# Assessment of water penetration risk into building façades throughout Brazil

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## Abstract

The penetration of atmospheric water into façades is a major source of problems regarding building habitability and the durability of construction materials. This study analyses the exposure of Brazilian façades to the two main climate factors responsible for this penetration: wind-driven rain and driving rain wind pressure. For this purpose, daily weather records obtained between 2005 and 2014 of data collected at 171 weather stations distributed throughout the country were analysed. Both exposure factors were combined to globally assess the risk of water penetration into enclosures at each site. In addition, the relationships between the different exposure indices calculated from daily, monthly and annual records were determined and were compared with the results obtained in other countries. From this analysis, detailed isopleth maps are provided that allow a graphical characterisation of the moisture exposure conditions of façades anywhere in Brazil. In general, an increased risk of penetration was identified in the flat areas of the South and Northeast regions of the country due to the effect of strong coastal winds simultaneous with rainfall. The sites located in the Amazon basin present comparatively lower risks, despite a greater amount of rainfall, because the wind intensity is less in these inland areas.

## Keywords

Wind-driven rain; Wind; Water tightness; Risk; Façade design; Brazil

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## 1. Introduction

The penetration of rainwater into façades reduces the durability of buildings and causes serious conditions (such as corrosion, salt crystallisation, alkali-silica reactions, frost attack, sulphate and chloride ingress, etc.) that can result in soiling, discoloration, efflorescence, loss of adherence, deformations, cracking and falling materials (Basheer, Long, & Montgomery, 1994; Franke et al., 1998; Hall & Hoff, 2012; Ruedrich, Bartelsen, Dohrmann, & Siesgemund, 2011; Steiger, Charola, & Sterflinger, 2011; Tang, Davidson, Finger, & Vance, 2004). In addition to the economic cost associated with repairs and maintenance, the presence of moisture in materials also reduces their thermal insulation, increasing the amount of energy required for the management of the built environment and the emission of air pollutants associated with generating this energy (Budaiwi & Abdou, 2013; Dell'Isola, d'Ambrosio, Giovinco, & Ianniello, 2013; Jerman & Černý, 2012; Li et al., 2015). In addition, the health of people may be affected due to illnesses, allergies and unhealthy conditions associated with biological growths and humidity in interior spaces (Andersen, Frisvad, Søndergaard, Rasmussen, & Larsen, 2011; Suani et al., 2015; World Health Organisation, 2011).

To minimise the penetration of water, the design of façades should consider the climatic factors involved in the process of penetration (Kvande & Lisø, 2009). For example, rain diverted by the wind action (wind-driven rain or WDR) impacts façades, resulting in rainwater runoff on the building enclosures (Blocken, Derome, & Carmeliet, 2013; Erkal, D'Ayala, & Sequeira, 2012). In turn, the simultaneous wind pressure on this supply of water (driving rain wind pressure or DRWP) favours the penetration of water into the materials, even in new enclosures without significant surface defects (Cornick & Lacasse, 2005; Welsh, Galbraith, Mclean, & Kelly, 1997; Skinner & Morris, 1989). Therefore, assessing the exposure to both climatic factors (WDR and DRWP) is a necessary first step in defining design conditions that guarantee watertight enclosures at each location. Thus, various studies have recently been developed in several countries to characterise these exposures, e.g. Akingbade (2004); Chand and Bhargava (2002);

Giarma and Aravantinos (2014); Nik, Mundt-Petersen, Sasic, and de Wilde (2015); Pérez, Domínguez, Rodríguez, del Coz, and Cano (2012); and Sahal (2006).

In this paper, daily climate records collected over a decade at 171 weather stations distributed throughout Brazil were analysed to determine the WDR and DRWP exposures that characterise each point of the territory. Both exposures were also integrated into a single indicator defined by Pérez, Domínguez, Cano, del Coz, and Martín (2014) and Pérez, Domínguez, Rodríguez, del Coz, and Cano (2013a), to globally compare the risk of water penetration between the different locations studied. Finally, the results were represented using different exposure isopleth maps that characterise the exposures throughout the territory.

