Thermo-regulating Future City Envelopes with Multivalent Surfaces

Cities are urbanizing and modernizing at alarming rates as populations leave rural areas for new opportunities in urban centers. Today global urban populations have surpassed their rural counterparts and are expected to continue to collect the bulk of global populations. These future cities will become denser and hotter as natural self-regulating ecological systems are replaced with impervious surfaces.

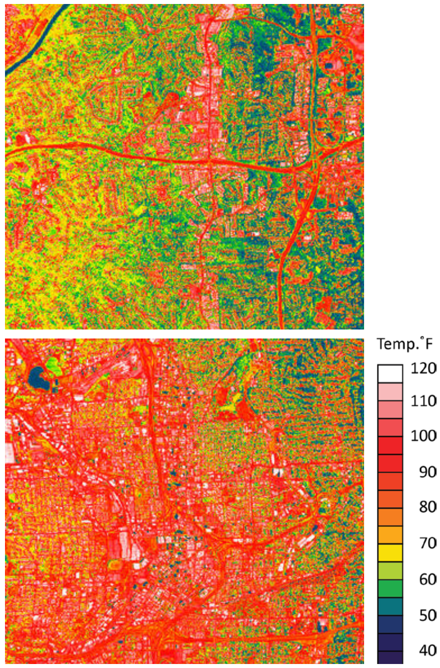
Anna Dyson
Rensselaer Polytechnic Institute

Jason Vollen
Rensselaer Polytechnic Institute

Kelly Winn
Rensselaer Polytechnic Institute

Modern cities with expanding urban populations quickly replace thermo-regulating vegetation with thermal mass. As a result, temperatures within the urban core can exceed surrounding temperatures by as much as 10°C in what was previously considered to be temperate climates[1]. Design for hyper-density means design for material density; hotter habitats require thermal sinking and the metabolism of solar energy that would normally be provided by flora. The majority of the urban growth is further projected to be in developing nations and will require low-maintenance durable envelope systems that mitigate variable solar resource in similar ways that used to be accomplished by natural systems as sustained ecologies.

By engaging principles from bioanalytics, energy flows through the building enclosure are harnessed to metabolize excess thermal and environmental loads. These 'energy exchange' envelope systems harnesses bioclimatic energy flows through diffuse surfaces and opaque wall systems in order to reach a more effective thermal balance. The building façade is thus tuned towards ever changing localized environmental conditions through the use of multi-scalar color, texture, and morphology extended and augmented with next-generation technologies as they become available for widespread introduction. Through this versatile manipulation of material systems the envelope can then become a source of reclaimed space in the expanse of future cities for the introduction of these emergent built ecologies. In this paper, the basic premise of pervious to non pervious surface comparison in relation to energy flows is explored through an initial rooftop simulation and extrapolated in discussion for potential system manifestations the problem is characterized and quantified relative to changing local climate context and design adaptability.

