



Characterisation of building exposure to wind-driven rain in the UK and evaluation of current standards

Scott Allan Orr^{*}, Heather Viles

School of Geography and the Environment, University of Oxford, S Parks Rd, Oxford OX1 3QY, UK



ARTICLE INFO

Keywords:

Wind-driven rain
Meteorology
Environmental monitoring
Extreme weather events
Moisture ingress
Building envelope

ABSTRACT

One method of estimating WDR exposure is semi-empirical formulae based on hourly meteorological data including ISO 15927–3:2009 and BS 8104:1992. These provide protocols to estimate extreme WDR exposure, such as the worst spell likely to occur in any given three-year period. This study characterises the amount of annual WDR exposure and the frequency and duration of directional WDR spells for eight sites in the UK from 1986 to 2015. To assess the utility of these standards for evaluating extreme WDR exposure at those sites, the worst spell likely to occur in any given three-year period is determined using a ‘return period’ approach from extreme value analysis (EVA). It is shown that in the context of the prevailing wind patterns in the UK wall orientation is an important factor in determining the frequency and duration of WDR spell properties. EVA is applied for eight sites in the UK from 1959 to 1991 to evaluate the methods and climatic data used in BS 8104:1992 and their relevance to current climate. Both standards underestimate the volumetric exposure of the ‘once every three years’ spell compared to EVA for methodological reasons but are useful tools to assess annual exposure and compare between sites.

1. Introduction

Wind-driven rain (WDR) or driving rain is rain given a horizontal velocity component by the wind and falling obliquely (Blocken and Carmeliet, 2004). WDR represents the main source of moisture and agent of deterioration for building facades (Erkal et al., 2012).

One method of evaluating the exposure of a building façade to WDR is semi-empirical formulae. In the mid-twentieth century, it was found that the quantity of rainfall with a horizontal component that would hit a wall surface is proportional to both precipitation and wind speed (Hoppestad and Norge, 1955; Lacy and Shellard, 1962). Subsequently, this product was used to estimate relative annual exposures across the UK (Lacy, 1976), relevant to assessing average moisture contents in walls (BSI, 1992) and the potential for deep-seated wetting (McCabe et al., 2013; Smith et al., 2011).

Many mechanisms that can physically alter porous building materials—such as salt migration, crystallisation stress, and biological growth—are dependent on the presence and movement of water. Additionally, intense spells are associated with rain penetration through edges of doors or windows (ISO, 2009). For these reasons, a rain spell approach was developed by the UK Met Office and the Building Research

Establishment to evaluate building exposures and relative risk for regions of the country (BSI, 1984; Prior, 1985).

Building on the 1976 annual exposure maps (Lacy, 1976) and a rain spell methodology, isoline maps of wind-driven rain were produced for the UK in BS 8104:1992 (BS 8104) (BSI, 1992) based on hourly meteorological data from 1959 to 1991. The spell indices represent the worst spell likely to occur in any three year period. BS 8104 remains the current reference for WDR exposure in the UK.

ISO 15927–3:2009 (ISO 15927) (ISO, 2009) was developed from the methods underpinning BS8104 as a generalised calculation procedure for assessing wind-driven rain exposure, which can be applied for time periods and locations for which appropriate data is available. The worst spell likely to occur in any three year period is represented by a percentile of the spell amounts occurring in a given time period for a specific wall orientation.

Methods based on extreme value analysis (EVA) acknowledge that weather events are rarely represented by normal distributions. Therefore, traditional statistical representations (i.e. percentiles) of weather events might be skewed by extreme random phenomena and are thus not suitable for characterising extreme WDR events. Current approaches to representing extreme wind-driven events use the Gumbel distribution

^{*} Corresponding author.

E-mail address: scott.orr@ouce.ox.ac.uk (S.A. Orr).

<https://doi.org/10.1016/j.jweia.2018.07.013>

Received 29 March 2018; Received in revised form 18 July 2018; Accepted 18 July 2018

(Nadarajah and Kotz, 2004) and the concept of return periods (Gumbel, 1941). Return periods are a well-established method originally used to assess flood risk that statistically represents the probability of a certain recurrence of events. The Gumbel distribution is “perhaps the most widely applied statistical distribution for problems in engineering” [12, p. 13], and frequently used for climate applications (Nadarajah, 2006).

Return periods combined with the Gumbel distribution have been used in conjunction to evaluate extreme WDR exposure (Pérez-Bella et al., 2012; Giarma and Aravantinos, 2014). However, these studies used scalar estimations of WDR exposure, which do not incorporate wind direction and wall orientation. This is important for assessing WDR exposure in the UK, as the polar jet stream introduces strong directional trends in wind speeds and prevailing wind directions.

Accurate assessments of building exposure to extreme rainfall events (e.g. the worst spell likely to occur every three years) are a crucial component of building management. WDR spells are becoming more important with expected increases in rainfall intensity and frequency in the 21st century [(IPCC, 2013), p. 23]. In a 2011 report evaluating the need for new guidance on wind-driven rain (Reid and Garvin, 2011), BRE Scotland advised that the UK climate had not changed sufficiently to render BS 8104 irrelevant. No mention of the opacity of calculation methods is made. These changes in climate challenge the relevance and applicability of the data and methods upon which current standards are based.

This paper characterises wind-driven rain exposure for eight UK sites (Fig. 1) between 1986 and 2015. It explores the frequency of occurrence of different spells as a function of annual precipitation and wall orientation. The validity of methods used in current standards to calculate the ‘once every three years’ spell are compared with extreme value analysis. A similar comparison to extreme value analysis to evaluate extreme WDR exposure from 1959 to 1991 assesses whether the data and methods that are the basis for BS 8104 are representative of the current UK climate. Guidance is provided on how to interpret ISO 15927–3:2009 and BS

8104:1992 for design and risk assessment.

2. Methods

2.1. Climate and sites

The UK has a temperate maritime climate, characterised by westerly air flows and depressions which particularly influence the western margins. Eight sites that experience different climates were selected to be studied (Fig. 1, Table 1). These sites exhibit individual trends in prevailing wind directions but also reflect the general prevalence of south-westerly winds (Fig. 2).

Long-term hourly meteorological measurements for these eight sites from 1986 to 2015 were obtained from the UK Met Office (UK Met Office, 2006a,b), and used to evaluate the current conditions of WDR exposure. Thirty years of hourly data has been used in the majority of works in the field (Fazio et al., 1995; DEFRA, 2009) and is considered the ideal period of measurements for using ISO 15927 (ISO, 2009). Using many years of data accounts for inter-annual variability to capture the general behaviour, and 30 is the recommended length for presenting statistical parameters by the World Meteorological Organisation (Guttman, 2010).

A secondary study period of 1959¹ to 1991 was used; this enabled an evaluation of BS 8104 using periods of data comparable to that upon which it was based. For three of the study sites (Boulmer, Leuchars, and Nottingham), the appropriate data format was not available during this period. Data from the nearest sites with appropriate data were used as substitutes (Leeming, Turnhouse, and Elmdon, respectively; see Fig. 1). These ‘proxy’ sites are used to approximate the climatic conditions for Boulmer, Leuchars, and Nottingham, as they experience similar (but not identical) climates.

2.2. Calculating WDR exposure from meteorological data

2.2.1. ISO 15927–3:2009

ISO 15927 (ISO, 2009) specifies two procedures for providing an estimate of the quantity of water likely to impact on a wall of any given orientation. It uses at least 10 (but ideally 20 to 30) years of hourly measurements of precipitation, wind speed, and wind direction to calculate the WDR exposure.

