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14. ABSTRACT
Maximum and minimum temperatures can be used to deepen our knowledge of the surface energy balance. Radiative and turbulent fluxes are the two major sources of energy fluxes at the Earth’s surface. Radiative fluxes are associated with downwelling short and longwave solar radiation and the subsequent emission of heat from the Earth’s surface at longwave frequencies. Turbulent flux is associated with the sensible (S) and latent (L) fluxes. Latent heat flux is associated with phase change of surface water (solid, liquid, and vapor) while sensible heat flux is driven by differences between skin and air temperatures.

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Report Title

Final Report: ARO Special Programs: Developing an Approach to Map Air Surface Maxima and Minima Temperatures by Exploring Surface Energy Balance

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Maximum and minimum temperatures can be used to deepen our knowledge of the surface energy balance. Radiative and turbulent fluxes are the two major sources of energy fluxes at the Earth's surface. Radiative fluxes are associated with downwelling short and longwave solar radiation and the subsequent emission of heat from the Earth's surface at longwave frequencies. Turbulent flux is associated with the sensible (S) and latent (L) fluxes. Latent heat flux is associated with phase change of surface water (solid, liquid, and vapor) while sensible heat flux is driven by differences between skin and air temperatures.
In this project, satellite-based observations such as land surface temperature (Ts) and classified land cover maps along with tower flux observations of urban and rural regions are utilized to characterize the surface energy balance components and to estimate the maximum and minimum temperatures. Available ground-based observations will be used to map air temperature using surface energy balance and spatio-regression models. Several components such as net radiation of shortwave and longwave along with air temperature, fluxes, and humidity are collected for different land cover types. The characteristics are more widely studied in rural regions with more natural background. However, a more comprehensive study in urban regions with impervious surfaces such as Asphalt, Concrete, and rooftops is needed to evaluate urban heat island and provide an accurate estimation of fine resolution air maximum and minimum temperatures.
This study is a short-term project to initiate efforts that can elevate our understating of surface energy balance using ground, satellite, and modeling information. New York City with its unique urban characteristics is chosen to collect the ground observations. Satellite information is utilized in the cities of New York and Baltimore. And finally an urban canopy model is used to characterize the surface energy balance components.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Norouzi, H, Vant-Hull, B, and Ramamurphy, P., CHARACTERIZING SURFACE ENERGY BUDGET COMPONENTS IN URBAN REGIONS USING COMBINATION OF FLUX TOWER OBSERVATIONS AND SATELLITE REMOTE SENSING MEASUREMENTS, American Geophysical Union (AGU) Fall Meeting, Will be presented in Dec. 2016.

Number of Presentations: 1.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Michael Sangobanwo	0.50	
FTE Equivalent:	**0.50**	
Total Number:	**1**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Brian Vant-Hull	0.30
Satya Prakash	0.35
FTE Equivalent:	**0.65**
Total Number:	**2**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Hamidreza Norouzi	0.10	
Prathap Ramamurphy	0.10	
FTE Equivalent:	**0.20**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Yoribaldi Olivo	0.50	Mechanical Engineering
FTE Equivalent:	**0.50**	
Total Number:	**1**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

The scientific report is provided through an attachment.

Technology Transfer

Table of Content

Developing an Approach to Map Air Surface Maxima and Minima Temperatures by Exploring Surface Energy Balance

Hamidreza Norouzi, New York City College of Technology
Brian Vant-Hull, The City College of New York
Prathap Ramamurthy, The City College of New York

Abstract

Maxima and minima temperatures can be used to deepen our knowledge of the surface energy balance. Radiative and turbulent fluxes are the two major sources of energy fluxes at the Earth's surface. Radiative fluxes are associated with downwelling short and longwave solar radiation and the subsequent emission of heat from the Earth's surface at longwave frequencies. Turbulent flux is associated with the sensible (S) and latent (L) fluxes. Latent heat flux is associated with phase change of surface water (solid, liquid, and vapor) while sensible heat flux is driven by differences between skin and air temperatures.

In this project, satellite-based observations such as land surface temperature (Ts) and classified land cover maps along with tower flux observations of urban and rural regions are utilized to characterize the surface energy balance components and to estimate the maxima and minima temperatures. Available ground-based observations will be used to map air temperature using surface energy balance and spatio-regression models. Several components such as net radiation of shortwave and longwave along with air temperature, fluxes, and humidity are collected for different land cover types. The characteristics are more widely studied in rural regions with more natural background. However, a more comprehensive study in urban regions with impervious surfaces such as Asphalt, Concrete, and rooftops is needed to evaluate urban heat island and provide an accurate estimation of fine resolution air maximum and minimum temperatures.

