Extreme Precipitation Analysis at Sizewell: Final Report

For - EDF

Date – February 2011

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Executive Summary

- 1 in 100, 1,000 and 10,000 year rainfall amounts for winter and summer have been estimated for Sizewell using a combination of observed and modelled rainfall amounts. The 10,000 year baseline estimates are slightly in excess of the range of Probable Maximum Precipitation (PMP) estimated for Sizewell which was estimated using three different methods (these do not account for climate change). The results of the analysis are summarised in the tables below.

- The climate change factors calculated were applied to the baseline 100, 1,000 and 10,000 year rainfall amounts for Sizewell estimated using the Flood Estimation Handbook. These estimates were compared against results from extreme value analysis of local rain gauge data and were found to be reasonable for the location.

Return Period (years)	Storm Duration	Baseline rainfall estimates (mm)	Winter estimates adj. for climate change (mm)	Summer estimates adj. for climate change (mm)
10,000	15 minutes	177.9	175.8 – 212.8	148.1 – 206.7
	1 hour	211.0	208.1 – 260.2	169.1 – 251.5
	1 day	307.9	301.7 – 412.6	218.6 – 394.1
1,000	15 minutes	82.2	81.8 – 95.4	70.9 – 92.7
	1 hour	103.6	103.0 – 124.6	85.7 – 120.3
	1 day	173.7	172.0 – 232.8	123.3 – 220.6
100	15 minutes	37.9	37.9 – 43.0	33.9 – 41.7
	1 hour	50.8	50.8 – 60.0	43.7 – 57.7
	1 day	97.9	97.9 – 132.2	71.5 – 123.4

Storm Duration	Range of PMP estimates (mm)
15 minutes	102 – 153
1 hour	180 – 181
1 day	256 - 290

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- Modelled daily precipitation amounts from the 11 member regional climate model ensemble, which were released alongside the UKCP09 climate projections, have been analysed.

- All members bar one projected an increase in extreme rainfall in winter, whereas changes in extreme summer rainfall are much less certain.

- To determine the climate change factors an approach was adopted to minimise the effects of natural variability inherent in each member. Extreme value distributions were fitted to multiple samples of the input data, which were sampled in 10 year blocks with replacement (a process known as bootstrapping). The sampled extreme value parameters were then averaged for each grid box which reduced the spatial variability to a large degree but not completely. Next, the extreme distribution parameter that expressed the climate change signal (i.e. that which depends on global temperature) was averaged over a large area. Here, only the scale parameter is assumed to change with global mean temperature. This parameter was averaged over an area of England and Wales between the Humber Estuary and London, Sizewell falling at the centre (in the north-south direction).

- There remains a large spread in the projected extreme precipitation amounts in the 11 member model ensemble, and so these results should be used with caution.

- The ensemble has been generated using the latest science available for extreme value analysis, but some of this science is still being developed and evaluated.

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1. Introduction

The aim of this study is to determine 1 in 100, 1 in 1000 and 1 in 10000 year daily and sub-daily extreme precipitation amounts at Sizewell including the effects of climate change. The Met Office has successfully completed a similar analysis for Hinkley Point (Met Office, 2010). As with Hinkley Point the study for Sizewell has been split into two phases. Phase 1 involved the estimation of the baseline extreme rainfall at Sizewell and an investigation into the ability of the Regional Climate Model (RCM) to reproduce these estimates. For Phase 2, climate change factors using RCM data were derived which will be applied to the baseline estimates to produce new estimates of extreme precipitation for a number of time periods between 2010 and 2099. An estimation of Probable Maximum Precipitation (PMP) has also been undertaken for Sizewell in order to confirm the validity of the derived rainfall estimates.

1.1 Sizewell power station

Sizewell power station is located in East Anglia on the east coast of Suffolk at approximately 647250E and 263500N (British National Grid Reference (NGR); see Figure 1). The site is 35 km east-north-east of Ipswich, 100 km east of Cambridge and 55 km south-south-east of Norwich. The nearest town, Leiston, is less than 3 km west-south-west. The altitude of the site ranges from sea-level to about 10 metres, and even further inland the area remains relatively flat with an altitude not much above 60 metres. Beyond Wattisham to the west lie the East Anglia Heights, an extension of the Chiltern Hills, and the highest area of ground in the region with an altitude in excess of 100 metres. Compared to the rest of the British Isles East Anglia receives very low annual average rainfall, being shielded by high ground in the west from the passage of Atlantic depressions, which are the main cause of rainfall in the UK though the winter. The monthly rainfall cycle is relatively flat compared with other areas of the UK due to the relatively high incidence of summer convective rainfall in the area. The Sizewell site itself receives, on average, less than 600 mm of rainfall per year.

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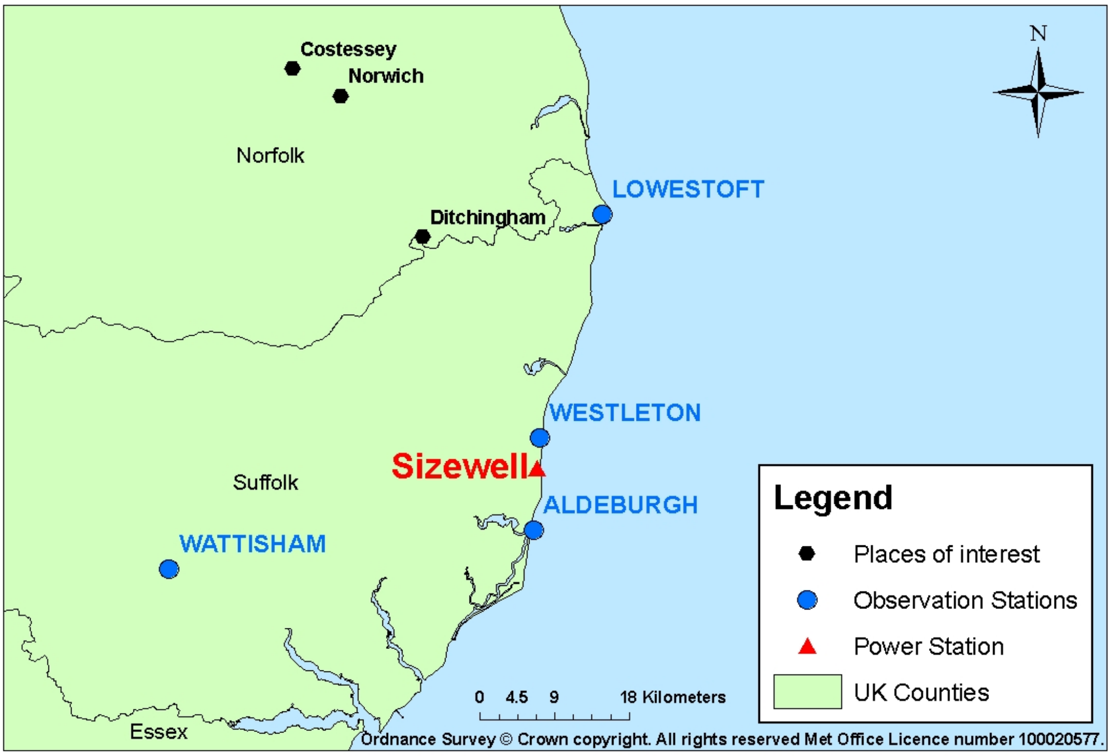

Figure 1. Sizewell power station and surrounding meteorological observation stations

1.2 Recent trends in climate at Sizewell

Jenkins et al. (2008) have analysed changes in temperature and rainfall for the UK in each of the four seasons. They divided the UK into a number of areas, and Sizewell lies within the "East of England" area, which includes both Norfolk and Suffolk. The following climate data are for this area. Between 1961 and 2006 daily maximum temperatures have risen by over 2°C in summer and winter, by 1.7°C in spring, and by 1.2°C in autumn. The changes in daily minimum temperatures are slightly smaller. In summer and autumn they have risen by 1.6°C and 1.8°C respectively and by 1.3°C in spring and autumn.

The number of days of rain (where daily rainfall is greater than or equal to 1 mm) between 1961 and 2006 have fallen by nearly 3 days during spring, but increased by 3 days in autumn. In summer, the number of days with rain has hardly changed (falling by less than 1 day), whereas in winter the number of days has increased by 2. However, none of these changes are significant at the 5% level.

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Overall, temperatures have risen in the East of England area and the number of days with rain per year has increased slightly. These trends in temperature and rainfall only refer to seasonal average changes. Extremes of temperature and rainfall may increase at a greater or slower rate. Any changes at Sizewell itself are likely to be modified from those for the east of England owing to its coastal location.

2. Methodology

The basic methodology applied in this study to calculate extreme rainfall amounts at a given location, and how they may change into the future, is as follows. First, estimates of extreme rainfall amounts for the return periods of interest are calculated using the Flood Estimation Handbook, a software based tool used in flood studies. These estimates are then checked by Extreme Value Analysis (EVA) of local rain gauge observations. Secondly, climate model data are analysed using EVA to calculate extreme rainfall amounts for the current climate (called the baseline), and the future periods of interest. The current climate is defined as 1961-1990, and the future periods are overlapping 30 year periods, 2010-2039, 2020-2049, ... 2070-2099. These time periods are used in the UKCP09 climate projections (Murphy et al., 2009). The extreme rainfall amounts calculated for the future periods are divided by the rainfall amounts for the baseline to calculate climate change factors. Finally, the extreme rainfall amounts calculated from observed rainfall data are multiplied by the climate change factors to obtain the future extreme rainfall estimates. Climate models are not perfect and may contain biases (i.e. rainfall at a given location may generally be higher or lower than is observed). The climate model data are used in this way to reduce the impact of any biases.

2.1 Flood Estimation Handbook method

The Flood Estimation Handbook (FEH) was developed by the Centre of Ecology and Hydrology (CEH) to provide a consistent approach to flood studies in the UK and is recommended by the Environment Agency as such. The accompanying software includes a rainfall Depth-Duration-Frequency (DDF) model which has been generated using EVA, similar to those techniques described in Section 2.1.2 below, from a historic archive of rain gauge records for the UK. This allows the estimation of a rainfall depth for a given return period and rainfall duration for any location in the UK. More information

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regarding the methods used in FEH can be obtained by consulting Appendix 10.1, the Met Office report "Extreme Precipitation at Hinkley Point – Final Report" (Met Office, 2010) or Volumes I-V of the FEH (Bayliss, 1999, Faulkner, 1999, Houghton-Carr, 1999, Reed, 1999 and Robson and Reed, 1999).

2.2 Extreme Value Analysis

When analysing the frequency and severity of extreme events, one of two main methods is usually used; either a cumulative frequency analysis or an Extreme Value Analysis (EVA). In the first method, the data (for example, daily rainfall measurements) are used to construct a cumulative frequency distribution, and an extreme event could be defined, for example, as any event where the measured value falls in the top 5% of rainfall values in the distribution. However there are several limitations to this approach: it is impossible to estimate the probability of an extreme event of greater magnitude than the maximum in the data series; the threshold used to identify an extreme event is also fairly arbitrary therefore the number and frequency of extreme events obtained from a cumulative frequency distribution is likely to be strongly dependent on the choice of threshold. The second method is Extreme Value Analysis (EVA) and is less constrained by these limitations and therefore is the preferred methodology used in this study.

EVA is a statistical method that can be used to estimate the probability and severity of events that are more extreme than any that exist in a given data series. EVA may be used to estimate the probability and severity of future events based on a limited set of data. For example, a 30 year observation record could be used to estimate extreme events over the next 100 years (Coles, 2001). By fitting an appropriate statistical distribution to a set of environmental observations the distribution can be extrapolated beyond the length of observations. However it is important to remember that the uncertainty in the projected extreme events will increase as the return period approaches the length of data available, and increases still further as the return period exceeds the length of the data series.

There are many different statistical models or distributions which can be used in EVA. Three statistical distributions have been applied to the data in this study: the Gumbel distribution, a three-parameter generalised extreme value (GEV) distribution and the Marked Point Process (MPP) distribution.

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These distributions are described by three parameters; location, scale and shape (μ, σ and ξ respectively). An example of an EVA curve fitted to some extreme temperature data, together with the effect of altering each of the location, scale and shape parameters, is given in Figure 2 (reproduced from Brown et al, 2008).

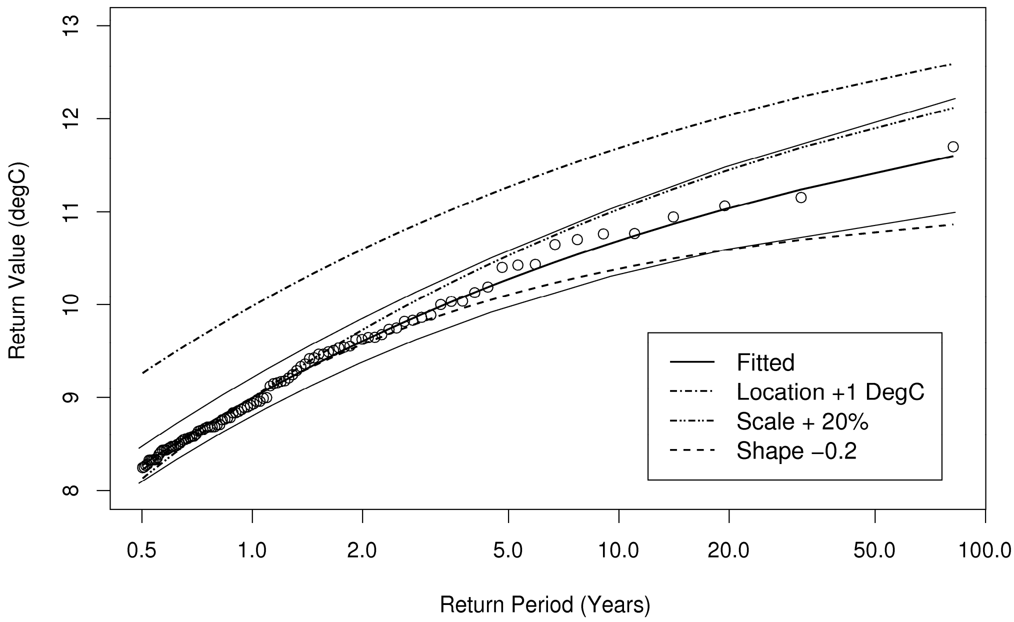

Figure 2. Return level curve derived from fitting a marked point process to the extreme (>98.5%) daily maximum temperature for the grid box containing London. Circles represent return levels derived from the data, the solid black line is the fitted values using the derived MPP distribution with associated 5-95% confidence intervals (lighter solid lines). Non-solid lines represent return-level curves where the distribution parameters are adjusted as described in the legend. Reproduced from Brown et al. (2008).

The thick solid line shows the fitted curve and the two thin solid lines the parametric uncertainty estimates. Increasing the location parameter moves the whole curve up the y-axis but does not change its shape. Increasing the scale parameter effectively rotates the curve about a point, changing the rate at which extreme values will change with increasing return period, but also does not change the shape of the curve. Reducing the shape parameter increases the degree of curvature, which, in the example shown in Figure 2, means that extreme values at larger return periods (e.g. 1,000 years) will only be slightly greater than those for a 100 year return period.

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The Gumbel and three-parameter GEV distributions are commonly applied to series of Annual Maxima (AMAX) data i.e. the maximum 24 hour observation from a full year of daily records. However, whereas the shape parameter may vary using the three-parameter GEV, the shape parameter is assumed to be zero when using the Gumbel distribution; therefore the fitted line through the observations is linear. The AMAX observations are ranked and plotted against the Gumbel reduced variate. The model fit is used to calculate rainfall depths of interest for a given reduced variate, the values of which correspond to the return periods given in Table 1.

Return Period (years)	Reduced Variate
1 in 5	1.5
1 in 10	2.3
1 in 100	4.6
1 in 1,000	6.9
1 in 10,000	9.2

Table 1. Values of reduced variate for each return period

The AMAX approach is limited by the amount of data available for analysis. Then MPP distribution applies a threshold to the complete series of observations and everything above this threshold is considered to describe extremes. This dramatically increases the amount of data available to fit the distribution to. The MPP distribution has two components: a Poisson process which models how many times the extreme threshold is exceeded and a Generalized Pareto distribution which models the amount by which the threshold is exceeded.

Before fitting the MPP distributions, it is necessary to define a threshold that classifies events as extreme. The threshold used for analysis of rainfall observations in this study may be different to that used for the analysis of the regional climate model data, because 150 years of data are available from the model, whereas only (roughly) 40 years of observations are available. A number of different thresholds are used (e.g., the 95^{th} – 99^{th} percentiles of the data to be analysed) and the quality of the fit of the EVA model to the data is tested using three different methods. This approach allows the best threshold choice to be found.

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When fitting MPP distributions the data are usually assumed to be independent and stationary. The latter term means that the mean of the distribution doesn't change in a systematic way with time (i.e. there is no trend in the data). With climate change this assumption may not be true. However, the MPP distribution can be used with non-stationary data by allowing one or more of the three MPP parameters (location, scale and shape) to depend on a climate variable which changes with time (Kharin and Zweirs, 2005). The threshold used to define extreme events will also change with time, to ensure the same proportion of events are analysed for all time periods. If this were not done, a greater number of events could be classed as extremes with increasing time and the EVA fit to the data would be erroneous. The modified versions of the three parameters are given below:

Equations 1, 2 and 3

$$\mu = \mu_0 + \mu_t C(t) \qquad \sigma = \exp[\sigma_0 + \sigma_t C(t)] \qquad \xi = \xi_0 + \xi_t C(t)$$

C(t) represents a climate variable which changes with time, and is called the covariate. In this work, the covariate is global mean temperature. Precipitation is known to increase as temperatures rise (because warmer air can hold more moisture), and so temperature is a suitable covariate for this work. Any non-stationarity in the MPP parameters is found by fitting the MPP model, and allowing one or more of the MPP parameters to change with the covariate. This is done in a hierarchical manner. First, all three parameters are assumed to be invariant with time. Next, just the location parameter is allowed to change with the covariate, then just the shape parameter, and then the location and shape parameters together, followed by all three parameters changing with the covariate. The quality of fit of the EVA model to the data in each case is calculated, and the best version identified.

