The City College of New York

NOAA-CREST
CENTER FOR EARTH SYSTEM SCIENCES AND REMOTE SENSING TECHNOLOGIES

QUANTIFYING THE HEAT STORED IN URBAN ENVIRONMENTS USING REMOTE SENSING TECHNOLOGY

Joshua Hrisko[1,3], Prathap Ramamurthy[1,3], Jorge E. Gonzalez[1,3], Hamidreza Norouzi[2], Abdou Bah[2]

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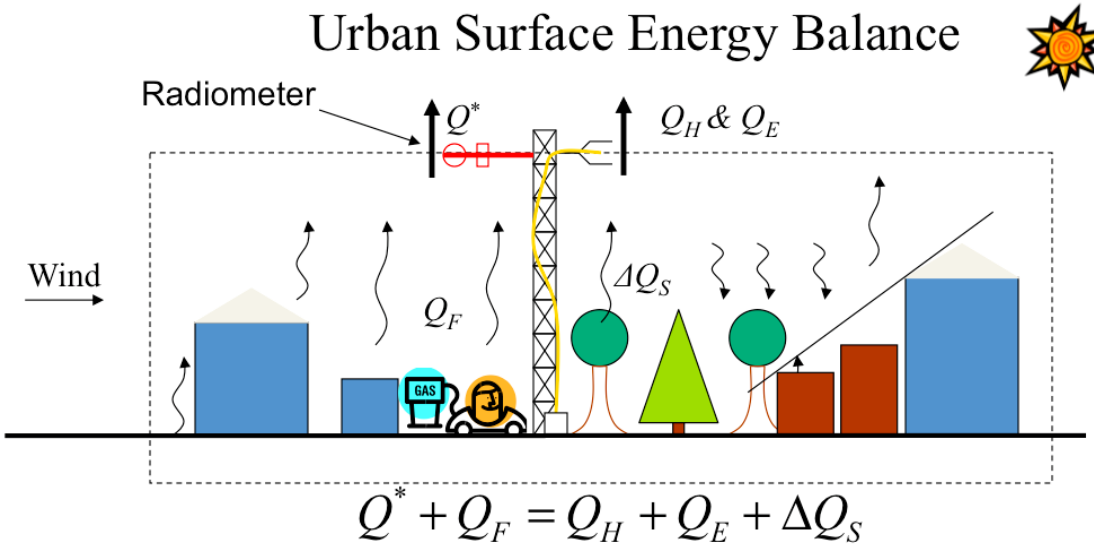
[2]New York City College of Technology, Brooklyn, NY

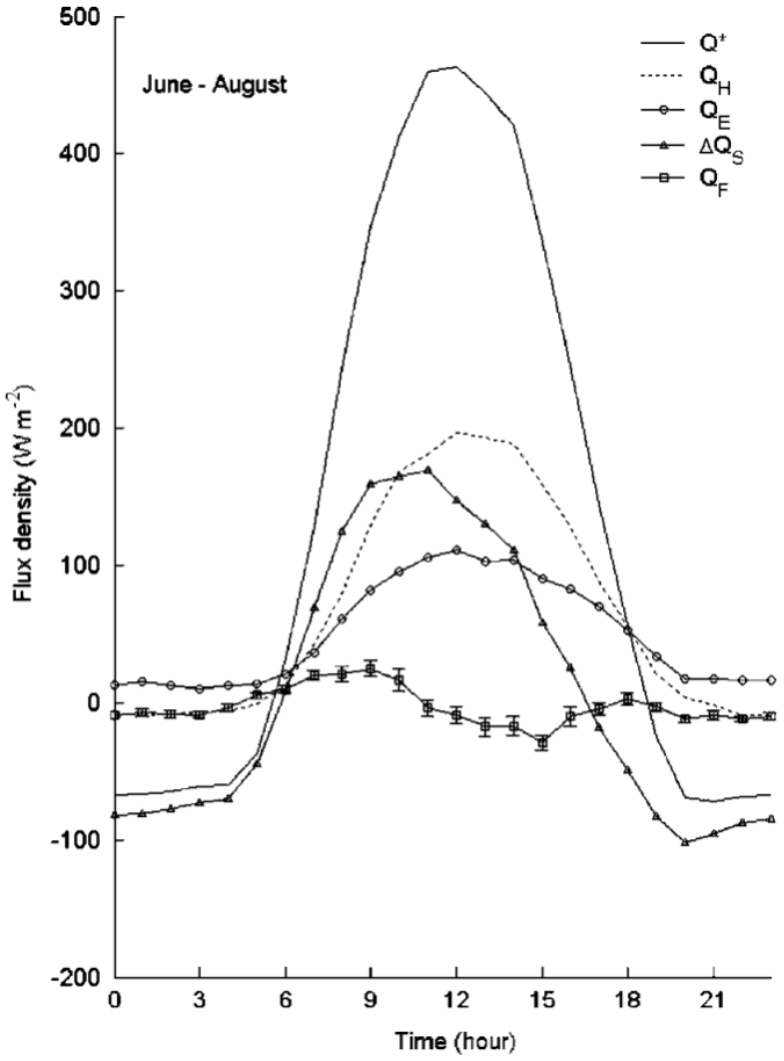
[3]NOAA-CESSRST, New York, NY

January 16, 2020



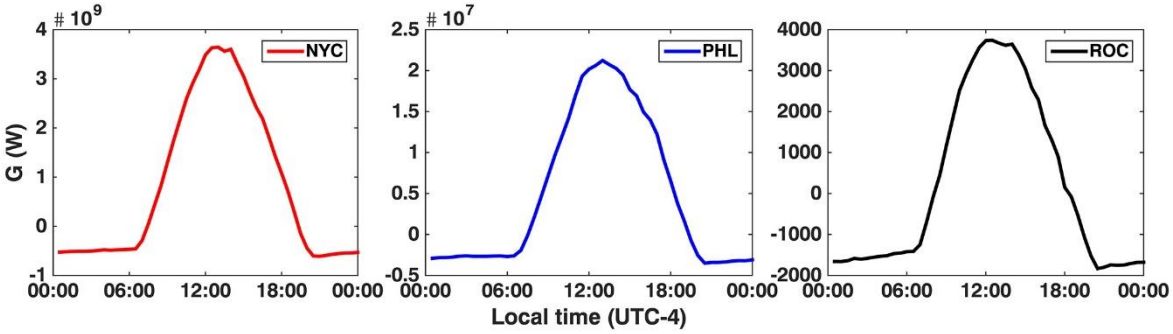
- Heat storage in urban areas is a significant term in the urban surface energy budget