These results provide for the first time a comprehensive characterisation of the water penetration exposure in Brazilian enclosures and can be used to establish normative design requirements that better fit the actual climatic conditions in each area of the country.  In turn, designers and manufacturers can use these results for develop more suitable enclosures for each location, thus improving the watertightness of Brazilian buildings and reducing its problems due to water penetration. In this regard, the analysis of the Brazilian case is of particular interest given the important building programs associated with the country's population growth and the significant climatic contrasts identifiable in its territory, from tropical climates in the Amazon basin to semi-arid climates in the East (Bottura, Ferreira, & de Oliveira, 2014; Kottek, Grieser, Beck, Rudolf, & Rubel, 2006).

## 2. Background

The water penetration process begins with the presence of rainwater runoff on upright building enclosures due to the impact of raindrops diverted by the wind (WDR). However, to penetrate into materials, the water supply must overcome the pressure thresholds caused by the surface tension and capillary pressure of the water contained in the façade deficiencies. In general, the smaller the size of pores, defects and gaps in the façade, the more relevant the DRWP value becomes to overcome these thresholds and promote the moisture progression (Cornick & Lacasse, 2005; Lacasse, O'Connor, Nunes, & Beaulieu, 2003).

Currently, various standardised trials allow for the characterisation of the relationship between each enclosure's design and its tightness against water penetration (American Society for Testing and Materials, 2009; Australian and New Zealand Standards Institution, 2008; European Committee for Standardization, 2001). In all of these trials, the two main climatic exposures involved in penetration are recreated: a supply of water on the outer surface of the test sample (WDR) and a simultaneous wind pressure applied thereto (DRWP). However, several studies have recently demonstrated the need to adjust these test parameters to more realistically reproduce the climatic circumstances under the operating conditions (Pérez, Domínguez, Cano, del Coz, & Álvarez, 2015; Sahal & Lacasse, 2008; Van den Bossche, Lacasse, & Janssens, 2013). Therefore, characterising the WDR and DRWP exposures in different locations is an essential step for improving these watertightness tests and developing design standards that are more reliable and suitable for the climatic conditions of each location (Künzel & Zirkelbach, 2013). Incorporating these exposure data to the test parameters, would allow a more reliable assessment of the façade design performance and would lead to a better use of these watertightness tests (Pérez, Domínguez, Rodríguez, del Coz, & Cano, 2013b).

Different approaches can be used to characterise both types of exposure, from numerical simulations based on computational fluid dynamics to semi-empirical methods adjusted according to field measurements (Blocken & Carmeliet, 2004; 2010). Although the numerical simulations provide highly accurate results (considering the increased exposure due to the wind flow acceleration near the side edges and the top of the building, and the influence of the building surroundings), this approach is laborious, and results can only be extrapolated under the same specific conditions that have been simulated (Kubilay, Derome, Blocken, & Carmeliet, 2015). Consequently, the semi-empirical methods are most commonly used for general characterisations under variable weather conditions and under different operating conditions.

To calculate the *WDR* value (l/m$^2$), these semi-empirical methods are based on the overall formulation established by the 'WDR relationship' (Eq. (1)), multiplying simultaneous records of wind velocity $U$ (m/s) and rainfall intensity $R_h$ (l/m$^2$). The empirical coefficient $k$ (s/m) varies depending on the configuration of the façade and the building, the raindrop-size distribution, and the $U$ and $R_h$ values (Straube & Burnett, 2000). Considering the wind direction $D$ (º) and the façade orientation $\theta$ (º), it is also possible to approximate the $WDR_\theta$ value that impinges on each possible façade orientation (Blocken & Carmeliet, 2006).