This study is a short-term project to initiate efforts that can elevate our understating of surface energy balance using ground, satellite, and modeling information. New York City with its unique urban characteristics is chosen to collect the ground observations. Satellite information is utilized in the cities of New York and Baltimore. And finally an urban canopy model is used to characterize the surface energy balance components.

Statement of Problem

As the solar energy is expended, some of it is stored in the ground, some returns to atmosphere by warming the air, and the remaining is used to evaporate surface water. Therefore, the surface energy balance equation can be written as:

$$(1-r)\,S\downarrow + L\downarrow = L\uparrow + H + \lambda E + G \qquad (1)$$

$(1-r)S\downarrow$ is the absorbed solar radiation, where $rS\downarrow$ is the incident radiation onto the surface and r is the albedo, defined as the fraction of $S\downarrow$ that is reflected by the surface. ($L\downarrow$) downward longwave radiation, ($L\uparrow$) emitted upward longwave radiation, (H) sensible heat, (λE) latent heat, and (G) the heat exchange by conduction. Expressed in a different manner, the net radiation absorbed by an object can be written as:

$$Rn = (1-r)\,S\downarrow + (L\downarrow - L\uparrow) = H + \lambda E + G \qquad (2)$$

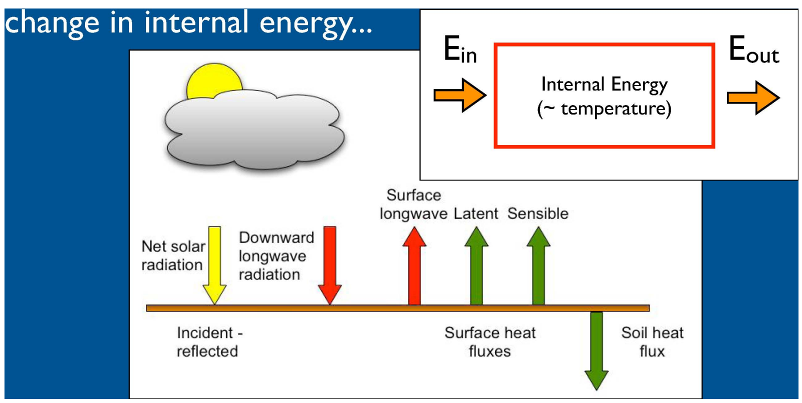

Figure 1: schematic energy fluxes components at the surface (From Hahmann, NCAR)

Surface condition in terms of material and its properties can affect any of the above factors, and a comprehensive spatial knowledge about these properties such as heat capacity and heat conductivity is required to understand the balance of energy at the surface level (Figure 1). Surface energy flux varies between day and night. Typically, during the day, surface energy balance is positive when net shortwave exceeds the net longwave loss. However, at nighttime there is no incoming solar shortwave, and this changes the sign of the remaining heat energy of the surface balance equation. The surface emits energy during daytime, while it needs more energy at night and causes to have downward latent and sensible heat flux from atmosphere to the surface. The difference between maxima and minima air temperature on a daily basis is an indicator of the response of the surface to the change in energy flux.

A recurring problem within climatology and meteorology is the optimization of interpolation techniques to generate maps of meteorological and climatic parameters using point measurements from climatic stations. Many military applications and installations are affected by temperature range from cold to hot weather. Accurate estimation of this parameter with a reasonable spatial scale will help making informed decision for military activities. Despite the large body of literature devoted to the production of environmental and climate layers, we still lack datasets at fine temporal and spatial resolution that will meet the need of many applications.

Experimental Setup:

The overall goal is to study the surface energy budget of individual urban materials (asphalt, concrete, black roofs and white roofs). To facilitate this process, we have begun to install a complete energy balance station over these distinct individual materials. The footprint of these stations will be restricted to the individual materials. The energy balance stations monitor the sensible and latent heat fluxes through eddy covariance method. These instruments correlate the fluctuate in the velocity field to the fluctuations in the temperature and humidity fields. To account for the incoming and outgoing radiation, a 4-component radiometer is used that can observe both incoming and outgoing longwave and shortwave radiation. Finally the storage term is estimated through the method of residuals. In addition to the primary components of the surface energy budget, the stations also monitor basic meteorological variables such as air temperature, relative humidity, barometric pressure and precipitation. These variables can be directly used to force urban land surface models. The flux instruments sample data at very high temporal resolution, around 20 Hz. The instruments are also operated continuously.

Two flux towers purchased from money leveraged from the Department of Defense (DoD), the Defense University Research Instrumentation Program (*DURIP*) grant and an internal funding through the City University of New York, the Graduate Research Technology Initiative (*GRTI*). They were installed to measure flux properties of test slabs of asphalt and concrete at Riverdale, the Bronx, NYC; a site more representative of most urban areas than Manhattan itself. Sensors were placed less than half a meter above the middle of each slab so that the measurements are less likely to incorporate fluxes from outside materials. This is a pilot study; the goal is to survey all surface types found in the city, including rooftops and parkland. Prediction of the fluxes from these surfaces can be used to model air temperature by linear combination of surface types and area fractions that influence surface parcels of air (Ramamurthy et al, 2015).

