Neighbourhood morphology and solar irradiance in relation to urban climate

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1. Introduction

Solar energy, relating to the heat and light from the sun, is one of the most promising of renewable energy sources. The total energy received by the Earth from the sun annually is many times greater than that produced by any other available energy source. In fact, the solar energy received annually by the Earth is many thousand times more than the total yearly energy consumption of mankind (Chen, 2011). Yet, solar energy is currently a tiny part of the total energy use; for example, solar energy is still only about 1% of the global electricity demand in the world. Solar energy production is, however, growing very fast, and may, in forecasts by the International Energy Agency, provide as much as 30% of the world's energy use by 2060.

Current climate change is widely attributed partly to increase in greenhouse gases in the atmosphere (e.g., Wallace and Hobbs, 2006). In particular, emission of carbon dioxide (CO_2) from human activities has increased since the industrial revolution, and particularly in the past decades. The increase in CO_2 in the atmosphere has been related to global rise in temperature during this time. One of the main aims of current research on climate change is to reduce or stop the increase of CO_2 in the atmosphere through various means. Since urban dwellers produce much CO_2, one principal mean is through reducing CO_2 emissions related to domestic and traffic fuel consumption.

In this respect, solar energy is a very attractive energy source because solar energy production is close to carbon neutral. 'Carbon neutral' here means that net CO_2 emission associated with the energy production is equal to zero. Solar energy production is, of course, not completely carbon neutral because there is carbon emission generated during the production of the solar photovoltaics (PVs) and, to a much less extend, the equipment for solar thermal power (Chen, 2011). However, the carbon footprint associated with solar energy is much less than that of any non-renewable energy source.

One of the great advantages of solar energy is that its production in large quantities does not necessarily require large power plants: it can be obtained everywhere where the sun shines, in large and small amounts and from panels of various sizes. This means that solar energy sources are available within urban areas (Sarralde et al., 2015), particularly from the roofs of buildings of various sizes and shapes. In fact, the fast growth in solar-energy use in the past decade has been largely related to installation of solar panels on the roofs of buildings in urban areas. Since the efficiency of such panels increases when they receive the heat and light from the sun for the long periods of time during the day, it follows that the orientation and form of buildings (and the roofs) on which the panels are located is of great importance for their energy production. Thus, urban morphology affects the potential for the generation of solar energy.

The aim of this paper is to present and discuss results as to the incoming solar radiation received in urban areas, using the city of Geneva as a case study. The relation between urban morphology and solar-energy potential, although of great importance for solar-energy production in urban areas, has received comparatively little attention (Sarralde et al., 2015). The received solar energy is normally given as power per unit area of the Earth's surface, that is, as power density, and referred to as irradiance, with the unit of W m^{-2}. Here we show how urban morphology affects the potential for the production of solar energy and discuss some of the climatic implications.

2. General urban form

We studied the building shapes and sizes, street patterns, and the spatial distribution of buildings and streets in 16 neighbourhoods of the city of Geneva in Switzerland (Fig. 1). The results show that size distributions of the areas of the building, the building perimeters, and the building volumes all follow approximately power-law size distributions, whereas the heights of the buildings follow a bimodal (two-peak) distribution. Using the Gibbs-Shannon entropy formula as a measure of dispersion or spreading (cf. Mohajeri et al., 2015) we calculate the area, perimeter, volume, and height entropies for the 16 neighbourhoods in Geneva and show that the entropies have strong positive correlations (R^2 = 0.43-0.84) with the average values of these parameters. By contrast, there are negative correlations (R^2 = 0.39-0.54) between building density or urban compactness (site coverage and volume-area ratio) and the entropies of building areas, perimeters, and volumes (Mohajeri et al., 2015).

