A NEW PARAMETERIZATION FOR SURFACE HEAT FLUXES IN DENSE URBAN ENVIRONMENTS

Estatio Gutierrez & Jorge Gonzalez[1]
Alberto Martilli[2]
Robert Bornstein[3]

[1]City College of New York, New York, USA
[2]CIEMAT, Madrid, Spain
[3]San Jose State U., California, USA

Outline

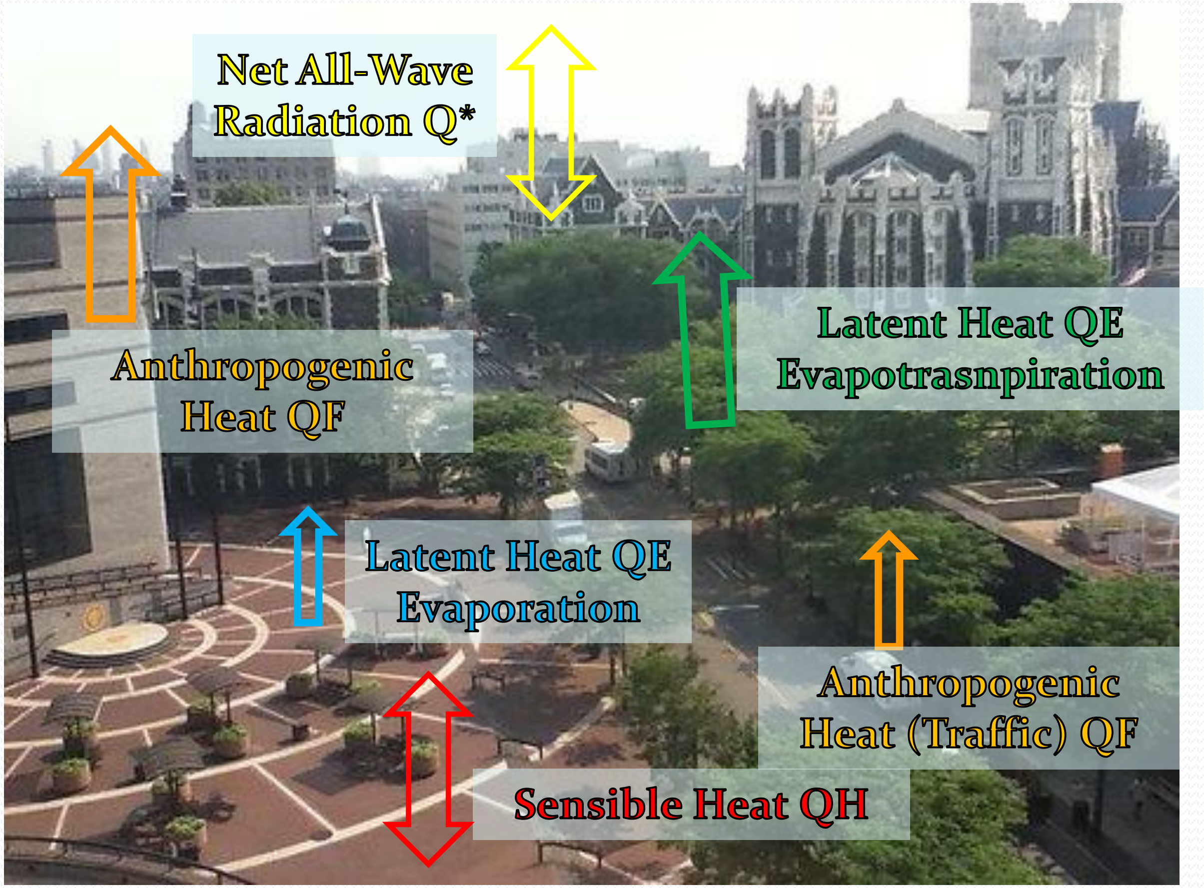
- **Overview of the Energy Balance in Urban Environments**
- **Science Questions**
- **Methodology**
- **Evaluation**
- **Results for Surface Heat Flux Partition**
- **Summary and Conclusions**

Energy Balance in Urban Environments

- Surface Energy Balance (SEB) :

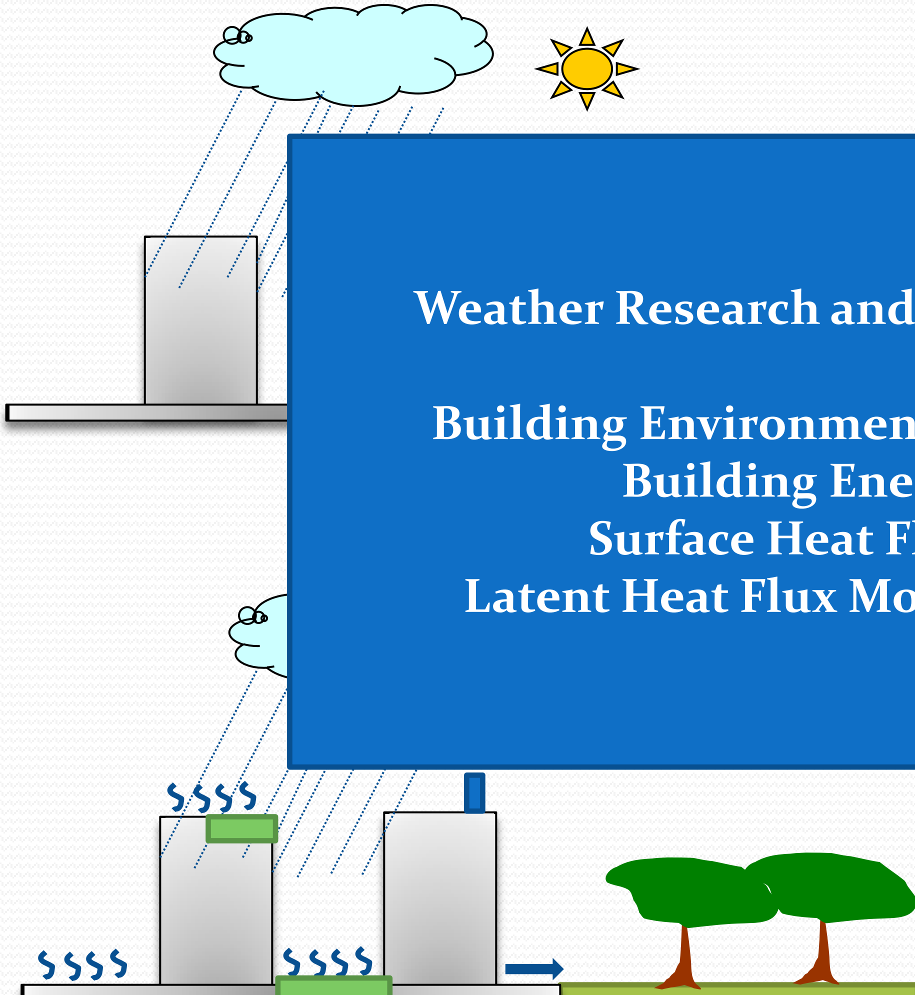
  SEB of an urban area can be defined as (Oke, 1998):

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S$$



Energy Balance in Urban Environments

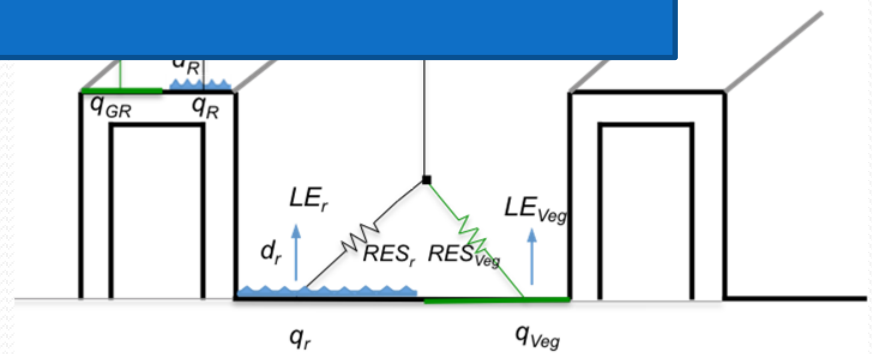
Water Balance



reas is

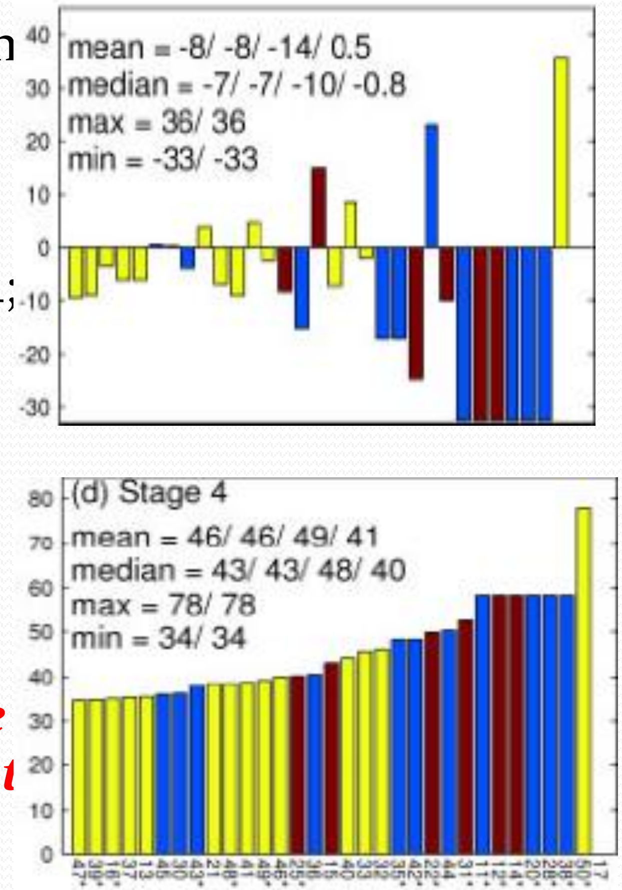
Weather Research and Forecasting Model (WRF)