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3. Data sources

Three main sources of data have been used in this study. First, rainfall measurements from the UK rain gauge network which are close to Sizewell and have similar site characteristics were obtained. A literature review of the highest recorded rainfall amounts close to Sizewell was carried out, as these events may not have been recorded at the sites identified previously. Secondly, daily rainfall data on a regular 5 km and 25 km grid, which were created by the National Climate Information Centre (NCIC; see also Perry and Hollis, 2005) were obtained. The third data source is the daily rainfall data from the 11 member regional climate model ensemble which were released alongside the UKCP09 projections (Murphy et al., 2009). These data sets are described in more detail in the following sections.

3.1 Rainfall measurements from the UK rain gauge network

A search was undertaken to find the most representative rain gauge records in the vicinity of Sizewell. As rainfall tends to increase with altitude over land, it is important that the altitude of each observation site is similar to the study site. Three suitable rain gauges were identified: Aldeburgh, Lowestoft and Westleton, which all record daily rainfall. Although some data are available at intervals of 3 hours at Aldeburgh it is of insufficient length to use in any analysis. No other representative rain gauges in the region record data at a sub-daily resolution. The locations of these gauges in relation to the existing power station at Sizewell are shown in Figure 1 and details of each site are given in Table 2.

Name	Distance from Sizewell (km)	Record length (years)	Easting (m)	Northing (m)	Altitude (m, AOD)
Aldeburgh	7.3	20	646600	256000	7
Lowestoft	33.0	73	654300	294600	25
Westleton	4.5	21	647241	267200	10

Table 2. Details of rainfall observation stations near to Sizewell (AOD: above ordnance datum)

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The daily time series from each site has been checked for missing data. To construct a time series of annual 24 hour maximum rainfall (AMAX) it is important that each year of the records is sufficiently complete so that the largest rainfall totals are likely to have been captured and to prevent seasonal bias. In this study, where more than 3 months of data were missing from any year, those years were excluded from the final AMAX record, though some expert judgement has been applied where appropriate. For example, 2002 in the Lowestoft record had a missing period of 3 months. However, it was decided to retain the data for 2002 as the 4th largest daily rainfall value in this record was recorded in October 2002, and during the missing period no notable rainfall events were recorded according to rainfall archives held by the National Climate Information Centre (NCIC) at the Met Office.

The final length of each record following this quality assessment is shown in Table 2. For each year the highest daily rainfall amount was found and an AMAX series compiled for each station (shown in Figures 2-4). The time periods which each record spans are shown below.

- Aldeburgh, 1965 – 1986 (Figure 3)
- Lowestoft, 1931 – 2003 (Figure 4)
- Westleton, 1989 – 2009 (Figure 5)

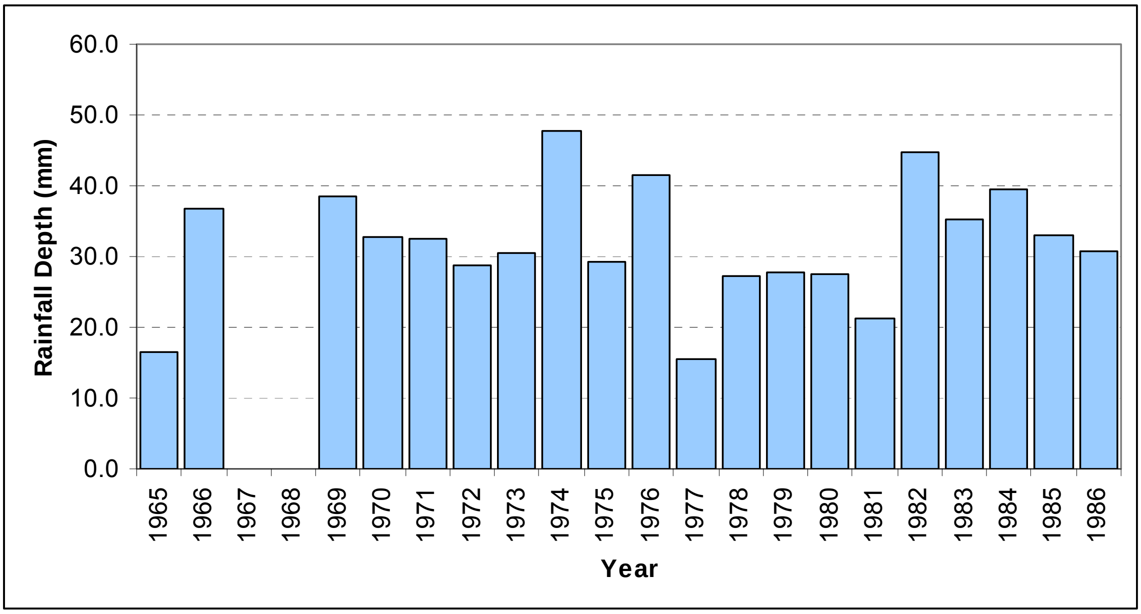

Figure 3. AMAX series of daily rainfall at Aldeburgh

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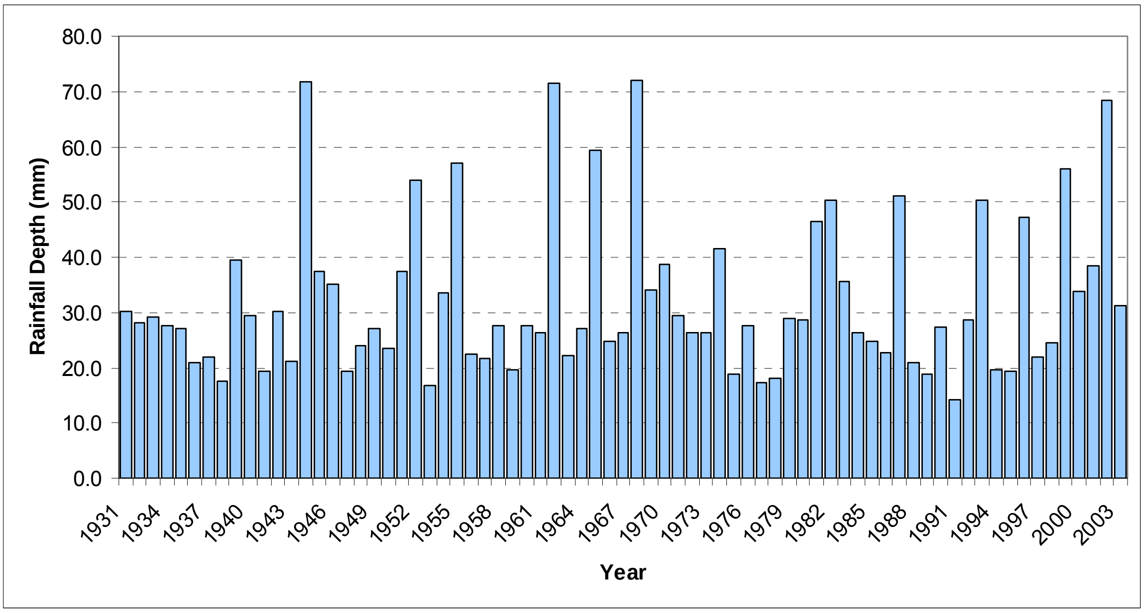

Figure 4. AMAX series of daily rainfall at Lowestoft

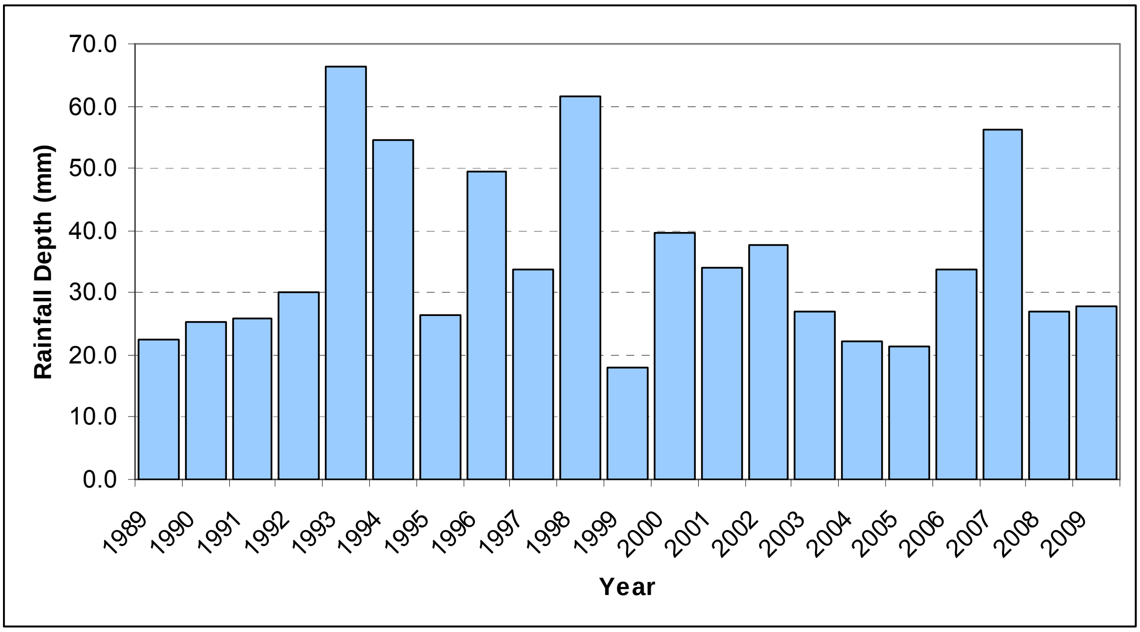

Figure 5. AMAX series of daily rainfall at Westleton

The largest recorded daily total at any of the stations is at Lowestoft in 1968 where a total of 72.1 mm was recorded (Figure 4). Three very similar amounts were recorded in 1944, 1962 and 2002 of 71.7, 71.4 and 68.3 mm respectively. It is perhaps unusual that the largest four rainfall totals in a series are so similar; however there is no reason in this instance to doubt the provenance of these values. Such large totals are not recorded at the other two sites, which given their length, is not unexpected. The maximum rainfall

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depths recorded at Aldeburgh and Westleton are 47.8 and 66.4 mm respectively. The larger rainfall totals, whilst significant, are not characteristic of extreme rainfall events which occur in the British Isles which may typically exceed 100 mm in 24 hours. These rainfall data have been recorded over a fixed 24 hour period (0900 to 0900 GMT). It is necessary to adjust the values so that the true 24 hour maximum rainfall values are used (since rainfall can occur in any 24 hour period). This procedure is described later in section 4.1.2.

3.2 Literature review of exceptional rainfall events near Sizewell

One of the most exceptional rainfall events in the UK, not covered by the observational period of any of Aldeburgh, Lowestoft and Westleton, occurred during August 1912 in East Anglia. An account of this event is provided by Mill in British Rainfall (Mill, 1913). Between 25th and 26th August, a trough was situated over the southern half of Britain and had been for several days. A secondary depression is thought to have formed late on 25th becoming a well developed small depression over the east of Kent during the morning of 26th. This subsequently moved northwards at around 20 mph reaching the northern tip of Norfolk by 6 pm. Hand et al. (2004) report that a rainfall depth of 186 mm fell in Norwich over 22 hours during this storm and in the Flood Studies Report (FSR) (Volume II, NERC, 1975) it is estimated that 210 mm fell in 48 hours. An isohyet map of the areal rainfall over 48 hours is shown in Figure 6. The darkest purple colour marks the extent of the area where rainfall in excess of 203.2 mm (8 inches) fell over the two days (though the majority was recorded on 26th) just east of Norwich (Mill, 1913).

Another notable event was recorded by Jackson (1974) where, during the morning of 1st August 1972 approximately 137 mm fell in around 3 hours at Costessey near Norwich. The 2-hour total for this storm is estimated to have been 114 mm. A more recent significant rainfall event occurred on 25th September 1994, when 147 mm was recorded at Ditchingham over a duration of only a few hours. The storm caused significant flooding and disruption to the transport infrastructure in the local area.

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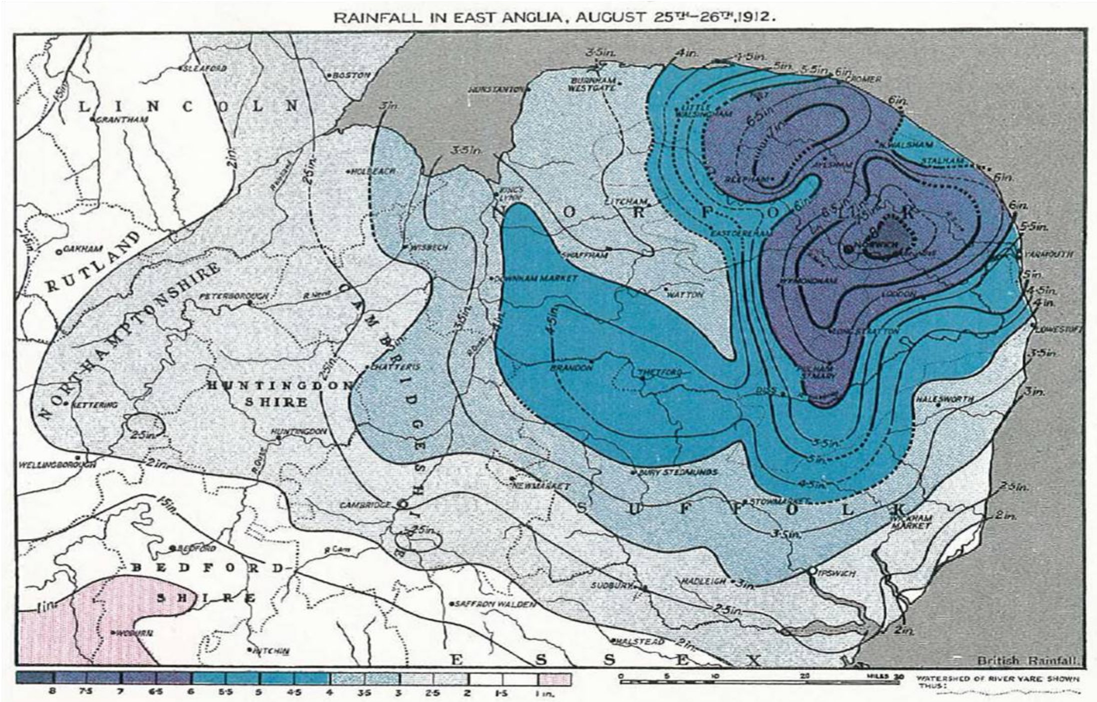

Figure 6. Rainfall isohyet map for the period 25-26th August 1912 for East Anglia (note rainfall values are in inches). The purple colour indicates areas where the rainfall depth exceeded 6 inches (152.4 mm), and the darkest area next to Norwich where the depth was greater than 8 inches (203.2 mm). Reproduced from Mill (1913).

These historic storms demonstrate the potential short-comings of using rain gauge records to estimate rainfall for very high return periods and that rainfall totals well in excess of those in each of the AMAX records are physically possible in this region of the UK.

3.3 National Climate Information Centre gridded daily rainfall data

The National Climate Information Centre (NCIC) have produced a dataset which contains gridded daily rainfall data at a resolution of 5 km (Perry and Hollis, 2005). In this dataset, rainfall data are available at every land point in the UK, and it is available freely for use with the UKCP09 climate projections. The NCIC gridded data were generated using the irregularly spaced rain gauge data and a regression model which accounts for the many parameters which could influence local rainfall amounts, such as altitude, distance from the coast, local topography, and urbanisation. Gridded daily rainfall data from 1958 to 2007 have been created, and these data have also been aggregated from the 5 km NCIC grid to the same 25 km grid used by the regional climate model

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(described in section 3.4). This time series of daily rainfall data has been used in Section 5 to compare with the RCM simulations.

3.4 Regional Climate Model simulations

Climate models are, in essence, a mathematical representation of the atmosphere, oceans and land surface and contain many equations based on physical principles. Our knowledge of all the different processes which occur within these three components is incomplete, and, owing to the finite resolution of the model, some key processes cannot be represented explicitly. For example, the flow of air upwards and over hills, convection and cloud formation, are important for modelling of rainfall, and take place at spatial scales smaller than the model resolution. They must be estimated using relationships with variables such as wind, temperature and humidity calculated at the scale of the model (here, 25 km). These relationships are called parameterisations. The nature of the equations used in the model mean that values for many parameters must be specified. Precise values for some parameters are difficult to obtain, and so their exact values are uncertain.

In order to explore the impacts of these uncertain parameters on the modelled climate, 16 global climate model simulations (collectively called an ensemble) were generated in which many of these uncertain parameters were changed slightly from their standard values. An additional simulation where all parameters had their standard values was also run. Further details are given by Collins et al. (2006, 2010). This set of 17 global climate simulations were used to provide boundary conditions for 17 RCM simulations of the present and future climate of the UK. Each RCM had the same set of parameter values as the global model used to provide the boundary conditions. However, an analysis of the RCM climates showed that the simulations of storms and precipitation in 6 of the RCMs were unacceptable (Murphy et al., 2009, Chapter 5), and so only climate data from the remaining 11 RCM simulations were analysed further. The climate projections from these simulations are referred to as the 11-member RCM ensemble, and were released alongside the UKCP09 climate projections. They were generated using a medium emissions scenario (A1B; IPCC, 2000). The UKCP09 projections also show results using a high (A1FI) and low (B1) emissions scenarios, but raw model data for these latter scenarios are not available. Daily rainfall data are available from each of

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the 11 versions of the RCM for the period 1950 – 2099, and will be used in the analysis in Sections 5 and 6.

4. Estimates of extreme precipitation for the current climate at Sizewell

To estimate how climate change may modify extreme rainfall at Sizewell, it is first necessary to identify the current day baseline rainfall conditions at the site. The FEH has been used to provide these and EVA of the daily rain gauge records described previously used to check the FEH estimates.

4.1 Flood Estimation Handbook estimates

The rainfall estimates extracted from the FEH for Sizewell (NGR 647200E and 263000N) are shown in Table 3. Rainfall amounts increase with both return period and the duration of an event. According to these estimates rainfall amounts could be as high as 178 mm in 15 minutes and 308 mm in 24 hours for the 1 in 10,000 year event. The guidance which accompanies the FEH-CDROM advises against deriving estimates for return periods in excess of 2000 years and for rainfall durations less than 30 minutes or longer than 16 days. This is because the estimates are extrapolations beyond the base rainfall data used to construct the DDF model and its calibration. Therefore the uncertainty associated with these estimates is higher and the results should be applied with caution.