$$WDR_\theta = k \cdot U \cdot R_h \cdot \cos(D - \theta) \tag{1}$$

As an example, the standard ISO 15927-3:2009 (European Committee for Standardization, 2009), defines an exponential fit and a $k$ value equal to 2/9 when hourly precipitation and wind velocity records are used (this empirical setting is based on field measurements gathered in the United Kingdom). Thus, the average annual value of WDR on a particular façade with $\theta$ orientation can be calculated considering the $m$ climatic records gathered over $N$ years in which the wind direction $D$ affects the orientation of the façade (Eq. (2)).

$$WDR_\theta = \frac{2}{9} \cdot \frac{\sum_{i=1}^{m} U_i \cdot (R_{h\,i})^{8/9} \cdot \cos(D_i - \theta)}{N} \tag{2}$$

However, in practice, this ISO standard is also not functional because hourly records collected over long periods (over 10 years) are required, which is still unusual in the weather stations of many countries. In addition, the validity of this empirical setting should be verified under climatic conditions different from the UK and for specific façade configurations and surroundings.

Given the above, exposure analyses in large land areas have usually simplified the 'WDR relationship' by ignoring its empirical setting and considering free-field conditions for wind-driven rain, e.g. Akingbade (2004); Chand and Bhargava (2002); Giarma and Aravantinos (2014) and Sahal (2006). In this way, the WDR value is characterised only by the combined effect of the characteristic wind and rain at each site (Eq. (3)). Thus, an annual Driving Rain Index, or *aDRI* ($m^2/s$), can be defined and is calculated by multiplying the $m$ simultaneous records of rainfall $R_h$ (mm) and wind velocity $U$ (m/s) collected over $N$ years. To allow the calculation of *aDRI* even in locations without wind direction records, the directional component is disregarded. This scalar result characterises the WDR exposure at the location without differentiating the specific exposure over each possible façade orientation.

$$aDRI = \frac{\sum_{i=1}^{m} U_i \cdot \left( \frac{R_{hi}}{1000} \right)}{N} \tag{3}$$

The recording interval of the $m$ data used determines the accuracy of the *aDRI* indicator, thus giving rise to the indicators *daDRI*, *maDRI* and *aaDRI* (based on daily, monthly and annual data, respectively), which are progressively less reliable (Blocken & Carmeliet, 2008; Ge, 2015). Despite the simplicity of this characterisation, it is also possible to adjust the results using correction factors $k$, which could be empirically obtained under the specific operating conditions at each site (Henriques, 1992).

In turn, the value of the DRWP exposure can be determined by averaging the wind pressure associated with the $m$ considered records (using Bernoulli's equation). In this way, the average value of the *DRWP* (Pa) on a façade with orientation $\theta$ (º) can be calculated considering the pressure coefficient $C_p$ (-), air density $\rho_{air}$ ($kg/m^3$), wind direction $D$ (º) and wind velocity records $U$ (m/s) concurrent with significant precipitation (> 0.05 mm). For this purpose, those records in which the wind does not generate a positive wind pressure on the façade orientation are ignored (Eq. (4)).

$$DRWP_{\theta}=\frac{\sum_{i=1}^{m}C_{p}\cdot\frac{1}{2}\cdot\rho_{air\ i}\cdot U_{i}^{2}\cdot\cos\left(D_{i}-\theta\right)}{m} \tag{4}$$

To generalise the calculation in a similar manner to the *aDRI* indicator, a conservative value for the $C_p$ coefficient equal to 1 and an air density of 1.2 kg/m$^3$can be adopted. The directional component can also be omitted, thereby obtaining a scalar value independent of the façade orientation (Eq. (5)). As in the case of the *aDRI*, using climate records associated with short intervals of time increases the accuracy of this characterisation.

$$DRWP=\frac{0.6}{m}\cdot\sum_{i=1}^{m}U_{i}^{2} \tag{5}$$

### 2.1. Integrated characterisation of the water penetration risk

As indicated, the penetration of water into materials occurs as a result of the simultaneous combination of WDR and DRWP on the building enclosure. However, both climatic factors are independent of each other; therefore, a high *aDRI* value and a low *DRWP* value may simultaneously occur (e.g., high rainfall accompanied by light winds). It is thus necessary to combine both exposures into a single indicator that is able to assess the simultaneous effect of both climatic factors, therefore evaluating the overall risk of water penetration into the façades at each site.