The wind-driven rain exposure I in an hour is calculated as:

$$I = \frac{2}{9} v r^{8/9} \cos(D - \theta) [\text{L m}^{-2}] \quad (1)$$

from average hourly wind speed v (m s^{-1}), hourly precipitation r (mm), hourly mean wind direction D ($^\circ$) for a specific wall orientation θ ($^\circ$). This semi-empirical formula “yields the amount of WDR passing through a vertical surface in an undisturbed airstream” [1, p. 1102], and is therefore reflective of the amounts of water that are expected incident to a vertical surface, ignoring obstacles and topography. This formula for wind-driven rain loads represents a realistic estimate of the exposure of a façade, as it is derived from the average characteristics of rain drops and their aerodynamic properties (Blocken and Carmeliet, 2004).

The **annual index** I_A is the average annual WDR exposure, defined as:

$$I_A = \frac{\sum \frac{2}{9} v r^{8/9} \cos(D - \theta)}{N} [\text{L m}^{-2}] \quad (2)$$

where the summation of I is taken over all hours for which $\cos(D - \theta)$ is positive for N years, i.e. wind is intersecting the wall orientation. I_A is synonymous to the summation of Equation (1) meeting the condition $\cos(D - \theta) > 0$ divided by the N years of data. The annual index I_A should be used for “considering the average moisture content of exposed building material or when assessing the likely growth of mosses and



Fig. 1. The sites evaluated in this study.

¹ Limited availability for Leeming, 1965 to 1991.

Table 1

Climatic data availability and basic meteorological and geographical characteristics of the study sites.

| Name | Time period | | Precipitation ^a | Elevation | Approximate distance from coast |
|------------|-------------|-----------|----------------------------|-----------|---------------------------------|
| | 1959–1991 | 1986–2015 | mm year ⁻¹ | m | km |
| Stornoway | X | X | 1187 | 14 | <5 |
| Leuchars | | X | 695 | 12 | <5 |
| Turnhouse | X | | 646 | 35 | <5 |
| Aldergrove | X | X | 854 | 62 | 20 |
| Boulmer | | X | 701 | 24 | <5 |
| Leeming | X | | 535 | 33 | 50 |
| Heathrow | X | X | 681 | 25 | 100 |
| Nottingham | | X | 849 | 118 | 100 |
| Elmdon | X | | 651 | 95 | 150 |
| Plymouth | X | X | 967 | 45 | <5 |
| Valley | X | X | 836 | 11 | <5 |

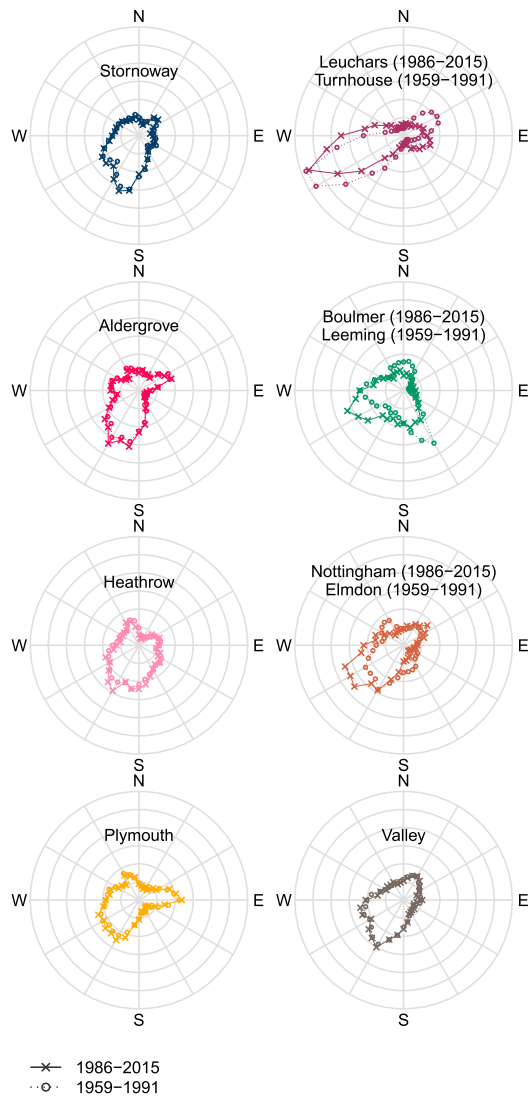
^a Over the specified time periods.

Fig. 2. Prevailing wind directions (represented by relative occurrence) for eight UK sites, based on measured hourly wind directions (UK Met Office, 2006a,b) from 1986 to 2015 and 1959 to 1991. For three sites, approximate ‘proxy’ climatic data from nearby sites has been used due to data availability.

lichens” [6, p. 4].

A **spell-specific index** I'_S is calculated for periods of WDR exposure which are separated by 96 h or more of no wind-driven rain exposure:

$$I'_S = \sum \frac{2}{9} vr^{8/9} \cos(D - \theta) [\text{L m}^{-2}] \quad (3)$$

where the summation is taken over all hours for which $\cos(D - \theta)$ is positive, i.e. wind is intersecting the wall orientation.

The **spell index** I_S represents the worst spell likely to occur in any given three year period. ISO 15927 represents I_S as the 67th percentile of the I'_S values, i.e. the value for which 33% of the I'_S values are higher. The spell index is representative of the risk of “rain penetration through masonry, which requires a prolonged input of water” [9, p. 12].

Using percentiles to represent an event with a respective rate of occurrence implies that the frequency of events in a given time period n is known. For example, if there are 60 spells occurring in one year, the worst spell likely to occur could be represented by the amount of WDR exposure below which 59 of the spell amounts may be found, i.e. $59/60 \times 100\% = 98.3$. More generally, this percentile P is represented by $(n - 1)/n \times 100\%$. If there were 75 spells occurring in a three year period, the worst spell (highest amount) to occur in that period would be represented by $(75 - 1)/75 \times 100\% = 98.6$. Therefore, the percentile representing the worst spell likely to occur in a three year period is dependent on the frequency of occurrence, i.e. how many spells are occurring. Although ISO 15927 does not use $(n - 1)/n$ to determine the percentile that represents the worst spell likely to occur in any three year period, this formula and example demonstrate the potential effect of natural variation in annual event occurrence on extreme events determined from percentiles.

Equations (1)–(3) include the wall orientation as part of the calculations. This means that the annual index and the spell index are directional metrics that do not apply to all orientations of a wall at a given site. Both I_A and I_S as presented here represent airfield conditions: WDR that would occur at a height of 10 m above ground level in the middle of an airfield with no other obstructions. To estimate the exposure for a specific façade, factors are provided in ISO 15927 that can be applied to the indices to account for terrain roughness, topography, obstructions, and the wall context.

2.2.2. BS 8104:1992

BS 8104 uses reference isoline maps to calculate WDR exposure in the UK. The reference maps divide the UK into subregions of similar WDR characteristics centred around pivotal sites. The subregions are divided further into geographical increments i to represent local variation. As in ISO 15927, the annual index I_A and spell index I_S are used. The procedure to determine values of I_A and I_S for a location is (BSI, 1992):

1. Look at the appropriate wind-driven rain map in Appendix B of BS 8104. Find the subregion in which the site is located. Find the geographical increment i for the site of interest. These increments are shown between contour lines.
2. Examine the rose for the particular subregion and method (I_A or I_S). Each rose gives 12 values corresponding to different orientations.

