The Urban Heat Island in Coastal/Urban Environments

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Coastal Urban Environments Research Group

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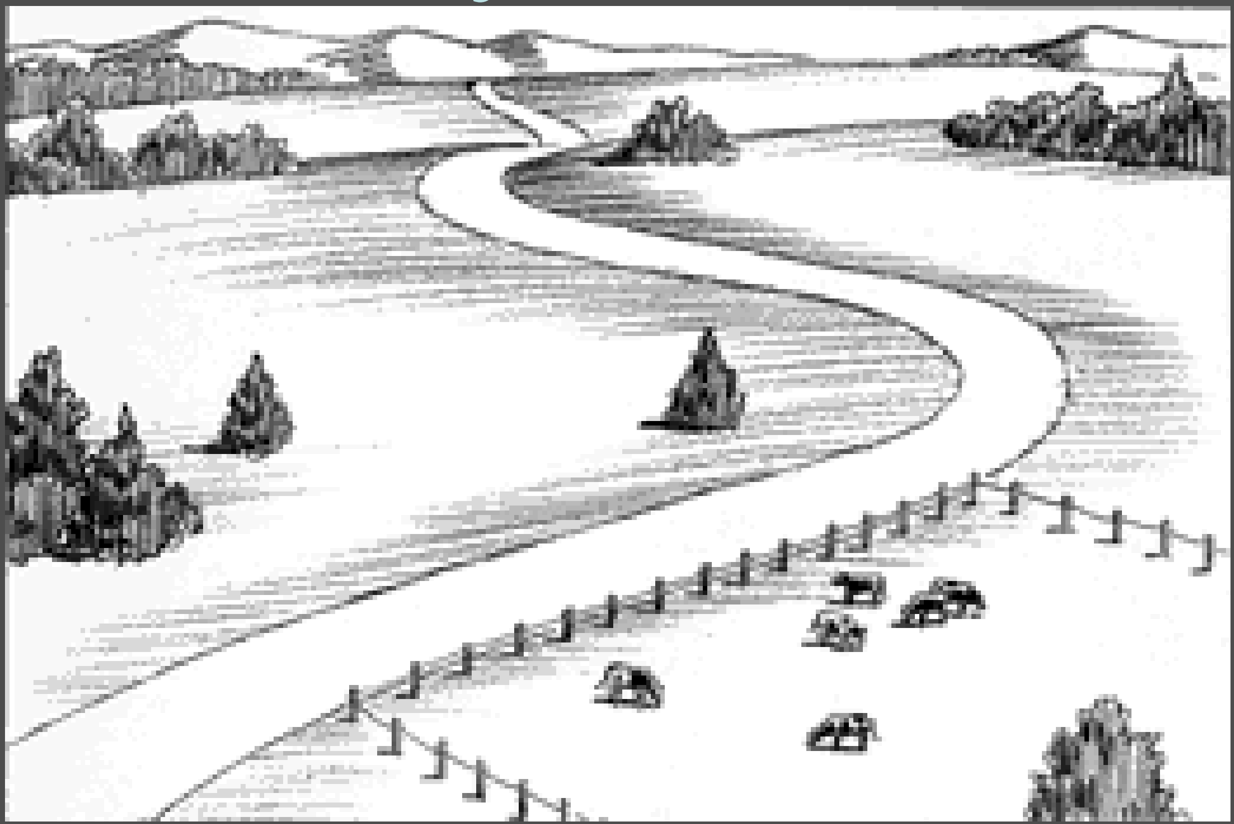
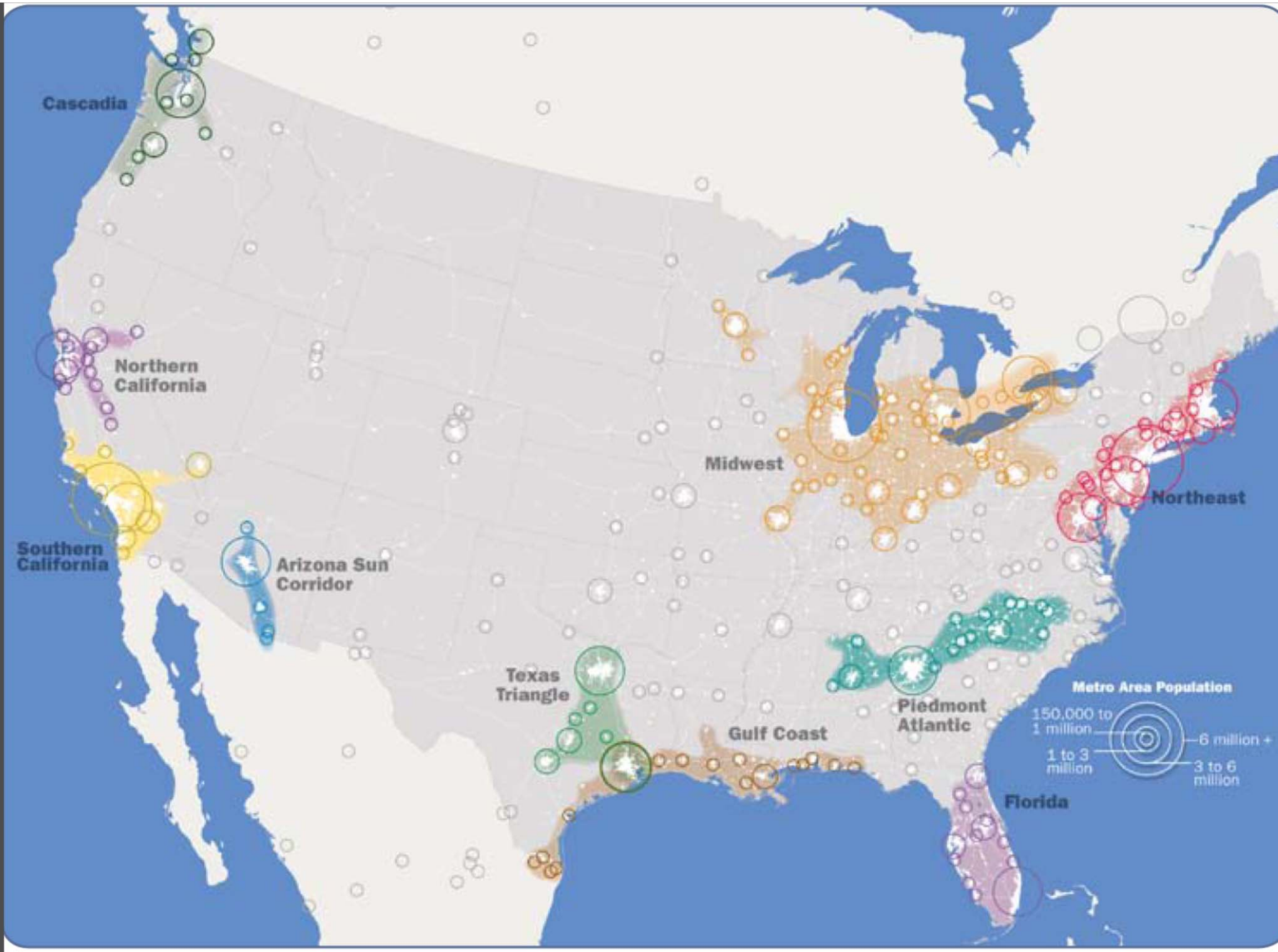
Outline

- URBAN HEAT ISLAND (UHI): DEFINITION AND BACKGROUND
- UHI IN COASTAL CITIES AROUND THE WORLD
- OBSERVATIONAL MEASUREMENTS AND ANALYSES PR & CAL Case Studies
  - Airborne Images
  - Modeling Experiments
- UHI in Dense Environments and Extreme Heat Events
- MITIGATION ALTERNATIVES
  - (SJU/Houston/LAX/SAC/NYC)
- REFLECTIONS AND OPEN SCIENCE QUESTIONS

City Growth

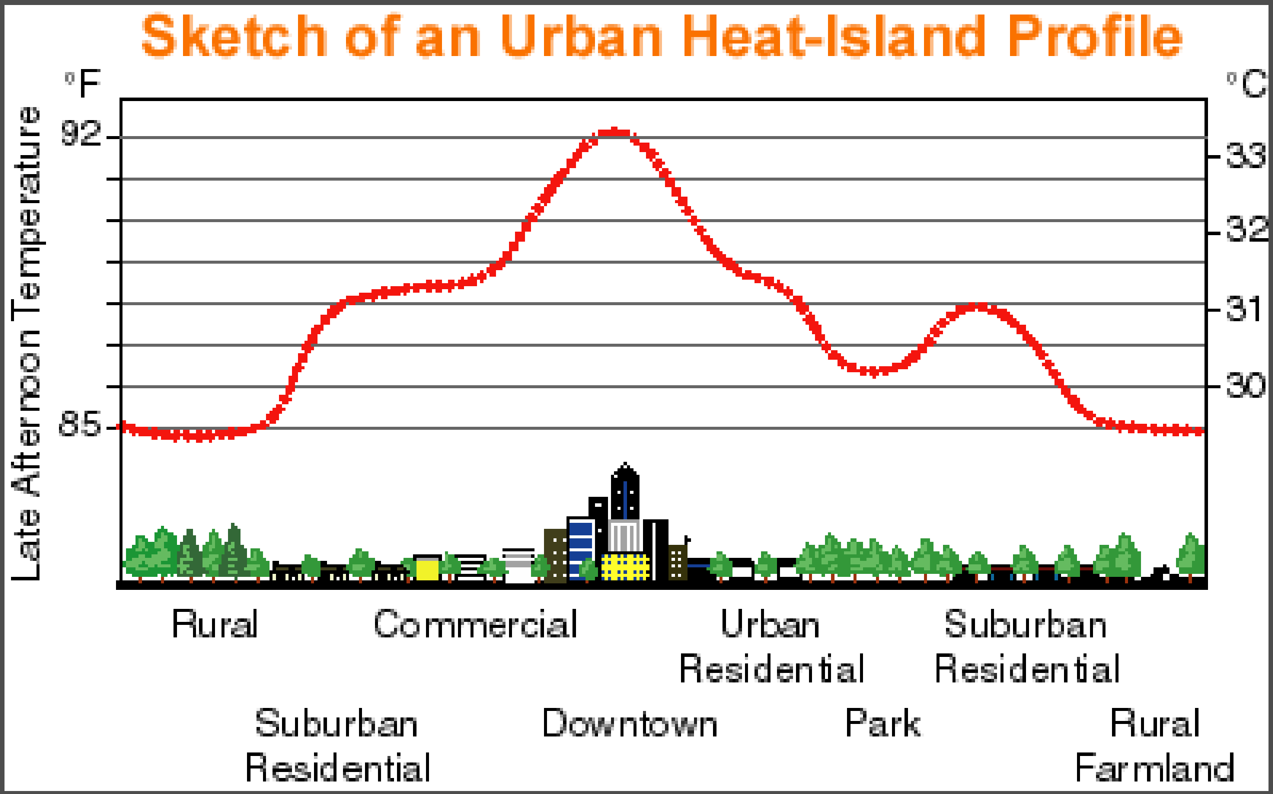


The growth of cities has accelerated in the last few decades, making their impact on the local environment more acute.



Emerging Megaregions in the United States. Source US 2050

Urban Heat-Island Effect



Courtesy of LBNL

Can be defined as the dome of elevated air temperatures that presides over cities in contrast to their cooler rural surroundings.

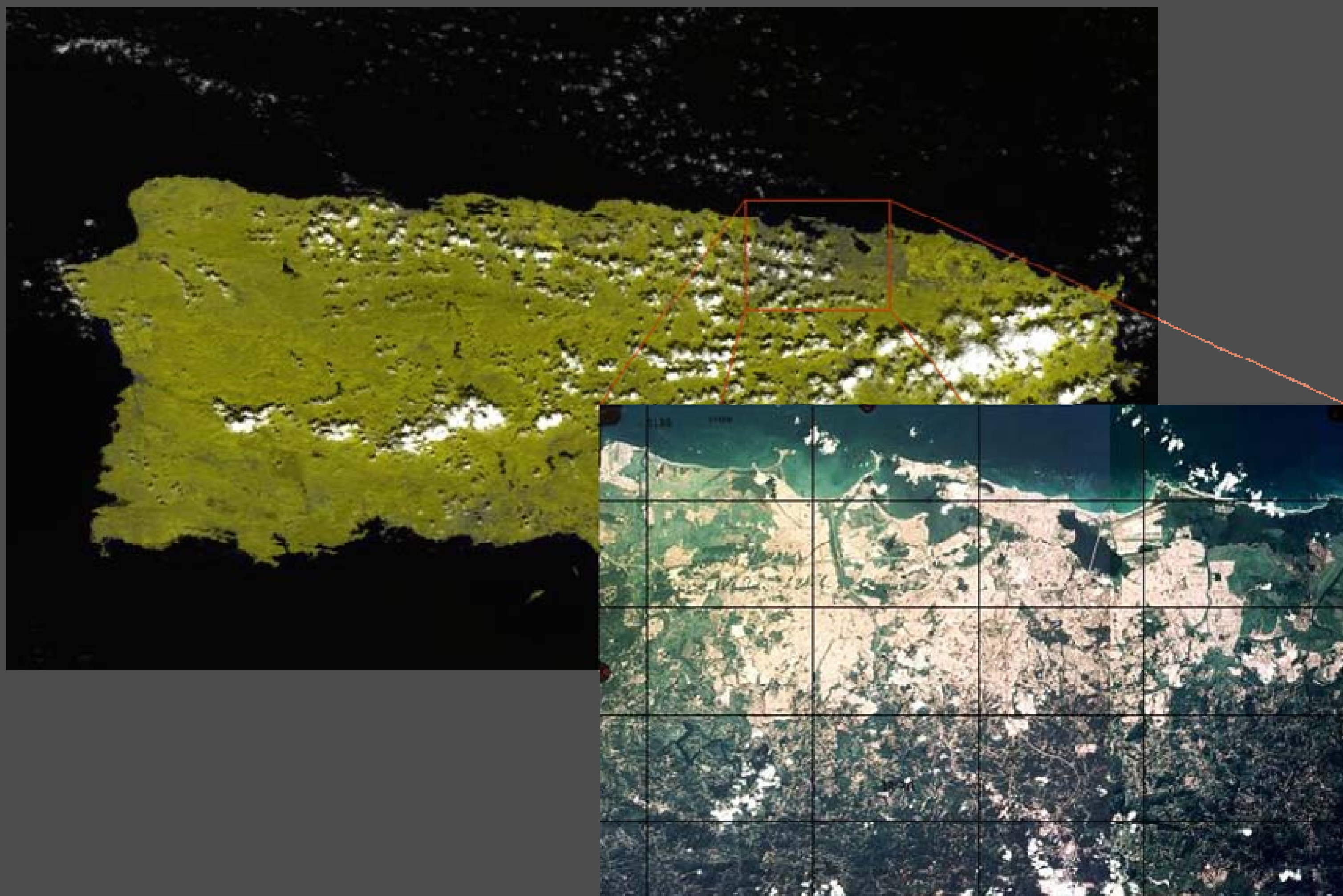
What leads to the formation of an UHI?

- **Paved urban surfaces.**
  - These make the penetration of precipitation on the soil virtually impossible.
  - Higher water runoff leads to small flash floods over the few vegetated surfaces available.
  - Situation provides little water for evaporation, and thereby, expends little net radiation on evaporation.
- **Cities have large vertical surfaces of different geometric shapes.**
  - They function like canyons affecting radiation and wind patterns.
  - Radiation is reflected back and forth off the walls of buildings resulting in entrapped energy and higher temperatures. Buildings also disrupt wind flow creating less heat loss.

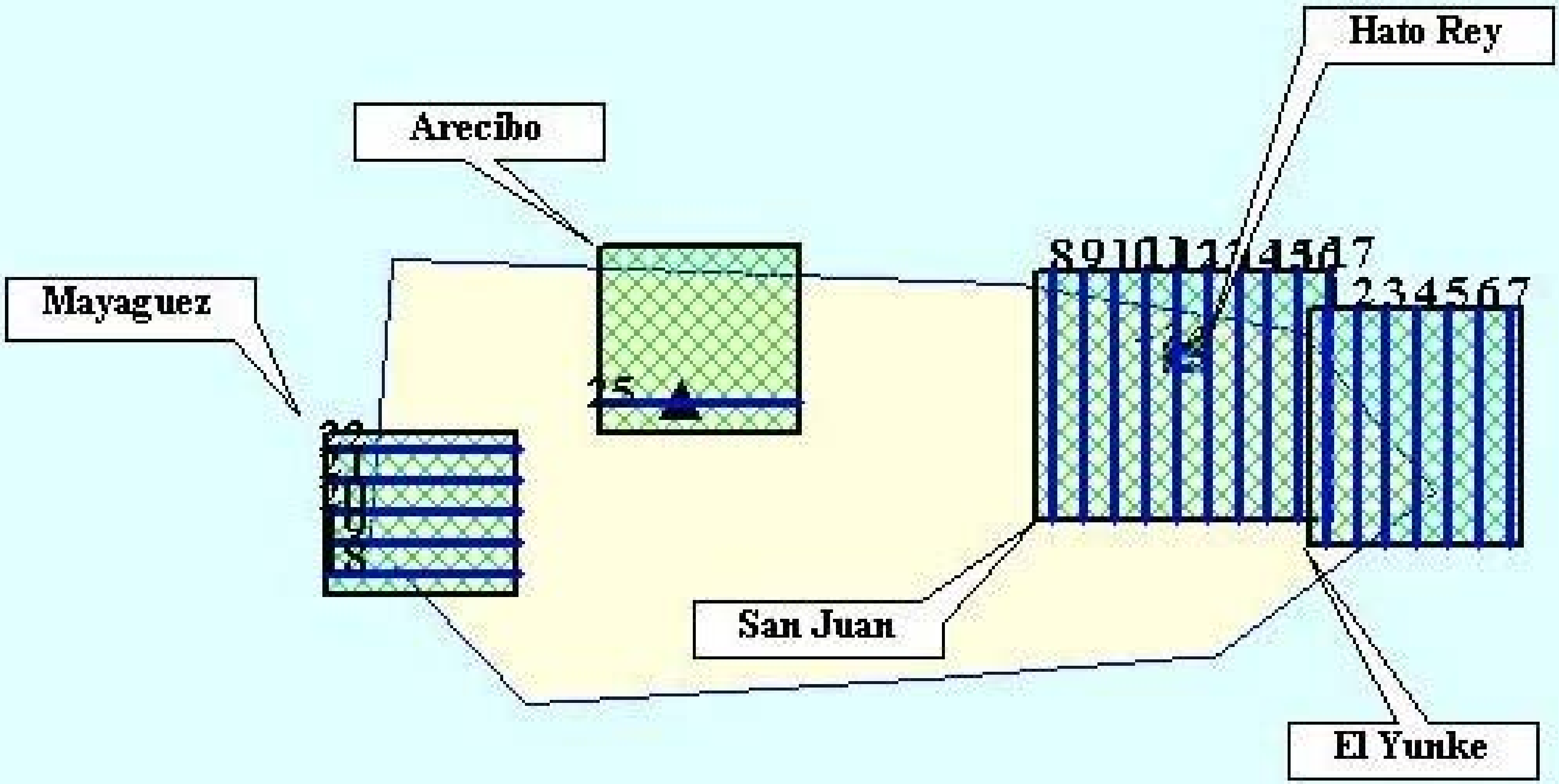
Urban Heat Island Induced Problems & Hazards

- Poor Air Quality
  - Hotter air in cities increases both the frequency and intensity of ground-level ozone.
- Risks To Public Health
  - The UHI Effect prolongs and intensifies heat waves in cities, making residents and workers uncomfortable and putting them at increased risk for heat exhaustion and heat stroke.
- High Energy Use
  - Hotter temperatures increase demand for air conditioning. This contributes to power shortages and raises energy expenditures.
- Global Warming
  - Urban Heat Islands contribute to global warming by increasing the demand for electricity to cool our buildings.
  - Each kilowatt hour of electricity consumed can produce up to 2.3 pounds of carbon dioxide (CO2), the main greenhouse gas contributing to global warming.
- Urban Heat Island – Induced Precipitation

