Urban Climate Archipelagos: A New Framework for Urban Impacts on Climate

By Shepherd, et all , posted on November 29th, 2013 in Articles, Climate

J. Marshall Shepherd, T. Andersen, Chris Strother, A. Horst
University of Georgia, Athens, Georgia

L. Bounoua
NASA Goddard Space Flight Center, Greenbelt, Maryland

C. Mitra
Auburn University, Auburn Alabama

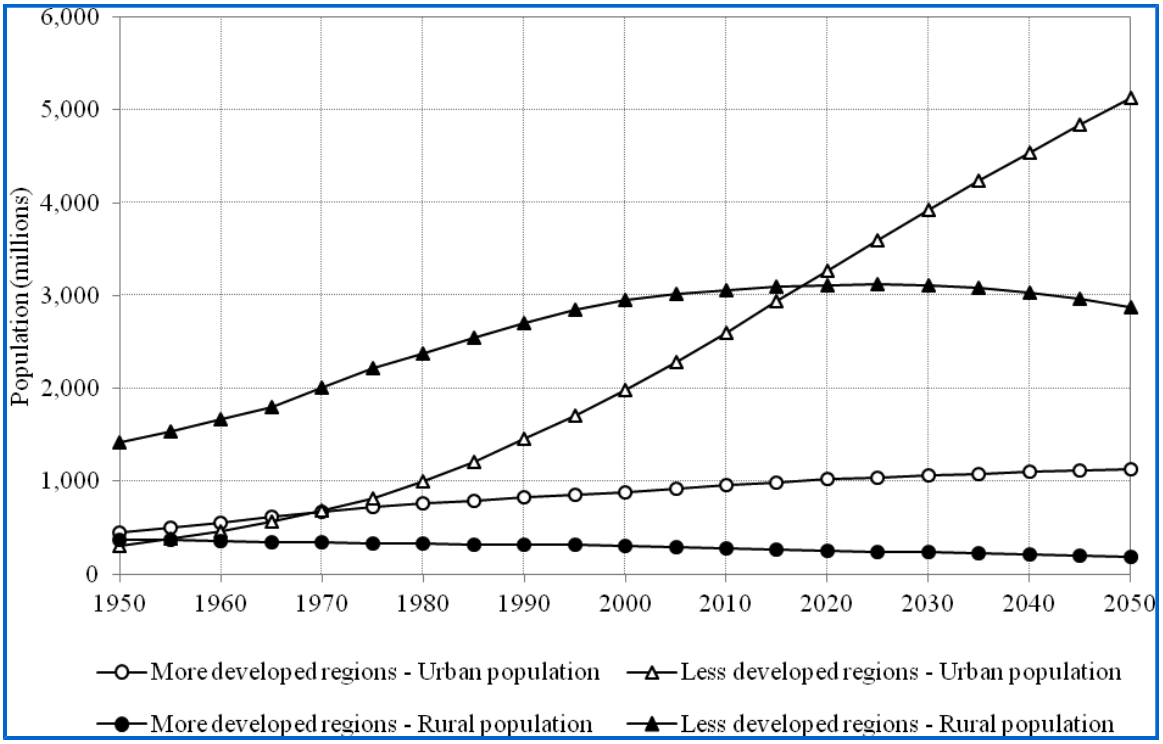

Figure 1 – Trends in urban and rural population growth. Source: UNPD 2012.

Introduction

Earth is increasingly an "urbanized" planet. The "World Population Clock" registered a Population of 7,175,309,538 at 8:30 pm (LST) on Oct. 6, 2013. Current and future trends suggest that this population will increasingly reside in cities. Currently, 52 percent of the world population is urban, which means we are a majority "urbanized" society. Figure 1 indicates this trend will continue, with particular growth in less developed regions.