Select the rose value r nearest to the orientation of the façade of interest

3. Add the rose value to the geographical increment to obtain the map value of I_A ($m_A = r_A + i$) and/or I_S ($m_S = r_S + i$).

If a site lies on a boundary of a subregion, contour, or orientation, the higher of the two figures should be taken. If desired, reducing factors can be applied to account for terrain roughness, topography, obstruction, and wall context.

The map value $m = i + r$ is provided for either the spell (m_s) or annual (m_a) index, which represents the conditions for a given wall orientation at a pivotal site, modified slightly to account for local variation. The annual index I_A in $L\ m^{-2}$ can be calculated from its respective map value m_A :

$$m_A = 6 + 19.93 \log_{10}(I_A/200) \quad (4)$$

The spell index I_S in $L\ m^{-2}$ can be similarly calculated from its respective map value m_S :

$$m_S = 10 + 19.93 \log_{10}(I_S/20) \quad (5)$$

The formula used to estimate hourly wind-driven rain exposure in BS 8104 is a simpler representation of WDR exposure than that used in ISO 15927 (Equation (1)). It is the product of hourly velocity and precipitation with the cosine of the prevailing wind direction and the wall orientation $I = rv \cos(D - \theta)$. This provides a “reasonably precise method of comparing different sites with respect to total amounts of WDR on walls” (Lacy, 1977), but does not estimate the actual exposure to WDR (Lacy, 1965).

2.2.3. Applying extreme value analysis to WDR spell exposure

To assess extreme WDR exposure, this study applied extreme value analysis (Fisher and Tippett, 1928; Smith, 1990). It is an established method used in environmental applications (e.g. (Smith, 1989)) to evaluate extreme deviations from the median of probability distributions. There are two practical approaches to using this technique to evaluate weather events:

- Generating an “Annual Maxima Series” (AMS) (Cunnane, 1973), i.e. the maximum values of the weather event occurring in individual years
- Using the “Peak Over Threshold” method (Leadbetter, 1991), where peak values over a certain threshold are recorded

It is difficult to define thresholds for WDR exposure that would represent clear impacts on a building envelope. Penetration through masonry constructions is a complex process that is dependent on a number of variables in addition to the amount of water hitting a surface during the spell. For this reason, the AMS is more appropriate for assessing WDR events.

The AMS approach can be combined with the concept of ‘return periods’, a classic technique to evaluate the occurrence of extreme weather events such as floods (Gumbel, 1941). A return period is an estimate of the likelihood of an event, which can also be thought of as an ‘expected frequency’. It can be converted into a probability of exceeding that value in any given year. For example a ‘once every three years’ spell has the probability p of occurring in any given year equal to $1/3 = 0.33$. It is likely that the 67th percentile in ISO 15927 is representing the value for which $1/3$ of amounts are higher. However, probabilities and percentiles should not be directly compared. A probability represents the likelihood of exceeding a spell amount in a single year within a given three-year period, but this does not imply that this value will be exceeded every three years (or in any specific three-year period). As discussed in Section 2.2.2, a percentile representing the occurrence of an extreme event is based on an amount of WDR that was exceeded once in a specific three-year period and is dependent on the number of spells.

Table 2

AMS values for a north-oriented wall in Stornoway between 1986 and 2015.

| Year | Maximum value of I'_S $L\ m^{-2}$ | Year | Maximum value of I'_S $L\ m^{-2}$ |
|------|----------------------------------------|------|----------------------------------------|
| 1986 | 44.95 | 2001 | 59.51 |
| 1987 | 121.8 | 2002 | 67.39 |
| 1988 | 106.8 | 2003 | 100.4 |
| 1989 | 151.7 | 2004 | 55.38 |
| 1990 | 31.26 | 2005 | 184.2 |
| 1991 | 56.79 | 2006 | 160.0 |
| 1992 | 63.71 | 2007 | 141.4 |
| 1993 | 106.9 | 2008 | 101.7 |
| 1994 | 40.44 | 2009 | 109.3 |
| 1995 | 67.78 | 2010 | 63.08 |
| 1996 | 99.76 | 2011 | 49.48 |
| 1997 | 66.79 | 2012 | 63.13 |
| 1998 | 162.6 | 2013 | 56.77 |
| 1999 | 69.65 | 2014 | 95.98 |
| 2000 | 73.94 | 2015 | 59.96 |

The AMS method has previously been applied to evaluate the ‘once every three years’ spell in Spain (Pérez-Bella et al., 2012, 2013). The semi-empirical calculation from ISO 15927 of hourly exposure (Equation (1)) is used, with periods of 96 h or more without WDR exposure between spells. This representation is analogous to the ‘wind-driven rain relationship’ described by Blocken and Carmeliet (Blocken and Carmeliet, 2004).

Pérez-Bella et al. used a scalar daily parameter, but defined spells as separated by 4 days (96 h) without precipitation (Pérez-Bella et al., 2012, 2013). This daily scalar value was found to correlate well with I'_S values calculated from hourly [scalar] data. However, this method does not incorporate the directional properties of WDR spells, which are an important consideration in the UK context (see Section 2.1).

The ‘expected frequency’ approach can be combined with a probability distribution of extreme values, such as the Gumbel distribution (Gumbel, 1958). In this way, it is possible to determine the spell exposure likely to be exceeded in any given three year period. One benefit of the AMS method is that the results are independent of the ‘population size’ (number of spells), i.e. comparisons can be made between sites and time periods that experience different numbers of spells.

Worked example of the AMS method. 768 WDR spells were calculated to occur in Stornoway between 1986 and 2015 for a wall oriented north.² From these, the AMS values (the highest spell exposure occurring in each year) can be determined (Table 2).

The cumulative distribution function for the Gumbel distribution is (Gumbel, 1941, 1958):

$$f(\alpha, x^*, u) = e^{-e^{-\alpha(x^* - u)}} \quad (6)$$

in which x^* is the WDR exposure likely to be exceeded in the return period. The average of the AMS values $\bar{x} = 87.75$ has a standard deviation $\sigma_x = 40.19$. u is the mode. α is the dispersion parameter, which is a ratio of the standard deviations of the population and a reduced variable population:

$$\alpha = \frac{\sigma_y}{\sigma_x} = \frac{\sqrt{\sum \frac{(x_i - \bar{x})^2}{N}}}{\sum \frac{(y_i - \bar{y})^2}{N}} \quad (7)$$

The reduced variable is only a function of the number of years N , indicated by $i = 1, 2, \dots, 30$:

$$y_i = -\ln \left(\ln \left(\frac{N+1}{i} \right) \right) \quad (8)$$

² Spells that occurred across calendar years were allocated to the year in which the majority of the hours within the spell occurred.

for which the reduced variable data average from $\bar{y} = 0.536$ and standard deviation $\sigma_y = 1.131$. Therefore $\alpha = \sigma_y/\sigma_x = 0.02815$. The mode u is calculated by:

$$u = \bar{x} - \bar{y} \frac{1}{\alpha} = 68.70 \quad (9)$$

A return period of three years implies a probability of occurrence $p \approx 0.67$. Therefore, the WDR x^* that is likely to be exceeded once every three years = $1 - p = 0.33$:

$$\begin{aligned} 0.33 &= 1 - f(\alpha, x^*, u) \\ &= e^{-e^{-\alpha(x^* - u)}} \\ &= e^{-e^{-0.02815(x^* - 68.70)}} \end{aligned} \quad (10)$$

which can be solved to show $x^* = 100.8 \text{ L m}^{-2}$. This represents I_5 : the WDR exposure likely to be exceeded once in any given three year period. A generalised and rearranged form can be used to calculate the I_5 from a set of AMS values:

$$x^* = \frac{-1}{\alpha} \ln \left(\ln \left(\frac{1}{1-p} \right) \right) + u \quad (11)$$