Following parameters/components of surface energy are acquired through field measurements:

Turbulent Fluxes: Fluxes by the surface are sensible heat and latent heat (ET). These parameters are estimated using LI-COR 7500A and LEEF Flux System.

Net Radiation: at each site net radiation is measured using LI-COR 7900-101.

Ground heat flux: the ground heat flux is monitored continuously using LI-COR 8100 and LI-COR 7900-101 through measurement of soil temperature. Moreover, soil temperature sensors at three different depths will allow us to understand the heat conduction at the locations that soil is permeable and is not paved surface.

Eddy Covariance: in large-scale analysis, in order to understand how the energy is exchanged between the surface and atmosphere, other than a vertical dimension a horizontal dimension is also added to the equation.

A sample of these flux measurements appears in Figure 3, showing hourly averages of sensible and latent heat vertical fluxes compared to air temperature over asphalt. For clarity the more directly measured radiative fluxes and other weather variables have been omitted. The causal relationship between sensible flux and changes in air temperature are evident for all days except June 9, which may have been cooled by regional flow off the ocean. The connection between dewpoint/humidity (not shown) and latent heat flux is less evident in the data, likely because these surfaces are not strong moisture sources.

Modeled fluxes of urban landscapes based on this campaign of measurements when combined with regional forecasts should provide a more accurate prediction of surface air temperature and humidity than regional forecasts alone.

Figure 2: Flux towers installed at Manhattan College. Left: Asphalt. Right: Concrete.

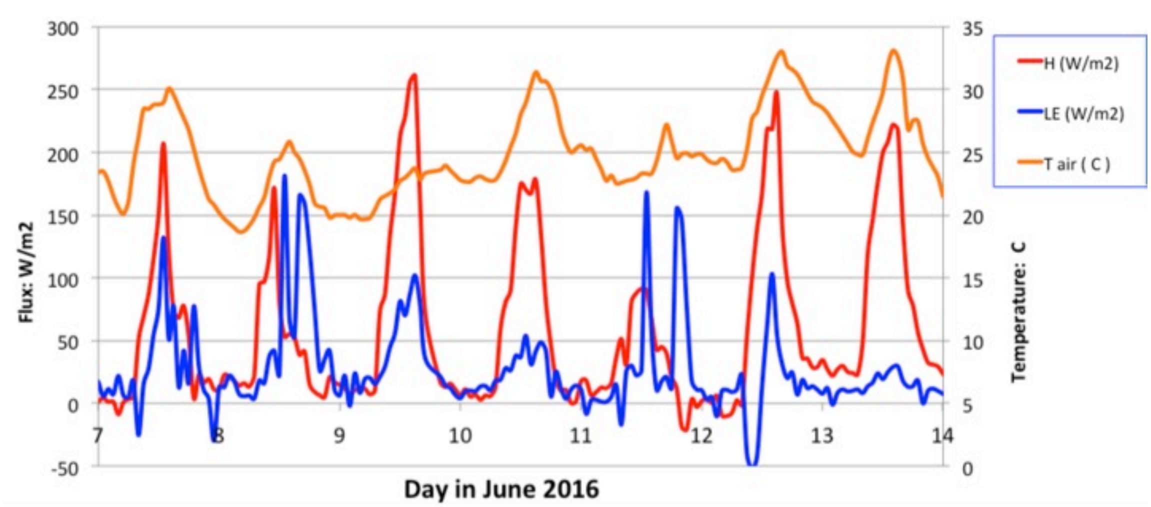

Figure 3: vertical fluxes of sensible and latent heat for the week of June 7-14, 2016.

Urban Canopy Model:

For further investigations we use a single layer urban canyon model (SLUCM). This SLUCM are thoroughly calibrated by the observations and the anthropogenic heat. The above concerns can be overcome by coupling the observations to an urban canopy model, commonly termed as UCM. The UCM is a single column urban land surface scheme that is gaining wide acceptance in the urban climate community. UCMs represent the urban area as an infinite rectangular cavity bordered by two buildings (usually of equal height in the single layer representation; an infinite regular array of cubes can also be represented with minor modifications to the model). UCMs have the ability to distinguish various urban facets like rooftops, roads and walls. The urban facets can be modeled with distinct physical and thermal properties. And through adoption of more realistic representations for thermal-hydrological processes, including in-canyon vegetated soils and water storage capacity for impervious materials, the energy and mass exchanges of these various facets with the atmosphere can be independently determined.

