Assessment of Building Wind-driven Rain Exposure in China in the Future Climate of 2050

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Abstract

Wind-driven rain is the main source of moisture in buildings and has a direct impact on the longevity and thermal performance of the building envelope. To mitigate the impact of wind-driven rain on buildings under climate change, this paper analyses three Representative concentration pathways (RCP) scenarios (RCP2.6, RCP4.5, RCP8.5) based on Meteonorm climate data and estimates the wind-driven rain forecast in China for the next 30 years. A long-term wind-driven rain exposure map and a wind-driven rain growth map were plotted for three future emission scenarios for China in 2050. The growth rate of wind-driven rain was calculated accordingly. Based on the wind-driven rain exposure, 10 representative Chinese cities were selected. Using the ASHRAE 160-2016 standard, wind-driven rain patterns were derived for the facade orientations of 16 buildings in 10 cities under three future climate scenarios. The results show that China's total wind-driven rain exposure will increase under all three future climate scenarios. In addition, the RCP4.5 scenario shows the highest increase. From a regional perspective, south-eastern China is exposed to high wind-driven rainfall in the current scenarios and may also be exposed in future scenarios; the absolute increase in wind-driven rainfall is also the highest. There are some differences in the exposure to wind-driven rainfall and the increase in exposure to wind-driven rainfall in cities of different climate zones in China, with the increase in coastal areas being significantly higher than in inland areas. In Shanghai, wind-driven rain exposure increases in both summer and winter.

Highlights

A. Wind-driven rain index under three RCP scenarios are projected.
B. Increase in wind-driven rain is more pronounced in coastal areas than inland.
C. Increase rate of wind-driven rain index under RCP 4.5 is the largest.
D. Wind-driven rain’s seasonal change in summer and winter should be studied.

Introduction

Moisture in the building envelope accelerates the deterioration of the building envelope, impairs the thermal insulation properties of the building and directly affects the indoor environmental humidity and temperature, as well as the health of the occupants (C.G. Bornehag, 2001). The continuous cycle of water erosion and drying can cause building materials to lose their original strength and rigidity. In addition, water erosion damage to the building envelope necessitates a range of maintenance, repair and replacement works throughout the life cycle of the building. This further increases the economic and environmental burden.

Wind-driven rain, which is the main source of moisture in building envelopes, is rain that falls obliquely due to the horizontal velocity of the wind. The intensity of wind-driven rain is mainly related to wind speed and rainfall. Methods for determining the intensity of wind-driven rain are mainly divided into three methods: experimental, semi-empirical and numerical simulation methods (Blocken and Carmeliet, 2004). The experimental method provides a testing basis for the semi-empirical and numerical simulation methods. The numerical simulation method mainly focuses on the distribution of wind-driven raindrops, which affects the overall geometrical structure of the detailed building. The semi-empirical method is a fast and simple approach to quantify the intensity of wind-driven rain on building walls.

The data used for the semi-empirical method are derived from meteorological data measured by a meteorological station. Lacy (Lacy and Shellard, 1962) suggested the direct calculation of the product of wind speed and rainfall to estimate wind-driven rain. This parameter is referred to as the wind-driven rain/rain index. The wind-driven rain index derived from one year of meteorological data is called the annual wind-driven rain index. It has no direct relationship to specific geometric details of the building and is therefore typically used to characterise the exposure to wind-driven rain in a given area and then make direct comparisons with other areas. Countries such as the UK (Lacy, 1964), Canada (D.W., 1963), Spain (Pérez-Bella et al., 2012, 2013), Greece (Giampa and Aravantinos, 2011), India (Chand and Bhargava, 2002) and China (Qian and Zhang, 2021) have assessed the exposure of their countries to wind-driven rain according to a wind-driven rain index and produced wind-driven rain exposure maps. To assess exposure using the wind-driven rain index, it is assumed that a raindrop is not reflected after colliding with a wall, and is thus an indicator of free wind-driven rain. Hoppesstad (1955) proposed an approach to calculate the actual wind-driven rain acting on a wall by introducing a
wind-driven rain index. Taking the above factors into account, many standards and methods have been developed along, including ISO 15927-3:2009 (ISO 2009) and ASHRAE 160-2016 (ASHRAE 2016), to calculate wind-driven rain. Several studies have been carried out on standards for the calculation of wind-driven rain. Based on ASHRAE 160-2016, Sughwan Kim (Kim et al., 2022) investigated the amount of wind-driven rain in different cities in South Korea. Chen (Chen et al., 2022) investigated the difference between ISO and ASHRAE semi-empirical calculation standard results according to the actual wind-driven rain using an actual wind-driven rain experiment in Shanghai area.