1


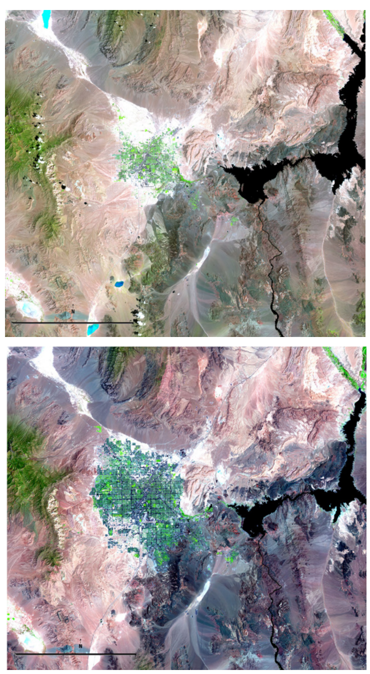
2


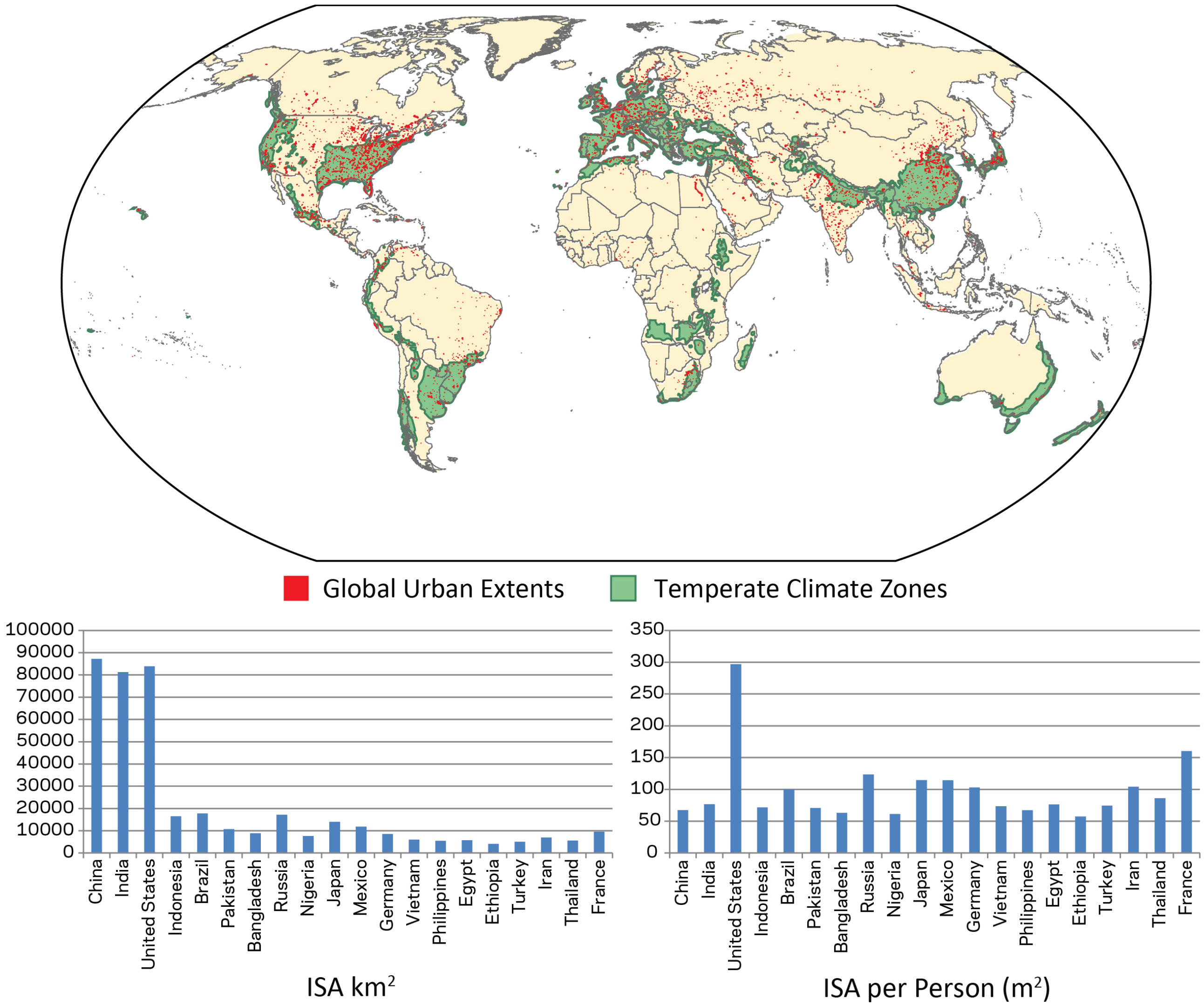
Figure 1: Thermal satellite imagery Atlanta, GA suburbs (top) and the city center (bottom), Credit: NASA/Goddard Space Flight Center Scientific Visualization Studio.

Figure 2: Satellite images of Las Vegas, NV from 1984 (top) and 2007 (bottom) showing development and resulting stress on water resources. Credit: US Geological Survey (USGS), NASA/Goddard Space Flight Center

