On the significance of the climate-dataset recording interval in characterising wind-driven rain and simultaneous wind pressure. Part I: Scalar approach

José M. Pérez-Bella[a], Javier Domínguez-Hernández[a,*], Enrique Cano-Suñén[a], Juan J. del Coz-Díaz[b], Mar Alonso-Martínez[b]

[a] *Department of Construction Engineering, Engineering and Architecture School, University of Zaragoza, 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

The joint action of wind-driven rain and wind pressure is the main cause of water penetration in building facades, which causes various habitability and durability problems. The most widespread characterisation of both climate factors is based on exposure indices calculated in free-field conditions from records of precipitation - wind velocity (scalar indices) and wind direction (directional indices). The time resolution of this climate dataset defines the calculation effort and the accuracy obtained, and average daily, monthly, or annual records are typical due to their greater availability. This paper investigates the influence of the recording interval on the accuracy of these scalar exposure indices (driving-rain index, hereafter aDRI, and driving-rain wind pressure, hereafter DRWP) by assessing the nature and magnitude of errors associated with each time resolution. For this purpose, 10-min, hourly, daily, monthly and annual meteorological data collected over 15 years in 6 Spanish weather stations at locations characterised by different environments and topography are analysed. In addition, relationships capable of adjusting indices of any time resolution to an accuracy similar to that reached through 10-min records are proposed. In general, the value of driving-rain wind pressure exhibits greater sensitivity than the driving-rain index at this time resolution, incorporating significant errors even with daily datasets. In turn, the use of monthly and annual records should be discarded, given their high uncertainty. The results demonstrate how the daily datasets for aDRI indices and hourly datasets for DRWP values are sufficient to characterise these exposures with errors of less than 11%.

Keywords

Wind-driven rain; Wind pressure; Building façades; Climatic data; Error

[*] 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

Rainwater penetration into facade materials causes various durability problems, such as erosion, corrosion, frost attack, salt crystallisation, surface soiling and discoloration, loss of adherence, deformations, cracking, and falling materials [1-5]. It is also one of the main factors affecting the hygrothermal performance of the building, reducing its thermal insulation and increasing energy consumption and emission of air pollutants [6-8]. In addition, this moisture is associated with different health problems for the tenants [9].

The penetration of atmospheric water is produced by a combination of rainwater on the facade and the action exerted by the wind on this water supply. The rain diverted by wind action (wind-driven rain, hereafter WDR) and the simultaneous driving-rain wind pressure (DRWP) are thus the main climatic factors involved in the penetration process [10-12]. Determining both parameters is a necessary task to evaluate the characteristic exposure conditions in each site and thus to define facade designs that guarantee the necessary watertightness.

The most widespread and functional method for determining WDR exposure is based on semi-empirical approaches, establishing experimental adjustments from wind and precipitation data collected under free-field conditions [13-14]. Thus, it is possible to define "airfield" indices associated with each location (i.e., relative to free-field conditions), which can subsequently be refined using empirical coefficients to represent the specific conditions of each facade (such as surroundings, topography, and geometry) [15-17].

The study of DRWP has received much less attention than WDR exposure, despite its crucial role in the penetration process (reflected in the standardised watertightness tests) [11, 18-21]. The few studies performed have used the Bernoulli equation to determine the DRWP value, considering only the wind velocity records concurrent with precipitation events [22-24].

These exposure indices can be scalar (representing the overall exposure value at the site) or directional by also evaluating wind direction data to determine the exposure on each possible facade orientation [15, 25-26]. The directional results provide more comprehensive information but also require a greater calculation effort and access to additional weather data, which are not always available.

In this sense, the recording interval of the climatic data constitutes another important limitation that decisively influences the accuracy of the exposure indices. The climate datasets conventionally used to characterise these exposures (daily, monthly and annual) are obtained as arithmetic averages of raw measurement data generally not available (collected every 1, 5, and 10 min). In turn, these raw data reflect the linearisation of the meteorological sensor outputs [27]. Thus, these arithmetic means are a source of co-occurrence and averaging errors (due to omitting the simultaneity of wind only with rainfall intervals and to the mathematical averaging of the raw data, respectively) [28-31].

Some studies have addressed the required time resolution of these datasets for WDR calculations based on computational fluid dynamics (CFD), focusing their efforts on proposing improved averaging techniques for the raw measurement data [29-30]. However, recent work has demonstrated that these improved techniques are not suitable to semi-empirical calculation methods [32]. Thus, a systematic approach that determines the errors associated with different recording intervals has not yet been developed for semi-empirical calculations of WDR exposure (much less for DRWP exposure). Consequently, there are currently no guidelines to evaluate the accuracy and uncertainty of multiple studies conducted using datasets with low time resolution.

This article develops an exhaustive task of analysis of 10-min records collected between 2001 and 2016 in 6 meteorological stations in the northwest of Spain, obtaining airfield exposure indices of WDR and DRWP based on 10-min, hourly, daily, monthly and annual datasets. This analysis aims to reduce this lack of information, offering a broad perspective on the nature and magnitude of errors associated with each recording interval for locations with different characteristics. In addition, general adjustment relations between the indices calculated from each dataset of different time resolution are proposed. For clarity and given the diverse climatic data involved, this study is divided into two distinct parts: the significance of the recording interval on the scalar results (Part I) and on the directional results (Part II).

2. Background

Characterisation of the WDR exposure at sites can be performed by means of experimental measurements, CFD methods and semi-empirical correlations [15]. Experimental measurements are costly and entail long periods of observation. In turn, CFD methods require a significant calculation effort and high-quality input data adapted to each specific situation. Only semi-empirical methods allow a simple and functional characterisation of the exposure in a large number of sites, although their thoroughness is inferior to the other methods.

These semi-empirical methods are based on the 'WDR relationship', which uses free-field climate records generally gathered at most of the weather stations and empirically fitted coefficients [13, 33]. By multiplying simultaneous records of wind velocity U (m/s) and precipitation intensity R_h (l/m^2), this relationship allows estimation of an airfield WDR value (l/m^2), using the value α (s/m) as a coefficient physically related to the terminal falling velocity of raindrops and that depends on the intensity of precipitation at each time point [14, 34]. Standards such as ISO 15927-3 or ASHRAE 160P also incorporate dimensionless coefficients (grouped here under the designation $F_{wall\ indices}$) to determine the WDR exposure on each specific facade, considering its shape (e.g., height, cover, and geometry), the terrain roughness, the topography of the surroundings and nearby obstructions (Eq. 1) [16-17]. To ensure the representativeness of the results, the calculation should be performed by averaging at least 10 years of climate data (as stated in ISO standard 15927-3).

$$WDR = F_{wall\ indices} \cdot \alpha \cdot U \cdot R_h \tag{1}$$

By also incorporating simultaneous records of wind velocity D (º), it is possible to determine the directional distribution of the exposure in each facade orientation θ (º). For this, Eq. (1) would be multiplied by cos(D-θ), thus considering only the wind direction records when the analysed facade is in a leeward position (cosine projection with positive value) [15-17, 25]. In this work, scalar indices are referred to those exposure values that do not incorporate climate records of wind direction, thus providing only global (non-directional) exposure information.