Climate change and extreme events are projected to increase in the future as the climate becomes warmer, as indicated in the Fifth and Sixth UN IPCC reports on climate change (IPCC, 2021). To better cope with the impacts of climate change on buildings, Tarek Dukhan (Dukhan and Sushama, 2021) studied the changes in the wind-driven rainfall exposure in Canada under the RCP8.5 scenario under future scenarios. They concluded that wind-driven rain increased on the southeast coast and west coast of Canada due to changes in precipitation. Vahid M. Nik (2015) explored the uncertainty of climate change models, the influence of different materials and sizes of facades, and the impact of a single wind data variable by analyzing the changes in the amount of water that wind and rain penetrate through the outermost exterior wall. As China is located in the south-east of the Eurasian continent, its eastern part is influenced by a monsoon climate, while the north-west has a continental climate, including a typical plateau climate. At the same time, China has the most existing buildings in the world. In order to mitigate the impact of climate change on building performance, maintain building performance under future climate, it is necessary to investigate the changes in China’s wind-driven rain exposure under future climate scenarios.

Therefore, three representative concentration models - RCP2.6, RCP4.5 and RCP8.5 - have been selected for this study. The objective of the research is to analyse the impact of climate change on the risks and changes in exposure to wind-driven rain in different regions of China over the next 30 years from a national and representative city perspective.

**Data and Research Methods**

Wind-driven rain can be seen from two different perspectives. The first is the wind-driven rain exposure index (DRI), which is the product of wind speed and rainfall (1). In this case, two parameters, rainfall and wind speed, are used and can be obtained directly from meteorological observations. In most papers, the wind-driven rain index and the wind-driven rain exposure maps for a given area are calculated using the following equation:

\[
DRI = U_{10} \times R_h \tag{1}
\]

In Qian’s article (2021), they concluded that the results of the wind-driven rain calculation were unambiguous in terms of monthly mean and daily mean. With Qian’s (2021) results, in this paper, the monthly average data is chosen as the aDRI calculation data, which is obtained using the following equation:

\[
maDRI = \frac{1}{12} \sum_{i=1}^{12}(\frac{R_{h,i}}{1000}) \tag{2}
\]

where \(n\) is the number of years included in the data. In this paper, the selected data are those from the future year 2050, and thus, \(n\) equals 1, \(R_{h,i}\) is the monthly total precipitation of the \(i^{th}\) month, and \(U_{10}\) is the monthly mean wind speed of month \(i\).

\[
R_{wdr} = \alpha \times U_{10} \times R_h \times \cos \theta \tag{3}
\]

The second form, wherein the direction of wind drives the rain exposure, considers factors such as the final velocity of raindrops, wind direction, and the shape of the building structure.

As in previous studies, ASHRAE 160-2016 has been chosen as the standard for calculating wind-driven rain exposure at different orientations in representative cities:

\[
R_{wdr} = \alpha \times F_E \times F_D \times F_L \times U_{10} \times \cos \theta \times R_h \tag{4}
\]

where \(F_L\) is an empirical constant equal to 0.2 kg · s/ (m³ · mm), \(F_E\) is the rainwater exposure factor and \(F_D\) is the rainwater runoff coefficient, both related to the surrounding terrain and the height of the building. Most previous studies show that the results of ASHRAE calculations are overestimated compared to the actual results. Considering the ASHRAE 160-2016 standard model and combining it with the results of Kubilay (Kubilay et al., 2014) and Chen (2022) studies, the improved semi-empirical model considering a correction factor of 0.505 is:

\[
R_{wdr} = 0.151 \times U_{10} \times \cos \theta \times R_h \tag{5}
\]

**Analysis of national wind-driven rain exposure change**

**Data visualization and comparative verification**

Based on the maDRI obtained using equation (2), ArcGIS 10.8 software and kriging interpolation method, an exposure map of China's total driven rain index was obtained.