Building Environment Parameterization (BEP)
Building Energy Model (BEM)
Surface Heat Flux Model (Hydro)
Latent Heat Flux Model from Buildings (CT)



Energy Balance in Urban Environments

- Evaporation from engineered pavements and its cooling effect have long been ignored in most urban models (Nakayama and Fujita, 2010).
- In highly urbanized areas, Q_E is not negligible (Grimmond and Oke 1995; Grimmond et al. 2004; Christen and Vogt 2004; Moriwaky and Kanda 2004; Offerle et al. 2006a; Offerle et al. 2006b; Kotthaus and Grimmond 2014).
- The omission of water is a main contributor to the inadequacy of current urban canopy models in predicting evaporation and latent heat budget (Grimmond *et al.*, 2010).
- ***Cooling loads from buildings are a main source of anthropogenic heat in summertime (Smith et al, 2009).***
- ***Cooling towers may have an important impact in the sensible/latent heat ratio (Sailor et al., 2007; Munck et. al 2013).***



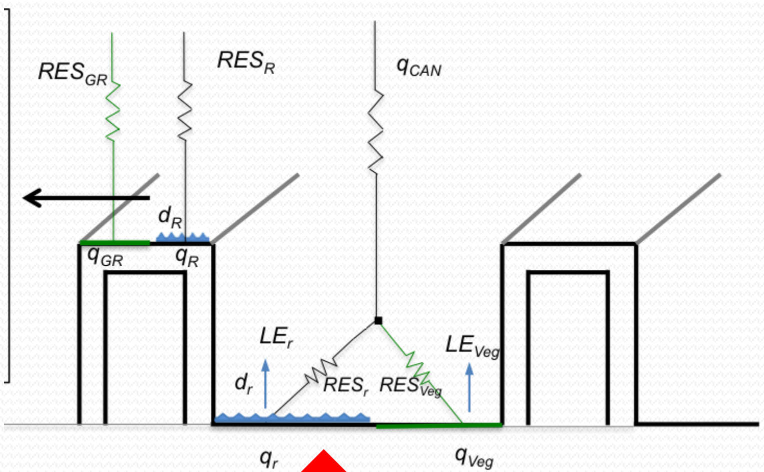
Q_E RMSE and MBE from 32 UCM (Grimmond et al., 2011).

Science Questions

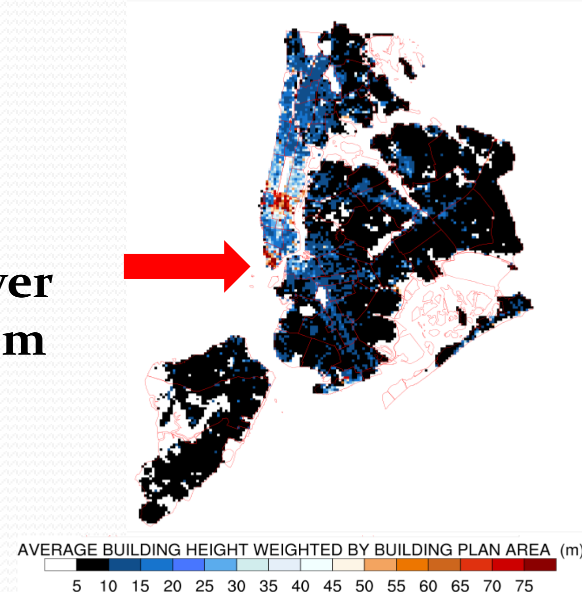
Specific science/engineering questions:

- ***Major Questions:***
  - What may be the latent heat contribution to the total surface energy balance in dense urban environments?
  - What is the effect of anthropogenic heat (latent + sensible) production in the surface energy balance in urban environments during warm seasons?
- ***Sub Questions:***
  - What may be the partition of anthropogenic latent/sensible heat in dense urban environments?
  - What may be the role of anthropogenic heat in summertime local climate and extreme weather heat events in complex urban environments?
  - What may be the role of anthropogenic heat in the initiation and evolution of the Planetary Boundary Layer in complex urban environments?

Methodology-I



Average Building height PLUTO (over entire city) at 250 m (Right



(a) Urban hydrology
(b) Building data assimilation
(c) Drag coefficients schemes.

Sectional drag coefficient (Default) = 0.4

Drag coefficient as a function of the building packing density (Santiago and Martilli 2010):

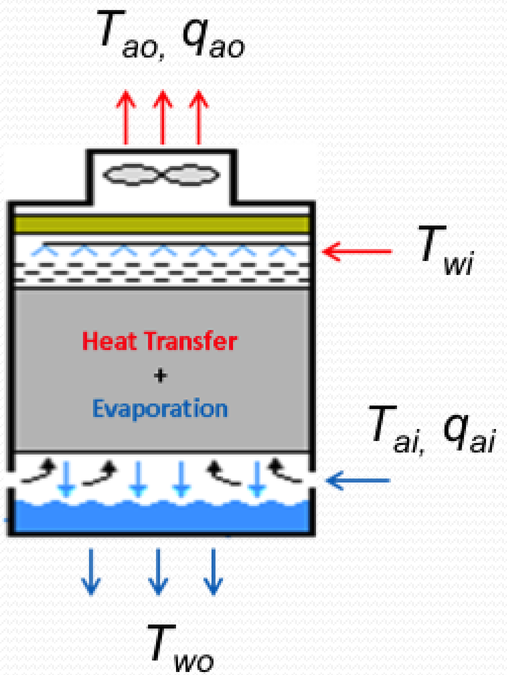
$$C_{deq}(\lambda_p) = \begin{cases} 3.32x\lambda_p^{0.47} & for\ \lambda_p \leq 0.29 \\ 1.85 & for\ \lambda_p > 0.29 \end{cases}$$

Hydrology Model for Impervious surfaces (to represent missing latent heat component) & improved mechanical surface representation.

Methodology-II

Cooling Tower Parameterization (to represent anthropogenic latent heat)

Cooling Tower Scheme



- **Effectiveness:**

  Ratio of the actual heat transfer to the maximum rate permitted by the second law of thermodynamics

$$\varepsilon = \frac{Q^*}{ma(h_{sai} - h_{ai})}$$

- Energy Balance (Air):

$$Q^* = m_a(h_{ao} - h_{ai})$$

$$C_p T_{ao} + q_{vao}(C_{pw} + L) = hai + \varepsilon(h_{sai} - h_{ai})$$

- **Condenser Heat Exchange:**

  Refrigerant R-134s (Typical Pressure : 160 psia, Saturation temperature: 43.3 °C, Superheated temperature (T_{Ref}) out of the compressor: 60 °C)

$$Q^* = C_{min}(T_{wo,cond} - T_{wi,cond}) \qquad T_{w_o,cond} = T_{w_i,CT}$$

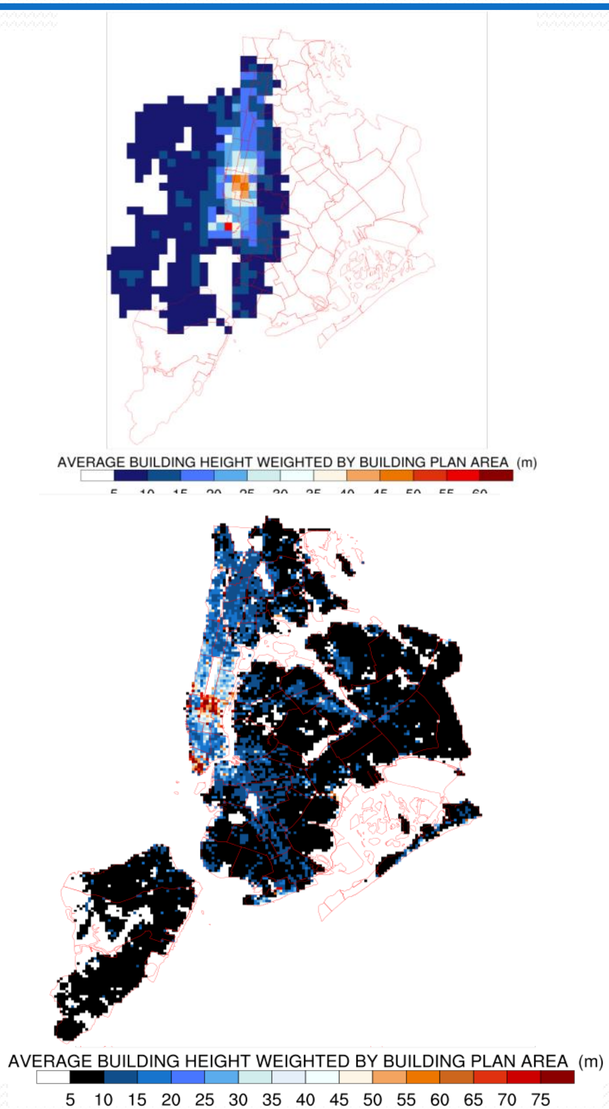
$$q_{max} = \frac{Q^*}{\varepsilon} = C_{min}(T_{Ref} - T_{wi,cond})$$