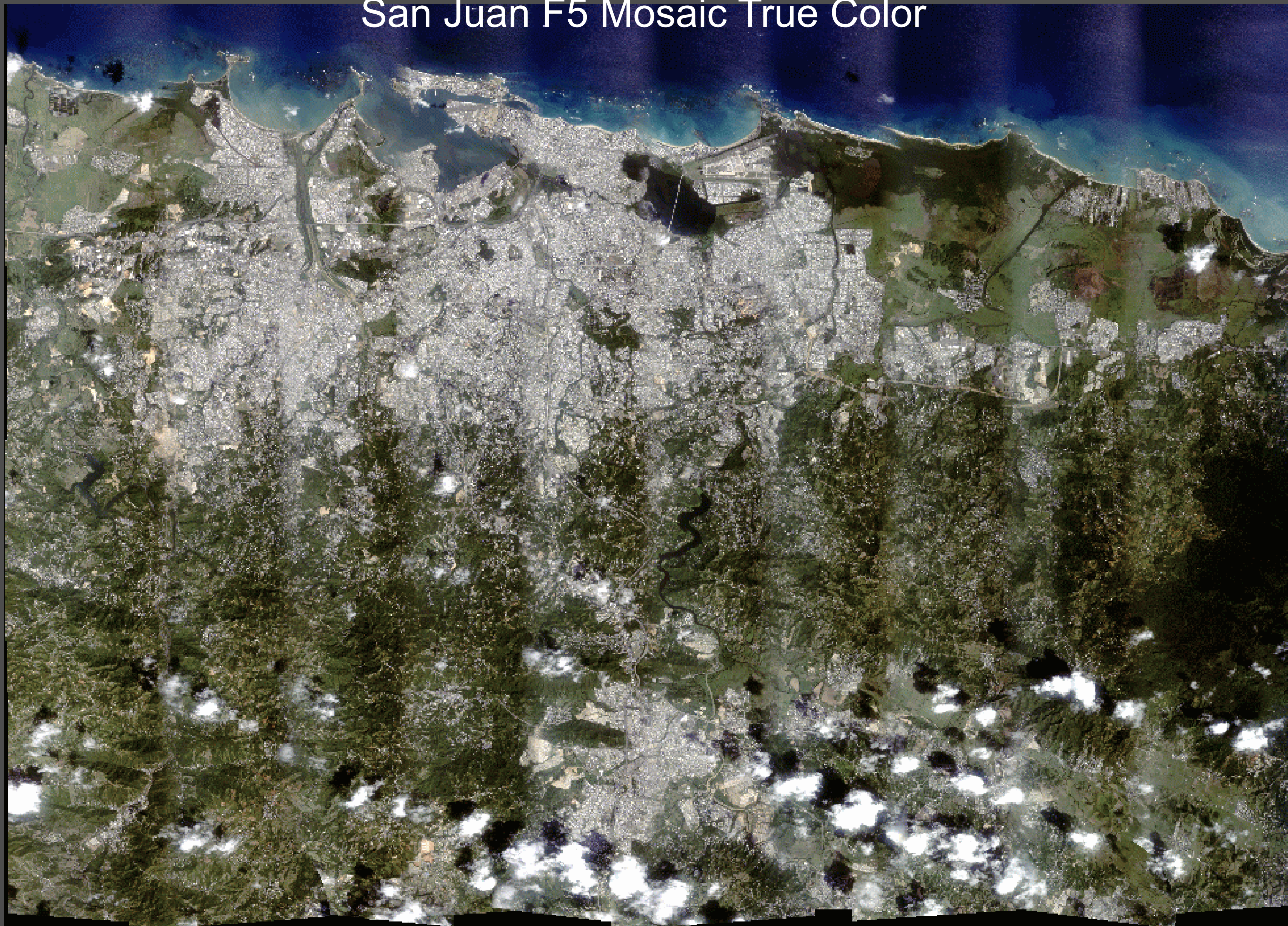
UHI: The Case of SJU PR



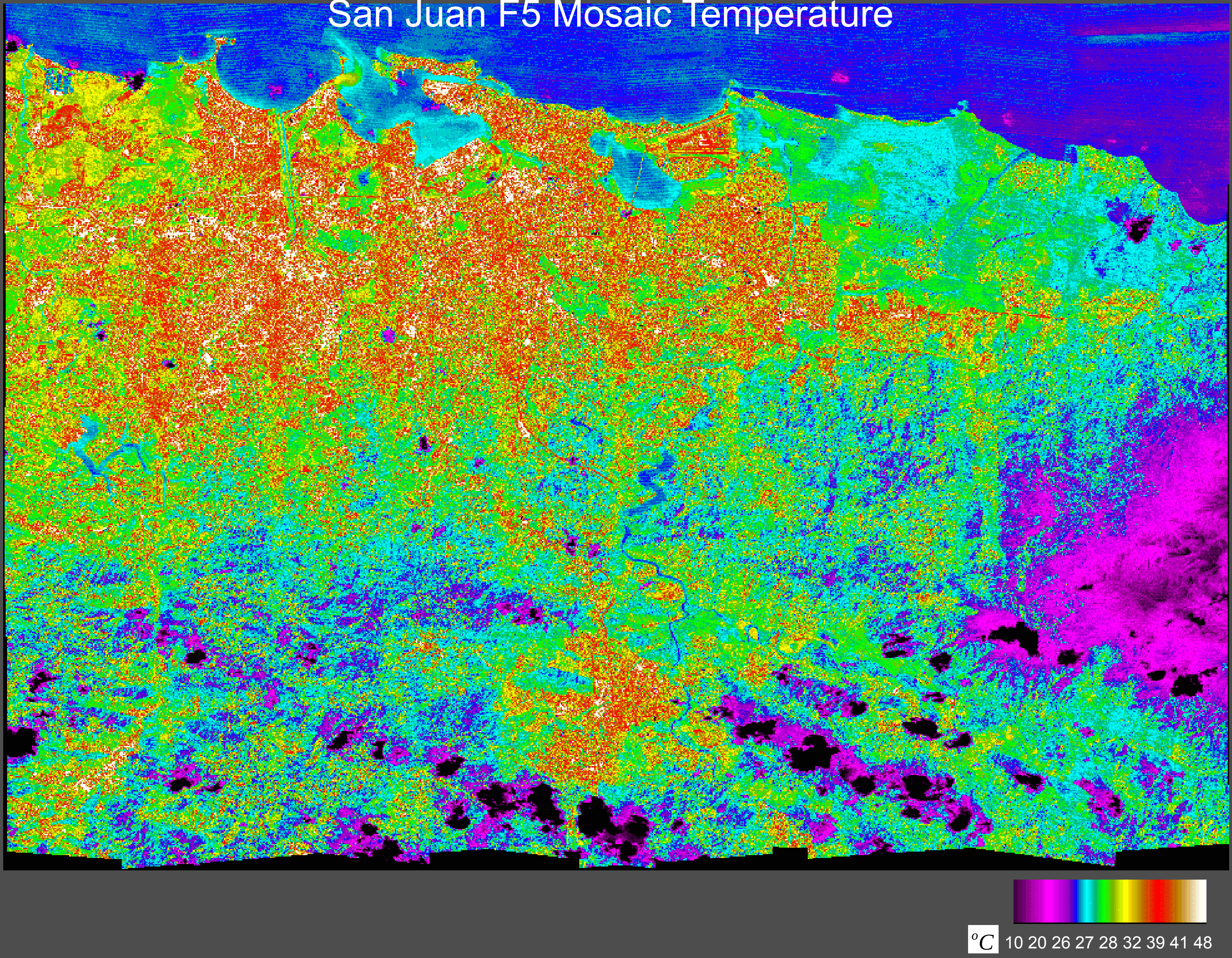
Flight Plan



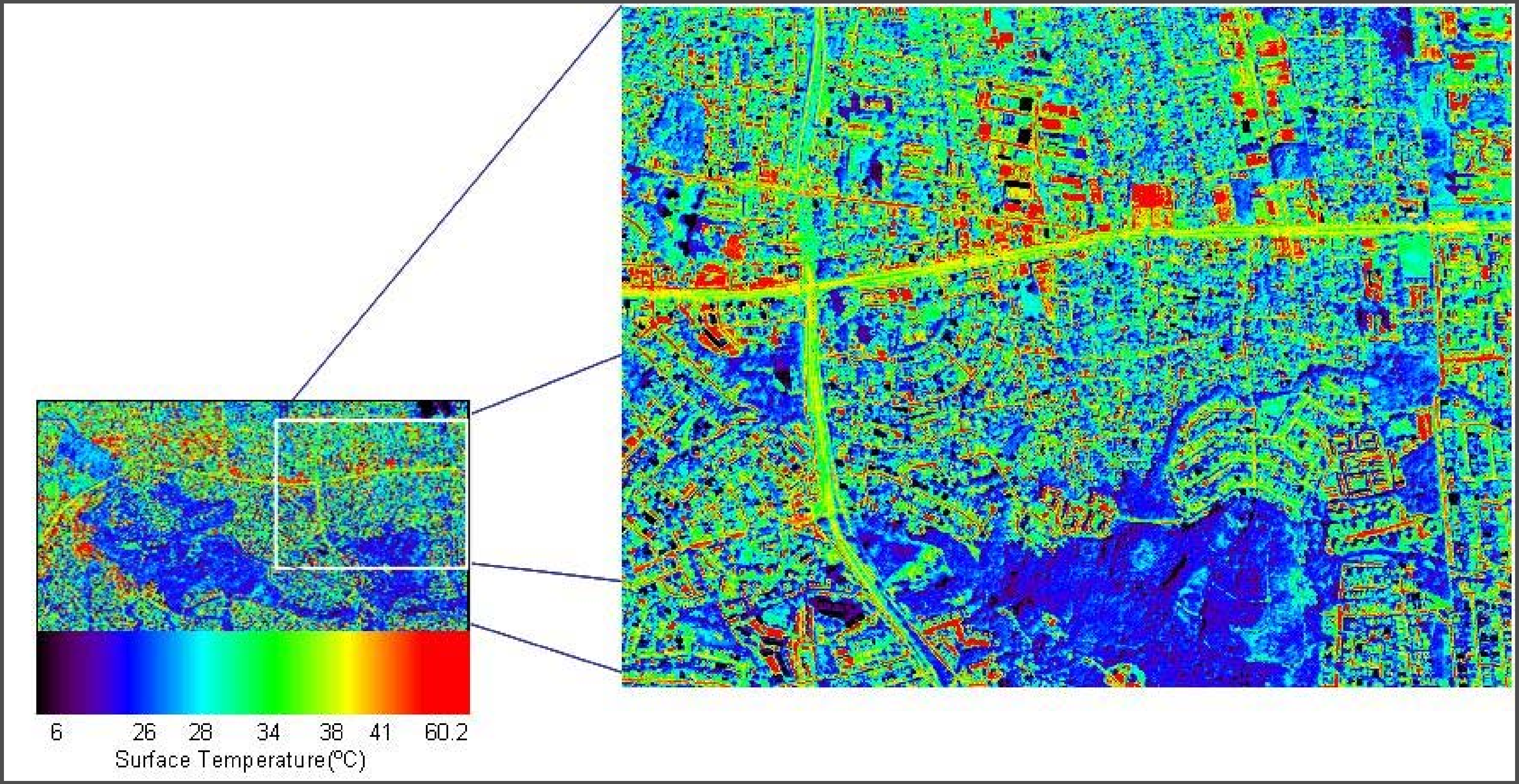
San Juan F5 Mosaic True Color



San Juan F5 Mosaic Temperature

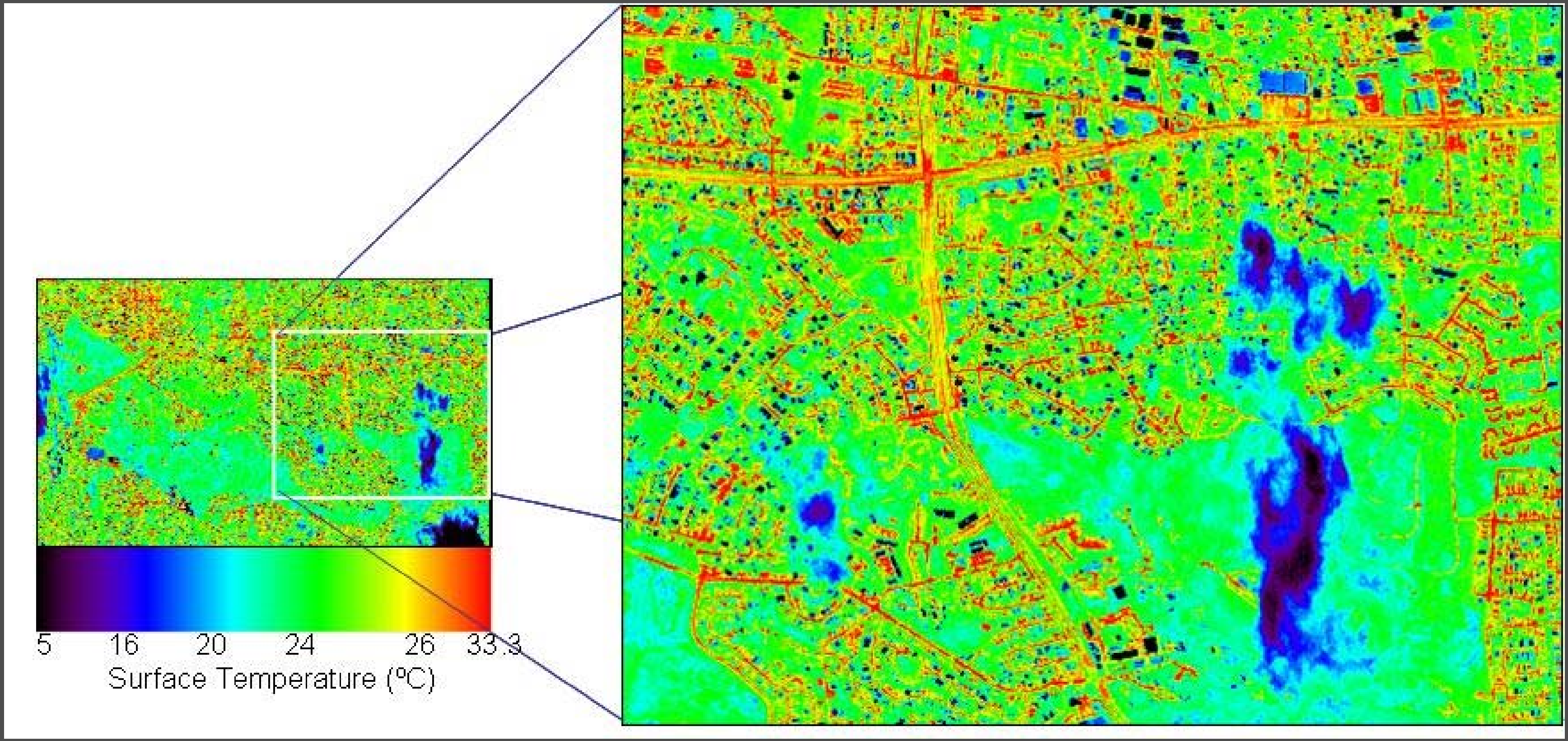


Sample of ATLAS images for San Juan

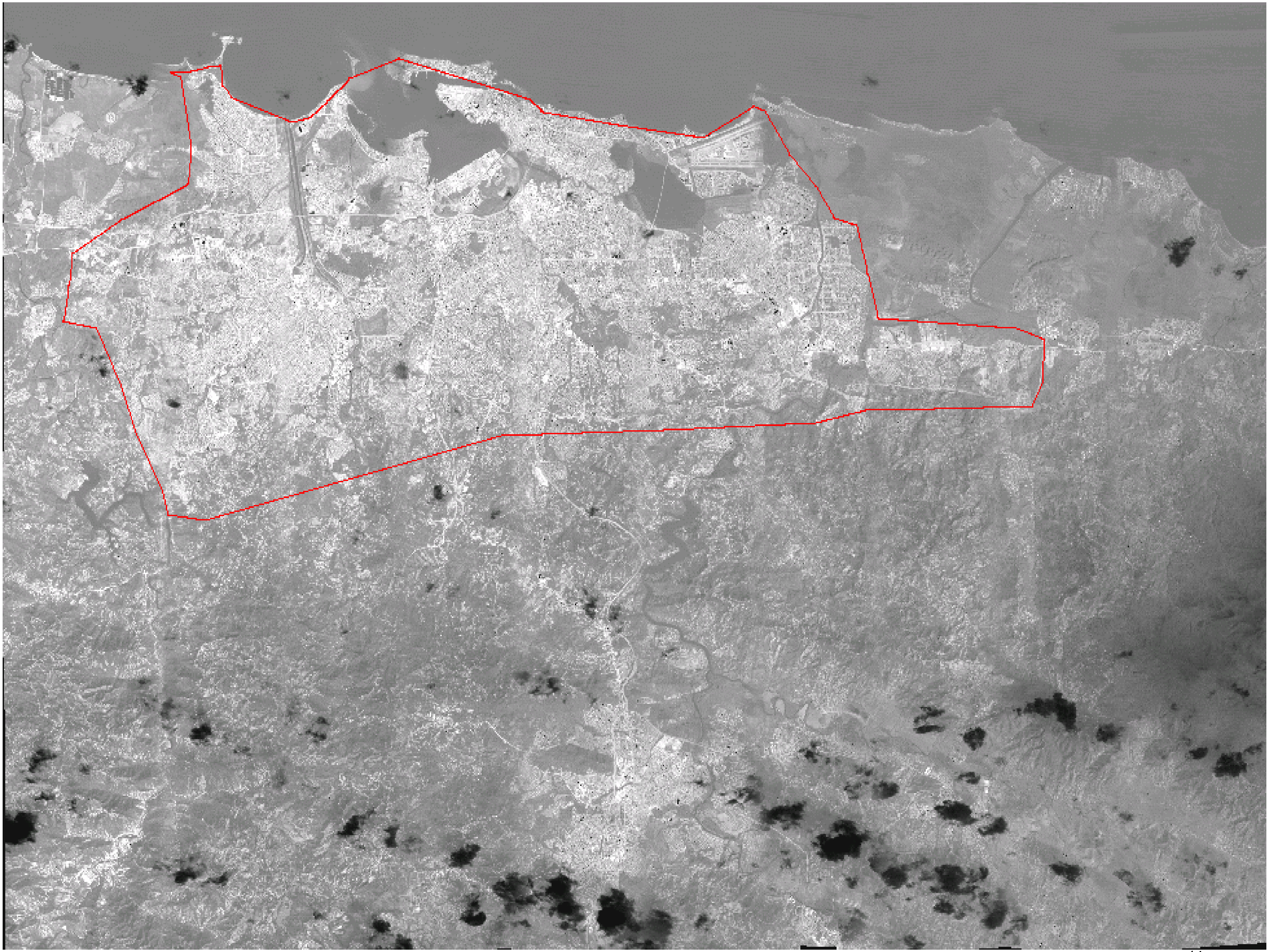


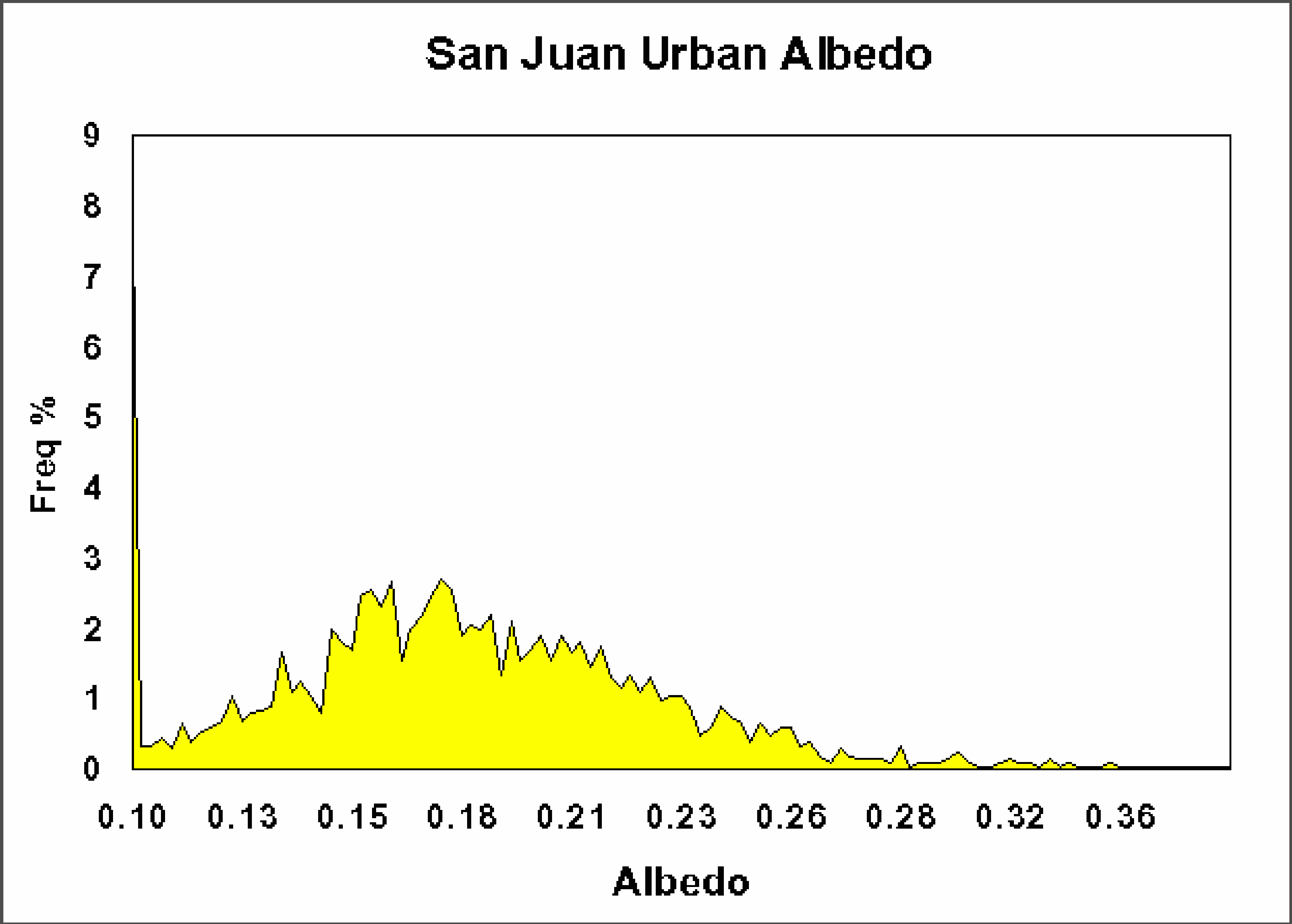
Daytime image of the ATLAS sensor taken at 10 meters. February 16, 2004. (f1.231)