In terms of ecological impacts, urbanization is one of the more significant and long-lasting forms of land transformation, and its extent of increase is at least proportional to population growth and economic development. Urbanization exerts environmental and climatic pressures on surrounding lands that are not fully understood. Viewed from the perspective of the amount of space it currently occupies, urbanization appears to be a minor form of land transformation. It is estimated that urbanization in the U.S. occupies about 3 percent of the land surface (Imhoff et al. 2004).

In terms of climate impacts, urbanization affects its environment through different physical mechanisms: 1) the reduction of the fraction of vegetation and the subsequent reduction in photosynthesis and plant's water transpiration and interception, 2) the alteration of water infiltration and surface runoff and their impacts on soil moisture and the water table, 3) the alteration of surface albedo and its effect on the surface energy partitioning, and 4) the modification of the surface roughness and its implication for the turbulent exchanges of water, energy, and momentum fluxes, all of which affect climate.

The urban heat island (UHI) is a fairly well-understood urban-climate interaction (Grimmond et al. 2010; Stone et al. 2010; Zhou and Shepherd 2010). Urban areas are known to create the so-called UHI effect. On the other hand, using satellite observations over 38 of the most populous cities in the continental U.S., Imhoff et al. (2010) have shown that on a yearly average, urban areas are substantially warmer than the non-urban fringe by 2.9 degrees Celsius (C), except for urban areas within arid climates which behave as an urban heat sink. They also show that the UHI amplitude is remarkably asymmetric with an average 4.3 degrees C in summer and only 1.3 degrees C in winter. Seto and Shepherd (2009), Mitra et al. (2011) and Shepherd (2013) described how the urban environment affects other major climate systems (e.g., the water cycle, biogeochemical cycles, and weather).

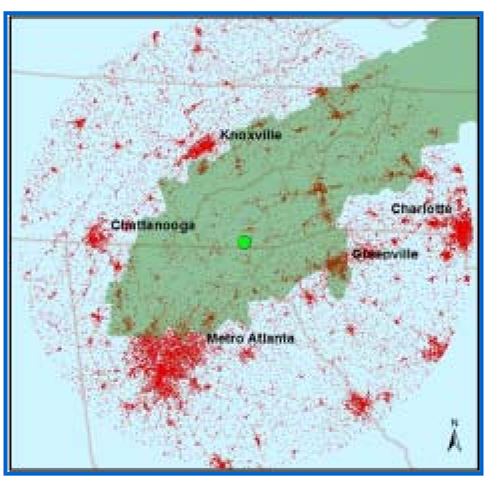

Figure 2 – "Ring of Asphalt" around the Southern Appalachia, circa 2006.

Red represents areas of urban impervious land cover as derived from the National Land Cover Dataset (NLCD). Image Credit: Generated by co-Author Strother using NLCD.

Motivation

Li and Bou-Zeid (2013) found, in a study of heat islands and heat waves, that the impact of cities is larger than the sum of its parts. Similarly, our recent work on urban rainfall effects in southern Appalachia and mid-Atlantic region have revealed a similar finding. For example, our work with the National Science Foundation-funded Coweeta Long Term Ecological Research (LTER) site has revealed an emerging "Ring of Asphalt" around the Southern Appalachians (Figure 2). Using the National Land Cover Database (NLCD), we found that this region has experienced a 15.5 percent increase in urban land cover from 1992-2006. Within this "ring," chains or systems of urban areas are apparent, particularly from Atlanta to Charlotte along the Interstate 85 corridor.

The primary objective of this paper is to introduce a new framework and terminology for thinking about and studying urbanization and its effects on the climate system. The secondary objective is to provide a set of "starter" research questions under the framework of "urban climate archipelagos" or UCAs. The literature is rich with papers on UHI or individual impacts of cities. However, the vantage point of space and with models, we can now see that "chains of cities" provide a different type and scale of forcing on the climate system.

What is an Urban Climate Archipelago (UCA)?

