7th International Building Physics Conference

IBPC2018

Proceedings

SYRACUSE, NY, USA

September 23 - 26, 2018

Healthy, Intelligent and Resilient Buildings and Urban Environments

ibpc2018.org | #ibpc2018

Greening rooftops to reduce heat islands: How large is large enough?

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ABSTRACT
Green roofs, with adequate water supply, have been proven as effective measures to reduce urban environmental temperature. The benefits of large-scale deployment of green roofs have been studied mainly through numerical simulations with unrealistic high penetration scenarios, where all rooftops across the entire metropolis is assumed to be retrofitted. In this study, the scale dependence of the cooling effect of green roofs is investigated with a coverage of 25% over buildings at local, city, or regional scales. We compared results at 6 major U.S. cities to assess the response of the scale dependence to geoclimatic conditions. High-resolution weather simulations reveal that the cooling of near-surface air temperature by green roofs increases non-linearly with the scale of deployment. The shape and geoclimatic setting (geographic and climatic characteristics) of metropolitan areas control the scaling that some city centers are not able to achieve a significant cooling by greening their own rooftops. Uniform deployment of green roofs at the regional scale, on the other hand, provides a substantial temperature reduction with a very low cooling efficiency per intervention area. Cities should carefully revisit the scale dependences of cooling benefit and efficiency of green roofs to develop resilient plans meeting their expectations.

KEYWORDS
Cooling efficiency; Green roof; Heat island mitigation; Urban planning

INTRODUCTION
Urban heat island (UHI), a phenomenon that urban areas are significantly warmer than surrounding rural areas, is a big sustainability challenge that has been documented in global cities (Peng et al. 2011). Elevated temperatures adversely affect energy demand, water resource, and resident health in urban environment that cities have recognized the need to mitigate heat island effects under the changing climate (Grimm et al. 2008). Among the proposed strategies in the literature, green roof has gained increasing popularity due to its environmental benefits including temperature reduction, storm water retention, aesthetic improvement and habitat provision (Carter and Fowler, 2008).

In-situ measurements reported that replacing conventional roofs with green roofs can reduce daily maximum surface temperature by up to 30 ºC (Wong et al. 2003). Consequently, reduced diurnal temperature variation substantially cut building heat gain and increase energy efficiency (Parizotto and Lamberts 2011). These measurements are consistent with building-scale numerical simulations (Sailor et al. 2012). At the large scale, however, the benefits of green roofs to the whole city can only be evaluated through simulations because no urban region has yet achieved a sufficiently extensive intervention. Recent developments allow accurate simulations of green roofs in climate models (Yang et al. 2015). Nevertheless, existing studies have focused on the maximum potential benefit of green roofs, i.e., 100% coverage uniformly over the entire metropolitan area (Georgescu et al. 2014).

In reality, land use development, economic activity and government structure diverge vastly among districts and communities at the sub-city scale as well as between different metropolitan areas that execution of mitigation policies can vary extensively. Take the New York metropolitan area for example, green roofs can be implemented by the city for its dense urban core (Manhattan), for the whole New York city, or in cooperation with surrounding counties in the state of New Jersey. Temperatures in cities are closely related to the fraction and spatial configuration of urban green space (Jin and Dickinson 2010), yet the quantitative scaling laws of cooling benefits from green roofs remain unknown. This study provides a first attempt to bridge this gap by simulating green roofs in different cities to address the following questions: How large does green roof need to be to produce a considerable cooling for city centers? How do the cooling benefits from green roofs scale with their spatial extent? Will the scale dependence change with geoclimatic conditions?

METHODS

In this study, we used the Weather Research and Forecasting (WRF) model, a non-hydrostatic regional climate model developed by the National Center for Atmospheric Research (Skamarock and Klemp 2008), to simulate the effects of green roofs on regional climate. The WRF model has successful applications over major metropolitan areas around the world (Chen et al. 2011), whose parameterization of green roofs was developed and tested based on field measurements (Sun et al. 2013). Six metropolitan areas across the United States were selected for high-resolution weather simulation in this study, including Los Angeles (LA), New York City (NYC), Miami, Chicago, Phoenix and Pittsburgh. For each studied region, the fine-resolution domain (see Figure 1) has 160 by 160 grid cells covering the entire metropolitan area. Each grid is 1 km long and 1 km wide. To assess the performance of green roofs in a "typical" summer, we referred to the 1981-2010 climate normal released by the National Centers for Environmental Information for different metropolis. As a result, Pittsburgh and Chicago were simulated for year 2013, and LA, Miami, Phoenix, and NYC were simulated for year 2014. All simulations were run from 0000 UTC on 10 July to 0000 UTC on 14 August.

