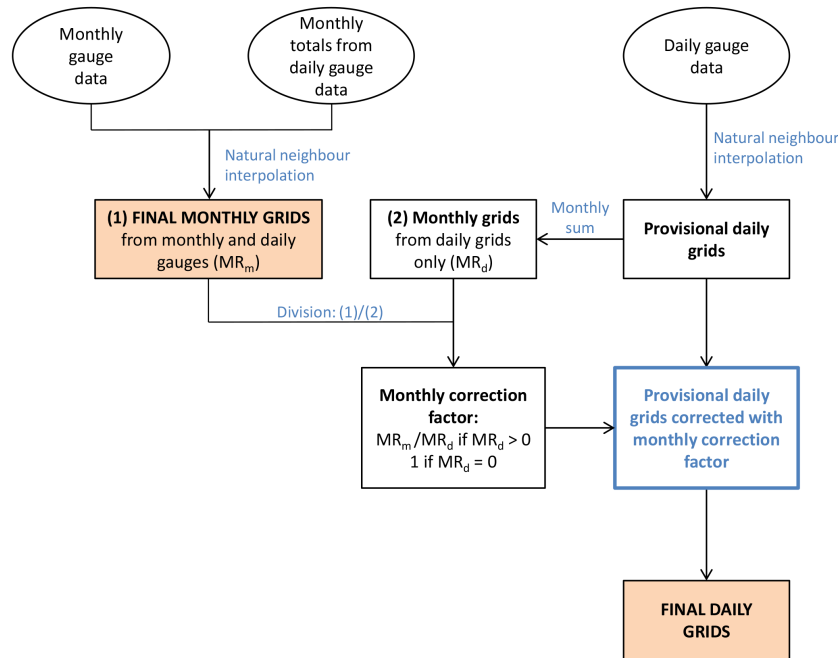
The natural neighbour interpolation method is a development of the Thiessen approach (Gold, 1989; Ledoux and Gold, 2005; Sibson, 1981). First, for each operational rain gauge  $i$  at time step  $t$ , its Thiessen polygon  $T_{i,t}$  is defined: this is the polygon within which no other operational gauge is closer. Traditionally this was derived manually by connecting the perpendicular bisectors of the lines connecting neighbouring gauges. In the automated grid-based implementation used here, it is approximated by the set of grid points for which no other gauge is closer.

Then, for each grid point  $p$ , the Thiessen polygons are reconstructed ( $\hat{T}$ ) treating the grid point as an additional gauge. The grid point then possesses its own Thiessen polygon  $\hat{T}_{p,t}$  at a time step  $t$ , which overlaps part of the original Thiessen polygons ( $T_{i,t}$ ) for the neighbouring rain gauges (only one in the case a rain gauge being coincident with the grid point). Each rain gauge  $i$  at time  $t$  that has part of its original Thiessen polygon  $T_{i,t}$  overlapped by the Thiessen polygon for the grid point ( $\hat{T}_{p,t}$ ) is included in the rainfall interpolation at the grid point  $p$ , and the weight associated with rain gauge  $i$  is proportional to the area of overlap:  $\text{area}(T_{i,t} \cap \hat{T}_{p,t})$ . The natural neighbour weight ( $w_{i,t}(p)$ ) of a neighbouring rain gauge  $i$ , when interpolating at point  $p$  at time  $t$  is

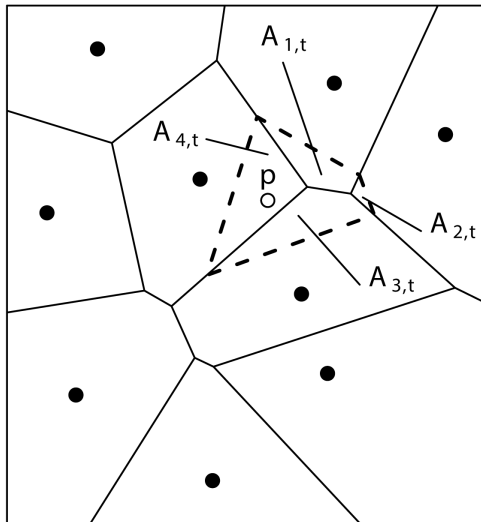
$$w_{i,t}(p) = \frac{\text{area}(T_{i,t} \cap \hat{T}_{p,t})}{\text{area}(\hat{T}_{p,t})}. \quad (2)$$

A schematic illustrating the natural neighbour method is provided in Fig. 5. In automated grid-based implementation, the areas are approximated by the number of grid points contained in the polygon. Whilst estimating the monthly grids, all monthly rainfall observations and daily data from rain gauges with a full month recorded are used to construct the Thiessen polygons.