$$T_{w_i,cond} = T_{w_o,CT} = T_{wb,air}$$

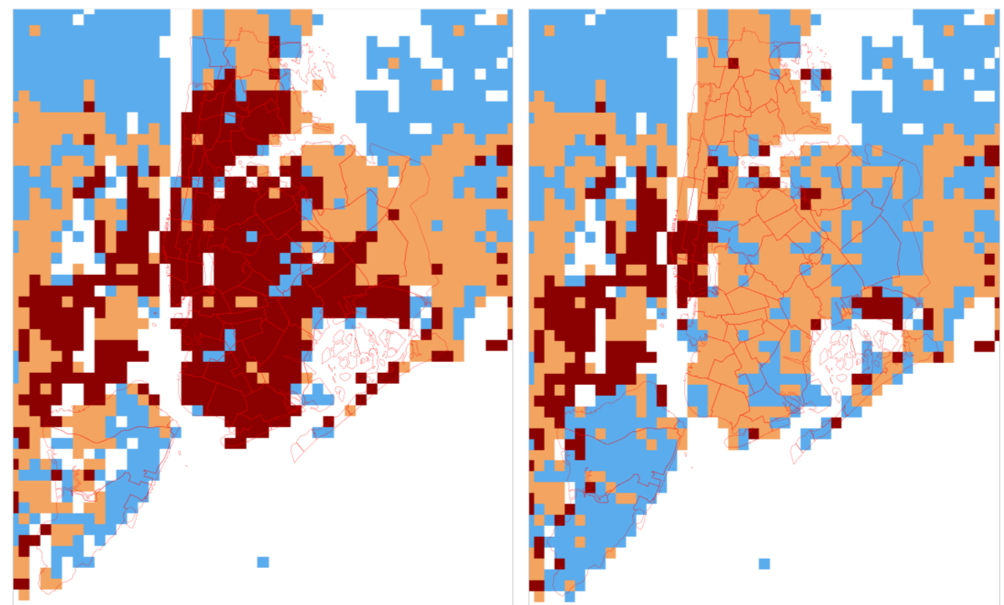
Methodology-III

Primary Land Use Tax Lot Output (PLUTO) Assimilation

PLUTO created by the Department of City Planning contains detailed tax lot building information for NYC.



Mean Building Height NUDAPT (Top) and PLUTO (Bottom)



LCLU from 2006 USGS National Land Cover Dataset (Left) and PLUTO (Right)

Methodology-IV

Ensemble Runs

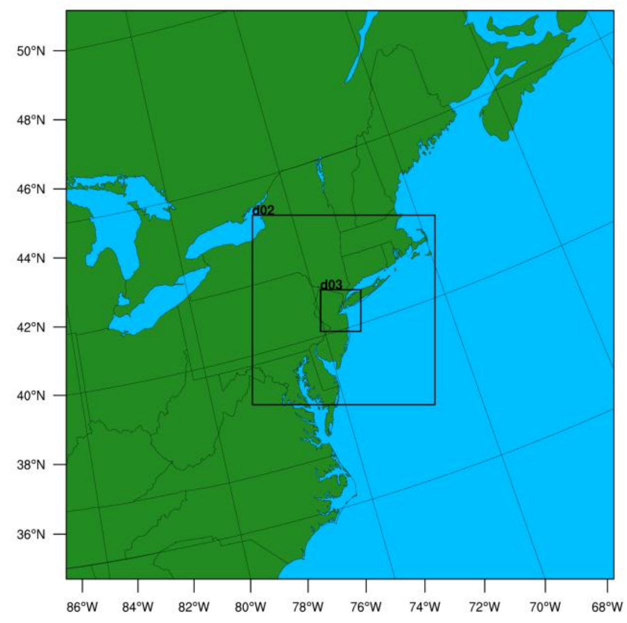
RUN	MODEL	PERIOD
1	BEP+BEM _Cd_const	June 2010
2	BEP+BEM	June, July, August 2010
3	BEP+BEM + Hydro	June, July, August 2010
4	BEP+BEM + Hydro + CT	June, July, August 2010
5	BEP+BEM	July 2013
6	BEP+BEM + Hydro	July 2013
7	BEP+BEM + Hydro + CT	July 2013

BB (Default BEP+BEM)
Hydro (BEP+BEM + Hydrology)
Hydro+CT (BEP+BEM + Hydrology + Cooling Tower)

Methodology-IV

Model Setup

- Three one-way nested domains with a grid spacing of 9, 3 and 1 km are defined. Initial and boundary conditions from NARR (resolution: 32 km). NCEP/MMAB data at 0.083 degree will update the sea surface temperature every 24-h.
- Vertical resolution of 51 terrain following sigma levels (33 levels in the lowest 1.5 km, first level ~10m).
- PBL Parameterization: BouLac (Bougeault-Lacarrere 1989)
- Radiation Schemes: RRTM (Mlawer et al. 1997) and Dudhia (Dudhia 1989).
- Microphysics: Single Moment 6-class (Hong et al. 2004).
- Urban surfaces properties were adopted from Salamanca et al. (2014).
- Building glass fraction and floor occupancy were obtained from the US-DOE (Deru et al. 2011).



Model Domains

NYC Evaluation
Datasets

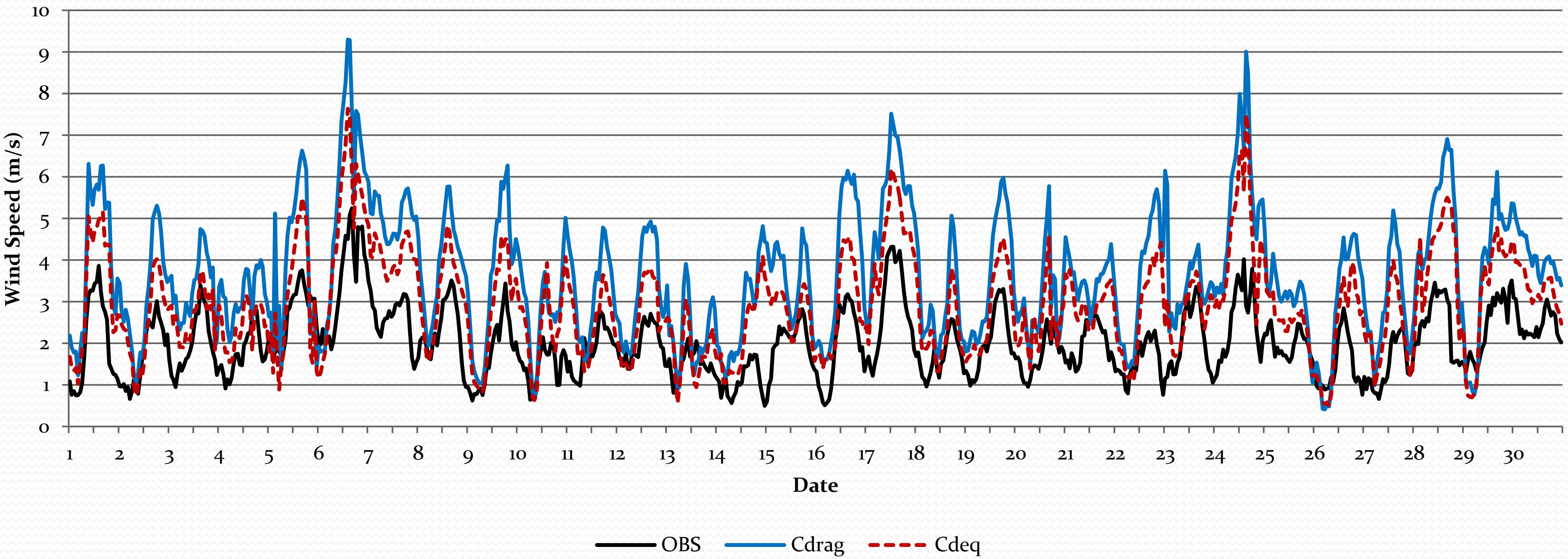
- **Summer 2010:**
  - Hourly precipitation, temperature, wind and humidity data from 102 stations located at rooftops (NYCMetNet).
  - Stations with <10% of missing data were selected.

- **July 2013:**
  - 3-minute temperature and humidity data from NOAA-CREST and the Consortium for Climate Change Risk in the Urban Northeast (Vant-Hull et al. 2014)
  - Stations located at midtown and downtown Manhattan were used.

NYC Evaluation (Summer 2010)

Drag Coefficient

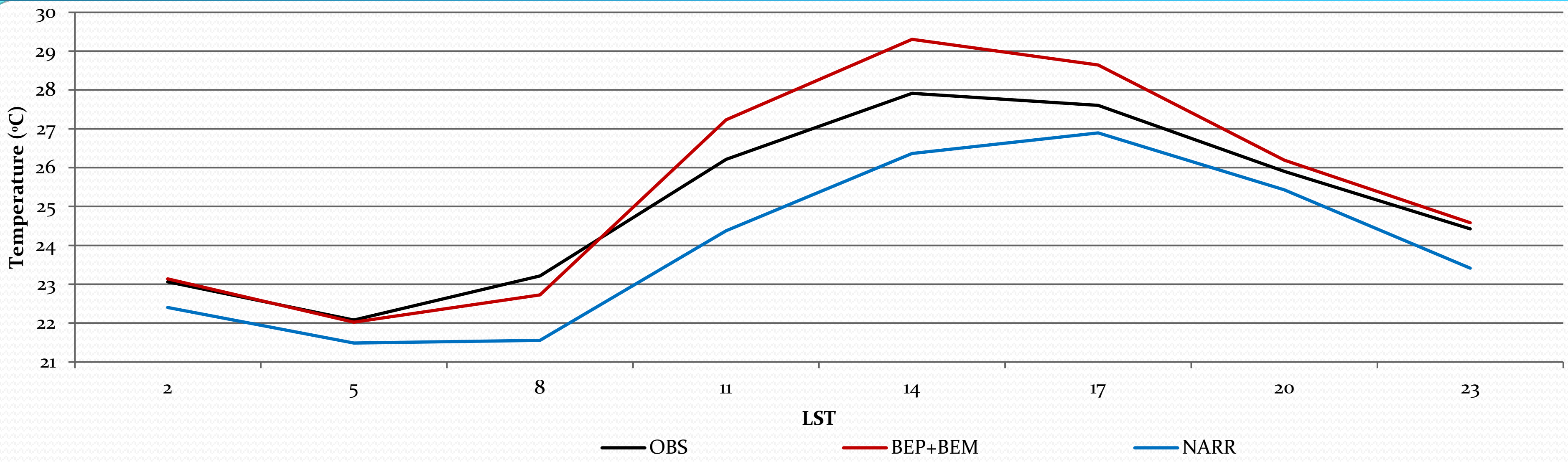
	RMSE		MAE		MAPE	
WS	Cdrag	Cdeq	Cdrag	Cdeq	Cdrag	Cdeq
SI	**2.78**	**2.48**	**2.36**	**2.09**	**121.576**	110.29
BK	**2.06**	**1.434**	**1.67**	**1.14**	**70.48**	**46.85**
QN	**2.19**	**1.57**	**1.79**	**1.26**	**68.49**	**49.02**
BX	**2.21**	**1.39**	**1.83**	**1.11**	**109.71**	**69.67**
MN	**2.15**	**1.05**	**1.76**	**0.83**	**145.08**	**58.14**
NJ	**2.46**	**2.66**	**2.07**	**2.26**	**103.16**	112.79



