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Influence of rainfall on the thermal and energy performance of a low rise building in diverse locations of the hot humid tropics

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Abstract

Rainfall is seldom addressed in the analysis of climates for building design, usually neglected for building thermal performance calculations, and there is very little research about its potential cooling effect. This research aims to estimate and compare the influence of natural rainfall on the thermal and energy performance of a low-rise building in diverse locations of the hot humid tropics to assess its significance. Through whole building simulations in *WUFI Plus,* a parametric study based on rain intensity is conducted to estimate the hygrothermal performance of a small building (free-running and air-conditioned) at wet, wet-dry and dry locations of the Tropics. Taking a holistic approach, this study observes aspects which are seldom regarded in thermal and energy simulations, like impacts to the outdoor environment and the role of water; and makes a closer approximation to reality than previous research which observes rain events only during daytime and in relation to isolated building components. The results show that rain can have an important cooling influence, although is usually more appreciable to the exterior of the building than to the interior. When the effect of rain is neglected, the total heat transfer per unit area from all outdoor surfaces to the surroundings can be overestimated by 20% in a rainy month and by 10% in a year; as well as by 7% in a rainy month and by 5% in a year from all indoor surfaces to the indoor air. Maximum temperature reductions due to rain can be 7.4°C for outdoor surfaces, 1°C for indoor surfaces, 0.4°C for indoor air temperature and 0.5°C for indoor operative temperature. The differences in thermal and energy performance result from consumption of relatively small amounts of rainwater (up to 67 kg in a rainy month and up to 448 kg in a year), which gives an idea of the potential of the rainwater surplus in the humid tropics for natural cooling in buildings and urban sites.

Keywords: Evaporative Cooling; Natural Cooling; Hot Humid Tropics; Wind Driven Rain; Low Rise Building

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1. Introduction

Until recently the interest in research about rainfall influences on buildings has been mainly driven from a perspective of protection from rain penetration and from mechanical damage. The majority of research progress and literature on this subject comes from the field of building science/physics, where the effects of rainfall are considered mostly in how they challenge the integrity of buildings, like in Straube & Burnett [1] and Choi [2]. A similar approach is seen in literature of climate responsive architecture, like Koenigsberger [3] and Evans [4], who provide recommendations for building design that refer only to rain protection, waterproofing and heavy rain issues.

There is little research focusing on positive impacts of rainfall on buildings, particularly thermal and energy performance in hot climates. Despite research on wind driven rain which observes the hygrothermal performance of building materials and assemblies, most of it focuses on the content and transport of moisture [5] and its impact on performance and durability. Usually there is no distinction about the contexts where the research on rainfall and buildings is conducted. Most of the pioneering research on this subject is from locations with temperate and cold climates (Canada, UK, Netherlands, Germany, etc.), where buildings are exposed to alternating hot and cold seasons and the combination of rain loads with cold temperatures presents big challenges for the materials and construction systems (freeze-thaw damage, condensation). But it is evident that this situation is dissimilar for locations with permanent hot climates, and therefore the approach to rainfall and buildings should have some differences. One of these differences is that buildings in hot locations can benefit from the natural cooling effect of frequent rainfall.

The natural cooling potential of rain has been reported since many decades ago from diverse disciplines related to buildings [5-7]. However it is not until the present decade that this potential has become a common topic of discussion in building and urban cooling research, as in Blocken et al [8] and Saneinejad et al [9]. This interest has been triggered by the search of solutions for urban heat island (UHI) mitigation and for imbalances of sensible-latent in the built environment. Ironically the initiative is led by countries with little precipitation and with short hot seasons. Conversely, there is a lack of attention to the potential of rainfall for building and urban cooling in the hot humid tropics, which have significant precipitation and permanent hot seasons.

1.1. Existing research in the humid tropics

Research on the influence of rainfall on building thermal performance in the humid tropics is scarce. Perhaps the first was the project carried out by Rao [6], using a test room facility with the objective of measuring the energy performance of a building envelope under intermittent rainfall that is frequent in Singapore. Reductions of 25% in the energy consumption of the test room were reported, as result of intermittent rainfall over a plastered brick wall. Even so, the experiment is based on simulated rainfall by spraying water over the wall on **a bright sunny day,** a combination that rarely happens in hot humid weather and is not representative of most typical days.

Another research was conducted by Mendes et al [10], which demonstrate the importance of incorporating combined heat and mass transfer into building energy simulations for hot humid climates. A dynamic model of one vertical wall (oriented to south, in Florianapolis, Brazil) was used to analyze how moisture storage and transport affect the cooling loads, under different conditions including rain. However, the rain factor is incorporated in the model only as initial high moisture content in the wall. The results show maximum errors of up to 56% in daily cooling loads when moisture factors are neglected; as well as increments in the daily cooling loads due to rain (up to 44% for sunny week and 107% for cloudy week), since the wall receives almost no direct radiation and stays moist.