The estimated rainfall for a grid point  $p$ , at time  $t$  ( $rc(p, t)$ ), is then derived using the natural neighbour inter-



**Figure 4.** Schematic overview of the generation of daily and monthly 1 km gridded rainfall estimates for the UK.



**Figure 5.** Illustration of the natural neighbour method for time step  $t$ . The solid lines represent the original Thiessen polygons  $T_{i,j}$  for each of the  $i$  rain gauges (solid circle). The dashed line represents the Thiessen polygon  $\hat{T}_{p,t}$  for the grid point  $p$  (open circle). The overlap between  $T_{i,t}$  and  $\hat{T}_{p,t}$  is labelled  $A_{i,t}$  ( $A_{i,t} = \text{area}(T_{i,t} \cap \hat{T}_{p,t})$ , Eq. 2).

pulation and SAAR (61–90) normalised rainfall:

$$rc(p, t) = \text{SAAR}(p) \sum_{i=1}^n w_{i,t}(p) \frac{r_{i,t}}{\text{SAAR}_i}, \quad (3)$$

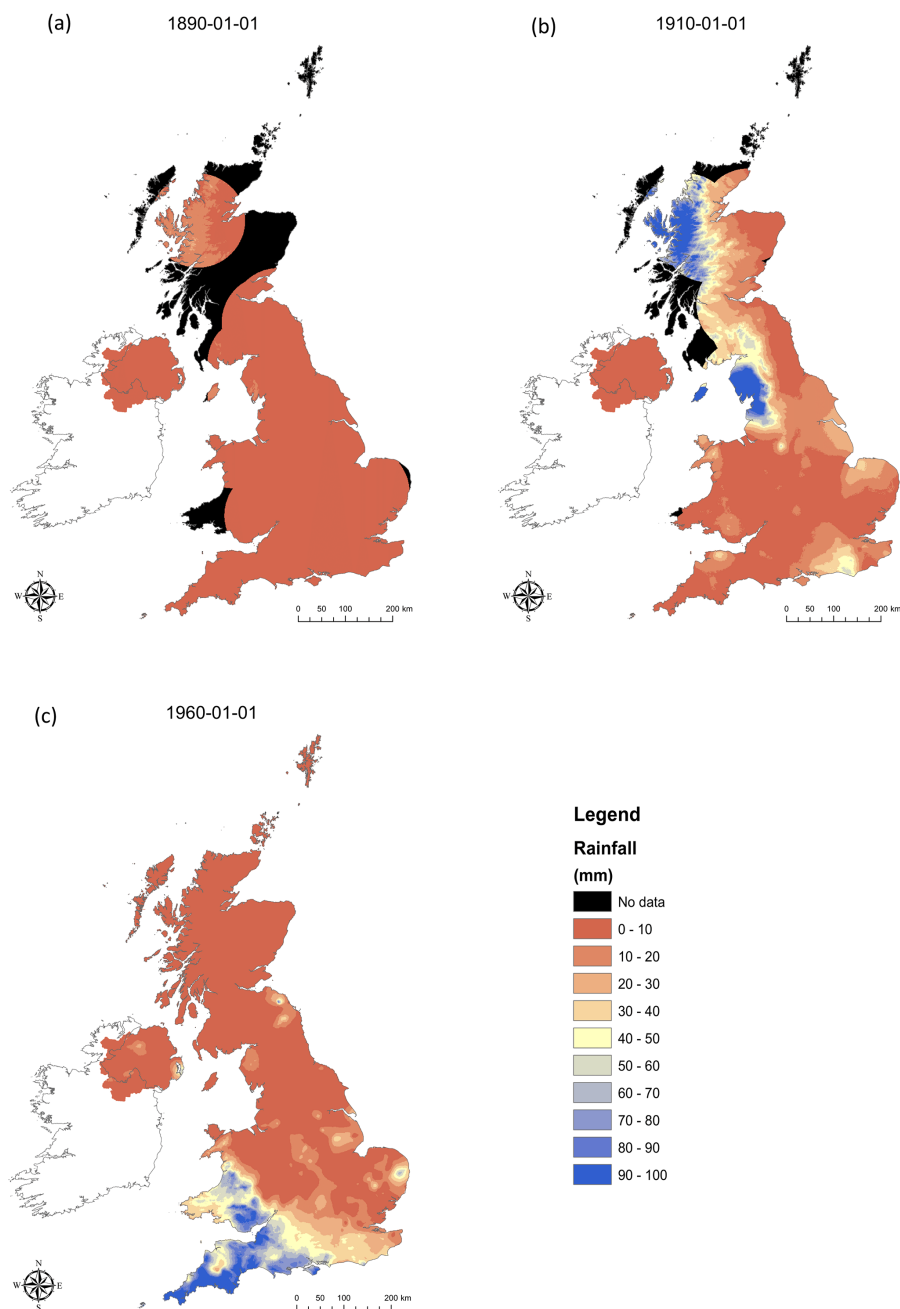
where  $\text{SAAR}_i$  and  $\text{SAAR}_p$  are the SAAR values at rain gauge  $i$  and grid point  $p$  respectively. At the next time step (i.e.  $t + 1$  day or  $t + 1$  month), if the set of operational rain gauges has changed, the weights must be recalculated.