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Return period/ duration	Point rainfall estimates (mm)		
	15-minute	1-hour	Daily
1 in 2 years	9.2	13.7	34.2
1 in 5 years	13.4	19.5	45.3
1 in 10 years	17.2	24.6	54.6
1 in 100 years	37.9	50.8	97.9
1 in 1,000 years	82.2	103.6	173.7
1 in 10,000 years	177.9	211.0	307.9

Table 3. FEH rainfall return period estimates for Sizewell (obtained using AMAX records, at a point location for a sliding duration[1])

4.2 Extreme Value Analysis at Lowestoft

The rain gauge record for Lowestoft has been used as the primary data source to compare with FEH as this record is longest (73 years). In studies of extreme rainfall it is often the case that an AMAX series will contain one or more outliers caused by a rainfall event with an unusually long return period. However, in the case of Lowestoft there are no obvious outliers. The highest four values are instead very similar; between 68.3 and 72.1 mm. There is no reason to doubt the accuracy of these values but based on historical information regarding severe events in eastern England it would not be unreasonable to have expected daily totals well in excess of these values. The absence of such rainfall amounts will reduce the rainfall estimates at high return periods, which may ultimately lead to an under-estimate of potential rainfall at the site. Therefore, additional GEV distributions were sampled using methods described in Section 2.2. The plot in Figure 7 shows the results of EVA at Lowestoft. Three models have been fitted to the AMAX data and extrapolated to find rainfall estimates beyond the length of the rainfall record. A linear relationship has been derived through least squares fitting (Gumbel distribution), a three-parameter relationship has also been fitted after Jenkinson (1955, 1969) and a distribution fitted using the MPP. The FEH estimates for the point closest to the gauging station at Lowestoft have also been plotted to compare how realistic the values are (black dashed line).

[1] Storm totals are accumulated for any start time in a 24-hour period. This reflects reality more closely as storm events may traverse the fixed measuring periods (i.e. 0900 - 0900 GMT) used at gauging sites.

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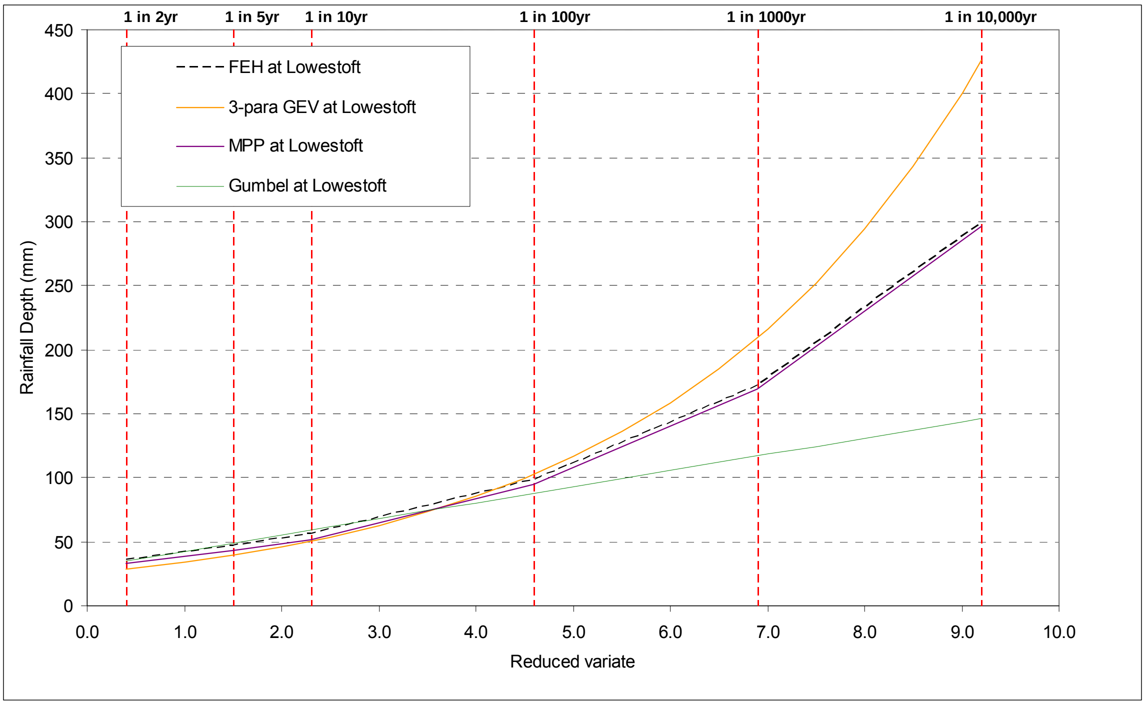

Figure 7. Frequency analysis of AMAX rainfall record at Lowestoft

The rainfall estimates are summarised in Table 4. Note that the estimates using the Gumbel, the three-parameter and MPP distribution models have been converted to 24 hour totals for a 'sliding duration' by multiplying by 1.16 (Faulkner, 1999) to match the FEH results. This ensures the EVA results can be compared with FEH.

The rainfall estimates calculated using all four methods are very similar for return periods up to 100 years (see Table 4) and therefore the greatest confidence can be attributed to these results. However, as the return period increases the difference between the rainfall estimates derived from each curve also increases. At the 1,000 and 10,000 year return periods the FEH estimates are almost identical to the MPP relationship, and this is very encouraging. The linear fit (Gumbel distribution) however is significantly lower than the other curves beyond the 100 year return period. This is not unexpected, because of the lack of relatively high rainfall totals in the AMAX series. Based on the historical evidence of rainfall events in eastern England the 10,000 year linear estimate (146.2 mm) is too low. A similar amount of rainfall (137 mm) fell in just <u>3 hours</u> near Norwich in 1972 and Ditchingham in 1994 (147 mm). Therefore the Gumbel

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relationship would appear a poor representation of extreme rainfall at Lowestoft beyond the 100 year return period.

Return Period	FEH at Lowestoft	Gumbel distribution	Three-parameter distribution	MPP distribution
1 in 2 years	35.7	34.6	32.4	32.9
1 in 5 years	46.8	48.9	45.8	42.9
1 in 10 years	56.1	58.4	57.3	52.0
1 in 100 years	98.7	88.0	114.1	95.2
1 in 1,000 years	172.0	117.1	221.9	169.4
1 in 10,000 years	299.3	146.2	428.0	296.3

Table 4. Daily rainfall estimates using EVA and comparison against FEH estimates for Lowestoft

The three-parameter relationship generates a 10,000 year estimate which is well in excess of FEH (over 100 mm more) and the other fitted curves. Again the lack of large rainfall totals in the time series means the curve increases almost exponentially, generating a rainfall estimate well in excess of any 24 hour rainfall total recorded anywhere in the UK. Therefore this estimate is also considered to be a poor representation of rainfall at the site.

It is not possible to determine which estimate is 'correct' as the results rely upon extrapolations of local available gauged records. The MPP fitting method in this instance is considered a more robust approach as the application of a threshold to identify the largest events each year means that there is a greater 'pool' of data to fit the model to. The MPP estimates are closest to the FEH estimates for Sizewell and therefore provide evidence that the FEH results are not unrealistic. The FEH estimates are generated using an even larger pool of AMAX records because many stations in the local area within a radius of the point of interest are included in the EVA analysis. This approach should in theory capture more significant rainfall events in the local area and therefore the greatest confidence should be placed in these results. The main conclusion though is that the FEH estimates of rainfall depths are not unreasonable when compared with the estimates calculated directly from the rain gauge data recorded at Lowestoft.

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4.3 Extreme Value Analysis at Aldeburgh / Westleton combined

Lowestoft is around 33 km to the north of Sizewell and ideally the gauged records closer from Aldeburgh and Westleton (which are only a few km distant) would be used as the primary data in the analysis. Such a long record of rainfall does not exist in close proximity to Sizewell and the individual records at Aldeburgh and Westleton are too short for estimating extreme rainfalls with the very long return periods required. However, they are sufficiently close to each other (they are only about 12 km apart) and are both located on the coast at similar altitudes, for it to be reasonable to consider merging their records. The records do not overlap in time (the records at Aldeburgh stopped in 1987, and the record at Westleton did not begin until 1989) so it is not possible to assess the homogeneity of the records over a shared time period. However a comparison of the Annual Average Rainfall (AAR) at each location indicates a difference of only 40 mm, with Westleton being the wetter of the two sites. Monthly rainfall totals, admittedly assimilated over different time periods, show a very similar annual cycle; the difference in rainfall by month being less than 6 mm. Based on this analysis, and that Sizewell lies at a point on the coast between these two sites, the rainfall measurements from Aldeburgh and Westleton have been merged to create a single longer data series. The resulting 41 year AMAX record is shown in Figure 8 and is now long enough for the EVA technique to be used.

The results of the EVA using the combined records from Aldeburgh and Westleton are shown in Figure 9. Both a Gumbel distribution and the MPP distribution were fitted to the rainfall data. The three-parameter distribution did not fit the data well and so results from this method are not shown. The resulting rainfall estimates from the Gumbel and MPP methods are shown in Table 5 together with the FEH estimates for Aldeburgh and Westleton separately. The two series of FEH estimates differ very marginally from each other as expected given their close proximity, as the rainfall estimates have been generated using near-identical rain gauge data.

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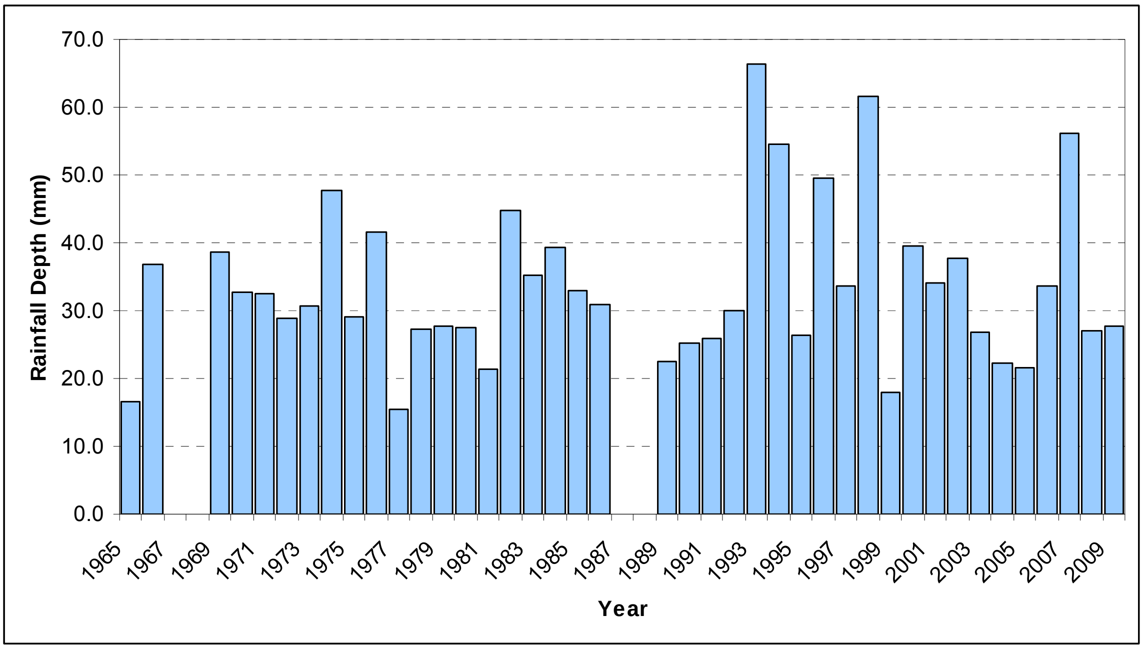

Figure 8. Merged AMAX series of Aldeburgh and Westleton

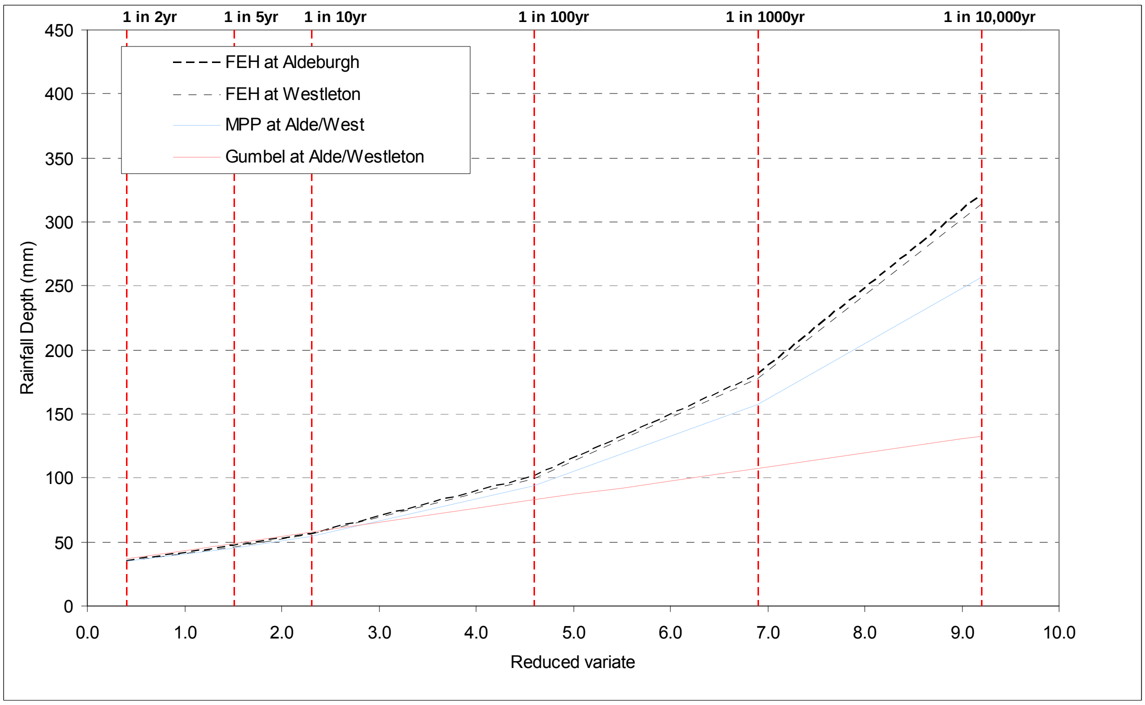

Figure 9. Frequency analysis of AMAX rainfall records at Aldeburgh / Westleton

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Return period	FEH at Aldeburgh	FEH at Westleton	Gumbel distribution	MPP distribution
1 in 2 years	35.3	34.9	36.8	35.0
1 in 5 years	46.9	46.2	49.1	45.0
1 in 10 years	56.5	55.7	57.2	53.9
1 in 100 years	101.6	99.8	82.7	93.9
1 in 1,000 years	180.7	177.2	107.7	157.0
1 in 10,000 years	321.1	314.1	132.6	256.8

Table 5. Daily rainfall estimates using EVA and comparison against FEH estimates for Aldeburgh/Westleton

As with Lowestoft, there is good agreement between the different methods up to the 100 year return period, but beyond this there is considerable divergence particularly from the Gumbel relationship. As already discussed, the resulting rainfall estimates obtained from the Gumbel relationship at the 10,000 year return period are significantly lower than historic storms recorded in the region and therefore this relationship can be considered to be a poor representation of rainfall at the sites. The rainfall values from the MPP are much closer the estimates from FEH but are consistently lower. The largest difference is approximately 60 mm at the 10,000 year return period. However, given that the result is based on an extrapolation of rainfall data well in excess of the length of the record, it is expected that the estimates would be lower than FEH, which is based on a larger pool of data. Also, given that the results of the MPP are not widely different from FEH this indicates that the FEH estimates are reasonable.

4.4 Comparison of Flood Estimation Handbook estimates at Sizewell with rain gauge Extreme Value Analysis estimates

In order to assess how rational the FEH rainfall estimates at Sizewell are, they are compared against the return period estimates generated from the most robust EVA of local rain gauge records in the previous two sections. The results are presented in Table 6 below and shown in Figure 10. In reality the FEH estimates generated for Sizewell are very similar to the FEH estimate for each of the rain gauge sites. Therefore much of the discussion presented in Sections 4.2 and 4.3 also applies here.