The most recent and detailed study on the effect of rain on building heat gains and energy use was developed in Singapore by Jayamaha, Wijeysundera and Chou [5, 11, 12]. It involved several experimental studies and developed validated mathematical models to estimate the thermal performance of buildings under more realistic conditions that include rain. Results of several tests show average heat gain reductions **for rain days** of 17%, 12% and 10%, and annual heat gain reductions of 7%, 5% and 4% due to rain effects over porous exterior walls. Yet, this research is based on isolated walls only and conduct simulations using discrete “characteristics days” that together represent an entire year; an approach that neglects the influence of orientation and the continuity of a dynamic real situation.

Although precipitation is a noteworthy characteristic of the hot humid tropics and its influence over the thermal and energy performance of buildings is appreciable, there has been no additional progress on this topic in the last two decades. Many facets of rain effects on buildings in the humid tropics remain to be explored.

1.2. Objective of this research

This research aims to estimate and compare the influence of natural rainfall on the thermal and energy performance of a low-rise building in diverse locations of the hot humid tropics, to assess its significance and variation in a range of hot humid conditions. It also looks to overcome weaknesses of previous research which only observe rain events during daytime and in relation to isolated building components.

This study is developed with a holistic approach, integrating aspects which are seldom regarded in thermal and energy simulations. Some key aspects of this research are that it:

- Considers dynamic weather conditions and the correlations between climate variables.
- Uses a whole building approach, considering the orientation of all components of the building envelope.
- Assesses indoor and outdoor performance of the building, particularly the resulting influences on its surroundings
- Emphasizes the water factor, not only temperatures and heat transfer; estimating amounts of water absorbed and released by the building envelope and their equivalences in latent heat.

2. Methodology

The influence of rainfall on the thermal and energy performance of a low-rise building was assessed through a parametric study based on rain intensity. For this, a dynamic whole building hygrothermal simulation was conducted at six locations in the Tropics with varied precipitation regimes: wet, wet-dry and dry.

The hygrothermal model has been implemented using the program *WUFI Plus*, a whole building Heat, Air and Moisture (HAM) modelling software developed by the *Fraunhofer Institute for Building Physics (IBP)* based on the model of Künzel [7]. This tool has been selected for several reasons:

- Its capability to simulate the hygrothermal behavior of building envelope components coupled to the thermal performance of the building.
- It has been validated against several field experiments, other calculations and standards; and is even used as benchmark for testing results of similar tools.
- Is one of few existing HAM software that integrate wind driven rain (WDR) as a boundary condition.

3. Description of the model

3.1. Study sites and climate data

The selection of locations for this study considered the following criteria (in order of importance):

- Hot temperatures in phase with a notable rainy season (monthly averages above 23 ºC and 150 mm/month). Preference was given to locations with hot temperatures all year long.
- High humidity, to observe the efficacy of evaporation (monthly averages above 16.8 ºC dew point temperature).
- Rainfall intensity. Locations with high, moderate and low precipitation were considered, to cover the diversity of climates in the humid tropics.

The six locations selected are: *Douala (Cameroon), Singapore, Cairns (Australia), Darwin (Australia), Lodwar (Kenya) and Khartoum (Sudan)*; which provide a broad representation of temperature, humidity, wetness and rain intensity ranges, as shown in Fig. 1. The last two are dry locations serving as baselines for analysis.

The chosen source of climate data for the simulation was the meteorological database and software Meteonorm, because of its homogeneity and the possibility to generate hourly climate data for any location world-wide. While its models can realistically reproduce the intensity and distributions of driving rain events only to a limited extent, Meteonorm data has been proved suitable for hygrothermal simulations, and is confirmed as appropriate for the purposes of this study due to its basis on measured long-term values and good correlation between variables.