As the selected grid point  $p$  moves away from a particular rain gauge (but within the domain of the rain gauge network), the weight for the gauge diminishes gradually to zero until it is no longer a natural neighbour. Therefore the natural neighbour interpolation method provides a gradually varying surface, unlike the Thiessen approach which consists of a series of plateaux with sharp edges between them. Nevertheless, it should be noted that the method can give rise to discontinuities in gradient at gauge locations, although these are of minor concern for areal rainfall applications.

The natural neighbour interpolation method, although more computationally demanding than the triangular planes method, makes greater use of the locally available data as it uses all neighbouring recording gauges instead of only three. Importantly, this method is less computationally demanding than kriging methods whilst providing comparable interpolation results; the main difference is that kriging provides a map of the standard error statistic of the gridded rainfall estimates.

### 3.3 Monthly correction procedure

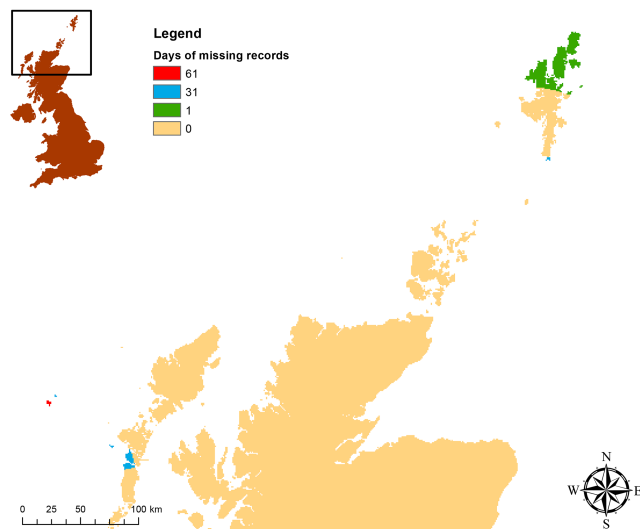
The same interpolation methodology is applied to derive daily and monthly grids. However, the rain gauge network, and therefore data, used may be different: the daily grids are derived based on daily rain gauges only, whereas the monthly



**Figure 6.** Rainfall map showing missing data (in black) (a) on 1 January 1890, (b) on 1 January 1910 and (c) on 1 January 1960.

grids make use of both the monthly rain gauges and the daily rain gauges with complete record for the month. Although the monthly grids may be more reliable, due to a higher amount of gauged data, the consequence is that the gridded monthly estimates and the monthly totals based on daily grid estimates may differ. Thus a correction step was added, after the creation of the monthly grids and the provisional daily grids, to ensure that the monthly sum of daily rainfall depth matches the estimated monthly depth (Fig. 4). For a given month, when all daily grids are estimated from interpolating

the daily rain gauge data (provisional daily grids), these estimates are summed up to provide a monthly estimate from daily data ( $MR_d$ ). For each grid point, this estimate ( $MR_d$ ) is compared with the monthly gridded value ( $MR_m$ ). To ensure that the daily grids and the monthly grids are in agreement, a correction factor  $\frac{MR_m}{MR_d}$  is applied to each daily point estimate for the month.