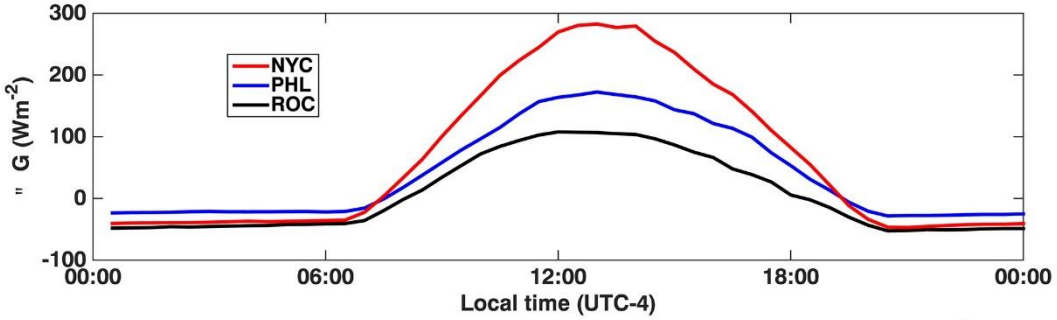
https://my.mech.utah.edu/~pardyjak/efd/murray.html



- Heat storage in urban areas is a significant term in the urban surface energy budget

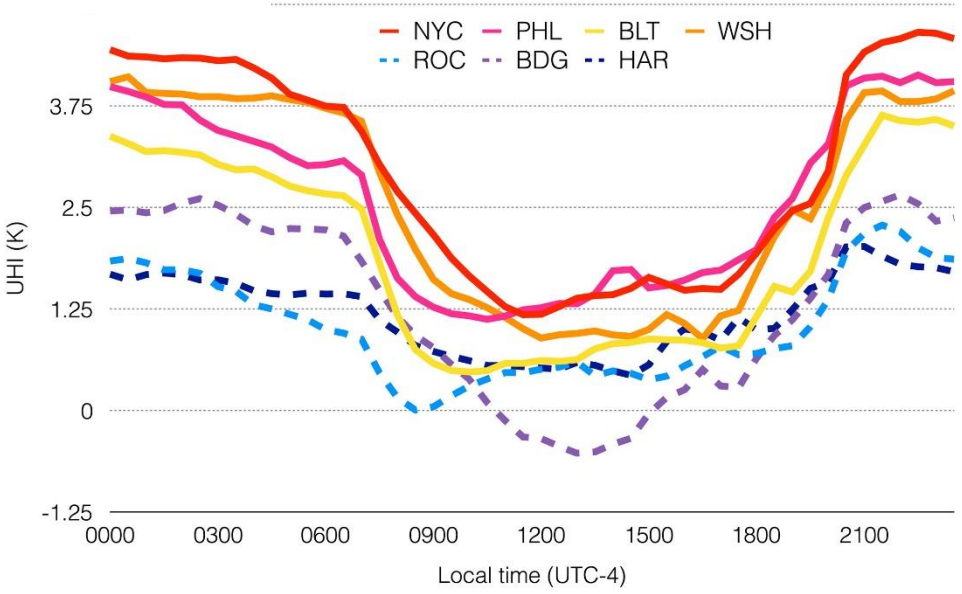
Offerle, B., Grimmond, C.S.B. and Fortuniak, K. (2005), Heat storage and anthropogenic heat flux in relation to the energy balance of a central European city centre. Int. J. Climatol., 25: 1405-1419.



