Effects of Urban Environment's Structures Over Solar Irradiance Availability

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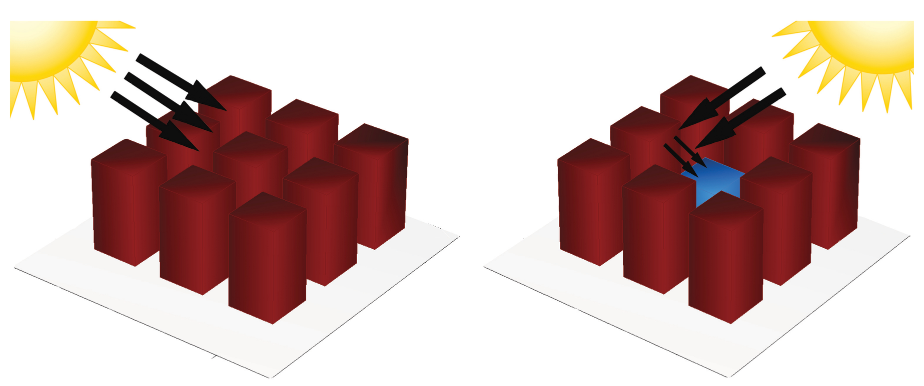
Motivation

Solar radiation is becoming an ever more significant resource to be used by renewable energy technologies, such as rooftop photovoltaic arrays, allowing power production in urban environments without any pollutant emission. The study of solar radiation in urban environments is also crucial to investigate its effects on urban-scale fluid dynamics. The present study analyzes how the morphology of a city influences the availability of solar irradiance in urban environments. The ratio between rooftop areas and the total area of the city (**plan area fraction**), the average value ($\boldsymbol{\mu}$) and the standard deviation of buildings heights ($\boldsymbol{\sigma}$) are parameters that strongly influence the possibility to produce power with rooftop photovoltaic technologies. The presence of surrounding buildings may considerably reduce the amount of radiation reaching a specific rooftop, or may increase it, reflecting or scattering the radiation.



The results of this study represent useful guidelines to optimally take advantage of solar energy in urban context. Moreover, it provides useful data to understand how urban fluid dynamics phenomena are affected by city structures.

QES Radiant

The building-resolving radiation transfer model "QES Radiant", presented by Overby et al. in 2016 [1], have been employed. Thanks to graphics processing units (GPU), it uses accelerated ray tracing techniques to simulate balances of solar radiations for millions of patches over surfaces equivalent to whole cities domains.
The present work employs QUIC to build city models and QES Radiant to run simulations for city models for 24 hours on the 22nd of June and on the 21st of December for a latitude of 40^o.

QES Radiant decomposes the net all-wave radiation (Q^*) into longwave (incident and reflected or emitted) and shortwave (incident and reflected or emitted) [1]. For this work, only shortwave has been assumed relevant.
Shortwave radiation is modeled to be received by each patch as direct, diffuse or scattered. Direct radiation comes directly from the sun; diffuse radiation is scattered by the atmosphere; while scattered radiation is scattered or reflected by solid surfaces in the domain, such as buildings.
QES Radiant allows to assign values to direct (S_{Dir}) and diffuse (S_{Dif}) radiation, using measured data, or to calculate those components using solar models. Specifically, the model by Monteith et alii (2008) [2] has been employed. It is a cloudless sky radiation model that computes the global solar irradiation as the sum of S_{Dir} and diffuse S_{Dif}. The relative air mass in the model is computed using the model presented by Atwater et alii [3].

$$S_{Dir} = S_0[e^{-m(\tau_m+\tau_a)}] \cdot cos(\theta_s)$$

$$S_{Dif} = 0.3 \cdot S_0[1 - e^{-m(\tau_m+\tau_a)}] \cdot cos(\theta_s)$$

$$m = \frac{35}{\sqrt{1 + 1224 \cdot cos^2(\theta_s)}}$$

with τ_m being the molecular extinction coefficient, τ_a being the aerosol extinction coefficient, θ_s being the solar zenith angle and S_0 being the solar constant ($1367 W/m^2$)