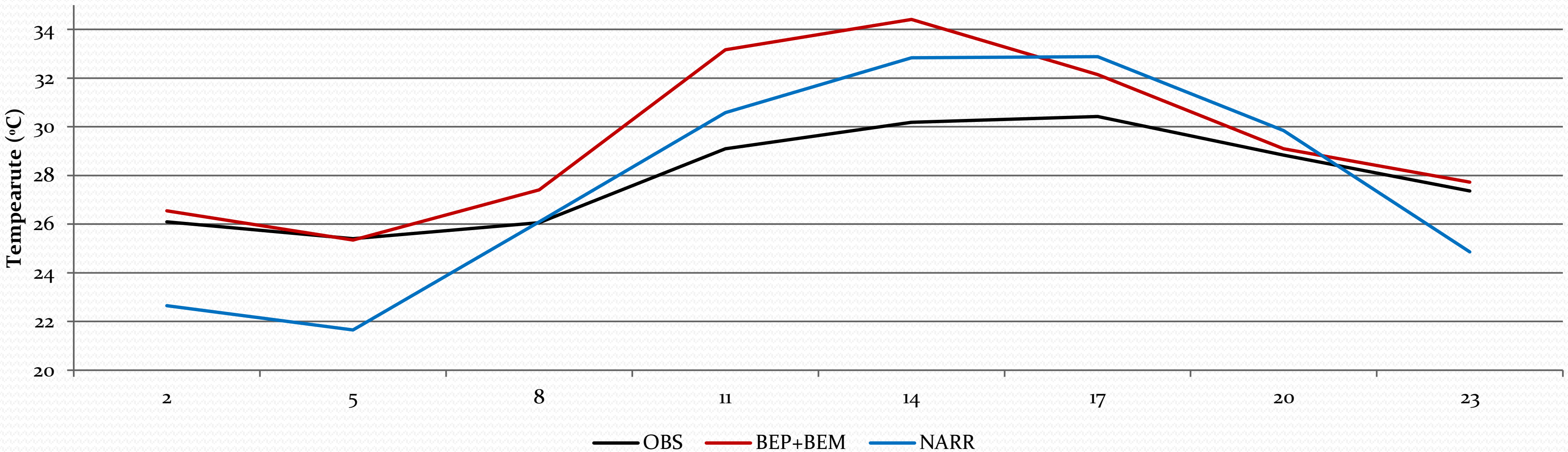
Average wind speed at the location of the weather stations for observations, Cdrag, and Cdeq simulations.

NYC Evaluation

Temperature NARR vs BEP+BEM



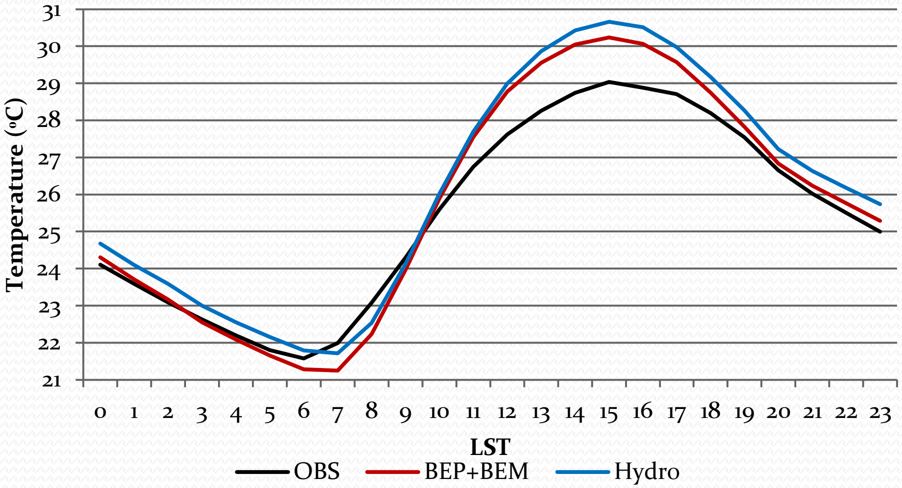
Observed and Modeled Temperature Daily Cycle (Summer 2010).



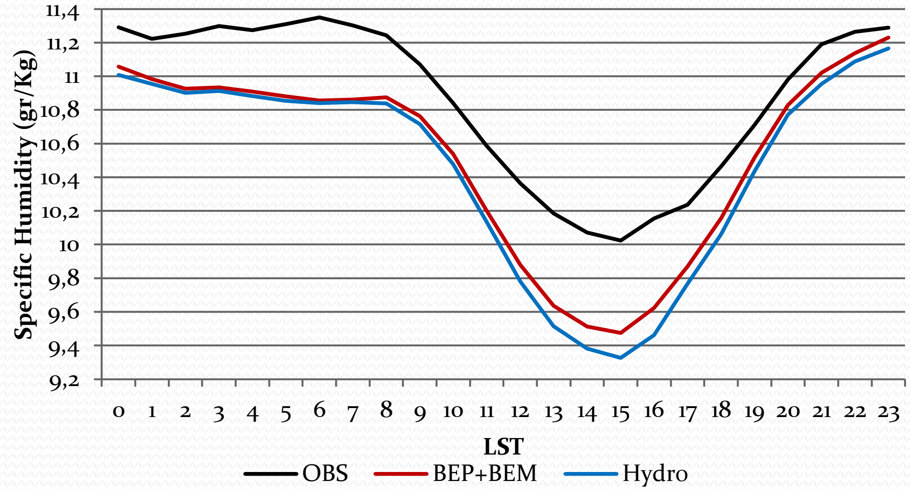
Observed and Modeled Temperature Daily Cycle (July 2013).

NYC Evaluation (Summer 2013)

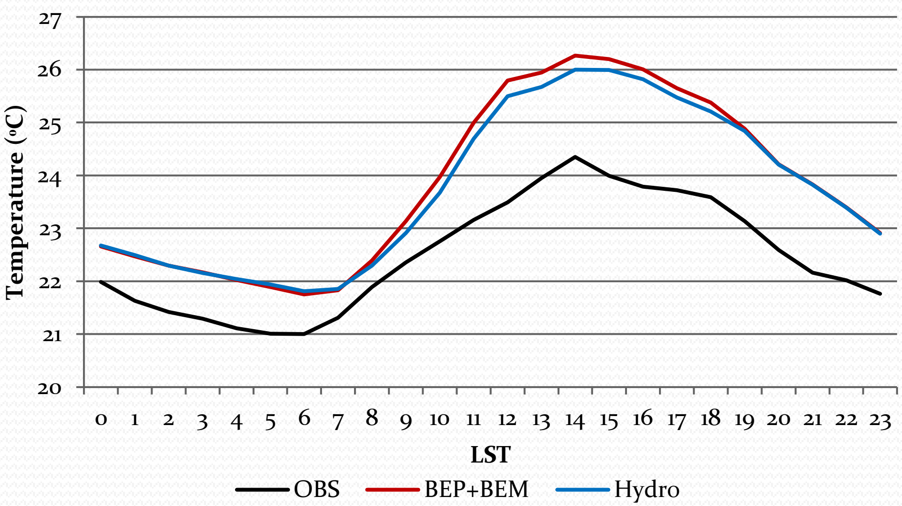
Temperature and Humidity



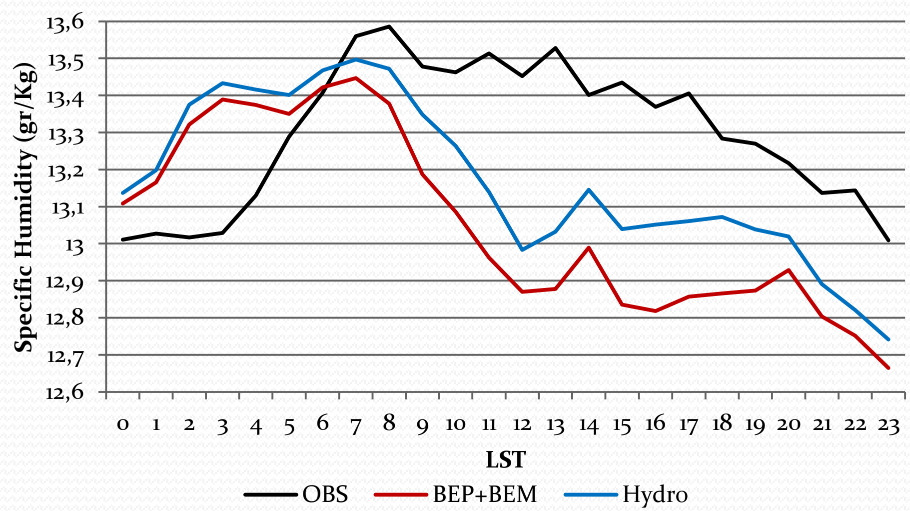
Observed and Modeled (BEP+BEM and Hydro)
Temperature Daily Cycle for Dry Days.



Observed and Modeled (BEP+BEM and Hydro)
Specific Humidity Daily Cycle for Dry Days.