Based on this WDR relationship, the annual driving-rain index (aDRI) is the simplest and most generalised indicator to evaluate the average annual exposure at each location [13, 26, 31, 35-38]. For its scalar calculation, the coefficient α, directional characterisation and wall indices (i.e., obtaining an airfield index) are ignored. This gives an *aDRI* value (m^2/s), which qualitatively characterises the scalar exposure from the *k* records collected at the site over *N* years (see Eq. 2). In spite of its simplicity, this index can be used as reference to obtain more refined results, incorporating adequate values for the coefficient α and the wall indices.

$$aDRI = \frac{\sum_{i=1}^{k} U_i \cdot \left(\frac{R_{h\,i}}{1000} \right)}{N} \tag{2}$$

On the other hand, the penetration of water into building facades does not depend exclusively on the water supply provided by wind-driven rain. On the contrary, it depends strongly on the simultaneous existence of wind pressure on the facade that is capable of overcoming the surface tension and capillary pressure of the water contained in the material deficiencies. Thus, it is estimated that this is the most sensitive parameter related to water penetration in facades without openings and pores greater than 1 mm [11]. Therefore, characterising the DRWP exposure at the location is of equal interest to studying the WDR.

The most widespread method of determining the value of *DRWP* (Pa) is based on the analysis of the *m* wind velocity records *U* (m/s), which are simultaneous to intervals with precipitation during the studied period ($m \leq k$). This is performed using the Bernoulli equation (Eq. 3), where C_p (-) represents the pressure coefficient (usually equal to 1) and ρ_{air} the air density (generally set at 1.2 kg/m^3). As in Eq. 2, this result represents the scalar exposure associated with the site (in free-field conditions), and the factor cos(D-θ) can also be incorporated to obtain the directional distribution of the DRWP exposure.

$$DRWP = \frac{\sum_{i=1}^{m} C_p \cdot \frac{1}{2} \cdot \rho_{air} \cdot U_i^2}{m} \tag{3}$$

In both equations (Eqs. 2 and 3), it is possible to use climate data with different recording intervals and therefore different time resolution, without there being uniformity in the studies developed so far [11, 15, 23-24, 26, 31, 35-38]. On the contrary, in each case, the available climate records (usually annual, monthly or daily data) have been used. However, the selected recording interval influences the accuracy of the results by incorporating two types of errors in the exposure indices: a co-occurrence error (e_1), which is due to not exhaustively recording the simultaneity of wind and precipitation events, and an averaging error (e_2), which is due to the smoothing of the values of the climatic variables when averaging of the raw data [29-30].

To these errors other uncertainties must be added, which are associated with the collection of records through the meteorological sensor outputs: small-scale variability of the atmosphere conditions, noise in electronic devices, precipitation gauge errors, disturbances in wind measurements due to topographic effects and random instrumental errors among others. These random uncertainties can be minimised by collecting the sensor outputs as 2- to 10-min averages, recording wind data at 10 m above ground level in an open field (free-field conditions), and using recording precipitation gauges with high resolution [27]. In this sense, the 10-min records ensure a good representation of the rapid variations that characterise precipitation and wind phenomena [39-41].

Some works have proposed weighted averaging techniques for the raw measurement data, obtaining climate datasets to calculate with less error the WDR exposure using CFD methods [29-30]. However, a recent study has shown that these weighted techniques reduce the accuracy of semi-empirical calculations [32]. Assessing climate records collected over 6-12 months in 3 Canadian cities, this study also identified an average error close to 12% in the WDR airfield indices obtained from hourly datasets, compared to those calculated using 5- and 10-min records. However, the errors associated with other conventional intervals (daily, monthly, and annual) were not analysed, nor was the nature of the error (e_1 and e_2) differentiated. Using 30 years of daily records in 80 Spanish locations, another study quantified the e_1 and e_2 errors present in the monthly and annual airfield indices of WDR (with respect to their daily equivalents), concluding that both sources of error were equal and similar in the monthly and annual indices [31]. The same study was performed in 41 Greek cities, obtaining analogous results, although with a higher prevalence of averaging error [42].

All of these studies are partial approximations to the problem in which the climatic series are not very representative, or the analysis of the most conventional recording intervals is obviated, or the error with respect to recording intervals sufficiently exhaustive (e.g., 10-min records) is not identified. In addition, none of them analyses the effect of the time resolution of the dataset on the DRWP characterisation. Consequently, to the best of the authors' knowledge, a systematic study that comprehensively characterises the effect of the time resolution of the dataset on the accuracy of the semi-empirical airfield indices of both WDR and DRWP exposures has not yet been conducted.

Thus, guidelines to assess the real accuracy of the exposure results obtained from datasets of low time resolution are lacking. Given that these studies are the most common (due to the difficulty in accessing hourly data with the representativeness required by ISO 15927-3 and ASHRAE 160P standards), most of the published characterisations for both exposures have been performed without knowing their real uncertainty range [15, 35-38]. Similarly, although adjustment relationships have been defined between daily, monthly and annual exposure indices, extrapolations to achieve an accuracy similar to that of the indices based on raw measurement data have not yet been developed.

To clarify these issues, this paper analyses hourly, daily, monthly and annual climate records, identifying the nature and magnitude of the errors associated with each record interval in the scalar airfield indices defined by Eqs. 2 and 3. To compare and assess these errors, the exposure values calculated from 10-min records are taken as a reference. In addition, adjustment relationships to extrapolate results with an accuracy similar to that defined by 10-min records from the indices obtained through any time resolution of the dataset are proposed.

3. Error assessment in the scalar characterisation of WDR and DRWP airfield indices

3.1 Research scope

The increasing deployment of automatic weather stations equipped with data-loggers capable of collecting and transmitting raw data in real time (or storing them until download) offers new possibilities to incorporate better-time-resolution records in the calculations previously described.

For this study, 6 automatic stations installed since 2000 in the northwest of Spain (Galicia region) have been selected. The choice of these stations is justified by the availability of sufficiently representative meteorological datasets, which has allowed the examination of 15 years of records in all of them (1 Feb. 2001 – 31 Jan. 2016). At each station, more than 780,000 10-min intervals have been analysed, with simultaneous records of precipitation intensity and wind velocity (measured at 10 m above open flat ground). Less than 1.5% of the analysed intervals lack records, as a result of failures, problems with data transmission or storage, maintenance, etc., which guarantees the representativeness of the historical series. The reliability and longevity of these datasets ensure that the results obtained are not influenced by years of exceptional climatology nor by prolonged interruptions of the records.

The devices used to record these climatic variables conform to the guidelines set by the World Meteorological Organisation (see Fig. 1) and form part of the official meteorological network of the region of Galicia [27, 43]. To obtain the dataset corresponding to other usual recording intervals (e.g., hourly, daily, monthly and annual), 10-min records have been arithmetically added and averaged using a spreadsheet program.

Fig. 1. Characteristics and location of the 6 analysed weather stations.

Bordered by the Atlantic Ocean on its northern and western boundaries (see Fig. 2), Galicia presents the highest WDR and DRWP exposures in Spain, especially near the coast and the numerous ocean-drowned river valleys [23, 24, 31]. The west coast and the interior of the region are characterised by a topography of low hills and subject to strong winds from the Atlantic Ocean. It also has an oceanic climate with dispersed precipitation throughout the year and seasonally more intense (in autumn and winter). In northern and eastern Galicia, the more rugged topography (reaching elevations of up to 2,100 m near the O Invernadeiro station) reduces the influence of the ocean on the local climate. This makes possible the existence of a warm-summer Mediterranean climate, with more concentrated rainfall in autumn and winter [44].

