Optimised method for estimating directional driving rain from synoptic observation data.

José M. Pérez-Bella [a], Javier Domínguez-Hernández[a,*], Beatriz Rodríguez-Soria[a], Juan J. del Coz-Díaz[b], Enrique Cano-Suñén[a]

[a] *Department of Construction Engineering, Engineering and Architecture School, University of Zaragoza (UZ), María de Luna, s/n, 50018, Zaragoza, Spain*

[b] *Department of Construction Engineering, University of Oviedo, Edificio Departamental Viesques nº 7, 33204 Gijón, Spain.*

Abstract

In this article, the annual directional exposure to driving rain and its characteristics are analysed and discussed at four Spanish sites that are characterised by different rainfall levels and topographical and wind conditions. For this study, the *present weather observation method* is used, which is based on average annual rainfall data and synoptic observations of the present weather. The results of this study are compared with those obtained by applying the ISO 15927-3:2009 standard, which is based on the semi-empirical analysis of hourly wind and rainfall data. This study identifies the intrinsic dependence of the aforementioned synoptic method on the weather conditions that exist at each site, which affect the reliability and accuracy of the estimates. Thus, corrective changes that would enable the synoptic method to generate more reliable approximations are proposed, and a new optimised methodology is presented; the precision of the new method relies on synoptic observations but is independent of weather conditions. The results, validated at four Spanish sites, suggest that in the absence of hourly data for implementing the ISO standard, this optimised synoptic method is able to generate reasonably accurate estimates of the annual directional exposure to driving rain, regardless of the particular site conditions.

Keywords

Driving rain; Wind; Rainfall; Weather observations; Synoptic method; Building enclosure performance; Spain

[*] Corresponding author. Department of Construction Engineering, University of Zaragoza (UZ), María de Luna, s/n, 50018, Zaragoza, Spain. Tel.Fax: +34 976 76 21 00.
E-mail address: javdom@unizar.es (Javier Domínguez-Hernández)

1. Introduction

Atmospheric precipitation that is accompanied by gusts of wind is responsible for moistening building exteriors and penetrating these exteriors with water, which leads to damage and reduced performance of insulation and other energy-saving features of buildings (del Coz et al., 2011, 2012; Sanders, 1996; Tang et al., 2004). An understanding of the level of exposure to wind-driven rain (WDR) that a building envelope component is exposed to is a fundamental requirement for establishing designs that minimise these moisture-related issues.

In recent years, the analysis of hourly climate data related to precipitation, wind speed, and wind direction has emerged as a standard method of determining the directional exposure of building envelopes to driving rain. Although the use of CFD models (Blocken and Carmeliet, 2002, 2007; Choi, 1991, 1993, 1994a, 1994b) has been shown to determine the exposure of the envelope to driving rain with precision and versatility (Blocken et al., 2010, 2011), alternative semi-empirical methods that are based on the analysis of weather data also continue to be employed for estimating this exposure, as these semi-empirical methods are considered to be reasonably reliable and easy to use (Blocken and Carmeliet, 2010).

One notable semi-empirical method is the ISO 15927-3:2009 standard (ISO, 2009), which provides an estimate model based on analysing hourly climate data to determine annual directional exposures under reference conditions ('... *at a height of 10 m above ground level in the middle of an airfield, at the geographical location of the wall* '). In absence of WDR measurements or validated numerical simulations, the ISO Standard results are the next best estimate. This standard also provides correction factors based on the surrounding terrain conditions that allow for the conversion of the free-field WDR intensity to the WDR intensity on a building façade.

However, the vast majority of countries do not have the hourly climate data that are necessary for the strict implementation of this standard, as the time period in which the available data was gathered is often insufficient, or the number of weather stations at which the data are collected are not representative (Chand and Bhargava, 2002; Giarma and Aravantinos, 2011; Pérez et al., 2012; Rydock et al., 2005). Given these frequent difficulties in applying the standard estimate model, several alternative semi-empirical methods are employed that estimate the directional exposure to driving rain from other available meteorological data.

A representative example of an alternative calculating method is specified by the ISO standard for countries in which simultaneous hourly rain and wind data are not available. However, this method, which uses 12-hour wind data averages and qualitative recordings of the presence and intensity of rain to calculate the period during which the building exterior is moistened, is less accurate and reliable (due to its less quantitative nature) than the approach based on hourly data.

Another of the most representative alternative methods to quantitatively estimate directional exposure was introduced by Rydock et al. and is referred to in this article as the *present weather observation method* (Rydock et al., 2005). This method uses only mean annual precipitation values and synoptic observations of the present weather, encoded in accordance with an international standard (WMO, 2011). This method's application at certain Norwegian and British sites has been proved to be useful for providing reasonably accurate approximations of the directional distribution of annual driving rain at several of the locations that were examined (Rydock, 2007).

This article examines the synoptic weather and hourly data recorded at four Spanish weather stations to assess the accuracy of the present weather observation method at these sites relative to the ISO 15927-3:2009 standard. This analysis reveals the intrinsic dependence of the synoptic method on the particular climatology of each individual site. For certain rainfall conditions, this dependence produces significant errors, thereby affecting the reliability and accuracy of the overall results.

The newly optimised methodology proposed in this study, which is also based on the analysis of synoptic observations, ensures that the accuracy of calculations is less influenced by site-specific weather conditions (wind speed during precipitation events and directional distribution, intensity and total amount of rainfall); thus, the optimised method estimates the annual directional exposure of building envelopes to driving rain with greater accuracy and reliability than the original synoptic method.

2. Background

The simultaneous measurement of rainfall intensity and wind speed during a precipitation event can allow the 'WDR Relationship' (Blocken and Carmeliet, 2004), to be used to calculate the amount of rain diverted onto a vertical surface by the wind. If the wind direction is known, the amount of water received by each building exterior can be directionally defined. In the 1950s and 1960s, Hoppestad (1955) and Lacy (1965) addressed the relationship between these climatic measurements and the driving rain received by buildings, and their research has become the starting point of the semi-empirical estimation methods that are currently used.

Currently, the ISO 15927-3:2009 standard provides a method for determining the annual directional exposure to driving rain I_A (mm/annum) in free-field conditions (assessed by the airfield index) that uses simultaneous hourly rain R_h (mm), wind U_{10} (m/s), and wind direction D (°) data. This method recommends using data collected over a period of at least 10 years (preferably 20 or 30 years).

The directional-type calculation (see Equation 1) of the standard method allows for moderately precise quantification of the amount of water that impacts at a particular orientation Θ (°) over the course of a year. In the equation below, which is used for this quantification, only positive results are considered, i.e., the sum below only incorporates the hours when the wind drives a nonzero amount of rain onto the envelope over the course of the N years that are analysed.

$$I_{A_{\Theta}} = \frac{2}{9} \frac{\sum U_{10} \cdot \left(R_h\right)^{8/9} \cdot \cos\left(D - \Theta\right)}{N} \qquad (1)$$

2.1 Present weather observation method

In the absence of adequate hourly data in Norway, Rydock et al. (2005) defined the present weather observation method for estimating annual directional exposure to driving rain, which relies on synoptic observations that are commonly available in most countries. These synoptic observations include meteorological data collected at various times throughout each day (3 to 8 records per day), and the results are tabulated using an internationally standardised numerical code from the World Meteorological Organization (WMO, 2009). As they are numerically coded, the resulting records are easily analysed in spreadsheet programmes and can be used to conduct weather forecasts.

This present weather observation method uses the $7wwW_1W_2$ data set of the coding (see Table 1), which is focused on the results of the present weather observation at the time of recording; specifically, the method employs the codes representing rain (codes 60-65) or rain showers (codes 80-82). The characterisation of the present weather by a specific code is subject to the judgment of the recording observer.