3. Results

3.1. Annual frequency of wind-driven rain spells

These eight sites across the UK experience an average of 14–30 WDR spells per year, depending on the annual precipitation and wall orientation (Fig. 3). How many rain spells there are in a given year is determined by several factors. By definition, it is dependent on the grouping and frequency of precipitation, as well as predominant wind directions. Fig. 3 demonstrates that there is an inverse relationship between the average annual precipitation and the numbers of spells that occur. The higher the precipitation, the less likely it is that there will be a period of 96 h or more without any WDR exposure. In general, fewer but longer spells are experienced by south-western oriented façades, as they are hit more frequently by prevailing winds in the UK. Exposed locations such as Stornoway have fewer rain spells than other sites, as periods of 96 h or more without driving rain are less frequent due to higher annual precipitation.

For wall orientations that do not intersect with prevailing wind directions (i.e. $\theta = 0$ to 90° , northerly and easterly façades) the number of spells per year is between 24 and 30. There is a greater variation between the sites for southwestern façades (14–23) and there is consistently fewer spells occurring than on their northeasterly counterparts. If a scalar (non-

directional) index is used (e.g. (Pérez-Bella et al., 2012)), fewer spells could be expected. This is because a scalar representation of WDR exposure incorporates all precipitation as WDR exposure. In contrast, a directional representation of WDR exposure allows for precipitation to occur without having WDR exposure, if the wind direction is not intersecting with a given wall orientation.

The significant variation in the number of spells occurring for different sites and wall orientations demonstrates the limitations of percentile representation of extreme WDR events, since the percentiles representing extreme events are dependent on their frequency of occurrence. As well, percentiles are only accurate for determining the frequency of events if the exact number of spells occurring during the period are known. If long-term averages of annual frequency are extrapolated to a three year period, calculations resulting from percentiles will be estimations of extreme events. For example, from 1986 to 2015 a façade oriented to 120° in Stornoway experienced an average of approximately 20 spells per year. If this is extrapolated to 2002 to 2004, the ‘once every three years’ spell is represented by $P = (60 - 1)/60 \times 100\% = 98.3$. However, from 2013 to 2015 this site only experienced 54 spells (as defined by ISO 15927). Then, the accurate percentile representation of the ‘once every three years’ spell would be the $P = (54 - 1)/54 \times 100\% = 98.1$. Based on accurate event occurrence at this site and orientation from 1997 to 1999 $P = 98.5$ ($n = 69$). In both of these cases, using $n = 60$ would approximate, but not represent, the worst spell that occurred in these three year periods. For the sites and orientations included here, the ‘once every three years’ spell could be represented by percentiles ranging from $P = 97.6$ to 98.8 . In these cases, the percentiles could be heavily influenced by extreme random phenomena.

3.2. Duration of wind-driven rain spells

Based on the assessment of spell length at eight sites from 1986 to 2015, short spells are most common. The distribution of the duration of WDR spells is primarily driven by the wall orientation (and therefore prevailing wind direction), but is also dependent on the annual precipitation (Fig. 4). By comparing Figs. 3 and 4, it can be seen that spells tend to be longer for wall orientations that experience fewer spells. Exposed regions with higher annual precipitation will have more longer spells compared to sites with lower levels of precipitation. For example, Fig. 4 shows that a south-facing façade at Stornoway experienced 40 WDR spells lasting between 1000 and 2000 h, while a façade oriented similarly at Heathrow experienced 10. Conversely, the same wall orientation in Stornoway experienced 200 spells lasting less than 100 h while its Heathrow counterpart experienced twice as many. The average time between sequential WDR spells was between 7.38 and 11.5 days. There is

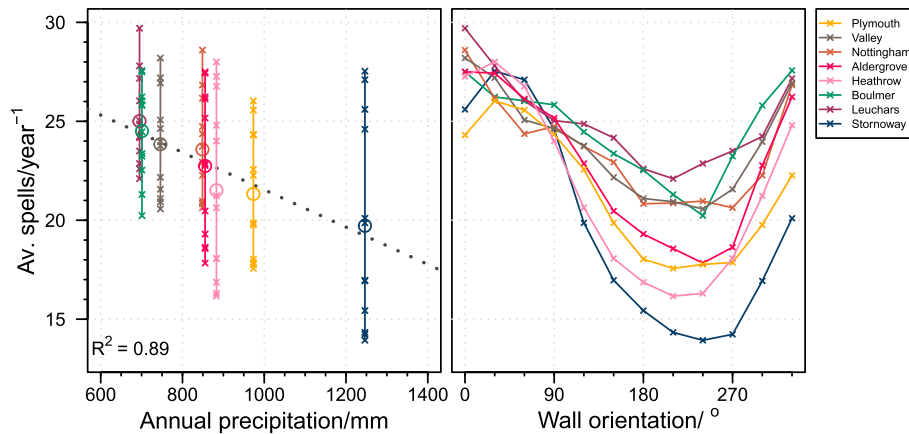


Fig. 3. The number of wind-driven rain spells occurring at different sites in the UK from 1986 to 2015, as a function of average annual precipitation (left) and wall orientation (right). The linear fit of annual precipitation and average number of spells per year was taken on the average value across all wall orientations, represented by open circles. Smaller x's represent the average annual number of spells for different orientations at the respective site.

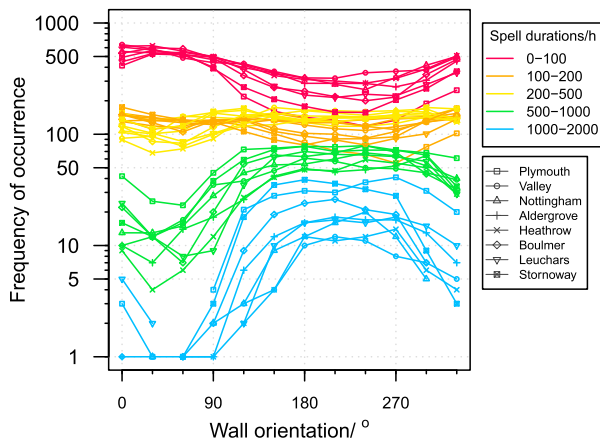


Fig. 4. Frequency of occurrence of wind-driven rain spells of different lengths for eight UK sites at 12 wall orientations between 1986 and 2015.

no clear relationship between this inter-spell time and annual precipitation, wall orientation, or prevailing wind directions.

3.3. Amount of wind-driven rain

The amount of annual indices $I_{A,ISO15927}$ (as calculated from ISO 15927, i.e. Equation (2) applied to the hourly meteorological data) and spell indices $I_{S,EVA}$ (from extreme value analysis) varied between 110 and 1212 $L m^{-2}$ and 31 and 494 $L m^{-2}$, respectively, across the eight sites from 1986 to 2015 (Fig. 5). This was dependent on site characteristics and wall orientations. The most extreme exposures impacted southern and western wall orientations for western coastal sites. In contrast, the exposures for northern and eastern wall orientations were more homogenous across sites.