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		Lowestoft		Aldeburgh/Westleton
Return Period	**FEH at Sizewell**	**Three-parameter distribution**	**MPP distribution at Lowestoft**	**MPP distribution at Alde/West**
1 in 2 years	34.2	32.4	32.9	35.0
1 in 5 years	45.3	45.8	42.9	45.0
1 in 10 years	54.6	57.3	52.0	53.9
1 in 100 years	97.9	114.1	95.2	93.9
1 in 1,000 years	173.7	221.9	169.4	157.0
1 in 10,000 years	307.9	428.0	296.3	256.8

Table 6. Daily rainfall estimates using EVA of rain gauge records compared with FEH estimates at Sizewell

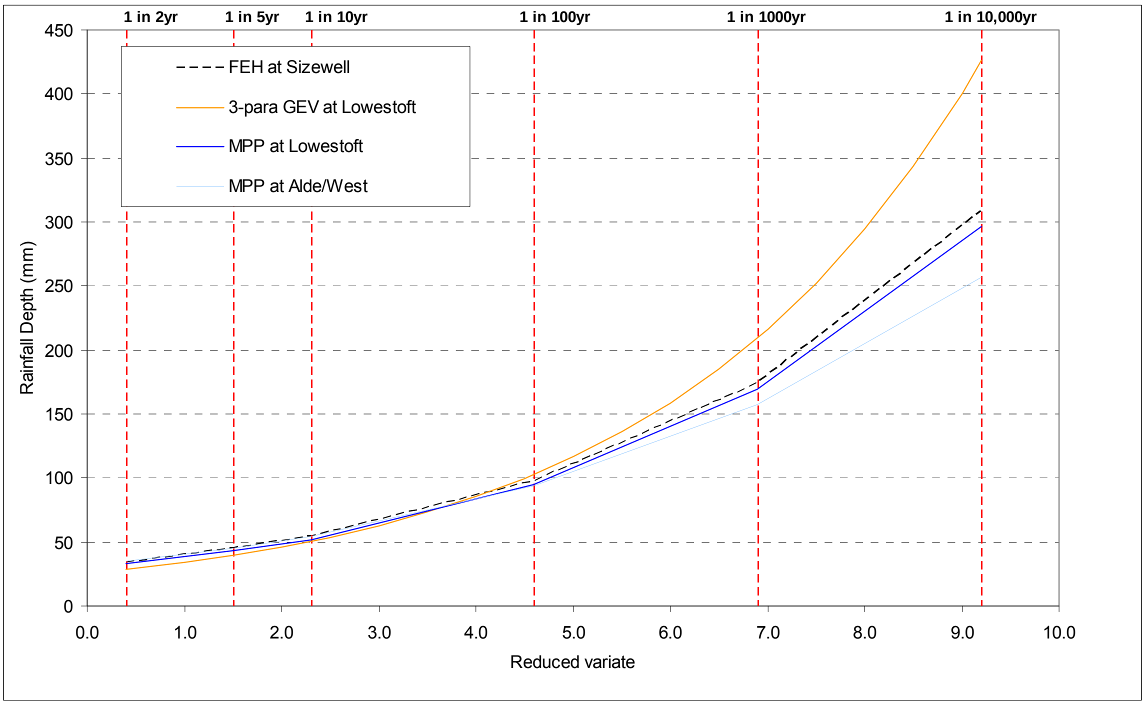

Figure 10. Comparison of return period estimates for Sizewell

A high level of confidence can be attributed to the estimates up to the 100 year return period. This is shown in Figure 10 where the rainfall estimates generated from the FEH and the rain gauge data are very similar. Beyond the 100 year return period there is some disagreement between the methods, particularly at 10,000 years. The estimates

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produced using the three-parameter distribution are 48.2 and 120.1 mm more than FEH at the 1 in 1,000 and 10,000 year return periods respectively. This is not unexpected given that the relationship rises exponentially. This may be in part due to the length of rainfall records available (no more than 73 years). The records, by chance, may not contain a true sample of extreme events thus reducing the rainfall estimates at very long return periods and failing to constrain the top end of the three-parameter distribution. However, the amounts seem high for this region of the British Isles, and the 10,000 year estimate is well in excess of the largest ever recorded 24 hour rainfall total (in Cumbria during November 2009) and is therefore considered to be too high.

The MPP EVA has produced estimates at each of the rain gauge locations which are very comparable with the FEH. This is particularly true at Lowestoft where results are almost the same. The combined record at Aldeburgh and Westleton underestimates rainfall compared with FEH by just over 50 mm. However, the results differ from FEH by only about 15 mm at the 1,000 year return period. These results are very encouraging and suggest that the daily FEH estimates are reasonable for the Sizewell region and can be used as the baseline estimate for extreme rainfall at Sizewell.

It should be noted that Stewart et al. (2010) addressed concerns from reservoir engineers that 10,000 year estimates of rainfall from the FEH DDF model were too high and sometimes exceeded the Flood Studies Report (FSR, see Appendix 9.1) estimate of Probable Maximum Precipitation (PMP) (see Section 7). To address these concerns a new DDF model was developed using a larger amount of rainfall data for 71 UK locations and compared with FEH and the FSR (see Appendix 9.1), the predecessor to FEH. The results showed that FEH rainfall depths estimated at very long return periods, i.e. beyond 1,000 years, were in excess of the new DDF model. The new model has not been released officially, pending further research, but is likely to replace the existing version of FEH. However, of the 71 points investigated, the closest to Sizewell was Wattisham (Figure 1) which produced 10,000 year 24-hour rainfall estimates which are 56-70% of those produced using the current version of FEH at Wattisham. As a result of this research Defra has issued revised guidance to Panel Engineers which suggests that FEH should not be used for estimating rainfall with return periods of 10,000 years.

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Therefore, in the absence of the newly released software, the FEH estimates in this study may provide a liberal rainfall estimate of extreme rainfall at Sizewell, although being comparable to the independent analysis of local rain gauges close to Sizewell.

There are insufficient rain gauge records near Sizewell to conduct a similar analysis to assess the sub-daily estimates produced in FEH. Therefore, the FEH estimates must be considered the best estimation of sub-daily extreme rainfall at Sizewell as well. The 114 mm of rainfall recorded at Costessey in just 2 hours in 1972 (Jackson, 1974) indicates that it is at least feasible to record very significant rainfall amounts over short durations in this part of the country.

In conclusion, the FEH estimates generated at Sizewell are considered reasonable based on the analysis of historic rainfall events in the region and the EVA of local rain gauge records. The revised version of FEH is due for release towards 2012, pending the appropriate funding (Stewart, 2011, Pers, Comm.), and if and when the software is released, EDF may wish to revisit the return period estimates from this study and also at Hinkley Point (Met Office, 2010).

5. Extreme precipitation estimates from modelled data

In this section, the analysis of the daily rainfall data from the 11-member regional climate model data ensemble (11-RCM) is presented. In section 5.1, summary statistics of the modelled rainfall data are compared with those calculated from the observed rainfall data discussed in section 3.1. Next, extreme rainfall estimates for the present climate are calculated using the full EVA method (section 5.2) from the 11-RCM data and the observed rainfall, and the two sets of results are compared in section 5.3. The derivation of the climate change factors is described in section 5.4.

5.1 Summary statistics

To assess the ability of RCM simulations to simulate estimates of extreme rainfall at Sizewell the statistical properties of the RCM simulations (up to the present day), for the nearest coastal land grid square to Sizewell, have been compared against observation datasets. The observation datasets include the daily record from Lowestoft, the merged daily record from Aldeburgh and Westleton and National Climate Information Centre

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(NCIC) gridded daily rainfall data (Perry and Hollis, 2005). Daily rainfall data from 1958 to 2007 have been aggregated from the 5 km NCIC grid squares to represent the rainfall over the RCM grid square (25 km x 25 km) closest to the location of Sizewell. In order to be more comparable, an Areal Reduction Factor (ARF; NERC, 1975) has been applied to the rain gauge observations to scale the values to the equivalent area covered by the RCM data. Summary statistics from the measured rainfall amounts and the 11 RCM ensemble are shown below in Table 7 and Table 8 respectively. These tables provide a comparison between the observed data and the modelled data though the data are of different lengths.

	Lowestoft (1931-2003)	**Aldeburgh/ Westleton (1965-2009)**	**NCIC 25 km (1958-2007)**
Mean	1.5	1.4	1.6
Median	0.0	0.0	0.1
75%ile	1.5	1.2	1.7
99%ile	15.2	15.5	15.3
Skewness	5.2	5.1	4.3
Maximum	66.0	60.8	55.8

Table 7. Summary statistics of observed daily rainfall

	A	C	H	I	J	K	L	M	O	Q	**X**
Mean	1.7	1.6	1.9	1.7	1.4	1.5	1.7	1.8	1.9	1.6	1.9
Median	0.2	0.3	0.4	0.3	0.2	0.2	0.3	0.4	0.4	0.3	0.4
75%ile	1.9	1.9	2.0	2.1	1.7	1.8	1.9	2.1	2.2	1.8	2.2
99%ile	14.9	14.5	17.6	15.7	12.5	13.1	16.0	16.7	16.6	15.0	16.9
Skewness	3.9	4.3	5.6	4.0	4.1	3.8	4.2	5.2	4.0	3.9	4.9
Maximum	43.7	65.5	92.8	51.5	67.0	51.4	55.0	105.0	54.5	44.1	92.3

Table 8. Summary statistics of RCM daily rainfall (1950-2009)

A comparison of the statistics of the measured rainfall data in Table 7 indicates that the distributions of the observational rainfall records are very similar. The distributions of the observed data are most typical of a J-shaped distribution which is very positively skewed due to the high frequency of zero values and low rainfall totals. The highest maximum rainfall is recorded in the Lowestoft record and the lowest in the NCIC data. This is not unexpected given that the NCIC values represent an area average value for a 5 km x 5 km grid square thereby tending to smooth out the higher rainfall amounts recorded during localised rainfall events at rain gauges.

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The RCM summary statistics demonstrate that the distributions of each time series are very similar to the observed records. However, the summary statistics of the RCM data are on average slightly higher. The medians indicate that there are a smaller proportion of dry days in each series compared with the observations. However the focus of this study is the top end of the distribution, described by the 75th and 99th percentiles and the maximum. The values for the 75th and 99th percentiles are on average slightly larger than the observed record which indicates a larger proportion of higher rainfall amounts in the RCM data compared with the observed records. The maximum RCM values range from 43.7 to 105.0 mm and three of the RCM runs (H, M and X) have generated a greater maximum total well in excess of the maximum at Lowestoft. This is encouraging as it indicates that the RCMs are capable of generating large rainfall totals which is important for calculating a realistic climate change factor. Interestingly, RCM runs H, M and X are the same model runs which generated the largest rainfall totals for the same study at Hinkley Point (Met Office, 2010). This adds further credence to the assumption that some of the underlying parameter settings of each RCM may encourage increased precipitation.

5.2 Analysis of RCM rainfall using Extreme Value Analysis

EVA has been undertaken on all datasets for the present-day climate. A suitable threshold to define extreme events is needed. Here, the 98.5th percentile was used. This threshold is illustrated in Figure 11 using the NCIC gridded data (at 25 km resolution) for the period 1958-2007. EVA has also been applied to each of the RCM simulations of daily rainfall for the period 1949-2008, the daily records at Lowestoft between 1931-2003 and the combined daily Aldeburgh / Westleton record from 1965 to 2009. Rainfall depths at varying return periods have been calculated by fitting each dataset to the MPP distribution. Diagnostic plots suggest that the models are generally a good fit to the data. The shape parameter for all of the rainfall datasets is slightly positive, between 0.01 and 0.23, indicating an unbounded distribution with return levels increasing more quickly as the return period increases.

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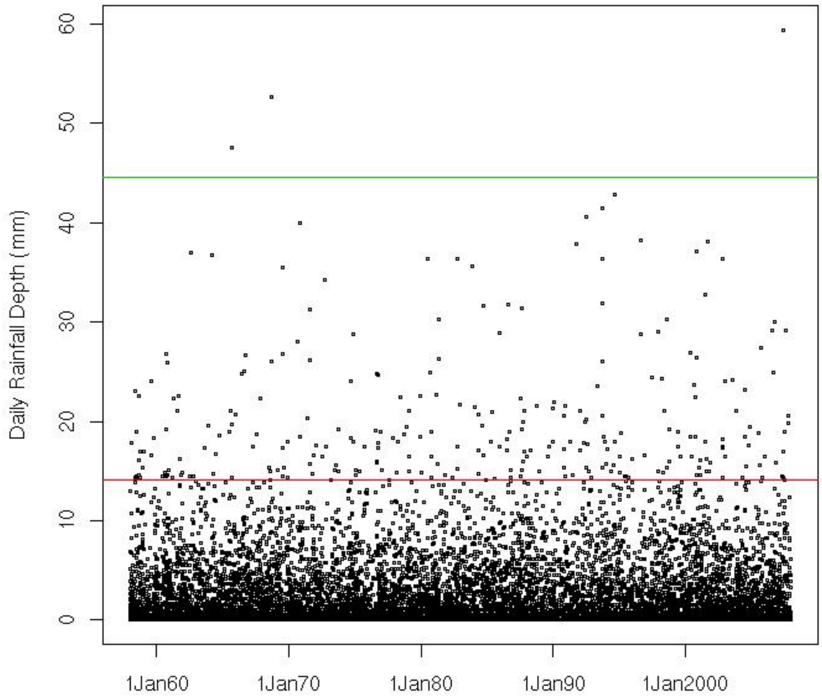

Figure 11. Example plot showing the 98.5% threshold (red line) and 10 year return period estimate (green line) constructed by fitting daily rainfall data to the MPP distribution

5.3 Results from Extreme Value Analysis

The results of the EVA are presented in Figure 12. This enables a comparison of the estimated rainfall depths using the observed records (Lowestoft and Aldeburgh/Westleton and NCIC gridded) and the 11 RCM datasets.

The results obtained from the observed datasets produce very similar rainfall depth estimates up to the 100 year return period. Beyond this the results begin to diverge. Of the three datasets, the Lowestoft record produces the greatest estimates at the 1,000 and 10,000 year return level. This is to be expected given the additional length of record (back to 1931) available for analysis compared with the other observation records. The NCIC record produces the lowest estimates; however, they are only different from the Lowestoft results by 22.8 mm and 58.9 mm at the 1,000 and 10,000 year return period respectively.

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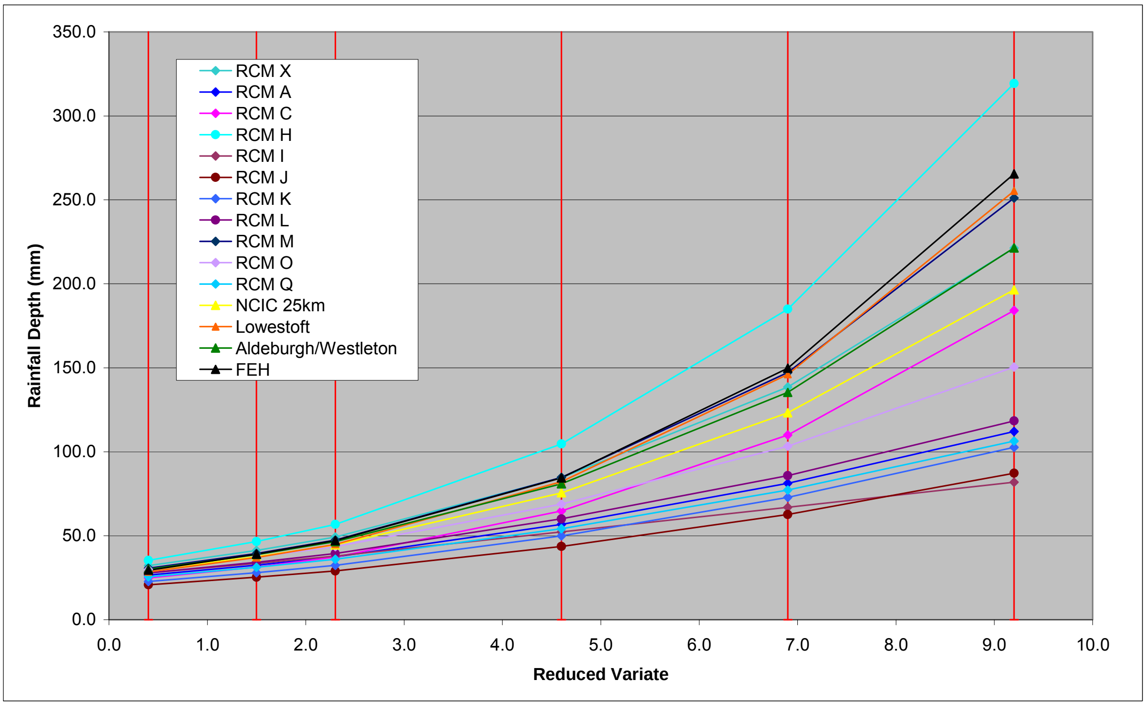

Figure 12. Present day rainfall return period estimates for observed and RCM datasets using the MPP distribution and FEH estimates at Sizewell for a fixed duration.

The estimates derived using the RCM simulations in Figure 12 at the lower return periods compare very well against the estimates produced from observations, and the greatest confidence can be attributed to these results. However, at the higher return periods, the overall trend in the estimates produced for 7 of the 11 RCM simulations are biased towards an underestimation of rainfall depths at all return periods compared with observed records, most prominently at the highest return periods. The exception to this trend are RCMs C, M, and X which closely replicate the range of estimates produced from the observed data sets for rainfall depths out to the 10,000 year return period. RCM H produces the largest estimates, some way above the estimates from observations. Generally, the error in rainfall estimates for the RCM runs increases as the return period increases. This is not altogether surprising given that estimates at return periods larger than 100 years are extrapolations beyond the bounds of the time series of data used in the analysis.

Figure 12 also compares the results of the EVA with the daily FEH estimates (shown by the black line) obtained for Sizewell in Section 4.1. With the exception of RCM H, the FEH estimates are greater than those generated using other RCM simulations. The

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estimates generated using RCM M closely match those of the FEH estimates. The smallest differences between FEH and the majority of the other estimates are at the lower return periods e.g. at 1 in 10 years, the difference between FEH and the lowest estimates produced by an RCM simulation is 25.6 mm. Compared with observations, there is very good agreement between estimates up to the 1 in 100 year return period, though the FEH estimates are slightly higher than those produced by the observations in all instances. This trend continues at the higher return periods though the difference between the estimates increases. This is not unexpected as the estimates are based on extrapolations far beyond the length of the observational record. As some of the RCM simulations more closely reflect the results generated from the observations and the FEH, whereas others are an underestimate, this would indicate inherent differences between the data in each RCM simulation. This conclusion is common to the results in the previous study at Hinkley Point (Met Office, 2010) which suggested that the underlying parameters used to derive the RCM runs should be investigated further in order to explain the differences between each RCM dataset. The results of this investigation are presented below in Section 5.4. An important conclusion from this section, however, is that the results obtained by applying EVA to the observations are not significantly different from the FEH estimates so as to consider them inappropriate to describe rainfall return periods at Sizewell.

5.4. Derivation of climate change factors

The full EVA model (section 2.2) was fitted to daily rainfall from each of the 11-RCM members for the full period of the simulation, 1949 – 2099. Data for winter (defined as December, January and February) and summer (June, July and August) were analysed separately. Extreme rainfall in winter will be produced by weather fronts, whereas summer extremes are produced by localised convective storms, and so extreme rainfall amounts in each season could change at different rates.

Any non-stationarity in the MPP parameters is found by fitting the MPP model, allowing one or more of the MPP parameters to change with the covariate (see section 2.2). The model with a time-dependent parameter is deemed to be a significantly better description of the data than the same model with a time-invariant parameter if the deviance between the two models exceeds the 90th percentile of the chi-squared

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distribution with one degree of freedom (Coles, 2001). Previous analysis (Met Office, 2010) has shown that the climate change signal manifests itself most strongly in the scale parameter. The covariate is global average temperature for the time period of interest. Precipitation is known to increase as temperatures rise, and so temperature is a suitable covariate for this work. UK averages or average temperatures for East Anglia could have been used, but these temperatures will by much more variable than global averages and would introduce greater uncertainty into the results.