Table 1.
Encoding group $7wwW_1W_2$ for present weather (extract). Source: WMO Manual on Codes.

As the encoding group Nddff (see Table 2) encodes data that indicate the associated wind speed and direction at the recording time (averaged over the previous 10 minutes), it is possible to consider simultaneously the rain codes discussed above, the wind speed, and the wind direction (in increments of

10° and always referenced to the north) for a location. This process can determine both the number of rain events or rain showers that occur at the location in question for each wind direction D and the average wind speed U_D that is associated with each of these events. As the coded directions are tabulated in 10° intervals, subsequent estimates will always be made based on that tabulation.

Table 2.
Nddff encoding group for wind direction and speed. Source: WMO Manual on Codes.

The synoptic method first normalises the frequency ($Nf_{events\ D}$) with which rain-related events occur at a site for each wind direction D (°) and, using the average wind speed for each direction U_{10D} (m/s) during rain events and the average annual precipitation R_{hA} (mm/annum) at the site, estimates the directional exposure to driving rain, using a conversion factor equal to 0.206 s/m (Eq. 2). As discussed for the ISO standard, the summation in Equation 2 considers only positive results, i.e., only events during which the wind drives a nonzero amount of rain onto an orientation Θ are included in the sum.

$$Nf_{\text{events D}} = \frac{\sum \text{events recorded}_{\text{D (codes 60-65 and 80-82)}}}{\sum \text{events recorded}_{\text{(codes 60-65 and 80-82)}}}$$

$$I_{A_{\Theta}\ \text{present weather observation method}} = 0.206 \cdot \sum_{D=0}^{360} Nf_{\text{events D}} \cdot R_{hA} \cdot U_{10D} \cdot \cos\left(D - \Theta\right) \qquad (2)$$

By analysing the theory of this approximation model, several intrinsic aspects that impact its accuracy and reliability can be identified:

- The directional distribution of rainfall used ($Nf_{events\ D}$) is based solely on the number of rainfall events in each direction but not on their intensity. This distribution thus assumes an identical amount of precipitation for all events in all directions (a phenomenon that is only possible at locations with homogeneous rain), which may induce inaccuracies under certain weather and rainfall conditions (Rydock et al., 2005). This aspect was also identified as a problem by Rydock (Rydock, 2007).

- The rainfall events considered by the method (codes 60-65 and 80-82) include neither less intense precipitation, such as drizzle (codes 50-59), nor those rains that start and end between recording periods and therefore pass unnoticed at the time of the synoptic record of the present weather. Consequently, the number of events used to determine the directional distribution ($Nf_{events\ D}$) and the average wind speed during precipitation events for each direction (U_{10D}) may be significantly less than the actual number of rainfalls. This discrepancy can cause significant errors if the number of rain events is low, which is common in dry locations or in areas where rainfalls tend to occur mostly in the form of brief showers, as occurs in certain Mediterranean regions.

- The calculation of the average velocity U_{10D} as the simple arithmetic mean of the wind speeds of all rain events from one direction leads to random reductions or augmentations in the estimated exposure to driving rain. As the existing relationship between wind speed and rainfall intensity is highly unpredictable and is contingent on the particular characteristics of storms at each location, the method of averaging wind speeds from each direction produces random errors in each case that are difficult to measure.

Greater heterogeneity of rainfall intensities and fewer recorded rainfall events cause the present weather observation method to be less accurate. In addition, the accuracy of the quantitative estimate obtained from the synoptic method must be considered with caution (Rydock et al., 2005), due to uncertainty regarding the relationship between wind speed and precipitation intensity. Therefore, it can be concluded that the method's results are intrinsically dependent upon the climate characteristics at each location where it is applied.

To address these reliability concerns, this paper proposes a new *optimised synoptic method* that overcomes the aforementioned limitations by including an analysis of the heterogeneity of rainfall distribution and the estimated distribution of wind speeds relative to precipitation intensity. This optimised method uses another set of encoded content obtained from the same synoptic data that records the amount of rainfall at a given location and thus allows the optimised method to both account for any rainfall event and analyse a greater number of events, even at sites with low rainfall.

To validate this optimised methodology, this study examined hourly and synoptic weather data compiled by the Spanish Meteorological Agency at four Spanish sites representing different rainfall and wind conditions.

3. The analysis of the present weather observation method at four Spanish sites

The four sites studied (see Figure 1) are associated with varied precipitation rates, topography, and wind regimes, allowing this study to evaluate the accuracy of the synoptic method under different types of driving rain conditions.

Madrid is located inland on the Iberian Peninsula, which is far from the coast and is located at an altitude of 609 m. This city is protected from significant winds, and its rainfall of 382 mm/annum is characteristic of locations in the drylands of southern Europe. Barcelona, which also has the low rainfall typical of dry Mediterranean climates, is at sea level and is subject to moderate coastal winds. San Sebastian, found on the coast of the Bay of Biscay, and Vigo, which is on a Galician ria, are located at a similar altitude, and these cities' locations on the Atlantic cause high annual rainfall; in fact, the rainfall experienced by these cities is similar to or higher than the rainfall experienced by British or Norwegian cities (Vigo's rainfall is 1670 mm/annum). San Sebastian is also subjected to especially strong coastal winds.

Figure 1. Map of Spain illustrating the locations of the four weather stations used in this study.

Hourly records of rainfall, wind speed, and wind direction from the period from 1998 to 2011 (14 years) are available at the four sites, thereby permitting the implementation of the hourly estimate methodology included in the ISO 15927-3:2009 standard. In addition, synoptic data are available relating to the same period (collected at 0, 3, 6, 9, 12, 15, 18, and 21 UTC), allowing the results from the implementation of the ISO standard to be compared with those obtained from the present weather observation method. This comparison is shown in Figure 2, which uses directional intervals of 10°.

Figure 2. Plot of average annual driving rain versus wall angle I_A that is determined using the ISO standard method (bars) and the present weather observation method (broken line) over the 1998-2011 time period at four Spanish locations. Angles are measured in degrees from north.

From analysis of only the hourly results in Figure 2 (bars), Vigo and San Sebastian demonstrate notably significant directional exposure variations (41 mm/annum at 70° and 1070 mm/annum at 210° in Vigo, 68 mm/annum at 80° and 1319 mm/annum at 300° in San Sebastian). In Vigo, the greatest quantities of driving rain come from the SW, whereas in San Sebastian, the majority of the driving rain comes from the NW.

In Madrid and Barcelona, which have a much lower rainfall (see Fig. 1), the difference in exposure among the different orientations is lower with maximal driving rain from the NE for Barcelona and from the S and SW for Madrid. In the case of Madrid, the exposure to driving rain is distributed in a particularly uniform manner with a difference between the maximum (200°) and minimum (80°) values of only 100 mm/annum.

The exposure value also varies significantly between the sites analysed. Although San Sebastian has a lower annual precipitation, it presents a maximum exposure (1319 mm/annum) greater than Vigo (1070 mm/annum). Both sites have maximum exposures much higher than Barcelona (285 mm/year) and Madrid (147 mm/annum). Regarding the minimum exposure, the four locations have similar values, ranging from 68 mm/annum at San Sebastian to 41 mm/annum at Vigo.

The analysis of the overall results obtained in Figure 2 demonstrates that for all four locations, a single orientation of maximum and minimum exposure can be clearly identified; this orientation is consistently determined by both methods. However, it is also clear that the precision of the synoptic method varies at each site, resulting in quantitative estimates that differ from the results of the standard method in several cases. In particular, although the present weather observation method very accurately reproduces the standard method results in the case of Vigo, relatively poorer correspondence between the two methods is observed for San Sebastian, Barcelona, and Madrid.