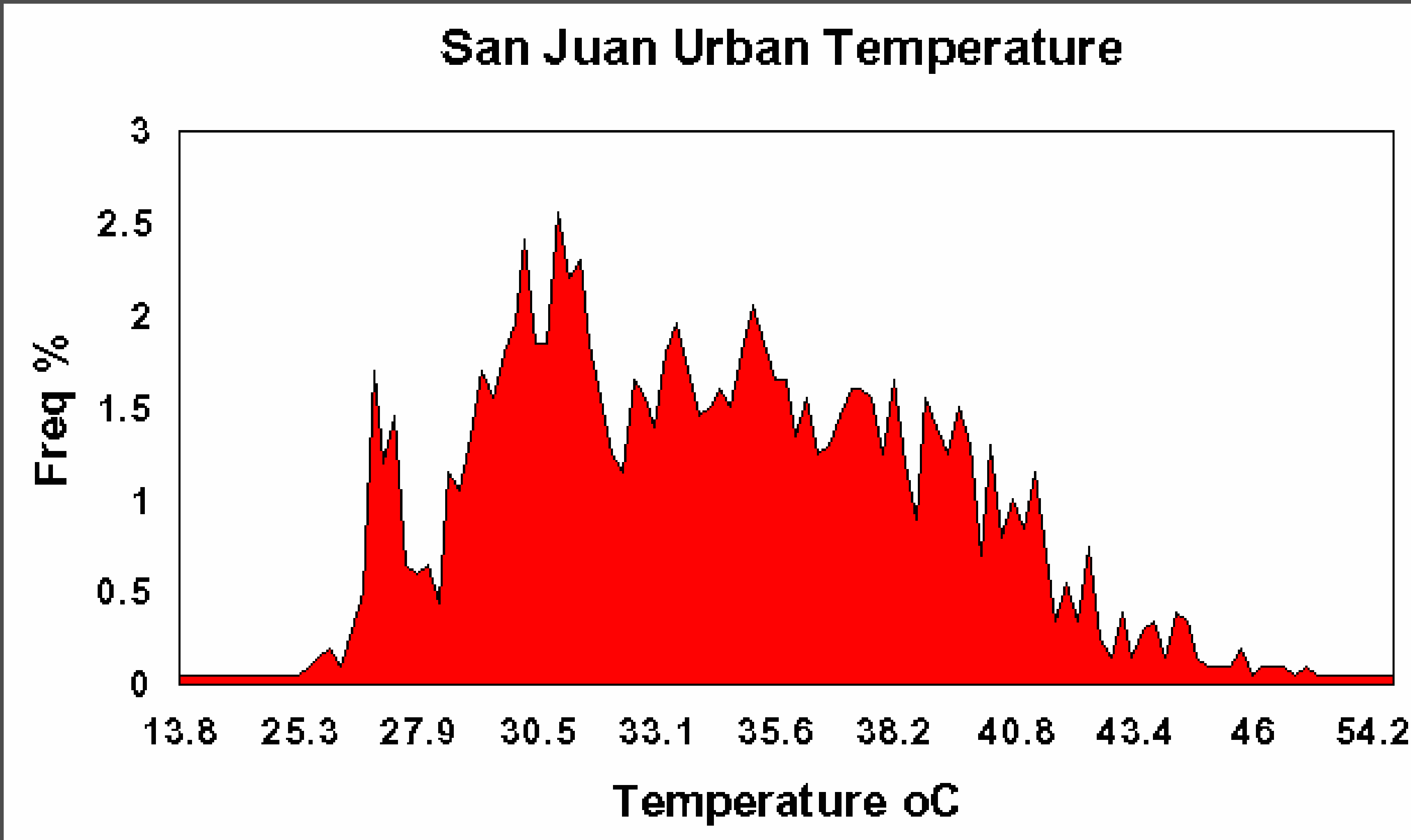
Sample of ATLAS images for San Juan

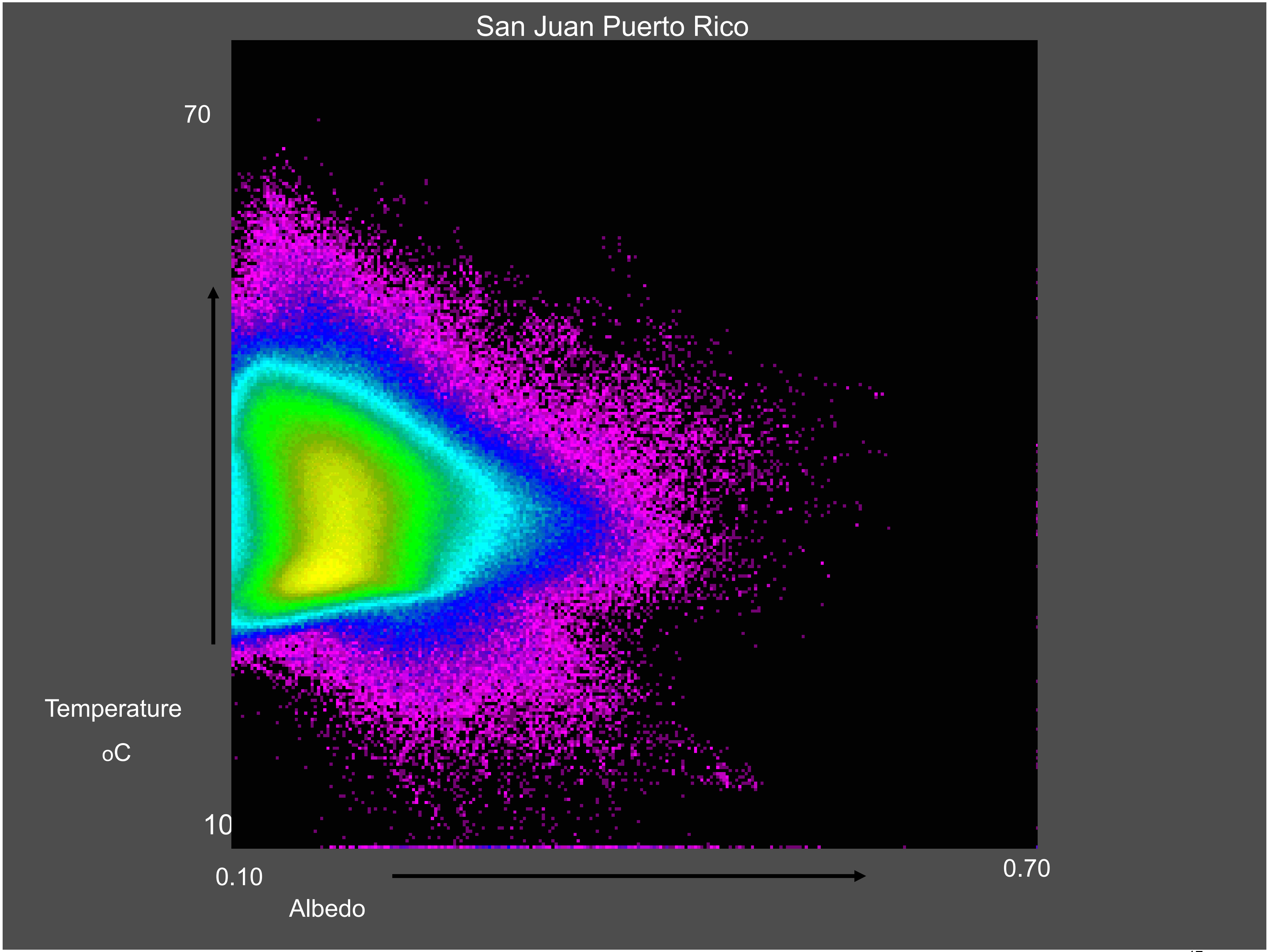


Nighttime image of the ATLAS sensor taken at 10 meters. February 16, 2004. (f2.231)

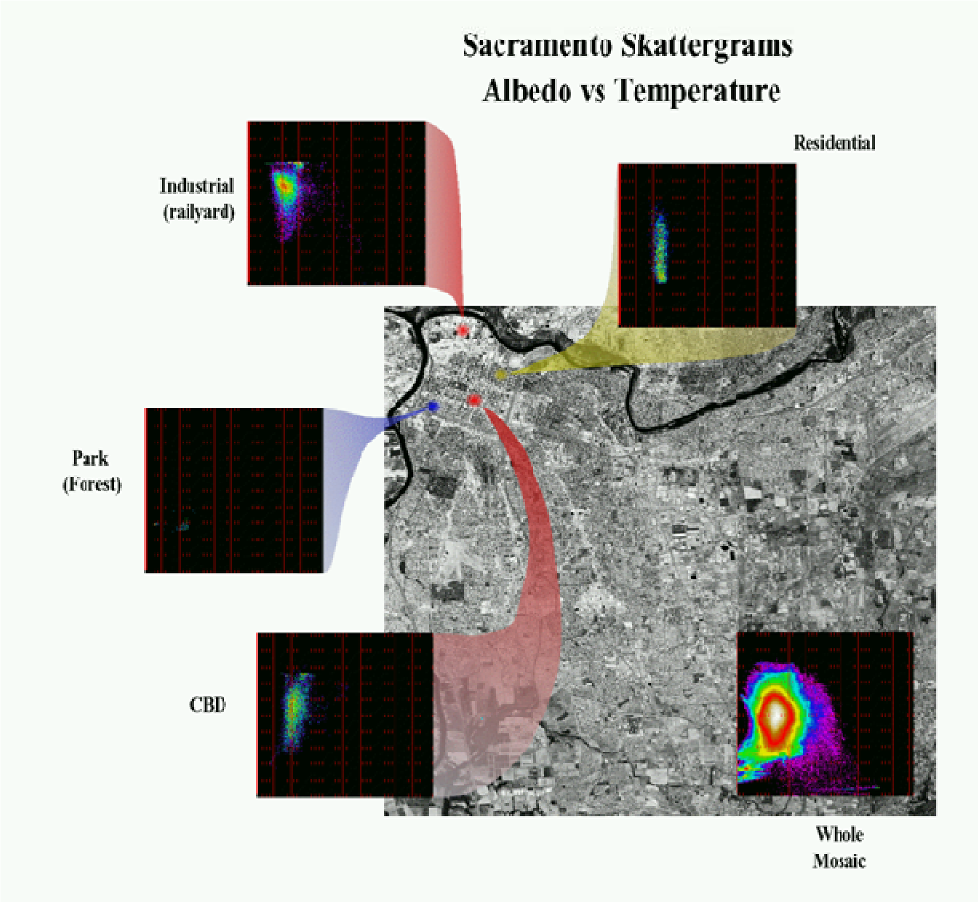


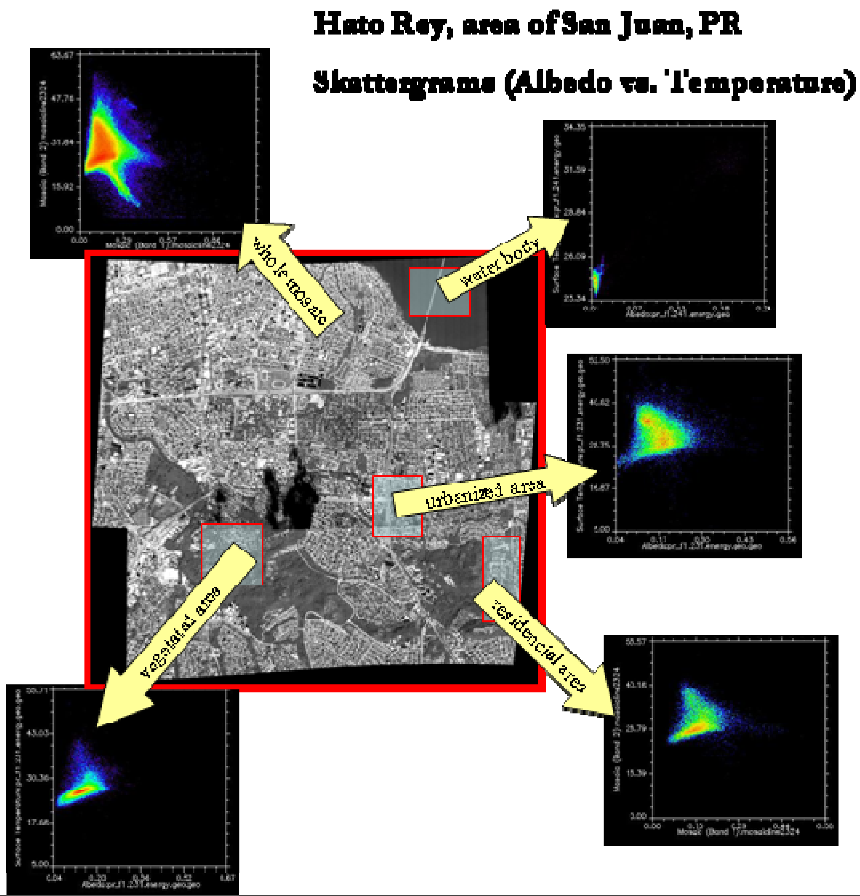

San Juan Urban Albedo
Freq %
9
8
7
6
5
4
3
2
1
0
0.10
0.13
0.15
0.18
0.21
0.23
0.26
0.28
0.32
0.36
Albedo


San Juan Urban Temperature
Freq %
3
2.5
2
1.5
1
0.5
0
13.8
25.3
27.9
30.5
33.1
35.6
38.2
40.8
43.4
46
54.2
Temperature oC


San Juan Puerto Rico
70
Temperature
oC
10
0.10
Albedo
0.70

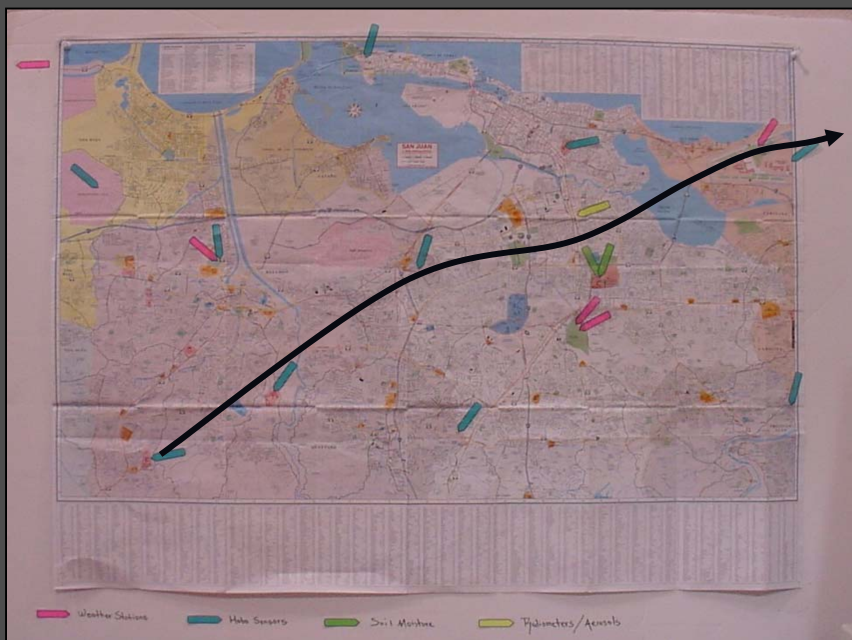
Comparison of UHIs for Two-Different Cities (Sacramento & SJU)

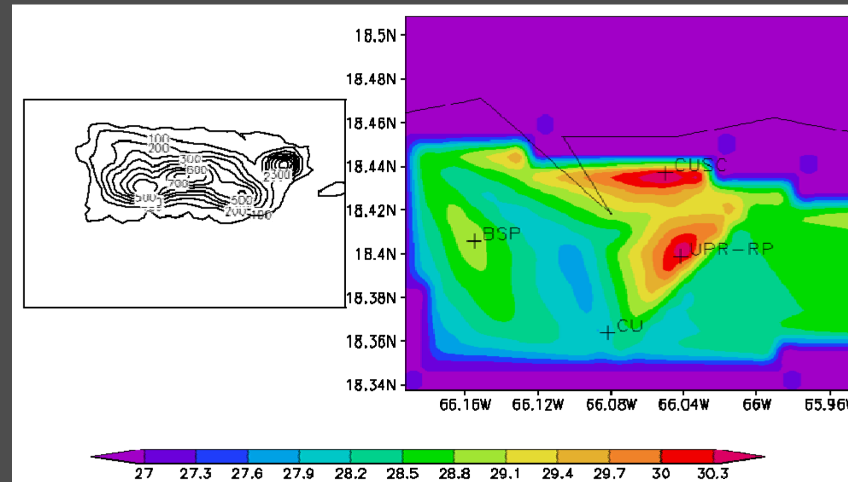


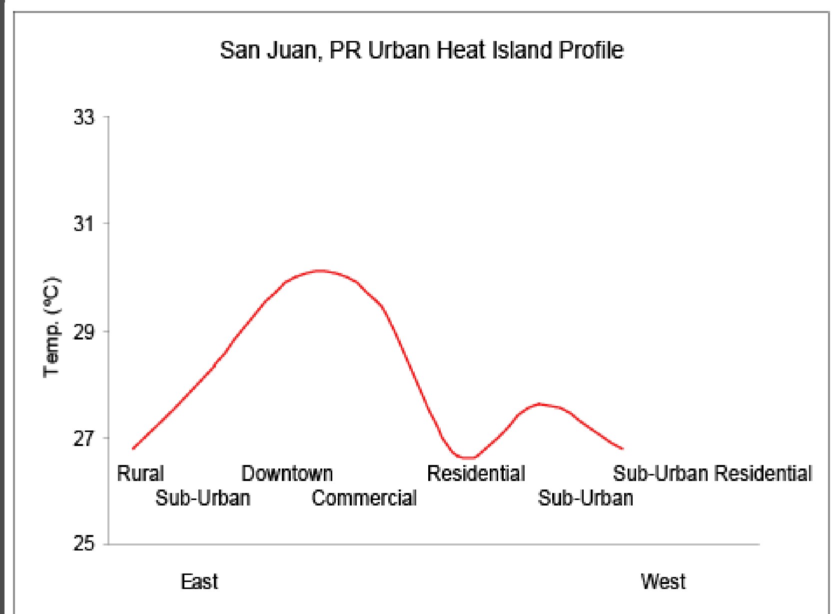


Observational Analysis for SJU

- Urban Heat Island Studies in San Juan





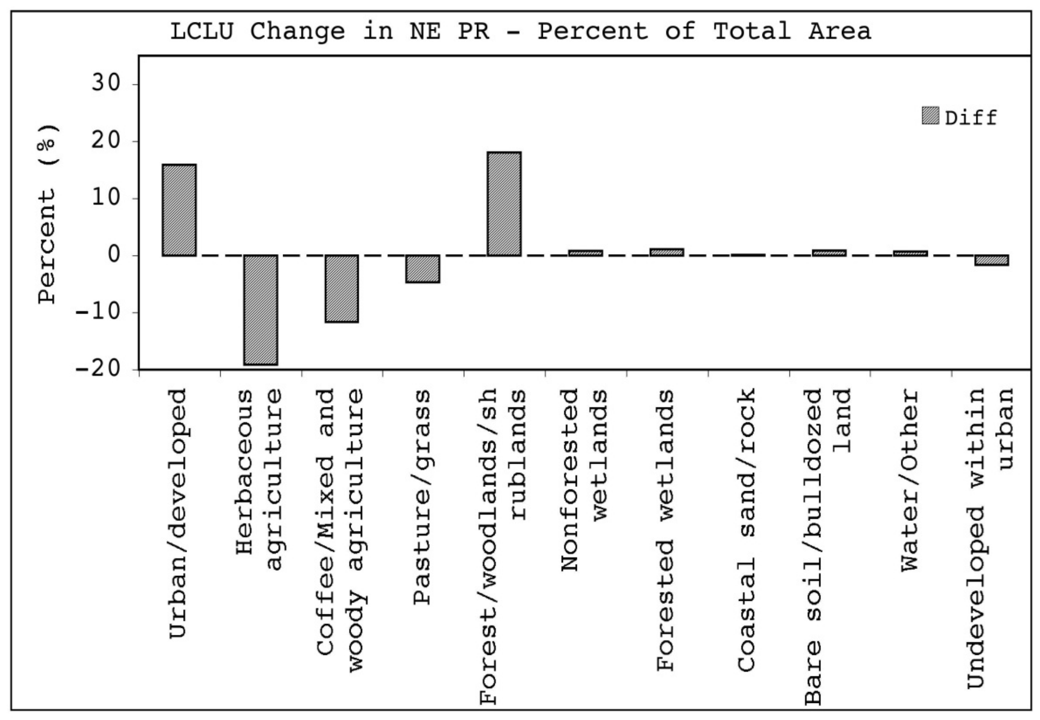


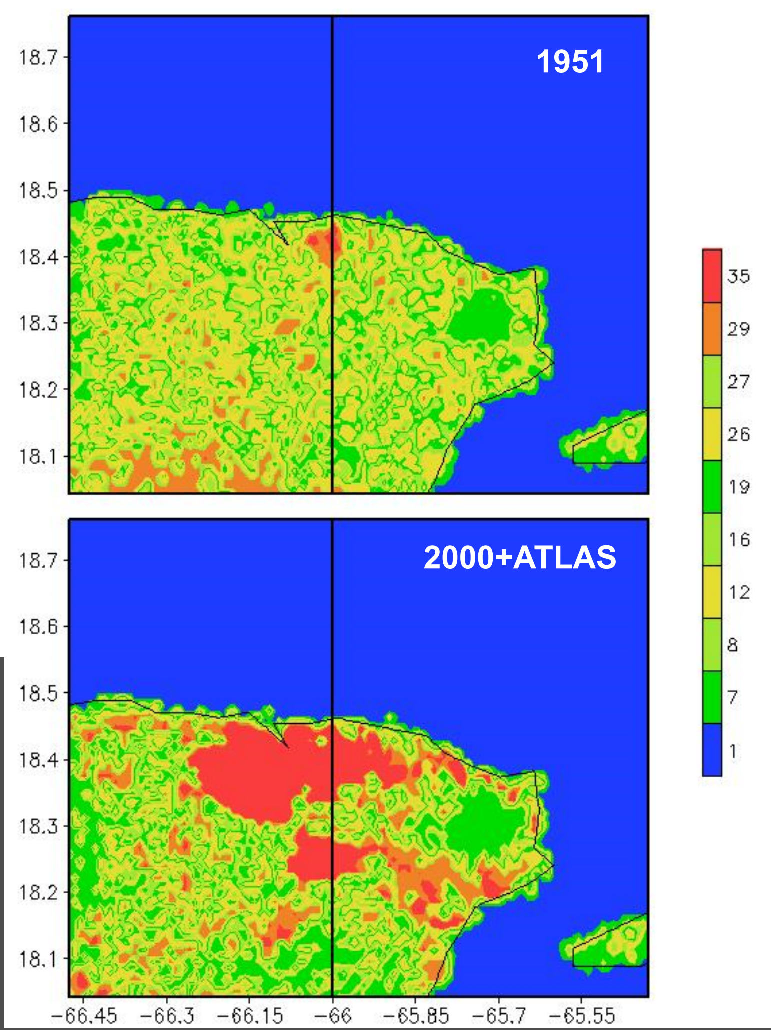
Weather stations and temperature sensors were deployed in the metropolitan area of San Juan, P.R. and its surroundings, the data show strong indications of an Urban Heat Island.