Results of fitting to the whole period of data (1949-2099) show that sampling uncertainty (manifesting as natural variability) is affecting the derivation of the climate change signal. The spatial patterns of changes in extreme precipitation amounts are not physically plausible. For example, allowing the scale parameter to be non-stationary can produce changes in extremes that have high spatial variability which is greater than would be allowed by the processes affecting extreme rainfall. To minimise this variability, two approaches have been adopted. First, bootstrapping of the input data for the extreme distribution fitting was performed. In this approach, extreme distributions were fitted to multiple samples of half the input data, sampled in 10 year blocks with replacement. 50 bootstraps were used. The MPP parameters obtained from the bootstrapped data were then averaged for each RCM grid box. This averaging reduced the spatial variability to a large degree but did not eliminate it completely. Climate change factors for 1 in 10,000 year extreme precipitation events in winter for every RCM grid box assuming a global temperature increase of 4 ºC are shown in Figure 13 for all 11 RCM members. This temperature rise was chosen purely for illustrative purposes and does not correspond to a particular emissions scenario or time.

These climate change factors are still highly variable across the UK domain, although the variability has been reduced. There are also considerable differences in the climate change factors between each RCM member.

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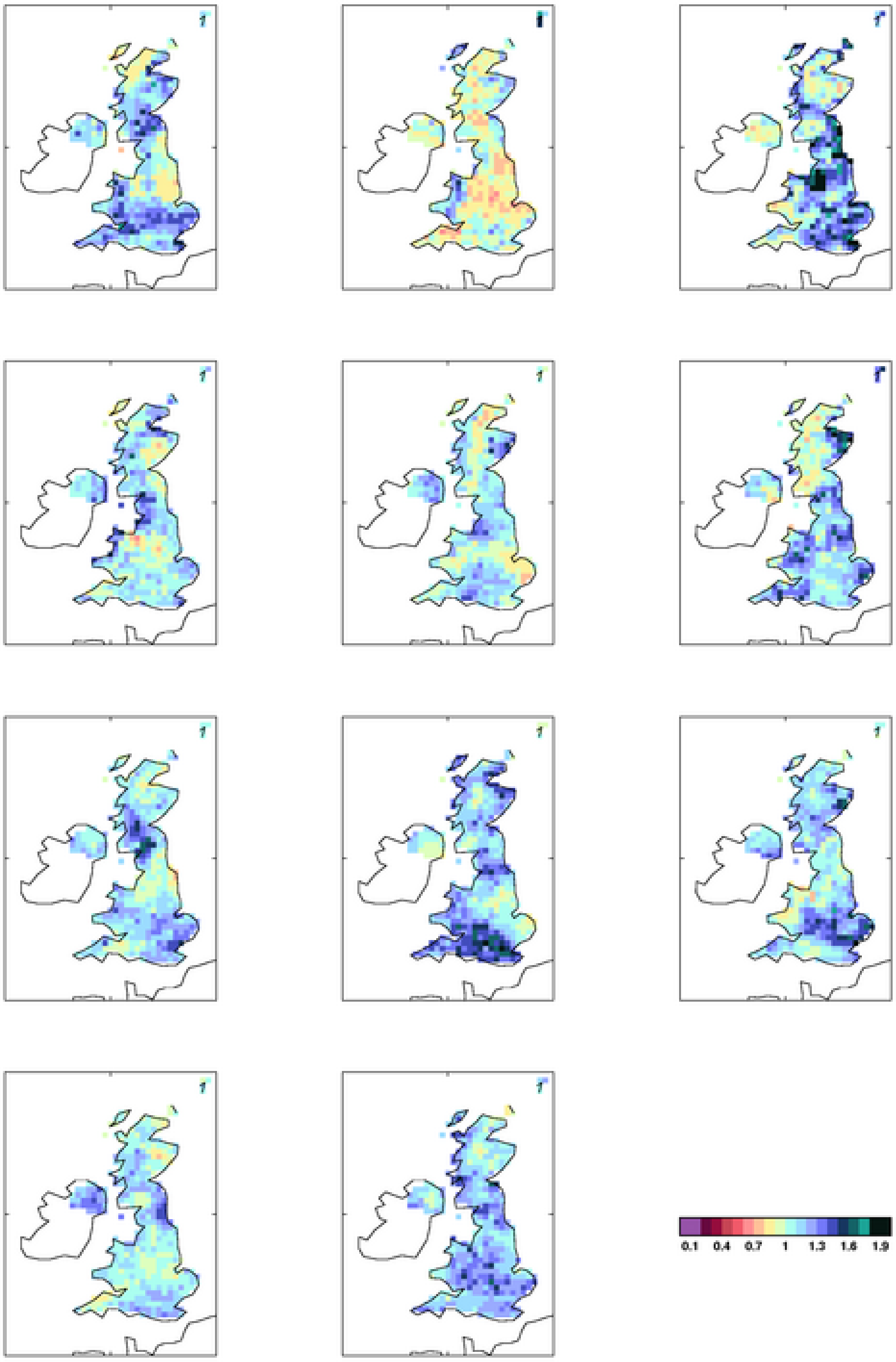

Figure 13. Climate change factors for the end of the 21st century, for 1 in 10,000 year return period rainfall in winter. These factors were calculated using a global temperature rise of 4 ºC for illustrative purposes only. Despite the efforts to reduce the impact of variability, there are still some differences in the climate change factors across the country and between each ensemble member.

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The second approach adopted, to further reduce the impact of natural variability, was to average the extreme distribution parameter that expressed the climate change signal (i.e. that which depends on global temperature, here, the scale parameter) over a particular region. For the Hinkley Point application (Met Office, 2010) this parameter was averaged for the regions of England and Wales south of The Wash. This area was chosen as a compromise between having a larger area to better average out the sampling uncertainty and a small enough area where the climate change signal can be considered to be quasi-constant. For Sizewell, a similar approach was taken. The scale parameter was averaged over an area of England and Wales between the Humber Estuary and London, so that Sizewell lies at the centre (in the north-south direction).

Return levels were calculated using the location and shape parameters calculated for Sizewell itself and the averaged value of the scale parameter. The return levels were found for the baseline period (1961 – 1990) and the future, which are overlapping 30 year periods (as used in the UKCP09 projections). The covariate used to calculate the values of the scale parameter was the global mean temperature for each 30 year period, and the uncertainty was calculated using the probabilistic data from the UKCP09 climate projections (Murphy et al., 2009). The location and shape parameters have constant values. The resulting frequency distributions from each RCM member were combined to create a “best estimate” distribution of climate change factors for Sizewell for each 30 year period, for summer and winter. Examples of these distributions are shown in Figure 14. It can be seen that there is still considerable difference between the change factors from each of the RCMs (this is especially true for summer) and together form a poor sample of possible future climate change uncertainty. Overall, all models except 1 project an increase in winter precipitation extremes, whereas there is poorer agreement for summer extremes.

Climate change factors for a range of percentiles were calculated from the combined distribution for each season and 30 year period (i.e. 2010-2039, 2020-2049 ... 2070-2099) for each return period for the A1B emissions scenario. Change factors for 1 in 10,000 year rainfall events are given in Table 9.

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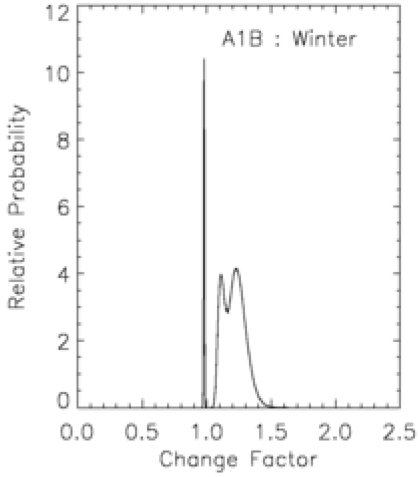

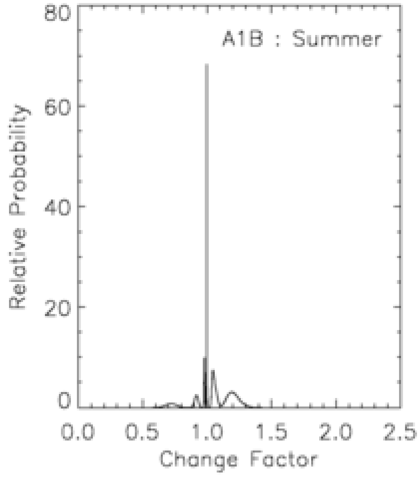

Figure 14. Example of combined distributions using 11 RCM results (A1B Scenario), for winter and summer during 2070-2099, for a 1 in 10,000 year rainfall event.

2010-2039		
Percentile	**Winter**	**Summer**
5th	0.99	0.88
25th	1.04	0.98
50th	1.07	1.01
68th	1.08	1.04
75th	1.09	1.06
84th	1.10	1.08
95th	1.12	1.10

2020-2049		
Percentile	**Winter**	**Summer**
5th	0.99	0.85
25th	1.06	0.99
50th	1.09	1.02
68th	1.11	1.07
75th	1.12	1.08
84th	1.13	1.10
95th	1.16	1.12

2030-2059		
Percentile	**Winter**	**Summer**
5th	0.99	0.81
25th	1.07	0.97
50th	1.11	1.02
68th	1.13	1.07
75th	1.15	1.10
84th	1.17	1.13
95th	1.19	1.16

2040-2069		
Percentile	**Winter**	**Summer**
5th	0.99	0.78
25th	1.08	0.97
50th	1.13	1.03
68th	1.16	1.08
75th	1.17	1.12
84th	1.20	1.16
95th	1.23	1.19

Table 9. 10,000 year climate change factors calculated for a range of percentiles, winter and summer, for each 30 year time period between 2010 and 2070 (A1B scenario).

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2050-2079		
Percentile	**Winter**	**Summer**
5th	0.98	0.75
25th	1.10	0.96
50th	1.15	1.03
68th	1.19	1.09
75th	1.20	1.14
84th	1.23	1.18
95th	1.27	1.22

2060-2089		
Percentile	**Winter**	**Summer**
5th	0.98	0.73
25th	1.11	0.96
50th	1.17	1.03
68th	1.21	1.10
75th	1.23	1.15
84th	1.26	1.21
95th	1.31	1.26

2070-2099		
Percentile	**Winter**	**Summer**
5th	0.98	0.71
25th	1.12	0.95
50th	1.19	1.05
68th	1.23	1.11
75th	1.25	1.17
84th	1.29	1.23
95th	1.34	1.28

Table 9 (continued). 10,000 year climate change factors calculated for a range of percentiles, winter and summer, for each 30 year time period between 2050 and 2099 (A1B scenario).

1 in 100 and 1 in 1,000 year change factors can be found in Table 20 and Table 22 in the Appendix, sections 10.4 and 10.5. These factors must be used with caution, owing to the spread between the individual RCM members, and the very poor sampling of possible future climate change uncertainty.

6. Daily and sub-daily estimates of precipitation at Sizewell accounting for climate change

The climate change factors obtained in Section 5.4 are now applied to the baseline 100, 1,000 and 10,000 year rainfall amounts for Sizewell for the present day, which were estimated using the FEH methodology. The results in Section 4 indicated that the FEH estimates of daily and sub-daily rainfall for return periods out to 10,000 years are reasonable. As such these estimates are used as the baseline rainfall depths for Sizewell upon which the climate change factors are applied.

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An additional reason for this recommendation is that the methodology used below to apply the climate change amounts to sub-daily durations relies on the ratio of the daily baseline rainfall to the sub-daily amounts. However, as was also the case at Hinkley Point, there are no sub-daily rain gauge data available near to the site of long enough record to assess whether or not the sub-daily estimates should be adjusted, thus it would seem prudent not to adjust the daily rainfall as a result. The baseline rainfall depths for Sizewell are presented in Table 10 below.

Return Period/ Duration	**Point Rainfall Estimates (mm)**		
	15-minute	**1-hour**	**Daily**
1 in 100 years	37.9	50.8	97.9
1 in 1,000 years	82.2	103.6	173.7
1 in 10,000 years	177.9	211.0	307.9

Table 10. FEH Rainfall return period estimates for Sizewell (obtained using AMAX records at a point location for a sliding duration). These are the baseline estimates to which the climate change factors will be applied.

6.1 Adjustment of baseline rainfall to account for climate change

The factors calculated in Section 5 can be applied directly to the baseline daily rainfall estimates in Table 10 using Equation 4 because the RCM rainfall output is calculated for a daily duration. However, these factors cannot be directly applied to the sub-daily durations. Therefore the growth factor (i.e. the ratio) between each sub-daily estimate and the daily estimate at each return period has been calculated (Table 11) and used to scale the climate change estimates for the daily duration to a more realistic estimate of sub-daily rainfall using Equation 5.

Equation 4

$$\textit{Daily Rainfall Depth (mm)} = \textit{change factor} \times \textit{baseline daily rainfall}$$

Equation 5

$$\textit{Sub-daily Rainfall Depth (mm)} = \left(\left[(\textit{change factor} - 1) \times \textit{ratio} \right] + 1 \right) \times \textit{baseline rainfall}$$

It may be assumed that the ratios given in Table 11 may vary in the future with climate change. Indeed, Lenderick and Van Meijgaard (2008) suggest that hourly extreme

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rainfall is likely to increase more than daily extremes in large parts of Europe. However research in this field remains very limited, thus, for the purposes of this study the ratios are assumed to remain constant.

Return Period/Duration	Growth Factor/Ratio	
	15-minute	1-hour
1 in 100 years	0.387	0.519
1 in 1,000 years	0.473	0.596
1 in 10,000 years	0.578	0.685

Table 11. Calculated growth factors between daily and sub-daily rainfall estimates obtained from FEH at different return periods for Sizewell.

The results of applying the equations above produce estimates of extreme rainfall depths at Sizewell at the three different durations for each season (winter and summer) and each 30 year time period, from 2010-2039 to 2070-2099. The results for the 10,000 year rainfall are presented below in Section 6.2, Table 12. The results for 100 and 1,000 year rainfall depths can be found in the Appendix, Section 10.4 Table 20 and Section 10.5 Table 22 respectively.

6.2 Extreme rainfall estimates for Sizewell accounting for climate change

The baseline 10,000 year return period rainfall estimates for Sizewell have been adjusted using the climate change factors calculated in Section 5 for seven percentiles in the range 0.05 – 0.95. The adjusted rainfall estimates for winter and summer throughout the 21st century are shown in Table 12 and an example of the resulting rainfall growth curves can be seen in Figure 15. The summary data enables EDF and the ONR to reach mutual agreement on a rainfall amount that is most appropriate for drainage design at the site, not just in terms of rainfall depth, but also through consideration of estimated design life of the project (approximately 60 years).

The ranges of estimates calculated for Sizewell compared against those obtained for Hinkley Point (Met Office, 2010) are higher for each duration and return period. The climate change factors for each site do not differ significantly but it is the underlying baseline rainfall estimates from FEH which are the underlying cause for the differences between the two sites.

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2010 – 2039 Winter				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.99	176.9	209.6	304.8
0.25	1.04	182.0	216.8	320.2
0.50	1.07	185.1	221.1	329.5
0.68	1.08	186.1	222.6	332.5
0.75	1.09	187.2	224.0	335.6
0.84	1.10	188.2	225.5	338.7
0.95	1.12	190.2	228.4	344.8

2010 – 2039 Summer				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.88	165.6	193.6	271.0
0.25	0.98	175.8	208.1	301.7
0.50	1.01	178.9	212.4	311.0
0.68	1.04	182.0	216.8	320.2
0.75	1.06	184.1	219.7	326.4
0.84	1.08	186.1	222.6	332.5
0.95	1.10	188.2	225.5	338.7

2020 – 2049 Winter				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.99	176.9	209.6	304.8
0.25	1.06	184.1	219.7	326.4
0.50	1.09	187.2	224.0	335.6
0.68	1.11	189.2	226.9	341.8
0.75	1.12	190.2	228.4	344.8
0.84	1.13	191.3	229.8	347.9
0.95	1.16	194.3	234.1	357.2

2020 – 2049 Summer				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.84	161.5	187.9	258.6
0.25	0.98	175.8	208.1	301.7
0.50	1.02	180.0	213.9	314.1
0.68	1.05	183.0	218.2	323.3
0.75	1.08	186.1	222.6	332.5
0.84	1.11	189.2	226.9	341.8
0.95	1.13	191.3	229.8	347.9

2030 – 2059 Winter				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.99	176.9	209.6	304.8
0.25	1.07	185.1	221.1	329.5
0.50	1.11	189.2	226.9	341.8
0.68	1.13	191.3	229.8	347.9
0.75	1.15	193.3	232.7	354.1
0.84	1.17	195.4	235.6	360.2
0.95	1.19	197.4	238.5	366.4

2030 – 2059 Summer				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.81	158.4	183.5	249.4
0.25	0.97	174.8	206.7	298.7
0.50	1.02	180.0	213.9	314.1
0.68	1.07	185.1	221.1	329.5
0.75	1.10	188.2	225.5	338.7
0.84	1.13	191.3	229.8	347.9
0.95	1.16	194.3	234.1	357.2

Table 12 - 1 in 10,000 year rainfall estimates (in mm) for durations of 15 minutes, 1 hour and 1 day at Sizewell by season for 2010-2039, 2020-2049 and 2030-2059 for a range of percentiles.