Metropolitan areas in this study have developed sustainability plan to mitigate climate change. Though the primary goal of these actions is to reduce greenhouse gas emissions, the need of mitigating urban heat islands is explicitly outlined and the use of green roofs is recognized by Chicago, NYC, and Pittsburgh. To obtain plausible scenarios of green roofs, we went through the land use planning and development map for each studied metropolitan area and identified three (local, city, and regional, Figure 1) levels of implementation. A set of three simulations was then carried out to estimate the cooling benefit of green roofs at three levels, assuming a 25% areal coverage on building rooftops. To focus on the effect of geoclimatic conditions and to exclude the impact of water availability, green roofs were well irrigated in all runs such that soil moisture maintained evapotranspiration at 75% of the potential evapotranspiration rate. Following previous studies (Sun et al. 2013), thermal properties of roofs were (1) conventional roof: albedo (a) = 0.3, thermal conductivity (k) = 1.0 W m^{-1} K^{-1}, heat capacity (C) = 2.0 MJ m^{-3} K^{-1}; (2) green roof: a = 0.3, k = 1.1 W m^{-1} K^{-1}, C = 1.9 MJ m^{-3} K^{-1}.

RESULTS

Figure 2 shows the reductions in average T_2 (air temperature at 2 m above the surface) over the local-scale planning area (red areas in Figure 1) with different levels of green roof implementation. We focus on these areas because they are the urban cores with the highest population density within the city. Temperature reductions among studied regions are found to scale with green roof areas differently. In the first group of metropolitan areas, including

NYC, LA and Pittsburgh, the cooling benefit increases considerably with the area of green roofs. Upscaling the deployment of green roofs from the local scale to the regional scale, daytime mean T_2 reduction increases from 0.03 ºC to 0.21 ºC for NYC, from 0.03 ºC to 0.12 ºC for Pittsburgh, and from 0.05 ºC to 0.18 ºC for LA. In the second group of cities (Chicago, Miami, and Phoenix), however, temperature reductions over urban cores by green roofs are largely independent of the intervention scale. Daytime mean T_2 over Chicago center decreases by an additional 0.02 ºC after increasing green roof areas from 0.52 km^2 in the local plan to 679.19 km^2 in the regional plan. The scale dependence of nighttime cooling for individual metropolitan areas is consistent with the daytime trend.