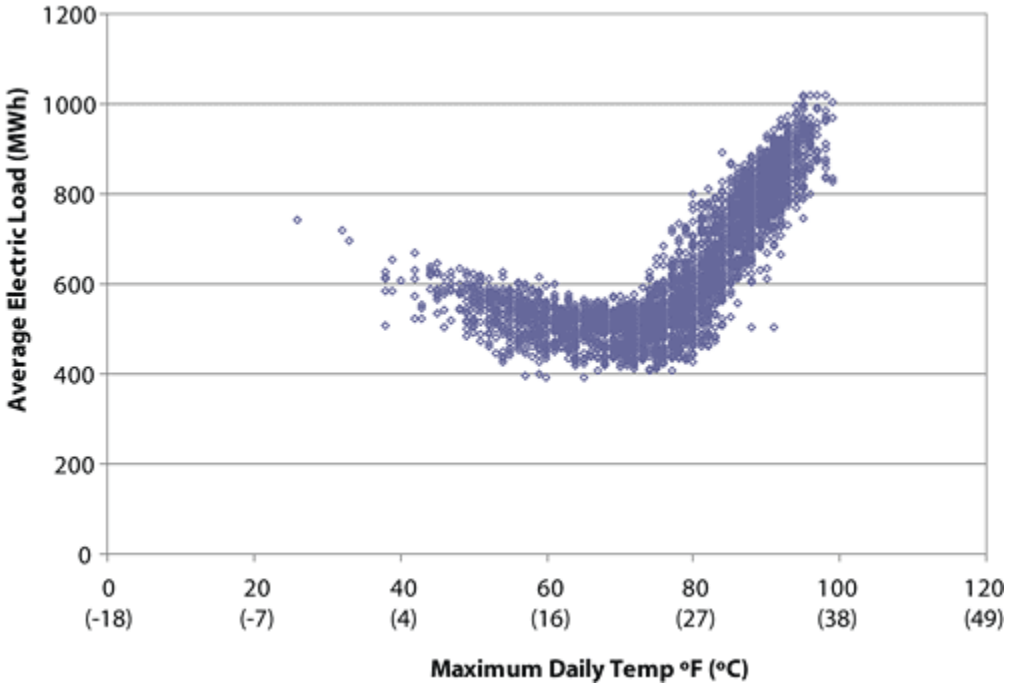


- UHI and heat storage are inextricably linked

"…this overwhelming disparity in storage heat flux is the primary factor that controls the daily pattern of UHI among cities"



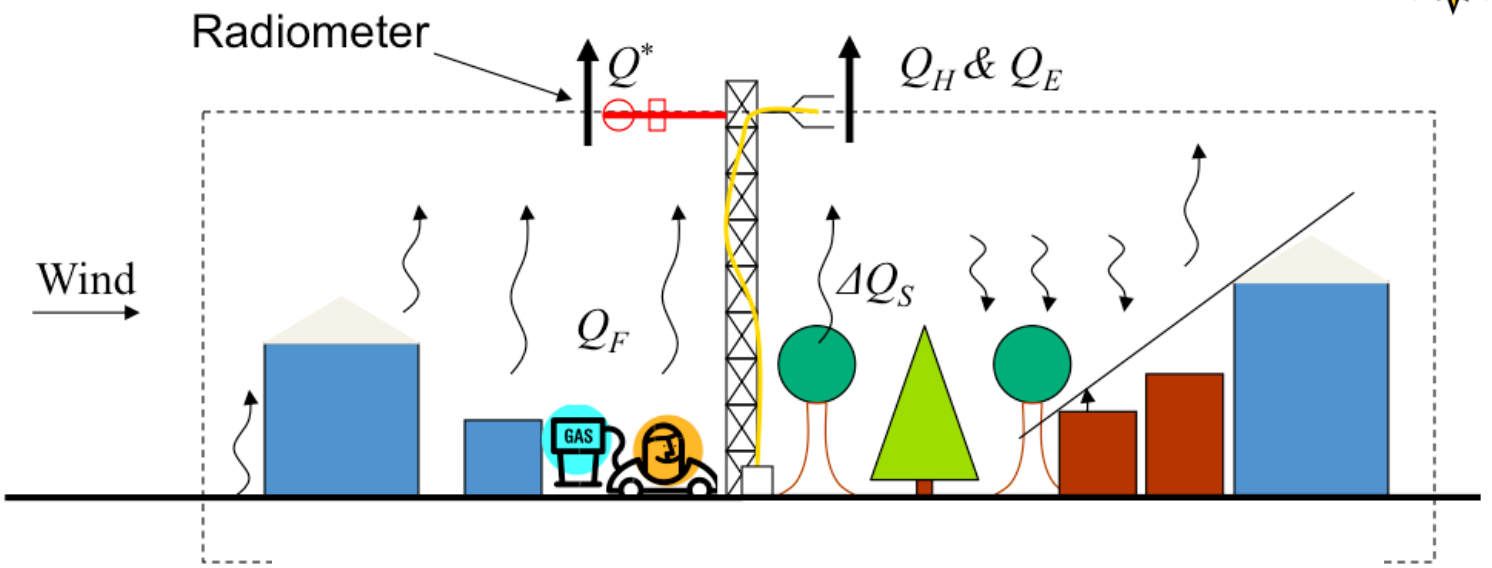
Ramamurthy, P., and Bou-Zeid, E. (2017), Heatwaves and urban heat islands: A comparative analysis of multiple cities, *J. Geophys. Res. Atmos.*, 122, 168– 178.



- Heat storage can also be used to approximate sensible heat fluxes, which can help predict air temperatures – ultimately relating to electric loads

United States Environmental Protection Agency. https://www.epa.gov/heat-islands/heat-island-impacts

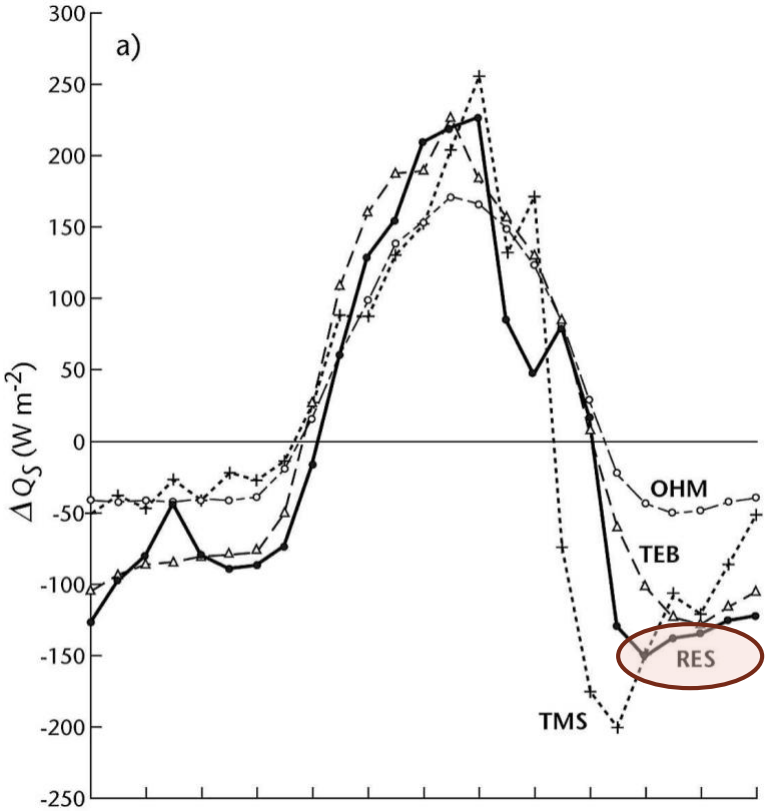
Urban Surface Energy Balance



$$\Delta Q_s = (Q^* + Q_F) - (Q_H + Q_{LE})$$

https://my.mech.utah.edu/~pardyjak/efd/murray.html

Previous Work



$$\Delta Q_s = (Q^* + Q_F) - (Q_H + Q_{LE})$$

ΔQ_s ≡ Heat storage [$\mathrm{W \cdot m^{-2}}$]