**Figure 7.** Map of total days of missing records (for daily grids) for the period post-1961 for northern Scotland (no missing records in rest of UK).

### 3.4 Calculation thresholds

The accuracy of the rainfall estimates is affected by the density of the rain gauge network and the distance to the closest rain gauges. For the pre-1961 grids, there was a concern that the lower density of digitised rain gauge data would give rise to unrepresentative estimates in some locations that were a long way from any rain gauge. It was therefore decided not to compute a rainfall estimate when a grid point was more than 100 km from the nearest operational rain gauge. The effect of this threshold varies according to the availability of digitised rain gauge data: for example, out of a total of 244 343 UK grid points, the number of points excluded on 1 January 1890, 1910 and 1960 were respectively 46 394, 20 604 and 34 (Fig. 6a to c). From 1961 onwards, the 100 km threshold has virtually no effect, with only some remote Scottish islands affected on isolated days (Fig. 7). In order to provide users – especially modellers – with the spatial and temporal extent of gaps, two sets of three ancillary grids were produced (one set for monthly data and one for daily data):

- year of the first missing data for each grid point,
- year of the last missing data for each grid point,
- total number of days with missing data for each grid point for the whole period.

The data set also contains, for every day and month, a grid of the distance to the closest operational rain gauge.

## 4 Quality control of the input rainfall data

Causes of error in rain gauge data include hydrometric and meteorological factors (Sect. 2.1), and human factors such as misreading and typing errors. Rainfall observations held in the national database are subject to extensive quality control by both the rain gauge operators and by the Met Office at the point of submission to the archive. A further quality control procedure is applied during the production of the CEH-GEAR data set to identify erroneous rain gauge observations in the daily rainfall input data set. The procedure was designed to further scrutinise exceptionally high rainfall values by comparing the daily measured rainfall with an estimate of the 1-day rainfall with a 200-year return period at the gauge location. This estimate was made using the latest Flood Estimation Handbook rainfall depth–duration–frequency model, which is a development of the model documented in Stewart et al. (2010). For the period 1961–2012, there were 687 observations in GB and 34 in NI that exceeded the 200-year return period rainfall.

For those high rainfall events exceeding the 200-year return period rainfall, a manual investigation was undertaken to identify whether the extreme rainfall recorded was genuine. The identified high rainfall events were cross-referenced with a historical database of extreme events for the UK for the period 1886–2005 published by Svensson et al. (2009). Those events present in the historical extreme events database were considered to be genuine. Then for each of the remaining events, the rain gauge data was investigated using a time series plotter in order to identify likely multiday rainfall accumulations which had not been flagged as such in the historical records. Any high rainfall identified as the result of a multiday accumulation was rejected.

For the remaining events, each selected event was compared with the three nearest rain gauges stations within a radius of 10 km. In instances where the three rain gauges were recording 20 % or more of the investigated rainfall event, the event was classified as genuine. Where significantly lower rainfall depth (< 20 %) was recorded at these neighbouring gauges, the selected rainfall event was considered erroneous and was therefore rejected from the input data set. Where no decision could be made, a manual investigation was required and the number of neighbouring rain gauges investigated increased (up to 10 within a 10 km radius). Where uncertainty remained, the event was classified as genuine, as the recording may be the result of localised rainfall.

## 5 Validation of the method

The suitability of the natural neighbour method as a daily rainfall interpolation procedure for the UK was assessed using measured rainfall data for the period 2007–2010 from the tipping bucket rain gauge network operated by SEPA (Scottish Environment Protection Agency). Scotland was chosen because rainfall interpolation is generally more demanding



there because of the higher spatial variability of rainfall (due to the terrain) and the relatively sparse rain gauge network.