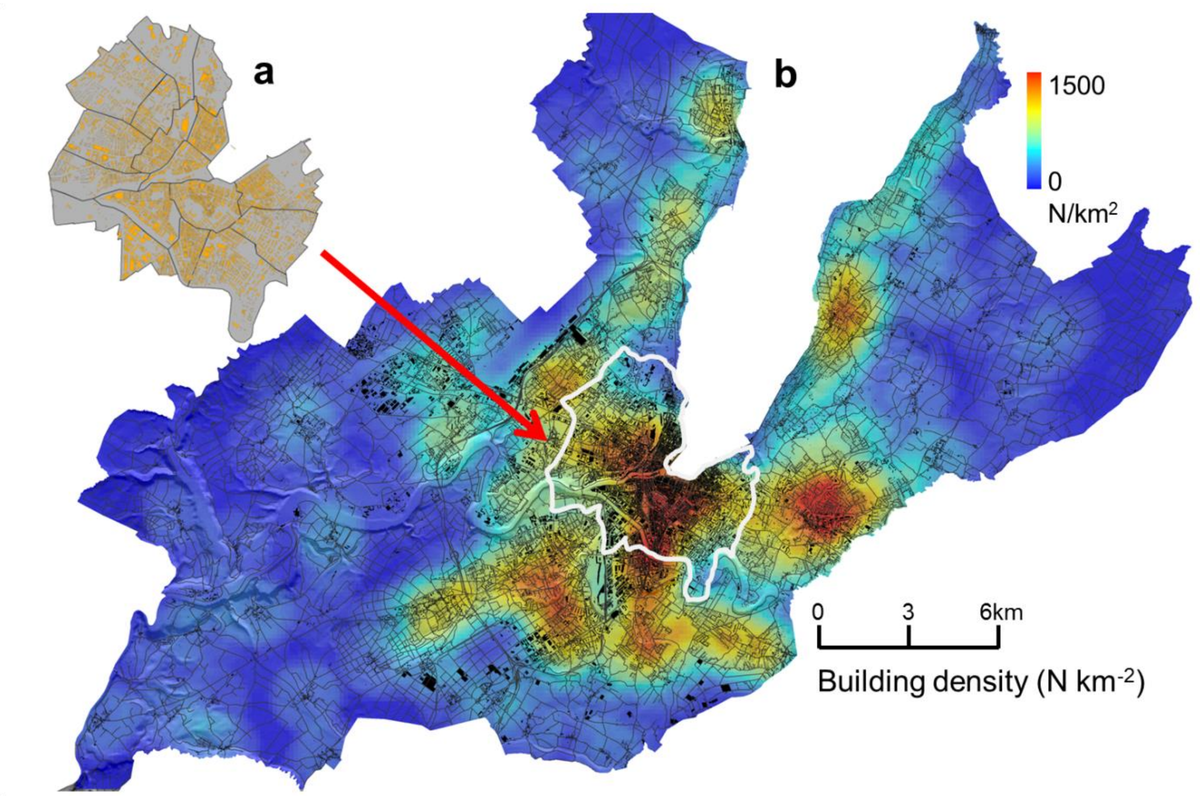

Fig. 1. (a) The city of Geneva is composed of 16 neighbourhoods or zones with a total of about 11,400 buildings and 3400 streets. (b) The building density, measured as number of buildings per square kilometre, is highest in the old central part of the city, and changes irregularly with distance from the centre to the suburbs and rural areas.

3. Urban form in relation to solar irradiance

To explore the effects of urban form, particularly the density of the built environment, on the potential for solar energy production in urban areas, we compared the neighbourhood morphologies with the annual and monthly solar irradiance for each of the 16 neighbourhoods in Geneva (Fig. 1) using the simulation tool CitySim (Robinson et al., 2009). Here we use the annual results, which show a negative correlation between building densities and solar radiation (Fig. 2a). This means that as the density of the buildings increases, that is, the number of buildings per unit urban area increase, then the received solar energy, measured as radiation, decreases.

We also explored the effects of street density on solar radiation. As the street density increases, the received solar radiation decreases (Fig. 2b). Again, the results show clearly that the denser the network – here the street network – the less is the received solar radiation. By contrast there is a positive correlation between entropy of the street lengths and solar radiation, indicating that the greater the variation in street length the greater the received solar radiation.