INTRODUCTION: MATERIAL IMPACT ON MICROCLIMATE

While the concern of modern cities focuses on envelope transparency as the social interface between users and their greater social and environmental context, the challenge of material intensive future cities will rest in the execution of opaque envelope systems and activated surfaces that reintroduce thermo-regulative systems to an unyielding built environment. A new logic of receptive surfaces, intelligent articulation, and modified topology, while restoring as many of the functions of the original natural systems as possible, represents a new ecology reconnecting urban populations with the dynamic and fluid systems of the local environmental context. Urban and suburban developments often experience elevated temperatures when compared to natural landscapes in surrounding rural areas. Dramatic temperature differences of up to 22°F (12°C) can be observed during the night, especially in climates where a normally significant diurnal temperature swing and cooler nighttime temperatures should normally be expected[2]. Limited diurnal swings are especially problematic for bioclimatic architectural strategies; such as heat sink thermal storage, nighttime ventilation, and evaporative cooling, intended to temper conditioned spaces. The most notable and significant contribution to the urban heat island phenomena is the rapid replacement of vegetated surface area with the impervious materials of the construction industry. Artificial surfaces constructed from the impervious and heat-collecting materials that compose roads, sidewalks, and buildings, which described as impervious surface area (ISA), can be clearly seen in progressive USGS Landsat satellite photographs of rapidly growing urban centers. As a result, solar radiation is more readily converted to heat energy and absorbed by common dry construction materials, as opposed to vegetated surfaces, which convert solar radiation to chemical energy through photosynthesis, or moist surfaces which allow solar energy to transform into latent rather than sensible heat resulting in lower surface temperatures. (Fig. 1) The Urban heat island (UHI) effect due to the proliferation of impervious surfaces can lead to temperature differences on common roofing and pavement materials of up to 50 to 90°F (27 to 50°C) over air temperature[3]. As a result, an observable temperature increase in average daytime surface temperatures of up to 18 to 27°F (10 to 15°C) in developed urban areas that is stored as sensible heat and released at night reducing diurnal swing significantly[4].

The effect of urban heat island is most significant in heavily vegetated environments. A notable reversal of the process occurs in dry-arid climates and desert environments with cities such as Las Vegas NV and Phoenix AZ that significantly increase the amount of vegetated surface area and water features over the surrounding desert at the expense of stress on the water supply. In Fig. 2 the increasing urban sprawl and vegetated surfaces of Las Vegas and the resulting water stress and shrinkage on nearby Lake Meade on the Nevada-Arizona border can be clearly seen from satellite imaging. The future material composition of the built environment should take this important distinction into account. Though the simple return of vegetated surfaces and water features to urban environments can reduce surface temperatures and UHI by as much as 28°C on a hot day[7], in many climates green roof strategies proves unfeasible due to the added stress that would be placed on scarce water resources. As a result, the impact of UHI is relative to the natural vegetation of the surrounding environment and the



3

original climate type. Climate types that naturally contain significant vegetation (e.g., moist climates in the eastern US; Koppen Cfa, Dfa, etc.) can be significantly altered due to impervious urban surfaces to hotter subtropical or hot-arid climate types that do not normally exist naturally. These hotter cities not only lead to significantly altered thermal environments, but heat stress in plants and longer growing seasons;[8] as well as, animal species that are either acclimatized to the microclimate or invasive species common to hotter climates, such as insects and pests.[9] Local changes in climate should be of particular concern for heavily urbanized cities in comfortable temperate climates, which are susceptible to becoming hotter and more tropical. Fig. 3 shows how the overlap of urban extents and temperate climates in North America, Europe, and Asia pose a significant problem for local climate change due to urban development. This is a substantial problem for the United States in particular with significantly more impervious surface area (ISA) per person than other developed countries.

As populations in developing nations trend towards urbanization, the proliferation of impervious surfaces continues to grow. Cities are urbanizing and modernizing at alarming rates as populations leave rural areas for new

Figure 3: Overlapping temperate climatic regions with developing urban environments. (top) Credit: composite based on maps from NASA SEDAC 2012[5]. Impervious surface area total km2 in top twenty countries with highest overall ISA and ISA per person by m2 in top twenty countries with highest overall impervious surface area. (bottom) Credit: Based on data from Elvidge et.al. 2007[6].