The SEPA tipping bucket network has around 200 rain gauges with a resolution (bucket size) of 0.2 mm and provides 15 min rainfall totals for use in real-time flood forecasting (Cranston et al., 2012). An automated quality control procedure (Howard et al., 2012) has been applied to the data with the aim of removing any major errors that may exist. Simple tests are first performed on each individual rain gauge record before more involved comparisons to neighbours are made. Robust statistics (median and median absolute deviation) form the basis for identifying and removing outliers. To ensure the quality-controlled tipping bucket records provided an independent source of validation data, the tipping bucket rain gauges located at the exact same location as a rain gauge used to derive CEH-GEAR rainfall grids were removed, leaving a validation subset of 138 tipping bucket rain gauges with recorded rainfall values in the period under study (Fig. 8). To give a fairer assessment of the performance of the interpolation procedure, only the days when the tipping bucket was at least 5 km away from any of the daily gauges used to derive the rainfall grids were retained from this subset. This left a total of 75 796 days out of the original 152 812 days with valid records, recorded across 121 tipping buckets.

The accuracy of the daily rainfall estimates was assessed by means of

- Absolute errors ( $\epsilon$ ): absolute value of the difference between the estimated rainfall ( $rc_p$ ) and the observed values at the gauges ( $rc_o$ ):

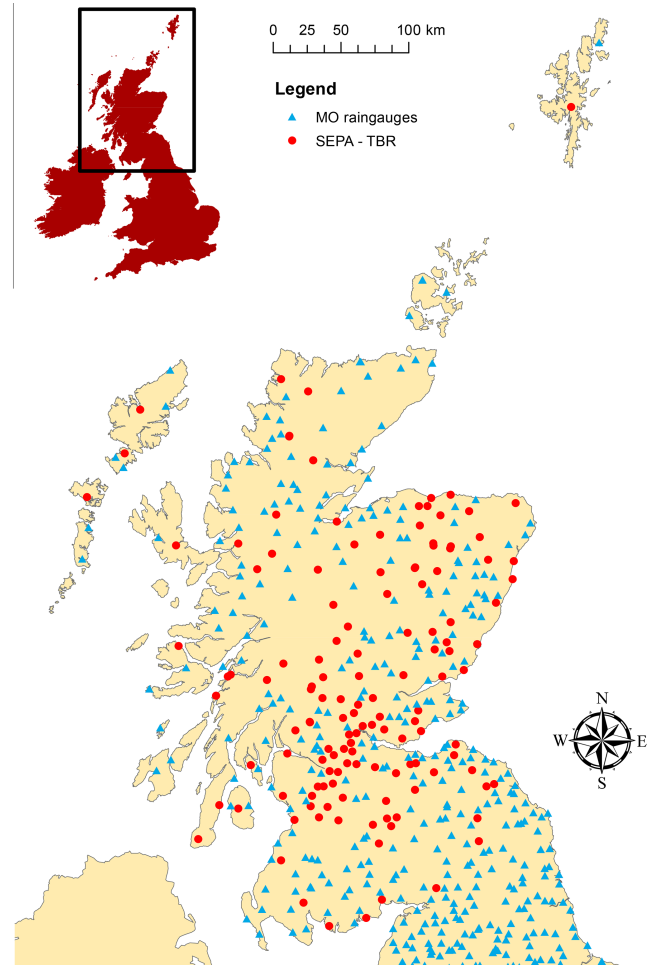
$$\epsilon = |rc_p - rc_o|. \quad (4)$$

- Absolute relative errors ( $\delta$ ): ratio of the absolute error and the observed value, absolute relative errors are only computed where  $rc_o > 0$ :

$$\delta = \left| \frac{rc_p - rc_o}{rc_o} \right|. \quad (5)$$

The repartition of the absolute error  $\epsilon$  (Eq. 4) across several ranges of observed events ( $rc_o$ ) was analysed (Table 1). Overall,  $\epsilon$  is equal to 0 in about 25 % of the cases, and smaller than 0.5 mm in approximately 57 % of the cases: an encouraging result. For smaller events (i.e.  $rc_o < 2$  mm), about 78 % of the absolute errors are  $\leq 0.5$  mm. For increasing levels of observed rainfall, high values of  $\epsilon$  are more frequent, although where  $rc_o \geq 20$  mm (48 % of studied events),  $\epsilon$  is equal or lower than 5 mm: a relatively small error when compared to the observed rainfall. Indeed, results for the relative absolute error ( $\delta$ ) (Table 2) indicate that although for events of higher intensities  $\epsilon$  can be quite high, these are still relatively small compared to the actual observed values (low values of  $\delta$ ).