Previous studies of Pérez et al. (2014) and Pérez et al. (2013a) have proposed a Risk Index of Water Penetration or *RIWP* for this purpose. To calculate the *RIWP*, a value between 0 and 1 is assigned to each climate factor, considering the minimum and maximum exposure values present in the *j* analysed locations (Eqs. (6) and (7)). These normalised values will be higher at locations with increased exposures.

$$aDRI_{normalised\ j} = \frac{aDRI_j - aDRI_{\min}}{aDRI_{\max} - aDRI_{\min}} \tag{6}$$

$$DRWP_{normalised\ j} = \frac{DRWP_j - DRWP_{\min}}{DRWP_{\max} - DRWP_{\min}} \tag{7}$$

Finally, according to Eq. (8), both normalised values are integrated into the *RIWP* indicator (-), the value of which represents the joint severity of the climatic conditions at the site. Because the importance of each exposure factor regarding the water penetration depends on the size of the pores, cracks and gaps present in the materials (Lacasse et al., 2003; Van den Bossche, Lacasse, Moore, & Janssens, 2012), the $\alpha$ and $\beta$ coefficients may be used to adjust this equation for different surface finishes (i.e., for different pressure thresholds to overcome). For a generic characterisation, a value equal to 1 for both coefficients can be adopted, thereby assuming a similar influence of both exposures on the penetration process.

$$RIWP_j = \sqrt{\alpha \cdot \left(aDRI_{normalised\ j}\right)^2 + \beta \cdot \left(DRWP_{normalised\ j}\right)^2} \tag{8}$$

Next, the WDR and DRWP exposures present in 171 Brazilian weather stations are analysed using daily climate records collected between 2005 and 2014. To the best of the authors' knowledge, this is the most comprehensive study developed in a South American country (in 2013, 29 weather stations in Chile were analysed), enabling an approximate characterisation of exposure conditions throughout the country (Pérez, Domínguez, Cano, del Coz, & Alonso, 2013). The calculation of the *daDRI* and *DRWP* indices are complemented by the *RIWP* value determination in each location and the production of isopleth maps that graphically show the exposure conditions anywhere in the country.

## 3. Assessment of WDR and DRWP exposures in the Brazilian territory

### *3.1. Oceanic, atmospheric and topographic factors affecting the Brazilian climate*

With more than 8,500,000 km$^2$, Brazil is the largest country in South America, encompassing the central and eastern part of the subcontinent from the equator to beyond the 30°S latitude. The country is divided into five major regions (North, Northeast, Central-West, Southeast and South), each of which is composed of three or more states. However, the distribution of the population in the country is not uniform and is concentrated mainly in the coastal areas. Due to the current rapid development of these urban areas and the importance of improving their enclosure designs, the evaluation of the exposure conditions in these coastal zones is of great interest. In contrast, very low population densities characterise large areas of the interior of the country.

Urban areas located along the Brazilian coast (with more than 7,500 km in length) are under the influence of warm oceanic currents associated with the South Atlantic Gyre. Thus, the South Equatorial Current flows from the Gulf of Guinea and reaches the Brazilian coast near the 5º S parallel (Cape São Roque). A portion of this current is diverted to the Southwest (Brazil Current), flowing by the Brazilian coast until reaching the Uruguayan coast. The other part is diverted to the Northwest (North Brazil Current or NBC) and, after joining with other equatorial currents, flows with intensity to the Caribbean Sea (Peterson & Stramma, 1991; Steele, Thorpe, & Turekian, 2009). Both warm boundary currents moderate the climate on the coast, but the increased intensity and temperature attained by the NBC on its way through the equator cause greater evaporation and rainfall than the Brazil Current.