Fig. 2. Location of the 6 weather stations selected for the conducted study. *Darker colours represent higher elevations*.

In addition to this climatic variety and high exposure, the 6 stations are characterised by different environmental conditions, elevation, topography and distance to the coast. Two of the stations correspond to coastal locations (CIS Ferrol and Corrubedo) located less than 1 km from the ocean and at low elevation. CIS Ferrol is also located in the important Ría de Ferrol (a wide ocean-drowned river valley), bordered by low hills. The Pedro Murias station is located in the area of other small estuary denoted Ría de Ribadeo less than 4 km from the coast and on a flat terrain. Above 350 m of elevation, the stations of Queimadelos and Campus Lugo are located in wooded and urban environments, respectively. The last station is located at 1,026 m elevation, in the mountains of the interior belonging to the Natural Park O Invernadeiro.

The stations located close to the coast and subjected to strong ocean winds are highly exposed to wind (mean wind velocity of 4.09 m/s in Pedro Murias and 3.17 m/s in CIS Ferrol), whereas for stations located inland, only O Invernadeiro reaches 2.30 m/s (due to its higher elevation). The Queimadelos station, at 371 m and in a wooded environment, presents the lowest wind exposure (mean wind velocity of 1.37 m/s). There are also significant rainfall variations, ranging from 948 mm/year in Campus Lugo to 1,785 mm/year in Queimadelos. The O Invernadeiro station, due to its altitude, also has a high rainfall (1,651 mm/year). Altogether, this variety of conditions guarantees the representativity and validity of the obtained results for different types of locations and exposure conditions.

3.2 Calculations and results

Using the climate datasets associated with different recording intervals, the scalar exposure indices described in Eqs. 2 and 3 have been calculated for each location. For clarity, each exposure index is prefixed with an acronym *j* to represent the recording interval used in its calculation (i.e., "*h*" for hourly calculations, "*d*" for daily, "*m*" for monthly and "*a*" for annual). Thus, the values used as reference (based on 10-min records) are denoted as *10'aDRI* and *10'DRWP*. These results are presented in Table 1.

Table 1.
Exposure results to wind-driven rain and simultaneous wind pressure for climate datasets of different time resolution.

These exposure indices are consistent with those identified in 2014 by another study conducted in the region of Galicia, which produced two exposure isopleth maps from daily records collected at 80 stations [24]. Only Campus Lugo, with a value of 2.06 m^2/s, slightly exceeds the range 0-2 m^2/s indicated by the daDRI isopleth map for its area. Likewise, only the dDRWP value from O Invernadeiro (5.10 Pa), exceeds the range of 0-5 Pa marked by the isopleth exposure map for its zone. This consistency with previous results reinforces the validity of the values presented in Table 1.

However, the presented values show that the exposure calculated using datasets with a smaller recording interval (and that are therefore more accurate and realistic) is higher to that identified by the daDRI and dDRWP indices. It follows that the exposure characterisation provided by these exposure maps, like many others available in the bibliography and obtained from low-time-resolution records, need additional corrections to avoid underestimating the actual exposure in the sites. Quantifying the magnitude of these underestimates according to the recording interval used in the calculation is therefore a key factor to improve the accuracy of this type of study.

To analyse the nature of the errors associated with each time resolution *j*, the same previous calculation has been repeated (Eqs. 2 and 3), but those 10-min wind records corresponding to intervals without precipitation were removed from the hourly, daily, monthly and annual averages. The result eliminates the co-occurrence error, obtaining exposure indices in which only the averaging error e_2 (see Table 2) appears. For clarity, the subscript e_2 is incorporated into these refined exposure values (without co-occurrence error).

Table 2.
Exposure results without co-occurrence error for climate datasets with different time resolutions.

The difference between the 10-min exposure values and the values thus refined for each recording interval *j* allows characterising the characteristic averaging error at each time resolution (e_2). The e_1 error can then be obtained as the difference between the total error (i.e., e_1 + e_2) and the error linked exclusively to the mathematical averaging of the climate records, e_2 (Eqs. 4-8). The results of this analysis are presented in Table 3 (expressed as percentages).

$$ {}_{\mathrm{j}}aDRI\ error\ \left(e_1+e_2\right)=\frac{100\cdot\left({}_{\mathrm{j}}aDRI-10'aDRI\right)}{10'aDRI} \tag{4}$$

$$ {}_{\mathrm{j}}aDRI\ error\ e_2=\frac{100\cdot\left({}_{\mathrm{j}}aDRI_{e2}-10'aDRI\right)}{10'aDRI} \tag{5}$$

$$ {}_{\mathrm{j}}DRWP\ error\ \left(e_1+e_2\right)=\frac{100\cdot\left({}_{\mathrm{j}}DRWP-10'DRWP\right)}{10'DRWP} \tag{6}$$

$$ {}_{\mathrm{j}}DRWP\ error\ e_2=\frac{100\cdot\left({}_{\mathrm{j}}DRWP_{e2}-10'DRWP\right)}{10'DRWP} \tag{7}$$

$$ error\ e_1=error\left(e_1+e_2\right)-error\ e_2 \tag{8}$$

Table 3.
Percentage errors derived from the non-co-occurrence of wind and rain (e_1) and from the averaged data (e_2) for climate datasets of different time resolution (regarding 10-min values).

As expected, the magnitude of the errors increases with decreasing time resolution of the climate dataset. However, this growth is not proportional to the recording interval, nor are the errors similar in both exposure indices for the same time resolution. Nor do the factors causing the error have the same influence on the different recording intervals (see Figs. 3 and 4). It is also observed that although both e_1 and e_2 tend to underestimate the existing exposure, in the case of hourly datasets, both sources of error can counteract each other, thus reducing the resulting error.

Fig. 3. Magnitude and nature of the aDRI error associated with each recording interval and its fluctuation for the different analysed locations.

Fig. 4. Magnitude and nature of the DRWP error associated with each recording interval and its fluctuation for the different analysed locations.

4. Discussion

By analysing the results presented in Table 1, it can be observed that the sites subjected to a greater mean wind velocity also exhibit higher values of 10'DRWP exposure (see Fig. 1). This correlation is consistent with the high coefficients of determination R^2 identified between values of DRWP and wind pressure in different countries [24, 26, 38]. However, site pluviometry is not a determining factor in estimating the aDRI value, making a specific analysis of precipitation and simultaneous wind records to determine the WDR exposure unavoidable.

The maximum values of WDR and DRWP exposure are identified at stations closest to the coast (Corrubedo 7.98 m^2/s and 40.82 Pa, respectively), thus presenting a greater risk of water penetration in the facades. Pedro Murias and Queimadelos, somewhat further from the coast, have lower WDR exposures than Corrubedo and CIS Ferrol. Campus Lugo, in an urban environment in the interior of Galicia, exhibits the lowest aDRI value (2.23 m^2/s). Despite its distance to the coast, O Invernadeiro reaches a 10'aDRI value of 5.39 m^2/s, due to its elevation and high rainfall. In contrast, its DRWP value is lower than that of the coastal stations. In this sense, the lowest values of DRWP exposure occur in stations characterised by their urban and forest environment: Campus Lugo (4.20 Pa) and Queimadelos (3.57 Pa).