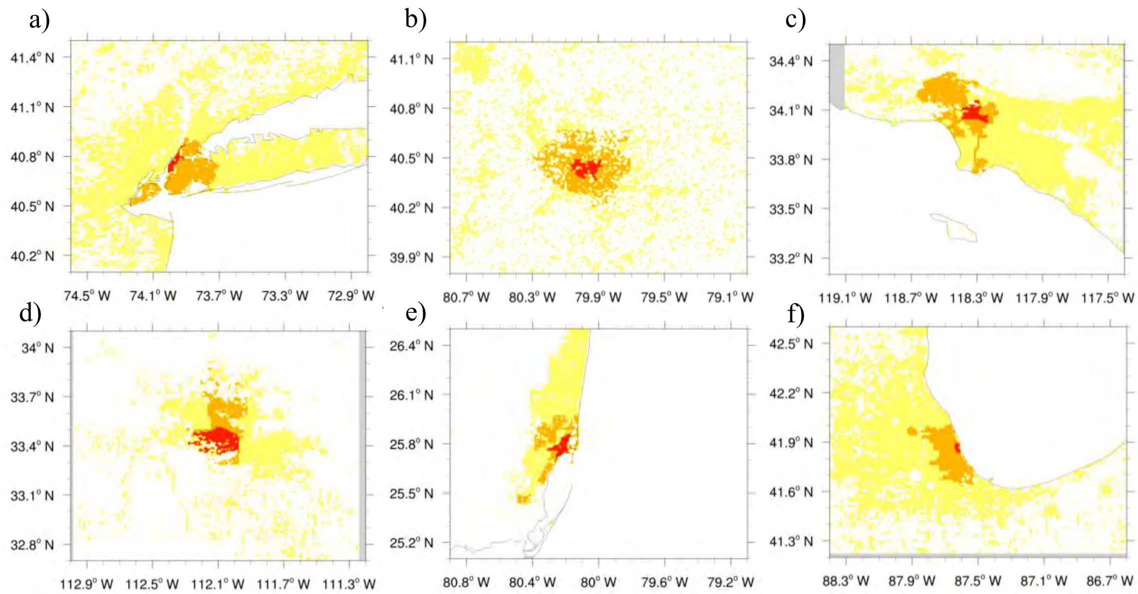

Figure 1. Spatial extent of green roofs at local (red), city (orange), and regional (yellow) scales. a) NYC, b) Pittsburgh, c) LA, d) Phoenix, e) Miami, f) Chicago.

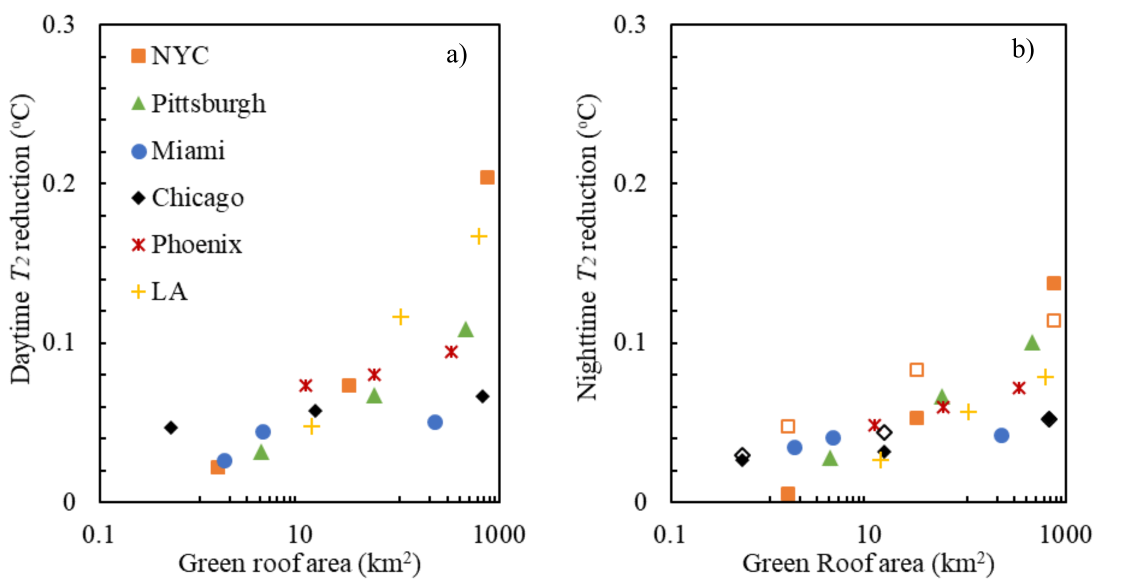

Figure 2. Scale dependence of simulated reductions in 2-m air temperature over the local planning areas by green roofs. a) daytime (0700-2000), b) nighttime (2100-0600).

Spatial distribution of the cooling by different green roof plans is plotted in Figure 3. Chicago and NYC are shown as examples to explain the dissimilar scale dependence between the two groups of cities. Greening 25% of Manhattan's rooftops leads to a negligible cooling over Manhattan and causes a small cooling downwind to the west and to the north of NYC. Adopting green roofs at the city scale creates surface cooling in upwind areas, consequently Manhattan is able to achieve a reduction of about 0.15 ^{o}C in T_2 at 1400 local time. And a uniform implementation of green roofs over the entire metropolitan area can reduce T_2 over Manhattan by about 0.36 ^{o}C at 1400 local time. Due to the existence of sea breeze, city and regional plans provide cooling benefits for Manhattan by greening its upwind areas. Similarly, strong scale dependences of the cooling benefit in LA and Pittsburgh are caused by implementing green roofs over buildings in upwind areas.