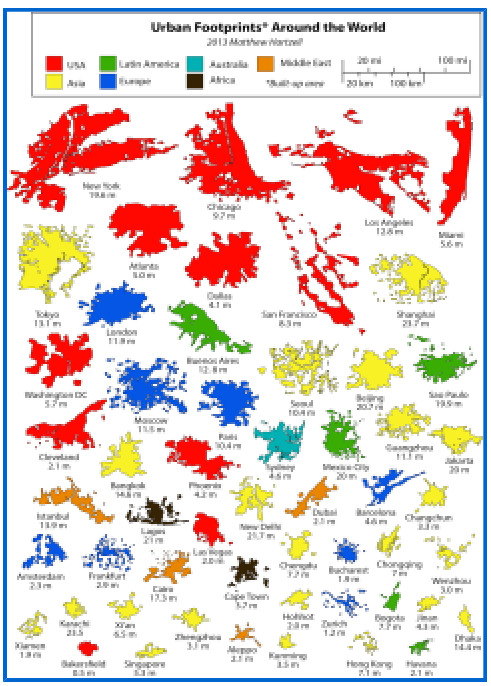

Figure 3 – Global urban footprints. Image Credit: Matt Harzell.

Clearly, urban land cover can act as a forcing function on the climate system. Most studies have focused on individual UHIs or their impacts on rainfall, health, and other indirect processes. Figure 3 is a compelling geographic representation of global urban footprints generated by Geographer Matt Harzell. Clearly, the shapes and sizes vary, but what happens when systems or chains of urban footprints begin to aggregate or align? Increasingly aggregated urban regions are becoming apparent on the landscape. The concept of aggregate urban landscapes is not new. French geographer Jean Guttman's book "Megalopolis" described the urbanized region from Boston to Washington, D.C. Derived from the Greeks, Megalopolis means "very large city." In contemporary times, the Oxford Dictionary of Geography describes a Megalopolis as "any many-centered, multi-city, urban area of more than 10 million inhabitants, generally dominated by low-density settlement and complex networks of economic specialization." According to the Indian Census, an "urban agglomeration" is a continuous urban spread constituting a town and its adjoining outgrowths or two or more physically contiguous towns together with or without outgrowths of such towns. A total of 160.7 million persons (or 42.6 percent of the urban population) live in Million Plus UAs/Cities, according to the Government of India.

Figure 4 is a satellite image from the Suomi NPP satellite of "Lights at Night" in the U.S. At many geographic locations, a "chain" of urban landscapes is apparent. Guttman's Megalopolis is also apparent. An archipelago is defined as "a chain of islands." It stands to reason that a chain or collection of urban areas would produce an aggregate impact on temperature, moisture, or precipitation. The overarching idea, which emerged from our contribution to a NASA-funded Interdisciplinary Science project on urban climate, is an extension of the concept of an "Urban Heat Island.

Figure 4 – Lights at night in the United States. Data is from the day/night band of the Visible Infrared Imager Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership (NPP) satellite. Image Credit: NASA.

Urban Climate Archipelagos (UCAs) are hypothesized to have a scale magnification effect on climate processes. A good analogy is the effect of one mountain on cloud-precipitation processes versus a chain or range of mountains, which extends the "scale of impact" on cloud or precipitation processes. Rosenzweig et al. (2005) mentioned UHI archipelagos in a discussion of heat islands in New Jersey. However, they were referring to individual "hot spots" within the overall heat island of a single metropolitan area, such as Philadelphia. Ohashi and Kida (2002) explored large cities in proximity to each other and how they worked to produce an atmospheric "chain" flow. They found that the urban-sea breeze circulation of a Japanese coastal city affects air pollution in a nearby inland city. In Figure

5, a cross section from weather model run depicts how the wind flow (represented by the arrows) interacts when two cities (Case 3) are present in the simulation.