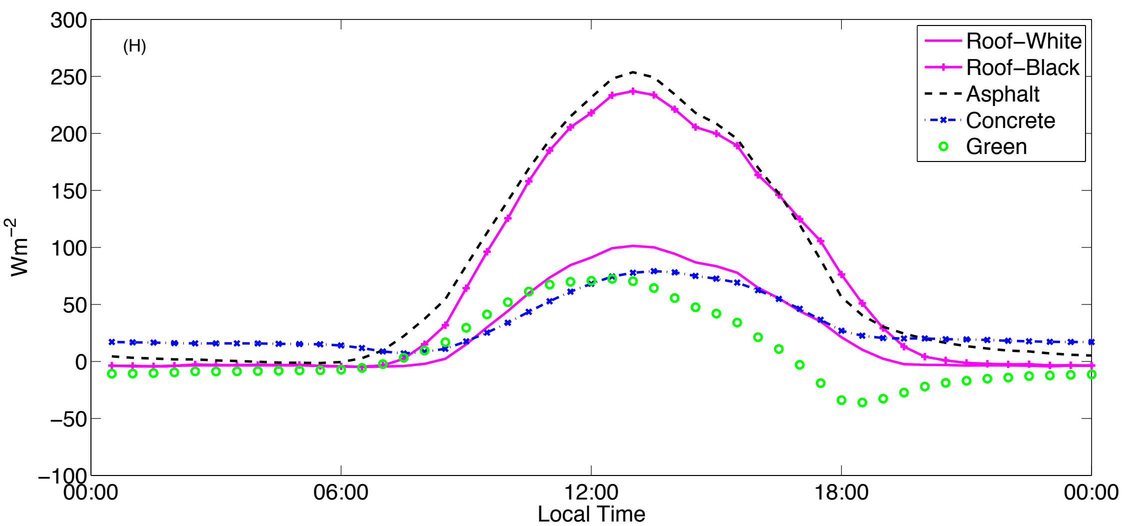

Figure 4: Modeled sensible heat flux from different surfaces. The UCM was used to produce this plot.

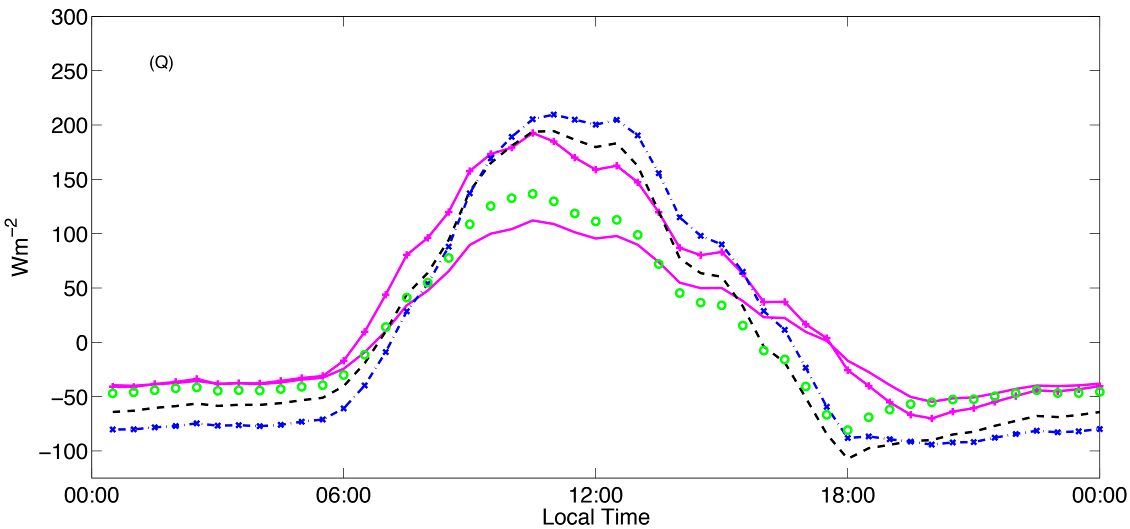

Figure 5: Modeled storage heat flux from different urban surfaces.

Mapping Air Temperature:

Previous attempts to map air temperature in urban settings have been underway at the City University of New York since 2012. Field campaigns using mobile instrumentation mapped the air temperatures along the shady sides of streets over 8 fixed routes. A total of 19 separate afternoons were averaged to produce the "summer afternoon climatology" shown on the left of Figure 1, where the units are in standard deviations from the average. The procedures and data produced are described in Vant-Hull et al (2014) and are also described in the project website

http://glasslab.engr.ccny.cuny.edu/u/brianvh/UHI/.