Additionally, the high solar radiation near the earth’s equator produces warming and the rise of air in the atmosphere, generating strong convective storms and low-pressure areas. These atmospheric circulations in both hemispheres (Hadley cells) determine an Inter Tropical Convergence Zone (ITCZ) of high rainfall, which moves according to the seasonal variations of the thermic equator of the planet (Peters & Richter, 2014; Xie & Carton, 2004). The annual displacement of the ITCZ over the Brazilian territory, from Venezuela (in the North) to near the 20º S parallel (except the Northeast region), determines the duration and intensity of the monsoon-type rainy season affecting each area of the country (see Figure 1).

**Figure 1** The most relevant oceanic/atmospheric/topographic factors affecting the Brazilian climate

Moreover, the South Atlantic Anticyclone, which is almost permanently located in the Southeast of Brazil (at approximately 25°S/15°W), tends to reduce rainfall in the South, Southeast and Northeast regions. This effect is reinforced by the descent of dry air carried by the Hadley cell, especially when the ITCZ is at its northernmost position (Dima & Wallace, 2003; Richter, Mechoso, & Robertson, 2008). This complex interaction among atmospheric conditions explains the climatic contrasts of the country, from semi-arid climates (in the inland areas of the Northeast region, away from the influence of the warm oceanic currents) to the tropical climates that are home to the main rainforest of the world (in the North region, under the rainy influence of the ITCZ) (Kottek et al., 2006).

In general, the entire Amazon basin has very high annual rainfall, even surpassing 3,500 mm in its Northwestern zone. Rainfall decreases progressively eastward, although the annual rainfall usually remains above 1,000 mm. Only the Northeast region of Brazil, almost unaffected by the ITCZ and seasonally subjected to dry winds descending from the Hadley cell, has mean rainfall values lower than 500 mm (see Figure 2).

The country's topography also plays an important role in defining these weather conditions. There is a large mountainous area (the Brazilian highlands) along the Central-West and Southeast regions, with elevations that occasionally reach high altitudes a few kilometres from the coast (Pico da Bandeira, 2,891 m). These elevations gradually descend toward the Amazon River, forming its extensive drainage basin. Overall, north of latitude 10°S, the altitude is always less than 500 m, which favours the penetration of strong ocean winds into the territory. Finally, the craton named the Guiana Shield is located at the northern end of the territory where the country's highest altitude is reached (Pico da Neblina, 2,994 m).

These Guiana Highlands separate the Amazon basin from the Orinoco River basin, containing microclimates with less rainfall than the rest of the Amazon basin.

Thus, the coastal areas of the North and South regions of Brazil are subjected to strong ocean winds that penetrate inside the country or run parallel to the Guiana Shield due to the lack of coastal mountains. However, the highest values of wind velocity are identified in the Northeast region (around Cape São Roque) with average records higher than 5 m/s (at a height of 10 m above ground level). In the Southeast region, the presence of the Brazilian highlands limits the action of these winds, slowing down their velocity inland to mean values of 2-4 m/s. Finally, the weakening of these winds when reaching the Central-West region results in average wind velocity values below 2 m/s (see Figure 2).

**Figure 2** Mean rainfall and wind velocity maps of the country between 1961 and 1990 (from the National Institute of Meteorology of Brazil). *Darker colours and longer arrows represent higher precipitation and wind velocity*

### *3.2. Analyses performed*

In this study, the exposure conditions on the façades of Brazilian buildings under the combined effect of rain and atmospheric wind were evaluated. To that end, daily records corresponding to the intensity of rainfall and the average wind velocity measured at a height of 10 m over clear and obstacle-free terrain were analysed (World Meteorological Organization, 2008). All of the studied series were provided by the National Institute of Meteorology of Brazil - INMET (2015) and feature a period of 10 years (from 1/1/2005 to 31/12/2014). Those weather stations with less than a decade of records were excluded, as were those with more than 5% missing records. This screening protocol ensured that the study results were representative and reliable within the context of the Brazilian climate.