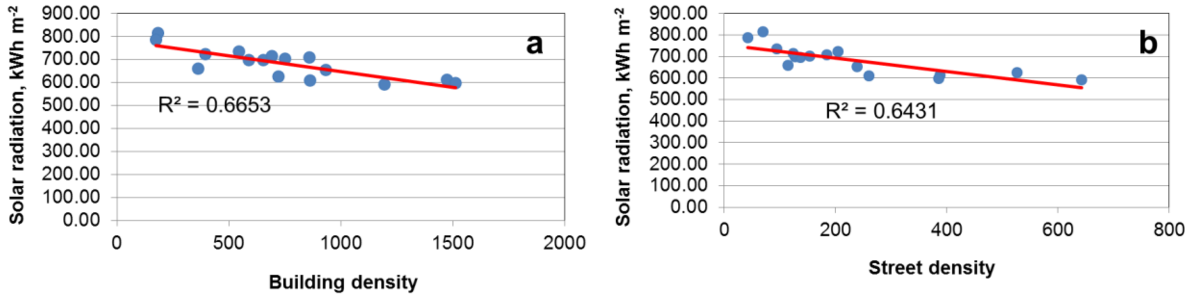

Fig. 2. (a) Correlation between the annual solar radiation and building density in Geneva. (b) Correlation between the annual solar radiation and street density in Geneva.

To explore the relations between building configurations and solar radiation we mapped the building density and compared it with the solar radiations. The results (Fig. 3) show a very close inverse relationship between the density and the received radiation. The central, old parts of the city of Geneva have the highest building density and the lowest radiation. By contrast, the outer and more recent parts tend to have lower building densities and much higher radiation.

For the street network, we compared the length entropy of the streets with the radiation (Fig. 4). The length entropy varies positively with the average street length, as has been demonstrated for many cities (Gudmundsson and Mohajeri, 2013). Thus, the greater the average length of the streets in a neighbourhood or a part of a city, the higher is the street-length entropy. This follows because entropy is a measure of spreading or dispersal, hence here a measure of the spreading of the street network, that is, the increase in the average length of the streets between the various neighbourhoods of Geneva. The correlation between the entropy and the received radiation is very strong (R^2 = 0.83), as is also seen on comparing the maps. The low entropy – related to short average street length – is essentially confined to the central old part of the city, which is also the part receiving least solar radiation. By contrast, the newer and outer parts have higher entropies (more spread street networks), and these are also the parts receiving the highest solar radiation.