The three aspects intrinsic in the present weather observation method that determine its accuracy and reliability can be validated and observed by analysing the results obtained from its application:

- One factor that creates uncertainty in the synoptic method is that the intensity of rainfall of each event is not considered. The importance of this factor can be assessed by analysing the normalised directional distribution of the comparatively heavy rainfall events (codes 62-65 and 81-82) and comparing the results with those obtained from analysis of the normalised directional distribution of all recorded rain events (codes 60-65 and 80-82). These two distributions are not identical but instead evince sharp differences in certain directions (see Figure 3).

Figure 3. Normalised frequency ($Nf_{events\ D}$) of all forms of rain observations (black bars) versus only the moderate or heavy rain observations (codes 62-65, 81, and 82) (gray bars) for the 1998-2011 time period at Vigo, San Sebastian, Barcelona, and Madrid. Angles are measured in degrees from north.

In San Sebastian, the significant differences that are observed between 300 and 350° (greater frequency of heavy rainfall) and between 140 and 240° (lower frequency of heavy rainfall) for these two distributions indicate the existence of a strong heterogeneity in rainfall intensity. Vigo, which experiences similar annual rainfall to San Sebastian, does not demonstrate the same pronounced differences between the two distributions, indicating that Vigo experiences more homogeneous precipitation than San Sebastian. Therefore, not assessing the intensity of each precipitation event induces an error in estimating driving rain through the synoptic method in locations with heterogeneous rains.

This same limitation was also identified in a previous study that sought to validate the synoptic method at three British sites (London-Heathrow, Manchester-Ringway, and Edinburgh-Turnhouse) by comparing the results of the present weather observation method with the results of the ISO standard method (Rydock, 2007). In that study, the unique concentration of moderate and heavy rains from specific wind directions caused the fit between the two methods to be much more inaccurate in Edinburgh than in either London or Manchester.

- In Madrid, there are sharp variations in the number of events recorded from nearby orientations (180º, 190º, and 200º). These sharp variations arise from discarding records of drizzle and from the smaller sample size that results from the relatively low rainfall at this location. In Vigo and San Sebastian, 2596 and 2820 rainfall events, respectively, were analysed over 14 years;

however, the number of analysed events was only 985 in Madrid and 860 in Barcelona over the same length of time.

For sites with few rainfalls (fewer number of available events), the values used by the synoptic approach ($Nf_{events\ D}$ and U_{10D}) are less representative of actual conditions, which can produce a greater estimating error. This is due to the fact that any extreme event considered will have more influence on the calculation of the average values, increasing their uncertainty. As shown in Madrid, the combination of heterogeneous and infrequent rainfall events can produce lower accuracy for the present weather observation method (relative to the standard).

- The mean wind speed calculated for each direction (U_{10D}) adds uncertainty due to the average error of the wind's speed magnitude at all locations. Although the ISO standard uses the sum of the product of rainfall intensity and wind speed at each hour to calculate driving rain totals, the synoptic method simplifies this calculation, instead using a value for average wind speed and the total rainfall assigned to each orientation. Figure 4 allows for the observation of this averaging error, as it presents a simple comparison of the two approaches to the calculation of driving rain for the four sites.

In particular, this comparison can be made by starting from the approximation of the ISO model, which performs the summation of the product of hourly precipitation R_h (mm) and the simultaneous wind speed U_{10} (m/s) for each of the wind directions D (°):

$$\sum U_{10} \bullet R_h \tag{3}$$

The values calculated using Equation 3 are subsequently compared with the approach proposed by the synoptic method, which uses the mean wind speed U_{10D} (m/s) during rain synoptic events calculated for each direction D (°) and the sum of the hourly rainfalls R_h assigned to that same orientation:

$$U_{10D} \bullet \sum R_h \quad (4)$$

Figure 4. Comparison of the hourly approach $\sum U_{10} \bullet R_h$ (bars) and the synoptic approach $U_{10D} \bullet \sum R_h$ (broken lines) over the 1998-2011 time period at four Spanish locations. Angles are measured in degrees from north.

At all four sites, it is clear that the approach proposed by the synoptic method causes significant deviations from the standard approach for certain directions. These deviations are more noticeable for Madrid and Barcelona, due to the larger scale of the graphs for these cities, but as shown in Table 3, sites with different weather conditions, such as Vigo or San Sebastian, also demonstrate significant deviations in the accuracy of the synoptic approach.

Table 3.
Orientation and relative deviation percentage of the two main absolute deviations from standard at each site that are caused by the use of average wind speed in the synoptic approach, as identified in Figure 4.

After analysing the results, it is clear that the present weather observation method produces inaccuracies, influenced by the specific conditions at the studied sites. It is therefore necessary to define a new method for synoptic estimating that is not subject to these limitations.

4. The use of synoptic data codes indicating precipitation amounts in the optimised synoptic method

In order to assess the intensity of rainfall events in the estimate, to increase the number of events analysed, and to reduce deviations caused by the use of average wind speed from each direction, a novel approach is proposed, which differs from that used by the present weather observation method. This new approach allows for more accurate and reliable estimates, regardless of the particular conditions of each site, but this approach also relies upon synoptic data.

This method replaces the subjective observation of the present weather (code $7wwW_1W_2$) with objective data relating to the intensity of recorded rainfall. Specifically, information related to the amount of rainfall recorded is used. This information is also included within the coding of synoptic data, as it is contained in the $6RRRt_R$ group and recorded every 6 hours (0, 6, 12, and 18 UTC) using the encoding scheme presented in Table 4. In Spain, at 6 UTC and 18 UTC, the rainfall collected over the previous 12 hours is codified, whereas at 0 UTC and 12 UTC, the collection is only recorded for the previous 6 hours (this record is also included in those at 6 UTC and 18 UTC, respectively). However, one can easily determine the amount of precipitation that has fallen in each 6-hour interval by simply subtracting the corresponding records at 0 and 12 UTC from those of 6 and 18 UTC, respectively.

Table 4.

Encoding group $6RRRt_R$ (extract). Source: WMO Manual on Codes.

As shown in Table 4, the synoptic data do not record decimal place values for rainfall greater than 1 mm. Furthermore, the need to codify rain collection and set the observation interval associated with each record (t_R) can lead to transcription errors. Both of these factors, taken together with a greater recording interval (measurements taken every 6 hours), prevent these rainfall data from being used directly in a 'WDR relationship' (Blocken and Carmeliet, 2004), due to the comparatively inaccurate results of the synoptic data relative to the data obtained by the ISO standard. However, the analysis of this data set does allow for the correction and minimisation of the limitations previously detected in the original synoptic method.

The encoding $6RRRt_R$ group presents also a limitation in northern countries since it records the amount of liquid precipitation and the water equivalent of solid precipitation. No distinction between liquid precipitation and solid precipitation is made and snowfall is not governed by the same principles adopted by the 'WDR Relationship'. Therefore, solid precipitation can introduce an element of uncertainty in the proposed method described below. Hence in cold climates where solid precipitations are common, this aspect could become an important limitation in the accuracy of exposure estimation. In such cases, the proposed method should be specifically validated.

4.1 The assessment of the directional intensity of rain

To assess the directional heterogeneity of the intensity of precipitation, in the *optimised synoptic method*, the directional distribution of rainfall is not calculated using the number of rainfall codes recorded from each direction (number of events); instead, this method uses the amount of rainfall recorded from each direction (mm). This approach also eliminates the subjective component derived from personal observations of the present weather.