As a result of the above criteria, of the 226 weather stations initially provided by the INMET, only 171 were finally selected for analysis. Although this study provides an average coverage of approximately 1 station for nearly every 50,000 km$^2$, the majority of the stations are concentrated in coastal zones, providing better coverage of most Brazilian urban areas. Therefore, the most populous regions (i.e., the Southeast region with more than 80 million and the Northeast region with more than 54 million inhabitants) have better coverage than the less populated areas (e.g., the North and Central-West regions, with a total of approximately 30 million inhabitants). It should be noted that although a significant number of stations (24 in total) were analysed in the states of Amazonas and Pará, these stations are concentrated near the main channel of the Amazon River and its major tributaries (Table 1).

**Table 1** Distribution of the 171 analysed stations and coverage of the Brazilian states

The analysed weather stations are commonly located near cities (in airports, airfields and open areas), thereby allowing their results to be considered representative of the free-field conditions existing in the corresponding urban centres. The distribution of stations throughout the country and the altitudes of these stations, ranging from 2 m (e.g., Florianópolis and Rio Grande) to 1,415 m above sea level (São Joaquim), provide a representative study of the conditions of moisture penetration into façades under the climatic conditions present throughout the entire territory.

### *3.3. Exposure results and risk of water penetration*

The WDR exposure of each location was characterised according to the *daDRI*, *maDRI* and *aaDRI* values using Eq. (3). The rainfall data necessary to calculate the *maDRI* and *aaDRI* values were obtained from the available daily records by calculating the summation of precipitation associated with each month and year within the range considered (2005-2014). Similarly, to calculate the wind velocity data, the monthly or annual averages of those daily records concurrent with rainfall were considered. Table 2 presents these results, showing for clarity only the Brazilian sites with the greatest WDR exposure.

**Table 2** List of weather stations with a *daDRI* value greater than 4 $m^2/s$ (*24 locations; data 2005-2014*)

In addition, the map in Figure 3 displays the geographical distribution of these results. The WDR exposure value is represented by smoothed isopleth lines, allowing its approximation at any point in the territory. For this purpose, a linear interpolation of the 171 *daDRI* values identified in the analysed locations was performed.

**Figure 3** *daDRI* isopleth map of Brazil (from daily records)

In turn, the DRWP exposure was characterised according to Eq. (5) using daily records of wind velocity simultaneous with rainfall. The mean wind pressure was calculated similarly, considering indistinctly all of the $U$ records available for the location. Table 3 presents both results for those stations with the greatest *DRWP* value. Using a linear interpolation of the results at each station, Figure 4 also shows an isopleth map of this *DRWP* value.

**Table 3** List of weather stations with a *DRWP* value greater than 4 Pa (*34 locations; data 2005-2014*)

**Figure 4** *DRWP* isopleth map of Brazil (from daily records)

These *daDRI* and *DRWP* values also allow the assessment of the combined exposure to both climatic factors, characterising the overall risk of water penetration at each site with respect to other places. For this purpose, the degree of exposure was rated between 0 and 1 (i.e., normalised values) using Eqs. (6) and (7); additionally, the indicator that integrates both exposures (the *RIWP* value) was calculated using Eq. (8). Table 4 presents the Brazilian locations at greatest risk (i.e., where the combination of the WDR and DRWP exposures is more favourable to the penetration of atmospheric water), considering $\alpha$ and $\beta$ values equal to 1 (covering a heterogeneous configuration of façade construction materials).