Q^* ≡ Net radiation [$\mathrm{W \cdot m^{-2}}$]

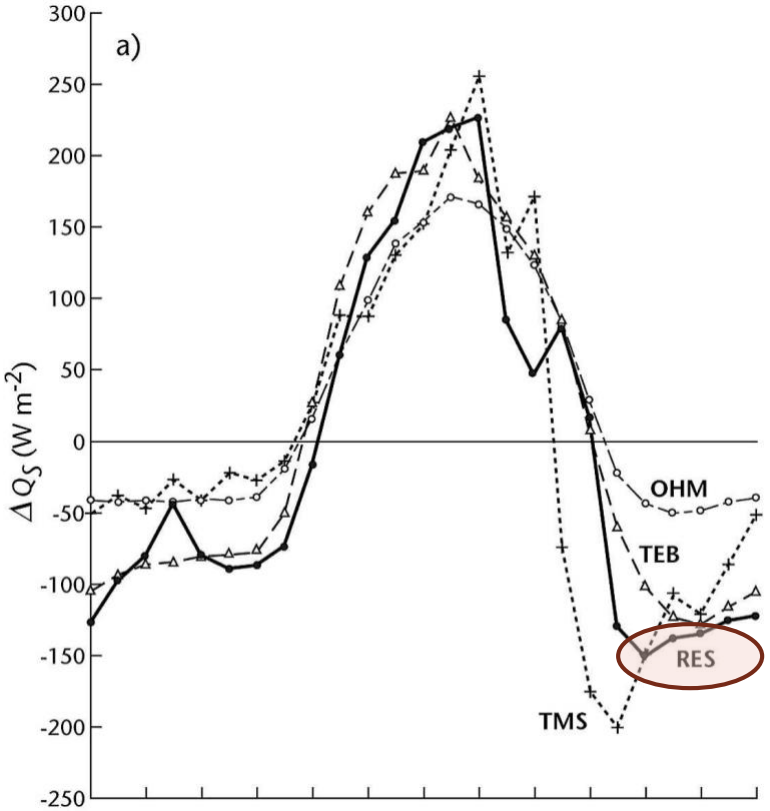
Q_F ≡ Anthropogenic Heat [$\mathrm{W \cdot m^{-2}}$]

Q_H ≡ Sensible Heat [$\mathrm{W \cdot m^{-2}}$]

Q_{LE} ≡ Latent Heat [$\mathrm{W \cdot m^{-2}}$]

Roberts, S.M., T.R. Oke, C.S. Grimmond, and J.A.Voogt, 2006: Comparison of Four Methods to Estimate Urban Heat Storage. *J. Appl. Meteor. Climatol.,* **45**, 1766–1781.

Previous Work



$$\Delta Q_s = (Q^* + Q_F) - (Q_H + Q_{LE})$$

"The instruments used to measure Q^*, Q_H, and Q_{LE} are expected to sense most of the Q_F contributions to the radiative and convective flux terms…" – therefore, Q_F is ignored here

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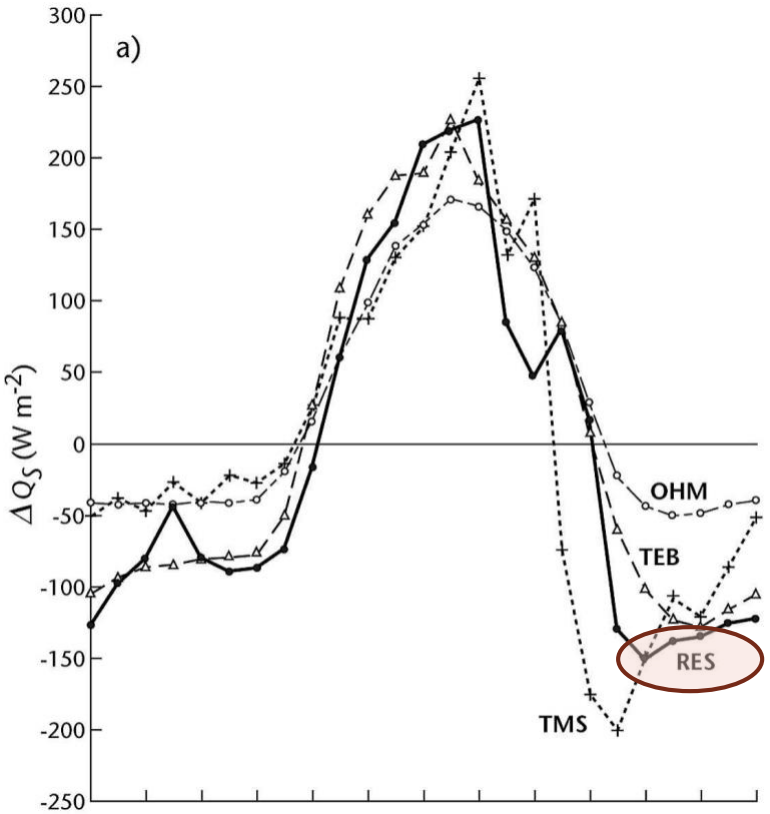