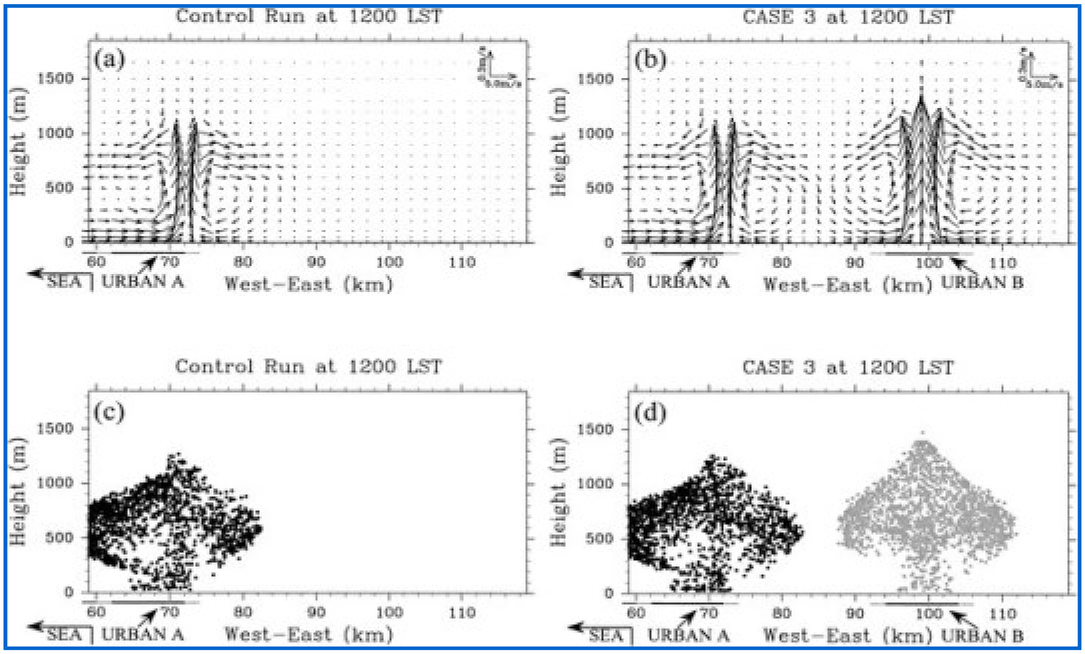

Figure 5 – Chain flow. Source: Ohashi and Kida, 2012, American Meteorological Society.

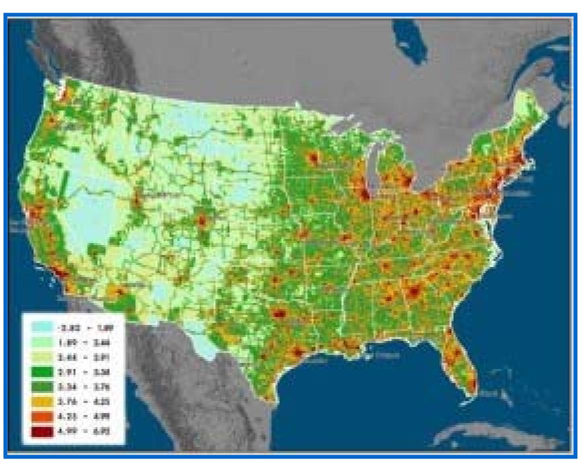

Figure 6 – U.S. carbon dioxide emissions in 2002 from various industrial, commercial, and residential sources for 2002. Units are

log base 10 of metric tonnes of carbon/gridcell/year. Image Credit: Vulcan Project, Purdue University.

Herein, we define Urban Climate Archipelagos (UCAs) as a chain of distinct urban entities with discernible aggregate impacts on at least one segment of the climate system. The idea builds upon the concepts of Megalopolis or "Urban Aggregations." However, it is distinctly unique because it incorporates a clear linkage to climate processes. The definition is more expansive than Rosenzweig et al. (2005)'s mention of archipelago, which focused on fractured elements within one larger UHI. While archipelagos have distinct independent members, UCAs are likely to have independent and synergistic affects on the climate. For this reason, we used the term "climate" rather than "heat" (i.e., UHA's).