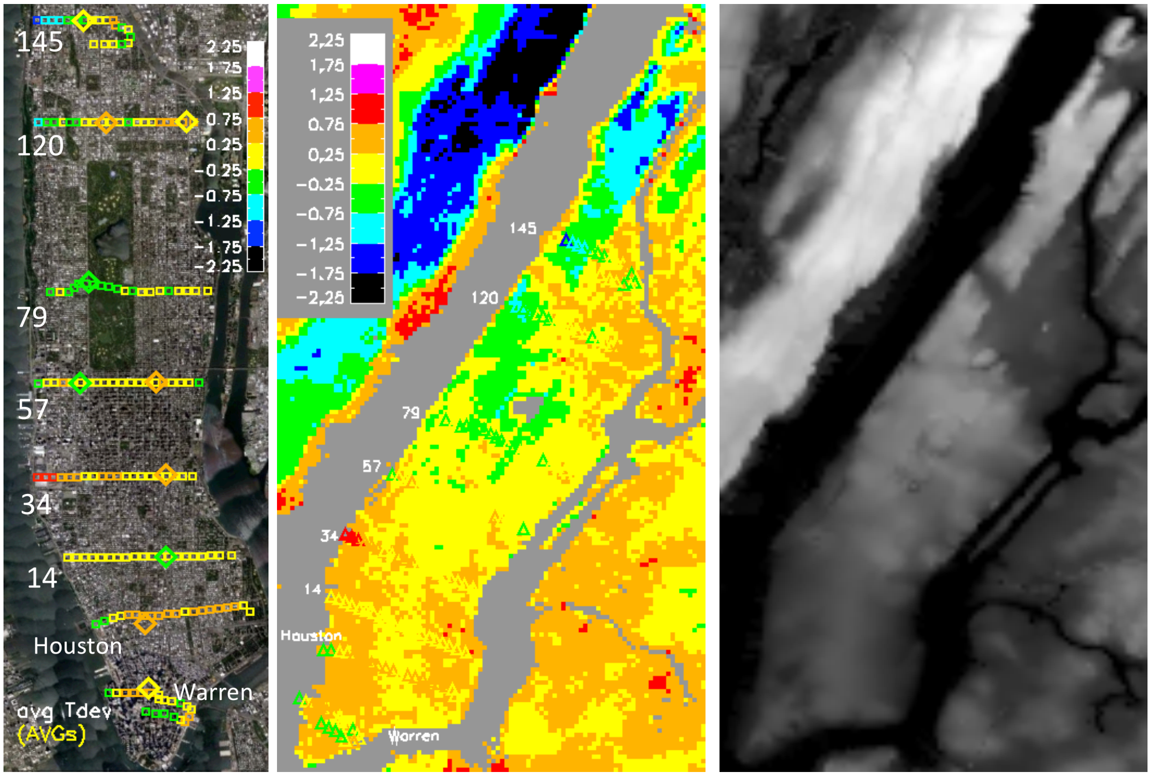

Figure 6: Air temperature field campaigns and statistical modeling based on it. Left: averaged observations. Middle: statistical model regressing temperature against surface features. Right: elevation map for comparison.

This temperature anomaly map was regressed against surface characteristics of vegetation density, elevation, water fraction, building geometry and albedo. The middle of Figure 6 shows a map produced by applying this regression to surface features (Vant-Hull et al 2015 and website). The left side shows a comparison to elevation, which was found to be the dominant factor, most probably due to wind exposure (Vant-Hull et al, 2016). The observations are superimposed as triangles on the map; a good match is indicated by triangles that fade into the background, which tends to occur in the more complex terrain of northern Manhattan. The correlation between observations and prediction is 0.66. There are several reasons for this imperfect match (Vant-Hull et al 2016). The first is an incomplete climatology so that temporal variations due to weather and turbulence are not averaged to zero. Perhaps more important is the incomplete physical description afforded by our set of predictors: material type and thickness was not accounted for, so that thermal transport and storage are not captured. If all physical variables are included in the calculations, it may be possible to move from a climatological approach to a more weather predictive approach.

Additionally, LandSat Visible images can be classified to major land cover types. Once the characteristics of each land cover type in energy balance is recognized using satellite and ground observations, the air temperature and can be mapped with a fine resolution classified images. Below you can see a LandSat image (Figure 7) that was classified to water, concrete, roads, and rooftops using a supervised classification technique. This is an ongoing study to map the air temperature.