To intuitively illustrate the levels of exposure to wind-driven rain in different regions, the country's wind-driven rain exposure levels are divided into five levels: shield, low, medium, high and strong. In addition, in order to analyse in detail the variation of wind-driven rain exposure levels with time and space, the map is further subdivided into 10 smaller interval scales, as shown in Table 1.

To check the reliability of the data obtained from Meteoronorm, the map of the current period obtained from Meteoronorm is compared with the map calculated from the weather station data mentioned in Qian’s paper. The results are shown in Figure 1a and Figure 1b. As shown in Figure 1a, the prevalence of exposure to wind-driven rain in south-east China, Guangdong, Hainan, Guangxi, Fujian, 'high' exposure (Qian and Zhang, 2021), in terms of regional distribution, the areas with "high" and "severe" exposure levels in...
Table 1: Definition of long-term WDR exposure classification

<table>
<thead>
<tr>
<th>Level</th>
<th>Shield</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>maDRI(m^2/s)</td>
<td>[0, 1)</td>
<td>(1, 1.5)</td>
<td>(1.5, 2)</td>
<td>(2, 2.5)</td>
<td>(2.5, 3)</td>
</tr>
</tbody>
</table>

The leading rain index ranges from 1-3 m^2/s.

Compared with the values reported in literature levels of wind-driven rain in other areas showed consistent results. The boundary line with a wind-driven rain index of 2 m^2/s was almost the same and is mainly bounded by the western part of Shandong - the central part of Henan - the central part of Hubei - the central part of Guizhou. Thus, the basic trend of the distribution of wind-driven rain exposure from 6 m^2/s in the southern and southeastern coastal areas to 3 m^2/s in the central area and finally to 1 m^2/s in the northwestern area is almost the same as in the literature (Qian and Zhang, 2021) (Figure 1b). The accuracy of the driving rain index calculated from Meteonorm data in the present work has been verified during the present time period.

Long-term wind-driven rain exposure maps for future scenarios

Based on the method described above, wind-driven rainfall exposure maps are obtained under three emission scenarios RCP2.6, RCP4.5 and RCP8.5 in 2050. Using RCP2.6 as a case study, between now and 2050, wind-driven rainfall in southeastern coastal areas, including southern China, will remain greater than 4 m^2/s, and will change over time, as shown in Figure 1a and Figure 2. This indicates that the high-exposure risk area is gradually expanding; in north-west China, wind-driven rain exposure has always been low and the distribution of wind-driven rain exposure is relatively stable. The wind-driven rain exposure map under the RCP2.6 scenario is shown in Figure 2.

Long-term changes in wind-driven rain exposure are mainly concentrated in five areas: south-eastern Sichuan and Chongqing, where WDR exposure increased slightly from low (1.5-2 m^2/s) to moderate (2-2.5 m^2/s); southern Qinghai wind-driven rain exposure increased gradually over time to over 1 m^2/s, from 'shield' to 'low'; southern Gansu wind-driven rain also changes from low(1.5-2 m^2/s) to moderately low (2-2.5 m^2/s), indicating a slight increase; in north-eastern China, wind-driven rain gradually expanded in the area with a low exposure level of 2 m^2/s; on the south-eastern coast, areas with 'high' and 'severe' risk of wind-driven rain exposure show a gradual expansion. The total exposure to wind-driven rain shows a gradual increasing trend across the country.

RCP4.5 and RCP8.5 also follow the same trend as RCP2.6. At the same time, it should be noted that the increase in the three scenarios is slightly different. In the RCP4.5 scenario, the increase is relatively higher than in the RCP2.6 scenario. Under the RCP8.5 scenario, the change is not significantly different from the RCP4.5; the value is slightly higher than in the RCP2.6.

We investigate the impact of different RCP scenarios on wind-driven rain exposure under future scenarios. In 2050, as the emission intensity of different scenarios RCP2.6, RCP4.5 and RCP8.5 increases, China's national wind-driven rain intensity will have an upward trend. However, the increase is uneven across regions, with only a few regions showing a significant increase. This trend is pronounced in southern Qinghai and parts of western Tibet, Yunnan and Guangdong provinces where wind-driven rain intensity is "high".