UCA's are apparent in carbon dioxide assessments produced by the Vulcan Project. Figure 6 represents U.S. carbon emissions in 2002. Several UCAs are apparent and their combined contributions are likely not trivial. The implications of carbon emissions from UCAs affect carbon dome-health relationships, regional climate-emission action plans, and biogeochemical cycling.

We conducted a preliminary analysis of trends in temperature in the eastern U.S. (1951-2006) using the Nature Conservancy's Climate Wizard Tool. The data is from the gridded PRISM dataset. Figure 7 reveals UCA signatures in the temperature trends and growth of the UHI chain in the region of the 50-year period of time. Ongoing work by our group, led by NASA postdoctoral associate Dr. Theresa Anderson, explores whether the "Mid-Atlantic" UCA has an impact on cloud and precipitation processes. Preliminary results, using the Weather Research and Forecast (WRF) model, suggest the UCA from "Richmond to Philadelphia" can have an impact on convective precipitation systems. In Figure 8, the precipitation totals are clearly enhanced along the archipelago, particularly in the Washington, D.C., and Baltimore area. Li et al. (2013) have found similar results for the region. Shepherd (2013) provides an overview of the physical mechanisms related to this "urban rainfall effect," and it stands to reason that a "chain of urban land cover" would exert broader influence on the hydroclimate system.

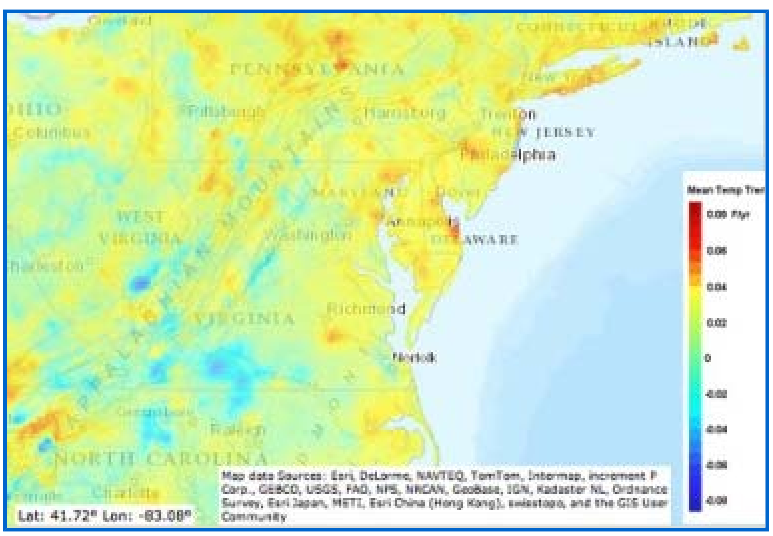

Figure 7 – Trends in temperature (1951-2006) for the eastern U.S. Units are degrees Fahrenheit/year. Image Credits: PRISM and Climate Wizard as generated by Author Shepherd.

UCA issues are apparent in rapidly urbanizing global nations as well. China and India, with their ever -growing urban populace, also are seeing an increase of these urban climate archipelagos. The India Census Report 2011 has noted an increase of urban agglomerations from 384 to 475 from 2001 to 2011. These numbers clearly highlight the need to access the climatic impacts of the UCAs on local, regional and global scale.

Future UCA Research Questions: A Starter List

The concept of Urban Climate Archipelagos is emerging and represents fertile ground for research going forward. In closing, we offer a set of potential scholarly research opportunities centered on the UCA concept:

- What are the spatio-temporal definitions of UCAs?
- Are there different classes or sub-divisions of UCAs?
- What is the global or regional distribution of UCAs and are there discernible space-time trends?
- What are the thermal impacts of UCAs on weather, climate, and related applications?
- Do UCAs increase the likelihood of an Urban Rainfall Effect reported by Shepherd et al (2010) and others?
- How are aspects of the biogeochemical cycle affected by UCAs?
- What is the UCA's scale of influence on the broader global climate system, and what are the implications for representing them in climate models?
- Are there "chain flows" or other interactions that emerge because of UCAs, and do they have implications for pollution, land surface hydrology, or weather processes?
- What are the policy and stakeholder implications of UCAs?
- What observational and modeling frameworks will be required to study UCAs?