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2040 – 2069 Winter				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.99	176.9	209.6	304.8
0.25	1.08	186.1	222.6	332.5
0.50	1.13	191.3	229.8	347.9
0.68	1.16	194.3	234.1	357.2
0.75	1.17	195.4	235.6	360.2
0.84	1.20	198.5	239.9	369.5
0.95	1.23	201.5	244.3	378.7

2040 – 2069 Summer				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.78	155.3	179.2	240.2
0.25	0.97	174.8	206.7	298.7
0.50	1.03	181.0	215.3	317.1
0.68	1.08	186.1	222.6	332.5
0.75	1.12	190.2	228.4	344.8
0.84	1.16	194.3	234.1	357.2
0.95	1.19	197.4	238.5	366.4

2050 – 2079 Winter				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.98	175.8	208.1	301.7
0.25	1.10	188.2	225.5	338.7
0.50	1.15	193.3	232.7	354.1
0.68	1.19	197.4	238.5	366.4
0.75	1.20	198.5	239.9	369.5
0.84	1.23	201.5	244.3	378.7
0.95	1.27	205.7	250.0	391.0

2050 – 2079 Summer				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.75	152.2	174.9	230.9
0.25	0.96	173.8	205.2	295.6
0.50	1.03	181.0	215.3	317.1
0.68	1.09	187.2	224.0	335.6
0.75	1.14	192.3	231.2	351.0
0.84	1.18	196.4	237.0	363.3
0.95	1.22	200.5	242.8	375.6

2060 – 2089 Winter				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.98	175.8	208.1	301.7
0.25	1.11	189.2	226.9	341.8
0.50	1.17	195.4	235.6	360.2
0.68	1.21	199.5	241.4	372.6
0.75	1.23	201.5	244.3	378.7
0.84	1.26	204.6	248.6	388.0
0.95	1.31	209.8	255.8	403.3

2060 – 2089 Summer				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.73	150.1	172.0	224.8
0.25	0.96	173.8	205.2	295.6
0.50	1.03	181.0	215.3	317.1
0.68	1.10	188.2	225.5	338.7
0.75	1.15	193.3	232.7	354.1
0.84	1.21	199.5	241.4	372.6
0.95	1.26	204.6	248.6	388.0

Table 12 (continued)- 1 in 10,000 year rainfall estimates (in mm) for durations of 15 minutes, 1 hour and 1 day at Sizewell by season for 2040-2069, 2050-2079 and 2060-2089 for a range of percentiles.

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2070 – 2099 Winter					2070 – 2099 Summer				
%ile	**Change Factor**	**15 minute**	**1 hour**	**Daily**	**%ile**	**Change Factor**	**15 minute**	**1 hour**	**Daily**
0.05	0.98	175.8	208.1	301.7	0.05	0.71	148.1	169.1	218.6
0.25	1.12	190.2	228.4	344.8	0.25	0.95	172.8	203.8	292.5
0.50	1.19	197.4	238.5	366.4	0.50	1.05	183.0	218.2	323.3
0.68	1.23	201.5	244.3	378.7	0.68	1.11	189.2	226.9	341.8
0.75	1.25	203.6	247.1	384.9	0.75	1.17	195.4	235.6	360.2
0.84	1.29	207.7	252.9	397.2	0.84	1.23	201.5	244.3	378.7
0.95	1.34	212.8	260.2	412.6	0.95	1.28	206.7	251.5	394.1

Table 12 (continued) - 1 in 10,000 year rainfall estimates (in mm) for durations of 15 minutes, 1 hour and 1 day at Sizewell by season for 2070-2099 for a range of percentiles.

It must be remembered that the 11 sets of RCM results poorly sample the “true” distribution of changes in extreme precipitation (hence the multiple peaks in the combined distribution shown in Figure 14). These climate change factors and 1 in 10,000 year precipitation amounts must be used with caution.

A summary of the range of 10,000 year rainfall depths projected out to 2099 for each rainfall duration period is presented in Table 13. In comparison with the baseline estimates (Table 10), there is the potential for a very slight decrease in daily rainfall in winter of up to 6.2 mm (0.05 percentile) as opposed to the largest projected increases of 34.9, 49.2, and 104.9 mm for 15-minute, hourly and daily durations respectively. The increases projected in summer are not as large (28.8, 40.5 and 86.2 mm) though the projected drop in precipitation extends to a maximum of 89.3 mm for daily rainfall.

Duration	**Winter**	**Summer**
	Range of estimates (mm)	**Range of estimates (mm)**
15 minutes	175.8 – 212.8	148.1 – 206.7
1 hour	208.1 – 260.2	169.1 – 251.5
1 day	301.7 – 412.6	218.6 – 394.1

Table 13. Range of 10,000 year rainfall estimates accounting for climate change to 2099.

There are a few key points to note from Table 12 and Table 13 some of which can be identified by examining Figure 15, which shows the rainfall depths calculated by applying

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the change factors to the 10,000 year baseline estimates for each 30 year time period, winter and summer.

A. Winter rainfall is consistently projected to be greater compared to the equivalent percentile and duration in summer rainfall.
B. The largest precipitation estimate (412.6 mm in 24 hours) is found under the winter 2070-2099 projections for the 95th percentile.
C. Values in winter and summer at the 50th percentile and above, all project an increase in precipitation at all rainfall durations.
D. The change factors calculated for both winter and summer up to 2099 at the 5th percentile consistently project a decrease in precipitation. There are also some projected reductions at the 25th percentile as well.
E. The range in projected rainfall amounts in both winter and summer increases with time.

Summary tables for the adjusted rainfall amounts for 100 and 1,000 year rainfall return periods can be found in the Appendix, section 10.4 (Table 21) and section 10.5 (Table 23) respectively. The same points detailed above can be attributed to the 1,000 year rainfalls and for the 100 year rainfalls with the exception of point D. During winter the projections at any percentile indicate an increase in precipitation, though the change factor may be as low as 1.002. In summer however, decreases in rainfall are projected at both the 5th and 25th percentiles.

It should be noted that the methodology used to derive the rainfall estimates has applied seasonal change factors to baseline estimates calculated using an annual time series (the annual maximum (AMAX)). Ideally seasonal baseline estimates would have been calculated at Sizewell, but this would only have been feasible for daily rainfalls, as there are no sub-daily rainfall observations available in sufficient quantity for a robust analysis. Therefore the use of the FEH is most appropriate. A further alternative would be to calculate the climate change factors annually, effectively the average between winter and summer, and apply this to the annual baseline estimates. However, given that the HadRM3 model cannot accurately resolve summer convection, but that winter frontal rainfall is well represented, a model that <u>could</u> resolve convection may be expected to produce climate change factors in excess of the winter factors calculated in this study,

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thus increasing the final winter rainfall estimates produced in Table 12. Therefore, as these estimates are being applied for the design of drainage to protect critical infrastructure, the approach adopted is the most resilient.

The greatest confidence is placed in the 1 in 100 year rainfall estimates, as this return period is closest to the length of the available precipitation record. The uncertainty in the return level increases with longer return periods as is discussed in the Appendix, Section 9.1 and is illustrated in Figure 2. Similarly, the uncertainty in the climate change factors also increases with longer return periods, as the climate change factors are calculated by dividing the future return level by the present day return level. This should be considered when selecting an appropriate design rainfall for drainage design.

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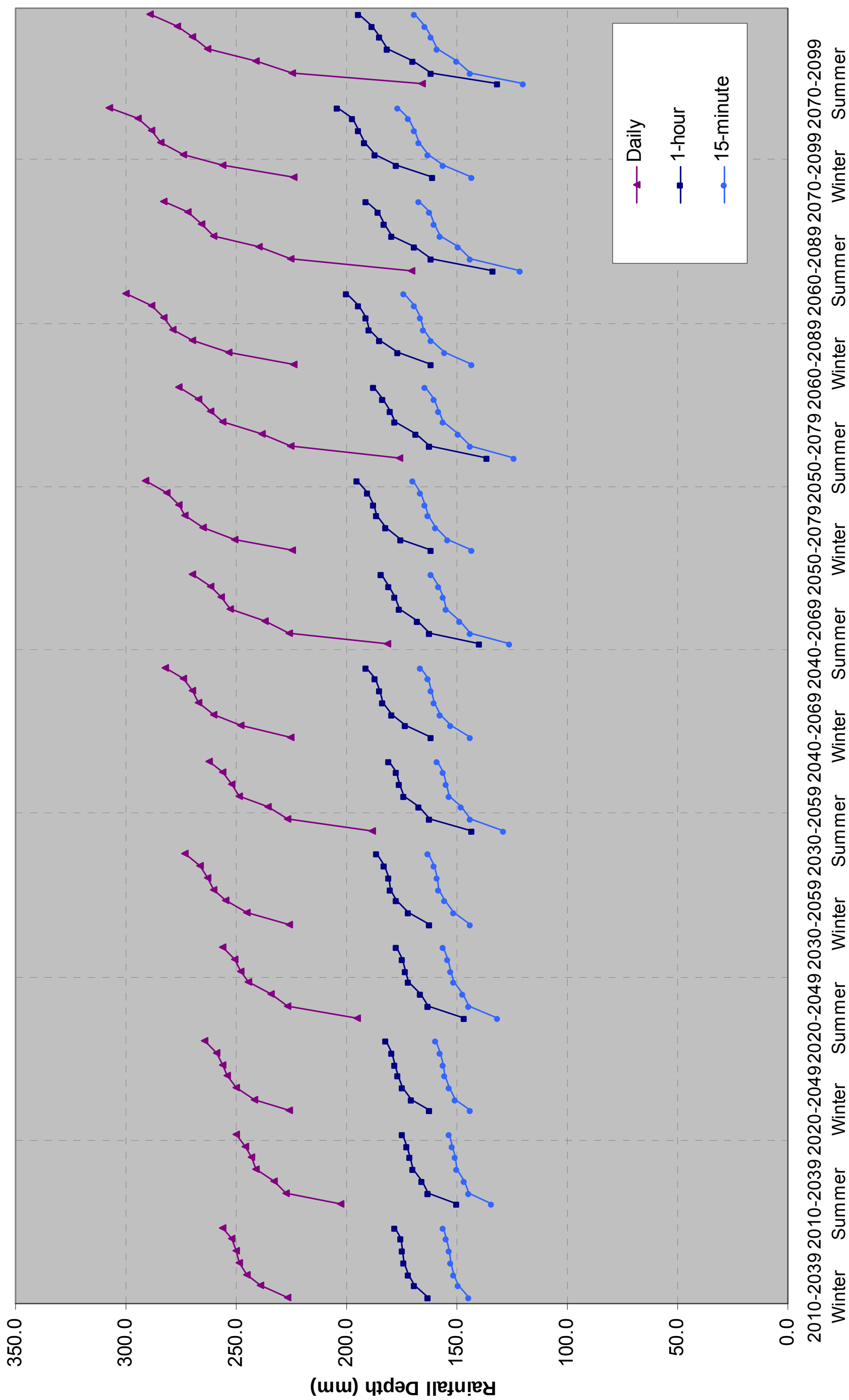

Figure 15. Summary of 10,000 year precipitation projections at the seven percentiles out to 2099. The seven points on each line indicate the rainfall depths for (starting at the bottom) the 5th, 25th, 50th, 68th, 75th, 84th and 95th percentiles respectively.

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7. Estimation of Probable Maximum Precipitation at Sizewell

Probable Maximum Precipitation (PMP) is a concept widely used in engineering design where the failure of a structure or system is considered to have severe consequences. PMP is a rationalised estimate of the upper limit of precipitation for a given duration and location, and is based on physical consideration of the structure of the atmosphere and rain producing systems, in combination with statistics (Lewis, 1991). Both the physical and statistical approaches are aimed at producing an estimate with a very long return period. The return period associated with PMP is not rigidly defined, but is considered to be in the order of 100,000 years or greater (US Corps of Engineers, 1997). It thus provides a check against the rainfall estimates of extreme rainfall, particularly the 10,000 year estimates, accounting for climate change produced in this study.

It is recommended in the “Guide to Hydrological Practices” (WMO, 2009) that multiple methods should be used in estimating PMP in order to asses the plausibility of the final maximised rainfall amount. In this examination, estimates of PMP have been derived from 3 methods:

1. World Meteorological Organisation (WMO) method (WMO, 1986)
2. Flood Studies Report (FSR) method (NERC, 1975)
3. Rapid statistical method (WMO, 2009)

7.1 Calculations of Probable Maximum Precipitation

7.1.1 WMO Method

The WMO method of estimating PMP is an international standard, fully documented in the Manual, WMO No. 332, (WMO, 1986). The basis of the method can be expressed in the formula shown in Equation 6,

Equation 6

$$M = \frac{R.W_{100}}{W_s}$$

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where M is the maximised area or point rainfall and R is the observed area or point rainfall amount. W_{100} is the precipitable water estimated from the dew point temperature with a 100-year return period for the month concerned, and W_s is the precipitable water estimated from a representative dew point for the observed storm. $T_{dew}(100)$ and T_{dew} will refer to the dew point temperature with a 100-year return period and representative dew point for the storm respectively.

The largest observed storm in the region, 'which will be maximised', is the 1912 storm detailed in Section 3.2. A limited amount of detailed information is available for duration of the rainfall event but the closest estimate to a daily total is 186 mm in 22 hours.

In absence of sufficient data regarding the storm, analysis of dew point data from Wattisham, the nearest weather station, with a sufficiently long record (see Figure 1) has been undertaken. For August, the month in which the storm in 1912 occurred, a mean annual maximum dew point temperature of 17.4 ^{o}C has been calculated, and this figure will be used as a basis for the estimation of W_s. Given that the a large storm could equally occur in July, when temperatures are very similar to those in August in East Anglia, estimation of $T_{dew}(100)$ has been carried out by a probability analysis of the annual maximum series of T_{dew} in both July and August. The results are illustrated in Figure 16 and summarised in Table 14.

Station	**Month**	**$T_{dew}(100)$ (^{o}C)**	**W_{100} (mm)**
Wattisham	July	22.5	64.5
Wattisham	August	22.0	62.0

Table 14. Estimates of $T_{dew}(100)$, W_{100} and maximisation ratio for Wattisham

The maximisation ratio (MR) may be calculated as shown below using the value for T_{dew}(mean) of 17.4 ^{o}C, the mean dew point temperature for August (the month in which the storm of 1912 occurred). The largest value of precipitable water is used from Table 14 as it is assumed that the storm could equally have occurred in July.

For T_{dew}(mean) = 17.4 ^{o}C, W_{mean} = 41.6 mm

For $T_{dew}(100)$ = 22.5 ^{o}C, W_{100} = 64.5 mm

So MR = W_{100} / W_{mean} = 64.5 / 41.6 = <u>1.550</u>

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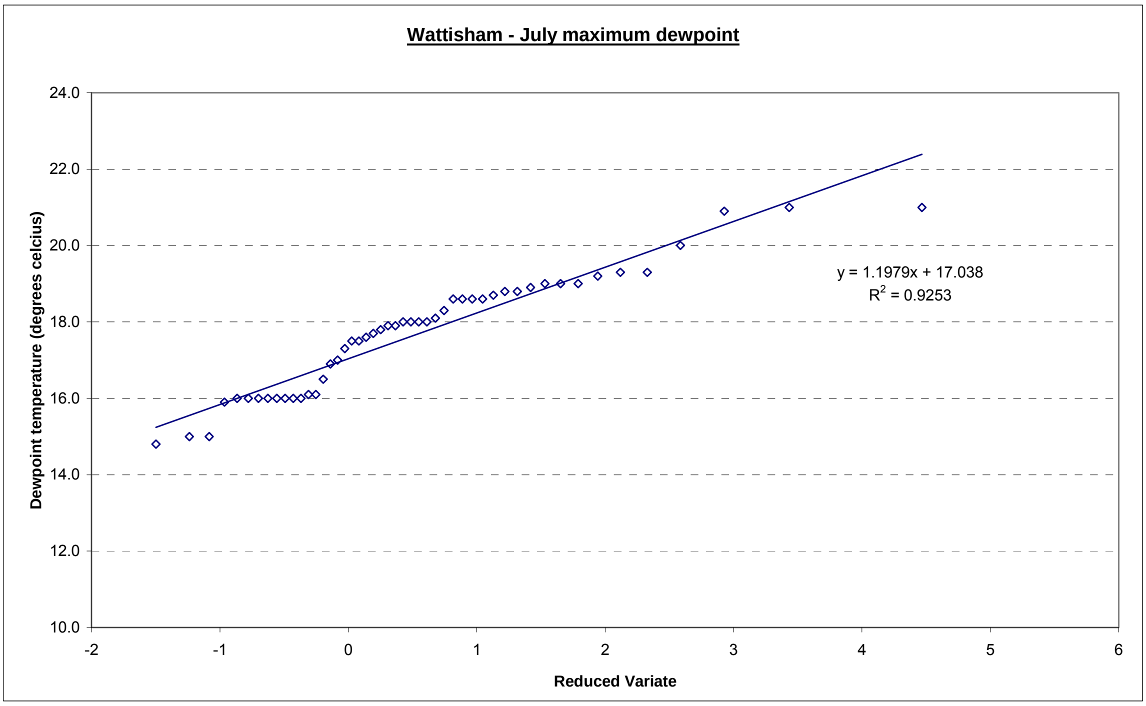
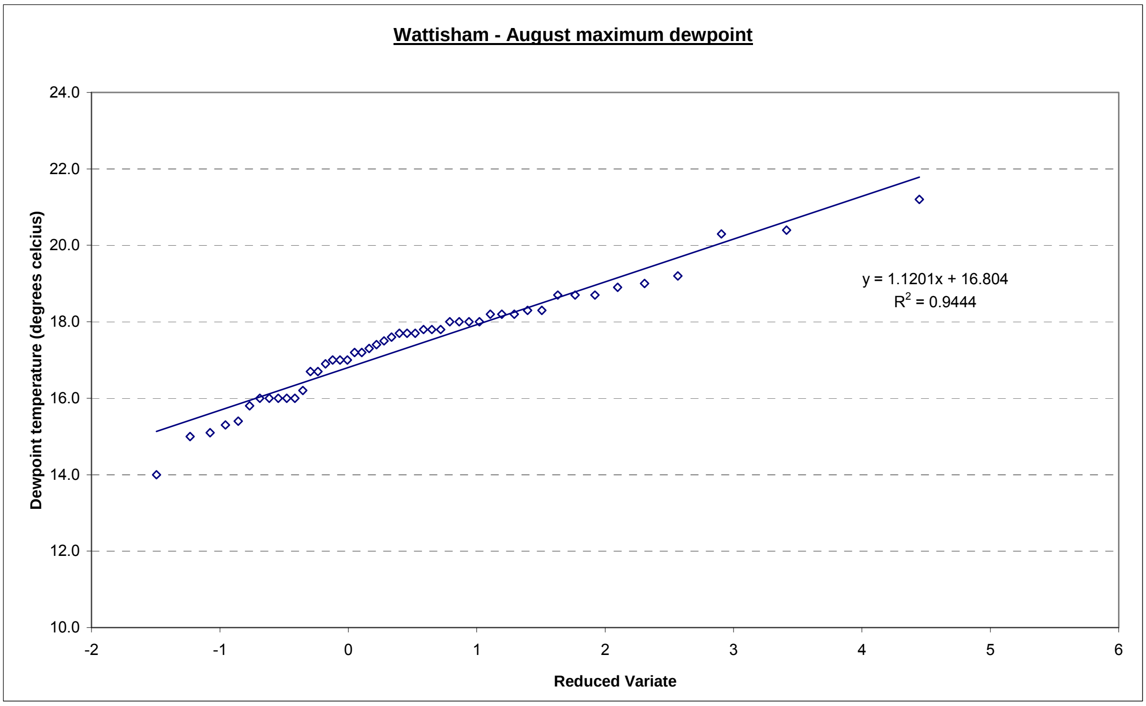


a) T_{dew} series for Wattisham, July



b) T_{dew} series for Wattisham, August

Figure 16. Examples of T_{dew} annual maximum probability plots (the Gumbel reduced variate is used here to estimate the return period of an event)

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As Sizewell and Wattisham are located close to sea level, no adjustment is required for orographic influence. Applying the maximisation ratio calculated above to the observed rainfall over 22 hours (186 mm) in 1912 yields a maximised rainfall of 288 mm (see below).