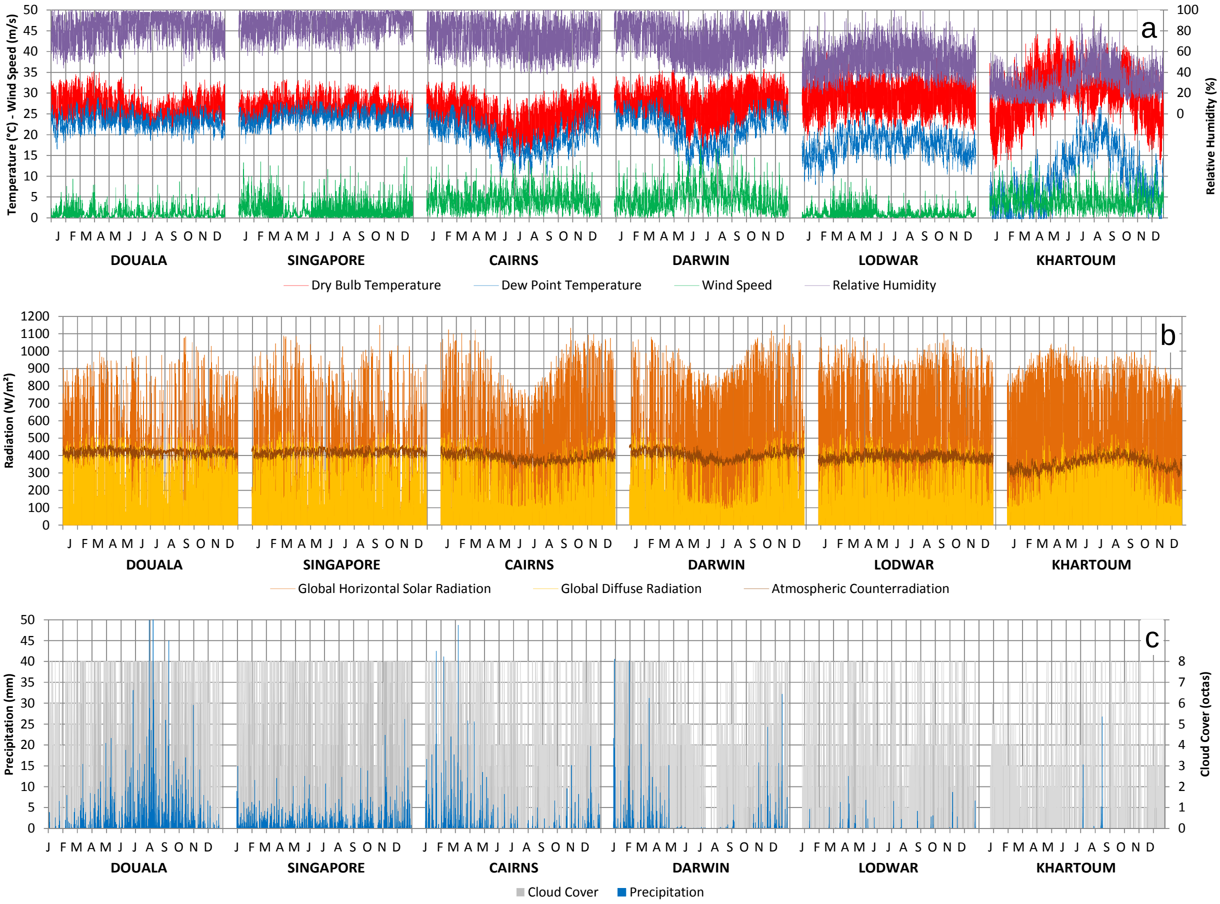

Fig. 1. Climate data graphs of the 6 selected locations: (a) Temperature, humidity, wind speed; (b) Solar radiation; (c) Precipitation, cloud cover.

3.2. Building configuration

The model used for the study is a small ($9m^2$), single zone, low-rise building (see Fig. 2). The building is configured with materials and construction systems customary for locations in the hot humid tropics. Detail of the dimensions of the building model and its components can be found in Table 1. To minimize the need for assumptions and arbitrary manipulation of the material properties, great effort has been put in selecting materials that have been well documented.

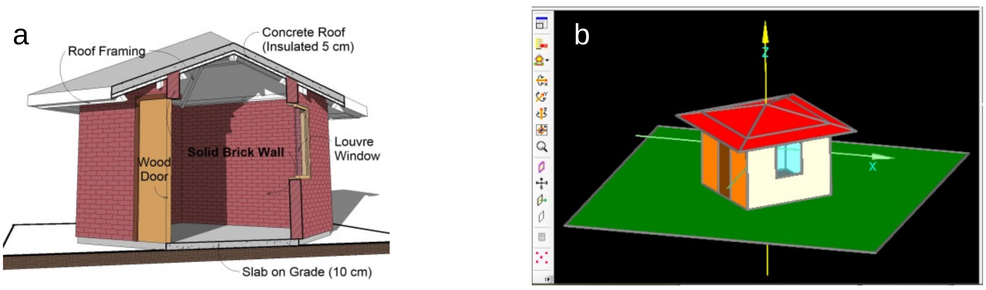

Fig. 2. Building model: (a) Actual configuration; (b) Visualization in WUFI Plus.

Table 1. Physical parameters of the building model.

Component	Roof	Wall NE	Wall SW	Wall NW	Wall SE	Door SW	Window SE	Floor	Net Volume
Area (m^2)	18.42	7.20	5.47	7.20	6.09	1.73	1.11	9.00	22.95 m^3
Thickness (m)	0.158	0.13	0.13	0.13	0.13	0.036	-	0.1	
R (m^2K/W)	1.484	0.217	0.217	0.217	0.217	0.387	0.200	1.554	

The properties of most of the materials selected for the study are detailed in [13] and can also be found in the *WUFI Plus* database. Other complementary information is supported by technical literature. Details of the physical properties of the materials and their respective components are described in Table 2.

Table 2. Hygrothermal and surface properties of the building model materials.