Considering the errors associated with each recording interval (Figs. 3-6), it is observed that the use of hourly datasets introduces an average error of 1.46% and 10.48% in the WDR and DRWP exposure values, respectively. In any case, the error varies between the analysed stations, depending on the particular characteristics of the atmospheric events at each site. Thus, the standard deviations σ for haDRI and hDRWP values reach 1.2% and 4.9%, respectively. In the case of daily datasets, the mean errors increase to 8.15% for the WDR values (still below the error associated with the hDRWP value) and 37.62% for the dDRWP values. Similar to the hourly errors, the variability is also significant (σ is equal to 4.0% for the daDRI indices and 10.7% for the dDRWP indices).

For their part, the monthly and annual datasets introduce very high errors in the scalar characterisation of the exposure, without there being a significant difference in accuracy between both recording intervals. Thus, the mean error for the maDRI values reaches 28.87% (σ = 8.8%) and is 31.83% for the aaDRI indices (σ = 10.6%). In the case of DRWP exposure, the mean error of the mDRWP values reaches 57.92% (σ = 10.1%), and that of aDRWP values reaches 59.47% (σ = 9.9%).

As observed, in general, the error associated with aDRI values is significantly less than that identified in the DRWP indices for the same recording interval. This fact can be explained by the different number of climatic variables involved in each exposure index, and by their variability during precipitation periods. In calculating the DRWP value, the magnitude of the error depends on the influence of the co-occurrence and averaging errors on a single variable (wind velocity). This meteorological dataset is highly variable, so it is especially sensitive to the averaging error. However, the aDRI index results from the product between this wind velocity dataset and the simultaneous precipitation data at each interval. This weighting reduces the sensitivity to the averaging error and also minimises the co-occurrence error: even if a wind velocity datum not simultaneous to precipitation is considered, its associated precipitation datum does not contribute to the precipitation interval, thus reducing the influence of this wind datum in the daDRI value calculation.

Thus, although the averaging error (e_2) is a secondary source of error for calculating the WDR exposure, it is clearly more influential than the co-occurrence error for the calculation of the DRWP exposure (Figs 5 and 6). Likewise, although co-occurrence errors (e_1) exhibit a similar influence on both exposure indices, this is slightly lower for the calculation of WDR exposure. For all of the above, the datasets used to characterise the DRWP exposure require a better time resolution than those employed for aDRI calculation if both characterisations are intended to have similar levels of uncertainty.

Fig. 5. Evolution of mean calculation errors in aDRI values for the usual recording intervals used for climate datasets (logarithmic scale).

Fig. 6. Evolution of mean calculation errors in DRWP values for the usual recording intervals used for climate datasets (logarithmic scale).

In summary, it can be said that the error committed (and also its dispersion or standard deviation) grows rapidly as the recording interval increases, stabilising for the monthly - annual interval. Based on the 10-min results, only the hourly datasets provide estimates of DRWP exposure with errors less than 11%. In the case of aDRI indices, only the hourly and daily datasets maintain an average error below this threshold. The distinct recording interval required to calculate both exposures with a similar level of accuracy is thus shown. Those climate datasets with lower time resolution (i.e., monthly and annual datasets), although they significantly reduce the calculation effort, should be discarded owing to their high uncertainty.

The above suggests the need to perform a critical re-analysis of the WDR and DRWP characterisation studies performed so far using climate datasets with low time resolution. Given the representativeness of the study conditions (long series of records with less than 1.5% of missing data and locations with different conditions), the obtained error ranges can serve as guidelines for this re-analysis, assessing the uncertainty associated with the recording interval used in locations subject to different environmental conditions and exposure.

4.1 Fitting relationships.

In any case, climate datasets with exhaustive and simultaneous precipitation and wind velocity records are often unavailable in many regions (the number of suitable weather stations is often insufficient, or the records cover a non- representative number of years). Therefore, several studies have identified simple linear regressions that allow extrapolating scalar values of WDR exposure associated with different recording intervals [26, 31, 36-38, 42]. In this manner, the possibility of improving the accuracy of the results obtained from deficient data series (e.g., from aaDRI or maDRI values, up to its corresponding daDRI estimation) exists.

In general, there is a great coincidence between the aaDRI-maDRI adjustments identified in different geographic areas, such as Spain, Brazil, Chile, Greece, India and Nigeria, with coefficients of determination higher than 0.95 [38]. However, Figs. 5 and 6 show that the improvement provided by these adjustments is not significant because the monthly indices maintain very high uncertainties, similar to the annual ones.

This coincidence between different regions is also maintained in the maDRI-daDRI and aaDRI-daDRI relationships: Fig. 7 compiles the linear regressions obtained for different countries from the results of studies that have analysed daily climate datasets [26, 31, 38, 42]. As observed, the adjustments associated with the 6 sites of Galicia are similar to those of the whole of Spain, in addition to those of other areas in middle latitudes, such as Greece and much of Chile. Brazil, located in a tropical zone and influenced by monsoon-type precipitations, presents a more divergent adjustment. This suggests that these adjustment relationships are related to the pluviometric and eolian patterns of each region, being similar in areas with similar climatic conditions (generically, mid-latitudes with seasonal rainfall).

Fig. 7. (a) Best-fit linear relationship between daDRI and maDRI; (b) best fit-linear relationship between daDRI and aaDRI, and its comparison with different countries.

For all of the above, it is presumed that the good correlations between the indices aaDRI-maDRI-daDRI also extend to scalar exposure indices obtained by datasets with a shorter recording interval. Thus, Fig. 8 shows the simple linear regression between the 10-min indices of WDR exposure and those corresponding to other recording intervals for the 6 stations analysed. In all cases, the strong correlation exists, with coefficients of determination close to the unit (especially for haDRI-10'aDRI and daDRI-10'aDRI adjustments).

These relationships could be used in areas with a similar climate as a first approximation to estimate accurate scalar indices of WDR exposure via low-time-resolution datasets. However, because no similar studies have been developed in other geographical areas, their validity and reliability should still be verified. It is up to subsequent studies to take on the challenge of analysing raw measurement data in other regions, verifying and refining, if appropriate, the proposed extrapolations.

Fig. 8. Best-fit linear relationship between 10'aDRI and aDRI indices of other recording intervals.

In turn, Fig. 9 presents the simple linear regression between the 10'DRWP index and the DRWP values associated with other recording intervals, for the 6 stations analysed. Given the absence of specific studies on the DRWP exposure variable, in this case, it is not possible to compare the similarity between adjustments obtained in different geographic regions, not even between DRWP values based on datasets with low time resolution).

However, it is observed in Fig. 9 that the coefficients of determination identified for these weather stations are similar to those of the aDRI indices, surpassing 0.97 for the 10'DRWP-hDRWP and 10'DRWP-dDRWP adjustments. As expected, this R^2 coefficient increases in both exposure parameters by reducing the recording interval considered.

On the other hand, several previous studies have found strong correlations between the wind pressure of the location and the value of DRWP in places as diverse as Chile, Brazil and Spain itself [24, 26, 38], reflecting the linkage of the DRWP value to the wind conditions of each site. Again, additional studies in other geographical areas will be necessary to verify that the proposed DRWP extrapolations can be used in regions with similar climatic conditions to those of this study.

Fig. 9. Best-fit linear relationship between 10'DRWP and DRWP indices of other recording intervals.