In order to explicitly quantify the degree of change in wind-driven rain exposure in each region, we directly calculate the increase in the wind-driven rain index in different regions depending on time and scenarios:

\[ \Delta \text{maDRI} = \text{maDRI}_{t,RCP} - \text{maDRI}_0, \]

where \( \text{maDRI}_0 \) is the exposure index for wind-driven rain at a given location in the current period and \( \text{maDRI}_{t,RCP} \) in 2050 under a given RCP emissions scenario.
Driving Rain Index Increase Map

Table 3: Classification of increased WDR index

<table>
<thead>
<tr>
<th>Classification</th>
<th>Weakening</th>
<th>Small increase</th>
<th>Medium increase</th>
<th>Large increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \text{dR} \text{d}(0.1 \text{m}^2/\text{s}) )</td>
<td>((-\infty, -2])</td>
<td>([-2, -1))</td>
<td>([-1, 0))</td>
<td>([0, 1))</td>
</tr>
</tbody>
</table>

Similar to the absolute mapping methods, ArcGIS and Kriging interpolation methods were applied to the wind-driven rain index increment data to produce a nationwide wind-driven rain index increment map (Figure 3). The changes in the different emission scenarios over the three years are significant, ranging from -0.2 to 0.6 m\(^2\)/s. To clearly distinguish the changes, they are divided into four levels: weakening, small increase, medium increase and large increase. The changes are further broken down into nine levels with a smaller scale, as shown in Table 3.

From Figure 3, under the RCP2.6 scenario, the wind-driven rain exposure index in a small number of areas shows a downward trend, especially in Southwest China and Taiwan exhibiting a decrease of 0.2 m\(^2\)/s; under the RCP4.5 scenario, the exposure level of wind-driven rain in the southeastern region increases significantly. There is a substantial increase of 0.4 m\(^2\)/s in Guangdong and other places. And the main body presents a medium-small increase. In the scenario of RCP8.5, the exposure level of wind-driven rain across the country increases more evenly than in the scenario of RCP4.5. In 2050, the driving rain index increases in almost all regions. However, the increase of RCP8.5 in the southeast region was not as significant as that of RCP4.5, and only in some areas, the increase in wind-driven rain exposure was greater than 0.4 m\(^2\)/s. And in RCP2.6 emission scenario, the overall increase in wind-driven rain exposure level is the smallest, which is mainly reflected in the continuous shrinking area of wind-driven rain exposure in southwest region. Until 2050, the increase in most areas will only be 0.2 m\(^2\)/s, while in RCP4.5 scenario, the increase in most parts of the southeast regions is around 0.4 m\(^2\)/s. Further, the
increase under the RCP8.5 scenario is between RCP2.6 and RCP4.5.

Comparing Figures 2 and 3, it can be observed that for the RCP4.5 scenario, the south-eastern region with the higher WDR index level shows a large increase in the WDR index growth map.

Changes in the rate of increase of wind-driven rain
34 datasets, subdivided by province, help to better summarise the unique climate of each province. This data strongly drives within-province data, and the use of provincial data reduces the unevenness of initial data points that can lead to a reduction in national representation. From the provincial data, Table 4 presents a least squares analysis of the correspondence between the data under the future scenario and that under the current scenario. The fitting model is as follows:

\[ y = ax + b \]  

In addition, the following assumptions can be made. For the area not affected by wind-driven rain (\( \text{maDRI} = 0 \)), according to the weather and carbon scenarios, it should not be affected by wind-driven rain in the future either (this area is idealised and does not exist in the real China region). According to the application model, the intercept \( b \) should be zero and the only parameter of the application result is the slope \( a \). The model is as follows,

\[ y = ax \]  

From this equation, the proportional relationship between the future scenario and the current scenario can be derived. The results of the adjustment are shown in Figure 4 and the percentage increase in the future scenario relative to the current scenario can be obtained, as shown in Table 3.

Figure 4 and Table 3 show that in 2050, wind-driven rain intensity increased the most under the RCP4.5 scenario, and the rate of increase for the three scenarios was RCP4.5 > RCP8.5 > RCP2.6.

