Radiative Shading Effects of Trees on the Built Environment in the Contiguous United States

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Introduction

Mounting empirical evidence shows that urban trees are effective in mitigating the thermal stress in the built environment, whereas large scale numerical simulations remain scarce.

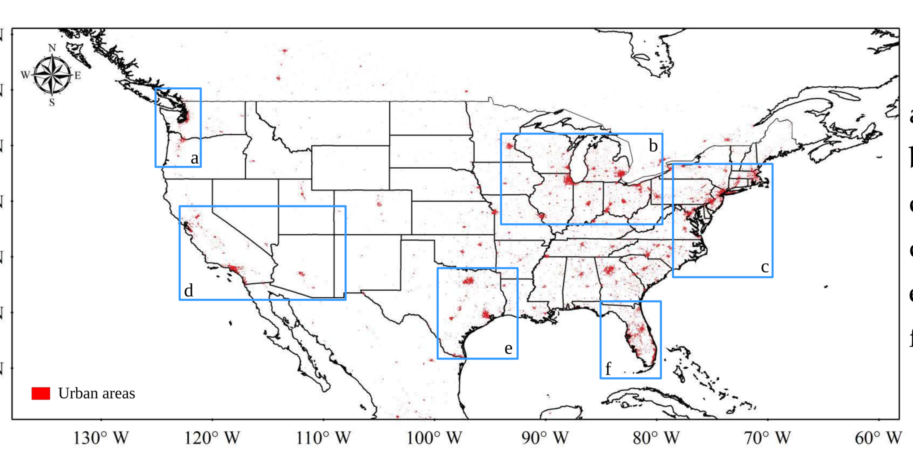
This study is exclusively focused on the effect of ***radiative shading***, as an important and stand-alone mechanism of urban trees in radiative cooling, pedestrian thermal comfort, and surface energy balance.

A **coupled Weather Research and Forecasting (WRF)–urban modeling system** was adopted in this study. Ensemble simulations were carried out over the contiguous United States.

Methodology

WRF-urban Modeling System

1. WRF version 3.6.1
2. Noah land-surface model (urban land-atmosphere interaction processes): 1-km modified IGBP MODIS 20-category vegetation (land-use) data
3. Meteorological input: daily FNL Operational Global Tropospheric Analysis data (2012-2014) [temporal resolution: 6 hours]
4. Urban surface: advanced single-layer urban canopy model (coupled shade trees)
5. Simulation period is 2012-2014, and the spatial resolution is 20 km



a. Cascadia
b. Great Lakes
c. Northeast
d. California-Arizona Sun Corridor (CA-AZ)
e. Texas Triangle
f. Florida

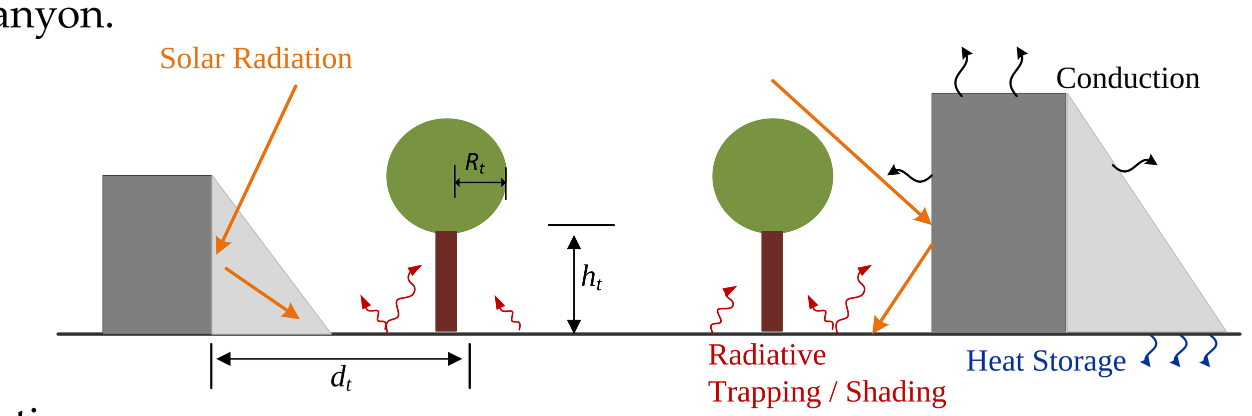
6. Ensemble simulations: six 1-year simulations [with 1-month spin-up] in total, 3 under the control scenario (without trees), 3 under the shaded scenario (with shade trees)

The impact of trees = mean (shaded cases – control cases)

Numerical Representation of Urban Shade Trees in WRF

Trees: interrupt the radiative rays transmitted between the canyon facets, and thus modify the view factors (VFs) between them.