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$$\boldsymbol{\Delta Q_s = Q^* - (Q_H + Q_{LE})}$$

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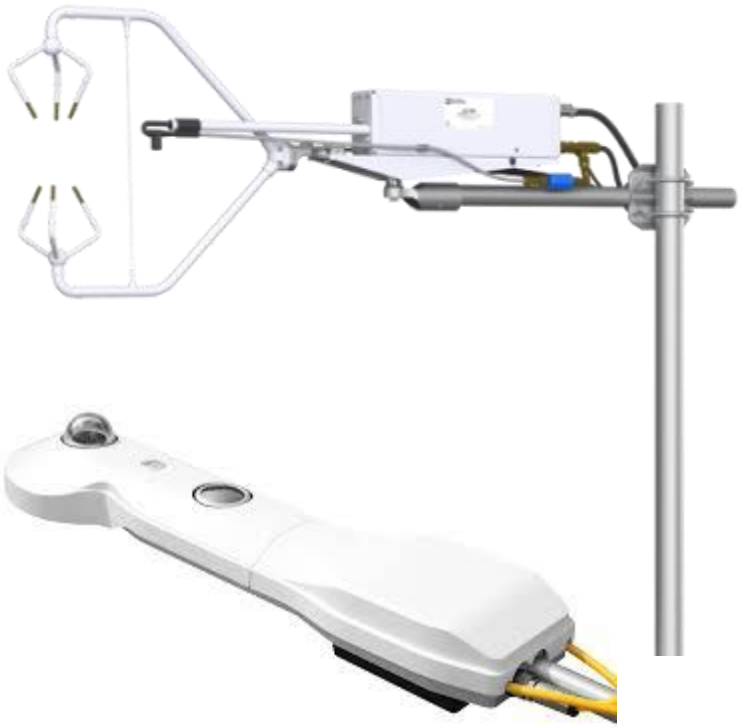
Instrumentation

$$\Delta Q_s = Q^* - (Q_H + Q_{LE})$$

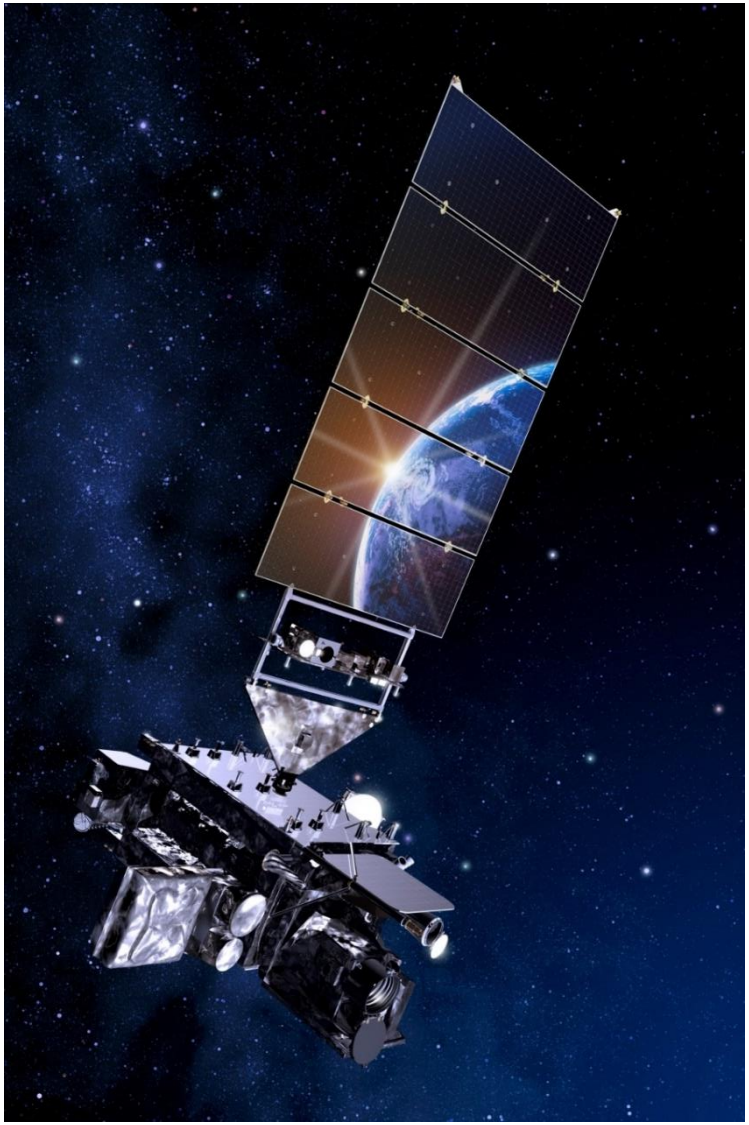
Component	Instrument
Q^*	Net Radiometer
Q_H	Sonic Anemometer + Gas Analyzer (H_2O)
Q_{LE}	



http://www.nysmesonet.org/networks/flux
https://data.neonscience.org/data-product-view

https://www.kippzonen.com/Product/85/CNR4-Net-Radiometer
https://www.campbellsci.com/cpec200