<table>
<thead>
<tr>
<th>City</th>
<th>Climate Zone</th>
<th>maDRI[m^2/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harbin</td>
<td>Frigid</td>
<td>1.29</td>
</tr>
<tr>
<td>Urumqi</td>
<td>Frigid</td>
<td>1.00</td>
</tr>
<tr>
<td>Beijing</td>
<td>Cold</td>
<td>1.38</td>
</tr>
<tr>
<td>Qingdao</td>
<td>Cold</td>
<td>2.76</td>
</tr>
<tr>
<td>Lhasa</td>
<td>Cold</td>
<td>0.91</td>
</tr>
<tr>
<td>Shanghai</td>
<td>Hot summer cold winter</td>
<td>5.03</td>
</tr>
<tr>
<td>Chongqing</td>
<td>Hot summer cold winter</td>
<td>2.28</td>
</tr>
<tr>
<td>Kunming</td>
<td>Temperate</td>
<td>2.98</td>
</tr>
<tr>
<td>Guangzhou</td>
<td>Hot summer warm winter</td>
<td>4.26</td>
</tr>
<tr>
<td>Hakou</td>
<td>Hot summer warm winter</td>
<td>5.32</td>
</tr>
</tbody>
</table>

Of the 10 cities, Harbin, Urumqi, Beijing, Qingdao, Shanghai, Chongqing and Guangzhou showed an overall increase in exposure to wind-driven rain, while Lhasa, Kunming and Haikou showed a decreasing trend. This is consistent with the pattern that in the wind-driven rain index growth map, the wind-driven rain index decreased in some parts of the south-west, while in the south-east the wind-driven rain index increased significantly. From the data for the seven growing cities, it can be concluded that the wind-driven rain of coastal cities changed significantly. Under the RCP2.6 scenario, the prevailing wind-driven rain in Qingdao in 2050 increased by 116 kg/(m^2·a) compared to the current scenario, and in Guangzhou under the RCP4.5 scenario, the prevailing wind-driven rain increased by 120 kg/(m^2·a) compared to the current scenario. The increase in inland cities is not significant; in Harbin the increase is only 40 kg/(m^2·a) and in Chongqing 27 kg/(m^2·a). In addition, in Beijing the increase is mainly reflected by an increase in the non-dominated wind-driven rain index. The climate change-induced increase in wind-driven rain exposure in coastal cities is significantly larger than in
inland cities; changes in wind-driven rain are directly related to changes in wind and rain. There is a significant difference between inland and coastal cities. Total precipitation decreases from the south-east coast to the north-west inland. Therefore, climate changes in wind-driven rainfall are more pronounced in coastal cities. It should be noted that the predominant urban orientation changes are within 22.5°, which is relatively small, except in Guangzhou, where there is a 90° change from southeast to southwest. This is because Guangzhou has two main wind orientations, including south-west and south-east. Among the three cities with decreasing wind-driven rain exposure, it can be found that Lhasa's wind-driven rain exposure decreased by 16 kg/(m²·a) in the RCP2.6 scenario in 2050, and Kunming's exposure decreased by 18.7 kg/(m²·a) in the RCP8.5 scenario. In addition, Haikou's exposure to storm rain in 2050 decreases by 125 kg/(m²·a) under the RCP8.5 scenario. However, the three cities with decreasing exposure to wind-driven rain were affected by the south-west monsoon, while the seven cities with increasing exposure were mainly affected by the south-east monsoon. The difference of wind-driven rain exposure can be explained by the differences in the monsoon climate in different regions. Table 6 shows the dominant orientation and wind-induced rain exposure in 10 cities.

**Changes in wind-driven rain exposure at different seasons of the year in Shanghai**

Seasonality is another aspect that is often taken into account in building thermal engineering. WDR exposure has a direct impact on the thermal performance of the building envelope, which in turn affects the heating and cooling energy consumption in winter and summer. In the ten cities selected, Shanghai has the highest exposure to wind rain and therefore the most significant changes in exposure to wind rain. Temperatures will drop below 0 degrees Celsius in winter, and the impact on building longevity and energy consumption will be more significant. For demonstration purposes, we will investigate the impact of wind-driven rain in Shanghai on a seasonal basis. The variation of wind-driven rain over time in different scenarios is shown in Figure 6. The selection of seasons follows the general method of dividing the seasons: spring (March, April, May), summer (June, July, August), autumn(September, October, November) and winter (December, January, February).