UHI & GW Impact Analysis for SJU

- Quantify the impact of the UHI in the local climate.
- Answer key science question:
  - **What are the combined effects of global climate change and LCLU in a tropical coastal region?**
- **Method: RAMS Simulations w/Updated Land Use (1km-res)**

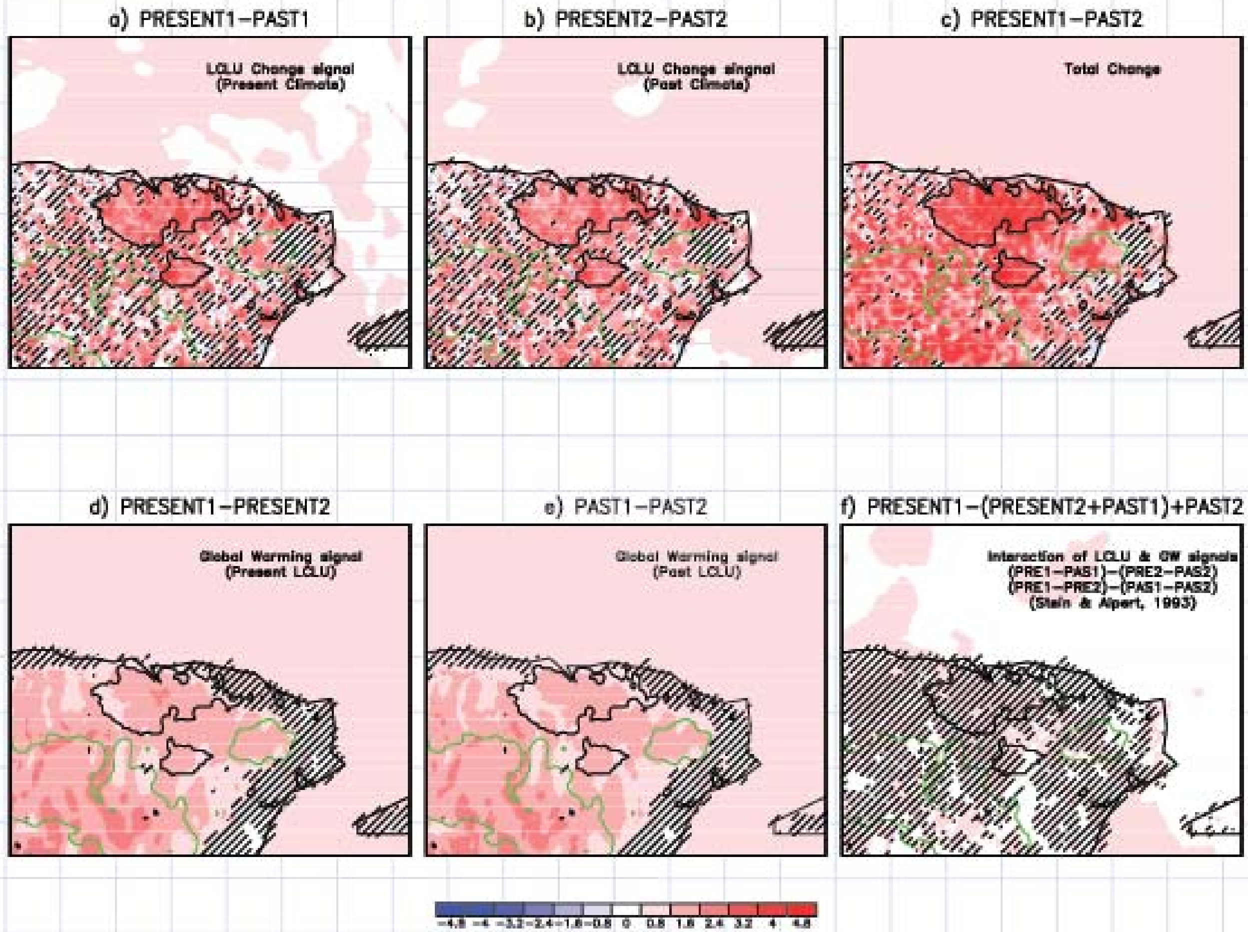
LCLU Specifications - Northeastern PR





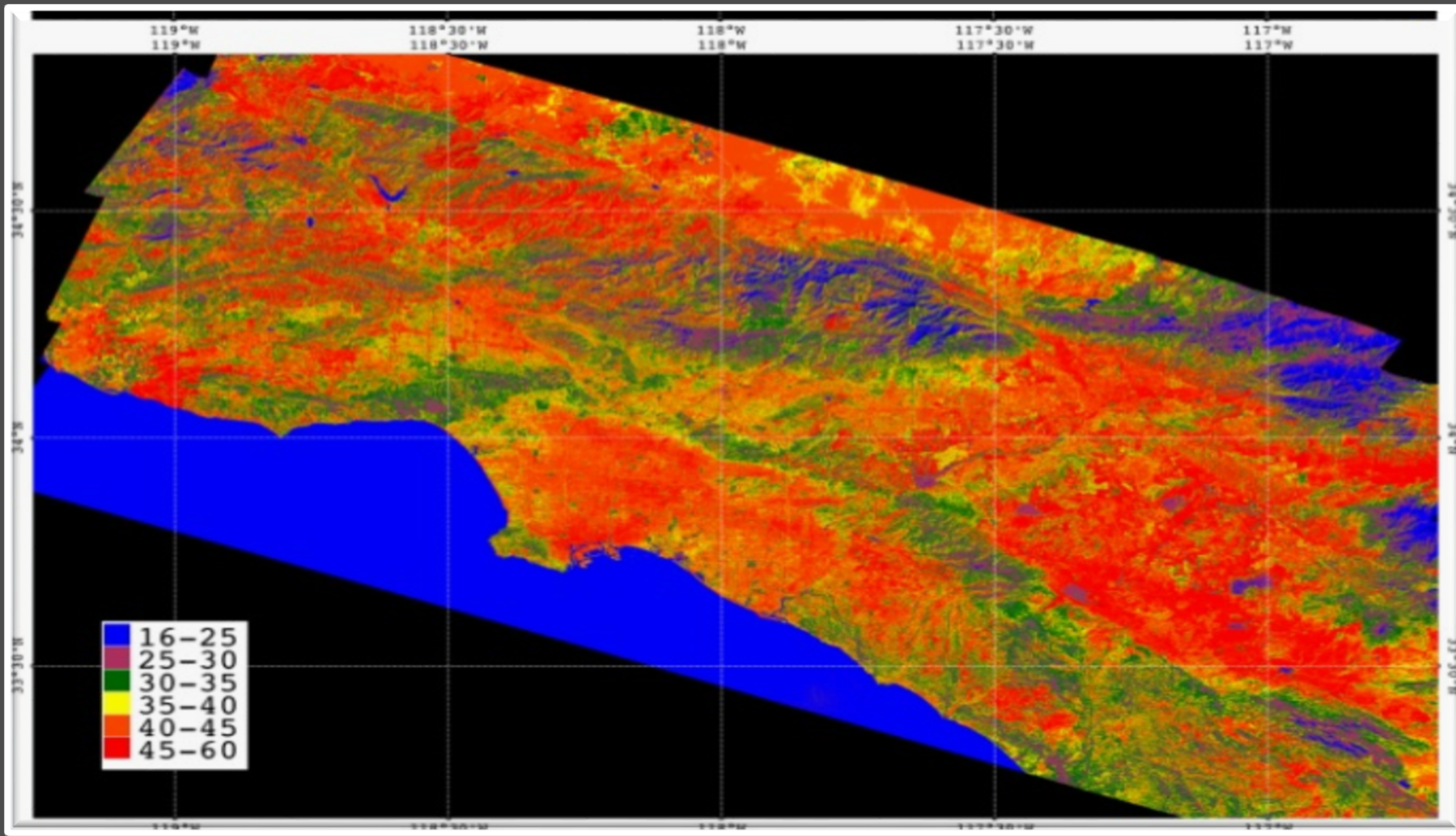
Description	class	1951	2000	Diff
Background/water	0			
Urban/developed	30	1.92	17.81	15.89
Herbaceous agriculture	8	19.19	0.09	-19.10
Coffee/Mixed and woody agriculture	12	12.38	0.76	-11.62
Pasture/grass	27	33.73	28.99	-4.74
Forest/woodlands/shrublands	3	9.37	27.43	18.06
Nonforested wetlands	16	0.00	0.76	0.76
Forested wetlands	19	0.00	1.08	1.08
Coastal sand/rock	26	0.00	0.14	0.14
Bare soil/bulldozed land	27	0.00	0.91	0.91
Water/Other	1	0.23	0.93	0.70
Undeveloped within urban	7	1.71	0.00	-1.71

Model Results: Maximum Temperature Change (˚C)



The LAX/SFO Case

Recent NASA/MASTER images for LAX



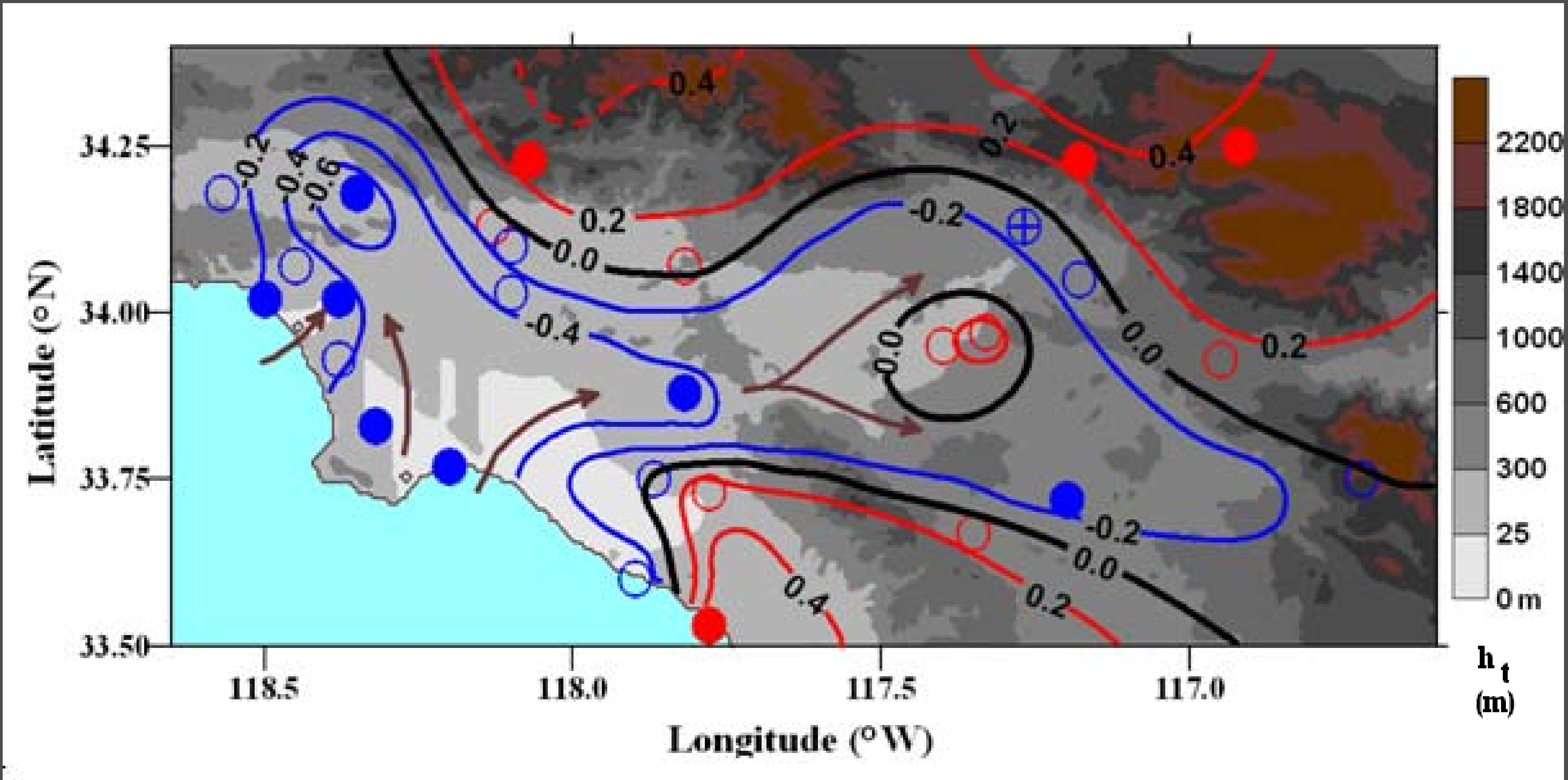
Daytime image of the Master sensor taken at 30 meters. September 24, 2013 (12:00 LT).

LAX-Result 1: Lebassi et al. (2009) J. of Climate

Observed 1970-2005 CA JJA max-Temp (^{0}C/decade) trends in SFBA & SoCAB show concurrent:

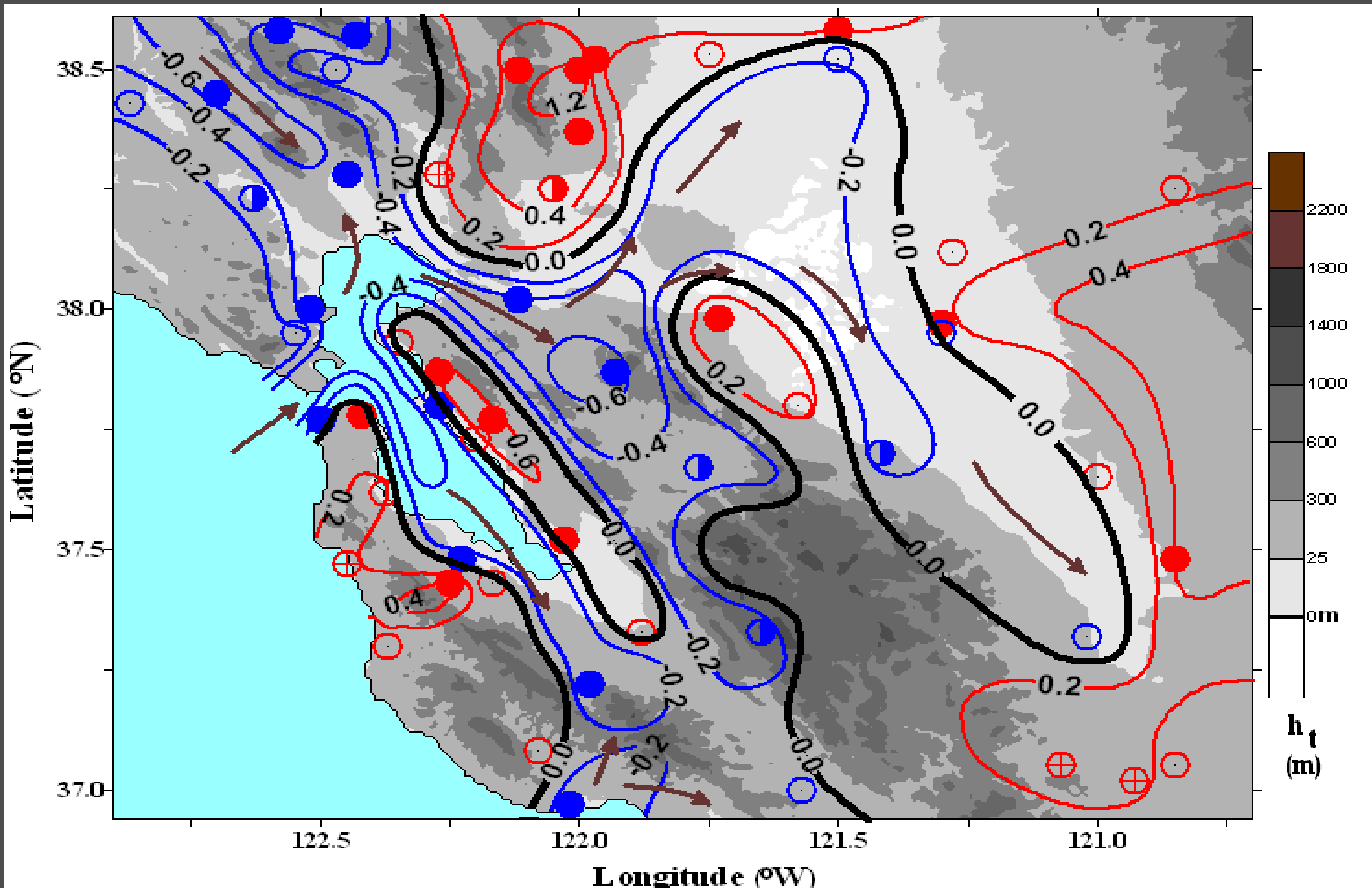
> low-elev coastal-cooling & > high elev & inland-warming

> signif levels: solid circles >99% & open circles <90%)



LAX-Results 2: Same for SFBA & Central Valley

COOLING AREAS: MARIN LOWLANDS, MONTEREY, SANTA CLARA V., LIVERMORE V., WESTERN HALF OF SACRAMENTO V.



Current Hypothesis: Observed Calif temp trends resulted from

a. GHG WARMING/LULC **and/or**

b. INCREASED INLAND WARMING →

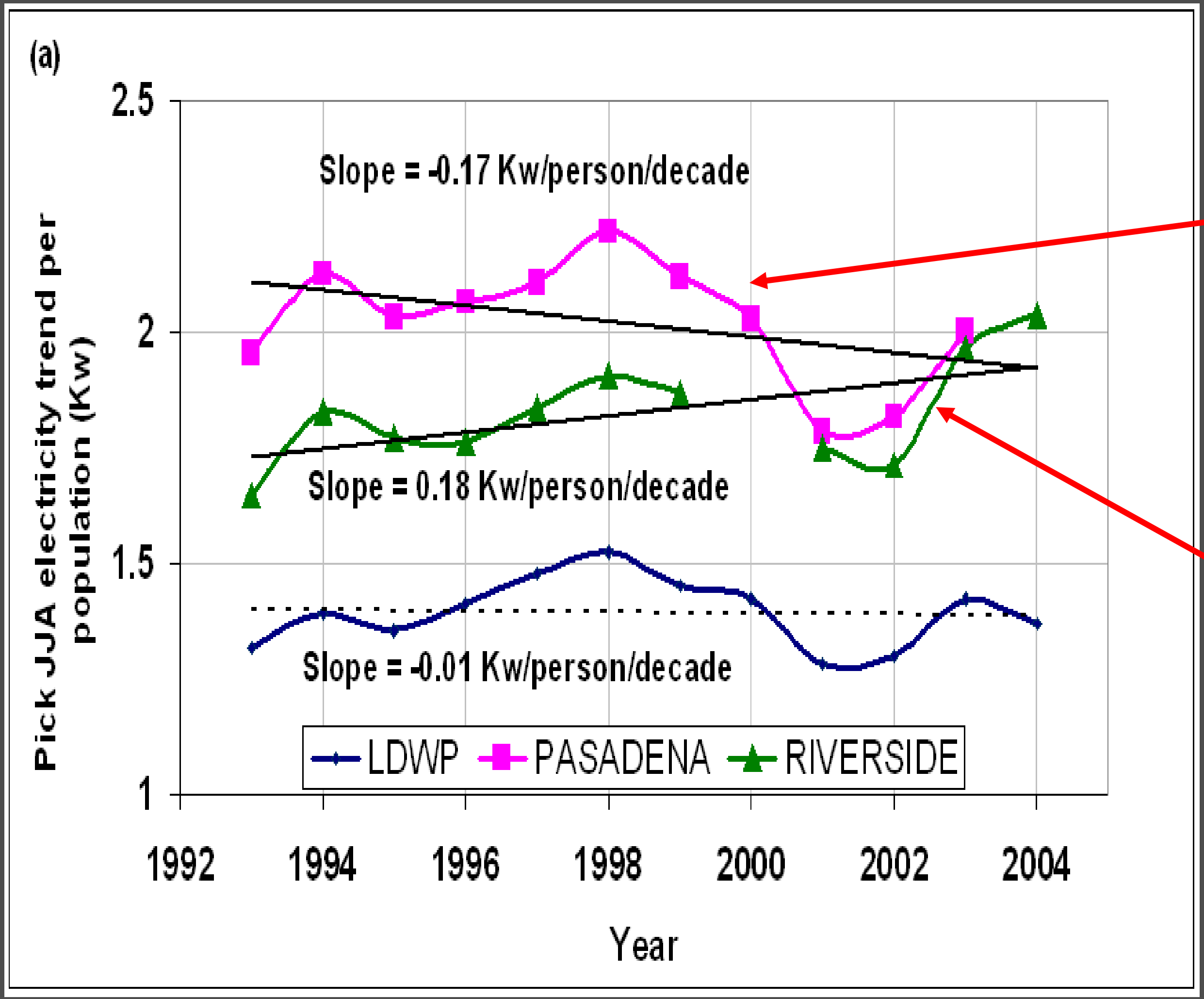
INCREASED HORIZONTAL T- & p-GRADIENTS (COAST TO INLAND)→

INCREASED SEA BREEZE FREQ, INTENSITY, PENETRATION, &/OR DURATION →

COASTAL REGIONS DOMINATED BY SEA BREEZES SHOULD THUS COOL DURING SUMMER DAY-TIME PERIODS

Impacts on Peak Summer Electricity-Trends for 1993-2004 (Kw/person/decade)

Data: LA Dept. of Water & Power (LDWP), Pasadena, Riverside

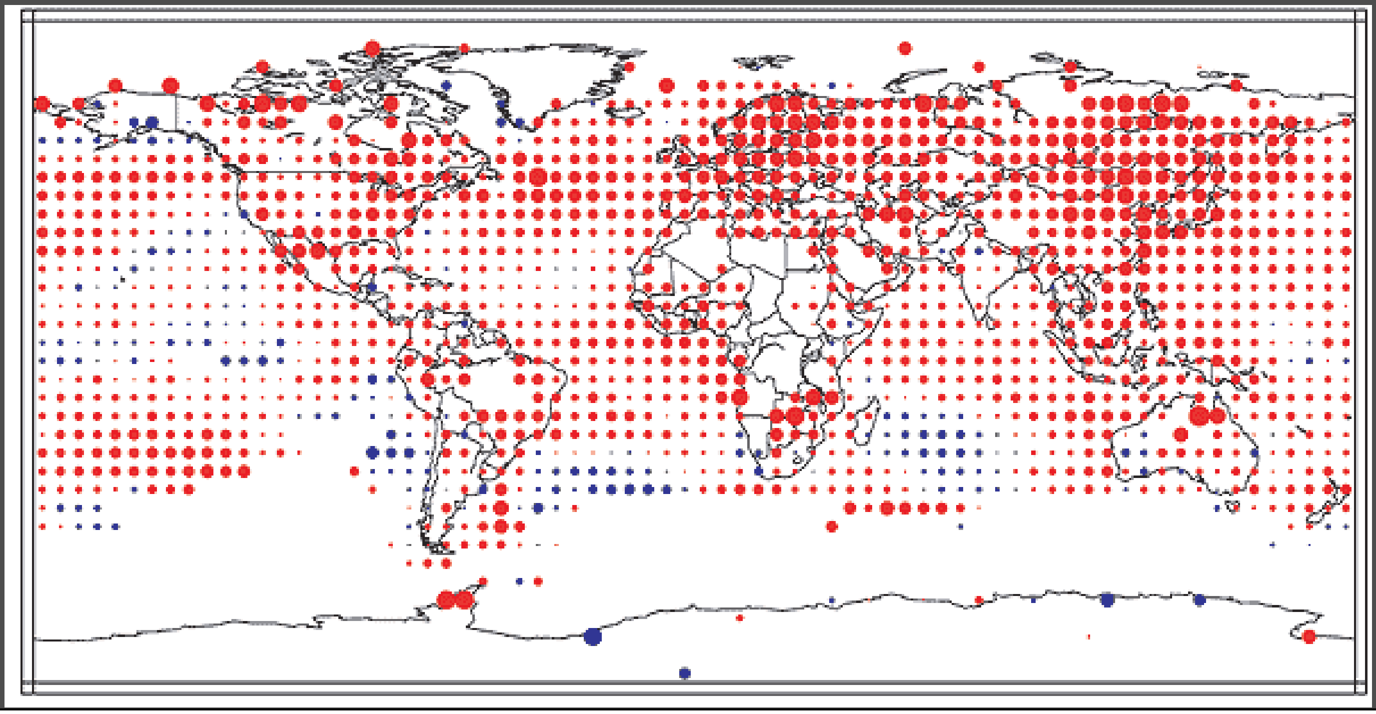


Results show:

- Coastal-cooling LDWP & Pasadena: down-trend (-7%/decade)
- Inland-warming Riverside: up-trend (10%/decade)

From: Lebassi et al. (2010)