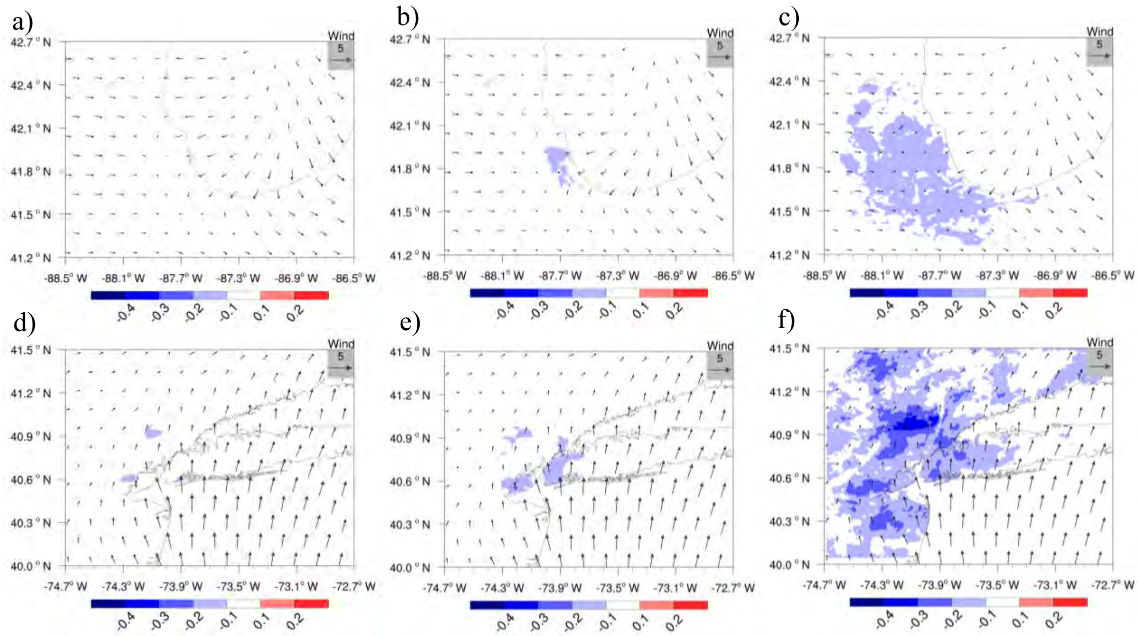

Figure 3. Simulated reductions in 2-m air temperature at 1400 local time with 10-m wind overlaid from deploying green roofs. a), b), c) local, city, and regional scales in Chicago; d), e), f) local, city, and regional scales in NYC.

The cooling effect of green roofs is more local and homogeneous in Chicago. At all levels, urban areas with green roofs are able to receive a noticeable temperature reduction. Nevertheless, a weak scale dependence is found because upscaling the mitigation plan for Chicago mainly involves altering downwind built areas. The comparison between results in Chicago and NYC demonstrates that both the geography of the metropolitan area and the climatic conditions play important roles in regulating the regional benefits of green roofs.

The scale dependence of cooling benefits in different metropolitan areas is very useful, but it is expected that larger green roof areas result in stronger temperature reductions. Cooling efficiency is a key factor if green roofs are to be implemented as a city-scale plan or regional policy. Here we estimated the cooling efficiency per unit area of green roofs at different scales in the studied metropolitan areas. The reductions of 2-m air temperature over the entire fine-resolution domain is considered to account for cooling benefits in downwind areas:

$$\mathrm{CE} = \int \frac{\sum_{x=1}^{N_x} \sum_{y=1}^{N_y} \Delta T_{x,y}\ (z)\ A_{grid}}{A_{int}} dz, \qquad (1)$$

where N_x and N_y are the number of grid cells in x and y directions, $\Delta T_{x,y}(z)$ is the temperature drop of each grid cell in the fine-resolution domain relative to the baseline without green roofs, A_{grid} and A_{int} denote the area of model grid and green roofs, respectively. In this study, we focused on a 1m thick slab centred at 2m and used T_2 to represent $\Delta T_{x,y}(z)$. Note that the integration over depth in equation 1 is necessary for obtaining a cooling efficiency over a physical volume. Figure 4 shows that cooling efficiency per unit area of green roofs decreases rapidly with the implementation scale. Different from the trend in Figure 2, geoclimate conditions are found to play a negligible role in determining the cooling efficiency over the fine-resolution domain. With an area of about 1.6 km^2 (e.g., local plans in NYC), daytime T_2 cooling efficiencies is about 30 ºC m. At the regional scale, the daytime and night maximum efficiencies of about 2.8 and 2.5 ºC m are found at NYC.