The WDR exposures can be characterised by group properties according to the amount and distribution across wall orientations (Table 3). The distinctions are driven primarily by a contrast between eastern and western sites, with an influence from coastal proximity. Additionally, the sites do not universally experience the highest exposures for southern and eastern wall orientations. Specifically, the eastern coastal sites (Leuchars and Boulmer) have the highest exposures for eastern façades, despite having southern and western prevailing wind directions. This is likely influenced by increased wind speeds for these orientations: even though easterly winds are occurring less frequently, they are more likely occurring in conjunction with higher wind speeds.

The $I_{S,EVA}$ values as determined from extreme value analysis are a significant component of the total (annual) exposure. Across all wall orientations the WDR exposure during the ‘once every three years’ spell is equivalent to at least 25% of the average annual exposure ($I_{A,ISO15927}$), and can be as much 50% in Plymouth.

3.4. Applicability of current standards

Two aspects of semi-empirical WDR standards affect their applicability to current design and risk analysis: changes in climate and calculation methodologies. To assess the similarity of the data used as the basis for BS 8104 to the more recent climate, the methods described in Section 2.2.3 are employed for meteorological data from 1959 to 1991. The amount of the annual ($I_{A,ISO15927}$) and spell indices ($I_{S,EVA}$) are compared to the equivalent indices for 1986 to 2015 (Section 3.4.1). The methods for calculating extreme event exposure are investigated by comparing the I_S values from ‘once every three years’ spell in BS 8104 and ISO 15927 with spell amounts from extreme value analysis during both time periods.

3.4.1. Change in climate

BS 8104 is based on climatic data from 1959 to 1991. As BS 8104 is a

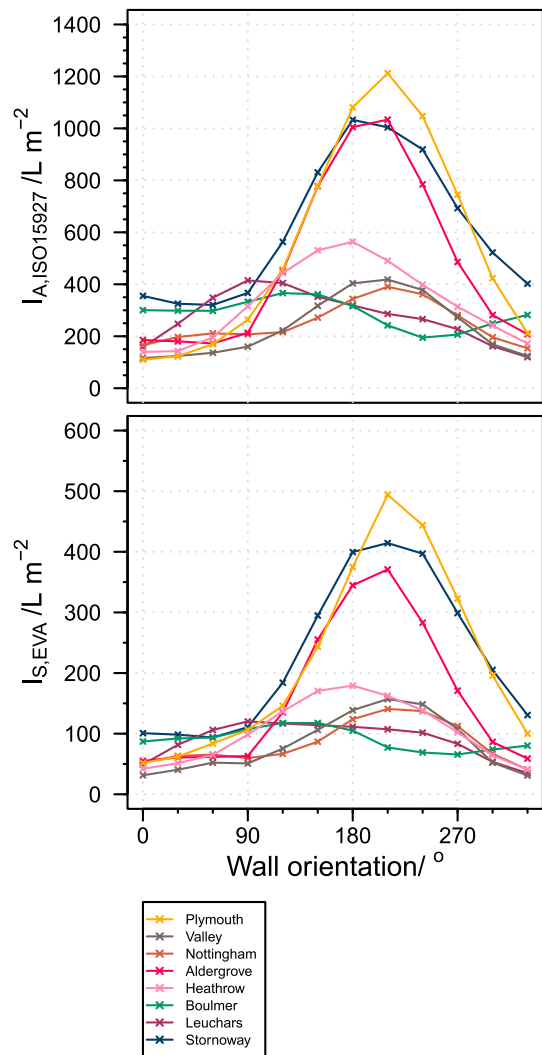


Fig. 5. Wind-driven rain exposure at eight UK sites for 12 different wall orientations (0° = north) between 1986 and 2015. Upper: Annual index I_A . Lower: Spell index ($I_{S,EVA}$), which is the statistical ‘once every three years’ spell.

Table 3

Sites WDR exposures characterised by group properties according to the amount and distribution across wall orientations.

| Group | Sites | WDR exposure (I_A and I_S) | Modal distribution |
|-----------------------|-----------------------------|-----------------------------------------------|-----------------------------------------|
| Western coastal sites | Plymouth, Valley, Stornoway | very high annual and spell exposure | steep, modes at $180\text{--}240^\circ$ |
| Eastern sites | Heathrow and Nottingham | low annual and spell exposure | broad, modes at 210° |
| Eastern coastal sites | Leuchars and Boulmer | low annual and spell exposure | broad, modes at 90° ^a |
| No group | Aldergrove | mid-range annual exposure, low spell exposure | broad, mode at 180° |

^a More prominent for annual index I_A

current tool used for design and assessment, it is important to determine if the conditions of WDR exposure during this period are representative of a more recent climate. To this end, $I_{A,ISO15927}$ and $I_{S,EVA}$ have been calculated for the same (or nearby) sites from 1959 to 1991.

For most sites the difference between $I_{A,ISO15927}$ and $I_{S,EVA}$ values between 1959 to 1991 and 1986 to 2015 was less than $50 L m^{-2}$, regardless

of wall orientation (Fig. 6). More recently Plymouth experienced significantly higher ‘once every three years’ spell for southern and western façades, while Stornoway saw a significant decrease in these extreme events for similar façades. Valley also experienced a more moderate (100 L m^{-2}) increase in the $I_{S,EVA}$ exposure for southern façades. The Met Office records do not indicate any changes in the location of these monitoring stations (UK Met Office, 2006a,b), suggesting that these changes in $I_{S,EVA}$ are attributable to a change in climate.

The changes in $I_{A,ISO15927}$ and $I_{S,EVA}$ represented by dashed lines in Fig. 6 are affected by local climate variation and should be taken with caution. They were calculated from different sites for the two periods due to data availability (see Fig. 1). This is demonstrated by the distributions of $\Delta I_{A,ISO15927}$ and $\Delta I_{S,EVA}$ across wall orientations experienced at these sites for 1959 to 1991 (Fig. 6). Turnhouse appears to be bimodal, with a prominent mode around 240° equal to that observed around 90° from 1986 to 2015. In 1959 to 1991 the mode of the distribution for Leeming $I_{A,ISO15927}$ is shifted to 120 to 150° , contrasting that identified for Boulmer from 1986 to 2015 centred around 90° . The distribution of spell durations and inter-spell periods do not vary significantly between 1959 to 1991 and 1986 to 2015. Although it is unknown how weather systems or the position of storm tracks are expected to change during the twenty-first century (Murphy et al., 2009), this supports the current consensus that weather patterns are not changing and that natural variability has a greater impact than climate change (Eames et al., 2011). This is likely due to negligible expected change in established wind patterns in the UK, including the dominating effect of the polar jet stream.

The comparison of $I_{A,ISO15927}$ and $I_{S,EVA}$ values between the two timelines suggests the meteorological data used to produce BS 8104 is

representative of more recent characteristics of the UK climate. However, the significant changes for the country's most extreme exposures perhaps indicates that these standards might be increasingly out of date for design and risk assessment. The validity of mid-to-late twentieth century meteorological data for representing the current climate should be revisited periodically to determine whether they remain a relevant tool.

3.4.2. Evaluation of current standards' methods for calculating extreme event exposure

BS 8104 and ISO 15927 include procedures to determine the ‘once every three years’ spell. Using the climatic data used to determine $I_{S,EVA}$ from extreme value analysis, the ‘once every three years’ spell is calculated from each of these standards. These are compared to the values of $I_{S,EVA}$ to evaluate their methodologies of calculating extreme event exposure.