Instrumentation

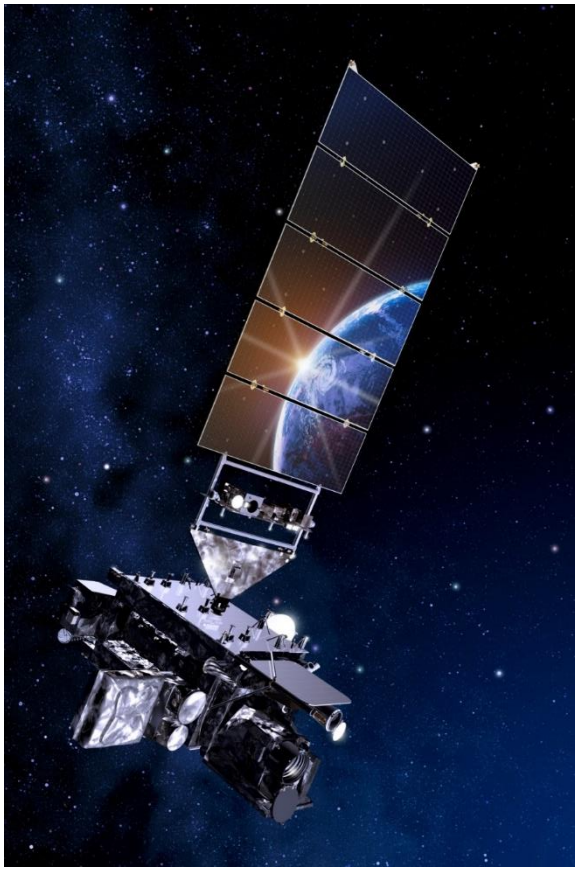


https://www.nasa.gov/directorates/heo/scan/services/missions/earth/GOES16.html

GOES-16 Satellite

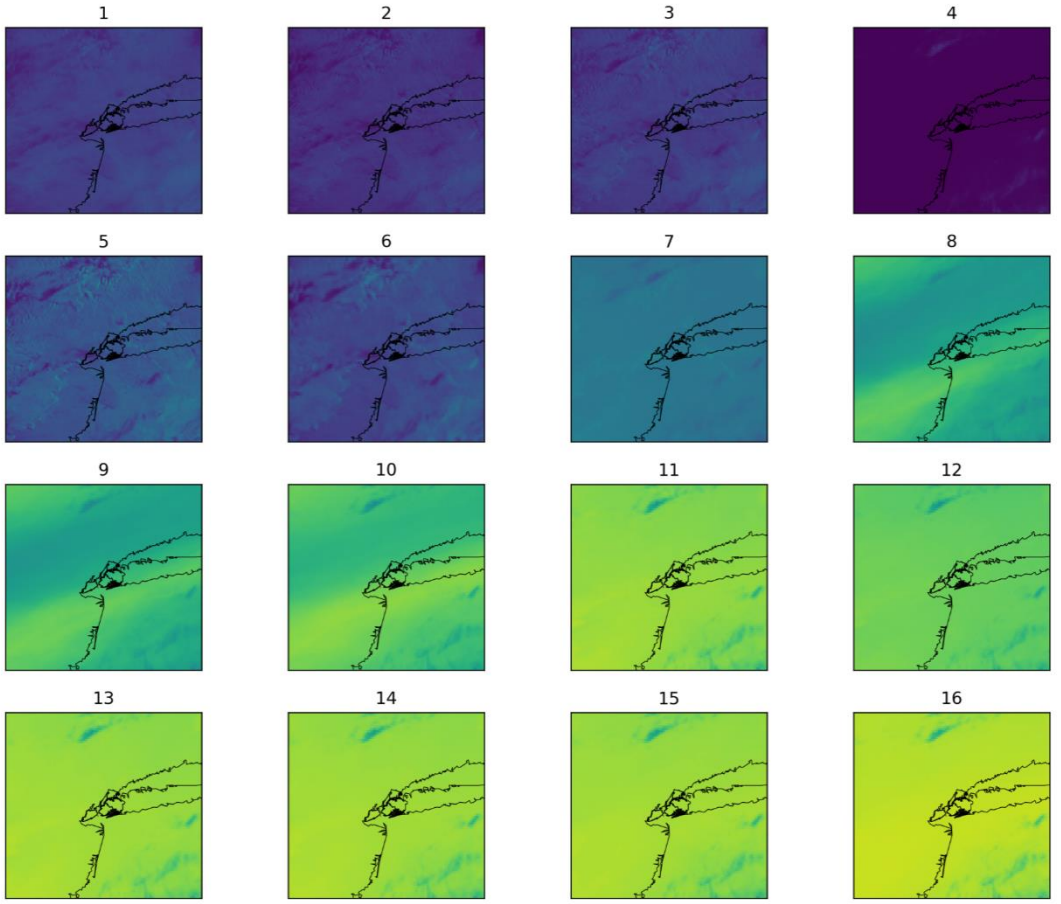
- 5-min time resolution
- 0.5 km - 2.0 km spatial resolution
- Positioned over east coast in U.S. (75.2 W)

Instrumentation



https://www.nasa.gov/directorates/heo/scan/services/missions/earth/GOES16.html

Spectral radiance (L_λ) for each of the GOES-16 bands



Hypothesis

$$\Delta Q_s = Q^* - (Q_H + Q_{LE})$$

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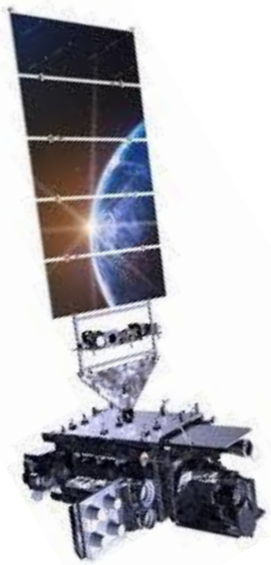
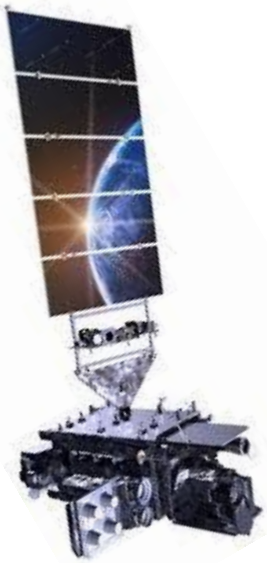