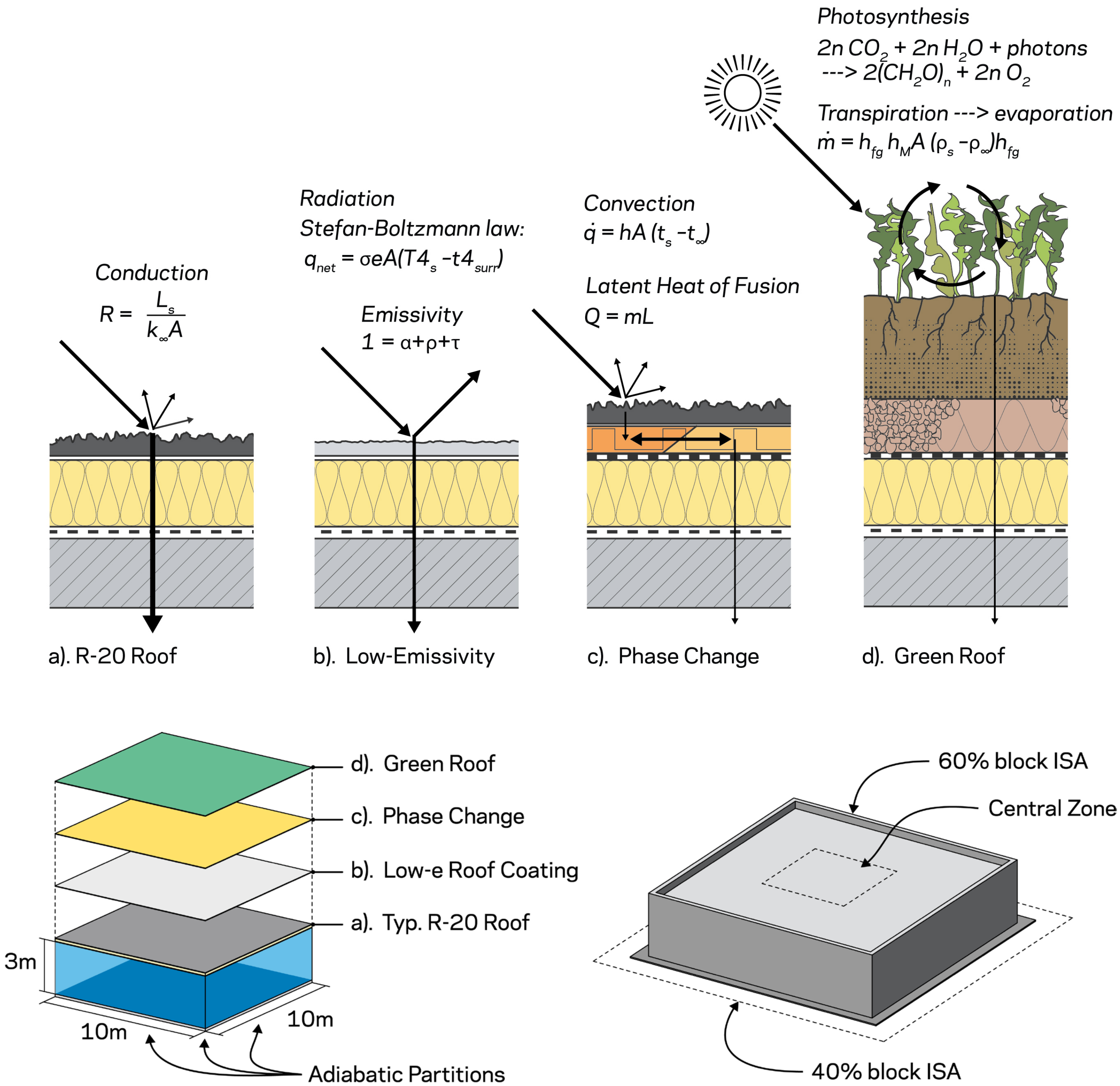
opportunities in urban centers. Global urban populations surpassed their rural populations by adding roughly 2.3 billion inhabitants between 1970-2011 and are expected to continue to collect the bulk of global populations as urban areas are expected to add another 2.6 billion people, while rural areas are expected to stop growing and begin to lose over 287 million as cities collect over 67% of the global population.[10] Cities will continue to trend denser and hotter as the sheer volume of impervious surfaces required to meet the needs of urban populations replaces the natural ecological systems that previously regulated the local climate. Design for hyper-density means design for material density; hotter habitats require thermal sinking and the metabolism of solar energy that would normally be provided by flora. Since the majority of the urban growth is projected to be in developing nations, future cities will require low-maintenance durable envelope systems that mitigate variable environmental loads as sustained ecologies to meet demand. At the same time, the material composition of the built environment can no longer simply consist of the mass reintroduction of vegetation to urban centers. As shown dramatically by Las Vegas, these materials systems must be designed to reduce water scarcity, and avoid off-loading solar energy to the environment to be trapped by greenhouse gasses. Instead, new building envelopes must metabolize collected solar energy for the use of building systems to meet energy demand. New material systems that respond to environmental resources in novel ways are needed to allow the normally impervious and unresponsive materials of the built environment to yield to climatic variability and potentially perform work for modern cities towards the alleviation of energy demand loads.