By associating the precipitation collected during each 6-hour interval with the wind direction recorded at the end of that time interval, one can normalise the amount of rain that has fallen in each direction ($Nf_{rainfall\ D}$), thereby eliminating the uncertainties associated with the parameter $Nf_{events\ D}$ and the possible heterogeneity of rainfall at the site:

$$Nf_{\text{rainfall D}} = \frac{\sum \text{Rainfall recorded}_{\text{D (from group 6RRRt}_{\text{R}}\text{)}}}{\sum \text{Rainfall recorded}_{\text{(from group 6RRRt}_{\text{R}}\text{)}}} \qquad (5)$$

The above Equation 5 assumes that the wind direction at the time of recording is representative of the wind direction of any precipitation that has occurred during the previous 6 hours; this supposition is not completely accurate. However, although the recorded wind direction is not strictly identical to the wind direction of all of the recorded precipitation, the wind direction values appear to be adequately representative, as evidenced by the greater accuracy of the final exposure results obtained.

4.2 The increase in the number of rainfall events analysed

The present weather observation method considers a rainfall event only if the precipitation can be encoded in a certain range at the time of recording (some rains and showery precipitations), dismissing the precipitation that begins and ends between each recording interval. The optimised approach quantifies all of the rain at a site, including habitual drizzle events at sites of low rainfall and dry climate, as well as those rainfalls that were not recorded through the observation of present weather.

Thus, compared with the original method, the *optimised synoptic method* significantly increases the number of rain events available for estimating and introduces the influence of low rainfall amounts and duration; these alterations in approach produce more representative synoptic estimates of exposure to driving rain. A greater number of available data for the optimised method allows a more representative estimation of actual conditions. Table 5 shows the number of events considered by each method to estimate the exposure at the four Spanish sites (i.e. codified events versus 6-hour intervals with rainfall).

Table 5.

Number of analysable events used to set the directional distribution of rainfall and calculate U_D at each site over the 1998-2011 time period.

4.3 The weighted estimate of average wind speed during precipitation events.

As indicated, estimating an average wind speed value *(U_{10D})* by calculating the simple arithmetic mean of the speeds of all precipitation events associated with each direction can lead to significant deviations in the results for certain directions (see Table 3). To reduce these deviations, the calculation of representative wind speed for each direction *D* can include weighting the contributions from each wind speed by the intensity of each precipitation event *i* that occurred when the wind speed in question was recorded (Blocken and Carmeliet, 2007, 2008):

$$U'_{10D} = \frac{\sum \text{Rainfall recorded}_{\text{D i (from group 6RRRt}_R\text{)}} \bullet \text{wind speed}_{\text{D i (from group Nddff)}}}{\sum \text{Rainfall recorded}_{\text{D i (from group 6RRRt}_R\text{)}}} \qquad (6)$$

By taking identified rainfall values based on the $6RRRt_R$ and Nddff groups (which indicates the amount of precipitation and associated wind speed) as a starting point (see Eq. 6), U'_{10D} accounts for the intensity of precipitation associated with the wind speed of each rain-related event. Although synoptic rainfall records are not as accurate as hourly values, this weighted calculation of the mean velocity provides a better approximation to the 'WDR relationship' of the ISO model (see Equations 3 and 4).

The use of this weighting approach will reduce the deviations from the standard results that are associated with certain directions, as these deviations are often generated by the simple averaging process for wind velocities that is used in the present weather observation method.

5. Results and discussion

Summarising the abovementioned changes, Equation 7, provided below, defines the *optimised synoptic method* to determine the annual directional exposure to driving rain. In this equation, R_{hA} (mm/annum) represents the average annual rainfall at the site, *D* (°) indicates the wind direction, *Θ* (°) indicates the analysed orientation and a conversion factor equal to 0.206 s/m is also adopted. As in previous estimates, only positive results are considered in the sum below, i.e., the sum incorporates only those events during which the wind has driven a nonzero quantity of rain on the orientation *Θ*.

$$I_{A\,\Theta\ \text{optimised synoptic method}} = 0.206 \cdot \sum_{D=0}^{360} Nf_{\text{rainfall D}} \cdot R_{hA} \cdot U'_{10D} \cdot \cos\left(D - \Theta\right) \qquad (7)$$

Figure 5 validates the estimate obtained by this *optimised synoptic method*, as this figure demonstrates a more accurate fit to the standard than the previous method for all cases, regardless of the specific weather at each of the sites.

Figure 5. Comparison of average annual driving rain versus wall angle I_A using the ISO standard (bars), present weather observation method (broken line) and optimised synoptic method (solid line) over the 1998-2011 time period at four Spanish locations.

It is observed that in Vigo, the fit obtained is similar to the fit generated by the previous method. In this instance, the fit obtained by the present weather observation method alone accurately matched the ISO standard, as the Vigo site featured a high number of analysed events, precipitation that was highly homogeneous, and small deviations due to U_{10D}. Even under conditions that are favourable to the previous method, the proposed *optimised synoptic method* produces comparable accuracy.

In San Sebastian, despite the heterogeneous directional distribution of precipitation, the new approach is notably accurate, objectively improving upon the previous approximation. Notably, the proposed estimate more accurately fits the results of the ISO standard for both maximum and minimum exposure values, as well as for transition values.

The fit is also more accurate in Barcelona, improving the estimate of maximum exposure. This site, which is characterised by a slightly homogeneous directional distribution of rainfall, had a smaller number of analysable events than either Vigo or San Sebastian, and the previous method demonstrated sharp deviations from the standard model in certain directions for this site, due to the calculation of the directional speed as a simple average. The optimised model therefore provides a superior estimate by improving upon all three of the aspects that were discussed above.

Finally, Madrid is subjected to heterogeneous precipitation, low rainfall, and significant deviations due to inaccurately estimated average wind speeds. As would be expected in such circumstances, the *optimised synoptic method* provides better estimates of exposures than the previous method in this instance, as the optimised method produces exposures that are more closely related to those estimated by the ISO standard.

At the four sites, the directions of maximum and minimum exposure are also identified by all three methods. With the proposed method, the fit of the estimate relative to the ISO standard is only influenced by the quality of the synoptic data available and is not affected by the site's particular climatological aspects, such as the heterogeneity of the precipitation that occurs at the location in question. If one considers the total quantity of driving rain that is accounted for in all directions, one also confirms for all cases that the *optimised synoptic method* approximates the overall exposure more accurately than the previous method does, as shown in Table 6. The calculated deviations for all angle intervals for the four sites are also shown.

Table 6.

Overall comparison of total estimated annual driving rain and detailed analysis in all directions over the 1998-2011 time period at four Spanish locations.

Although it requires slightly greater computational effort (but its implementation remains straightforward in the same spreadsheet programme used to determine the results of the present weather observation method), the proposed method fits with greater reliability and accuracy at all four of the studied sites to ISO estimates, overcoming the identified limitations of the original synoptic method.

The deviations observed in the Figure 5 with respect to the ISO standard (180º to 280º for Madrid and 280° to 40° for Barcelona), are due to the nature of the estimate methodology, which relies upon synoptic data that are less accurate than the data used by the standard method. However, for locations at which hourly data are not available, the newly proposed method provides a better approximation of the result of the ISO standard than the previous method, regardless of the rainfall, wind, and topographical conditions of the sites under study.

6. Conclusions

The present weather observation method was a key innovation that allowed commonly available climatic data to be used to determine annual directional exposure to driving rain with reasonable accuracy. In the paper, this synoptic methodology has been optimised, allowing it to reach more accurate and reliable results in other climates that are similar to the Spanish climate but different from those climates that were initially used for method validation (United Kingdom) or others that can present significant amounts of solid precipitation.