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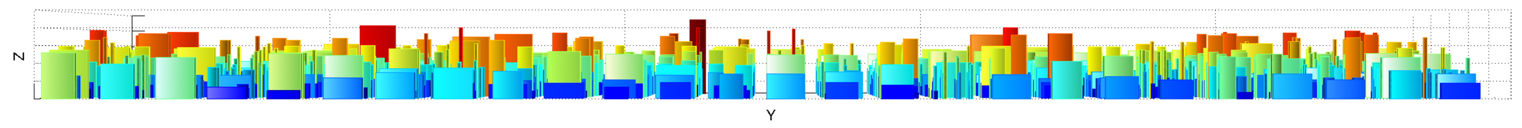
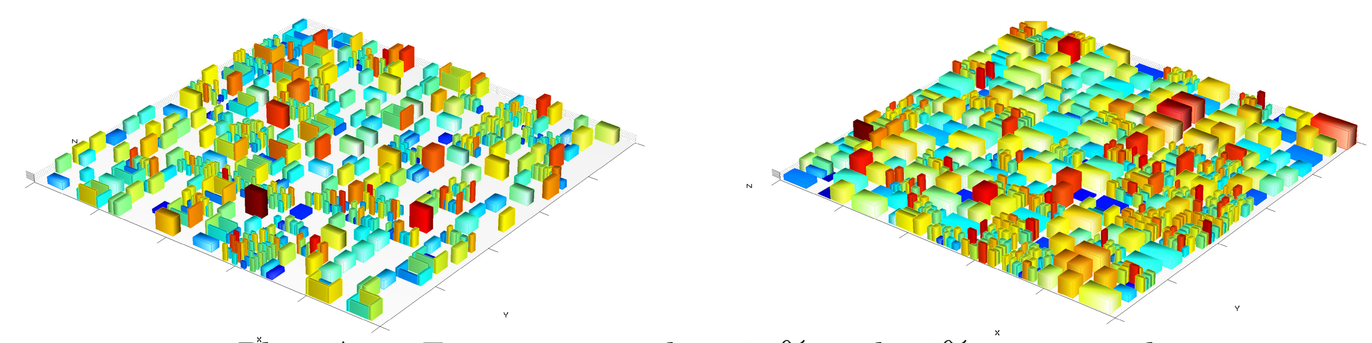
City generation

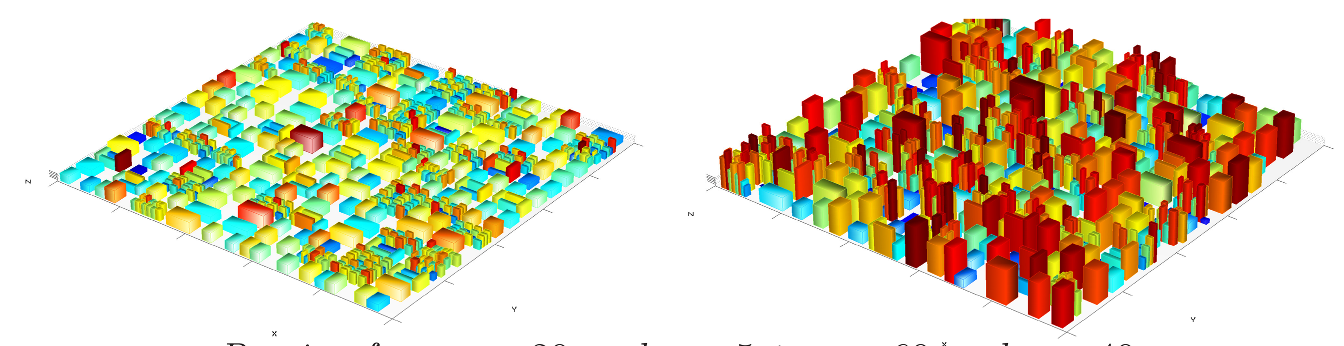


Different random city models have been taken into account. Buildings have been distributed in a 1000m by 1000m domain, pulling the buildings heights from a normal distribution. The mean value and the standard deviation of the distribution, together with the plan area fraction, are the considered variables.