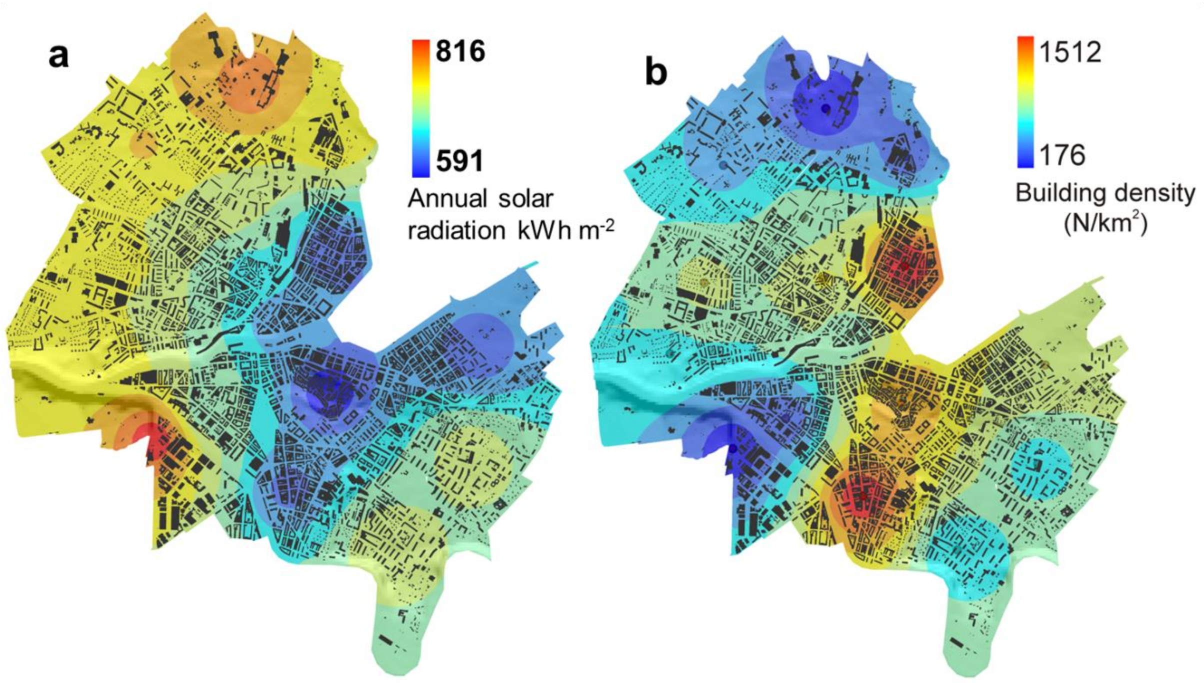

Fig. 3. (a) Variation in annual received solar radiation in Geneva. (b) Variation in building density in Geneva.

4. Discussion and conclusions

One of the most promising of renewable energy sources is solar energy. While not completely carbon neutral, its carbon footprint is small in comparison with most other energy sources. Solar energy is a particularly suitable energy source for urban areas because buildings, particularly the roofs, offer very suitable locations for solar panels. To increase the efficiency of urban solar energy, the optimal orientation of the buildings in relation to the sun is of an obvious benefit – and has in fact been used for thousands of years for heating and cooling purposes in many civilizations. Present technology makes it possible that the solar panel rotates during the day so as to align itself in the direction of the sun, thereby maximising the received radiation. However, as yet most panels are fixed because alignment panels are still too expensive for typical residential buildings.

Some of the problems with PVs that still remain include comparatively low efficiency (mostly about 20%), high costs, maintenance (particularly for large solar power plants – all panels must be kept clean from dust, leafs, etc, or else their efficiency decreases), and intermittent energy production (less during cloudy days, none during dark nights). For ordinary urban homeowners some of these problems can be, or are being, solved. The homes are generally connected to large power grids so that when no electricity is produced locally (e.g., during nights), energy can be obtained from the grid. By contrast, extra energy, that is, more energy than needed by the homeowner at a particular time (such as during sunny summer days), can be sold (put on) the grid. Efficiency of the PVs is gradually increasing (some currently under development have over 40% efficiency). Other problems with intermittent electricity production can, in theory at least, be solved with very large interconnected grids (perhaps extending between many countries). While PVs have been relatively expensive, their prices have being going down, particularly in recent years. The result has been exponential increase in the use of PVs, particularly in urban areas. Another potential for solar energy production is 'solar roads' or 'solar streets', ideas which are likely to be explored in the near future.