Simulating VFs: stochastic ray-tracing method based on the Monte Carlo algorithm developed by Wang (2014) – to capture the radiative exchange processes inside the street canyon.



<u>Assumptions</u>:

(1) Two symmetric rows of trees with cylindrical crown size of radius
(2) The ray blocking effect of trunks is negligible
(3) All facets are Lambertain and gray
(4) Dimensions of tree and canyon – determined by literature and standards

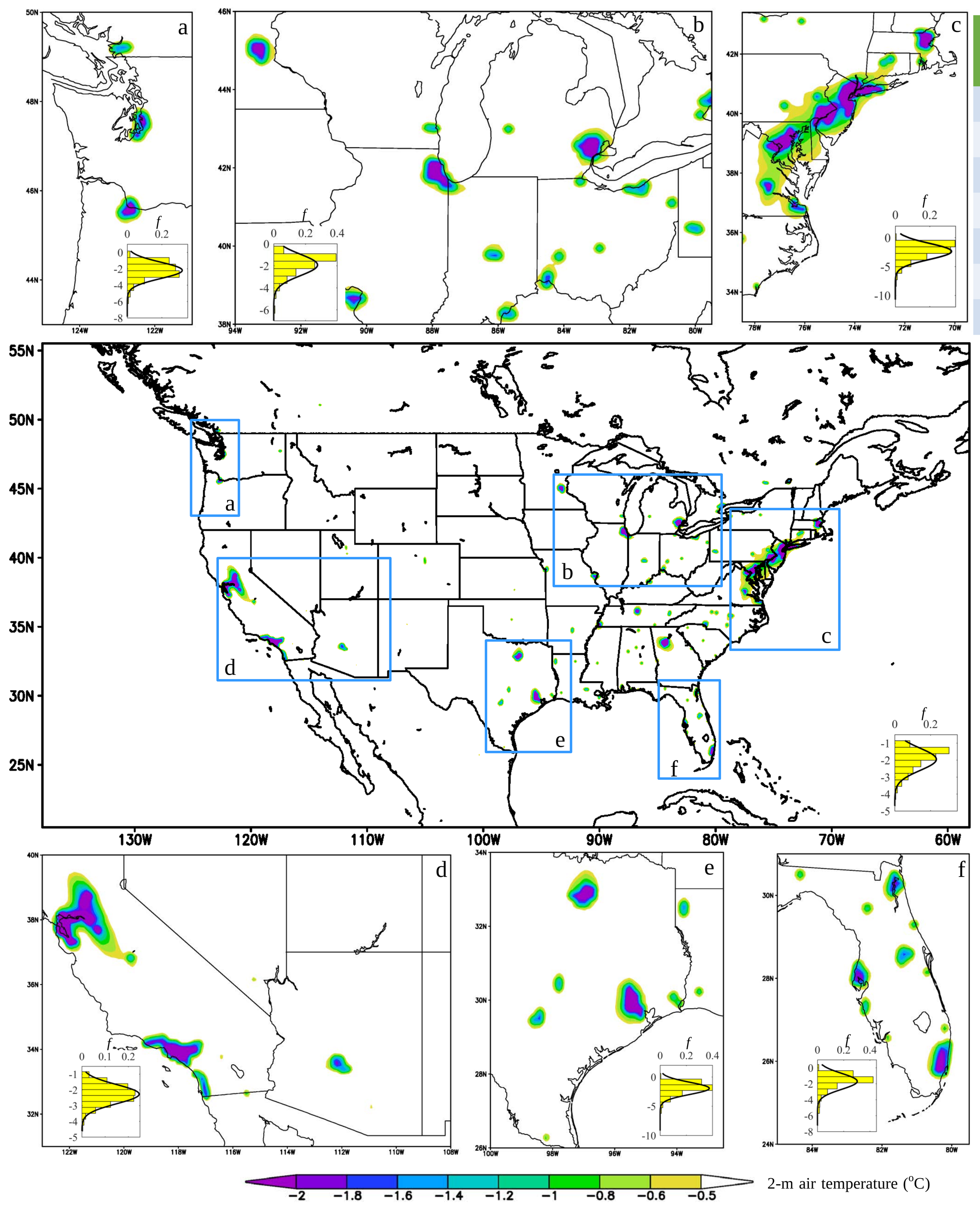
Model Validation

This model has been regionally validated against observed 2-m air temperature (T_2) and 2-m relative humidity (RH_2) from AZMET stations over Phoenix Metropolitan Area by Upreti et al. (2017).