Material Details			Bulk Density	Porosity	Specific Heat Capacity	Thermal Conductivity (Dry)	Water Vapor Diffusion Resistance Factor	Vapor Diffusion Thickness	Water Absorption Coefficient*	Free Water Saturation (100%)	Long Wavelength	Short Wavelength
No	Material	Component	ρbulk kg/m³	P	Cm J/kg·K	λ W/m·K	μ	Sd	A kg/m²·√s	wf kg/m³	εl Emiss.	εs Absorp
1	Concrete*	Roof/Floor	2300	0.18	850	1.6	180	-	0.018[a]	150	0.9	0.65
2	Expanded Polystyrene Insulation	Roof	14.8	0.99	1470	0.036	73.01	-	-	-	-	-
3	Solid Brick Masonry (with mortar)*	Walls	1900	0.24	850	0.6	10	-	0.083[a]	190	0.9	0.68
4	Eastern White Pine*	Door	460	0.81	1880	0.093	4427.4	0.01	0.0066[b]	450	0.8	0.9
5	Clay Loam	Ground	1361	0.476	850	0.35	50	-	-	-	-	-

**Water absorption coefficient at outdoor surface:* a= *0.0008 kg/m²·√s (waterproof),* b=*0.0017 kg/m²·√s (water repellent)*

3.3. Simulation cases

To estimate the influence of the rain, the thermal and energy performance of the low-rise building under normal weather conditions is compared to the performance under alternative rain intensities and a "thermal only" simulation approach. The test building is simulated in 2 modes, free running and air-conditioned, for each of four cases:

- Rain: with original average rain intensity and climate variables of the location.
- 0.5 Rain or 8 Rain: the intensity of the rain is *reduced to half* for wet and wet-dry locations, or *increased eight times* for dry locations (as if they had the precipitation levels of a wet location).
- No Rain: with no rainfall, but considering moisture transport and storage.
- Thermal Only: without calculation of moisture transport and storage (conventional approach for simulations).

Excepting for rain, the boundary conditions and other variables are exactly the same for all cases. The air change rate is 30/h for free-running mode and 1/h for air conditioned mode; the set-point for the latter is 25°C and 50% relative humidity (all day). The building has no occupants and no internal heat and moisture generation or storage. The period of simulation is one year from January 1st to December 31st (with one previous year of initialization).

3.4. Limitations of the model

As with any simulation tool, *WUFI Plus* has limitations. To minimize these, considerable effort has been made to select appropriate materials, use reliable sources of input data and include all the relevant variables to produce results that approximate reality as closely as possible. Aware of these limitations, this research is more concerned with relative differences among the simulation cases and climates, rather than absolute values of the results. However these latter are consistent with the ranges seen in reality. The most relevant limitations of the model are:

- The model is one-dimensional, so distributions of solar irradiance and WDR over outdoor surfaces are simplified.
- It does not account for variations in shortwave absorptivity and longwave emissivity when the materials are wet.
- It does not account for evaporative cooling effects in non-porous materials.
- It does not model in detail the immediate surroundings of the building.

4. Results

4.1. Free running buildings

The influence of rainfall over the free running building is assessed through temperature differences for indoor air (Ti), indoor and outdoor surfaces (Tsi, Tso) and operative temperatures (Top) between a building under local normal rain conditions and the three other cases listed above. These differences are illustrated in Fig. 3 & 4.

In terms of indoor air and operative temperatures most of the differences due to rain are too small to be relevant. In relation to the “Rain” case, Ti and Top are not higher or lower than 0.5°C for most of the cases (excepting the “Thermal Only” case). Considering the volume of the room and the rate of air change in the free running building (30/h), it is plausible that the influence of rain over Ti, Tsi and Top is dominated by the outdoor air.

The influence of rain is more visible in the surface temperatures. In relation to the “Rain” case, Tso and Tsi can respectively be:

- 3.0°C and 0.2°C higher at the roof, and 2.7°C and 0.7°C higher at walls for the “0.5 Rain” case in wet locations,
- 2.5°C and 0.2°C lower at the roof, and 4.0°C and 0.9°C lower at walls, for the “8 Rain” case in dry locations,
- 7.4°C and 0.6°C higher at the roof, and 4.0°C and 1.0°C higher at the walls, for the “No Rain” case,
- 7.3°C and 0.8°C higher at the roof, and 4.0°C and 1.8°C higher at the walls for the “Thermal Only” case.

As can be seen in Fig. 3, the patterns of temperature differences due to rain are similar among the six locations.