22-hour PMP = 186 x 1.550 = 288 mm

However, the estimate of $T_{dew}(100)$ is made from annual maximum 1-hour values of T_{dew}. The maximisation ratio should be adjusted to reflect the duration of the storm event. The WMO method recommends the use of 6-hour or 12-hour persistent T_{dew} values, i.e. the average of T_{dew} over those periods. Examination of persistence of dew point temperatures from several representative records at Wattisham suggests that the maximisation ratio may be reduced by a factor of 0.89 for a 24-hour period. The adjusted PMP figure for a 24-hour rainfall is given by the following calculation:

24-hour PMP = 288 x 0.89 = **256 mm**

As the maximum recorded rainfall of 186 mm at Norwich would have been treated as a 1-day value for the AMAX exceedance series should rainfall records have extended this far back in time, it is assumed that the 22-hour value of 288 mm can also be applied as a 1-day value.

7.1.2 FSR Method

The FSR method, which has not been changed by later editions of FEH, is similar to the WMO method, in that it is based on estimates of precipitable water. The process of calculation is made using graphs and tables in Chapter 4 of FSR Vol II (NERC, 1975). The starting point is the 1 in 5 year estimate of precipitable water (M5-6hr), based on 6-hour persistent dew point temperature. This statistic for the UK is presented as a map of iso-lines in Figure 3.8 of FSR, Vol II (NERC, 1975). The 1 in 5 year precipitable water for the area in which Sizewell is located is 45 mm. The point lies only a few kilometres from one of three regions estimated to have the highest amounts of M5-6hr precipitable water in the UK (in excess of 46 mm).

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FSR suggests that the maximum value of precipitable water is 20-25% greater than the M5 value: thus conservatively, the maximum precipitable water (P_w(max)) can be calculated using the following:

P_w(max) = 45 x 1.25 = <u>56.3 mm</u>

This value is only a few millimetres lower than the estimates for precipitable water from the T_{dew}(100) analyses at Wattisham, shown in Table 14 above, which are between 62.0 and 64.5 mm.

FSR bases maximisation on “storm efficiency”, which was obtained by analysing a number of major historic storms in the UK, including the Cannington/Brymore storm of 1924 (Glasspoole, 1924) assessed in Met Office (2010) for Hinkley Point. FSR recommends the multiplying of P_w(max) value by a factor of 3.86 to estimate the 2-hour PMP. Thus the 2-hour PMP value for Sizewell is:

56.3 x 3.86 = <u>217 mm</u>

FSR is not clear on the method to estimate PMP for other durations, but suggests various multipliers of average annual rainfall (AAR) (approximately 600 mm at Sizewell) and the 1 in 5 (M5) 2 day rainfall estimates. Multipliers for sub-daily storm durations are provided in generalised tables (Table 4.1 and 4.2 of FSR Vol. II (NERC, 1975), giving the following estimates:

15-minute PMP = 0.47 x 217 = **<u>102 mm</u>**

60-minute PMP = 0.83 x 217 = **<u>180 mm</u>**

The calculation to obtain the 24-hour PMP value is derived from a combination of the M5 2 day rainfall for Sizewell (48 mm), estimated using the Figure II 3.2 map in FSR, and the graph in Figure 2.4 which provides the growth factor of 5.7 based on the M5 2 day value.

24-hour PMP = 5.7 x 48 = **<u>274 mm</u>**

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7.1.3 Rapid statistical method

The Herschfield Method, described in the WMO Guide to Hydrological Practices (WMO, 1994; WMO, 2009) is a general statistical method, which is useful to check the validity of other estimates of PMP. It is specifically intended to be used to estimate PMP for point locations or small areas, and uses long-term annual maximum data. The estimation of PMP by this method is given by Equation 7,

Equation 7

$$PMP = P_{mean} + K.S_p$$

where K is a factor dependent on the magnitude of P_{mean} and duration, and S_p is the standard deviation of the annual maximum series.

It is recommended that if an annual maximum series contains one or more outliers, they should be excluded from the calculation of the mean and standard deviation. The Herschfield Method has been applied to the annual maximum daily rainfall series for Lowestoft and the combined Aldeburgh/Westleton record, in both of which no outliers were found to be present. Table 15 shows the results of the 24-hour estimate of PMP for each time series. The results are within 40 mm of each other; the larger of the two generated from the longer rainfall series available at Lowestoft. Using the longer of the two rainfall records, Table 15 gives a 24-hour PMP estimate of **290 mm**.

Location	1-day Mean (mm)	Standard deviation (mm)	K value	24-hour Mean* (mm)	24-hour PMP (mm)
Lowestoft	32.1	14.1	18	37.2	290
Aldeburgh/Westleton	33.6	11.7	18	39.0	250

Table 15. Estimates of 24-hour PMP by Herschfield Method. The value of K has been ascertained from Figure 29.3 of the WMO Manual (WMO, 1994, 2009)

* 1-day value converted to 24-hour value by multiplying by a factor of 1.16, as recommended by WMO (2009). Storm totals are therefore accumulated for any start time in a 24-hour period. This reflects reality more closely as storm events may traverse the fixed measuring periods (i.e 09-09 GMT) used at gauging sites (1-day mean value).

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As there are no observed 1-hour rainfall values from which an annual maximum series can be calculated, an approximation of the 1-hour PMP can only be estimated by using the generalised relationship between the values of K for 1 hour and 24 hours in Figure 29.3 of the WMO Guide (WMO, 1994). Using the 24-hour rainfall values, the K value for 1 hour is 12, i.e. 0.67 of the 24-hour value (K = 18). Applying this factor to the PMP estimates in Table 15 gives an average **1-hour PMP estimate of 181 mm** (the application of this factor is shown graphically in Figure 17). The straight line connecting these points can be extrapolated downwards to a duration of 15 minutes using Equation 8, where the duration (x) is in hours, and so x = 0.25 for a 15 minute period.

The application of Equation 8 provides an estimate for the 15-minute PMP of **153 mm**.

Equation 8

$$PMP = 30.113.\ln(x) + 194.3$$

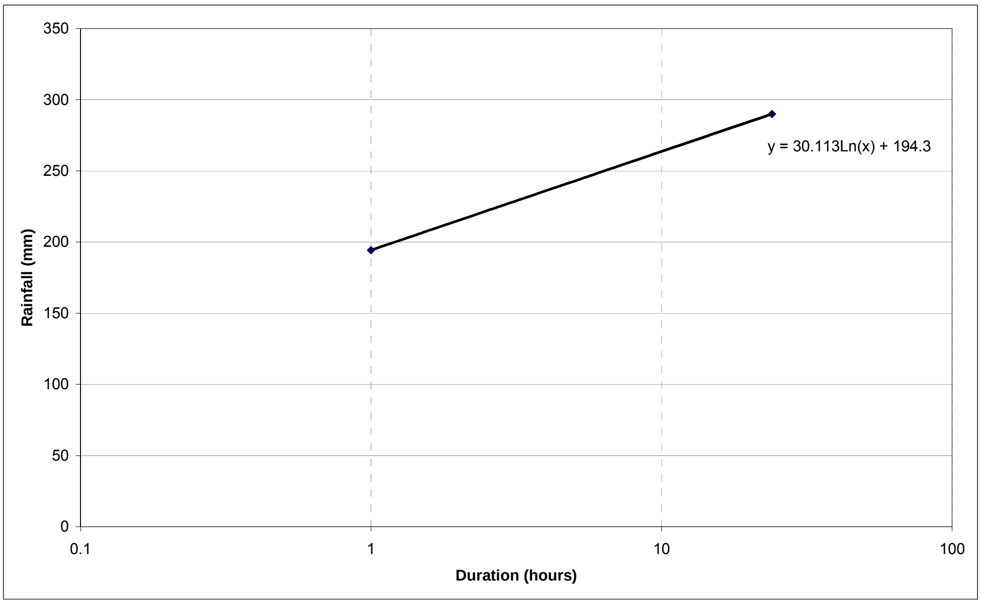

Figure 17. Relationship between 24-hour and 1-hour rainfall from WMO Guides (WMO, 1994; WMO, 2009). The 15 minute PMP value is calculated from the 1 hour value using Equation 8.

7.2 Summary of Probable Maximum Precipitation results

The three methods used in sections 7.1.1-7.1.3 to calculate PMP cannot be used in a way that all can produce consistent direct estimates of PMP at the specified time

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intervals (15 minutes, 1 hour and 1 day). Some methods use data, and others generalised factors. Given this, the range of estimates produced using the three methods are summarised in Table 16, column 2, and shown compared against the 10,000 year adjusted estimates in Figure 18.

Duration	Range of PMP estimates (mm)	10,000 year winter estimates (mm)
15 minutes	102 – 153	175.8 – 212.8
1 hour	180 – 181	208.1 – 260.2
1 day	256 - 290	301.7 – 412.6

Table 16. Range of PMP estimates and as a comparison, the range of 10,000 year winter rainfall estimates accounting for climate change (taken from Table 13, Section 5.2).

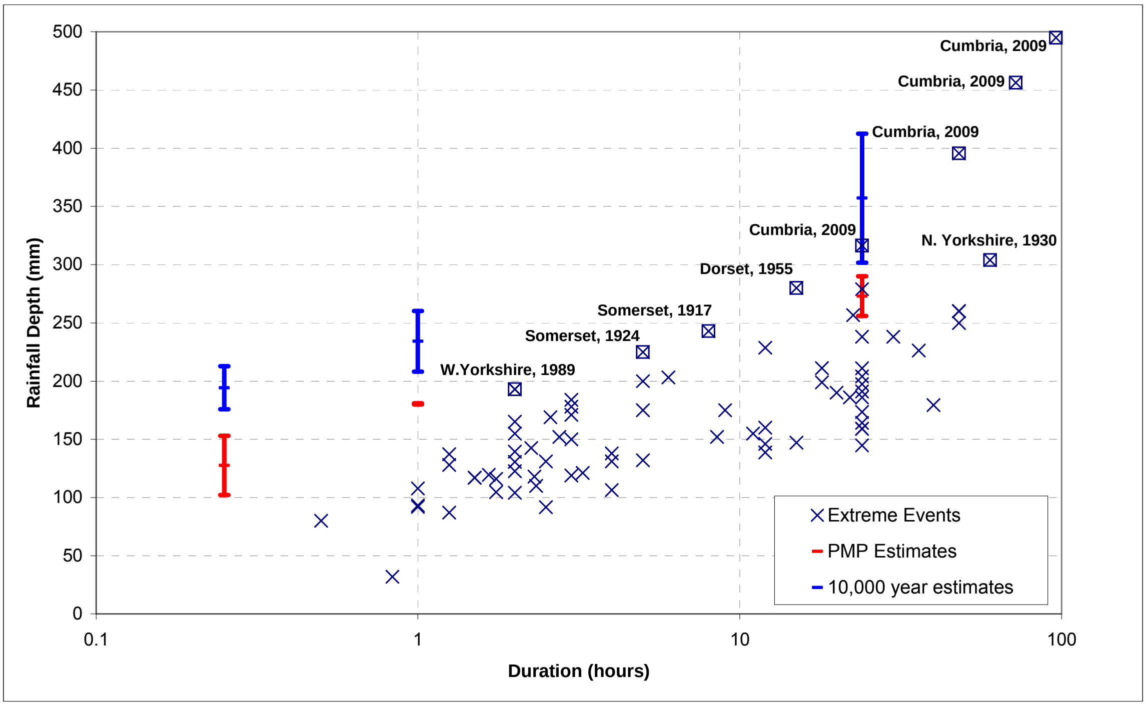

Figure 18. Range of rainfall estimates from PMP analyses (in red) compared with estimated range of 10,000 year return period rainfall at Sizewell (shown in blue). The graph also includes data for 63 of the largest rainfall events in the UK between 1900 and 2005 (reproduced from Stewart et al., 2010), plus the record rain depths recorded in Cumbria in 2009 when severe flooding and damage to properties and infrastructure occurred.

Figure 18 indicates that the range of 10,000 year rainfall estimates accounting for climate change (winter estimates) is acceptable as the results are not markedly different

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from the PMP estimates. It would be of concern if the rainfall estimates were greatly in excess of the estimated physical upper limits of precipitable water at Sizewell. Instead, the general trend is for the PMP estimates to fall just below the lower rainfall depth of the 10,000 year adjusted estimates.

The PMP estimates for Sizewell are not significantly different when compared to the PMP estimates at Hinkley Point (Met Office, 2010), though the general trend is towards lower rainfall depths at Sizewell. The main reason for this is that the depth of rainfall recorded in the storm in Norwich in 1912 is around 50 mm less than the Cannington / Brymore storm of 1924 which have been maximised in each instance. Given the similarities in dew point temperatures at both locations it is therefore not surprising that the Sizewell estimates are lower. This highlights a limitation of the WMO PMP method, the result of which is highly dependent on the choice and availability of suitably large storms for maximisation. In reality, there are few records in the UK in excess of 100 years in length which may capture suitable storms for maximisation. Furthermore, it is noted in Stewart et al (2010) that there are considerable concerns that the estimates for 10,000 year rainfall in FEH often exceed PMP estimates produced using the FSR PMP method for the same location. It has already been noted that the FEH estimates are quite high at the 1 in 10,000 year return period. Figure 18 shows the rainfall amounts of the largest storms on record in the UK. The range of rainfall depths calculated for Sizewell taking account of climate change are not significantly larger than the upper envelope of these observations which increases confidence in the derived rainfall amounts. The PMP estimates, particularly at the daily duration, fall below or within the region of this upper envelope, providing further evidence that the PMP results may be underestimates at Sizewell.

7.3 Climate Change and Probable Maximum Precipitation

The postulated future under various climate change scenarios gives a range of higher temperatures. This therefore implies that a warmer atmosphere will be capable of holding more moisture, and also implies greater thermodynamic activity. Thus dew point temperature (T_{dew}) may be expected to rise in a manner closely correlated with a rise in temperature (T). This will result in an increase in precipitable water (W). Using an increased estimate for $T_{dew}(100)$ will therefore increase the maximisation ratio W_{100}/W_s, as given in Equation 6.

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The WMO Manual (WMO, 1986) on the estimation of PMP does not include any guidance on making allowance for climate change. A new edition of the Manual has been published (WMO, 2009), however there remains no guidance as to the application of the PMP methodologies in a non-stationary climate.

8. Summary and recommendations

1 in 100, 1,000 and 10,000 year rainfall amounts for winter and summer have been estimated for Sizewell using a combination of statistical manipulation of observed data and modelled rainfall amounts. Modelled daily precipitation amounts from an 11 member regional climate model ensemble (A1B emission scenario), which were released alongside the UKCP09 climate projections, have been analysed using extreme value analysis (EVA). In this approach, a distribution defined by three parameters (called location, scale and shape) is fitted to the extreme precipitation data. One or more of the parameters may vary with climate.

To determine the climate change factors an approach was adopted to minimise the effects the natural variability inherent between each member, as investigated in the study of extreme rainfall at Hinkley Point (Met Office, 2010). Extreme value distributions were fitted to multiple samples of the input data, which were sampled in 10 year blocks with replacement (a process known as bootstrapping). The sampled extreme value parameters were then averaged for each 25 km grid box which reduced the spatial variability to a large degree but not completely. Next, the extreme distribution parameter (scale) that expressed the climate change signal (i.e. that which depends on global temperature) was averaged over a large area. For Sizewell this parameter was averaged over an area of England and Wales between the Humber Estuary and London, Sizewell falling at the centre (in the north-south direction).

During winter, all models except one project that extreme rainfall will increase. Changes in extreme summer rainfall amounts are much less certain, as several models project a decrease, whereas the remainder suggest an increase. The climate change factors for winter and summer rainfall were applied to the baseline 100, 1,000 and 10,000 year rainfall amounts, calculated using the FEH, to produce the final rainfall estimates for EDF and the ONR to consider in the context of drainage design and flood risk.

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The greatest confidence is placed in the 1 in 100 year rainfall estimates, as this return period is closest to the length of the available precipitation record. The uncertainty in the return level increases with longer return periods. In the same way, the uncertainty in the climate change factors increases with longer return periods, as the factors are calculated by dividing the future return level by the present day return level.

The calculation of PMP using three methods at Sizewell was an attempt to place an upper physical limit on precipitation. The 10,000 year rainfall estimates accounting for climate change lie above the range of estimates for PMP calculated for Sizewell however they are not significantly in excess. This provides confidence in the 10,000 year rainfall estimates.

Nevertheless, the climate change factors and projected precipitation amounts should be used with caution. There is still a large spread in the extreme precipitation amounts between the 11 models analysed here. Despite best efforts, this may still be due to a significant component of natural variability and in addition the spread may be due to the ensemble design to sample climate modelling uncertainty. The area over which the parameter containing the climate change signal has been averaged is arbitrary and is based on expert judgement of the spatial scale of the climate change signal.

The rainfall observations used come from a reasonably long record (roughly 70 years). However, it is possible that, by chance, the observations do not contain a representative sample of extreme events. There are no techniques currently available that allow an assessment of how representative a small period of data are of the "true" precipitation climatology without having access to that climatology.