Impacts on Urban Hydroclimate

Indicators: T_2 and RH_2

Daytime and nocturnal effects: results averaged at time instants around noon and midnight



Example: Annual mean daytime T_2

Region	Mean reduction	Daytime reduction	Nighttime reduction
CONUS	**3.06**	1.95	3.60
a	2.45	2.20	2.68
b	3.10	1.93	3.69
c	3.56	2.39	4.09
d	2.66	2.27	2.88
e	3.18	1.95	3.84
f	3.31	1.70	3.99

Primary mechanism: trees reduce the available energy impinged on canyon facets, modulating near-surface air temperature through sensible heat.

Daytime vs. nighttime: nighttime reduction of T_2 is slightly stronger due to the enhanced radiative cooling over the entire built environment. (see Upreti et al., 2017)

Spatial distribution: varied in different sub-regions due to different climatic and geographic conditions. (Other factors: clustered built environment, and atmospheric stability via heat transport)

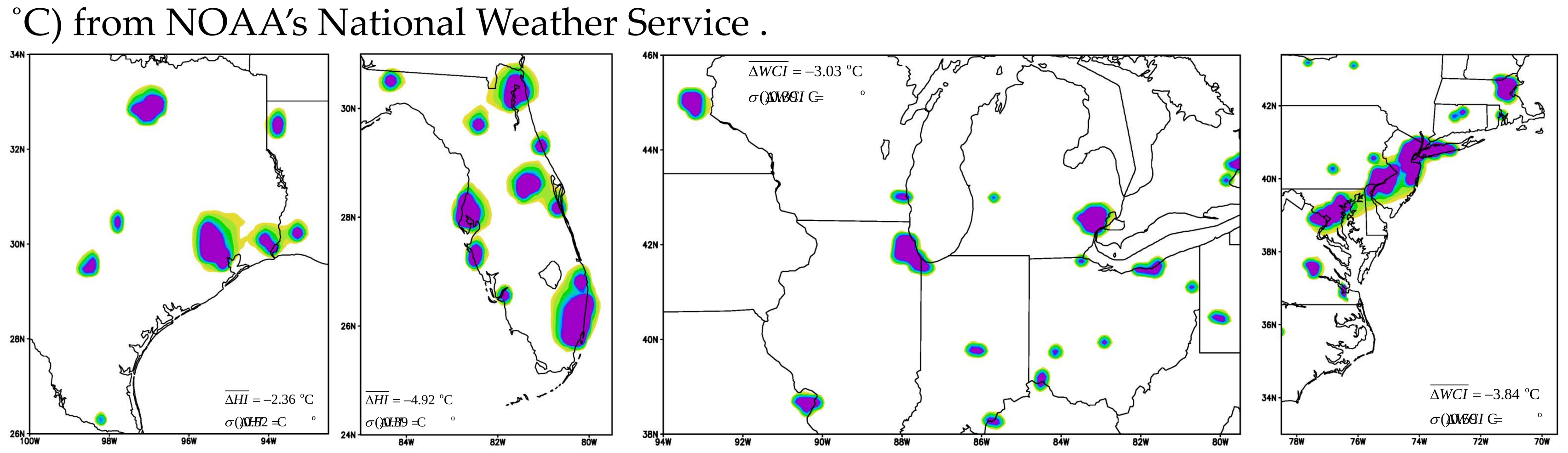
Seasonal variation: radiative cooling effect is stronger in winter that that in summer (available SW radiation)

Impact on RH_2:

1. Mean RH_2 increases by 13.62% with trees.
2. Temporal and spatial distributions are similar to those of T_2, as the increase in RH_2 is exclusively due to the decreased T_2.

Impacts on Outdoor Thermal Comfort

Indices: the heat index (HI) (when T2 > 26.7 ˚C) and wind chill index (WCI) (when T2 < 4.4 ˚C) from NOAA's National Weather Service .



Summer HI:

(1) Improvement of thermal comfort level in relatively humid regions is amplified by the higher humidity (FL), while the cooling effect of trees is impaired in relatively dry climatic zones (TX).

(2) The heat-related mortality in Texas Triangle and Florida during a severe heat wave is estimated to be at least reduced by ~16.3% with shade trees deployment (Anderson and Bell, 2011; Curriero et al., 2002).