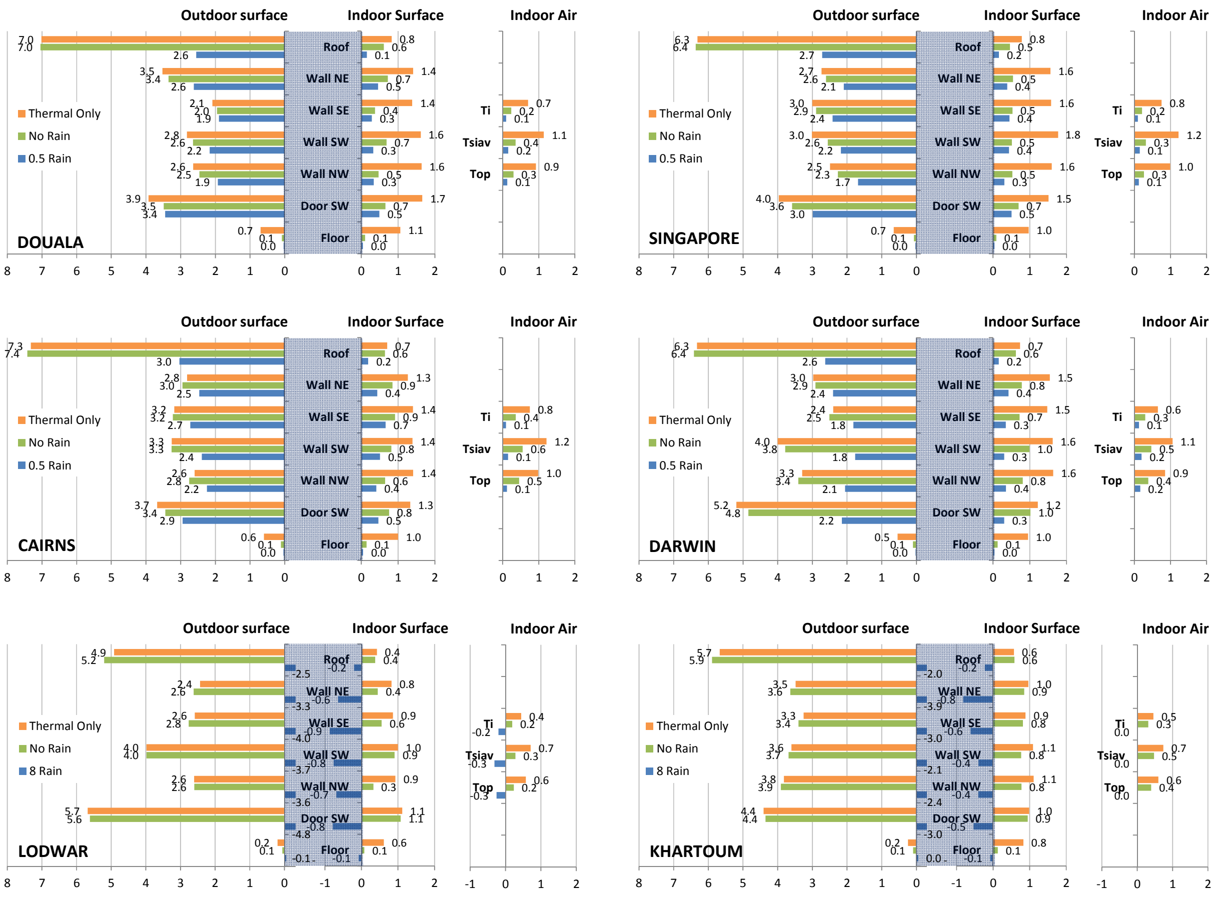

Fig. 3. Annual maximum temperature differences respect to “Rain” case, for all envelope surfaces and indoor air (in °C).

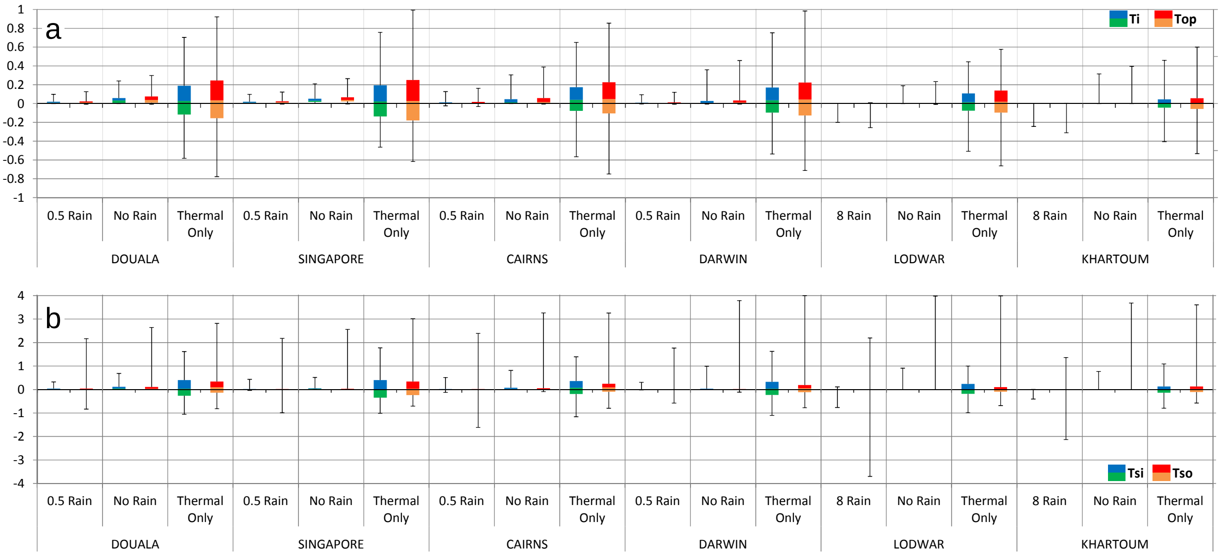

Fig. 4. Annual temperature differences respect to "Rain" case: (a) indoor air and operative temperature; (b) southwest wall surfaces (in °C).

4.2. Air conditioned buildings

The influence of rainfall over the air conditioned building is assessed through the differences in heat transfer from surfaces of all the building envelope components, with respect to a building under local normal rain conditions.