The methods in BS 8104 and ISO 15927 are underestimating the ‘once every three years’ spell amounts, compared to extreme value analysis (Fig. 7). For ISO 15927, taking the 67th percentile of I'_S values as the ‘once every three years’ spell is underestimating I_S exposure in the UK by roughly an order of magnitude. The reference maps used in BS 8104 are much closer to the $I_{S,EVA}$ values calculated from EVA. However, distances from the 1:1 ratio line in Fig. 7 can represent significant differences, and must be interpreted according to the logarithmic axis.

During both study time periods, the higher exposures of western coastal sites (Stornoway, Valley, and Plymouth) are significantly underestimated. For example, the comparison of I_S values in the bottom-left plot of Fig. 7 is based on meteorological data from 1959 to 1991. The values of $I_{S,EVA}$ for Stornoway (wall orientations 180 to 240°) range from

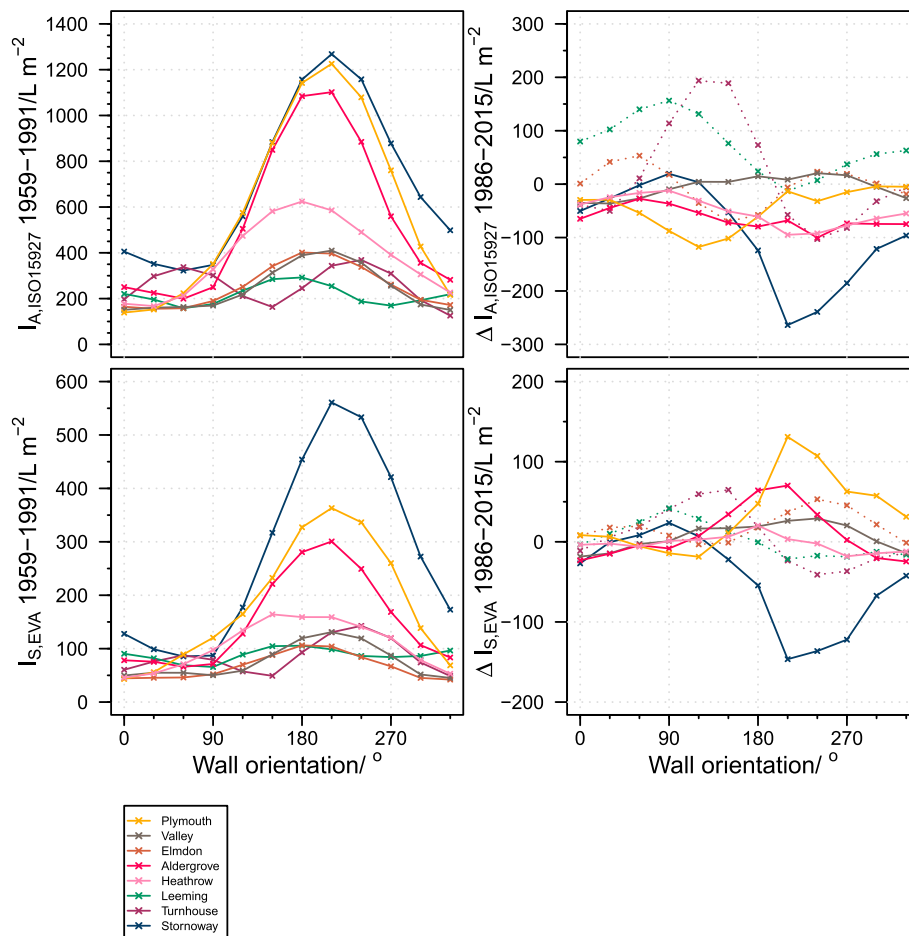


Fig. 6. Left: wind-driven rain exposure for eight UK sites for 12 different wall orientations (0° = north) from 1959 to 1991. Right: absolute changes in I_A and $I_{S,EVA}$ for 1986 to 2015 from 1959 to 1991.

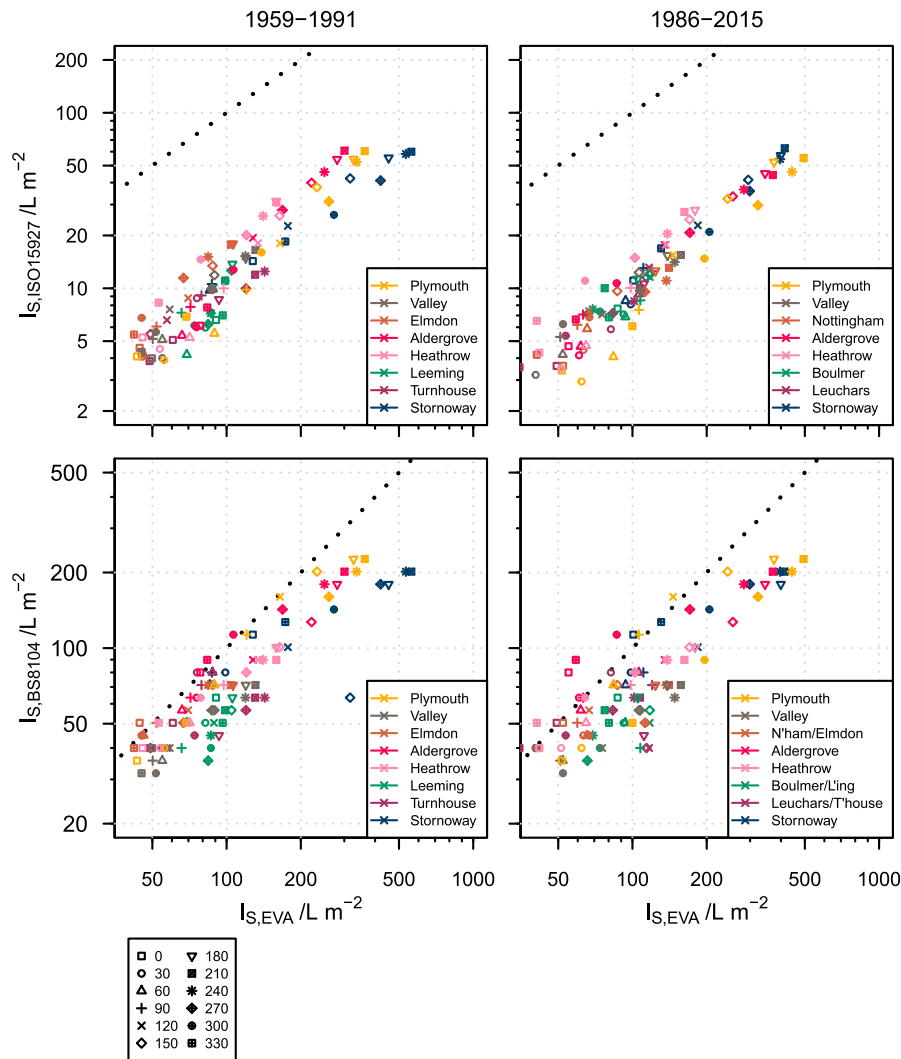


Fig. 7. A comparison of the ‘once every three years’ spell calculated from ISO 15927, BS 8104, and extreme values analysis for 1959 to 1991 and 1986 to 2015. The black dotted line denotes a 1:1 ratio. In the bottom right plot, the legend items with two names refer to the site for BS 8104 and EVA, respectively.

approximately 400 to 600 L m^{-2} . In contrast, BS 8104 calculations estimate these exposures to range from 180 to 200 L m^{-2} . Similar conclusions can be drawn for Plymouth and Valley during both time periods.