The theoretical underpinnings of the original synoptic methodology have been discussed, and it has been demonstrated that methodological and climatic aspects influence the accuracy and reliability of the results obtained by this method. Applying this method to four Spanish weather stations has clarified the nature of this influence, as the comparison of the results of the original method with the results obtained by the ISO

15927-3:2009 standard has clearly indicated the limitations of the present weather observation method under different rainfall, wind, and topographical conditions.

A novel *optimised synoptic method* has been proposed, which addresses and minimises these limitations by valuing the directional intensity of rainfall, optimising the calculation of wind speed during precipitation events, and considering a larger number of events in the analysis. The application of this method requires synoptic data that are common in most countries, as the optimised method analyses the coding group that indicates the amount of precipitation that has been measured during each recording interval.

The proposed developments provide an objective improvement in the use of synoptic meteorological records to estimate annual directional exposure to driving rain. The proposed methodology can be used with similar reliability at locations characterised by varied climates by decoupling the inaccuracies caused by external factors from the optimised method. In cold climate regions where significant solid precipitations influence the coding group that indicates the amount of precipitation, the optimised method must be specifically validated and applied with caution.

The validation of this new method at the four Spanish sites (Madrid, Barcelona, Vigo, and San Sebastian) examined in this study has shown that in all of these sites, the results of the ISO standard are more closely matched by the optimised method than by the previous method. The optimised method only requires synoptic observations and, in contrast to the original method, is not dependent upon the climatic conditions of the location that is being investigated.

Acknowledgments

The results presented were obtained from information provided by the Spanish Meteorological Agency, Ministry of Environment, Rural and Marine Affairs (AEMET). The authors wish to acknowledge the partial financial support provided by the Spanish Ministry of Science and Innovation through the Research Project BIA2008-00058 and the Research Project FICYT PC-10-33. Finally, the authors greatly appreciate the collaboration of the GICONSIME Research Group at the University of Oviedo.

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List of tables

Table 1.

Encoding group $7wwW_1W_2$ for present weather (extract). Source: WMO Manual on Codes.

ww (code table 4677). ***Numerals are in bold if they are used in the present weather observation method*.**	
50-59	Drizzle
60	Rain, not freezing, intermittent, slight at time of observation
61	Rain, not freezing, continuous, slight at time of observation
62	Rain, not freezing, intermittent, moderate at time of observation
63	Rain, not freezing, continuous, moderate at time of observation
64	Rain, not freezing, intermittent, heavy at time of observation
65	Rain, not freezing, continuous, heavy at time of observation
66-69	Rain, freezing / rain or drizzle and snow
70-79	Solid precipitation not in showers
80	Rain shower(s), slight
81	Rain shower(s), mdoerate or heavy
82	Rain shower(s), violent
83-89	Mixed showery precipitation and snow

Table 2.

Nddff encoding group for wind direction and speed. Source: WMO Manual on Codes.

dd	**True direction, in tens of degrees, from which wind is blowing (code table 0877)**
00	Calm
01	5º - 14º
02	15º - 24º
Etc.	*Etc.*
35	345º - 354º
36	355º - 4º
99	Variable or unknown
ff	**Wind speed in units indicated (knot)**

Table 3

Table 3.

Orientation and relative deviation percentage of the two main absolute deviations from standard at each site that are caused by the use of average wind speed in the synoptic approach, as identified in Figure 4.

Location	**Angle / Deviation (%)**		**Angle / Deviation (%)**	
Vigo airport	210º /	-6.65	220º /	-7.54
San Sebastian (Igueldo)	160º /	+43.16	170º /	+47.11
Barcelona airport	10º /	-32.33	40º /	+25.79
Madrid airport	250º /	+18.16	140º /	+26.15

Table 4

Table 4.

Encoding group $6RRRt_R$ (extract). Source: WMO Manual on Codes.

RRR (code table 3590)		**t_R (code table 4019)**	
000	No precipitation	**1**	Total precipitation during the 6 hours preceding the observation *(recorded at 0 UTC and 12 UTC in Spain)*
001	1 mm	**2**	Total precipitation during the 12 hours preceding the observation *(recorded at 6 UTC and 18 UTC in Spain)*
Etc.	*Etc.*		
988	988 mm		
989	989 mm or more		
990	Trace		
991	0.1 mm		
Etc.	*Etc.*		
999	0,9 mm		

Table 5

Table 5.

Number of analysable events used to set the directional distribution of rainfall and calculate U_D at each site over the 1998-2011 time period.

Location	Rainfall events (codes 60-65 and 80-82)	6-hour intervals with rainfall
Vigo airport airport	2,596	4,786
San Sebastian (Igueldo)	2,820	5,235
Barcelona airport	860	1,569
Madrid airport	985	1,728

Table 6

Table 6.

Overall comparison of total estimated annual driving rain and detailed analysis in all directions over the 1998-2011 time period at four Spanish locations.

Location	ISO standard (mm/annum)	Present weather observation method (mm/annum)		Optimised synoptic method (mm/annum)	
Vigo airport	16,507.45	16,796.87	(+1.75%)	16,346.74	(- 0.97%)
San Sebastian (Igueldo)	20,101.53	20,664.75	(+2.80%)	20,362.94	(+1.30%)
Barcelona airport	5,252.00	5,790.99	(+10.26%)	5,486.99	(+4.47%)
Madrid airport	3,185.62	3,512.82	(+10.27%)	3,351.43	(+5.20%)

Detailed analysis for all the angle intervals. Deviation produced (in mm/annum) by present weather observation method (1) and optimized synoptic method (2) from the ISO standard method:

Angle	Vigo airport			S. Sebastian (Igueldo)			Barcelona airport			Madrid airport		
	ISO	(1)	(2)	ISO	(1)	(2)	ISO	(1)	(2)	ISO	(1)	(2)
0º	128.4	0.5	31.1	767.1	-93.0	13.6	256.6	25.5	27.2	68.5	-2.5	1.3
10º	104.3	3.5	24.2	621.6	-76.9	21.4	272.2	30.2	24.5	66.9	-2.2	1.5
20º	83.6	6.6	18.0	478.9	-59.6	25.5	282.0	33.4	21.0	64.4	-2.0	1.8
30º	66.8	9.1	11.8	345.5	-39.0	30.5	285.2	35.4	17.2	60.9	-2.0	2.5
40º	55.8	11.0	6.9	239.1	-26.2	29.0	281.4	36.4	12.8	56.7	-1.6	3.2
50º	47.8	12.1	3.8	160.1	-14.8	27.5	271.0	35.5	6.9	52.3	-1.4	2.7
60º	43.4	13.7	1.9	106.6	-5.0	25.4	254.8	33.1	0.9	48.4	-1.4	2.0
70º	41.2	15.7	1.0	77.8	1.6	17.7	234.2	30.0	-4.5	45.5	-0.9	1.0
80º	44.5	17.8	-1.6	67.6	13.6	9.0	212.6	25.7	-7.3	46.1	0.0	-1.1
90º	58.4	21.0	-4.4	69.1	33.3	4.4	192.7	23.2	-8.5	50.0	1.9	-2.4
100º	101.9	29.7	-11.5	78.3	50.3	1.0	173.9	21.1	-8.8	57.0	4.0	-4.0
110º	176.8	39.7	-21.8	91.3	67.7	-1.1	154.6	17.0	-10.1	65.7	5.7	-5.7
120º	274.0	47.9	-33.7	106.4	83.4	-3.1	133.4	12.6	-11.6	75.8	8.8	-5.8
130º	385.1	56.2	-44.0	122.8	97.7	-5.2	112.0	8.8	-13.2	86.5	12.0	-4.2
140º	503.1	60.8	-52.8	140.1	110.2	-6.8	91.4	5.3	-13.2	98.2	15.2	-2.0
150º	621.2	60.5	-59.7	158.4	121.4	-6.8	74.3	2.0	-11.0	109.8	18.8	0.6
160º	734.9	56.7	-64.6	180.6	131.7	-6.1	63.0	0.4	-10.1	121.6	22.0	3.1
170º	839.9	51.1	-68.5	210.0	139.4	-2.0	55.9	1.3	-8.6	132.3	25.0	6.3
180º	928.5	43.4	-69.6	248.3	145.2	4.8	51.6	3.9	-7.4	140.3	27.5	9.4
190º	999.9	33.9	-67.8	301.8	146.3	11.6	49.9	6.1	-5.7	145.2	28.9	11.9
200º	1047.5	23.6	-62.6	367.8	142.0	14.9	49.2	7.3	-3.7	146.8	29.2	14.1
210º	1069.6	12.1	-54.9	446.4	134.6	19.5	48.9	8.3	-1.3	145.0	28.3	16.4
220º	1067.2	-0.1	-43.9	549.0	114.4	17.9	48.8	9.0	1.0	139.8	26.9	18.2
230º	1037.0	-12.7	-29.5	669.7	88.3	16.7	49.0	8.7	2.2	132.0	24.4	18.4
240º	980.3	-24.0	-12.9	800.2	57.5	15.1	50.4	7.7	3.5	122.2	21.1	17.9
250º	897.4	-33.8	5.1	934.5	21.7	8.3	53.5	6.8	5.3	111.2	17.5	16.6
260º	793.9	-42.1	21.3	1061.2	-9.3	0.8	61.1	5.3	9.3	101.7	13.7	13.8
270º	678.3	-47.3	36.5	1169.5	-32.0	-2.4	75.0	6.4	14.5	93.9	10.5	11.3
280º	573.4	-45.0	46.3	1252.1	-55.4	-4.2	93.5	8.2	19.9	87.7	7.2	8.0
290º	485.7	-39.1	51.1	1302.8	-75.2	-4.5	114.0	8.6	23.3	82.3	3.5	4.3
300º	410.8	-32.7	52.1	1318.8	-92.3	-4.5	133.9	8.8	25.6	77.8	1.2	2.0
310º	345.6	-23.7	52.0	1299.3	-105.4	-4.8	153.5	9.7	26.7	73.9	-0.7	1.1
320º	288.7	-15.9	50.6	1244.8	-114.3	-4.4	172.7	11.0	28.1	71.4	-2.3	0.5
330º	238.2	-10.8	47.9	1157.9	-117.6	-2.6	192.9	12.2	30.6	69.5	-2.9	0.3
340º	195.0	-7.0	44.0	1044.5	-114.5	-0.1	215.3	14.9	30.3	69.1	-3.2	0.1
350º	159.6	-3.0	37.7	912.0	-106.5	5.4	237.2	19.6	29.5	69.2	-3.0	0.6

Figure captions

Fig. 1. Map of Spain illustrating the locations of the four weather stations used in this study.

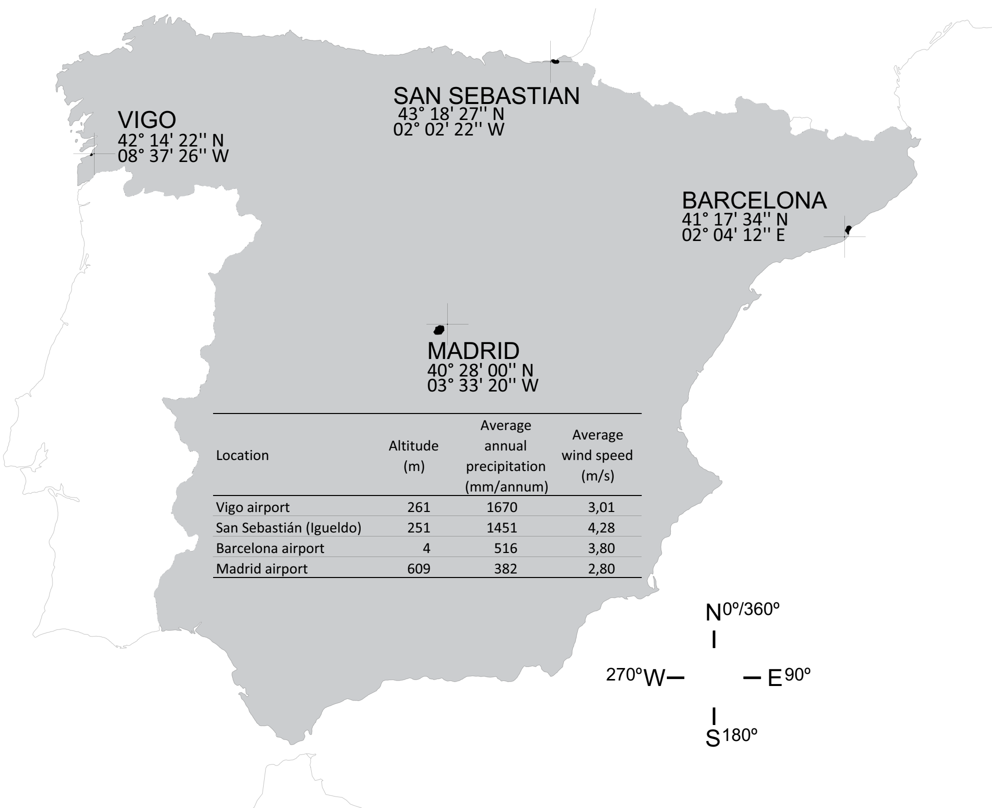
Fig. 2. Plot of average annual driving rain versus wall angle I_A that is determined using the ISO standard method (bars) and the present weather observation method (broken line) over the 1998-2011 time period at four Spanish locations. Angles are measured in degrees from north.

Fig. 3. Normalised frequency ($Nf_{events\ D}$) of all forms of rain observations (black bars) versus only the moderate or heavy rain observations (codes 62-65, 81, and 82) (gray bars) for the 1998-2011 time period at Vigo, San Sebastian, Barcelona, and Madrid. Angles are measured in degrees from north.

Fig. 4. Comparison of the hourly approach $\sum U_{10} \bullet R_h$ (bars) and the synoptic approach $U_{10D} \bullet \sum R_h$ (broken lines) over the 1998-2011 time period at four Spanish locations. Angles are measured in degrees from north.

Fig. 5. Comparison of average annual driving rain versus wall angle I_A using ISO standard (bars), present weather observation method (broken line) and optimised synoptic method (solid line) over the 1998-2011 time period at four Spanish locations.

Figure 1



Location	Altitude (m)	Average annual precipitation (mm/annum)	Average wind speed (m/s)
Vigo airport	261	1670	3,01
San Sebastián (Igueldo)	251	1451	4,28
Barcelona airport	4	516	3,80
Madrid airport	609	382	2,80

Figure 1. Map of Spain illustrating the locations of the four weather stations used in this study.