MATERIAL DEMAND OF MODERN CITIES

The ecological effect of discarding mass quantities of building debris is enormous, with 170 million tons of construction and deconstruction waste in the U.S. alone filling landfills.[11] Construction waste results in a tremendous waste of resources that do not return to the material cycle to feed the incredible material demand of urbanization. Similarly, there is a significant need for architectural systems that are designed for retrofit application. New construction requires new materials that must be harvested from the environment. 40% of all new raw materials go to the construction industry,[12] while only 20% of all construction and demolition debris are saved from the landfill to re-enter the material cycle through reuse or recycling.[13] As a result, materials that require high inputs of embodied energy for architectural membrane and structure construction are sent directly to the landfill. The availability of material resources is a significant factor to consider with respect to the speed in which the cities of the future are being built in developing countries. Thousands of square miles of natural landscape can be quickly developed and covered by the materials of the built environment in a matter of decades with the available land area of a city almost completely covered in paving and construction materials.

ENERGY MODELING: ROOF THERMAL TRANSFER

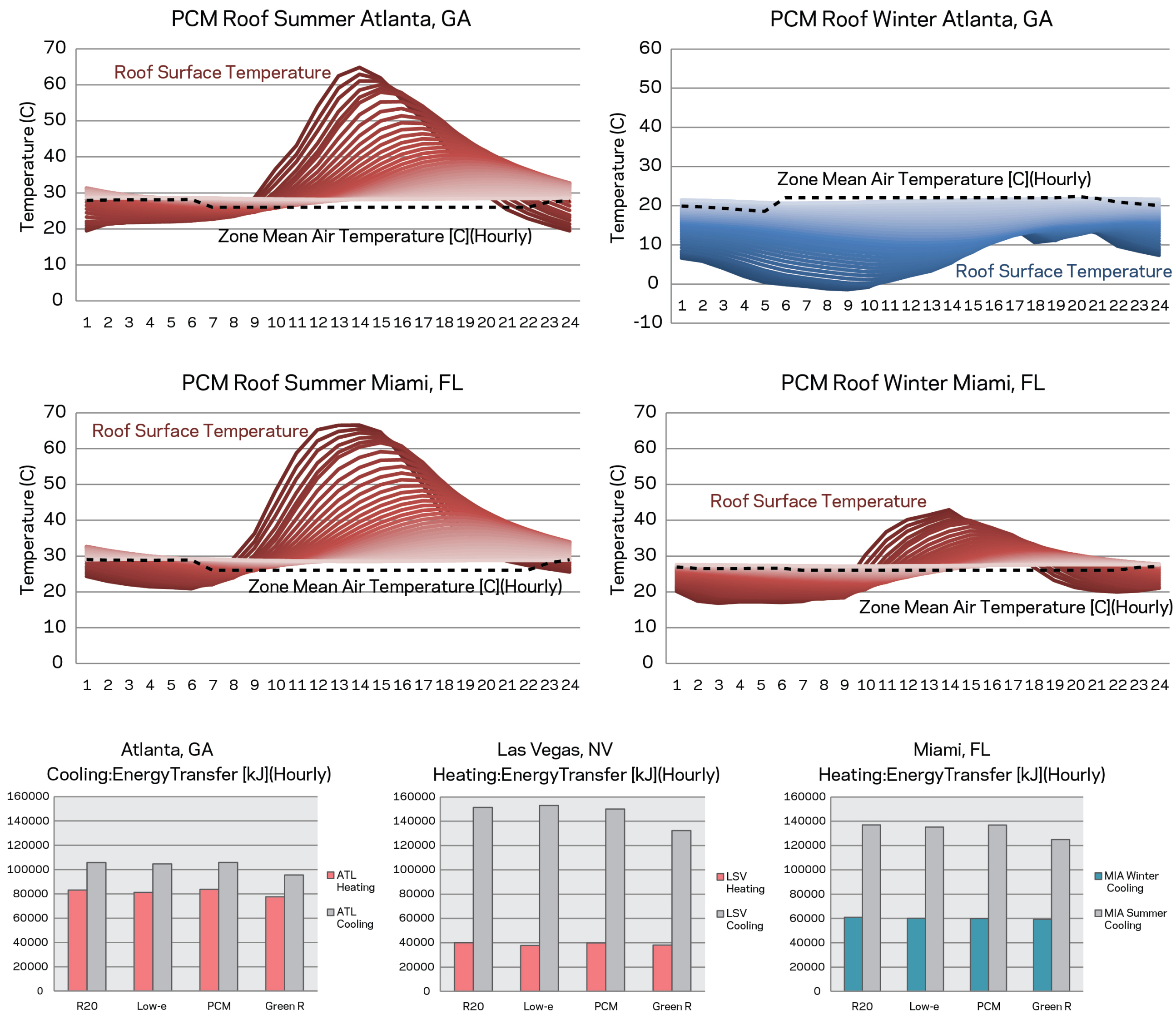
Fig.4 (bottom) shows the model setup developed for a Conduction Transfer Function (CTF) calculation using the EnergyPlus analysis tool. By comparing a range of common heat mitigation strategies, heat mitigation can be compared with strategies for metabolizing energy as opposed to strategies that