The BS 8104 I_s exposures calculated from 1959 to 1991 are more similar to those calculated from EVA during 1986–2015 than those calculated from the same time period. Although many aspects of the development of BS 8104 are documented (through (Lacy, 1976; Prior, 1985) etc.), how the ‘once every three years’ spell was determined is unclear. Without more information on this, it is difficult to discuss contrasts between BS 8104 and EVA in greater detail.

Comparing the calculated values of I_s from BS 8104 and ISO 15927 with $I_{s,EVA}$ is one method of evaluating the amount of WDR exposure determined by these standards. Another method is to convert the $I_{s,BS8104}$ and $I_{s,ISO15927}$ into equivalent return periods. This can be done by taking x^* in Equation (11) to be the calculated ‘once every three years’ spell from each standard. u and α are determined from the AMS series determined from extreme value analysis for that site and wall orientation. Then, the value of p can be solved for: this represents the probability that the value is exceeded in any given year. The ‘equivalent return period’ is represented by $1/p$. In this way, the equivalent return period is indicative of a point on the probability distribution function of annual maxima as determined from AMS. If the I_s calculated from a standard were equivalent to those calculated from EVA the probability of exceeding them in any given year would be $1/3$, equivalent to a return period of 3 years. It

should be noted that the ‘equivalent return periods’ are based on distributions determined from the AMS series, which do include the I_s values calculated from BS 8104 and ISO 15927: these ‘equivalent’ values should be considered as indicative values.

The probabilities of exceeding the ‘once every three years’ spells from ISO 15927 and BS 8104 and equivalent return periods are presented in Fig. 8. The probability of exceeding I_s as calculated from ISO 15927 in any one year is minimally variable, and is within 0.55 and 0.65. This is equivalent to a range of return periods between 1.48 and 1.81 years. The probability of exceeding I_s as calculated from BS 8104 exhibits a wider range and a strong dependency on wall orientation. The equivalent return periods range between 1 and 10 for $I_{s,BS8104}$. Fig. 8 suggests that the unclear methods originally used to compute the ‘once every three years’ spell in BS 8104 are especially unsuitable for wall orientations that typically have higher exposures, i.e. southern and western façades.

4. Discussion

The results presented here demonstrate that extreme WDR events for some regions of the UK are likely underestimated by ISO 15927 and BS 8104 when compared to the extreme value analysis approach. This section provides guidance on interpreting their output and discusses their applicability in current use.

WDR indices were originally proposed and developed for

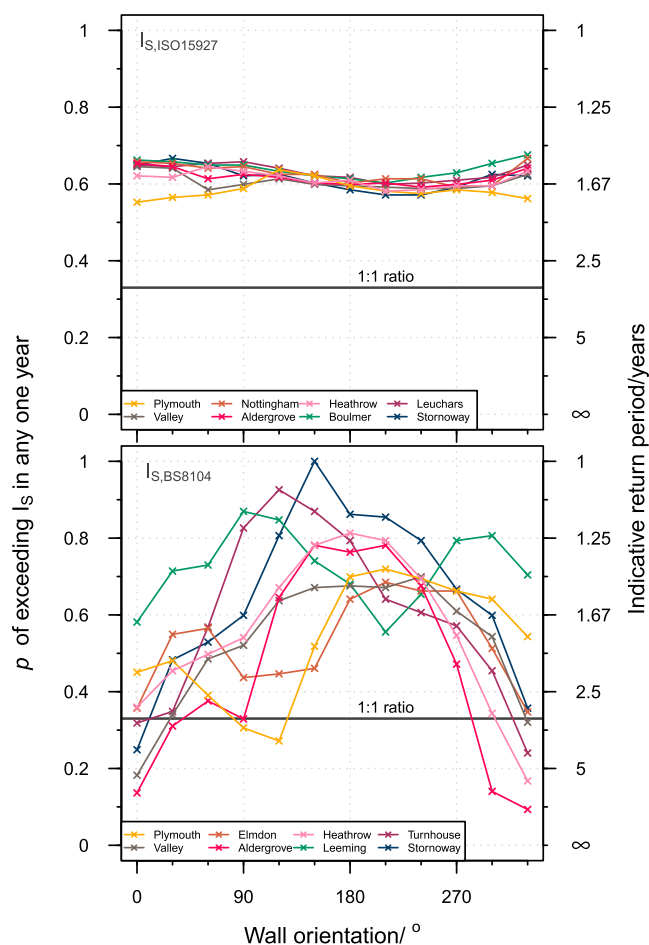


Fig. 8. The probabilities of exceeding the ‘once every three years’ spells calculated from ISO 15927 and BS 8104 in any given year. The equivalent return periods are presented on the right axis.

comparative purposes: “The annual mean WDR index gives, it is believed, a reasonably precise method of comparing different sites with respect to total amounts of WDR on walls. It enables a designer to compare the exposure of a place with that at another with which he is already familiar.” [5, p. 108]. By this definition, they remain a useful tool for design, because the extreme WDR spells calculated with BS 8104 and ISO 15927 have a reasonably proportional relationship with those calculated from EVA. However, this relationship is much less applicable for sites with more extreme climates and climatic variation. In these cases, using ISO 15927 and BS 8104 could lead to substantial under-designing for building elements exposure risks.

The annual index from both standards used to indicate average moisture contents and the likelihood of biological growth remain useful tools for these purposes. For BS 8104, this is because extreme WDR exposure appears to have not changed significantly since 1959 to 1991. This is in contrast to a gradual linear increase in UK temperatures observed from 1961 to 2006 (Jenkins et al., 2009). For ISO 15927, the annual index is a non-trivial summation of a set of exposures within a year and is not influenced by percentiles or the frequency of spells.

5. Conclusions

This paper employed extreme value analysis by combining return periods with a Gumbel distribution to evaluate extreme wind-driven rain exposure for eight sites across the UK. It was shown that the directional aspect (i.e. wall orientation) of exposure produces significant variation in

the quantity, duration, and amount of wind-driven rain spells experienced in the UK.

WDR exposure at the eight study sites from 1986 to 2015 demonstrated that the western coastal sites had high annual and spell exposure, especially for southern and western wall orientations in line prevailing wind directions. The intensity of exposure for northern and eastern wall orientations was more homogenous across the eight sites; the eastern coastal sites notably experienced the highest WDR exposure for eastern façades, demonstrating that wind speeds can have a dominating effect over prevailing wind directions.

The current standards are underestimating extreme wind-driven rain events such as the worst spell likely to occur in any given three year period when compared to a method based on extreme value analysis. In the case of BS 8104, this shortcoming is likely caused by a poorly understood methodology to identify extreme events, as current wind-driven rain exposures are not significantly different from those of the mid-to-late twentieth century for many sites in the UK. For ISO 15927, this is influenced by its protocol that incorporates percentiles. Despite this, they remain a useful semi-qualitative tool for characterising annual exposure for average moisture contents and comparing relative exposures between sites.

Assessment of WDR exposure for design and risk analysis needs to incorporate methods that are not affected by random weather phenomena, such as extreme value analysis. The approach employed herein of return periods combined with Gumbel distributions and probability can be a powerful tool to evaluate extreme WDR exposure. Being able to use meteorological data to evaluate the risks posed by WDR is an importance component of efficient and effective management and conservation of the historic built environment.

Acknowledgements

Funding: This work was supported by the UK Engineering and Physical Sciences Research Council grant for the Centre for Doctoral Training Science and Engineering in Art, Heritage and Archaeology (EP/L016036/1). We acknowledge the support of Historic Environment Scotland and the Natural Sciences and Engineering Council of Canada (funding reference number PGSD3-471105-2015). The authors are indebted to the supportive and helpful comments received from anonymous reviewers on an earlier draft of this paper.