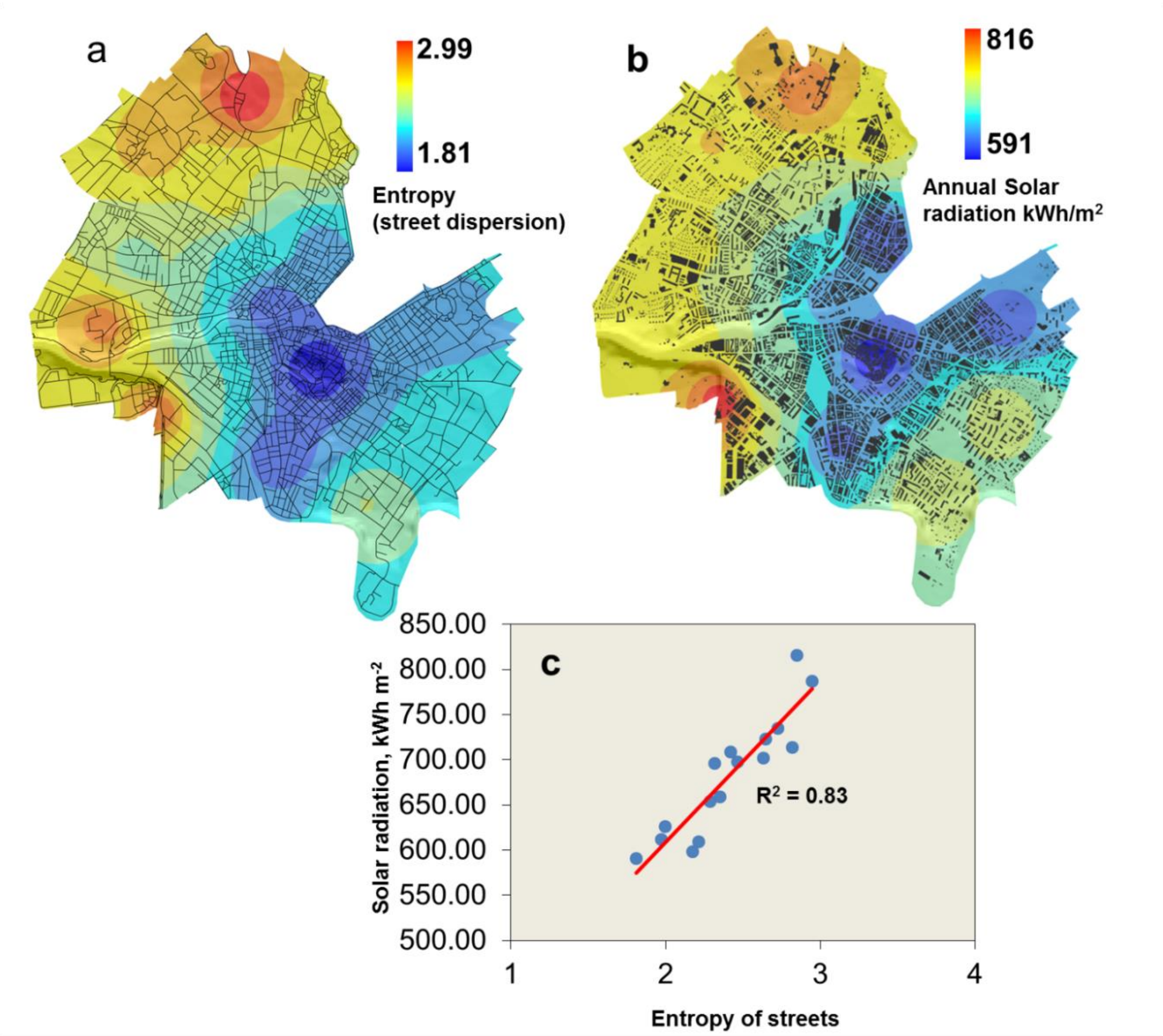

Fig. 4. (a) Variation in length entropy of the street network of Geneva. (b) Variation in received annual solar radiation in Geneva. (c) Correlation between received annual solar radiation and street-length entropy in the 16 neighbourhoods of Geneva.

In the present paper we show that building and street densities have large impact on the potential solar energy production. In particular, using Geneva as a case study, the results show that more dispersed areas of the city receive much more solar radiation, and thus have much greater potential for producing solar energy, than the dense parts, where, presumably, some of the roofs (or parts of them) and many of the facades are in shadow during part of the day. Since the use solar energy is growing exponentially, particularly in cities, these results have important implication for future planning and development of urban areas.

Solar energy is one of the most favourable energy sources in terms of carbon footprint and associated effects of climate. Urban areas have expanded enormously in the past decades, and are likely to do so in the coming decades. The results presented here suggest that careful planning of urban expansion should take into account the potential of buildings and, possibly, streets in functioning as locations for the production of solar energy.

Acknowledgment

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