An important influence on the quality of the estimate in the natural neighbour method is the representativeness of the



**Figure 8.** Map of SEPA tipping bucket rain gauges (TBR) used for validation purposes (red circles) and Met Office (MO) rain gauges network (blue triangles). The MO rain gauges are represented on the map only if they have data available for at least 50 % of the days between 2007–2010 (validation period).

nearby gauges and the density of the rain gauge network in the vicinity of the interpolated point. To assess the potential influence on the estimation procedure of the proximity of the closest gauge to the estimation target, the relationship between the distance to the closest gauge and the absolute relative error is assessed on all the available SEPA tipping bucket stations. The distance to the closest gauge is used as a simple indicator of the network density, although the number of gauges used in the estimation, the average distance and other network characteristics are also likely to have an effect. To give a full representation of the likely distances to the closest gauge used in CEH-GEAR, all available days for all 138 tipping bucket stations were used in this analysis, including those within 5 km of a daily or monthly gauge. For each available day, the distance to the closest gauge used in the interpolation procedure is used and the absolute relative error  $\epsilon$  is calculated. The relationship between the distance

**Table 1.** Repartition (%) of the absolute errors ( $\epsilon$  (mm), Eq. 4) across different ranges of observed rainfall ( $rc_o$ ) events for the observed data of the Scottish validation gauges, in which days were only retained when the tipping bucket was at least 5 km away from any of the daily gauges used to derive the rainfall grids.

Range of $rc_o$	Number $rc_o$	$\epsilon = 0$	$0 < \epsilon \leq 0.5$	$0.5 < \epsilon \leq 2$	$2 < \epsilon \leq 5$	$5 < \epsilon \leq 10$	$\epsilon > 10$
$rc_o \geq 0$	75 796	25.4	31.5	23.8	12.6	4.6	2.0
$rc_o > 0$	47 944	4.1	35.3	33.9	18.2	6.2	2.3
$0 \leq rc_o < 2$	48 593	38.7	39.0	15.5	4.0	1.6	1.3
$2 \leq rc_o < 5$	10 662	2.4	26.2	48.7	19.0	2.9	0.8
$5 \leq rc_o < 10$	8367	1.8	16.1	39.7	33.6	8.0	0.8
$10 \leq rc_o < 20$	6019	1.1	11.4	28.2	36.2	18.4	4.6
$rc_o \geq 20$	2155	0.5	5.1	14.1	28.4	29.0	22.8
$rc_o \geq 50$	96	1	1	2.1	10.4	22.9	62.5

**Table 2.** Repartition (%) of the absolute relative errors ( $\delta$ , Eq. 5) across different ranges of observed rainfall ( $rc_o$ ) events for the observed data of the Scottish validation gauges, in which days were only retained when the tipping bucket was at least 5 km away from any of the daily gauges used to derive the rainfall grids.

Range of $rc_o$	Number $rc_o$	$\delta = 0$	$0 < \delta \leq 0.3$	$0.3 < \delta \leq 0.6$	$0.6 < \delta \leq 1$	$1 < \delta \leq 2$	$2 < \delta$
$rc_o > 0$	47 944	4.1	38.4	25.3	19.5	6.1	6.6
$0 < rc_o < 2$	20 741	7.2	16.5	23.6	29.0	9.8	13.9
$2 \leq rc_o < 5$	10 662	2.4	43.8	27.9	17.3	6.2	2.3
$5 \leq rc_o < 10$	8367	1.8	57.1	27.8	11.1	2.0	0.3
$10 \leq rc_o < 20$	6019	1.1	67.1	23.8	7.2	0.7	0.0
$rc_o \geq 20$	2155	0.5	69.8	24.4	5.2	0.1	0.0
$rc_o \geq 50$	96	1	55.2	32.3	11.5	0.0	0.0

to the closest gauge and the smoothed median absolute error is shown in Fig. 9. The red line in the figure represents a smoothed estimate of the median function of the absolute relative error obtained by quantile regression: this is an indication of the overall behaviour of the estimation for the different rainfall classes. The median increases as the distance to the closest gauge used in the interpolation increases.