4. Conclusions

This manuscript analyses the effect of the time resolution of climate records on the accuracy of the semi-empirical scalar indices that characterise WDR and DRWP exposures. For this purpose, long series of 10-min, daily, monthly and annual records gathered at sites subject to different exposures and conditions have been used. Taking exhaustive 10-min records as a reference, this error analysis provides a broad perspective on the nature and magnitude of the uncertainties associated with each possible recording interval.

The results indicate that the main source of error for the calculation of aDRI indices corresponds to the use of wind velocity records that are not simultaneous to precipitation events (co-occurrence error). However, the error due to the average of the meteorological variables in longer intervals is more significant for the DRWP calculation.

In general, the error is reduced by using climate records with a better time resolution. However, DRWP indices present greater sensitivity to the time resolution of the dataset, requiring more exhaustive recording intervals to reduce their uncertainty range. Thus, the hourly and daily datasets may be considered sufficiently accurate to characterise the scalar WDR and DRWP exposures, respectively (with errors less than 11%). On the contrary, the monthly and annual climate records (in addition to the daily records for the calculation of the DRWP exposure) should be discarded, owing to their high uncertainty. The results provided can be used as a guide to reinterpret scalar exposures already obtained through low-resolution datasets, in addition to estimate the uncertainty of future results in which the available climate data do not reach the required quality.

In any case, fitting relationships capable of extrapolating accurate values of aDRI and DRWP (similar to those based on 10-min records), from low-resolution datasets have also been presented. The representativeness of the study conditions and their comparison with results obtained in other regions and climates suggest that these relationships can be useful in other places with similar climatic conditions. Nevertheless, it is still necessary to validate and refine these extrapolations, which opens a new and interesting line of work for the study of raw meteorological data in different regions of the world.

Acknowledgements

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Highlights

- Study of 10-min, hourly, daily, monthly and annually climate data, over 15 years
- Scalar calculation of WDR and DRWP exposure indices in Spanish locations
- Significance of the dataset recording interval on the accuracy of these indices
- Magnitude of the error sources associated with each possible recording interval
- Mathematical correlations for estimate the WDR and DRWP exposures

List of tables

Table 1

Table 1.
Exposure results to wind-driven rain and simultaneous wind pressure for climate datasets of different time resolution.

aDRI (m^2/s)	**CIS Ferrol**	**Pedro Murias**	**Corrubedo**	**Campus Lugo**	**Quimadelos**	**O Invernadeiro**
10'aDRI	**5.02**	**3.66**	**7.98**	**2.23**	**4.07**	**5.39**
haDRI	4.86	3.59	7.99	2.18	4.05	5.36
daDRI	4.76	3.59	7.00	2.06	3.62	4.83
maDRI	4.00	2.93	4.60	1.67	2.65	3.74
aaDRI	3.97	2.71	4.07	1.71	2.50	3.61

DRWP (Pa)	**CIS Ferrol**	**Pedro Murias**	**Corrubedo**	**Campus Lugo**	**Quimadelos**	**O Invernadeiro**
10'DRWP	**11.41**	**11.10**	**40.82**	**4.20**	**3.57**	**8.02**
hDRWP	10.61	10.84	35.90	3.63	3.00	7.06
dDRWP	8.29	8.67	22.04	2.56	1.84	4.56
mDRWP	6.11	5.51	10.83	1.99	1.24	3.24
aDRWP	5.96	5.19	10.18	1.92	1.20	3.19

Table 2

Table 2.
Exposure results without co-occurrence error for climate datasets with different time resolutions.

$aDRI_{e2}$ (m^2/s)	**CIS Ferrol**	**Pedro Murias**	**Corrubedo**	**Campus Lugo**	**Quimadelos**	**O Invernadeiro**
10’aDRI	**5.02**	**3.66**	**7.98**	**2.23**	**4.07**	**5.39**
$haDRI_{e2}$	4.97	3.63	8.05	2.22	4.08	5.40
$daDRI_{e2}$	4.97	3.60	7.93	2.17	3.99	5.30
$maDRI_{e2}$	4.66	3.52	7.63	2.06	3.80	5.06
$aaDRI_{e2}$	4.61	3.50	7.56	2.06	3.80	5.01

$DRWP_{e2}$ (Pa)	**CIS Ferrol**	**Pedro Murias**	**Corrubedo**	**Campus Lugo**	**Quimadelos**	**O Invernadeiro**
10’DRWP	**11.41**	**11.10**	**40.82**	**4.20**	**3.57**	**8.02**
$hDRWP_{e2}$	11.54	11.53	37.18	3.89	3.15	7.35
$dDRWP_{e2}$	9.49	9.99	28.36	2.85	2.28	5.10
$mDRWP_{e2}$	7.74	7.20	27.27	2.67	2.35	5.09
$aDRWP_{e2}$	8.08	7.50	30.81	2.83	2.78	5.53

Table 3

Table 3.
Percentage errors derived from the non-co-occurrence of wind and rain (e_1) and from the averaged data (e_2) for climate datasets of different time resolution (regarding 10-min values).

	haDRI			daDRI			maDRI			aaDRI		
	e_1	e_2	e_1+e_2	e_1	e_2	e_1+e_2	e_1	e_2	e_1+e_2	e_1	e_2	e_1+e_2
CIS Ferrol	-2.2	-0.9	-3.1	-4.3	-0.9	-5.2	-13.1	-7.2	-20.9	-12.7	-8.2	-20.9
Pedro Murias	-1.2	-0.7	-1.9	-0.2	-1.6	-1.8	-16.0	-3.9	-19.8	-21.6	-4.3	-25.9
Corrubedo	-0.7	+0.8	+0.1	-11.7	-0.6	-12.3	-38.0	-4.4	-42.3	-43.8	-5.2	-49.0
Campus Lugo	-1.9	-0.7	-2.5	-5.0	-2.9	-7.9	-17.8	-7.6	-25.4	-16.1	-7.6	-23.6
Queimadelos	-0.9	+0.3	-0.7	-9.2	-2.1	-11.2	-28.3	-6.6	-34.9	-31.8	-6.8	-38.6
O Invernadeiro	-0.7	+0.3	-0.4	-8.8	-1.7	-10.4	-24.4	-6.1	-30.6	-25.9	-7.1	-33.0

	hDRWP			dDRWP			mDRWP			aDRWP		
	e_1	e_2	e_1+e_2	e_1	e_2	e_1+e_2	e_1	e_2	e_1+e_2	e_1	e_2	e_1+e_2
CIS Ferrol	-8.2	+1.1	-7.0	-10.5	-16.9	-27.4	-14.3	-32.1	-46.5	-18.6	-29.2	-47.8
Pedro Murias	-6.2	+3.8	-2.3	-11.8	-10.0	-21.9	-15.2	-35.1	-50.4	-20.8	-32.4	-53.3
Corrubedo	-3.1	-8.9	-12.0	-15.5	-30.5	-46.0	-40.3	-33.2	-73.5	-50.6	-24.5	-75.1
Campus Lugo	-6.4	-7.2	-13.5	-6.7	-32.2	-38.9	-16.2	-36.3	-52.5	-21.6	-32.7	-54.3
Queimadelos	-4.3	-11.6	-15.9	-12.4	-36.0	-48.4	-30.9	-34.2	-65.1	-44.1	-22.2	-66.2
O Invernadeiro	-3.6	-8.4	-12.0	-6.8	-36.4	-43.2	-23.0	-36.6	-59.6	-29.2	-31.0	-60.2

Figure captions

Fig. 1. Characteristics and location of the 6 analysed weather stations.