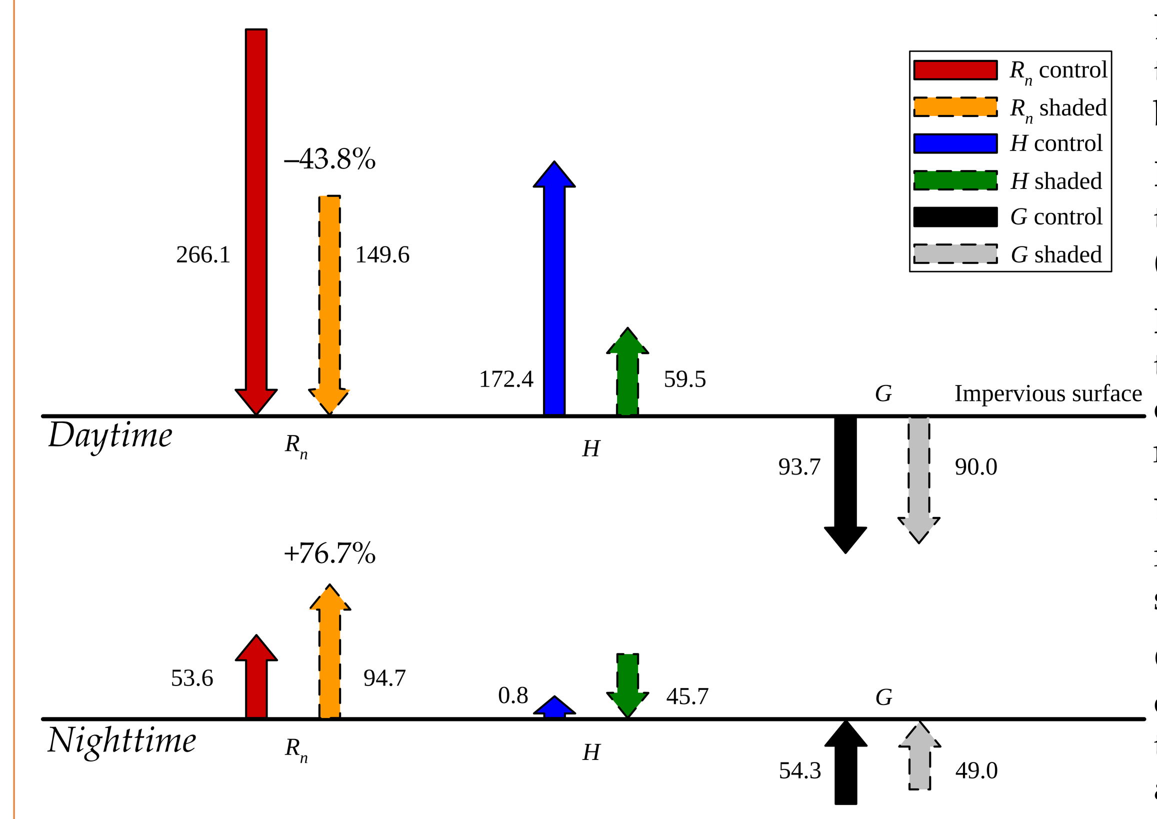
Winter WCI:

(1) We estimate the increases of mortality due to the reduced WCI in Northeast and Great Lakes to be ~24.0% and ~12.1%, respectively (Curriero et al., 2002).

(2) Planting too many shade trees is not recommended for cold regions like Northeast.

Impacts on Energy Balance of Impervious Surfaces

Surface energy balance equation: $R_n + \cancel{A_F} = \cancel{LE} + H + G$



Daytime net radiation: the interception of SW radiation by tree foliage

Nighttime net radiation: the enhanced radiative cooling (upward terrestrial radiation)

If normalized: the radiative cooling effect is comparatively stronger during nighttime

Upward sensible heat flux: reduces due to the cooler surface

Ground heat flux: comparatively intact due to that the thermal inertia of atmosphere is much less than that of engineering pavements

Implications to energy efficiency (cooling load in summer):

(1) Indoor cooling inside built structures has a strong correlation to the ambient temperature as well as the net radiation.

(2) The strong cooling potential of the outdoor environment by shading trees, together with the improved human thermal comfort, lead to prolonged period of outdoor activities and saving of cooling energy.

Conclusion and Perspective

- The new modeling framework was applied to simulate the impact of shade trees on all urban areas over CONUS.
- The reduction of ambient temperature by trees is more significant during nighttime than daytime, owing to the stronger relative radiative cooling. (implication to UHI)
- The two-fold impact of urban cooling by trees on both thermal comfort level and energy efficiency.
- Other biophysical functions of urban trees (ET, foliage variability, stomatal dynamics, root-soil interactions, etc.) are not included. (due to WRF platform limitation and the importance of singling out radiative cooling effect)
- We are developing an improved version to include more physical / biophysical processes.
- In the energy-water-climate repercussions, a portfolio of combined urban greening strategies instead of one particular form of mitigation method is needed.

Acknowledgement

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