Other Coastal Cooling Phenomena in the World

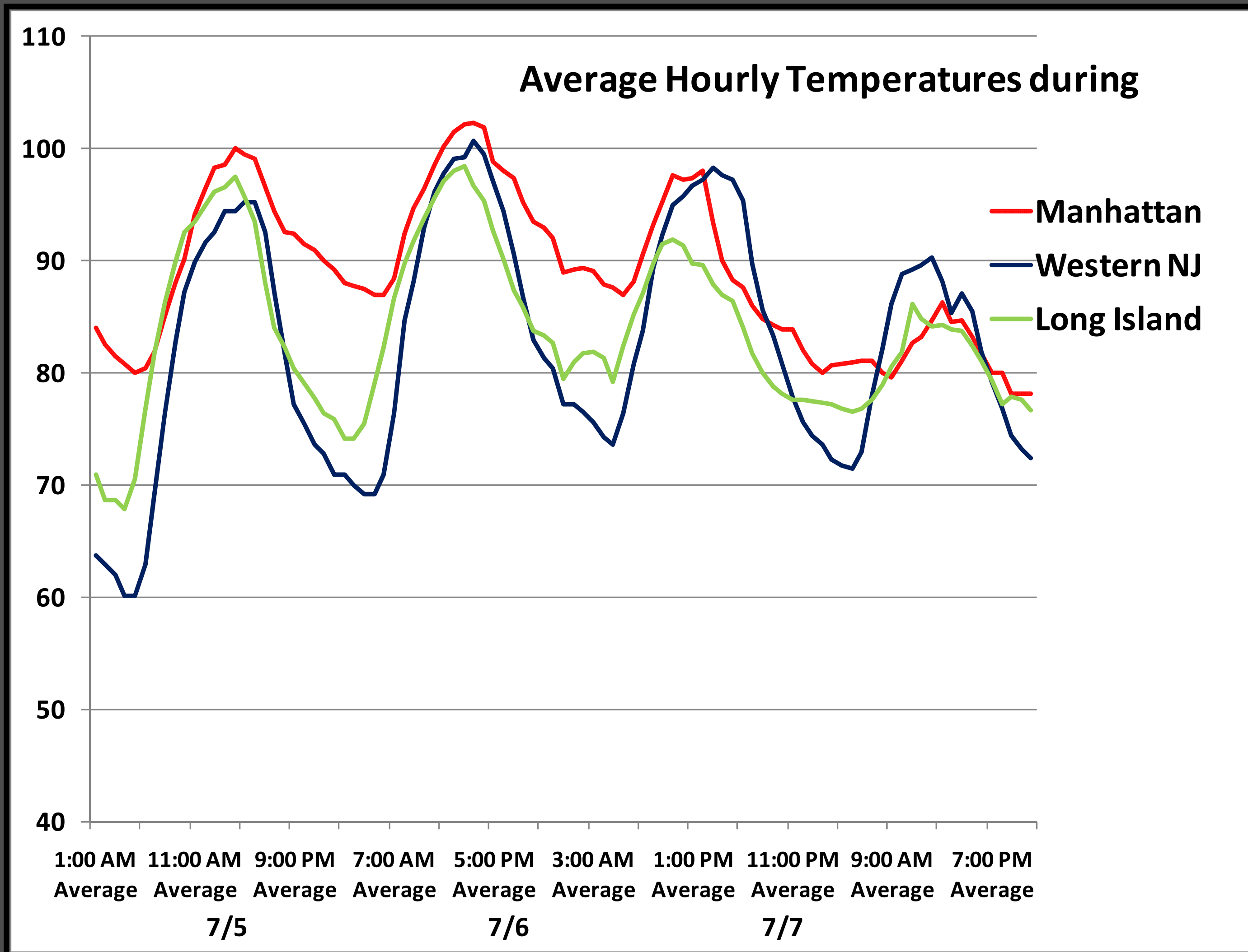


Similar coastal cooling effects have been recently reported in other regions of the world, more specifically, the South American coastline (Falvey and Garreaud, 2009, Gutierrez, 2009).

A global index to identify CC in other regions seems appropriate.

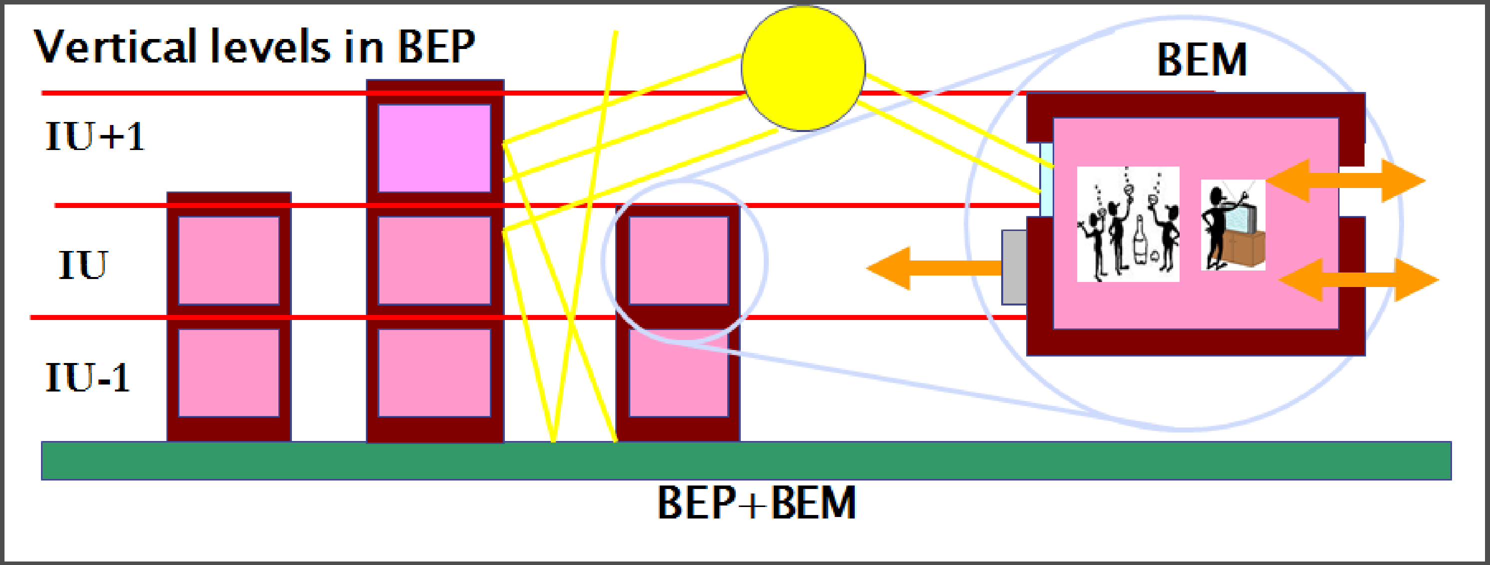
UHI in Dense Urban Environments and Extreme Events: NYC Case

NYC Summer 2010 Heat Wave Event



uWRF-A Next Generational City Scale Energy Model

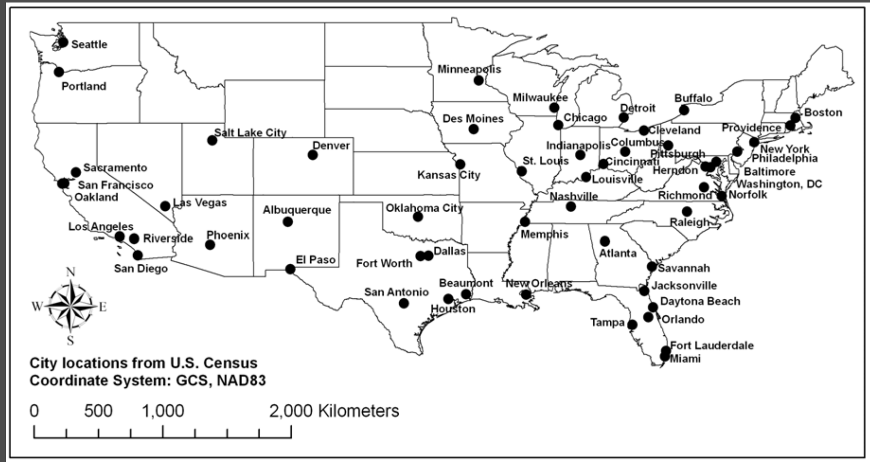
- BULK is a simple bulk scheme that defines a roughness length and thermal parameters to represent the effect of the urban areas.
- UCM is a single layer urban scheme (with the possibility to add a diurnal profile of the anthropogenic heat AH) that recognizes three different urban surfaces (walls, roofs, and roads).
- BEP is a multiple layer urban scheme (without the possibility to add AH) that permits a direct interaction with the PBL, and recognizes three different urban surfaces.
- BEP+BEM is a simple building energy model (BEM) linked to BEP:
- a) The time evolutions of floor air temperature and air humidity are estimated separately.
- b) Natural ventilation, heat generated by equipment and occupants, the convective heat through the walls, and the radiation through the windows are considered in the model.
- c) The heat needed for cooling/heating the indoor air temperature can be computed considering an air conditioning (AC) system model.



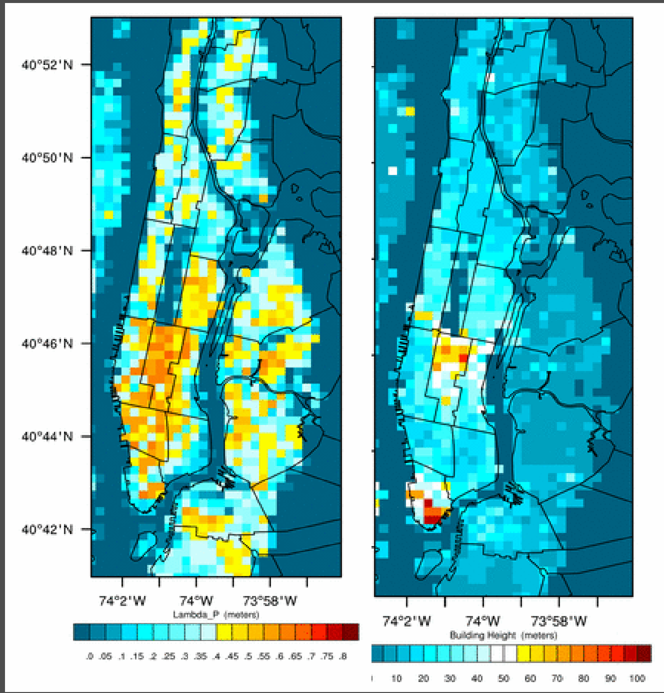
Methdology: Building Data:

National Building Statistics Dataset (NUDAPT):

The NBSD2 consists of 13 building statistics computed from airborne Lidar data and other sources of information by the National Geospatial-Intelligence Agency (NGA) at 250-m and 1-km horizontal spatial resolutions from three-dimensional building data for 44 metropolitan areas in the US (Burian *et al.,2008).*



Gridded NUDAPT Parameters



Building Area Fraction Building Height

Example of NUDAPT ingestion by table:

```
Index:      1             2               3
Type:  Commercial, Hi-dens Res, Low-dens Res
"
# ZR:   Roof level (building height)   [ m ]
#       (sf_urban_physics=1)

ZR: 47.2,  26.2, 19.2
```

Methodology
Land Use Assimilation

- Primary Land Use Tax Lot Output (PLUTO) was created by the New York City Department of City Planning (DCP) to meet the growing need for extensive land use and geographic data at tax lot level.
- Data were interpolated from an irregular grid with a NAD83 New York/Long Island projection to a regular WGS84 Lambert Conformal Conic with a resolution of 250 meters.
- Building heights are calculated by multiplying the number of building floors in the tax lot by a floor height of 3 meters.
- Building plan area fraction (λ_P):

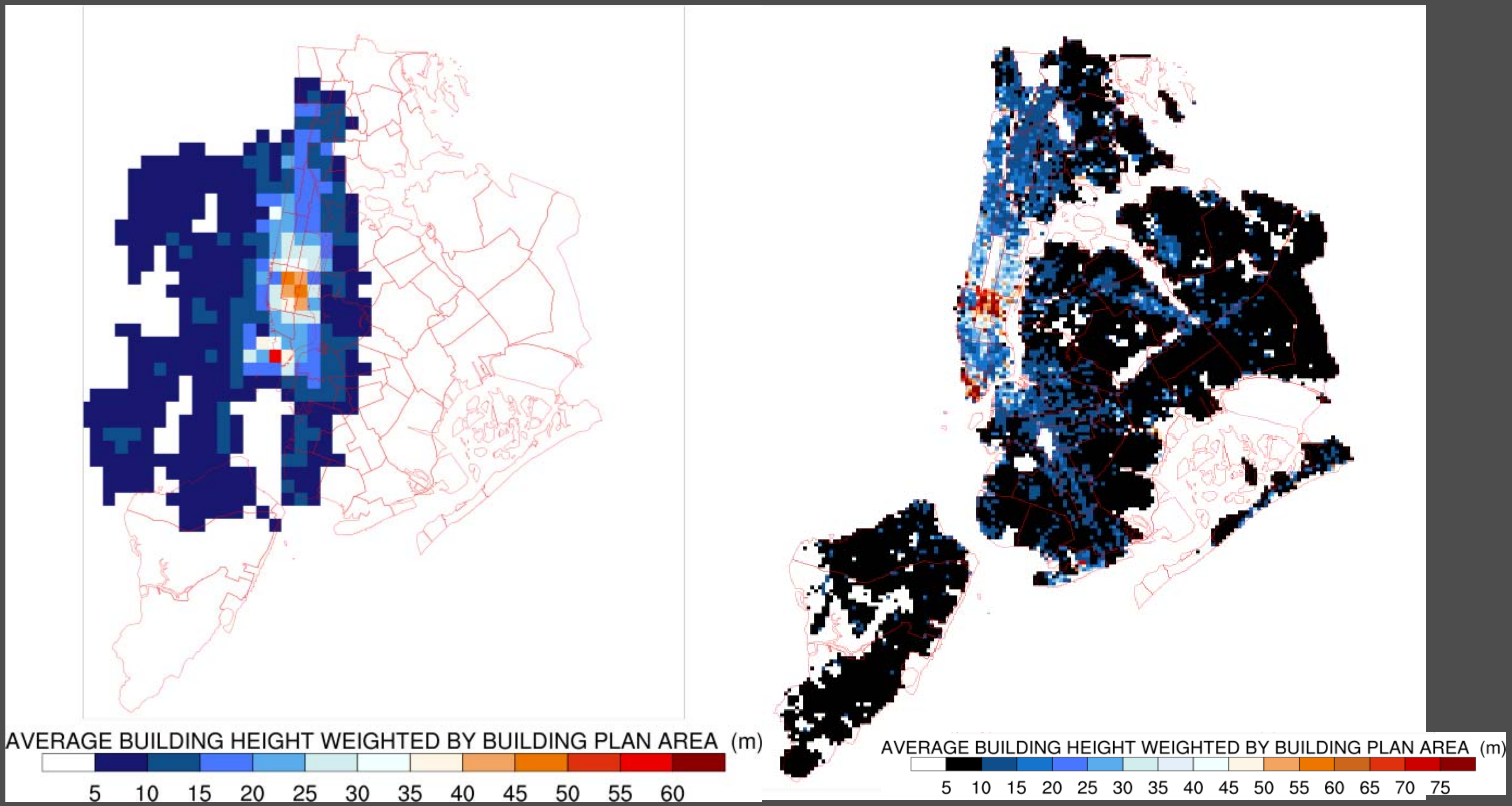
$$\lambda_P = \frac{A_P}{A_T} \qquad A_p = \frac{BldgArea - GarageArea}{NumFloors}$$

- Building surface area to plan area ratio (λ_B):

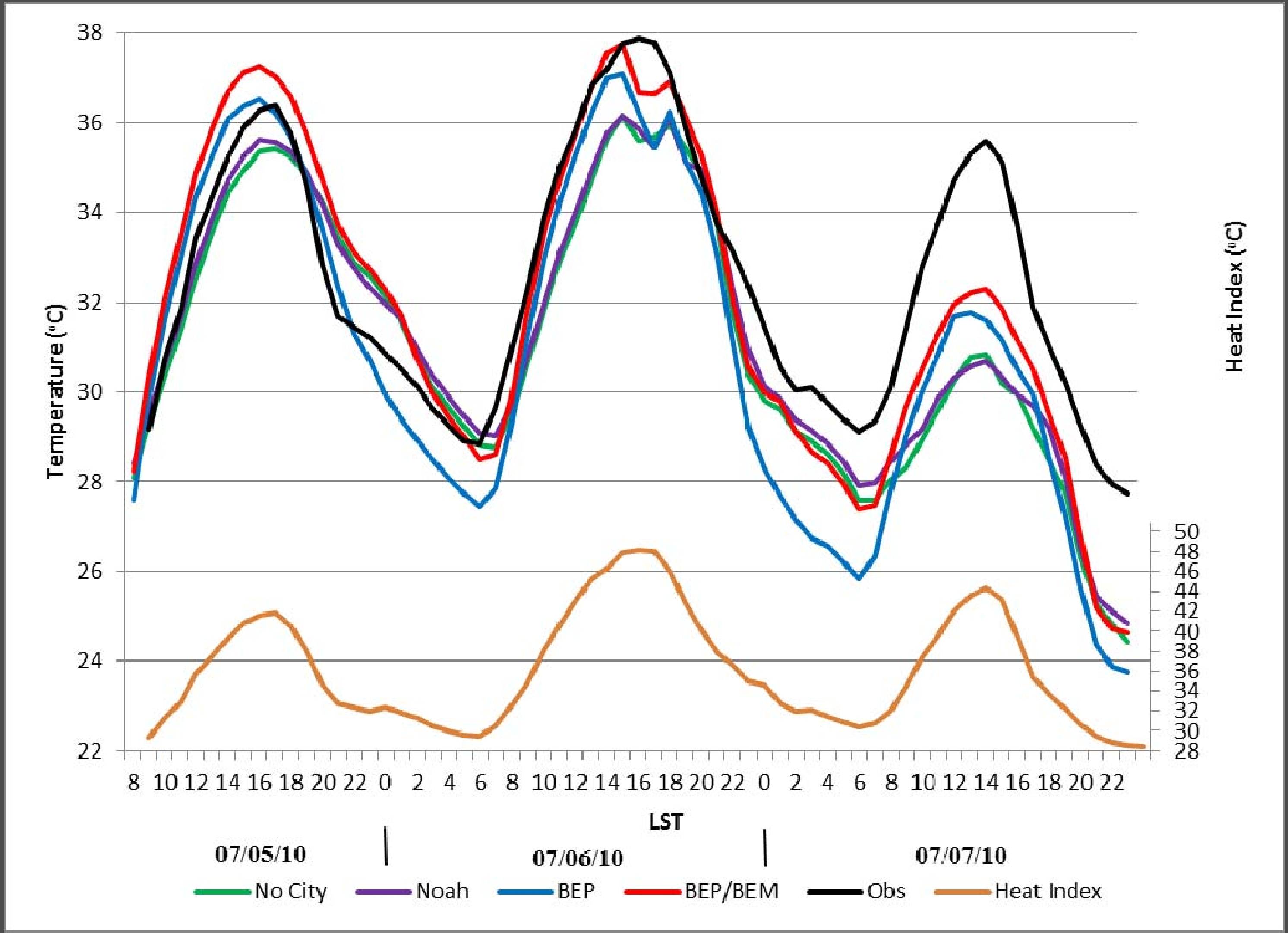
$$\lambda_B = \left(\frac{2h}{b} + 1\right)\lambda_p$$

Methodology

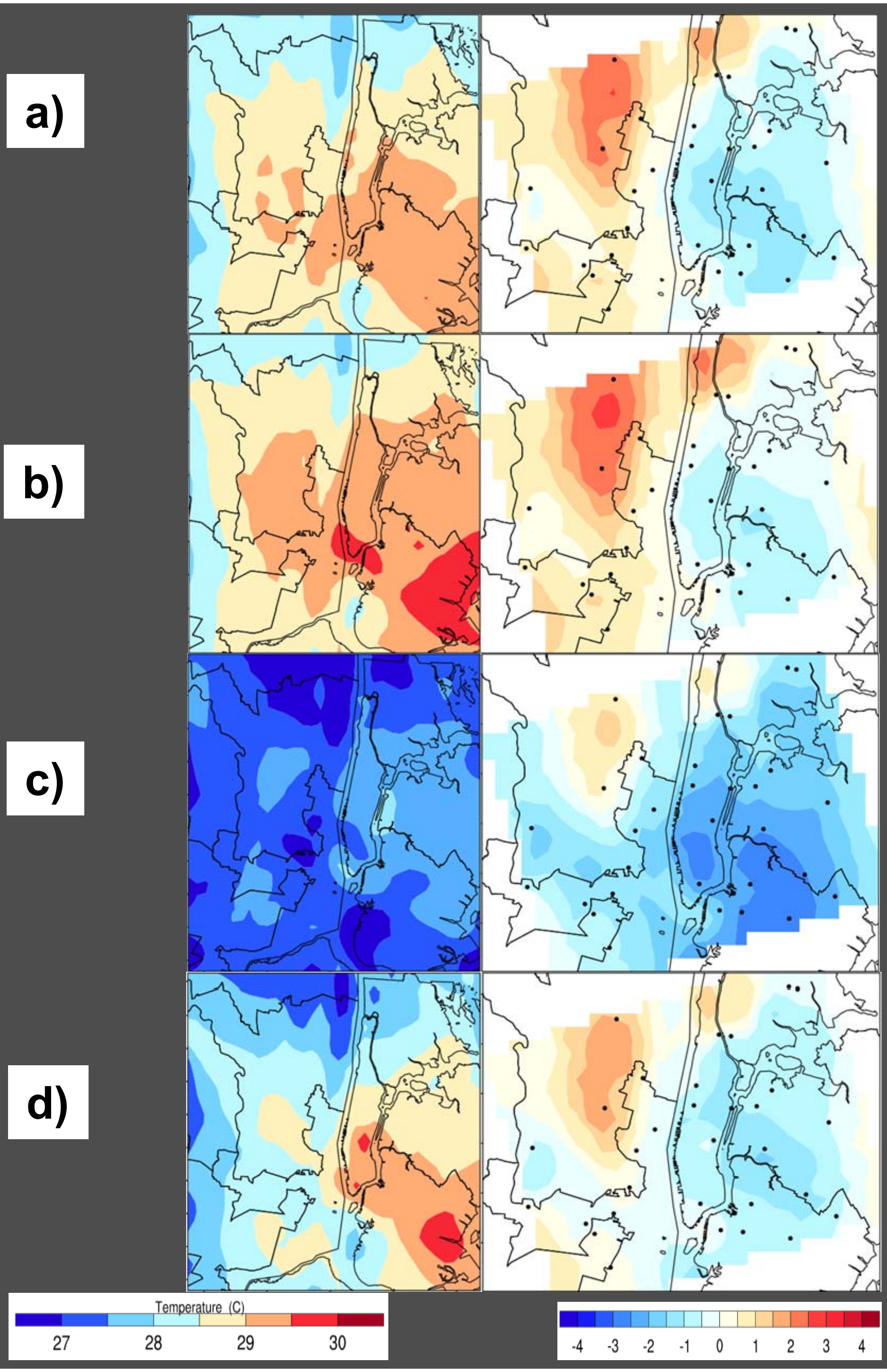
Primary Land Use Tax Lot Output (PLUTO) Assimilation