In absolute terms, the influence of rainfall on heat transfer is noticeable, particularly on outdoor surfaces. Fig.5 shows an evident disparity between wet and dry locations, as well as wide contrasts between the cases with rain and those with no rain at all. The difference in heat transfer per unit area in a year from the envelope surfaces can be:

- From outdoor surfaces to the surrounding air:
  - 48.0 kWh/m² more from the roof and 11.0 kWh/m² more from a wall, for "No Rain" & "Thermal Only" case
  - 9.8 kWh/m² more from the roof and 3.8 kWh/m² more from a wall; for the "0.5 Rain" case
- From indoor surfaces to the indoor air (indoor heat gains):
  - 5.4 kWh/m² more from the roof and 7.7 kWh/m² more from a wall, for the "Thermal Only" case
  - 5.2 kWh/m² more from the roof and up to 2.7 kWh/m² more from a wall, for the "No Rain" case
  - 1.0 kWh/m² more from the roof and up to 1.3 kWh/m² more from a wall, for the "0.5 Rain" case

These differences are also observed in relative terms for two periods: a month of the peak rainy season and a year. According to Fig. 6, the total heat transfer per unit area from the whole building envelope can be:

- From outdoor surfaces to the surrounding air:
  - 20% greater in a rainy month and 10% greater in a year, for the "No Rain" & "Thermal Only" cases
  - 5% greater in a rainy month and 2% greater in a year, for the "0.5 Rain" case
- From indoor surfaces to the indoor air (indoor heat gains):
  - 7% greater in a rainy month and 5% greater in a year, for the "Thermal Only" case
  - 4% greater in a rainy month and 2% greater in a year, for the "No Rain" case.
  - 1% greater in a rainy month and 1% greater in a year, for the "0.5 Rain" case.

At the dry locations, most yearly differences in heat transfer due to rain (absolute and relative) are too small to be relevant, even when the rain intensity is increased (only differences respect to the "Thermal Only" case are noticeable). However, the differences in heat transfer are appreciable for monthly totals at the peak rain season.

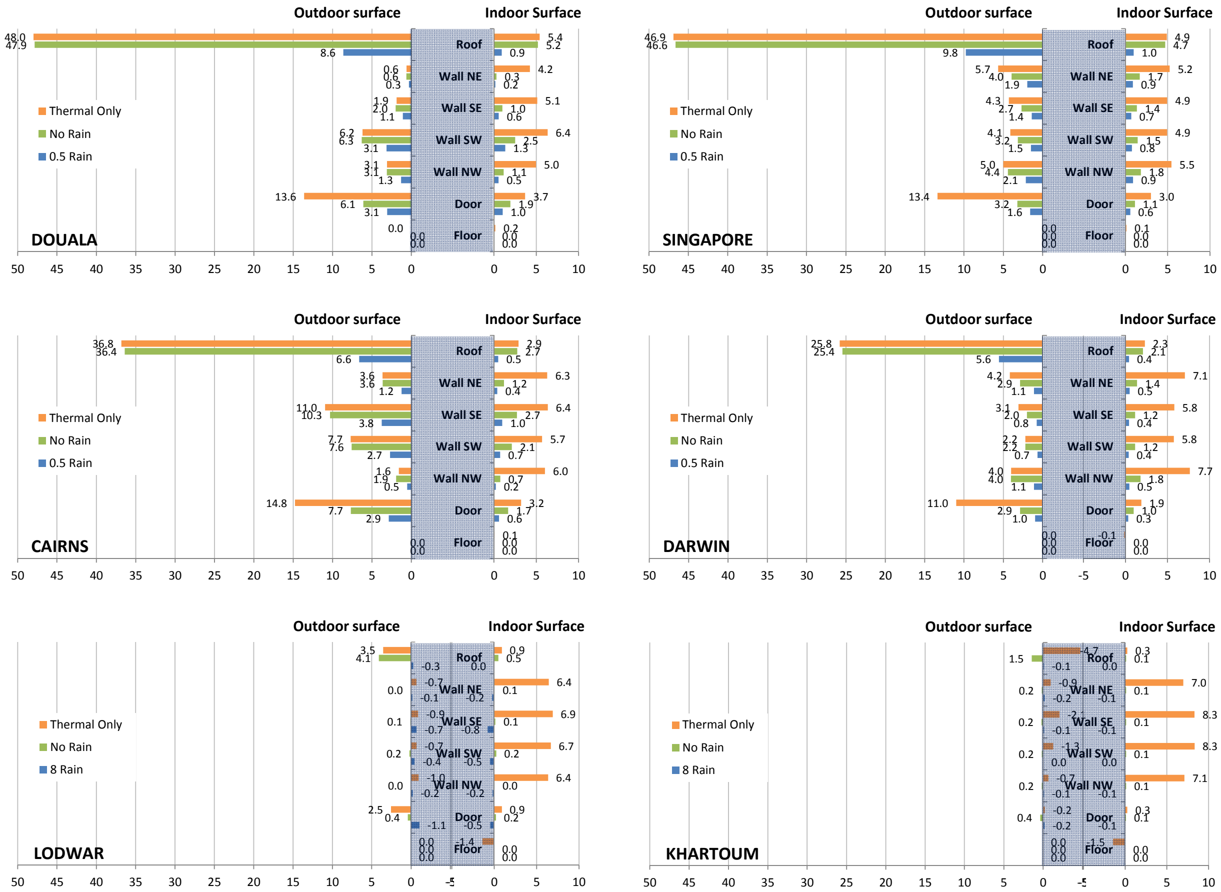

Fig. 5. Annual total heat flux differences respect to “Rain” case, for all envelope surfaces (in kWh/m²).