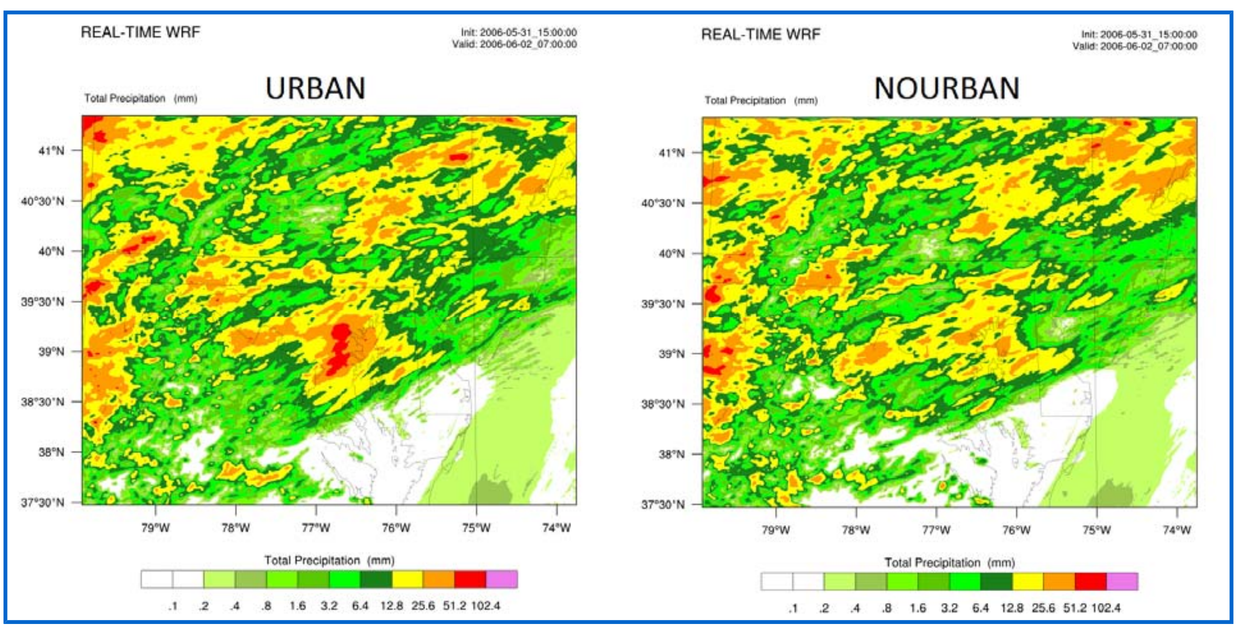

Figure 8 – Mesoscale model results illustrating how the convective precipitation field (in mm) varies with and without urban land cover in the WRF model simulation. Image Credit: Co-Author Andersen.

Acknowledgements: We would like to thank Dr. Thomas Mote for his insightful comments on the paper. We would also like to acknowledge support from the NASA IDS Program (NNX12AO24G), NASA Precipitation Measurements Mission Program (NNX10AH65G) and the NSF Coweeta LTER (DEB-0823293).

References

Gottmann, J. (1961) Megalopolis: The Urbanized Northeastern Seaboard of the United States. New York, The Twentieth Century Fund, 1961.