Variables	
μ	Average building height
σ	Standard deviation of building heights
PAF (Plan Area Fraction)	Ratio between the total rooftop area and the area of the city
Radiation	Total solar power per unit area

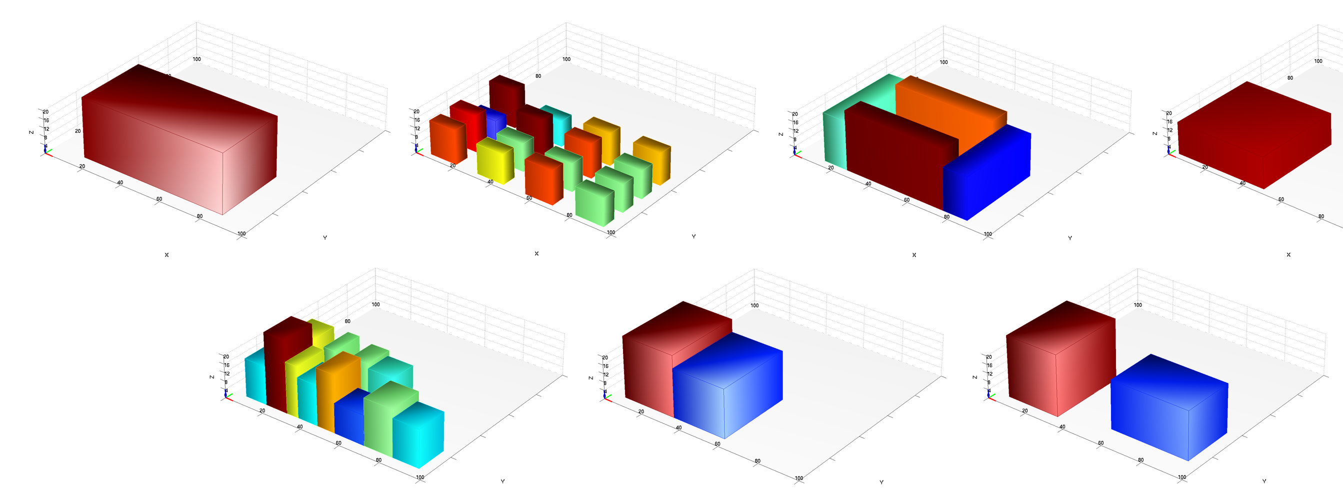


Plan Area Fractions equal to 20% and 50% respectively



Passing from $\mu = 20$ and $\sigma = 5$ to $\mu = 60$ and $\sigma = 40$

For real cities, μ varies from 10m to 60m, σ from 0m to 50m and PAF from 10 to 60, according to the literature [4, 5, 6]. To build a city, several blocks samples have been considered, in order to have a reasonable and exhaustive representation of real city blocks. Each city contains a random distribution of each of the following block types (100m x 50m):



The simulations compute the total solar energy collected on rooftops for each city. The total energy (in Joules) is then divided by the corresponding total rooftop area to compute an energy density ($\frac{W_{Daily}}{m^2}$) to facilitate comparison.

References

[1] Matthew Overby, Peter Willemsen, Brian N Bailey, Scot Halverson, and Eric R Pardyjak. A rapid and scalable radiation transfer model for complex urban domains. *Urban Climate*, 15:25–44, 2016.