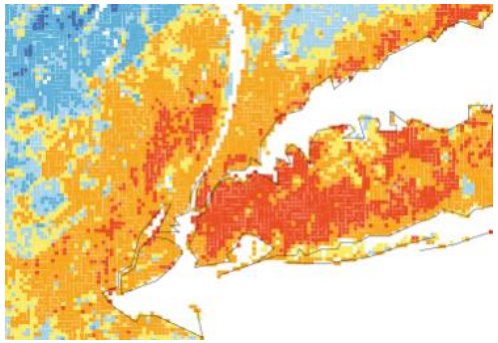
$$L_{\lambda_1 - \lambda_{16}}$$

Hypothesis

$$\Delta Q_s = Q^* - (Q_H + Q_{LE})$$

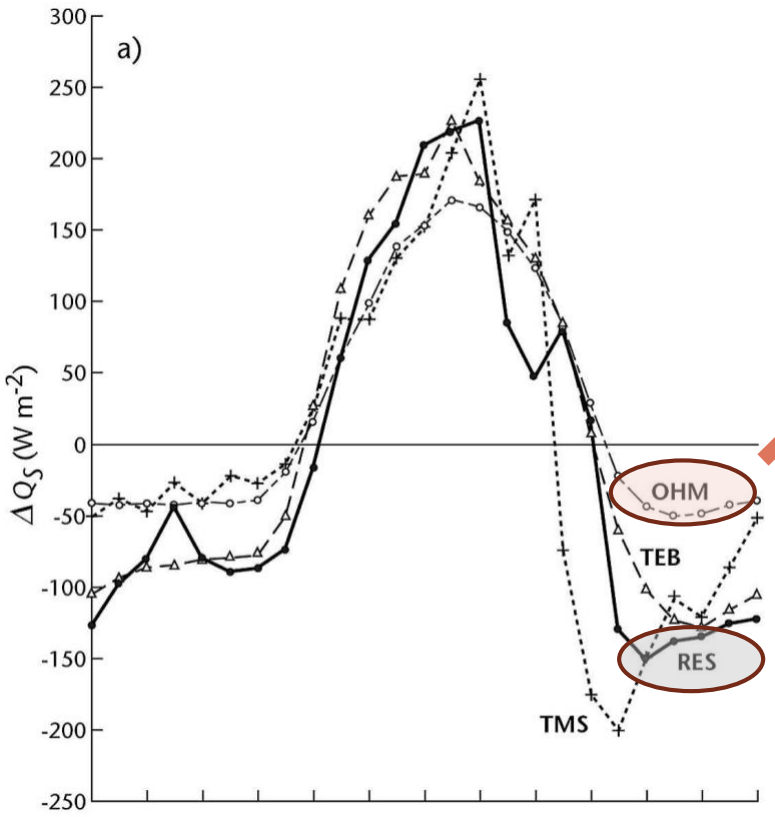


$L_{\lambda_1 - \lambda_{16}}$



ΔQ_s

Hypothesis



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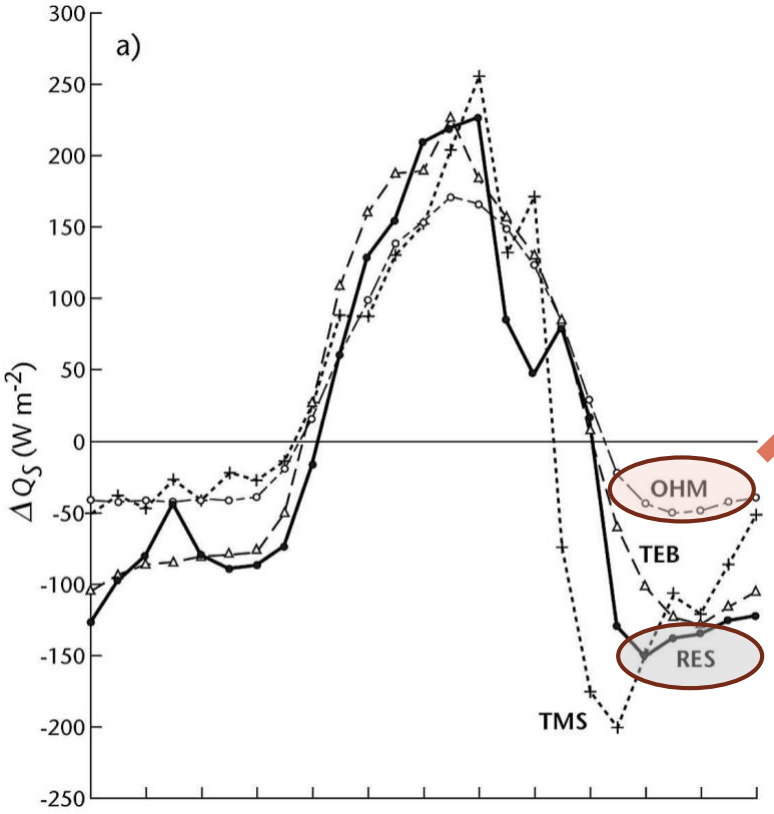
Objective Hysteresis Model