Under the current scenario, wind-driven rain is more significant in autumn and least in winter. The sequence
from largest to least exposure is: autumn>summer>spring>winter. For the thermal environment, we mainly focus on two seasons: summer and winter. The dominant direction of action of wind-driven rain in summer is S, with an intensity of 101.5 kg/(m²·a), and in winter is N, with an intensity of 56.4 kg/(m²·a). Of the three climate scenarios, RCP2.6 has the highest exposure in summer, directed towards the SE, with an exposure of 137.7 kg/(m²·a) and an increase of 36.2 kg/(m²·a). The RCP4.5 scenario has the highest winter exposure towards NNW, with an exposure of 85.3 kg/(m²·a), indicating an increase of 28.9 kg/(m²·a). Under RCP8.5, the summer exposure in the NE direction is the highest at 119.6 kg/(m²·a), indicating an increase of 18.1 kg/(m²·a). The winter exposure of 55.1 kg/(m²·a) is the highest in the NNW direction, indicating a decrease of 1.3 kg/(m²·a). Comparing the three years, the summer increase under the RCP4.5 scenario in 2040 is the highest, showing a value of 148.5 kg/(m²·a) (ESE) and an increase of 47 kg/(m²·a). The maximum winter exposure under the RCP4.5 scenario in 2040 was 58.8 kg/(m²·a) (NNW), indicating a change of 2.4 kg/(m²·a). Under the three future scenarios, Shanghai's exposure to wind-driven rain in summer and winter will increase to varying degrees.

Figure 7: Shanghai Four Seasons Wind-driven Rain Exposure Rose Chart

**Conclusion**

Based on Meteonorm meteorological data and a semi-empirical model approach, wind-driven rainfall exposure data are calculated under three future scenarios. Then, a wind-driven rain exposure map and a wind-driven rain increase map for China under the future scenario are generated using ArcGIS. We selected 10 representative cities, and compared and analyzed the changes of wind-driven rain in different orientations. We analysed the seasonal change of wind-driven rain in Shanghai. The main results of the study are summarised below.

(1) China's overall level of exposure to wind-driven rain will increase under three future climate scenarios. Under the RCP4.5 climate scenario, the country's overall level of exposure to wind-driven rain increases most rapidly in 2050 compared to the current scenario, when the level of exposure increases by 5.2%. The growth rates of the three scenarios in 2050 are in descending order: RCP4.5 (5.2%) > RCP8.5 (3.9%) > RCP2.6 (3.5%);

(2) According to the level of exposure to wind-driven rain in different regions of China, the overall regional distribution in the future and current scenarios is almost the same. The overall trend of wind-driven rain exposure gradually decreases from the southeast coastal area to the northwest inland area. The areas with changes and rainfall intensity are mainly concentrated in south-eastern Sichuan and Chongqing, southern Qinghai, southern Gansu and north-eastern China. In addition, the area with a "high" wind-induced rain exposure index is gradually expanding in the south-eastern region.

(3) The maximum increase in wind-driven rain in the three future scenarios is greater than 0.4 m²/s in the RCP4.5 scenario. This is higher than the maximum increase in the RCP8.5 scenario of 0.3 m²/s, significantly higher than the maximum increase in the RCP2.6 scenario of 0.2 m²/s, and in line with the growth rate.

(4) For buildings in 10 representative cities, wind-driven rain exposure increase or decrease in the dominant orientation by 30 kg/(m²·a) in inland areas, which is significantly less than the increase or decrease in coastal areas, which is about 130 kg/(m²·a). The distribution of urban areas with increased and decreased exposure is consistent with the findings shown in the map of increases in wind-driven rain exposure.

(5) From a seasonal perspective, in Shanghai, a region with hot summers and cold winters, in 2050, wind-driven rain exposure will increase by a maximum of 38% in summer under RCP2.6 and by 38% in winter under RCP4.5. The maximum increase in wind-driven rain exposure was 29 kg/(m²·a) and the impact of wind-driven rain on building energy consumption became more significant in summer and winter with the more cool and heat demand which is due to the less thermal insulation influenced by wind-driven rain.

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