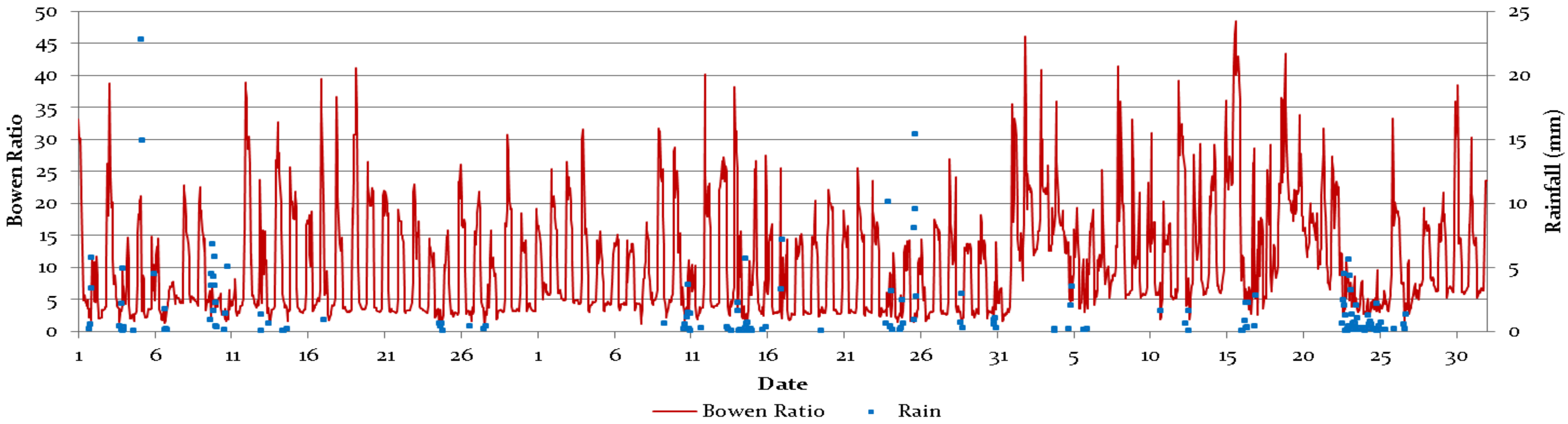


Observed and Modeled (BEP+BEM and Hydro)
Temperature Daily Cycle for Wet Days.

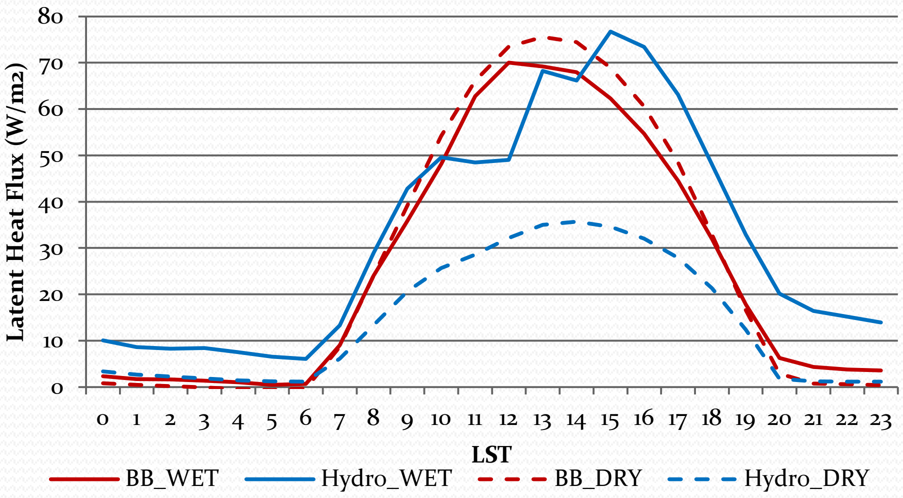


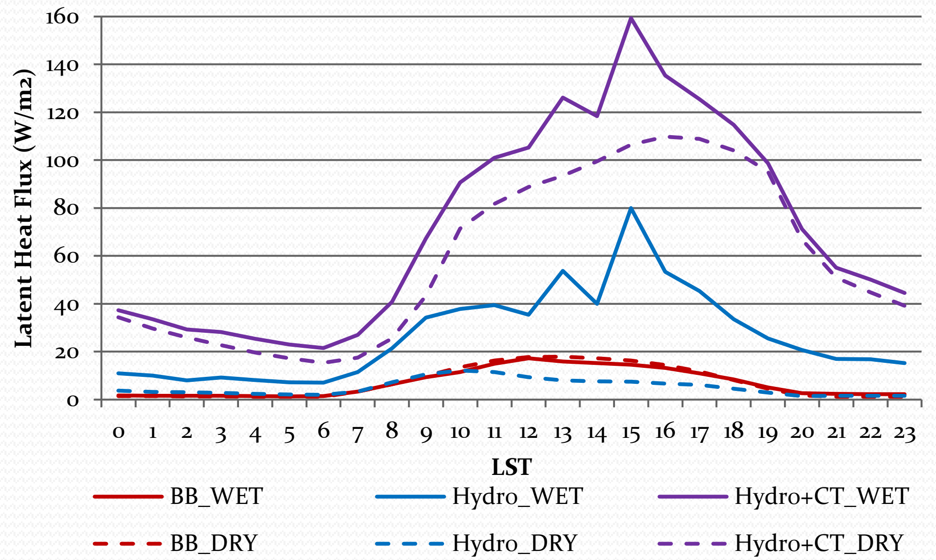
Observed and Modeled (BEP+BEM and Hydro)
Specific Humidity Daily Cycle for Wet Days.

Heat Partition (Summer 2010)



Hourly Bowen Ratio at Midtown Manhattan.

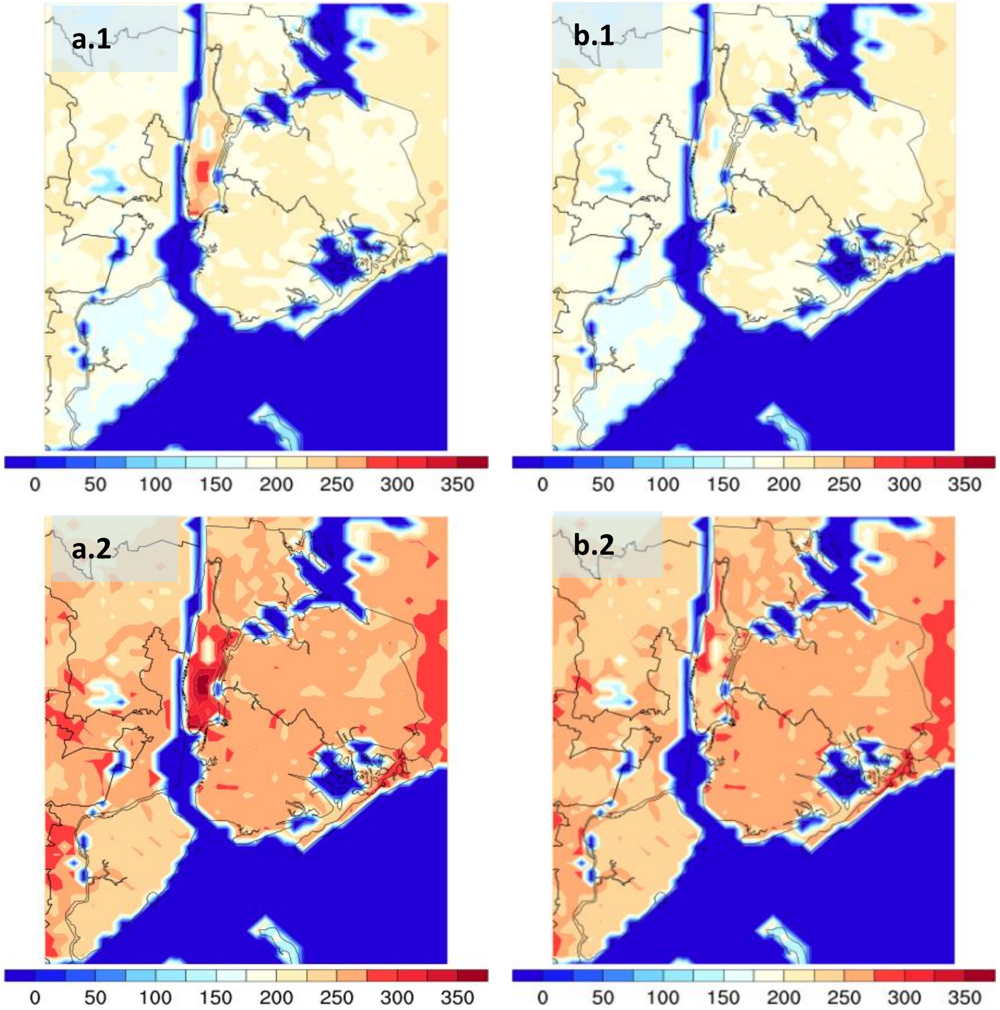




Modeled Latent Heat Daily Cycle for Residential (Left) and Commercial (Right) Areas.