Grimmond, C., M. Roth, T. Oke, Y. Au, M. Best, R. Betts, G. Carmichael, H. Cleugh, W. Dabberdt, R. Emmanuel, E. Freitas, K. Fortuniak, S. Hanna, P. Klein, L. Kalkstein, C. Liu, A. Nickson, D. Pearlmutter, D. Sailor, and J. Voogt (2010) Climate and More Sustainable Cities: Climate Information for Improved Planning and Management of Cities (Producers/Capabilities Perspective), Procedia Environmental Sciences, Volume : Pages 247-274, ISSN 1878-0296, 10.1016/j.proenv.2010.09.016. (http://www.sciencedirect.com/science/article/pii/S1878029610000174)

Li, D., and E. Bou-Zeid (2013) Synergistic Interactions between Urban Heat Islands and Heat Waves: the Impact in Cities is Larger than the Sum of its Parts. J. of App. Meteor. and Clim. 52, 2051-2064

Li, Dan, E. Zeid, M. Baeck, S. Jessup, and J.Smith (2013) Modeling Land Surface Processes and Heavy Rainfall in Urban Environments: Sensitivity to Urban Surface Representations. J. Hydrometeor, 14, 1098–1118.

Mitra, C., J.M. Shepherd and T. Jordan (2011) On the relationship between the pre-monsoonal rainfall climatology and urban land cover dynamics in Kolkata city, India. International Journal of Climatology, DOI: 10.1002/joc.2366

Ohashi, Y, and Kida H (2002), Local Circulations Developed in the Vicinity of Both Coastal and Inland Urban Areas: A Numerical Study with a Mesoscale Atmospheric Model. J. Appl. Meteor., 41, 30–45.

Population Reference Bureau (2013) 2013 World Population Data Sheet. Population Reference Bureau. Washington, DC. http://www.prb.org/pdf13/2013-population-data-sheet_eng.pdf.

Rosenzweig, C., W.D. Solecki, L. Parshall, M. Chopping, G. Pope, and R. Goldberg (2005) Characterizing the urban heat island in current and future climates in New Jersey. Global Environ. Change B, 6, 51-62, doi:10.1016/j.hazards.2004.12.001.

Seto, K., and J.M., Shepherd (2009) Global urban land-use trends and climate impacts. Current Opinion in Environmental Sustainability, doi:10.1016/j.cosust.2009.07.012.

Shepherd, J.M., J. Stallins, M. Jin, and T. Mote (2010a) Urbanization: Impacts on clouds, precipitation, and lightning. Monograph on Urban Ecological Ecosystems. Eds. Jacqueline Peterson and Astrid Volder. American Society of Agronomy-Crop Science Society of America- Soil Science Society of America, 354 pp.

Shepherd, J.M. (2013) Impacts of Urbanization on Precipitation and Storms: Physical Insights and Vulnerabilities. Climate Vulnerability. Ed. Roger Pielke. Elsevier, 1570 pp.

Stone, B., J. Hess, and H. Frumkin (2010) Urban Form and Extreme Heat Events: Are Sprawling Cities more Vulnerable to Climate Change than Compact Cities?, Environmental Health Perspectives,118(10), 1425-1428.

United Nations Population Division (2012) World Urbanization Prospects: The 2011 Revision: Highlights. United Nations Department of Economic and Social Affairs: Population Division. New York. http://esa.UN.org/UNup/pdf/WUP2011_Highlights.pdf.

Zhou, Y., and J.M.Shepherd (2010) Atlanta's urban heat island under extreme heat conditions and potential mitigation strategies, Natural Hazards, vol. 52, no. 3, pp. 639–668.

Enter keywords to search articles

Visit our Facebook Page! Follow us on Twitter! Subscribe to our RSS feed!

Monthly Newsletter

Donate Today

More Pages

- About
- Themes
- Announcements
- Events
- Earth Observation
- Politics
- Resources
- Sustainability
- Technology
- Volunteer & Contribute
- Would You Believe?

Earthzine Friends

- Original Articles
- People
- Letters
- Reviews
- Education
- OpEd
- IEEE Policy on Nondiscrimination