Figure 2

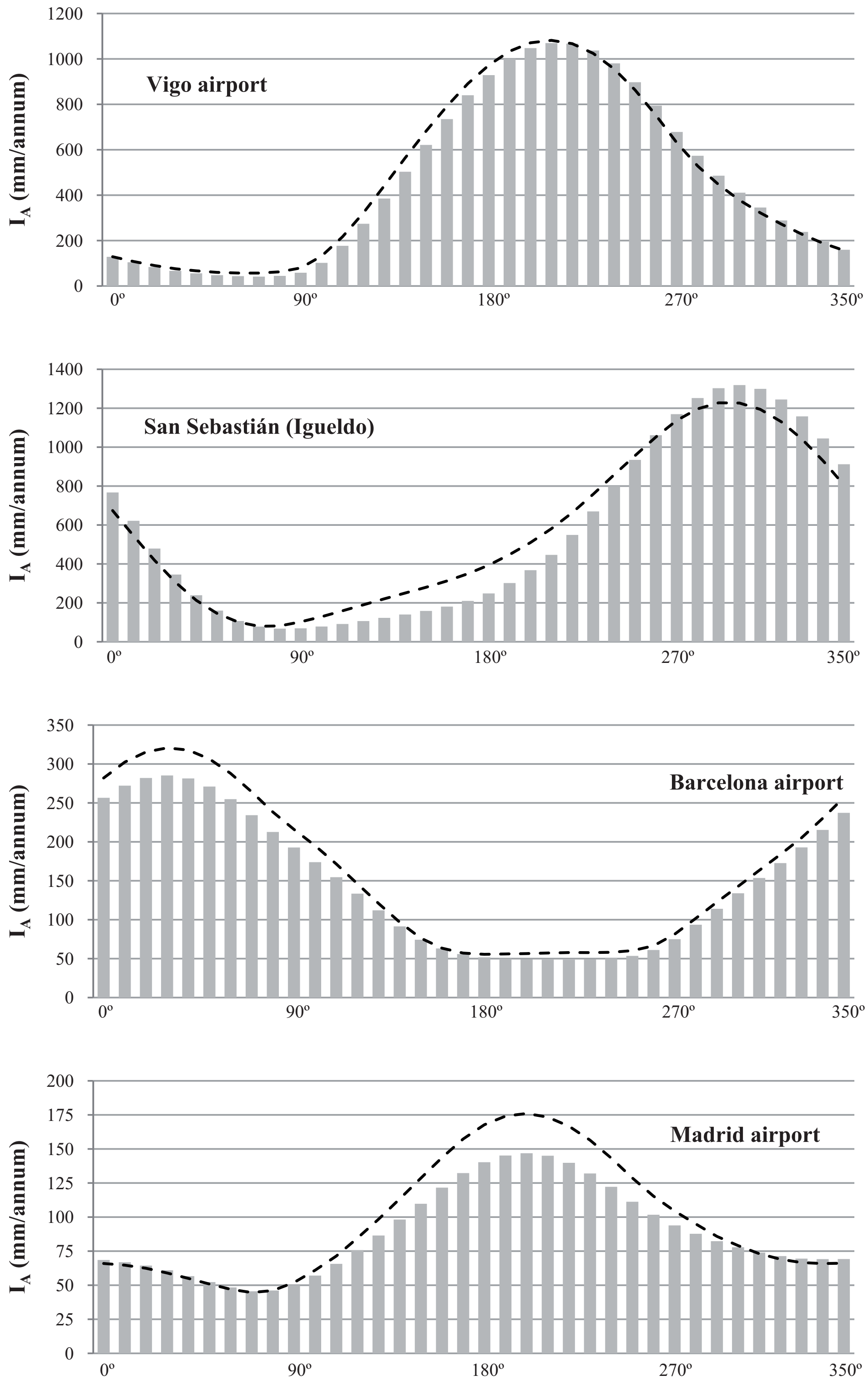


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Figure 3

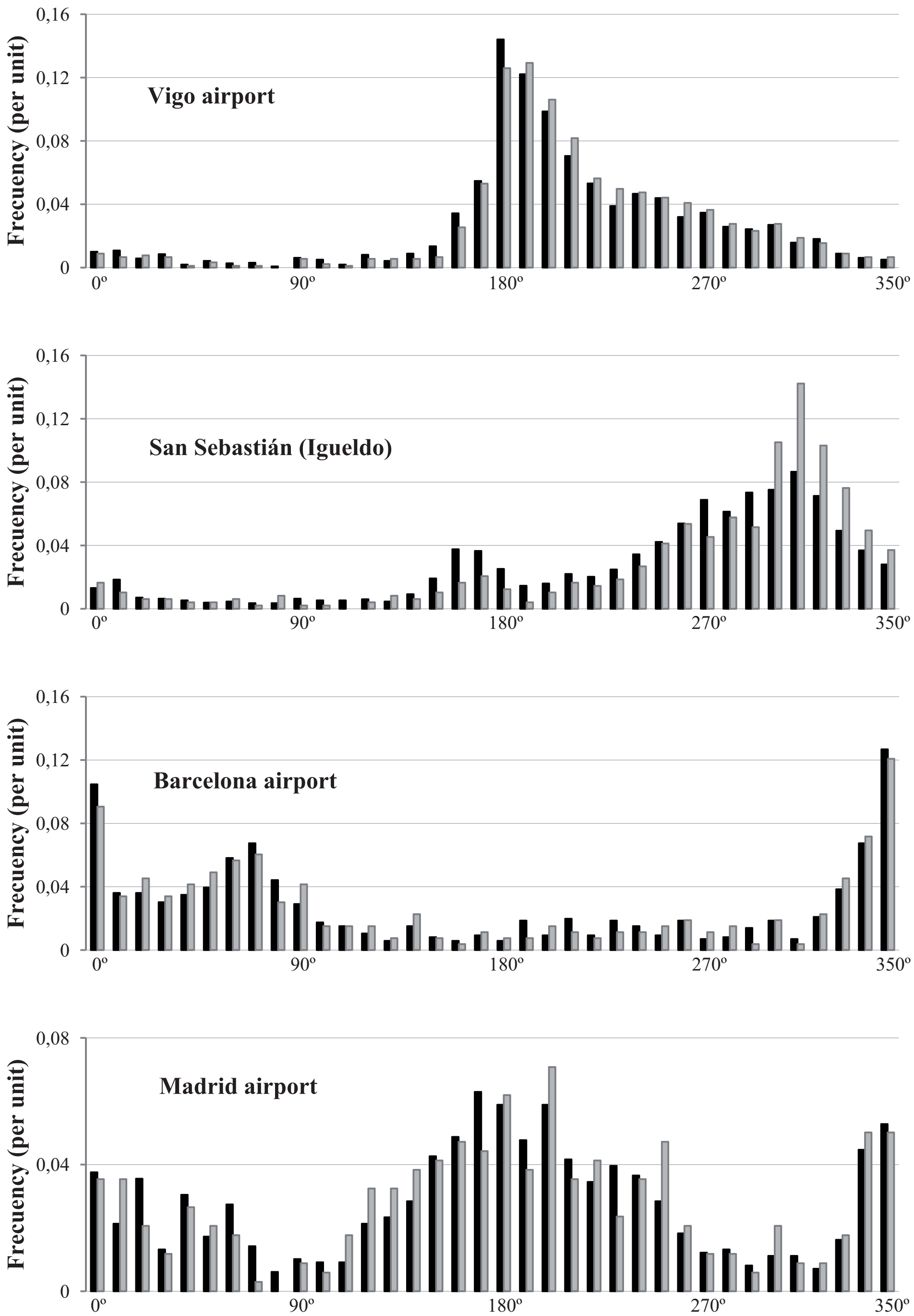

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Figure 4

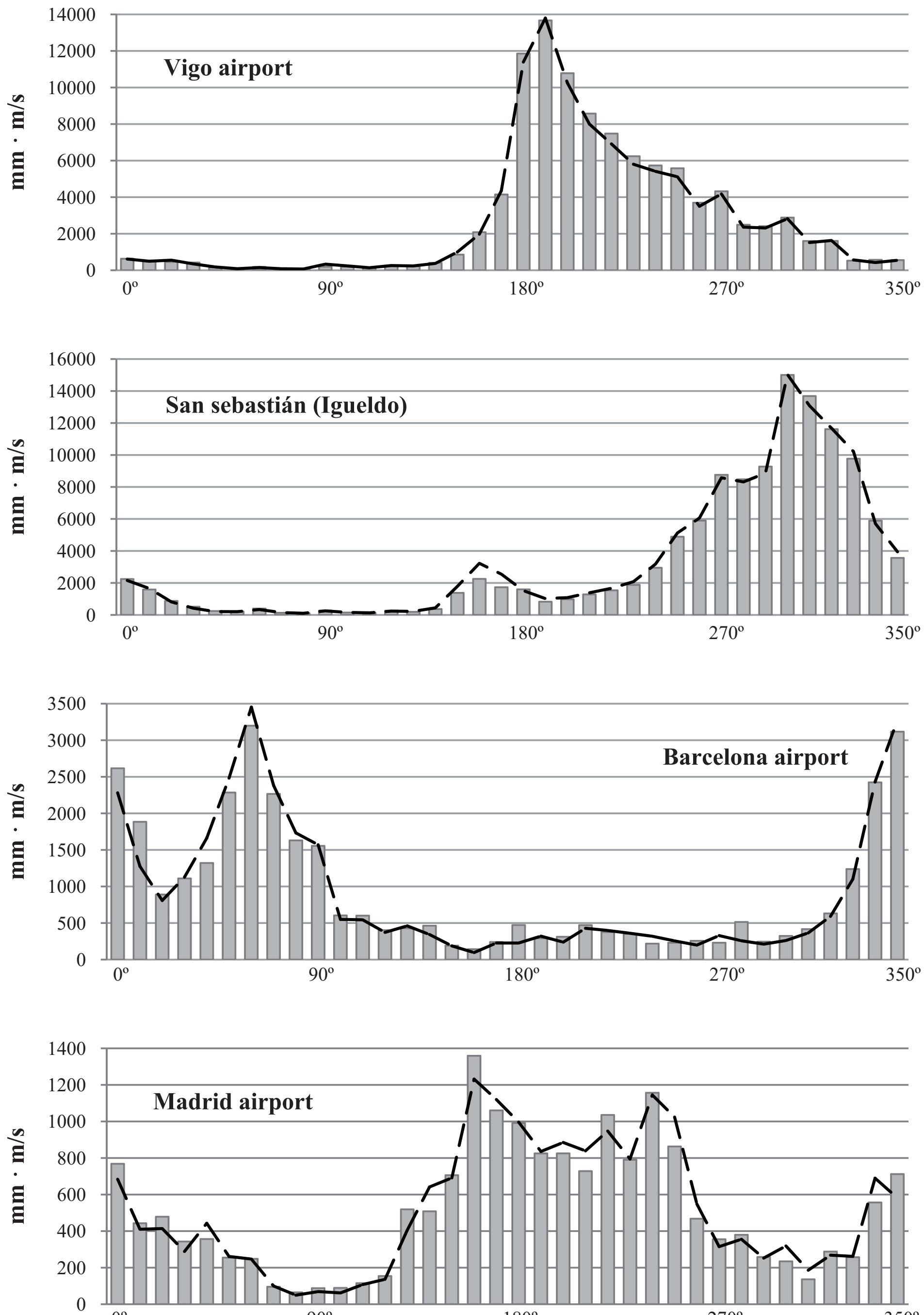

Figure 4. Hourly comparison $\sum U_{10}\bullet R_h$ (bars) versus synoptic approach $U_{10D}\bullet\sum R_h$ (broken lines), for