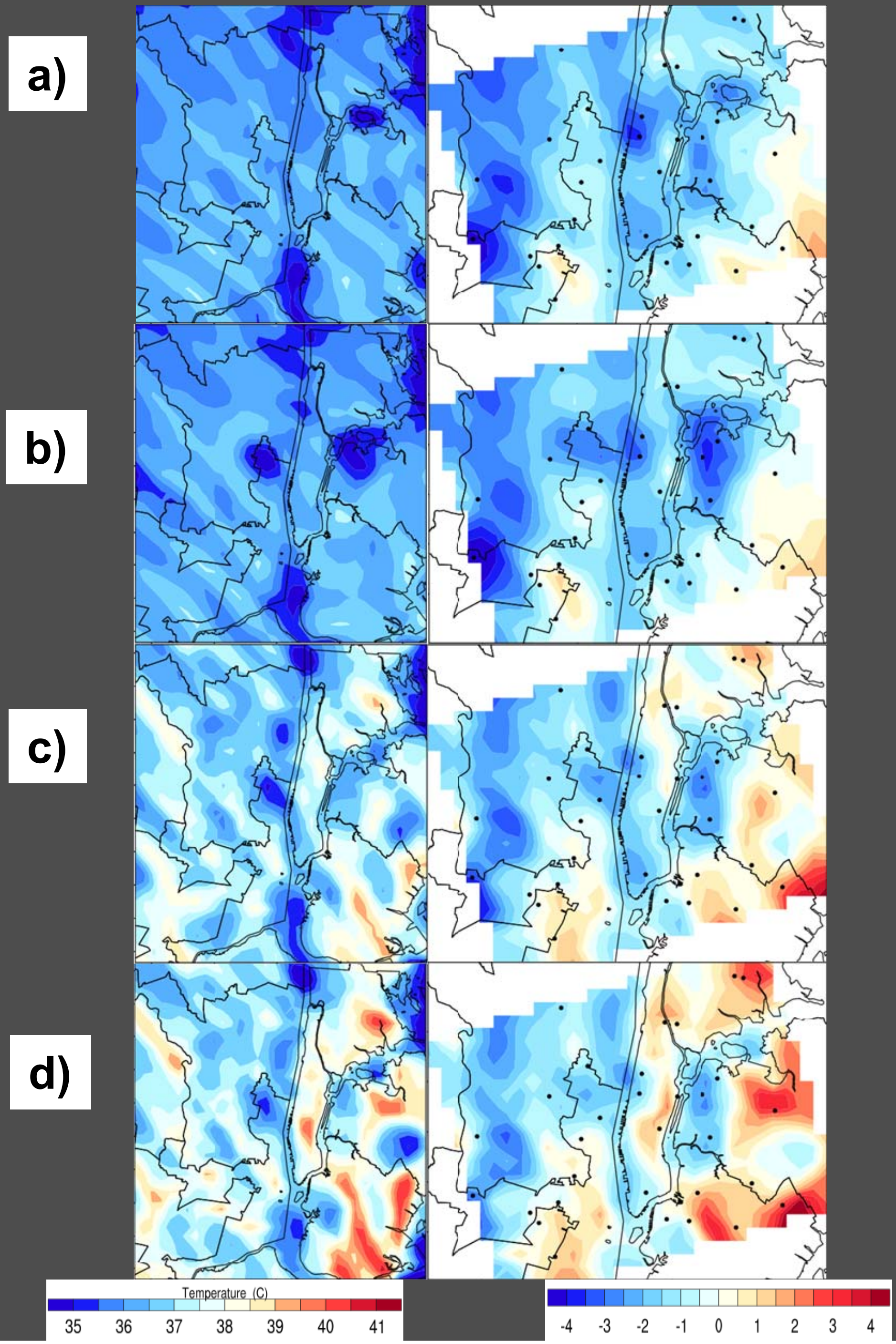
Average Building height from NUDAPT at 1 km (Left) and PLUTO at 250 m (Right)



Observed and modeled surface temperature and heat index time series from July 5th to July 7th .

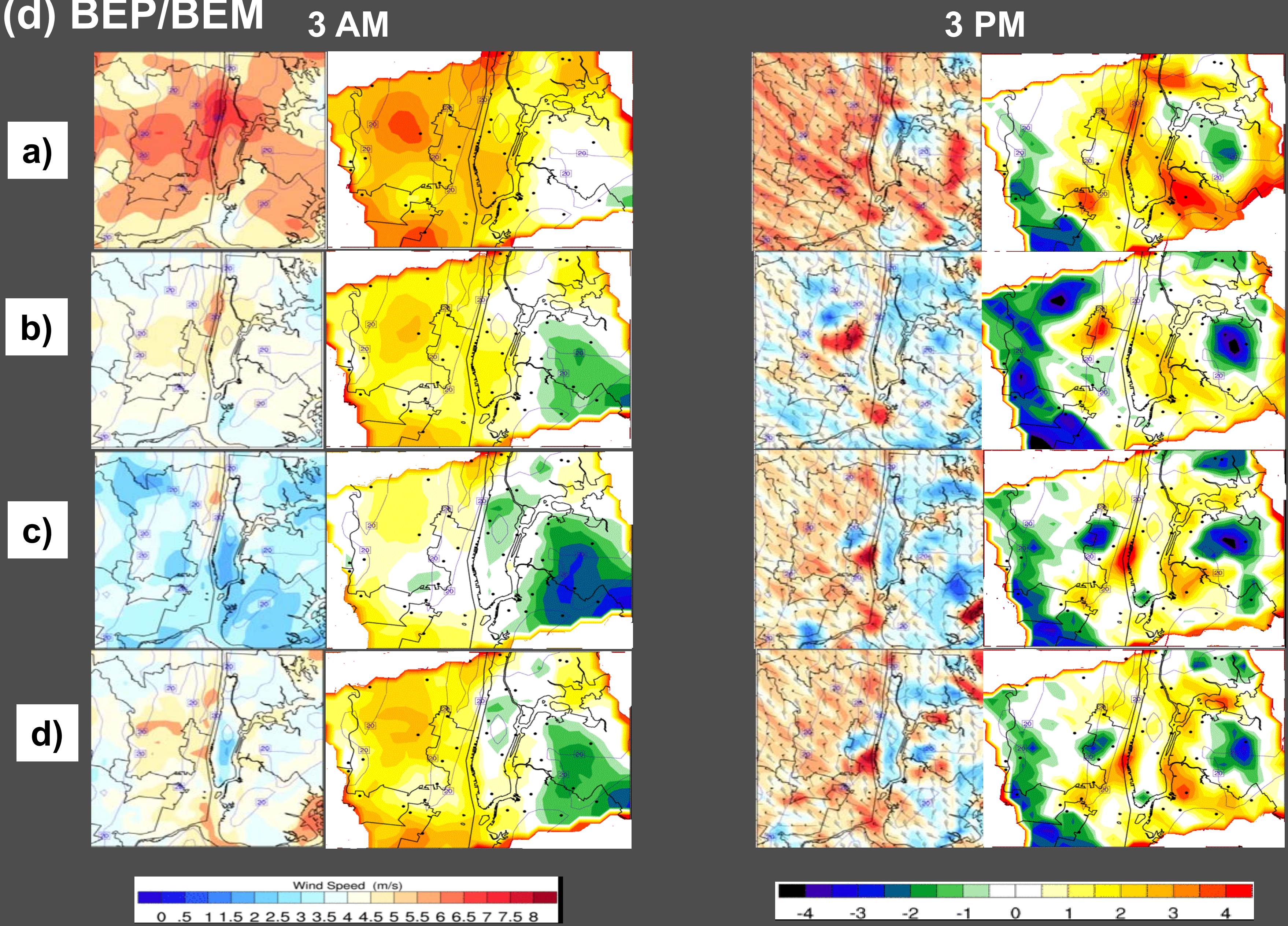


Temperature distribution (left) and temperature difference between observations and model output (right) at 0600 LST on July 6th for (a) No City (b) Noah (c)BEP (d) BEP/BEM.



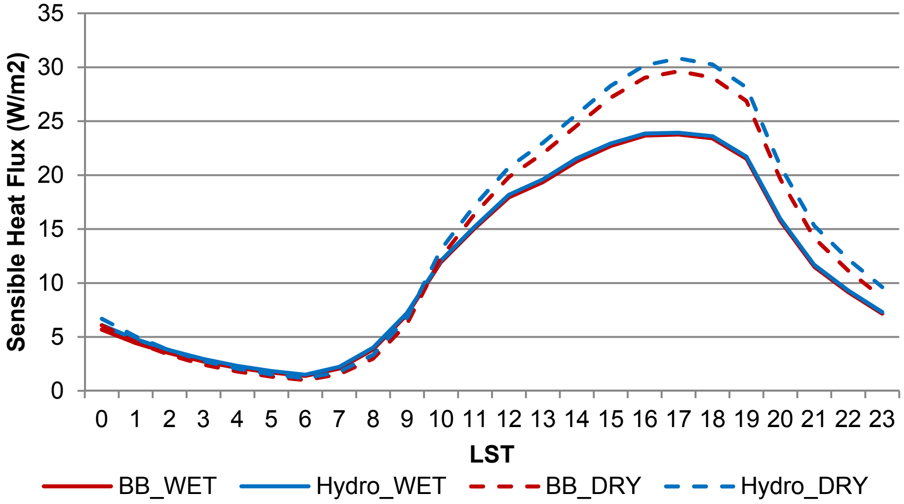
Temperature distribution (left) and temperature difference between observations and model output (right) at 01500 LST on July 6th for (a) No City (b) Noah (c)BEP (d) BEP/BEM.

Heat Wave Results (Model-Observations) Surface Wind Speed (Left) and Errors (Right): on July 6th for (a) No City (b) Noah (c)BEP (d) BEP/BEM

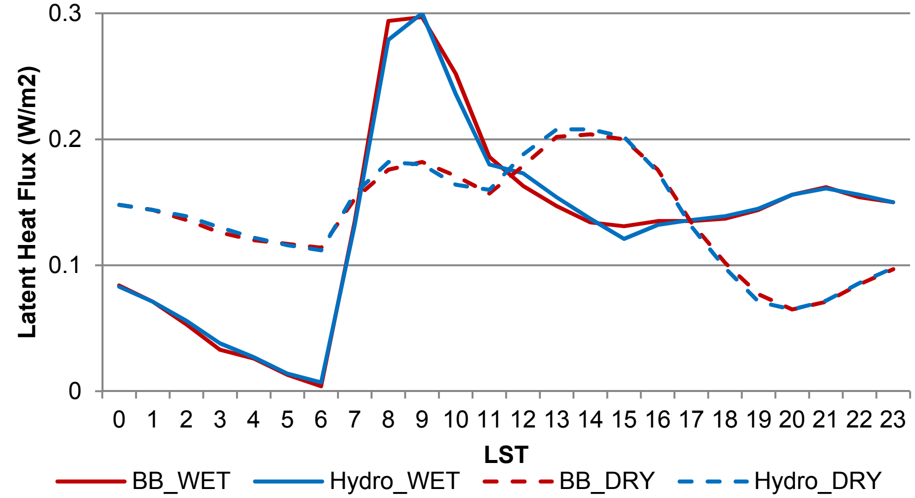


Anthropogenic Heat Partition

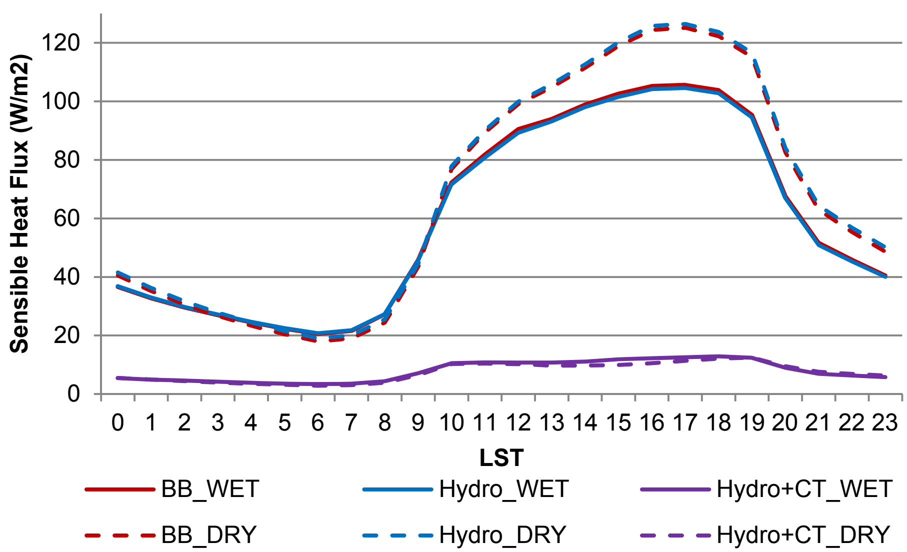
Daily Cycles



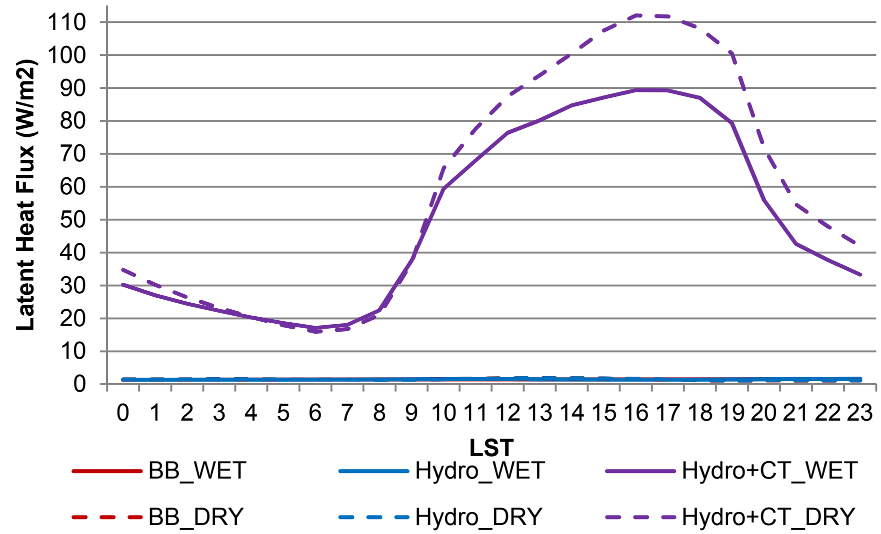
Modeled A/C Sensible Heat Daily Cycle for Residential Areas.



Modeled A/C Latent Heat Daily Cycle for Residential Areas.



Modeled A/C Sensible Heat Daily Cycle for Commercial Areas.

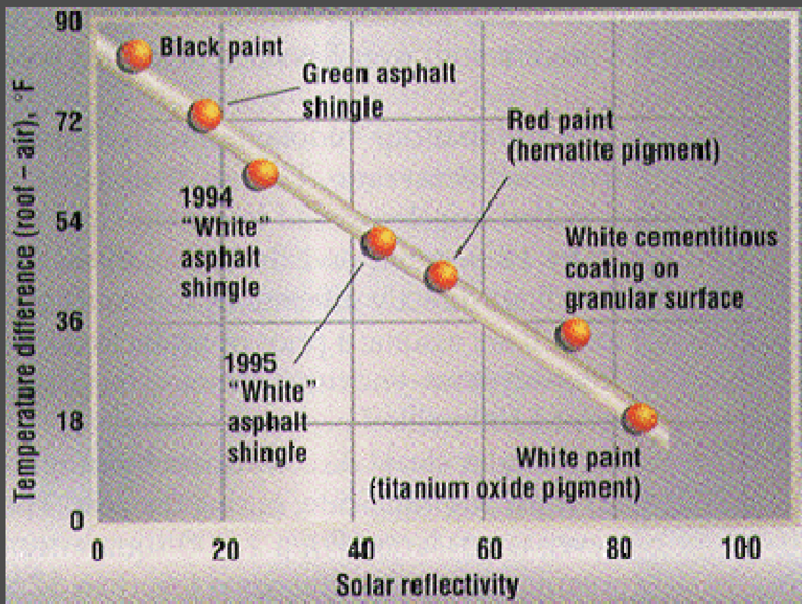


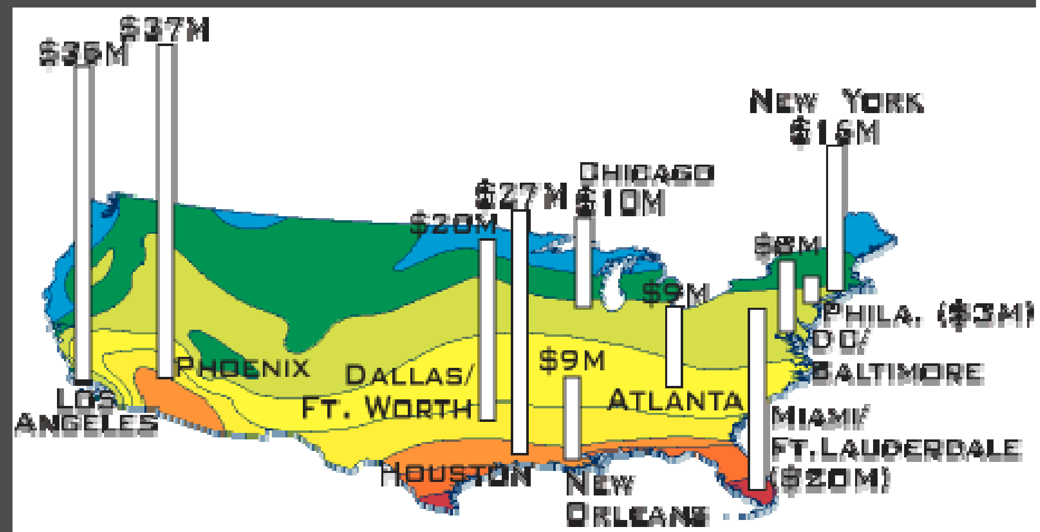
Modeled A/C Latent Heat Daily Cycle for Commercial Areas.

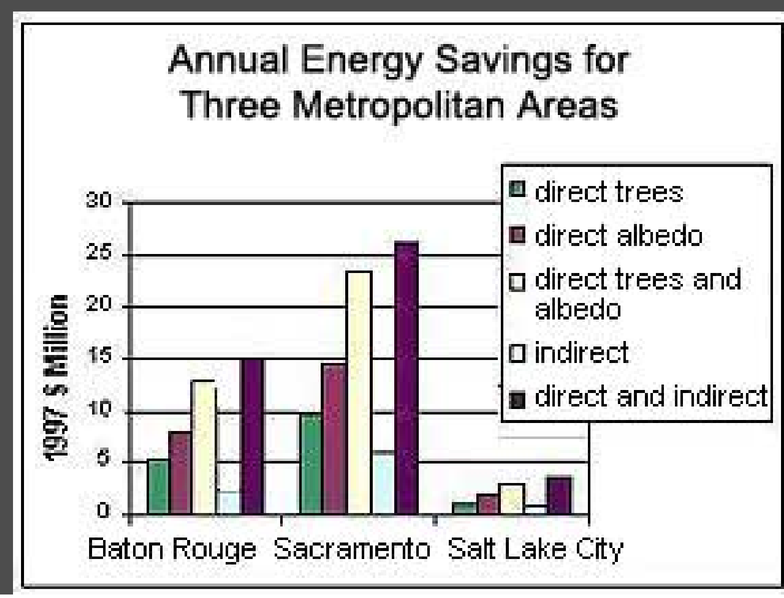
What Can Be Done? (i.e. Mitigation of UHI)

- Greening the landscape
- Reflecting the sun
- Planning the growth
- Community action

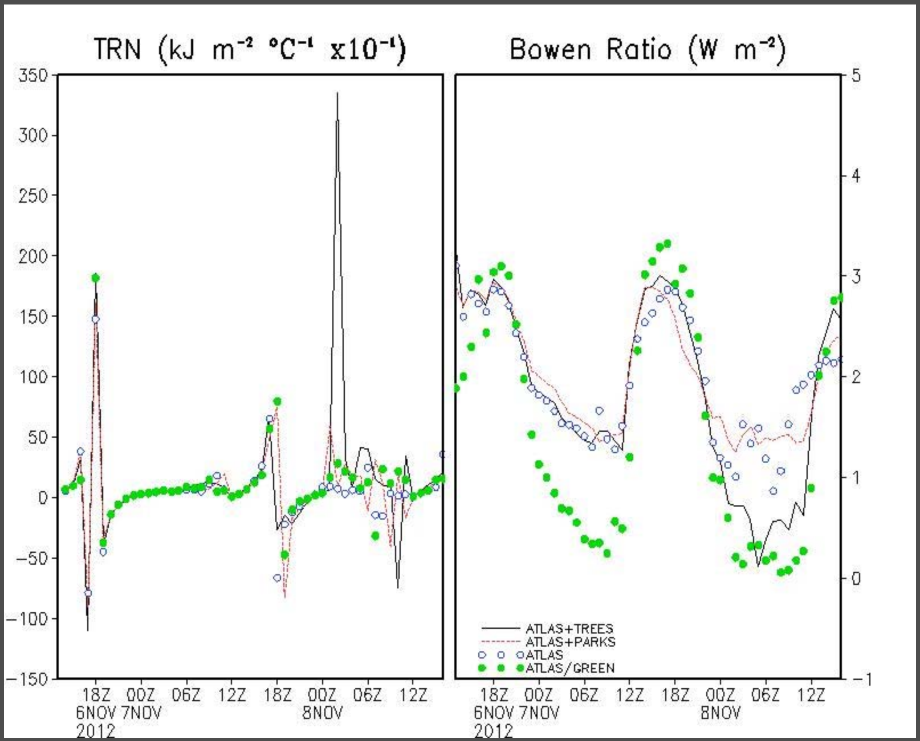
Reflective & Green Roofs







Possible Mitigating Alternatives for SJU
(Comarazamy et al. 2013)

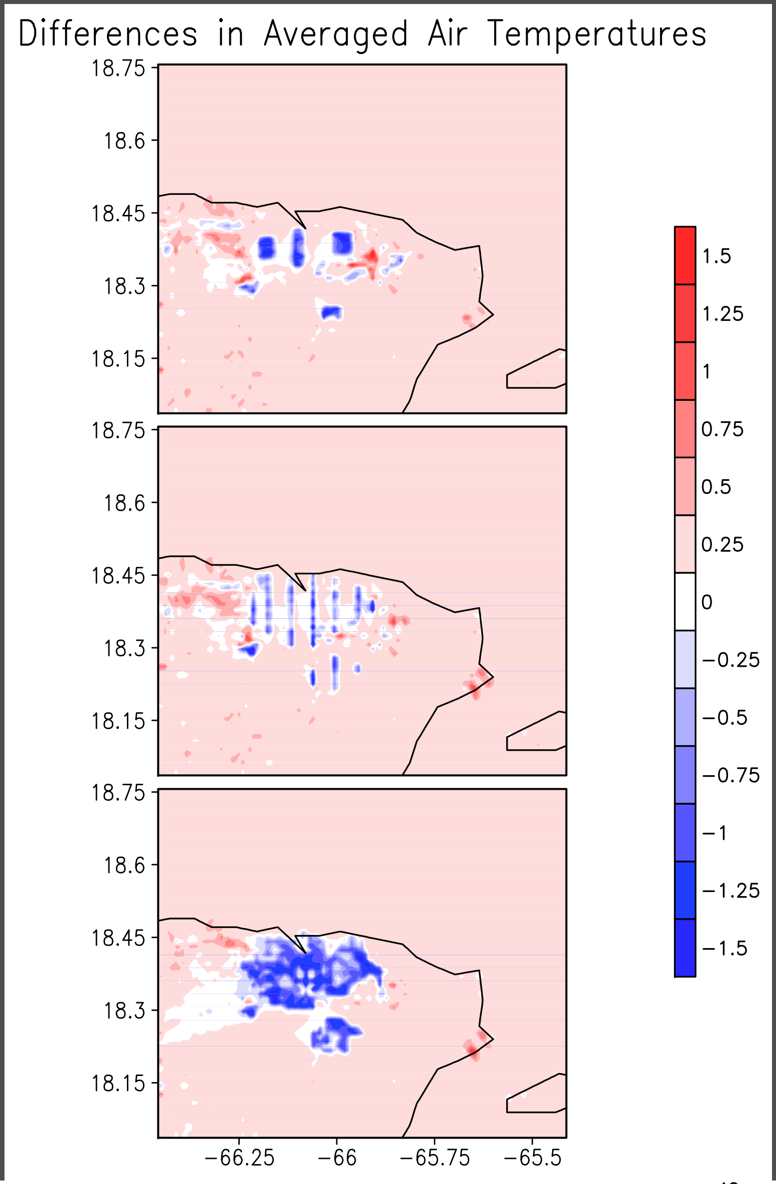


Averaged air temperature differences (ºC) at 2m AGL between Parks (Right-top), Trees (R-center), and Green Roofs (R-bottom) scenarios and corresponding TRN and B Ratio (Top).