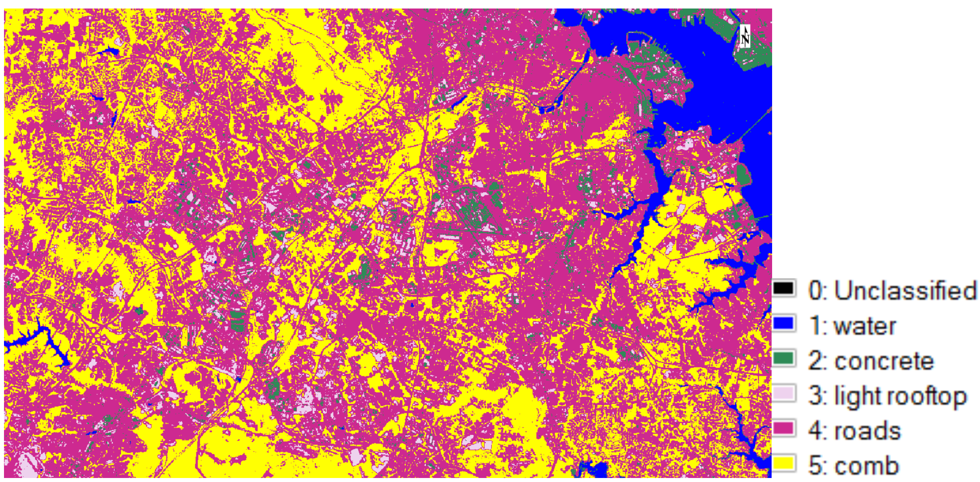

Figure 7: Classified LandSat image (August 2015) to major Land-cover types over Baltimore, MD.

The Relationship between Observed $LSAT_{5cm}$ and LST from MODIS Terra and Aqua

The other major component of this project was to provide a model that can estimate air temperature maxima and minima using satellite observed skin temperatures. The model is a spatio-temporal method that complements the ground observations study, satellite remote sensing and urban canopy modeling. A statistical model from the previous day to accurately estimate spatial daily minimum Land Surface Air Temperature at 5cm ($LSAT_{5cm}$) was developed using station data. Land Surface Temperature (LST) data were obtained using the Moderate Resolution Imaging Spectroradiometer onboard Aqua and Terra satellites MODIS at daytime and nighttime periods with normalized difference vegetation index (NDVI) data. These data along with geometric temperature and elevation information were used in a stepwise linear model to estimate minimum LSAT5cm during 2003-2011. Results revealed that utilization of MODIS Aqua nighttime data of previous day provides the most applicable and accurate model. According to validation result, the accuracy of the obtained model was acceptable during 2012 (RMSD= 3.07°C, R^2_{adj}=87%). The model underestimated (overestimated) high (low) minimum LSAT5cm. The accuracy of estimation in the wintertime was found to be lower than the other seasons (RMSD=3.55°C) and in summer and winter the error were larger than in the remaining seasons. The results of this study will be summarized in a journal publication.

As an example, the scatter plot of estimated and measured $LSAT_{5cm}$ based on Aqua nighttime LST of the previous day is shown in the Figure 8.

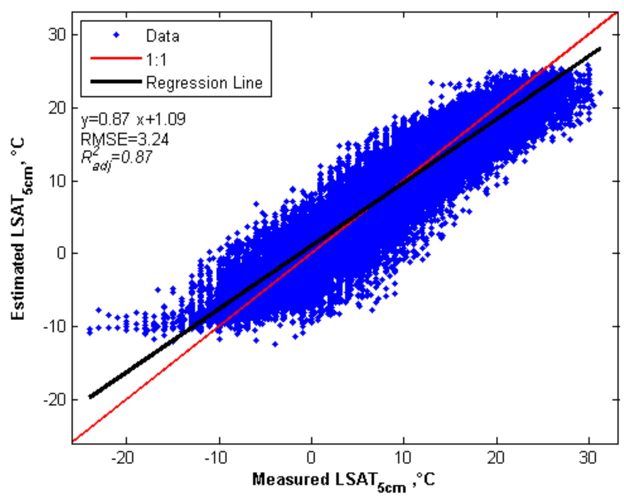

Figure: 8 Comparison of measured minimum $LSAT_{5cm}$ and its estimated values based on linear regression model for Aqua LST nighttime , NDVI data of the previous day, T_{geom} and Elevation during the years 2003-2011 .

In order to validate the model, data of measured minimum LSAT5cm during 2012 were used. MODIS Aqua nighttime LST of the previous day, NDVI, T_{geom} and Elevation of each station during the year 2012 were used and LSAT5cm computed using the model was evaluated (Figure 9). Calculated LSAT5cm by the model then compared with measured one at the stations. Despite the existence of large differences of elevation in the area (3924 to 110 masl), the values of RMSD= 3.07°C and R^2_{adj}=87% between measured and predicted minimum $LSAT_{5cm}$ showed acceptable results, but the model underestimates (overestimates) high (low) values of minimum $LSAT_{5cm}$.