Heat Partition (Summer 2010)

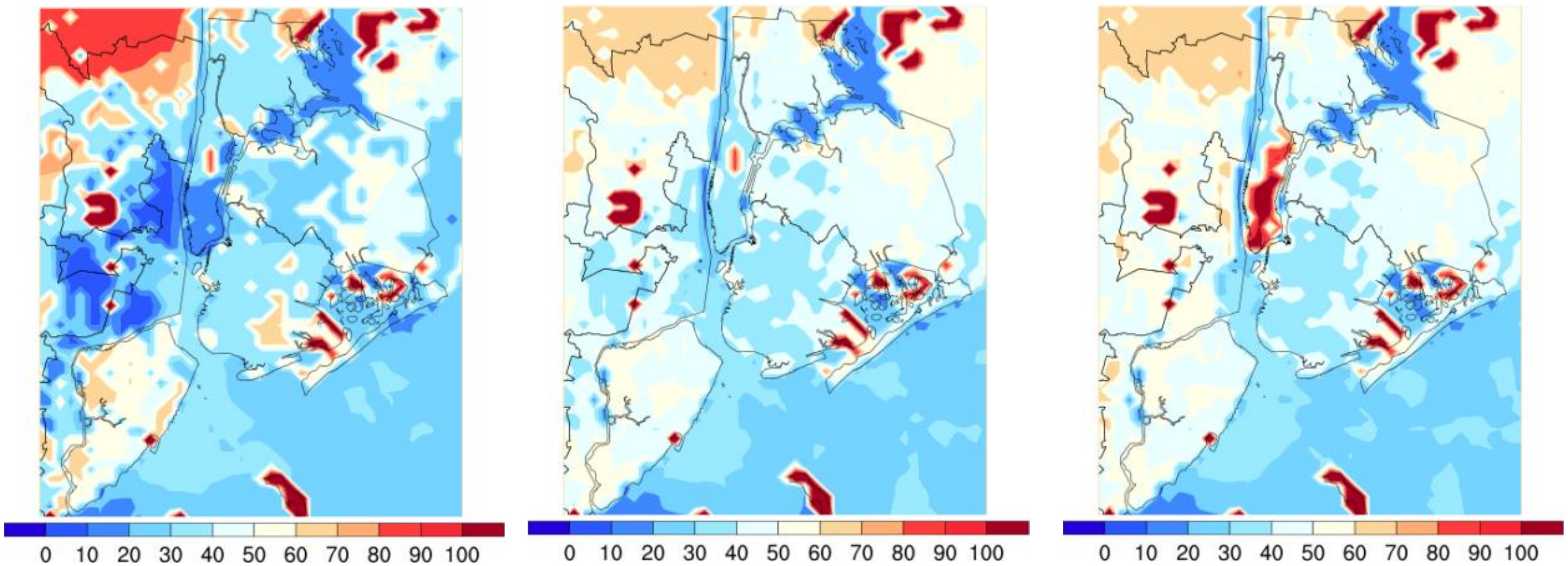
Spatial Distribution



Wet (1) and Dry (2) Days Average Daytime Sensible Heat Flux for Hydro(a), and Hydro+CT (b)

Heat Partition (Summer 2010)

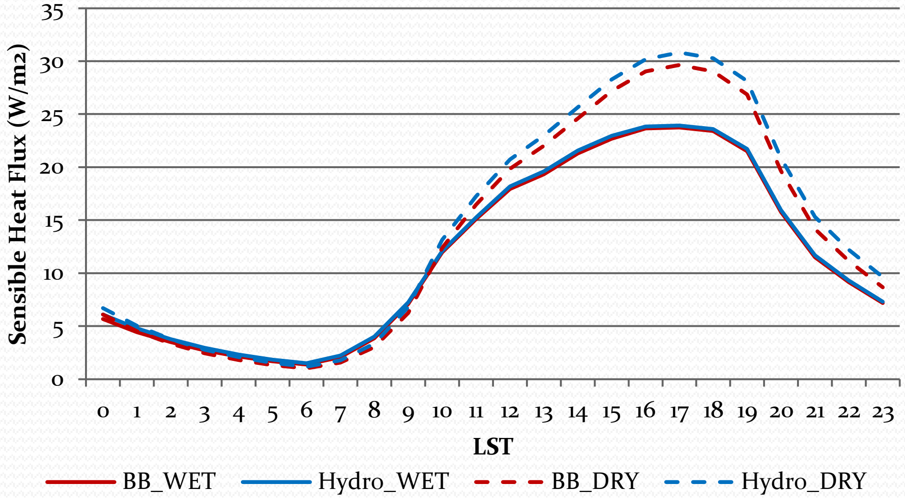
Spatial Distribution



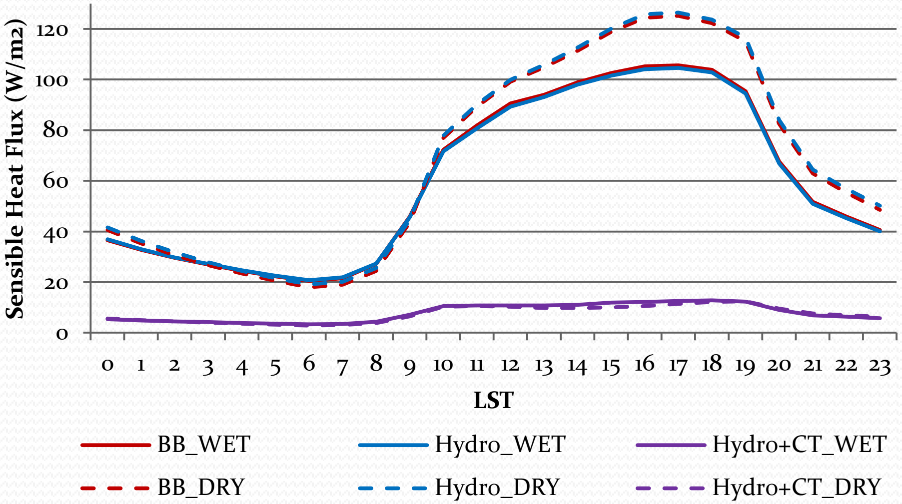
Wet Days Average Daytime Latent Heat Flux for BEP+BEM (a), Hydro(b), and Hydro+CT (c)

Anthropogenic Heat Partition (Summer 2010)

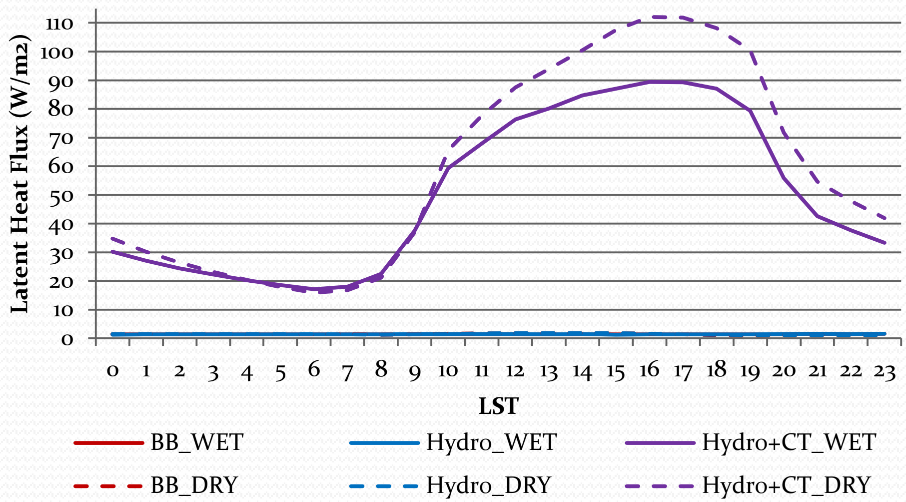
Daily Cycles



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



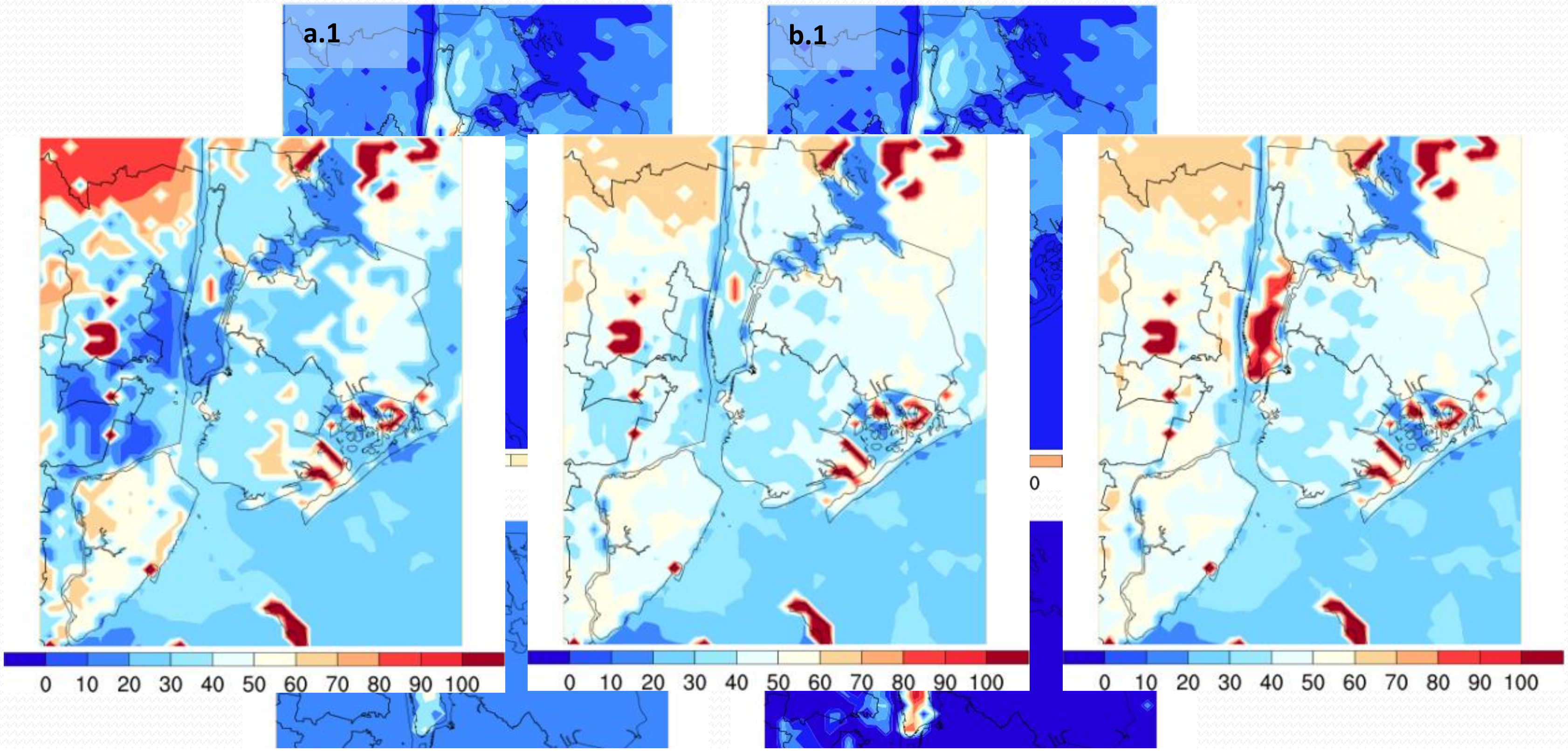
Modeled A/C Sensible Heat Daily Cycle for Commercial Areas.