The climate projections analysed in this report assume that there will not be any major volcanic activity during the 21st century (comparable to the eruption of Mt Pinatubo), and no major change in or collapse of the thermohaline circulation. These events would lead to major disruption to the UK climate. The climate projections have been generated with a single climate model. Other models may simulate different responses of UK precipitation to climate change. Similarly, climate projections using just one future emissions scenario have been analysed.

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Only 11 regional climate model simulations were produced for UKCP09. Future work at the Met Office will attempt to use the UKCP09 methodology to produce probability distributions of changes in extreme weather utilising a statistical emulator to sample all the relevant uncertainties as discussed in section 4.2. These new data will allow a much improved estimation of the “true” distribution of precipitation extremes to be obtained thereby allowing a refining of the values derived in this study and providing a more robust level of confidence.

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10. Appendix

10.1 Flood Estimation Handbook

The Flood Estimation Handbook (FEH) and accompanying software (FEH-CDROM) is the result of a concerted research effort by the Centre of Ecology and Hydrology (CEH) and its predecessor the Institute of Hydrology (IoH) and generally replaces the 1975 Flood Studies Report (FSR) (NERC, 1975). Some aspects of the FSR findings, e.g. design storm profiles and depth/area and depth/duration relationships are retained by FEH. The FEH aims to offer a consistent and clear solution to rainfall and flood frequency estimation for the analysis of historic events and, more critically, the design of structures influenced by river flow. The standard approach uses the methods and data incorporated in the FEH CD-ROM. By selection of appropriate data requirements estimates of rainfall depths for durations up to 16 days and return periods up to 10,000 years for any location or catchment in the UK can be obtained.

The FEH CD-ROM (Ver. 3.0[2]) has been utilised in this section of the study to provide rainfall depths at Sizewell. The methodology implicit in the FEH-CDROM obtains rainfall estimates based on the ‘pooling’ of representative local rain gauge records stored within the FEH within a radius from a specified point of interest. The stored records consist of AMAX (annual maxima) rainfalls of varying lengths and for durations of 1 hour to 8 days from over 6000 rain gauges in the UK. A depth-duration-frequency (DDF) model has been constructed from these data within the FEH and can confidently be applied to obtain rainfall estimates for storm durations of between 1 hour and 8 days out to a return period of 1,000 years. Any estimates beyond these confines (e.g. 15-minute rainfall durations and 10,000 year return periods) are produced by extrapolating the model and should therefore be treated with caution. Therefore the FEH results should not be applied in isolation, and analysis of local gauge records should be conducted as a method of checking. For more information regarding the underlying data sources and methodologies within the FEH, Volumes I-V of the FEH (Bayliss, 1999, Faulkner, 1999, Houghton-Carr, 1999, Reed, 1999 and Robson and Reed, 1999,) should be consulted.

[2] Although Version 2.0 was used to estimate rainfall depths at Hinkley Point the underlying rainfall data and model used in the software are the same in each version. Therefore no difference exists between the rainfall estimates obtained between each version of the software.

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10.2 Summary of rain gauge record data

Year	Months Missing
1947	Jul
1958	Nov, Dec
1986	Apr
2001	Aug
2002	Mar, Apr, May

Table 17. Summary of missing data in the digitised record at Lowestoft Farm Institute

Year	Months Missing
1967	Aug-Dec
1968	Jan-Apr, Aug-Dec
1969	Feb
1970	Dec
1971	Jan
1973	Nov
1975	Oct
1980	Feb, Sept
1981	Mar, Apr
1982	Apr
1985	Oct

Table 18. Summary of missing data in the digitised record at Aldeburgh School

Year	Months Missing
1988	Jan-Apr
2007	Feb

Table 19. Summary of missing data in the digitised record at Westleton

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10.3 Maximum likelihood estimation

Maximum likelihood estimation (MLE) is a statistical method used for fitting a statistical model to data, and providing estimates for the model's parameters. If the model parameters are known, the probability of a given event occurring may be calculated. MLE turns this concept around, and allows the likelihood of these parameters being correct to be calculated, given the data.

A simple example of MLE may be illustrated by flipping a coin. The coin will always land heads or tails, and if it is unbiased, the probability of the coin landing either heads or tails will be 0.5.

The probability of obtaining a particular number of heads and tails can be calculated using the binomial probability distribution equation, which is:

Equation 9

$$P = \frac{n!}{h!(n-h)!} p^h (1-p)^{n-h}$$

where P is the probability of a particular number of heads and tails occurring, n is the total number of times the coin is flipped, h is the number of heads obtained, and p is the probability of obtaining a heads. If the probability of obtaining a head is 0.5, then the probability of obtaining a given number of heads (= P) may be easily found from the equation.

However, instead of assuming the probability of obtaining a heads is 0.5, this probability can be estimated using MLE. Suppose the coin was flipped 100 times, and 52 heads and 48 tails were obtained (so n = 100 and h = 52). Many values of p may be used in the equation, from which corresponding values of P are obtained. Now, P is the likelihood, and the value of p which gives the greatest value of P (the maximum likelihood) is the best estimate of the value of p. The MLE value is thus the largest likelihood value, and in this simple example will be 0.52. In practice, MLE is much more complex, as the model which will be fitted to the data will have more than one unknown parameter.

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10.4 100 year precipitation tables accounting for climate change

2010 – 2039 Winter				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	1.00	37.9	50.8	97.9
0.25	1.05	38.6	52.1	102.8
0.50	1.08	39.1	52.9	105.7
0.68	1.09	39.2	53.2	106.7
0.75	1.10	39.4	53.4	107.7
0.84	1.11	39.5	53.7	108.7
0.95	1.12	39.7	54.0	109.6

2010 – 2039 Summer				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.89	36.3	47.9	87.1
0.25	0.98	37.6	50.3	95.9
0.50	1.01	38.0	51.1	98.9
0.68	1.03	38.3	51.6	100.8
0.75	1.05	38.6	52.1	102.8
0.84	1.07	38.9	52.6	104.8
0.95	1.09	39.2	53.2	106.7

2020 – 2049 Winter				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	1.01	38.0	51.1	98.9
0.25	1.07	38.9	52.6	104.8
0.50	1.10	39.4	53.4	107.7
0.68	1.12	39.7	54.0	109.6
0.75	1.12	39.7	54.0	109.6
0.84	1.14	40.0	54.5	111.6
0.95	1.16	40.2	55.0	113.6

2020 – 2049 Summer				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.86	35.8	47.1	84.2
0.25	0.98	37.6	50.3	95.9
0.50	1.02	38.2	51.3	99.9
0.68	1.04	38.5	51.9	101.8
0.75	1.07	38.9	52.6	104.8
0.84	1.10	39.4	53.4	107.7
0.95	1.12	39.7	54.0	109.6

2030 – 2059 Winter				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	1.01	38.0	51.1	98.9
0.25	1.08	39.1	52.9	105.7
0.50	1.12	39.7	54.0	109.6
0.68	1.14	40.0	54.5	111.6
0.75	1.15	40.1	54.8	112.6
0.84	1.17	40.4	55.3	114.5
0.95	1.20	40.8	56.1	117.5

2030 – 2059 Summer				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.83	35.4	46.3	81.3
0.25	0.97	37.5	50.0	95.0
0.50	1.02	38.2	51.3	99.9
0.68	1.05	38.6	52.1	102.8
0.75	1.09	39.2	53.2	106.7
0.84	1.12	39.7	54.0	109.6
0.95	1.15	40.1	54.8	112.6

Table 20. 1 in 100 year rainfall estimates (in mm) for durations of 15 minutes, 1 hour and 1 day at Sizewell by season for 2010-2039, 2020-2049 and 2030-2059 for a range of percentiles.

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2040 – 2069 Winter				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	1.01	38.0	51.1	98.9
0.25	1.10	39.4	53.4	107.7
0.50	1.14	40.0	54.5	111.6
0.68	1.17	40.4	55.3	114.5
0.75	1.18	40.5	55.5	115.5
0.84	1.21	41.0	56.3	118.5
0.95	1.24	41.4	57.1	121.4

2040 – 2069 Summer				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.80	35.0	45.5	78.3
0.25	0.97	37.5	50.0	95.0
0.50	1.02	38.2	51.3	99.9
0.68	1.06	38.8	52.4	103.8
0.75	1.10	39.4	53.4	107.7
0.84	1.14	40.0	54.5	111.6
0.95	1.18	40.5	55.5	115.5

2050 – 2079 Winter				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	1.01	38.0	51.1	98.9
0.25	1.11	39.5	53.7	108.7
0.50	1.17	40.4	55.3	114.5
0.68	1.20	40.8	56.1	117.5
0.75	1.21	41.0	56.3	118.5
0.84	1.24	41.4	57.1	121.4
0.95	1.28	42.0	58.2	125.3

2050 – 2079 Summer				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.77	34.5	44.7	75.4
0.25	0.96	37.3	49.7	94.0
0.50	1.03	38.3	51.6	100.8
0.68	1.07	38.9	52.6	104.8
0.75	1.12	39.7	54.0	109.6
0.84	1.17	40.4	55.3	114.5
0.95	1.21	41.0	56.3	118.5

2060 – 2089 Winter				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	1.01	38.0	51.1	98.9
0.25	1.13	39.8	54.2	110.6
0.50	1.19	40.7	55.8	116.5
0.68	1.22	41.1	56.6	119.4
0.75	1.24	41.4	57.1	121.4
0.84	1.27	41.9	57.9	124.3
0.95	1.31	42.4	59.0	128.2

2060 – 2089 Summer				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.75	34.2	44.2	73.4
0.25	0.96	37.3	49.7	94.0
0.50	1.03	38.3	51.6	100.8
0.68	1.08	39.1	52.9	105.7
0.75	1.14	40.0	54.5	111.6
0.84	1.19	40.7	55.8	116.5
0.95	1.23	41.3	56.9	120.4

Table 20. (continued) 1 in 100 year rainfall estimates (in mm) for durations of 15 minutes, 1 hour and 1 day at Sizewell by season for 2040-2069, 2050-2079 and 2060-2089 for a range of percentiles.

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2070 – 2099 Winter					2070 – 2099 Summer				
%ile	**Change Factor**	**15 minute**	**1 hour**	**Daily**	**%ile**	**Change Factor**	**15 minute**	**1 hour**	**Daily**
0.05	1.02	38.2	51.3	99.9	0.05	0.73	33.9	43.7	71.5
0.25	1.14	40.0	54.5	111.6	0.25	0.95	37.2	49.5	93.0
0.50	1.21	41.0	56.3	118.5	0.50	1.04	38.5	51.9	101.8
0.68	1.25	41.6	57.4	122.4	0.68	1.09	39.2	53.2	106.7
0.75	1.26	41.7	57.7	123.4	0.75	1.15	40.1	54.8	112.6
0.84	1.30	42.3	58.7	127.3	0.84	1.21	41.0	56.3	118.5
0.95	1.35	43.0	60.0	132.2	0.95	1.26	41.7	57.7	123.4

Table 20. (continued) 1 in 100 year rainfall estimates (in mm) for durations of 15 minutes, 1 hour and 1 day at Sizewell by season for 2070-2099 for a range of percentiles.

Duration	Winter	Summer
	Range of estimates (mm)	**Range of estimates (mm)**
15 minutes	37.9 – 43.0	33.9 – 41.7
1 hour	50.8 – 60.0	43.7 – 57.7
1 day	97.9 – 132.2	71.5 – 123.4

Table 21. Range of 100 year rainfall estimates accounting for climate change to 2099.

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10.5 1,000 year precipitation tables accounting for climate change

2010 – 2039 Winter				
%ile	**Change Factor**	**15 minute**	**1 hour**	**Daily**
0.05	1.00	82.2	103.6	173.7
0.25	1.05	84.1	106.7	182.4
0.50	1.07	84.9	107.9	185.9
0.68	1.09	85.7	109.2	189.3
0.75	1.09	85.7	109.2	189.3
0.84	1.10	86.1	109.8	191.1
0.95	1.12	86.9	111.0	194.5

2010 – 2039 Summer				
%ile	**Change Factor**	**15 minute**	**1 hour**	**Daily**
0.05	0.88	77.5	96.2	152.9
0.25	0.98	81.4	102.4	170.2
0.50	1.01	82.6	104.2	175.4
0.68	1.04	83.8	106.1	180.6
0.75	1.06	84.5	107.3	184.1
0.84	1.09	85.7	109.2	189.3
0.95	1.10	86.1	109.8	191.1

2020 – 2049 Winter				
%ile	**Change Factor**	**15 minute**	**1 hour**	**Daily**
0.05	1.00	82.2	103.6	173.7
0.25	1.06	84.5	107.3	184.1
0.50	1.09	85.7	109.2	189.3
0.68	1.11	86.5	110.4	192.8
0.75	1.12	86.9	111.0	194.5
0.84	1.14	87.6	112.3	198.0
0.95	1.16	88.4	113.5	201.5

2020 – 2049 Summer				
%ile	**Change Factor**	**15 minute**	**1 hour**	**Daily**
0.05	0.85	76.4	94.3	147.6
0.25	0.98	81.4	102.4	170.2
0.50	1.02	83.0	104.8	177.2
0.68	1.05	84.1	106.7	182.4
0.75	1.07	84.9	107.9	185.9
0.84	1.10	86.1	109.8	191.1
0.95	1.12	86.9	111.0	194.5

2030 – 2059 Winter				
%ile	**Change Factor**	**15 minute**	**1 hour**	**Daily**
0.05	1.00	82.2	103.6	173.7
0.25	1.07	84.9	107.9	185.9
0.50	1.11	86.5	110.4	192.8
0.68	1.14	87.6	112.3	198.0
0.75	1.15	88.0	112.9	199.8
0.84	1.17	88.8	114.1	203.2
0.95	1.20	90.0	116.0	208.4

2030 – 2059 Summer				
%ile	**Change Factor**	**15 minute**	**1 hour**	**Daily**
0.05	0.82	75.2	92.5	142.4
0.25	0.97	81.0	101.7	168.5
0.50	1.02	83.0	104.8	177.2
0.68	1.06	84.5	107.3	184.1
0.75	1.09	85.7	109.2	189.3
0.84	1.13	87.3	111.6	196.3
0.95	1.15	88.0	112.9	199.8

Table 22 - 1 in 1,000 year rainfall estimates (in mm) for durations of 15 minutes, 1 hour and 1 day at Sizewell by season for 2010-2039, 2020-2049 and 2030-2059 for a range of percentiles.

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2040 – 2069 Winter				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.99	81.8	103.0	172.0
0.25	1.09	85.7	109.2	189.3
0.50	1.14	87.6	112.3	198.0
0.68	1.17	88.8	114.1	203.2
0.75	1.18	89.2	114.7	205.0
0.84	1.20	90.0	116.0	208.4
0.95	1.24	91.5	118.4	215.4

2040 – 2069 Summer				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.79	74.0	90.6	137.2
0.25	0.97	81.0	101.7	168.5
0.50	1.03	83.4	105.5	178.9
0.68	1.07	84.9	107.9	185.9
0.75	1.11	86.5	110.4	192.8
0.84	1.15	88.0	112.9	199.8
0.95	1.19	89.6	115.3	206.7

2050 – 2079 Winter				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.99	81.8	103.0	172.0
0.25	1.10	86.1	109.8	191.1
0.50	1.16	88.4	113.5	201.5
0.68	1.19	89.6	115.3	206.7
0.75	1.21	90.4	116.6	210.2
0.84	1.23	91.1	117.8	213.7
0.95	1.27	92.7	120.3	220.6

2050 – 2079 Summer				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.76	72.9	88.8	132.0
0.25	0.96	80.6	101.1	166.8
0.50	1.03	83.4	105.5	178.9
0.68	1.08	85.3	108.5	187.6
0.75	1.13	87.3	111.6	196.3
0.84	1.18	89.2	114.7	205.0
0.95	1.22	90.8	117.2	211.9

2060 – 2089 Winter				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.99	81.8	103.0	172.0
0.25	1.12	86.9	111.0	194.5
0.50	1.18	89.2	114.7	205.0
0.68	1.22	90.8	117.2	211.9
0.75	1.23	91.1	117.8	213.7
0.84	1.26	92.3	119.7	218.9
0.95	1.31	94.3	122.8	227.5

2060 – 2089 Summer				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.74	72.1	87.5	128.5
0.25	0.96	80.6	101.1	166.8
0.50	1.03	83.4	105.5	178.9
0.68	1.10	86.1	109.8	191.1
0.75	1.15	88.0	112.9	199.8
0.84	1.20	90.0	116.0	208.4
0.95	1.25	91.9	119.0	217.1

Table 22 (continued) - 1 in 1,000 year rainfall estimates (in mm) for durations of 15 minutes, 1 hour and 1 day at Sizewell by season for 2040-2069, 2050-2079 and 2060-2089 for a range of percentiles.

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2070 – 2099 Winter				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.99	81.8	103.0	172.0
0.25	1.13	87.3	111.6	196.3
0.50	1.20	90.0	116.0	208.4
0.68	1.24	91.5	118.4	215.4
0.75	1.26	92.3	119.7	218.9
0.84	1.29	93.5	121.5	224.1
0.95	1.34	95.4	124.6	232.8

2070 – 2099 Summer				
%ile	Change Factor	15 minute	1 hour	Daily
0.05	0.71	70.9	85.7	123.3
0.25	0.95	80.3	100.5	165.0
0.50	1.04	83.8	106.1	180.6
0.68	1.10	86.1	109.8	191.1
0.75	1.16	88.4	113.5	201.5
0.84	1.22	90.8	117.2	211.9
0.95	1.27	92.7	120.3	220.6

Table 22 (continued) - 1 in 1,000 year rainfall estimates (in mm) for durations of 15 minutes, 1 hour and 1 day at Sizewell by season for 2070-2099 for a range of percentiles.

Duration	Winter	Summer
	Range of estimates (mm)	Range of estimates (mm)
15 minutes	81.8 – 95.4	70.9 – 92.7
1 hour	103.0 – 124.6	85.7 – 120.3
1 day	172.0 – 232.8	123.3 – 220.6

Table 23. Range of 1,000 year rainfall estimates accounting for climate change to 2099.

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