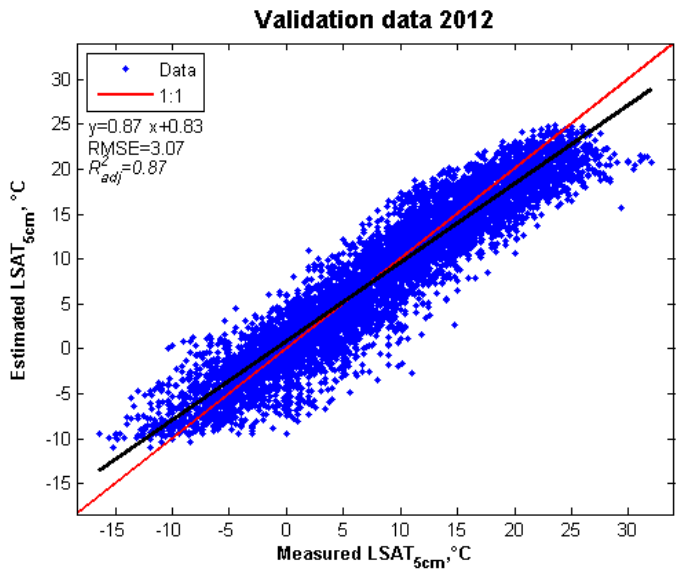

Figure 9: Comparison of measured minimum Land Surface Air Temperature (LSAT5cm) and its estimated values based on linear regression model for Aqua LST nighttime data of the previous day, T_{geom}, Elevation, and NDVI for validation of proposed model during 2012.

The seasonal evaluation of the model during 2012 (Figure 10) shows that the accuracy of estimations in winter and summer (RMSD=3.55°C and 3.14°C, respectively) were lower than spring and fall and also the spread of data for summer (R^2_{adj} =62%) and winter (R^2_{adj} =56%) were more than for spring and fall.

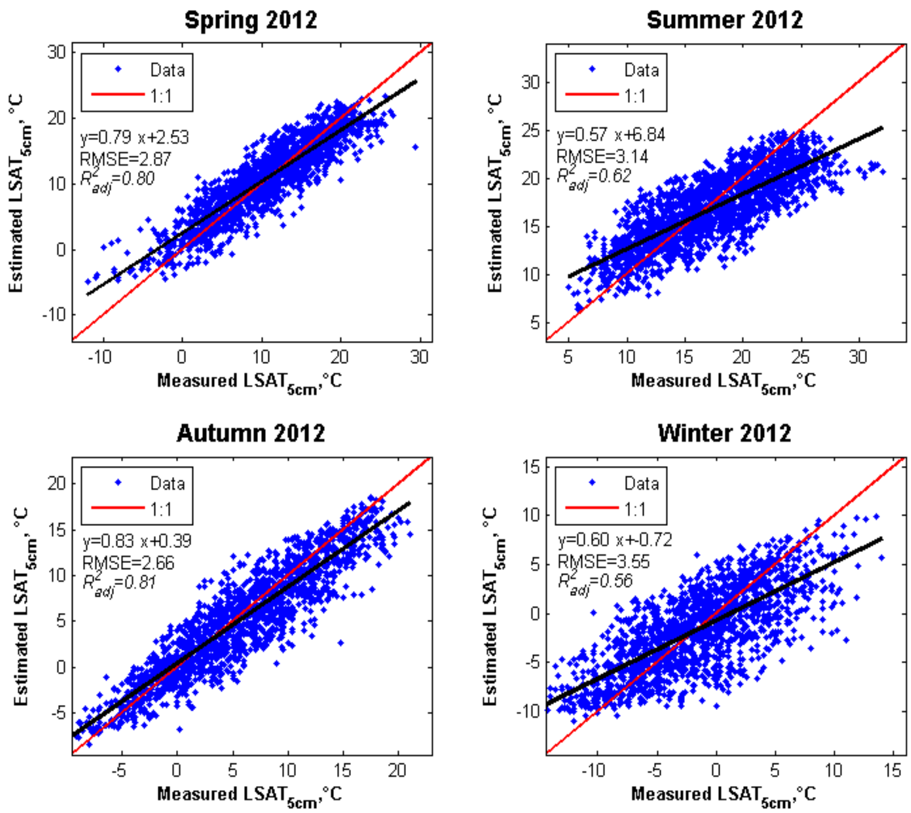

Figure 10: Seasonal comparison of measured minimum $LSAT_{5cm}$ with its estimated values based on linear regression model for Aqua LST nighttime data of the previous day, T_{geom}, Elevation and NDVI for validation during 2012.

Anthropogenic Heat:

In larger and denser cities, the waste heat released from residential, commercial and large public buildings contribute towards the urban surface energy budget. Buildings are equipped with heating ventilation and air conditioning systems that continuously exchange cleaner and warmer air (except during cold season) from the surrounding environment with the indoor air. The frequency of this exchange depends on the volume and physical characteristics of the building, occupancy and the outdoor thermal conditions. The energy spent to cool the air is released as waste heat back in to the atmosphere. This anthropogenic heat plays a major role in the urban surface energy budget and has to be accounted. For example in downtown Tokyo the net anthropogenic fluxes as could be as high as 250 - 400 wm-2 which is nearly 1/3rd of the overall net radiation term during summer months. Along with storage heat flux, this is one of the most uncertain terms in urban areas as there is a complete lack of methodology to directly observe it. Here we have used a building energy model and coupled it with high-resolution urban land cover database to estimate building and block-wise anthropogenic heat. The model was also directly validated with indoor energy use.