**Table 4** List of weather stations with a *RIWP* value greater than 0.7 (*24 locations; data 2005-2014*)

As a result, Figure 5 complements the partial characterisation provided by the previous figures (3 and 4) by representing the geographical distribution of this global indicator. In this way, a highly interesting complement is presented, thus identifying those areas in which the enclosure designs should ensure a greater degree of watertightness against atmospheric water.

**Figure 5** Risk Index of Water Penetration in Brazilian building façades

## 4 Discussion

As shown in Table 2 and Figure 3, the highest WDR exposure can be identified near the Cape São Roque, in the South region, and around the mouth of the Amazon River. In general, exposure decreases significantly in the interior of the country and on the coast of the Northeast region (except around Cape São Roque). Comparing Figures 2 and 3, it can be seen that there is no direct relationship between the WDR exposure and the rainfall distribution. This comparison highlights the importance of conducting a specific WDR analysis similar to that presented in this study to assess the moisture conditions of the building façades. Although the areas of greatest exposure do not have the highest rainfall records, these areas are characterised by strong coastal winds, which divert much of the rain to the vertical surface of the façades.

Furthermore, Table 3 and Figure 4 confirm the existence of these coastal winds simultaneous with rainfall, identifying a high DRWP exposure around Cape São Roque (Northeast Region) and in the south end of Brazil. This exposure is much lower in the interior of the country and in the Amazon basin, with a smaller amount of rain that impacts the façades and a lower possibility of penetration through the pores and gaps of the enclosure.

A clearer view of the global risk of water penetration throughout the country can be obtained by combining both exposures via the *RIWP* value (Table 4 and Figure 5). The greatest risk is concentrated in the South and Northeast regions; therefore, urban areas in these regions should incorporate specific measures to ensure greater watertightness in the design of their enclosures. In general, this penetration risk decreases towards the interior of Brazil, except in some specific sites (e.g., Codajás, Paracatu and Goias).

Additionally, Figure 6 identifies the comparative influence of both exposure factors in the calculation of the *RIWP* value. As can be observed, the locations with a greater risk of water penetration have high exposures to both WDR and DRWP (e.g., Natal, Santa Vitória do Palmar, Bom Jesus, Passo Fundo). All of these sites are located in the South and Northeast regions. Meanwhile, the risk at the locations in the North region is characterised by a high WDR exposure, which corresponds to the simultaneous higher rainfall and lower wind intensity (e.g., Codajás and Cametá). As expected, the lower rainfall and wind strength identified in the Central-West and Southeast regions cause only São Paolo and Juiz de Fora to have an *RIWP* value greater than 0.4 in these areas.

Although four locations with maximum risk conditions (as mentioned above) can be observed in Figure 6, the remaining points are distributed progressively in different *RIWP* ranges. For example, 59% of the analysed stations present *RIWP* values lower than 0.4 (101 of 171 stations), a similar percentage to that found by Pérez, Domínguez, Cano, et al. (2013) in Chile (55% of study sites). However, other countries, such as Spain, have exhibited major exposure differences (i.e., up to 80% of the sites analysed in that country had *RIWP* values of less than 0.4), which in contrast to Brazil or Chile, indicates the existence of highly exposed locations compared to a vast majority of sites with a low risk level (Pérez et al., 2013a).

**Figure 6** Graphical representation of the Risk Index of Water Penetration for the analysed locations

Additionally, the *daDRI*, *maDRI* and *aaDRI* values also allow establishing general relations to approximate the WDR exposure in other parts of the country. As demonstrated in Figure 7, the *daDRI* value of any site could be estimated with reasonable accuracy from the available monthly or annual climate records (i.e., from the *maDRI* or *aaDRI* values). The coefficient of determination $R^2$ is higher in the *daDRI*-*maDRI* relationship due to the greater accuracy of the monthly data compared to the annual data. Similar relationships were obtained for each Brazilian region, considering for each one only the results of their weather stations. All of these relationships can extend the characterisation of the WDR exposure to any location with limited climatic records, enabling an increased number of available results for producing more detailed and accurate isopleth exposure maps.