the period 1998-2011, at four Spanish locations. Angles are measured in degrees from north.

Figure 5

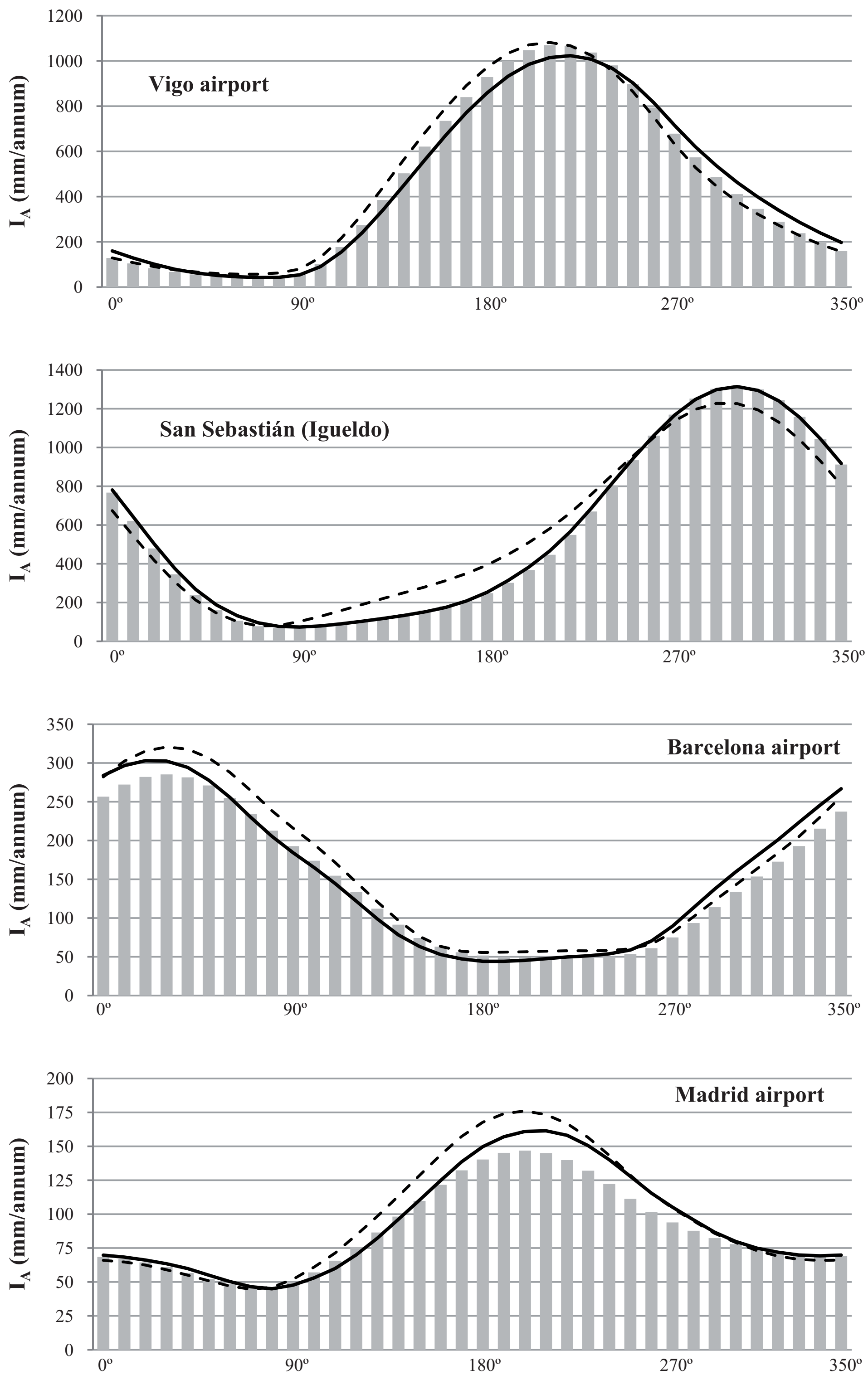

Figure 5. Comparison of average annual driving rain versus wall angle I_A using ISO standard (bars), present weather observation method (broken line) and optimised synoptic method (solid line) over the 1998-2011 time period at four Spanish locations.