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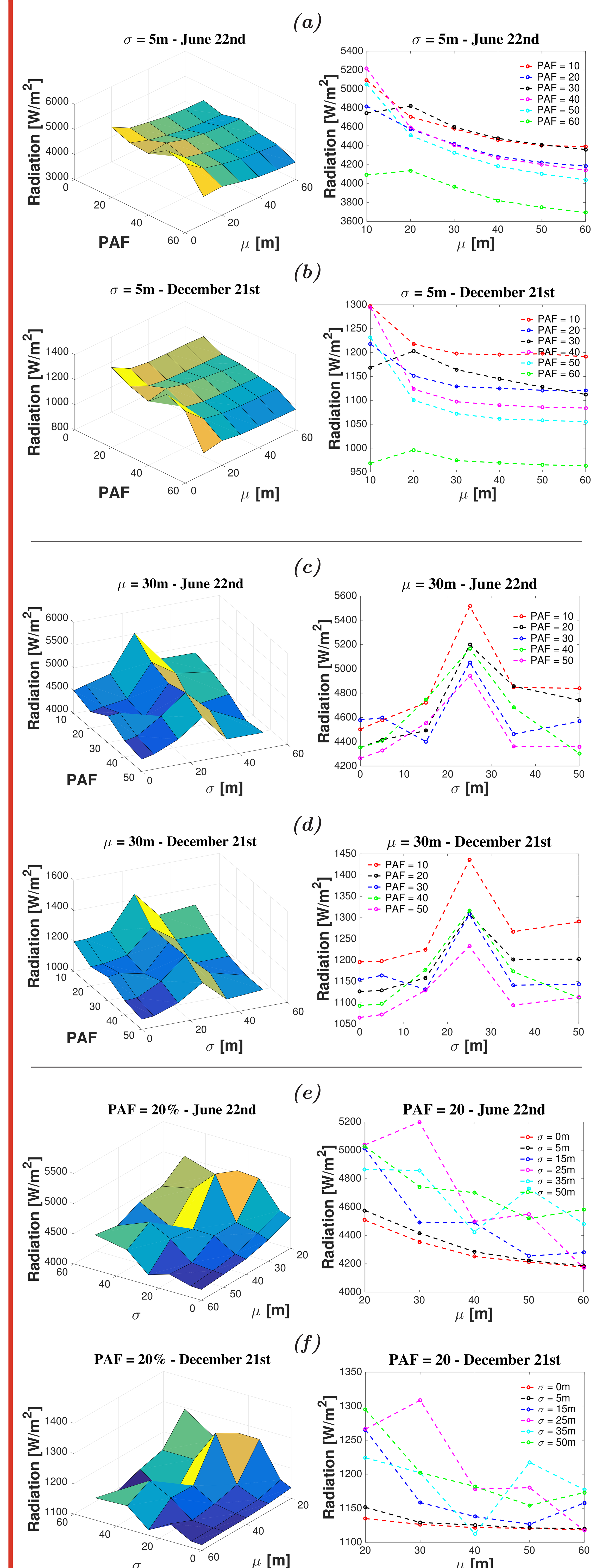
Results and Discussion



- Data for June and data for December follow a consistent trend.
- Increasing μ, the solar power decreases, because of more shadowing effects from surrounding buildings. Consequently, the solar power per unit area decreases.
- Figures **(a)** and **(b)** suggest no clear relationship between PAF and solar power. Even though more shadowing effects are present in compact cities (higher plan area fraction), reflections and scattering effects also come into play, increasing the radiation hitting rooftop surfaces.
- Figures **(c)** and **(d)** suggest that, fixing μ, there is an optimum value of standard deviation ($\sigma = 25$) that maximizes the incident solar radiation for each PAF.
- In figures **(e)** and **(f)**, the trend of solar radiation vs μ is consistent for $\sigma = 0$ and $\sigma = 5$. For higher σ there is no clear pattern. Further investigations will follow to analyze the role played by the combination of μ and σ.
- In general, shifting from an homogeneous city ($\sigma = 0$) to a more diverse one ($\sigma > 0$), the solar power received by rooftops tends to increase.
- In further investigations, simulations will be performed over a whole year.

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