**Figure 7** a) Best fit-linear relationship between *daDRI* and *maDRI*. b) Best fit-linear relationship between *daDRI* and *aaDRI*. Both relationships are also itemised for the 5 Brazilian regions

On the other hand, the *aaDRI*-*maDRI* relationship is similar to those previously reported in other countries (Figure 8). This similarity is greater with respect to countries with temperate climates than with respect to other countries also located in the intertropical zone (such as Nigeria and India). For example, Chile's relationship is very similar to that of the Brazilian territory, despite the significant climatic differences between the two countries. Therefore, these climatic differences do not seem to have a significant influence on the fitting relationships associated with the WDR exposure. Conversely, it seems that these relationships may be more linked to the prevailing nature of rain events in each region (Blocken & Carmeliet, 2008). The same conclusion could also be drawn by comparing the linear fits associated with each of the five Brazilian regions (Figure 7).

**Figure 8** Best fit-linear relationship between *maDRI* and *aaDRI*, and its comparison with other countries

Finally, the *DRWP* values can also be related to the wind pressure values, obtaining in this way the fit shown in Figure 9. The lower $R^2$ value compared to the relationships presented in the previous figure (i.e., 0.9057) reflects the greater randomness of the wind velocity regardless of its coincidence with precipitation. The resulting relationship is also compared with the linear fits identified in other countries by previous studies. Again, a very similar relationship to the one identified in Chile is observed, although other countries, such as Spain, show significant differences. Regardless, this relationship would allow an approximate estimation of the DRWP exposure value in any location, even in those without simultaneous records of wind velocity and precipitation.

**Figure 9** Best fit-linear relationship between *DRWP* and *mean wind pressure,* and its comparison with other countries

All of these relationships and isopleth maps allow, for the first time, an approximate characterisation of the moisture exposure conditions on the façades anywhere in Brazil. However, there are still significant distances between the points analysed, which can make these results inaccurate for locations with specific microclimates that are different from those in the surrounding areas. Therefore, reducing these distances by studying a larger number of weather stations is the main future challenge to improve the research presented herein. In this sense, a more extensive characterisation of the most populated areas of the country would be of great interest. In turn, these results could be adjusted more accurately considering the geometry and surroundings of each façade, rather than the free-field conditions.

## 5 Conclusion

This work has developed a comprehensive assessment of the climatic conditions conducive to the moisture penetration into the façades of Brazilian buildings. For this purpose, different scalar indicators of the WDR and DRWP exposures existing in different locations and climates distributed throughout the country have been determined. Additionally, an integrated indicator has been obtained to assess the overall risk of water penetration resulting from the combined effect of both climatic exposures. As a result, the isopleth maps presented should serve to improve the design of façades anywhere in the country, adapting their watertightness requirements to the actual operating conditions at each location. Finally, various useful relationships have been extrapolated, thus allowing the extension of this characterisation to other parts of the country with limited climate records.

The study results suggest that despite the high rainfall that characterises large parts of the country, the greater wetting of the façades and the increased risk of water penetration into materials is produced by the simultaneous action of rain and strong winds present on the North coast, around Cape São Roque and in the South of Brazil. All of these results can be used as a starting point by competent authorities to complement and enhance building codes in the country, and by designers and manufacturers to better adjust the façade designs to actual exposure conditions in each region. This should help to improve the watertightness of Brazilian buildings and should reduce costs and problems currently associated with the undue penetration of atmospheric water into the façades.

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# Figure captions

**Figure 1** The most relevant oceanic/atmospheric/topographic factors affecting the Brazilian climate.

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**Figure 3** *daDRI* isopleth map of Brazil (from daily records).

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**Figure 8** Best fit-linear relationship between *maDRI* and *aaDRI*, and its comparison with other countries.

**Figure 9** Best fit-linear relationship between *DRWP* and *mean wind pressure*, and its comparison with other countries.