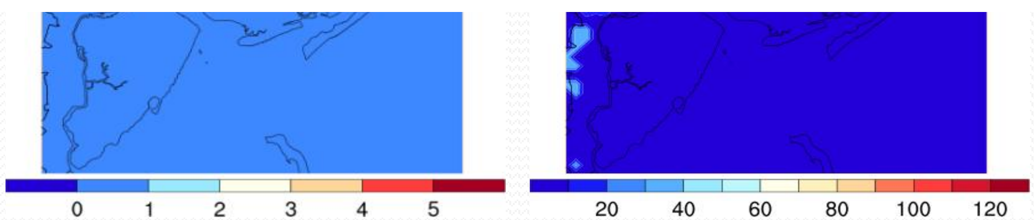
Modeled A/C Latent Heat Daily Cycle for Commercial Areas.

Anthropogenic Heat Partition (Summer 2010)

Spatial Distribution

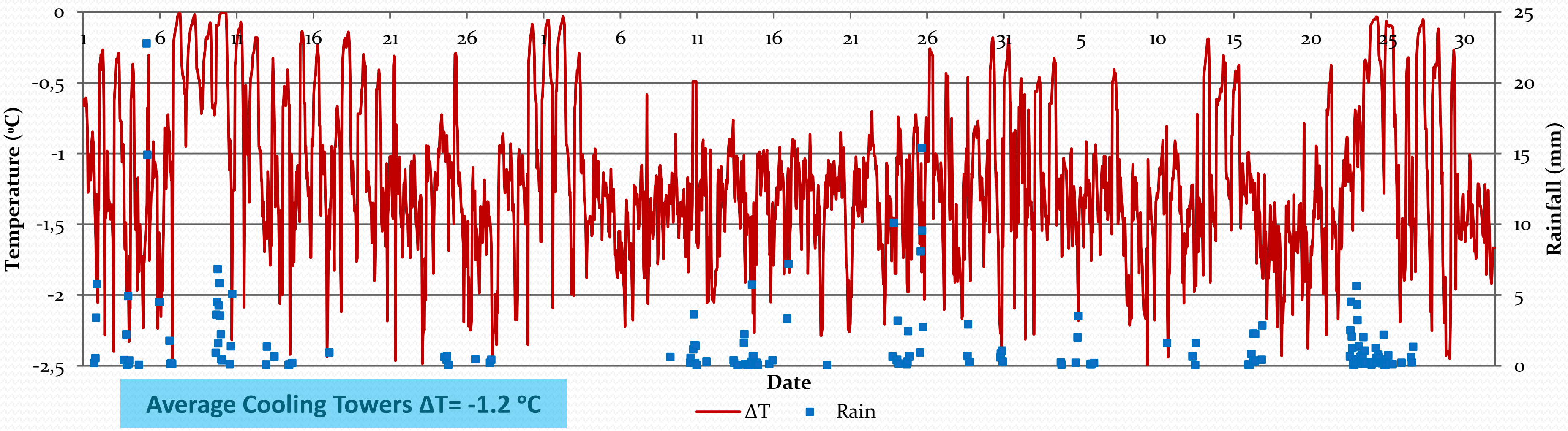


Wet Days Average Daytime Latent Heat Flux for BEP+BEM (a), Hydro(b), and Hydro+CT (c)



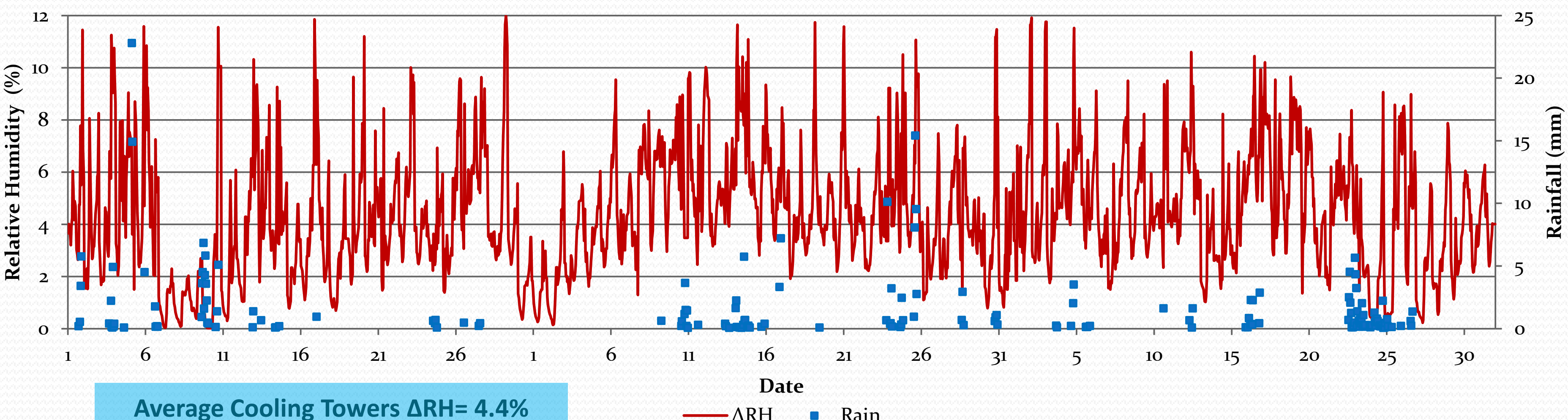
Dry Days Average Daytime A/C Sensible (1) and Latent (2) Heat Flux (W/m2) for Hydro(a), and Hydro+CT (b)

Impacts on Local Climate due to Cooling Towers



Average Cooling Towers ΔT= -1.2 °C

Hourly 2m Temperature Difference between Hydro+CT and Hydro.

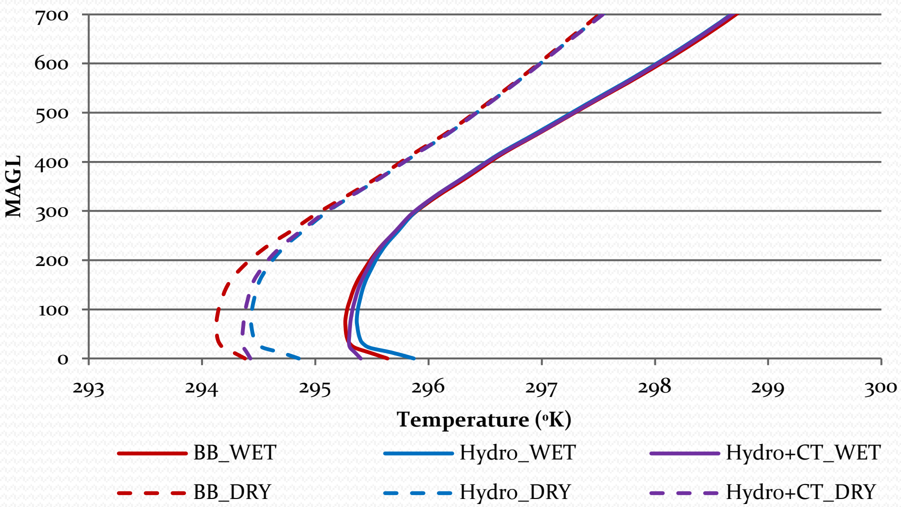


Average Cooling Towers ΔRH= 4.4%

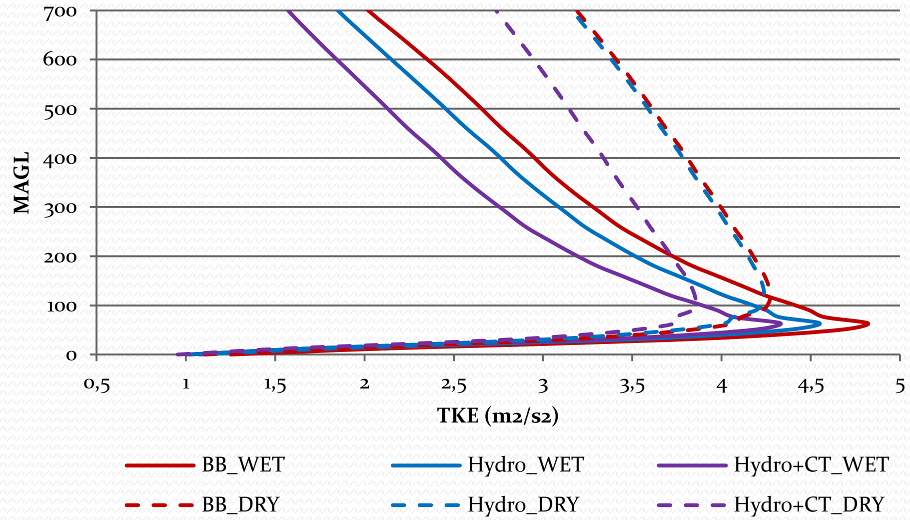
Hourly 2m Relative Humidity Difference between Hydro+CT and Hydro.