4

are devised to reflect energy. Due to thermal conditions caused by excessive UHI in urban centers, off-loading strategies that reflect unwanted energy back to the environment add to the negative effects of UHI. The cladding strategies selected are applied to a typical R-20 roof construction described by ASHRAE 90.1 2007 for Climates 2-8. Cladding types selected include: typical dark membrane roof, Low-e roof coating, a low melting temperature phase change material, and a green roof strategy. The strategy exploring the application of a phase change material was developed using a Conduction Finite Difference (CondFD) model with short calculation intervals in order to avoid the limitation of CTF for calculating materials with variable properties. The conduction zone model for the study was based on an isolated central zone of a generic office building type so that the roof could be studied directly while other zone surface could be modelled as simple adiabatic surfaces. Three cities were then selected in order to understand how the

Figure 4: Roof construction types by thermal strategy and governing expressions: a).R-20 Roof, b). Low-e Membrane, c).Phase Change, and d).Green Roof. (top) Thermal zone setup for EnergyPlus analysis (bottom left), and generic typical block with 10,000 sqft of ISA from roof surface area surrounded by sidewalk and pavement for green roof (bottom right).



5

Figure 5: Energy Plus CondFD simulation of roof construction with a phase change material in Atlanta and Miami (top), and Energy transfer totals for a typical summer and winter day for Atlanta, Las Vegas, and Miami. (bottom).

climatic conditions in urban centers, may start to shift as they become hotter environments. Three cities were selected to describe the trend towards hotter urban environments: Atlanta, GA as a warm-humid climate, Las Vegas as dry-arid climate, and Miami as tropical hot-humid climate.

As expected the low-e coating performed better than the generic membrane reflecting radiation in the summer and holding heat in the winter. The phase change strategy performed slightly ahead of the low-e coating under Las Vegas climate conditions due to the diurnal swing, but collected more heat under limited thermal swings. The phase change strategy was not as affective at limiting heat transfer though the roof construction as an exterior layer. The PCM was however, effective at delaying the impact of excessive heat gain 8-12hrs away from peak load times, suggesting that with secondary strategies, such as a heat transfer or thermoelectric system a phase change strategy could begin to utilize excess energy effectively. The green roof strategy performed effectively during cooling periods, yet limited heat from entering during heating periods. (Fig.4 top)

The nodal stepping through the PCM roof construction at the top of Fig.5 shows the diurnal swing and seasonal shift in Atlanta, GA for a typical summer and winter day and delayed propagation of heat through the roof section. Miami, FL shows how a more consistent heating condition begins to emerge in a more tropical hot-humid climate. The typical summer and winter performance for each typology is shown for the 3 cities. In some of the more extreme examples of ISA in large cities, such as Atlanta, 50-75% of an urban center can be taken up by ISA in an American city.[14] If we extrapolate that from the typical city block we describe in the study, these strategies have the potential to modify over 40% of the surface conditions in relation to the thermal environment with energy mitigation or transformation strategies for roof cover. If the difference between an untreated roof and a green roof can mean as much as 28°C reduction in temperature, material technologies that can similarly reduce surface and near surface temperatures could potentially cool heat island environments significantly, especially when considering other surfaces of the building, namely, the vertical facades which in dense urban areas constitute significantly more surface are and thus more potential to alter the local microclimate that the rooftop alone. Based on the conducted EnergyPlus analysis, a green roof system represents a savings of 49.3 kW in Las Vegas over a dark roof membrane, and 31 kW in Miami and 27 kW in Atlanta respectively for a typical city block with 10,000 sqft of impervious roof area. The low-e strategy performed roughly 10-15% as well as the green roof when compared in the more humid Atlanta and Miami conditions and failing to improve performance in Las Vegas. Conversely, the phase change roof construction performed roughly 7% as well as the green roof in Las Vegas cooling conditions and negligibly in Miami and Atlanta.