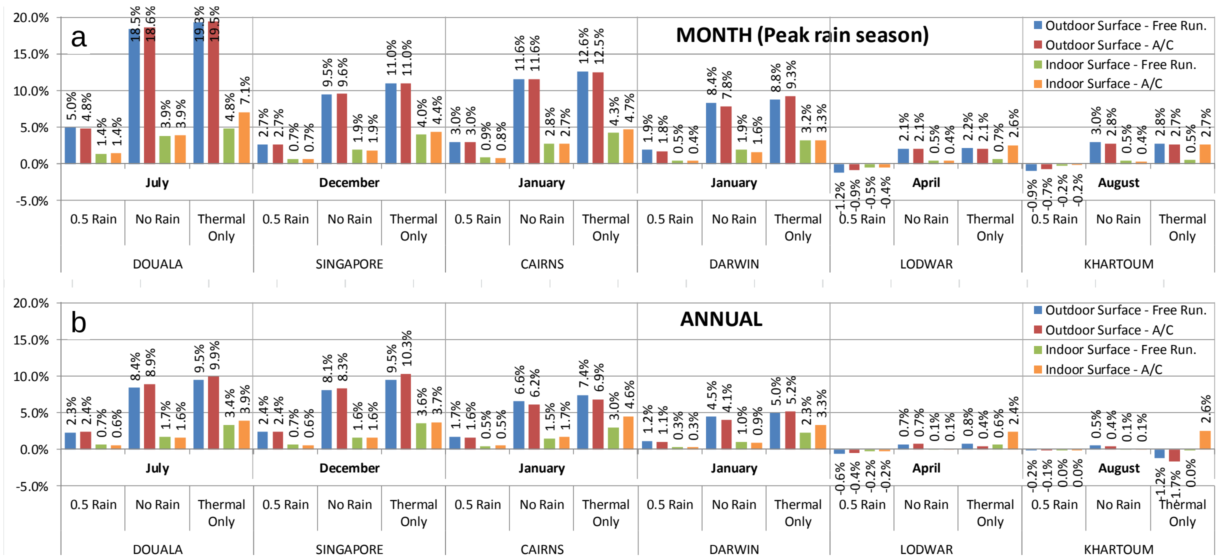

Fig. 6. Relative differences in total heat transfer per unit area from whole envelope surface, respect to “Rain” case: (a) Monthly; (b) Annual.

4.3. Water Consumption

Contrary to what is commonly assumed, the process of evaporation can be effective in hot humid contexts. The differences in thermal and energy performance outlined in the previous sections result from the evaporation of relatively small amounts of water. As shown in Fig. 7, the water consumed in the cases of wet locations ranges between 40 and 67 kg for the observed months of the peak rainy seasons, and between 296 to 448 kg for the annual totals. For dry locations these ranges are 17 to 19 kg for a month of the peak rain season and 28 to 60 kg for a year.

To give more meaning to these numbers, the maximum amount of water evaporated, 448 kg (equivalent to 448 liters or 0.45 m^3), is the same amount that the roof of the building model would collect from 32 mm of rain, considering its runoff efficiency. This amount is marginal for wet locations like Singapore and Douala, with annual precipitations of more than 2000 and 3500 mm respectively. The above highlights the potential of the rainwater surplus in the humid tropics for natural cooling in buildings and urban sites.

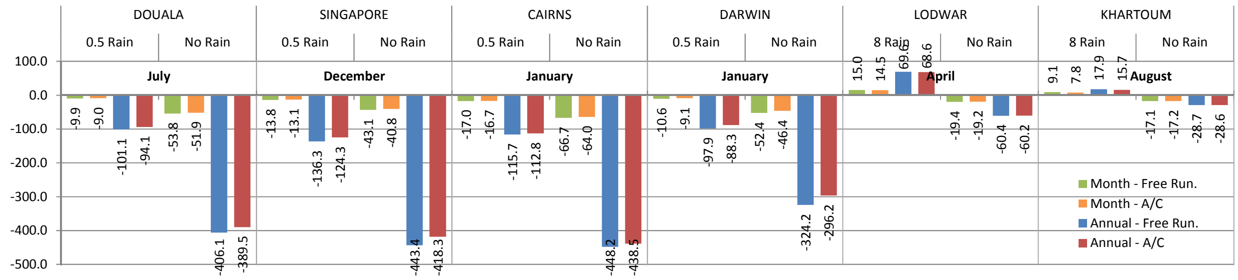

Fig. 7. Annual total differences of water evaporated from whole envelope outdoor surface, respect to "Rain" case (in kg).