Planetary Boundary Layer

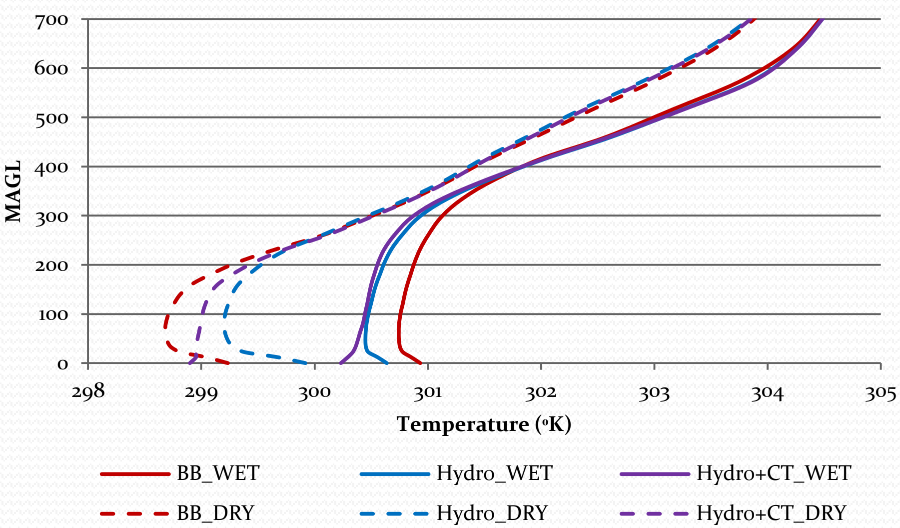
Vertical Profiles



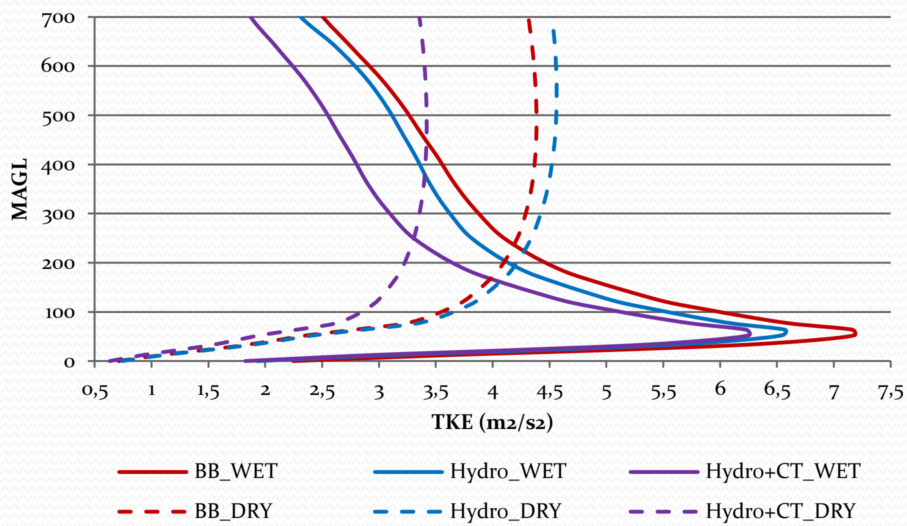
Potential Temperature at 0600 LST for Commercial Areas.



TKE at 1500 LST for Commercial Areas.



Potential Temperature at 0600 LST for Commercial Areas during Extreme Events.



TKE at 1500 LST for Commercial Areas during Extreme Events .

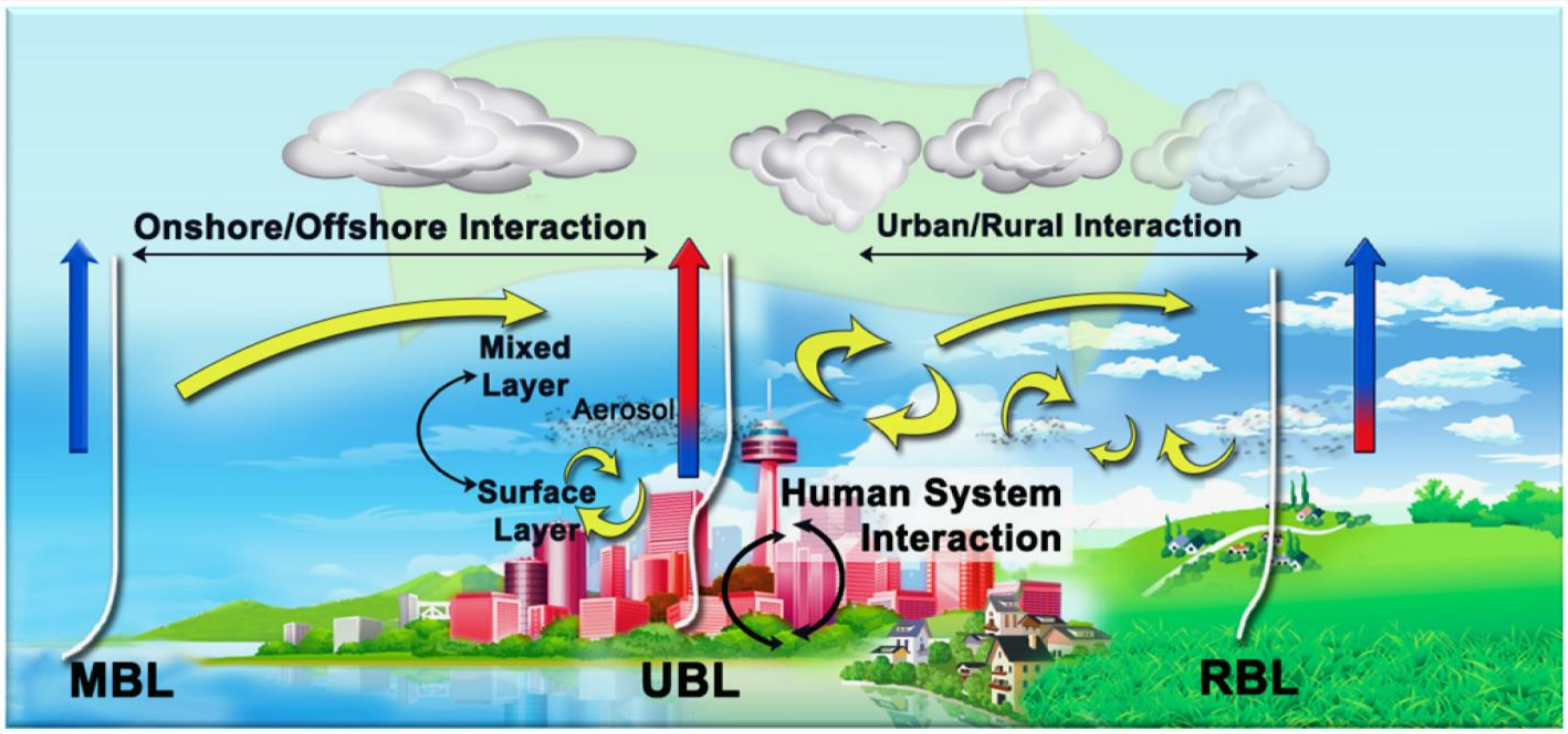
Summary and Conclusions

- **The new formulations properly represents sensible/latent heat daily cycles including anthropogenic heat partition for land use category (see next table).**
- **The hydrology scheme improves air moisture content prediction particularly during rainy periods.**
- **During wet days evaporation from impervious surfaces is the main source of latent heat in commercial areas.**
- **Evaporative cooling technology from the air conditioning devices diminishes between 80 and 90% the amount of anthropogenic sensible heat *with impacts in the local meteorology and urban climate*.**
- **Cooling towers *reduce the unstable conditions in the lower troposphere* during wet days while inducing neutral stability from the surface in dry days.**
- ***Future works will focus on further model validation (i.e. heat fluxes), scalability to regional scales (see posters by Ortiz et al. & Wu et al.), and transferability to other major cities.***

Summer/winter mean and maximum (in parenthesis) anthropogenic heat estimations (W/m^2) for different cities in commercial and residential sites.

	Summer		Winter		
City	**COM**	**RES**	**COM**	**RES**	**Reference**
Tokyo, Japan	(908)		(1590)		Ichibose et al. 1999
San Francisco, US	40 (60)		45(70)		Lu and Sailor 2004
Philadelphia, US	25 (50)		40(70)		
Toulouse, France	25	5	100	20	Pingeon et al. 2007
Tokyo, Japan	40 (86)	(18)			Moriwaki et al 2008
Osaka, Japan	93 (161)	55 (60)			Narumi et al. 2009
London, England	85	13	144	25	Hamilton et al. 2009
Seoul, S.Korea	52 (65)		57 (75)		Lee et al. 2009
Incheon, S.Korea	50 (59)		56 (70)		
Gyeonggi, S.Korea	26 (30)		28 (35)		
Sao Paulo, Brazil	11 (20.1)		13 (20.3)		Ferreira et al. 2011
Singapore,			84 (120)	13 (15)	Quah and Roth 2012
Indianapolis, US	32				Zhou et al. 2012
Houston, US	14.6 (144)				Lee et al. 2014
New York, US	23.5 (137.4)				
Chicago, US	26.3 (83.1)				
Los Angeles, US	23.9 (114.5)				
Phoenix, US	35 (54)	12 (25)			Chow et al. 2014
New York, US	**64 (126)**	**13 (31)**			**Present study**

The Holistic UBL



Methodology

Hydrology Model for Impervious and Natural Surfaces

Operational uWRF for NYC

- WRF-BEP/BEM daily real-time 72h simulations for NYC.
- Surface temperature, winds, hourly accumulated rainfall and energy consumptions products are available everyday at 9:00 AM.
- An automated evaluation system has been implemented and will be further improved

http://air.ccny.cuny.edu/ws/wrfn/thindex.wrfmetnet.php?initial=1