References

- Blocken, B., Carmeliet, J., 2004. A review of wind-driven rain research in building science. *J. Wind Eng. Ind. Aerod.* 92 (13), 1079–1130. <https://doi.org/10.1016/j.jweia.2004.06.003>.
- BSI, 1984. DD93:1984 - Method for Assessing Exposure to Wind-driven Rain. British Standards Institution.
- BSI, 1992. BS 8104:1992 - Code of Practice for Assessing Exposure of Walls to Wind-driven Rain. Standard. British Standards Institution.
- Cunnane, C., 1973. A particular comparison of annual maxima and partial duration series methods of flood frequency prediction. *J. Hydrol.* 18 (3), 257–271. [https://doi.org/10.1016/0022-1694\(73\)90051-6](https://doi.org/10.1016/0022-1694(73)90051-6).
- DEFRA, 2009. UK Climate Projections 2009 [cited 6 September 2017]. <http://ukclimateprojections.defra.gov.uk/>.
- Eames, M., Kershaw, T., Coley, D., 2011. On the creation of future probabilistic design weather years from UKCP09. *Build. Serv. Eng. Technol.* 32 (2), 127–142. <https://doi.org/10.1177/0143624410379934>.
- Erkal, A., D'Ayala, D., Sequeira, L., 2012. Assessment of wind-driven rain impact, related surface erosion and surface strength reduction of historic building materials. *Build. Environ.* 57, 336–348. <https://doi.org/10.1016/j.buildenv.2012.05.004>.
- Fazio, P., Mallidi, S.R., Zhu, D., 1995. A quantitative study for the measurement of driving rain exposure in the Montreal region. *Build. Environ.* 30 (1), 1–11. [https://doi.org/10.1016/0360-1323\(94\)E0028-P](https://doi.org/10.1016/0360-1323(94)E0028-P).
- Fisher, R.A., Tippett, L.H.C., 1928. Limiting forms of the frequency distribution of the largest or smallest member of a sample. In: *Mathematical Proceedings of the Cambridge Philosophical Society*, vol. 24. Cambridge University Press, pp. 180–190, 2.
- Giarmas, C., Aravantinos, D., 2014. On building components' exposure to driving rain in Greece. *J. Wind Eng. Ind. Aerod.* 125, 133–145. <https://doi.org/10.1016/j.jweia.2013.11.014>.
- Gumbel, E.J., 1941. The return period of flood flows. *Ann. Math. Stat.* 12 (2), 163–190. <https://doi.org/10.1214/aoms/1177731747>.

- Gumbel, E., 1958. *Statistics of Extremes*. Columbia University Press, New York.
- Guttman, N., 2010. *Guide to Climatological Practices*, Tech. Rep. 100. World Meteorological Organisation.
- Hoppestad, S., Norge, Slagregn i, 1955. Tech. Rep. vol. 13. Norges Byggeforskningsinstitutt.
- IPCC, 2013. Summary for policymakers. In: Stocker, T., Qin, D., Plattner, G.-K., Tignor, M., Allen, S., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P. (Eds.), *Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, pp. 3–32. www.cambridge.org/9781107661820.
- ISO, 2009. ISO 15927-3: 2009: Hygrothermal Performance of Buildings - Calculation and Presentation of Climatic Data – Part 3: Calculation of a Driving Rain Index for Vertical Surfaces from Hourly Wind and Rain Data, Standard. International Standards Organisation.
- Jenkins, G., Perry, M., Prior, J., 2009. *The Climate of the UK and Recent Trends*, Tech. Rep. UK Met Office.
- Lacy, R., Shellard, H., 1962. An index of driving rain. *Meteorol. Mag.* 91 (1080), 177–184.
- Lacy, R., 1965. Driving-rain maps and the onslaught of rain on buildings. In: RILEM/CIB Symposium on Moisture Problems in Buildings, vol. 3. Rain Penetration, Helsinki paper 3–4.
- Lacy, R., 1976. *Driving-rain Index*, Tech. Rep. Building Research Establishment.
- Lacy, R., 1977. *Climate and Building in Britain*. Her Majesty's Stationery Office.
- Leadbetter, M., 1991. On a basis for 'peaks over threshold' modeling. *Stat. Probab. Lett.* 12 (4), 357–362. [https://doi.org/10.1016/0167-7152\(91\)90107-3](https://doi.org/10.1016/0167-7152(91)90107-3).
- McCabe, S., Brimblecombe, P., Smith, B.J., McAllister, D., Srinivasan, S., Basheer, P.A.M., 2013. The use and meanings of 'time of wetness' in understanding building stone decay. *Q. J. Eng. Geol. Hydrogeol.* 46 (4), 469–476. <https://doi.org/10.1144/qjegh2012-048>.
- Murphy, J.M., Sexton, D., Jenkins, G., Booth, B., Brown, C., Clark, R., Collins, M., Harris, G., Kendon, E., Betts, R., et al., 2009. *UK climate Projections Science Report: Climate Change Projections*, Tech. Rep. Met Office Hadley Centre.
- Nadarajah, S., Kotz, S., 2004. The beta Gumbel distribution. *Math. Probl Eng.* 2004 (4), 323–332. <https://doi.org/10.1155/S1024123X04403068>.
- Nadarajah, S., 2006. The exponentiated Gumbel distribution with climate application. *Environmetrics* 17 (1), 13–23. <https://doi.org/10.1002/env.739>.
- Pérez-Bella, J.M., Domínguez-Hernández, J., Rodríguez-Soria, B., del Coz-Díaz, J.J., Cano-Suñén, E., 2012. Estimation of the exposure of buildings to driving rain in Spain from daily wind and rain data. *Build. Environ.* 57, 259–270. <https://doi.org/10.1016/j.buildenv.2012.05.010>.
- Pérez-Bella, J.M., Domínguez-Hernández, J., Rodríguez-Soria, B., del Coz-Díaz, J.J., Cano-Suñén, E., 2013. Combined use of wind-driven rain and wind pressure to define water penetration risk into building façades: the Spanish case. *Build. Environ.* 64, 46–56. <https://doi.org/10.1016/j.buildenv.2013.03.004>.
- Prior, J., 1985. *Directional Driving Rain Indices for the United Kingdom : Computation and Mapping (Background to BSI Draft for Development DD93)*. Building Research Establishment.
- Reid, J., Garvin, S., 2011. *Wind Driven Rain: Assessment of the Need for New Guidance*, Tech. Rep. A1533015. Building Research Establishment Scotland.
- Smith, B.J., McCabe, S., McAllister, D., Adamson, C., Viles, H.A., Curran, J.M., 2011. A commentary on climate change, stone decay dynamics and the 'greening' of natural stone buildings: new perspectives on 'deep wetting'. *Environ. Earth Sci.* 63 (7), 1691–1700. <https://doi.org/10.1007/s12665-010-0766-1>.
- Smith, R.L., 1989. Extreme value analysis of environmental time series: an application to trend detection in ground-level ozone. *Stat. Sci.* 367–377.
- Smith, R.L., 1990. Extreme value theory. *Handbook of Applicable Mathematics* 7, 437–471.
- UK Met Office, 2006a. MIDAS: UK Hourly Rainfall Data.
- UK Met Office, 2006b. MIDAS: UK Hourly Weather Observation Data.