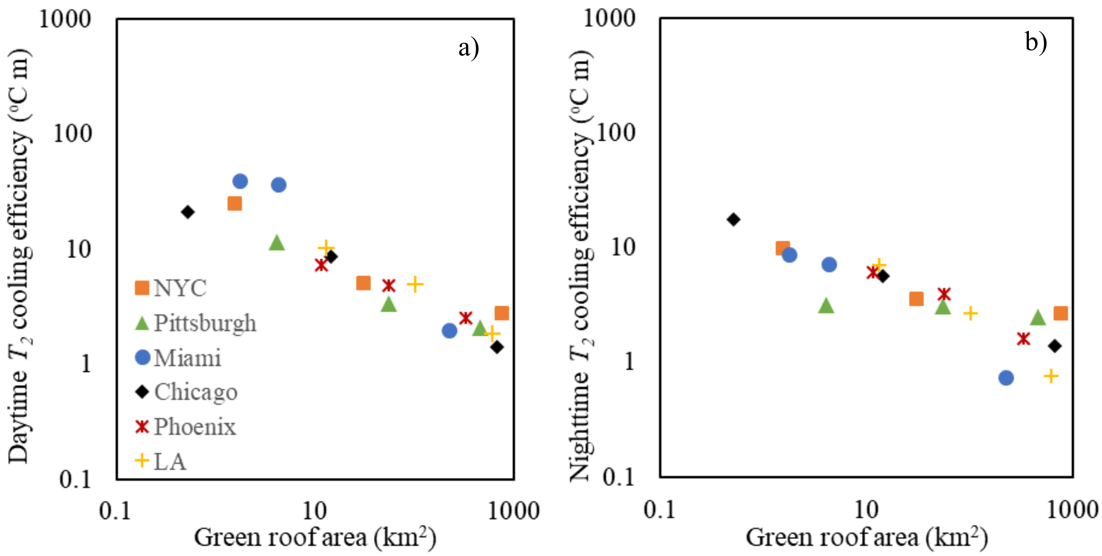

Figure 4. Scale dependence of the cooling efficiency of green roofs. a) daytime (0700-2000), b) nighttime (2100-0600).

DISCUSSIONS

Modelling results with a uniform 100% penetration intervention are at present the best available resource to guide green roof policy in context of long-term environmental adaptation. The 25% areal coverage used in this study is at the lower end of previous studies (Yang et al. 2015), but is still beyond the practical implementation potential in the foreseeable future. Using plausible scenarios based on cities' land use development map, this study provides new insight into effective green roof planning as mitigation strategies of heat island. We find that the scale dependence of T_2 reduction over urban cores is controlled by the geography of metropolitan area and its climatic conditions. To maximize the regional cooling benefits, deployment of green roofs should therefore focus on upwind areas. These upwind areas are critical to the thermal environment in the city during windy periods. Although wind direction varies continuously, planners should be able to identify the most probable wind directions. On the other hand, during periods of calm weather, the benefits of green roofs are more local.

CONCLUSIONS

This paper quantitatively examines and compares the scale dependence of cooling benefit and efficiency of green roofs for mitigating urban heat islands in six major U.S. metropolitan areas. Increasing the spatial extent of green roofs is usually treated as an effective way to mitigate heat islands. Our finding in this study, however, suggests that green roofs at city and regional scales may or may not provide significant additional benefits for urban cores. Green roofs have a direct impact on energy consumption of the building. Nevertheless, in terms of cooling the city, the effect is more indirect and cities should account for this scale dependence and for their unique geoclimatic setting.

ACKNOWLEDGEMENT

This work was supported by the US National Science Foundation under grant number ICER 1664091 and under the UWIN Sustainability Research Network Cooperative Agreement 1444758. The simulations were performed on the supercomputing clusters of the National Center for Atmospheric Research through project P36861020 and UPRI0007.

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