The monthly correction procedure (Sect. 3.3) is necessary to ensure the monthly sum of daily estimated rainfall depths and the estimated monthly grids match. Nevertheless, it is preferable that such adjustments have a minimal impact on the daily estimates. For the same Scottish validation gauges used in Table 1, the absolute difference ( $\varphi$ ) between the final estimates ( $\text{est}_{\text{mc}}$ ) including the monthly correction and the provisional estimates ( $\text{est}_{\text{pr}}$ ) (Fig. 4) obtained from the interpolation of the observed daily measurements is calculated:

$$\varphi = |\text{est}_{\text{mc}} - \text{est}_{\text{pr}}|. \quad (6)$$

Overall, for more than 90 % of the cases,  $\varphi$  is less than or equal to 0.5 mm (Table 3): the largest proportion of large differences occurs for higher rainfall events, where a difference larger than 5 mm remains relatively small.

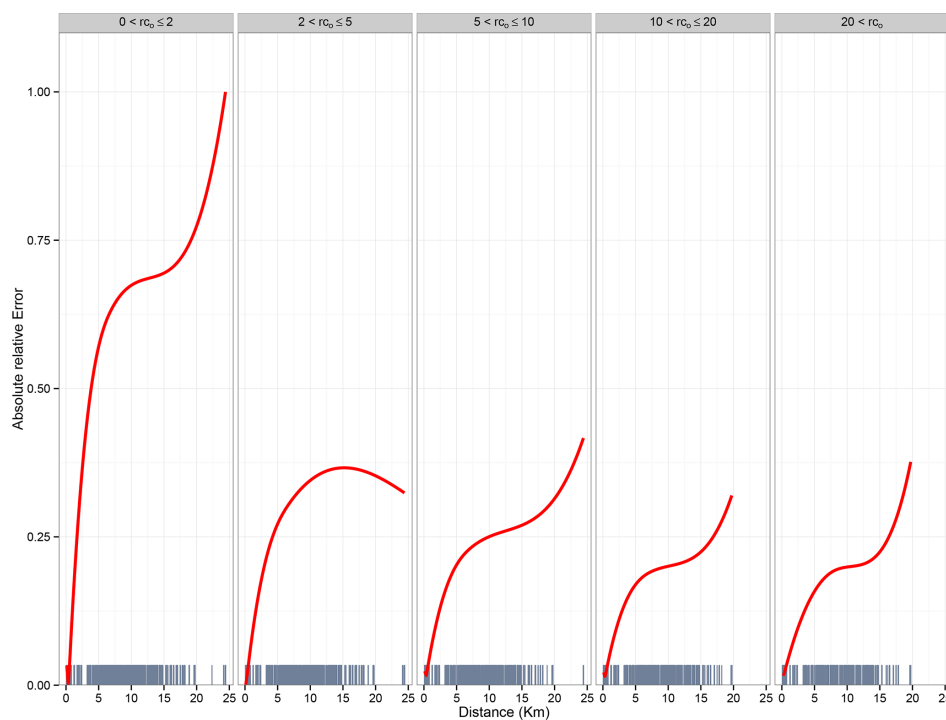
## 6 Limitations and recommendations

The CEH-GEAR data set is derived from daily and monthly rain gauge data using the natural neighbour interpolation method combined with a normalisation step based on AAR. As such, the quality of the rainfall estimates are highly dependent on the accuracy of the rain gauge data, hence the need for quality control of the input data. The quality control procedure focussed on high daily rainfall events and identified a set of recorded events that resulted from a multiday accumulation and therefore were discarded from the input data set. Although measures are in place to flag erroneous rain gauge data, some erroneous data may still remain in the underlying data. However, the Met Office national database of rain gauge observations (UK Meteorological Office, 2014) remains the most appropriate and abundant source of rainfall observation from which to derive gridded time series of daily and monthly rainfall in the UK.

It should be noted that highly localised convective storms, which can lead to flash flood events, in areas with low rain gauge density are unlikely to be accurately represented within CEH-GEAR if no rain gauge was operational nearby. Therefore, the use of CEH-GEAR is more suited to larger-scale studies such as catchment water balances or distributed modelling across the country/large regions, especially in areas with low rain gauge density.