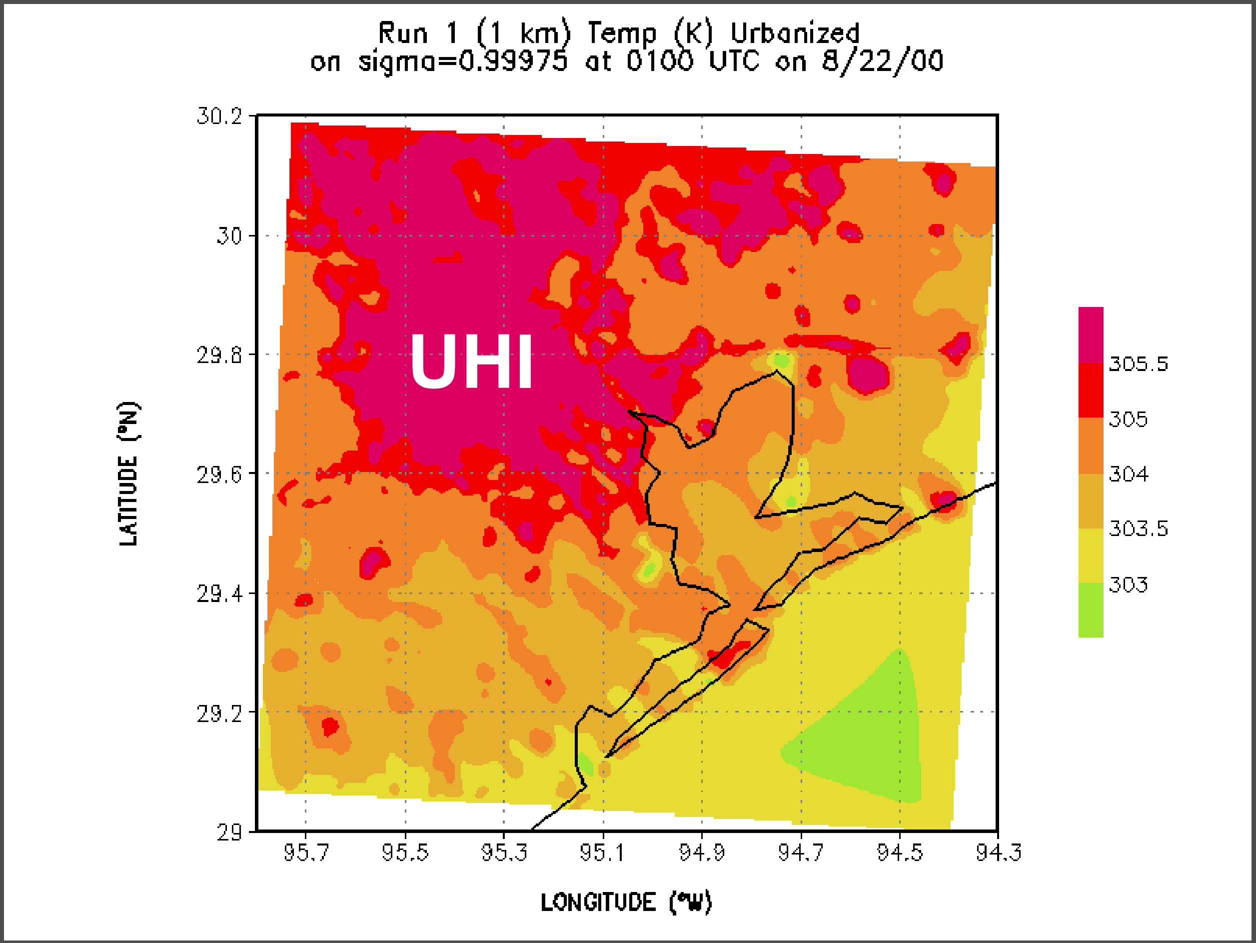
$$TRN = (R_n * dt) / dT$$

• $B = H / LE$

$$R_n = H + LE \pm G$$



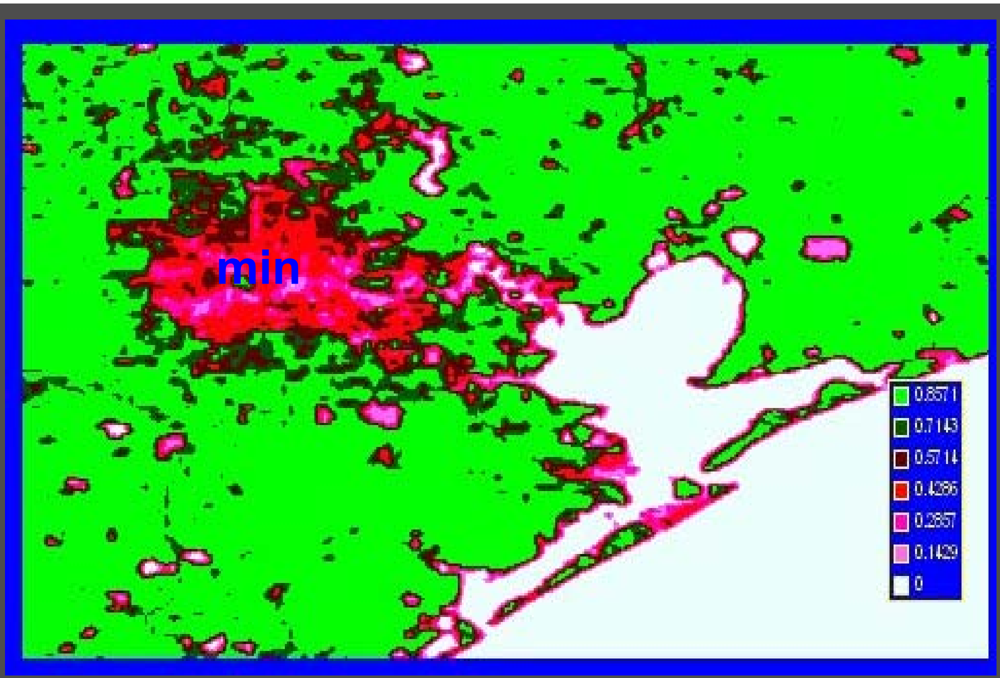
Houston Greening Case:
Urbanized Domain: UHI (8 PM, 21 Aug)



Simulations conducted with uMM5->3.5-K UHI

Courtesy of: Bornstein et al.

Houston Greening Case:



Base-case (current) veg-cover (0.1's)

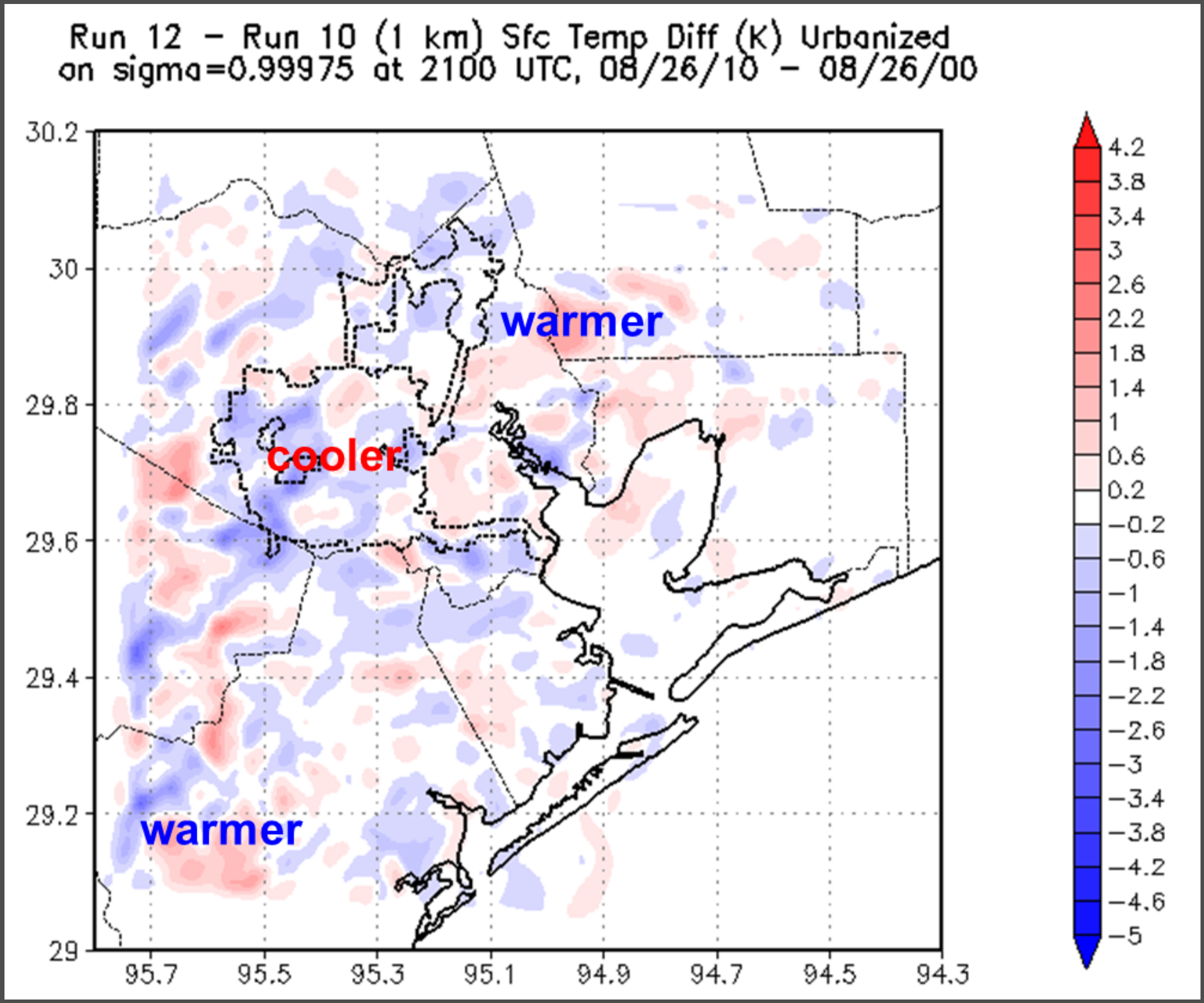
- urban min (red)
- rural max (green)

Modeled changes of veg-cover (0.01's)

- Urban-reforestation (green)
- Rural-deforestation (purple)

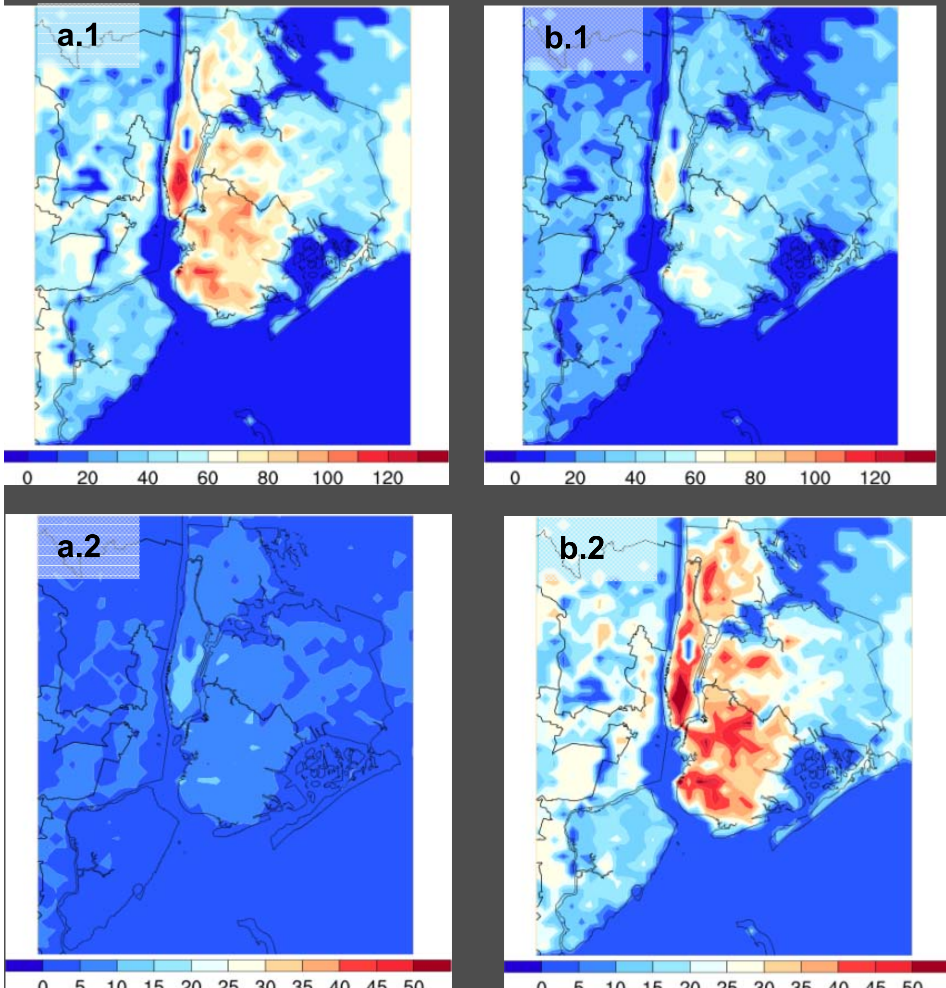
Houston Greening Case:

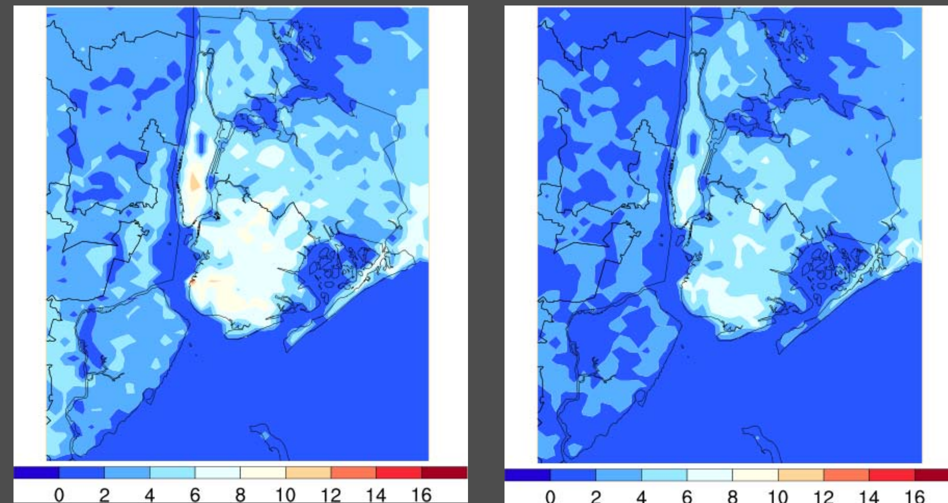
Run 12 (urban-max reforestation) minus Run 10 (base case) → near-sfc ∆T at 4 PM shows that: reforested central urban-area cools & surrounding deforested rural-areas warm



Mitigation Strategies for NYC

Heat Partition Spatial Distribution (W/m2)



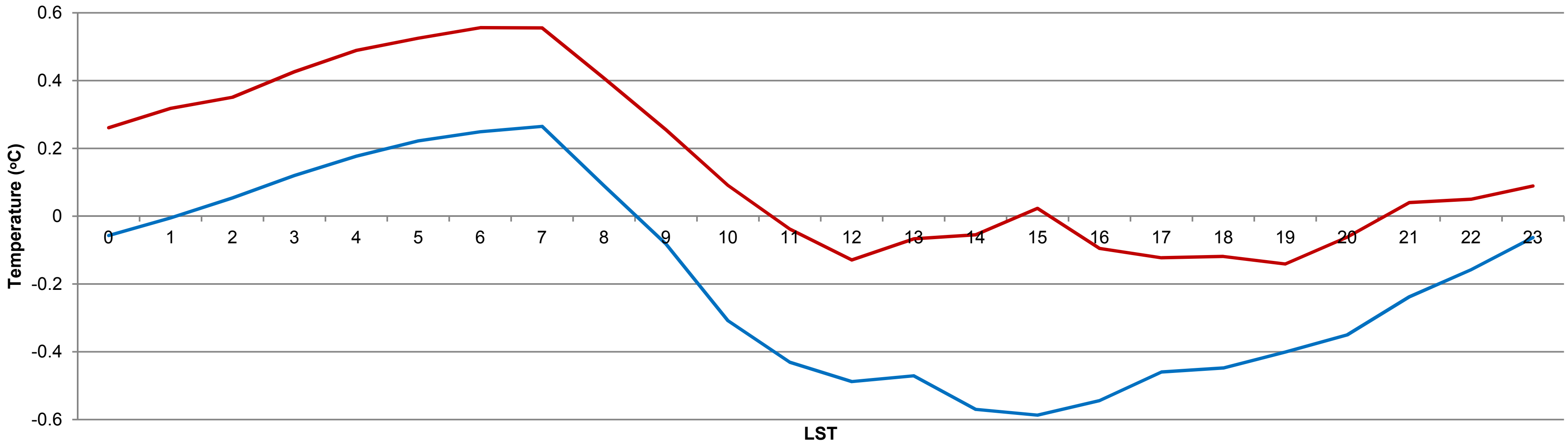


Average Daytime White Roof Sensible Heat Flux During Dry (Left) and Wet (Right) Days

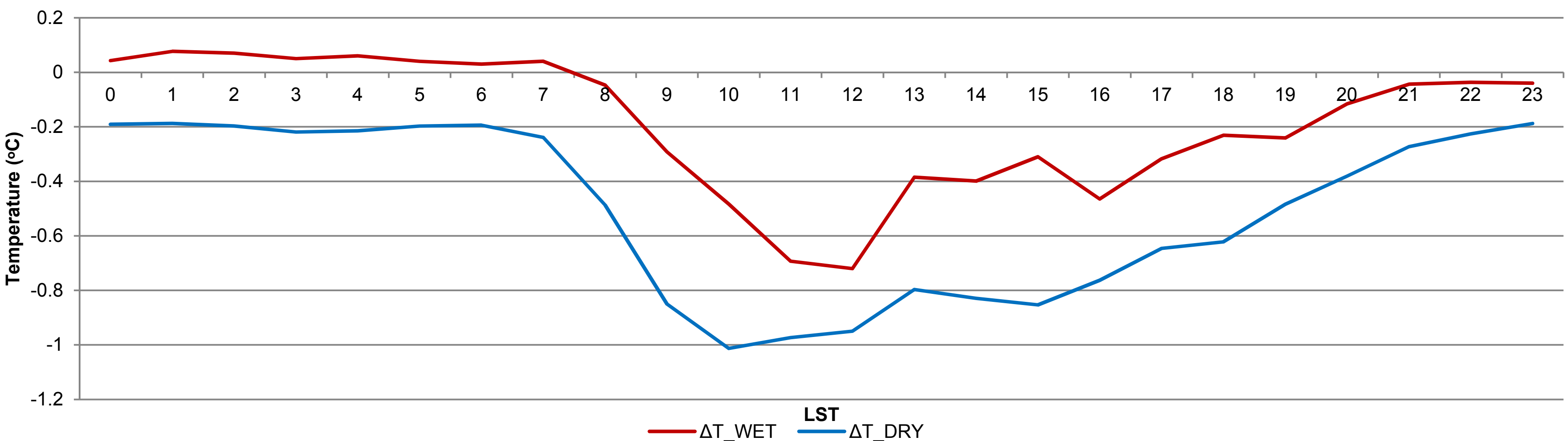
Average Daytime Roof Sensible (1) and Latent (2) Heat Flux for Hydro (a) and GR (b).

Mitigation Strategies for NYC

Green Roof Anthropogenic Heat and Temperature Impacts



2m Temperature Daily Cycle difference between GR and Hydro for Commercial Areas.



2m Temperature Daily Cycle difference between White Roofs and Hydro for Commercial Areas.