Fig. 2. Location of the 6 weather stations selected for the conducted study. *Darker colours represent higher elevations.*

Fig. 3. Magnitude and nature of the aDRI error associated with each recording interval and its fluctuation for the different analysed locations.

Fig. 4. Magnitude and nature of the DRWP error associated with each recording interval and its fluctuation for the different analysed locations.

Fig. 5. Evolution of mean calculation errors in aDRI values for the usual recording intervals used for climate datasets (logarithmic scale).

Fig. 6. Evolution of mean calculation errors in DRWP values for the usual recording intervals used for climate datasets (logarithmic scale).

Fig. 7. (a) Best-fit linear relationship between daDRI and maDRI; (b) best fit-linear relationship between daDRI and aaDRI, and its comparison with different countries.

Fig. 8. Best-fit linear relationship between 10'aDRI and aDRI indices of other recording intervals.

Fig. 9. Best-fit linear relationship between 10'DRWP and DRWP indices of other recording intervals.

Figure 1

CIS Ferrol
(Ferrol city municipality)
Coastal zone / drowned river valley
Altitude: 37 m
Rain gauge: R.M.Young 52202/03
Average rainfall: 1,257 mm/year
Anemometer: Ornytion 107H4M
Mean wind velocity: 3.14 m/s
Missing data: 0.98%

Pedro Murias
(Ribadeo municipality)
Coastal zone / drowned river valley
Altitude: 51 m
Rain gauge: R.M.Young 52202/03
Average rainfall: 986 mm/year
Anemometer: Ornytion 107U
Mean wind velocity: 2.94 m/s
Missing data: 0.65%

Corrubedo
(Ribeira municipality)
Coastal zone
Altitude: 30 m
Rain gauge: R.M.Young 52202/03
Average rainfall: 1,056 mm/year
Anemometer: R.M.Young 05106 MA
Mean wind velocity: 4.09 m/s
Missing data: 1.22%

Campus Lugo
(Lugo city municipality)
Inland / urban environment
Altitude: 400 m
Rain gauge: Campbell ARG100
Average rainfall: 948 mm/year
Anemometer: Ornytion 107U
Mean wind velocity: 1.79 m/s
Missing data: 0.57%

Queimadelos
(Mondariz municipality)
Forest zone
Altitude: 371 m
Rain gauge: Campbell ARG100
Average rainfall: 1,785 mm/year
Anemometer: Ornytion 107H/4
Mean wind velocity: 1.37 m/s
Missing data: 0.46%

O Invernadeiro
(Vilariño de Conso municipality)
Inland / mountain zone
Altitude: 1026 m
Rain gauge: Thies 5.4032.35.007
Average rainfall: 1,651 mm/year
Anemometer: Ornytion 107U
Mean wind velocity: 2.30 m/s
Missing data: 1.50%

Fig. 1. Characteristics and location of the 6 analysed weather stations.

Figure 2

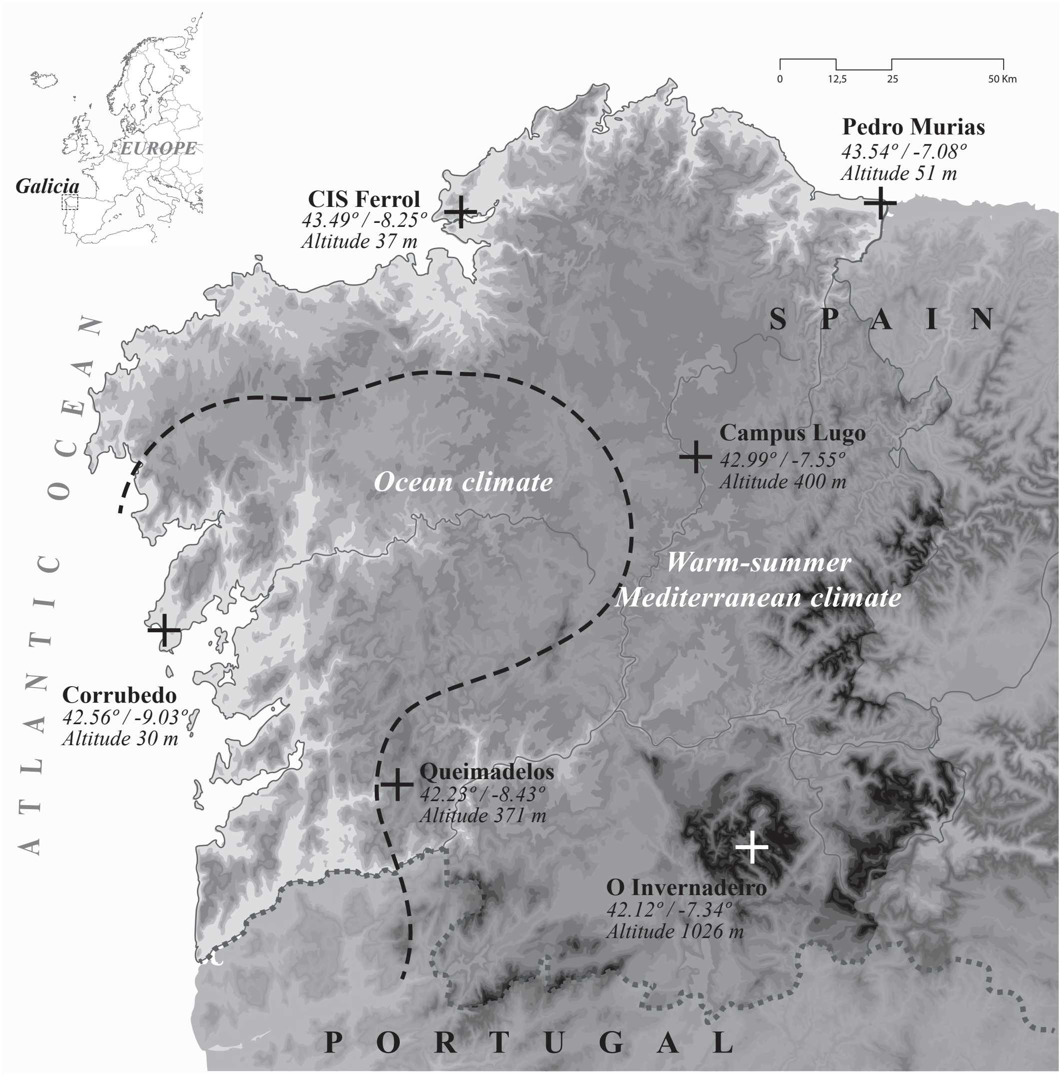


Fig. 2. Location of the 6 weather stations selected for the conducted study.
Darker colours represent higher elevations.