**Table 3.** Repartition (%) of the difference in absolute relative errors (Eq. 7) between the monthly corrected estimates and the standard estimates across different range of observed rainfall ( $rc_o$ ) events for the observed data of the Scottish validation data, in which days were only retained when the tipping bucket was at least 5 km away from any of the daily gauges used to derive the rainfall grids.

Range of $rc_o$	Number of events	$\varphi = 0$	$0 < \varphi \leq 0.2$	$0.2 < \varphi \leq 0.5$	$0.5 < \varphi \leq 1$	$1 < \varphi \leq 5$	$\varphi > 5$
$rc_o \geq 0$	75 796	56.6	29.4	6.5	3.9	3.4	0.2
$rc_o > 0$	47944	43.0	37.0	9.4	5.6	4.7	0.3
$0 \leq rc_o < 2$	48 593	69.8	25.8	2.4	1.0	0.8	0.1
$2 \leq rc_o < 5$	10 662	40.1	41.9	11.2	4.7	2.0	0.1
$5 \leq rc_o < 10$	8367	31.5	36.5	15.7	9.9	6.3	0.1
$10 \leq rc_o < 20$	6019	26.9	29.1	16.6	13.0	13.8	0.6
$rc_o \geq 20$	2155	20.8	21.5	12.4	14.6	26.7	4.0
$rc_o \geq 50$	96	15.6	11.5	6.2	10.4	41.7	14.6



**Figure 9.** Median absolute relative error represented as a function of the distance to the closest rain gauge for different observed rainfall event ranges. The grey lines along the  $x$  axis indicate the distance between the tipping bucket and the closest rain gauge used in the estimation procedure. Analysis carried out on the full Scottish validation data (138 tipping bucket rain gauges) including the days when the tipping bucket was at less than 5 km away from the daily gauges used to derive the rainfall grids.

The density of the rain gauge network in the vicinity of a grid point is also an important factor when assessing the quality of the rainfall estimates (Sect. 5). Only a fraction of the pre-1961 rain gauge data is available in digital form (Sect. 2.1); digitising the rest of the data would improve considerably the CEH-GEAR rainfall estimates for the period 1890–1960.

Further research on the spatial and temporal variation of the errors in CEH-GEAR data set is needed to quantify the uncertainty in rainfall estimates. High errors are expected in the North and West of the UK where much of the heavy

rainfall is due to orographic enhancement during periods of frontal or pre-frontal rainfall because the enhancement varies rapidly with altitude, whereas in the South and East of the UK, where the terrain is flatter, the errors are likely to be higher for localised convective storms rather than for frontal systems. Therefore, the effect of network density and the consequent uncertainty will vary spatially and temporally and is potentially quite complex to estimate.

The validation and analysis on the effect of network density described in Sect. 5 gives the reader an indication of the magnitudes of the errors and how the distance to the clos-

est gauge affects the error. This information, together with the minimum distance grids provided with the rainfall grids, gives users the tools to decide if parts of the CEH-GEAR estimates are suitable for their needs. For example, Fig. 9 shows that for rainfall observations greater than 5 mm, the median relative error has an inflexion point at around 15 km from which the error starts increasing rapidly with the distance to the closest gauge. Therefore, for some applications, the use of rainfall estimates at a point where the distance to the closest gauge is greater than 15 km may warrant further analysis.

## 7 Data access and terms of use

The Centre for Ecology & Hydrology – Gridded Estimates of Areal Rainfall (CEH-GEAR) data set is available from <http://doi.org/10.5285/5dc179dc-f692-49ba-9326-a6893a503f6e>. The data will be hosted on a THREDDS server managed by CEH-Lancaster. The following citation should be used for every use of the data:

Tanguy, M., Dixon, H., Prosdociimi, I., Morris, D. G., Keller, V. D. J. (2014). Gridded estimates of daily and monthly areal rainfall for the United Kingdom (1890–2012) [CEH-GEAR]. NERC-Environmental Information Data Centre doi:10.5285/5dc179dc-f692-49ba-9326-a6893a503f6e

The data set is available for download free of charge from the CEH Information Gateway. Licence terms apply.

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