5. Discussion

The cooling influence of rainfall on the low rise building is not as high as expected by the hypothesis that motivated this study. However, this does not mean that it is negligible.

Although in terms of indoor air and operative temperature the influence of rainfall is relatively small, it has an appreciable impact on outdoor surface temperatures and on heat transfer from the building envelope. Likewise, there is considerable variation in the magnitude of rain effects when observed in relation to different components and orientations of the building, at different time scales and at different periods of the daily and annual cycles. This confirms the importance of analyzing this matter from diverse perspectives and not only at the indoor environment.

Two reasons are identified as limiting the cooling influence of rainfall on the building despite its high intensities: a) *The amount of water hitting and being absorbed by the building is minimal in comparison with the amount of water available from precipitation* (see Fig. 8), due to the directional nature of the WDR and to the low water absorption capacity of the roof and walls (waterproof). Even with high intensity the rainfall does not impact the building surfaces at all times (except for roofs), and makes little difference if the building surfaces are saturated. And b) *Building surfaces wetted by rainfall generally coincide with unfavorable atmospheric conditions for evaporation (low solar radiation, low air temperature, high relative humidity)*. Therefore, the evaporative cooling from rain is slow and its short term effect over the temperatures of the building is limited.

Changes in rain intensity can make some appreciable differences as illustrated by the "0.5 Rain" and "8 Rain" cases. However, the frequency of rain plays a more active role in the cooling influence than the intensity. This is illustrated by a greater proportion of heat transfer reductions of Douala in comparison to Singapore, during peak rainy months, which is caused by the higher rain frequency in Douala, not by its higher rain intensity (see Fig 6).

Also, we can see that other factors are equally important for the cooling influence of rain, like the wind regime and the water absorption characteristics of materials. This is illustrated in Fig. 8, where slight rain combined with wind at moderate speed can have the same effect as very intense rain combined with low air speed.

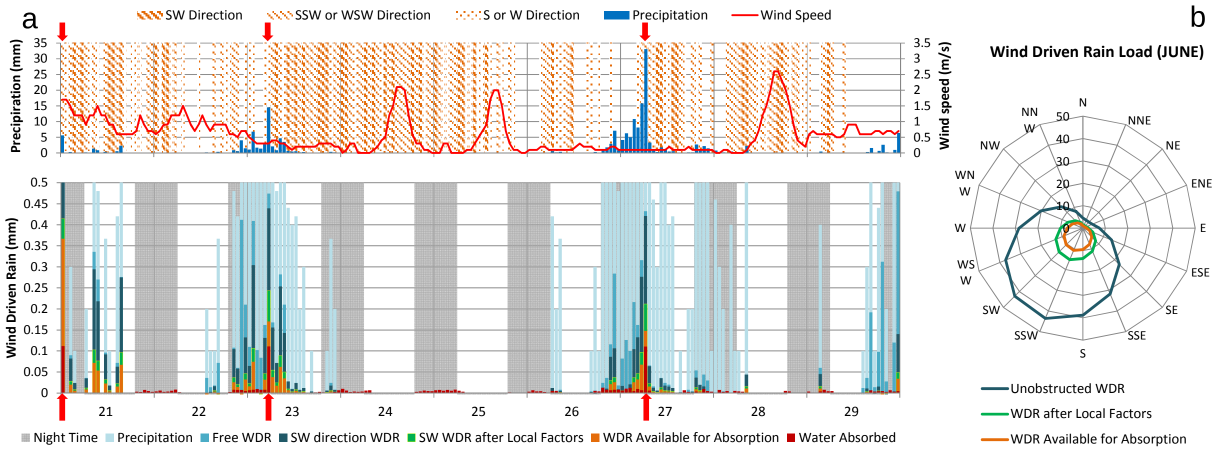

Fig. 8. Water amounts from "Douala" case (end of June): (a) Comparison of precipitation, WDR and water absorbed; (b) WDR sum.

6. Conclusions

The results of this research show that rain can have an important cooling influence over a low-rise building, although the effect is usually more appreciable to the exterior of the building than to the interior.

In free running buildings, rain can contribute to temperature reductions as high as 7.4°C for outdoor surfaces, 1°C for indoor surfaces, 0.4°C for indoor air and 0.5°C for indoor operative temperature. In air conditioned buildings, reductions on total annual heat transfer per unit area due to rain can be as high as 48.0 kWh/m² for roofs and 11.0 kWh/m² for walls, from outdoor surfaces to the building surroundings; and as high as 5.4 kWh/m² for roofs and 7.7 kWh/m² for walls, from indoor surfaces to the indoor air. When the influence of the rain is neglected, the total heat transfer per m² from all outdoor surfaces to the surroundings can be overestimated by 20% in a rainy month and by 10% in a year; as well as by 7% in a rainy month and by 5% in a year from all indoor surfaces to the indoor air.

The predominance of the rainfall influence over the roof is evident and the results confirm that this must not be neglected in wet locations. Rain still has a visible impact on the building interior even when the roof is insulated.

Although the cooling influence of rainfall is small in some cases, it is still positive for the thermal and energy performance of the building under a hot climate, as well as beneficial for the immediate building surroundings.

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