Figure 3

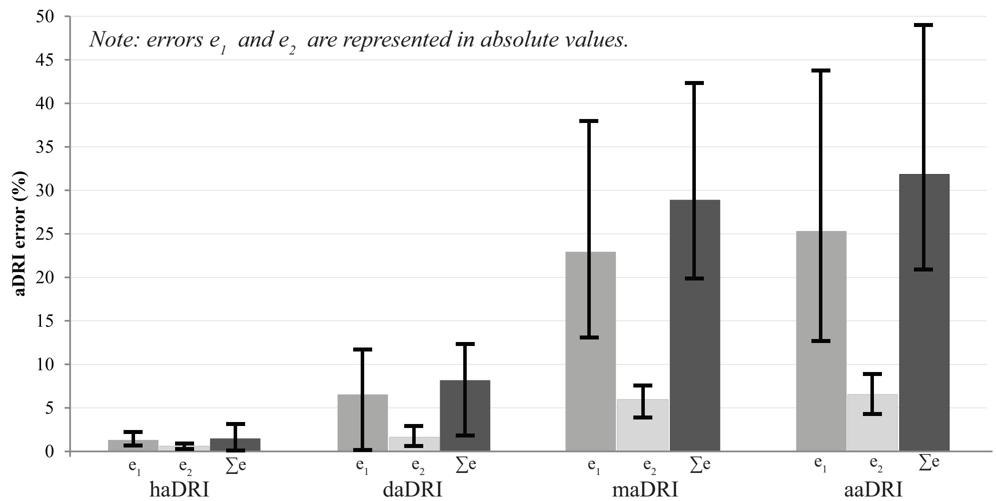


Fig. 3. Magnitude and nature of the aDRI error associated with each redording interval and its fluctuation for the different analysed locations.

Figure 4

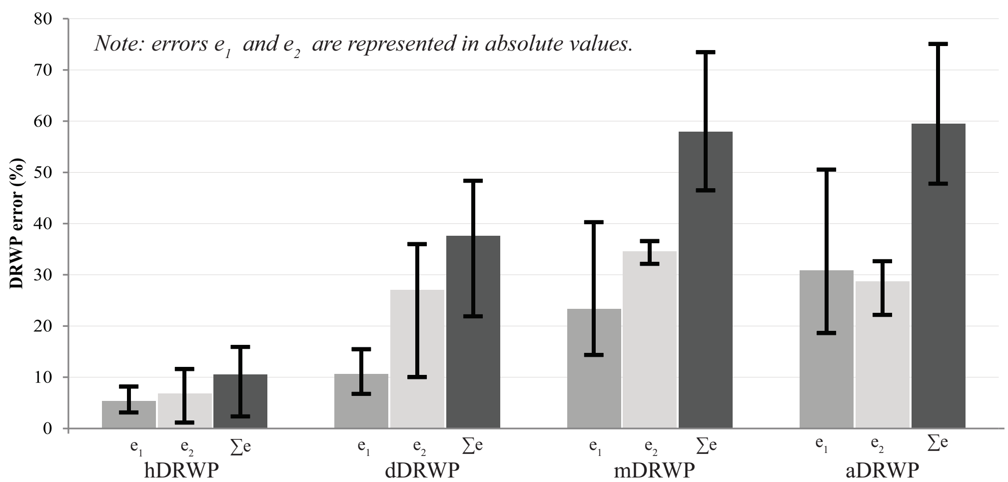
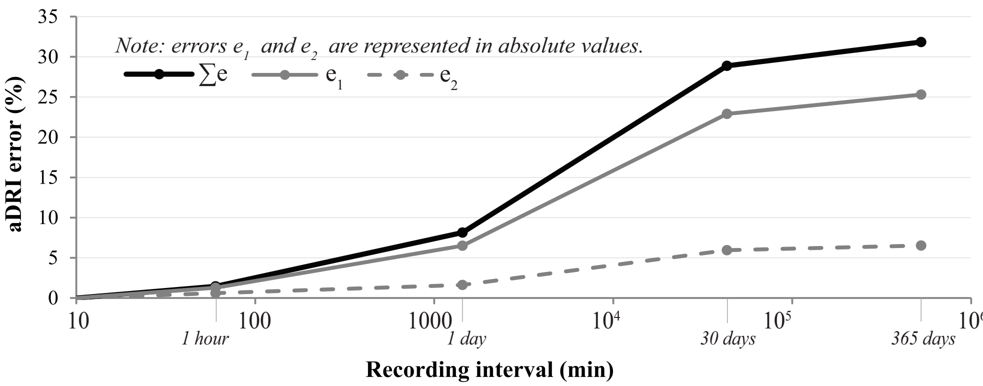


Fig. 4. Magnitude and nature of the DRWP error associated with each redording interval and its fluctuation for the different analysed locations.

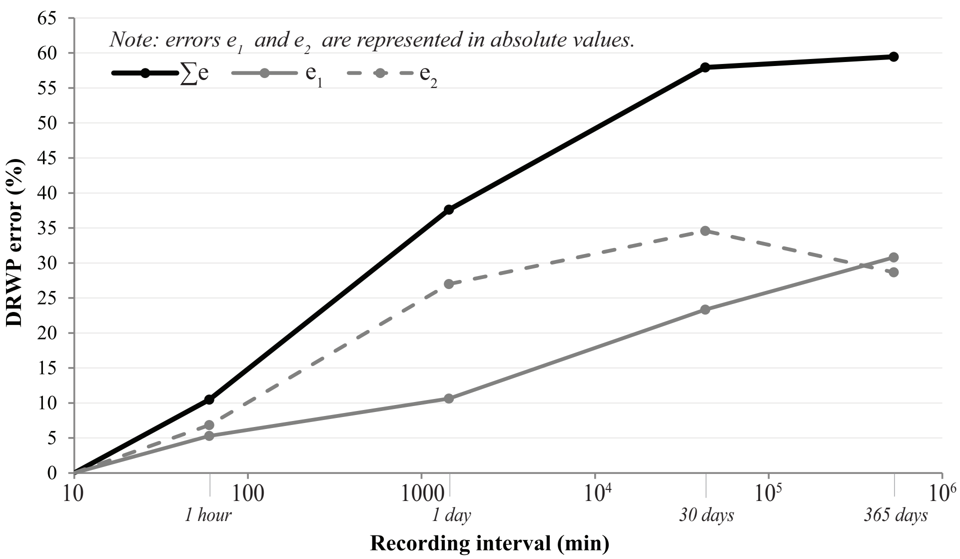
Figure 5



(%)	Hourly dataset	Daily dataset	Monthly dataset	Annual dataset
Total mean error	1.46	8.15	28.87	31.83
Standard deviation	*1.2*	*4.0*	*8.8*	*10.6*
Mean error e_1	1.28	6.51	22.91	25.30
Standard deviation	*0.6*	*4.2*	*9.3*	*11.3*
Mean error e_2	0.61	1.64	5.96	6.54
Standard deviation	*0.3*	*0.8*	*1.5*	*1.5*

Fig. 5. Evolution of mean calculation errors in aDRI values for the usual recording intervals used for climate datasets (logarithmic scale).

Figure 6



(%)	Hourly dataset	Daily dataset	Monthly dataset	Annual dataset
Total mean error	10.48	37.62	57.92	59.47
Standard deviation	*4.9*	*10.7*	*10.1*	*9.9*
Mean error e_1	5.29	10.62	23.33	30.81
Standard deviation	*1.9*	*3.4*	*10.4*	*13.4*
Mean error e_2	6.85	27.00	34.59	28.66
Standard deviation	*3.8*	*10.9*	*1.7*	*4.4*

Fig. 6. Evolution of mean calculation errors in DRWP values for the usual recording intervals used for climate datasets (logarithmic scale).