CONCLUSION

As a result of climate shift caused by prolific impervious surfaces and UHI, future subtropical cities will essentially override the normal heating and cooling of natural climate cycles replacing them with the problems of hotter and more extreme climate conditions where energy in the form of heat will continue to linger in and around urban centers. Atlanta for example, benefits from a seasonal shift to cooler weather, while the more tropical climate in Miami requires energy for cooling all year round. Without the seasonal and diurnal changes that are reduced by UHI and ISA of urban centers, heat mitigation strategies that are effective in temperate climates through cyclical thermal sinking and off-loading become impractical in subtropical conditions without cooling periods. It is necessary to start to begin stemming the adverse effects of continued development and the expansion of impervious surfaces, or the options for climatic design will become increasing limited in large urban centers. As it was shown through the EnergyPlus simulation, green roofs are an effective strategy for dealing with UHI and reducing surface temperatures. However, since these roofs have limitations due to resource availability and required maintenance, green roofs are often not a viable option in dry climates and more conventional building typologies. To address the excess of energy in urban centers new materials and building systems with the potential to transform and redistribute energy loads will be necessary reduce the impact of UHI and impervious surfaces.

REFERENCES

1. NASA/Goddard Space Flight Center Completed: 2005-05-16; Data Collected: 2001 http://svs.gsfc.nasa.gov/.
2. Oke, T.R. (1987) Boundary Layer Climates. New York, Routledge.
3. Berdahl P. and S. Bretz. (1997) Preliminary Survey of the Solar Reflectance of Cool Roofing Materials. Energy and Buildings 25:149-158.
4. Voogt, J.A. and T.R. Oke. (2003) Thermal Remote Sensing of Urban Areas. Remote Sensing of Environment. 86.
5. Center for International Earth Science Information Network(CIESIN)/Columbia University. (2012) "National Aggregates of Geospatial Data Collection: Population, Landscape, And Climate Estimates, Version 3 (PLACE III)." Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). http://sedac.ciesin.columbia.edu/
6. Christopher D. Elvidge et al. (2007) "Global Distribution and Density of Constructed Impervious Surfaces." Sensors, 7. www.mdpi.org/sensors
7. Department of Energy (2004) Federal Technology Alert: Green Roofs. DOE/EE-0298, Washington, D.C.
8. Zhang, X., M. A. Friedl, C. B. Schaaf, A. H. Strahler, and A. Schneider (2004), "The footprint of urban climates on vegetation phenology." Geophys. Res. Lett., 31, L12209, doi:10.1029/2004GL020137.
9. Meineke EK, Dunn RR, Sexton JO, Frank SD (2013) "Urban Warming Drives Insect Pest Abundance on Street Trees." PLoS ONE 8(3): e59687. doi:10.1371/journal.pone.0059687
10. United Nations, Department of Economic and Social Affairs, Population Division (2012). World Urbanization Prospects: The 2011 Revision. CD-ROM Edition – Data in digital form (POP/DB/WUP/Rev.2011) .
11. U.S. Environmental Protection Agency. (2008) "Lifecycle Construction Resource Guide." www.epa.gov/region4/p2
12. Lenssen and Roodman (1995). Worldwatch Paper 124: A Building Revolution: How Ecology and Health Concerns are Transforming Construction. Worldwatch Institute.
13. U.S. Environmental Protection Agency. (2009). "Estimating 2003 Building-Related Construction and Demolition Materials Amounts." http://www.epa.gov
14. Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., et al. (2001). Terrestrial Ecoregions of the World: A New Map of Life on Earth. BioScience, 51(11), 933–938.