Currently most people in the US reside in large metropolitan areas that consist of a dense urban core with high concentration of built spaces (mostly impermeable) surrounded by vast suburban enclaves that are a mix of built and natural surfaces (permeable). In large metropolitan areas this creates a gradient in water retention and heat storage capacity along the urban-rural transect. Both these factors combine to create an urban microclimate that is distinctly different compared to natural ecosystems. While the implications of increased thermal storage capacity is well understood, the role played by soil moisture deficit in shaping the climate at local and regional levels is poorly understood. To quantify this variability, we have instituted a dense surface observatory network in the New York Metropolitan area. This unique urban micro-network consists instrumentation to monitor soil moisture at multiple depths along with air temperature, relative humidity and precipitation (this is ongoing work which began very recently). We are also conducting numerical experiments to understand the impact of urban soil moisture deficit on local climate. In one such simulation conducted to partition the influence of storage flux, wind pattern and circulation and soil moisture deficit on urban heat island intensity (UHI), we found that the daily variability in UHI in NYC was sensitive to available energy and wind pattern. The long-term trend in UHI was however related to soil moisture deficit. In fact a prolonged heat wave period witnessed during summer 2006 correlated well with an extended dry period and the daily UHI in NYC almost doubled. Moreover, the urban soils also suffered from high degree of desiccation, owing to drier urban boundary layer.

Total Electricity Consumption by Zip Code

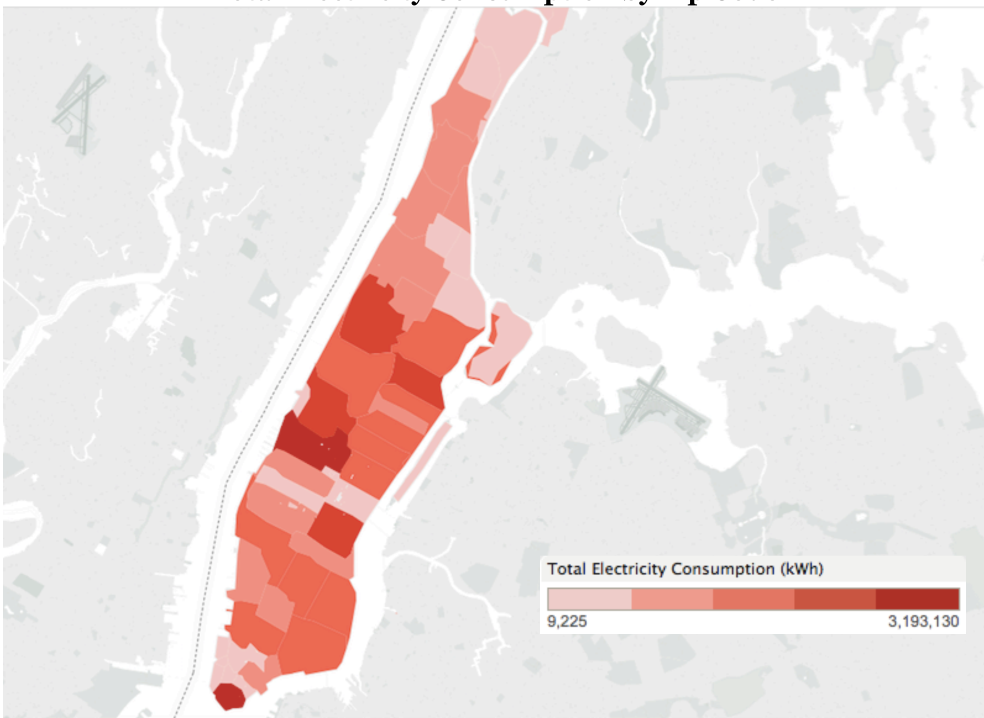

Figure 11: Modeled electricity consumption to estimate the amount of anthropogenic heat released from different urban parcels in the city. This will allow us to close the urban surface energy budget.

This short-term project has resulted in 3 conference presentations and two journal publications are under preparation. One will be submitted in September 2016.

This project aimed to initiate efforts to study surface energy balance components in mostly urban regions. Synergetic use of ground observations, satellite measurements, and urban canopy modeling results revealed a great potential to expand the knowledge with promising findings. Available bases such as established ground measurements, spatio-temporal methods, and modeling will enable us to expand them even further using a longer project. The urban surface energy still requires more extensive studies. A new proposal to expand this efforts is planned to be submitted to DoD.

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