Figure 7

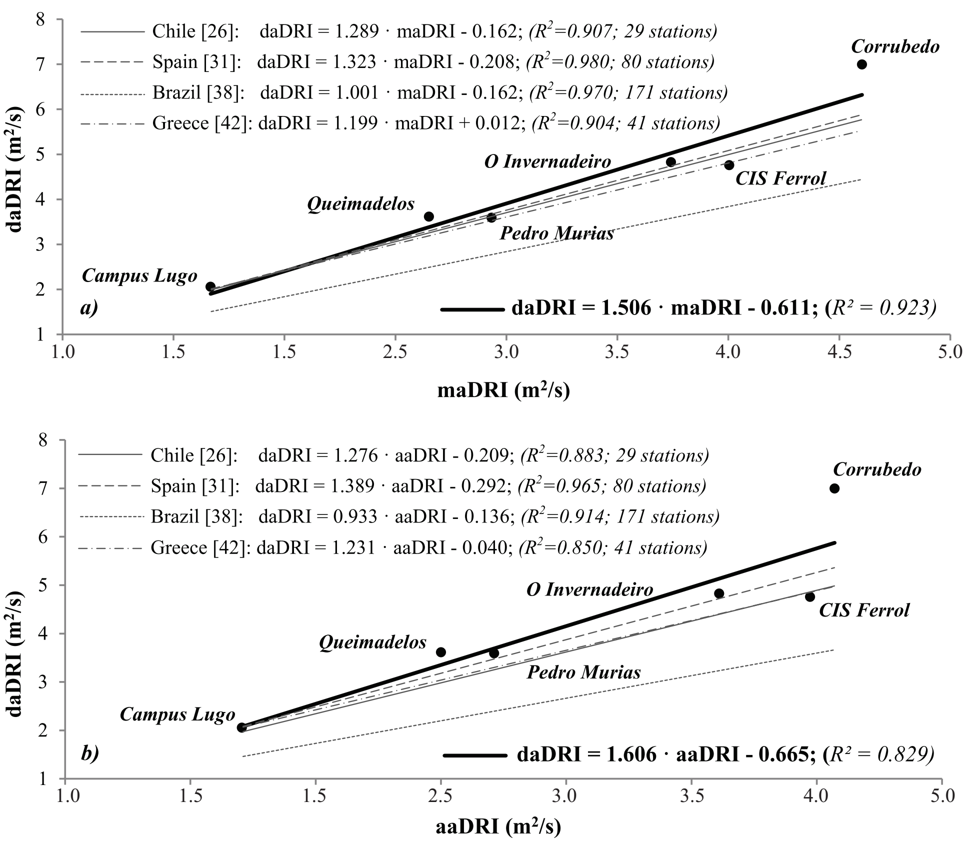


Fig. 7. a) Best-fit linear relationship between daDRI and maDRI; b) best fit-linear relationship between daDRI and aaDRI, and its comparison with different countries.

Figure 8

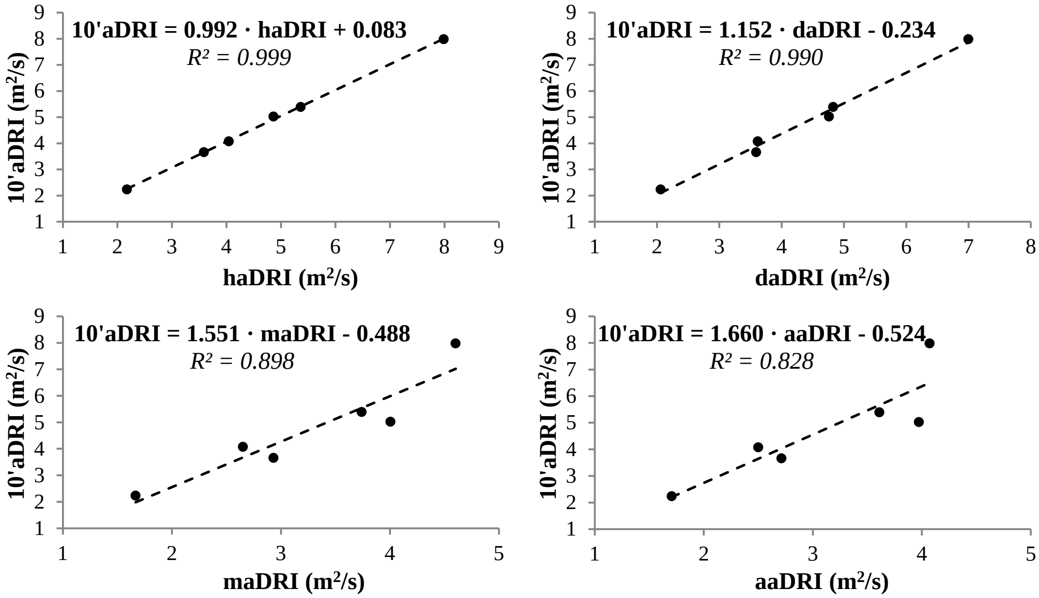


Fig. 8. Best-fit linear relationship between 10'aDRI and aDRI indices of other recording intervals.

Figure 9

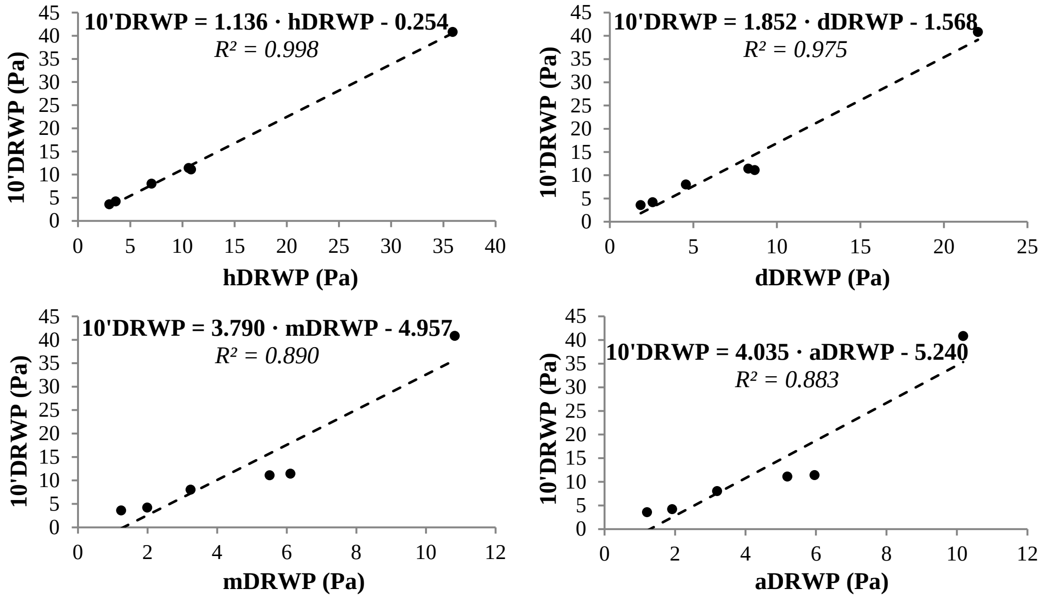


Fig. 9. Best-fit linear relationship between 10'DRWP and DRWP indices of other recording intervals.