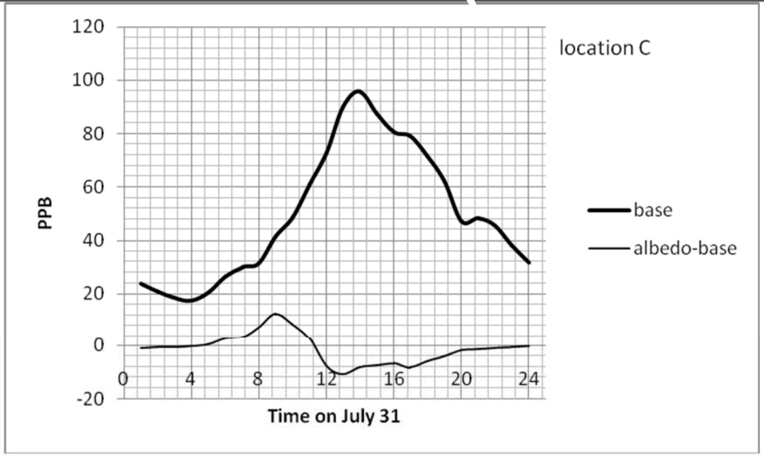
SMUD Cool Roof Program

Estimates of Savings

- **Average energy cooling load savings of 20%**
- **Average energy cooling load savings are 0.15 kWh/year/Sq.Ft.**
- **Average demand savings are 0.25 W/Sq.Ft.**

SMUD
SACRAMENTO MUNICIPAL UTILITY DISTRICT
The Power To Do More.™

Mitigation (white roofs) Impacts on Ozone (Sacramento)



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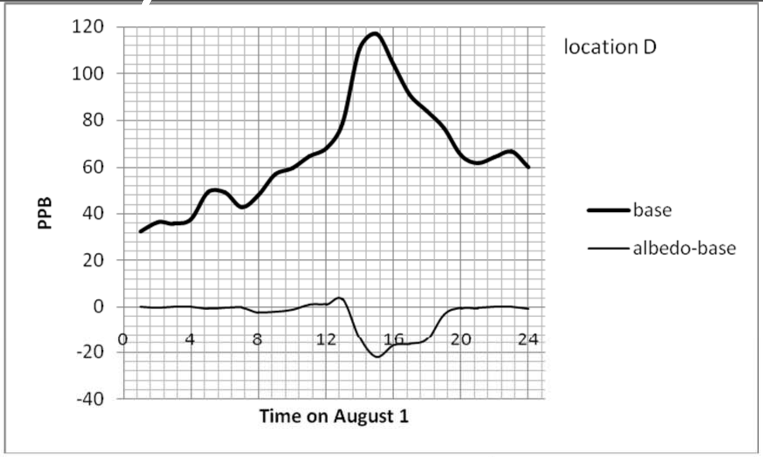

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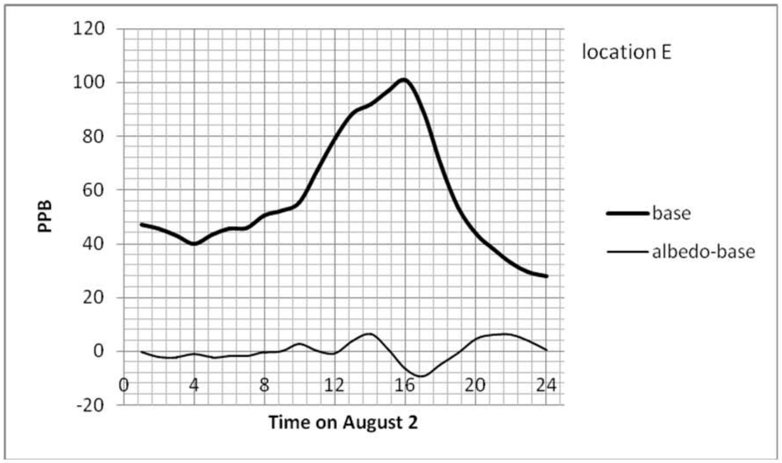


e

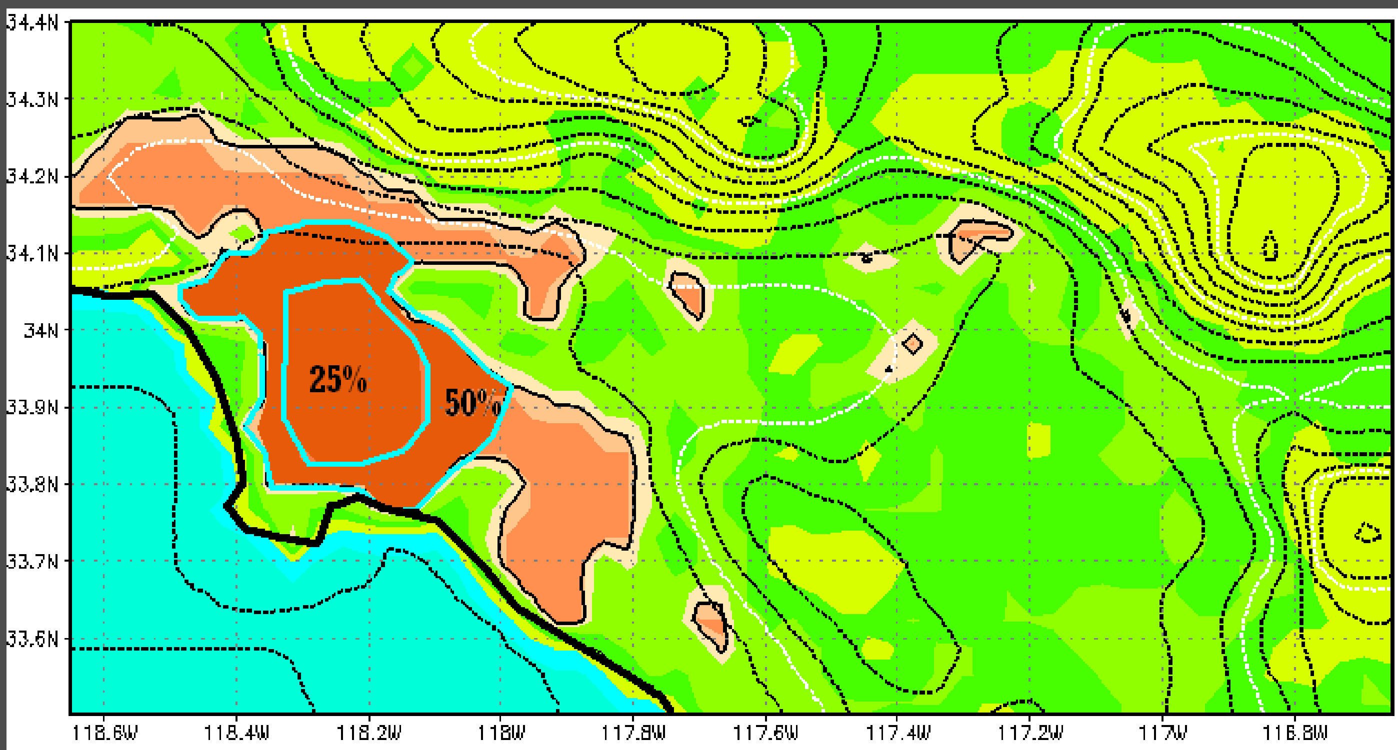
Base ozone concentrations (top, thick lines) and changes (bottom lines) time series at locations of each day's simulated domain-wide peak in Sacramento. Locations are downwind of Downtown. Source: Taha, H. *Atmospheric Environment.*

Altostratus Inc.

Impacts of Renewable Energy on UHI: LAX Case

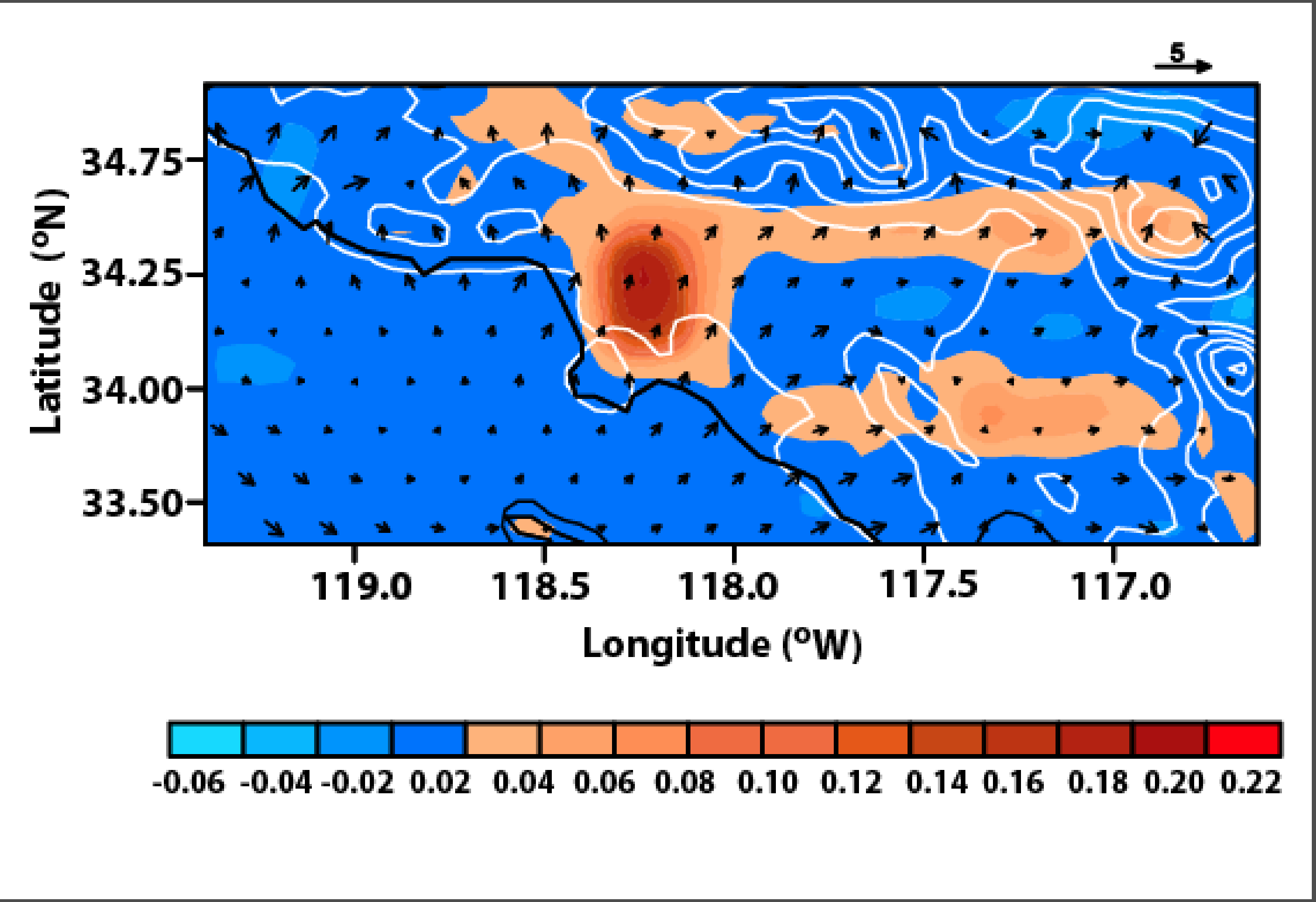
Solid lines: key topographic-height levels

- Input: Standard USGS land use classification
- Output: dominant class (colors), with parameter values as weighed averages
  - Grassland: green
  - Shrub land & agriculture, forest: yellow
  - Urban: red
  - PV: dark red in blue enclosure (25% & 50%)

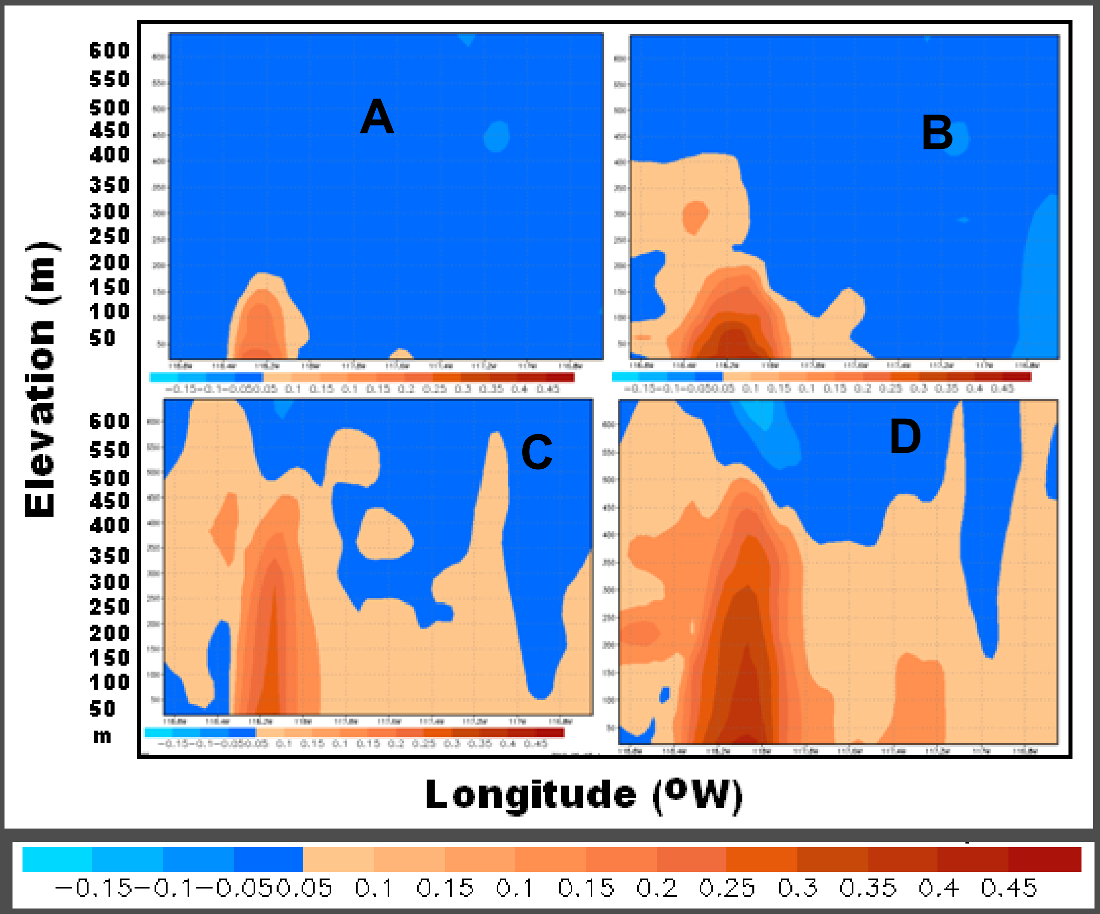


Run 1-Run3 (50% PV)

- Summer Thermal Response in LAX Area
- Stronger UHI, however still contained within the city
- In the morning before the sea breeze is initiated, the temperature increase is localized to the PV installed urban area.



Average July 1-23 2002 10 AM & 4 PM LST: Run 1 minus Run 3 T-Difference (ºF) and across Domain 2 at 33.95ºN in previous figure



A. 25% PV, 10 am

B. 50% PV, 10 am

C. 25% PV, 5 PM

D. 50% PV, 5 PM

Result:

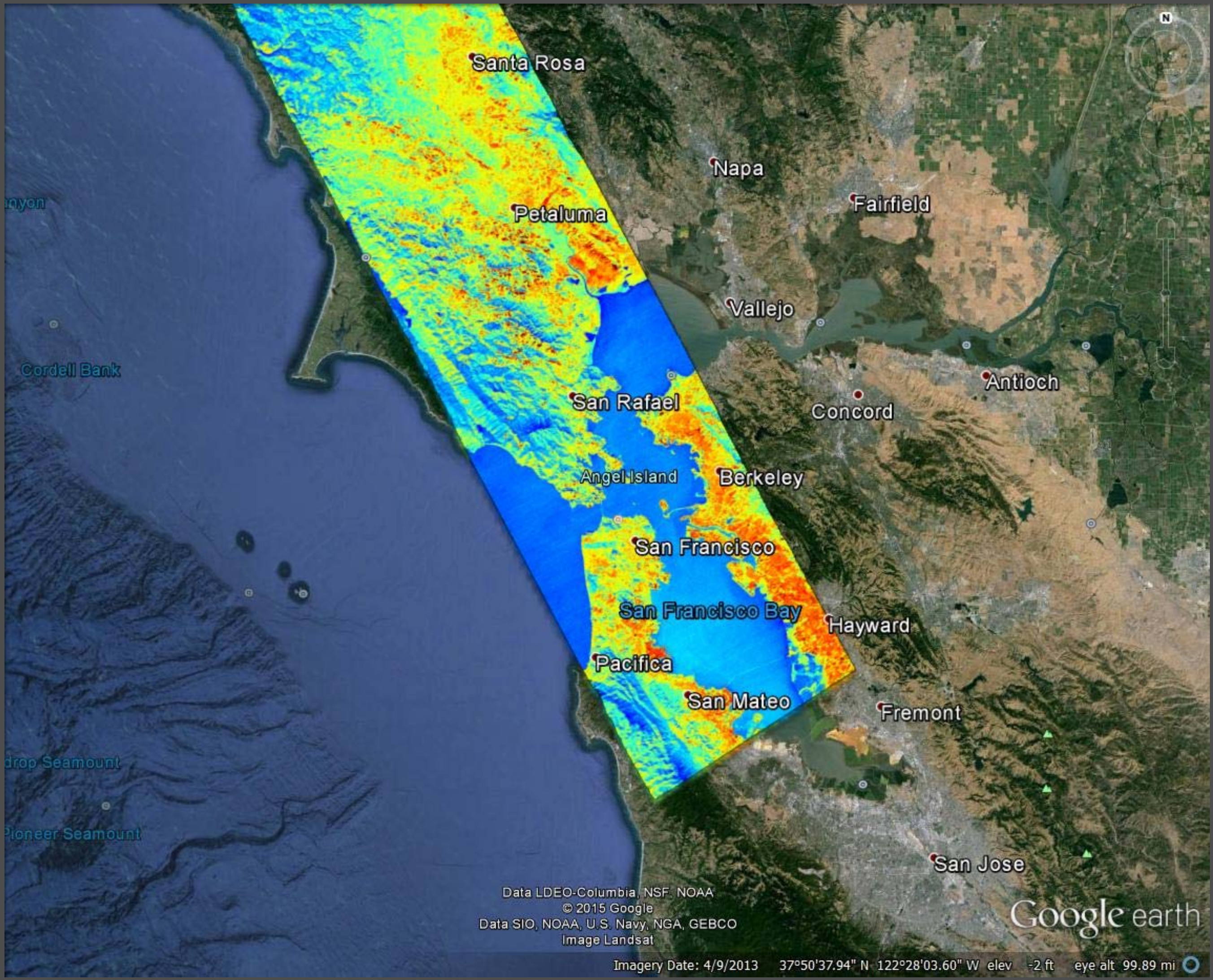
- For the 25% PV (A) the heating is very localized and shallow at 10am LST, while the 50% PV (B) is stronger and more spread
- By 4pm heating is advected inland due to the SB, more advection being from the 50% PV (D)

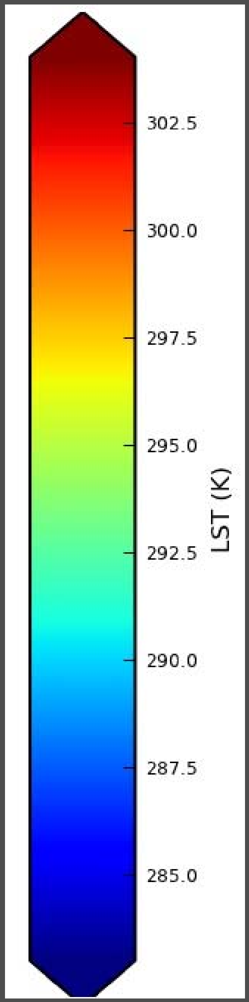
The heating is contained within the boundary layer

Summary

- **Urbanization (UHI) is a clear indicator of anthropogenic induced climate change.**
- **LCLU may induce changes in the regional climate impacting surface temperature, flow patterns, and the hydrological cycle.**
- **Remote sensors (HR & LR) can be combined with climate data & modeling tools to analyze UHI impacts over coastal metropolitan areas (see next slide for SFO).**
- ***For tropical regions; combined positive (negative) effects of LCLU changes and global warming on simulated maximum temperatures (precipitation).***
- ***Western coastal/rban regions show an unexpected reaction to LCLU+GW.***
- **Mitigation alternatives have demonstrated to be effective tools in reducing UHI; however, implementation must be careful, solutions are unique to the City.**

Land Surface Temperature (LST) over San Francisco . Image taken at 11/24/14 at 1:00pm local time Horizontal resolution: 35 m





Reflections for Coastal/Urban Regions

- Coastal/urban regions are particularly sensitive to climate changes, and respond **in unique ways** to global/regional environmental changes and to local dynamics.
  - The assumptions of positive feedback, may clearly not be correct.
- The complex D(LCLU+Climate) for coastal urban environments requires both: Long term climate records (SSTs; UA) & long term land surface properties *at the urban scale resolutions (**re: try to reconstruct the past!**)*.
- The future forecasting may require higher resolutions than we anticipated.

Open (Relevant) Science Questions

- How relevant is to measure UHI; and if so; what may be the strategies (i.e. sensors; frequency, use)
- What are the significant differences between UHI in coastal and inland areas; or between tropical and subtropical regions?
- What is the relationship of UHI and Global Warming?
- What may be strategies to mitigate UHI in present and future conditions?
- What are the connections between UHI and energy demands and related technologies, strategies?
- How densification may influence UHI, under mean and extreme conditions?

References

- Bornstein, R., and Q. Lin (2000), Urban heat islands and summertime convective thunderstorm in Atlanta: Three cases studies, *Atmos. Environ., 34,* 507–516.
- González, J. E., J. C. Luvall, D. Rickman, D. E. Comarazamy, A. J. Picón, E. W. Harmsen, H. Parsiani, N. Ramírez, R. Vázquez, R. Williams, R. B. Waide, and C. A. Tepley, 2005: Urban heat islands developing in coastal tropical cities. EOS Transactions, AGU, 86, 42, pp. 397 & 403.
- Jauregui, E., and E. Romales (1996), Urban effects of convective precipitation in Mexico City, *Atmos. Environ., 30,* 3383–3389.
- Lo, C. P., D.A. Quattrochi, and J. C. Luvall (1997),Applications of high-resolution thermal infrared remote sensing and GIS to assess the urban heat island effect, *Int. J. Remote Sens., 18*(2), 287–204.
- Luvall, J. C., D. Rickman, D. Quattrochi, and M. Estes (2005), *Aircraft based remotely sensed albedo and surface temperatures for three US cities,* paper presented at Cool Roofing: Cutting Through the Glare Roofing Symposium, Roof Consult. Inst. Found., Atlanta, Ga., 12–13 May.
- Shepherd, J. M., and S. J. Burian (2003), Detection of urban-induced rainfall anomalies in a major coastal city, *Earth Interact., 7*(4), doi:10.1175/1087-3562(2003)007<0001:
- DOUIRA>2.0.CO;2. Tso, C. P. (1995), A survey of urban heat island studies in two tropical cities, *Atmos. Environ., 30,* 507–519.
- United Nations Population Fund (1999), *The state of world population 1999*, 76 pp., New York. (Available at http://www.unfpa.org/swp/1999/index.htm)