$$\Delta Q_s = a_1 Q^* + a_2 \frac{\partial Q^*}{\partial t} + a_3$$

ΔQ_s

$\lambda_1 - \lambda_{16}$

Hypothesis



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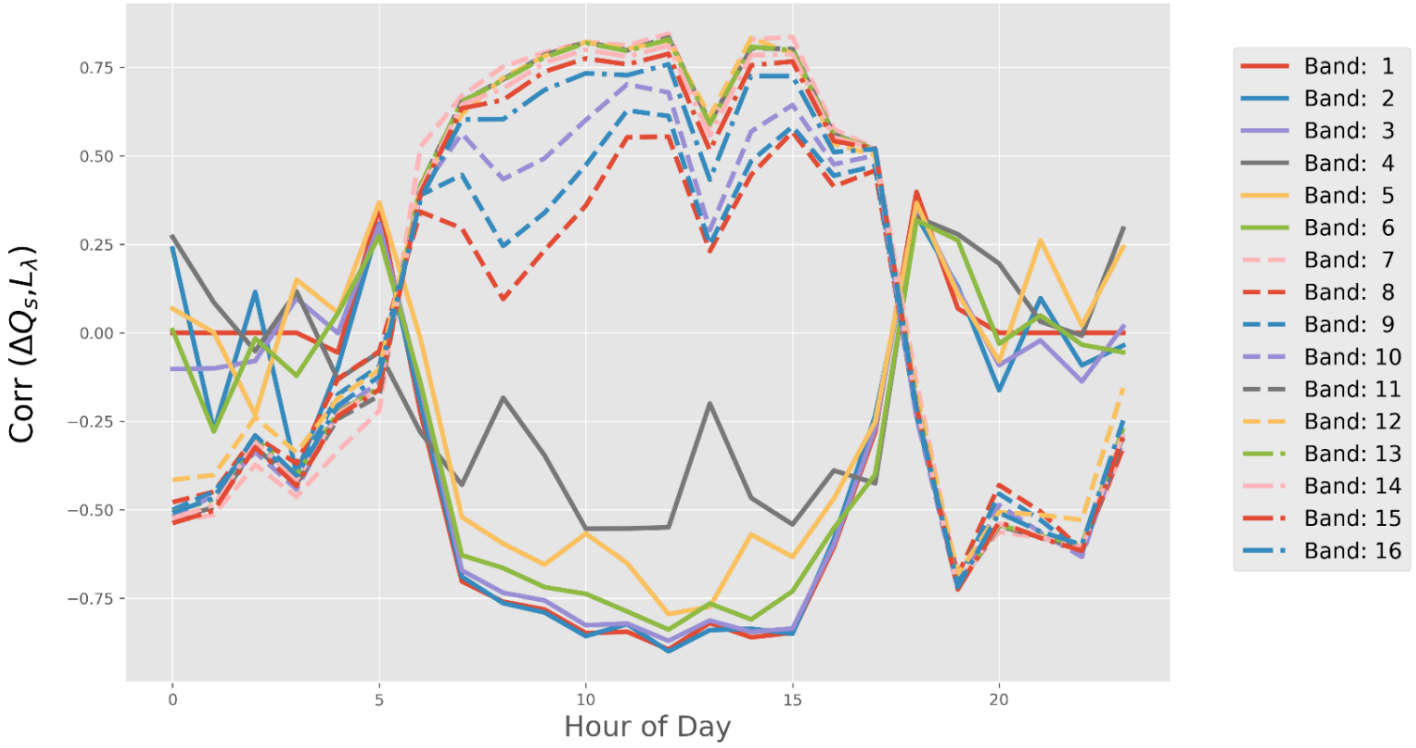
Objective Hysteresis Model

$$\Delta Q_s = a_1 Q^* + a_2 \frac{\partial Q^*}{\partial t} + a_3$$

$$\Delta Q_s = \sum_i \sum_j \left(a_{1,i,j} L_{\lambda_j} + a_{2,i,j} \frac{\partial L_{\lambda_j}}{\partial t} + a_{3,i,j} \right)$$

$a_1, a_2, a_3 \equiv$ coefficients

Hypothesis

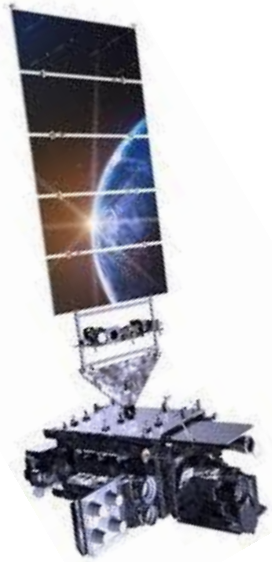


All stations exhibit similar correlative behavior over GOES-16 bands and local time

$$\text{Corr} \equiv \frac{\text{cov(x,y)}}{\sigma_x \sigma_y} = \frac{\sum_i (x_i - \overline{x}) \cdot (y_i - \overline{y})}{\sqrt{\sum_i (x_i - \overline{x})^2} \cdot \sqrt{\sum_i (y_i - \overline{y})^2}}$$

Implementation

$$\Delta Q_s = Q^* - (Q_H + Q_{LE})$$



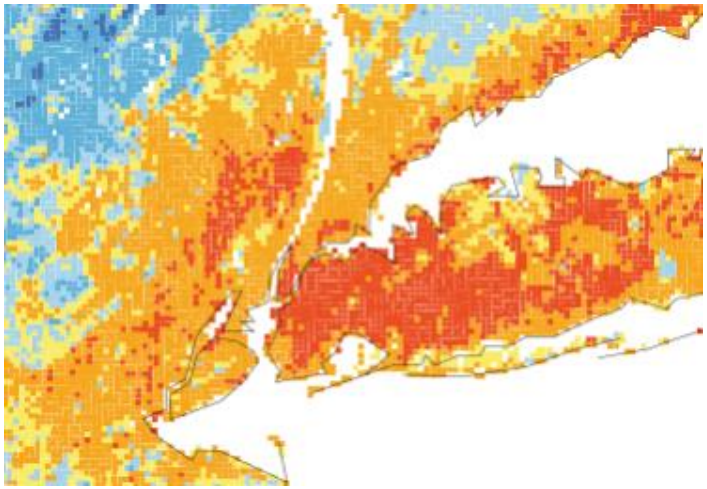
$L_{\lambda_1 - \lambda_{16}}$

$\Delta Q_s \propto L_{\lambda,j}$

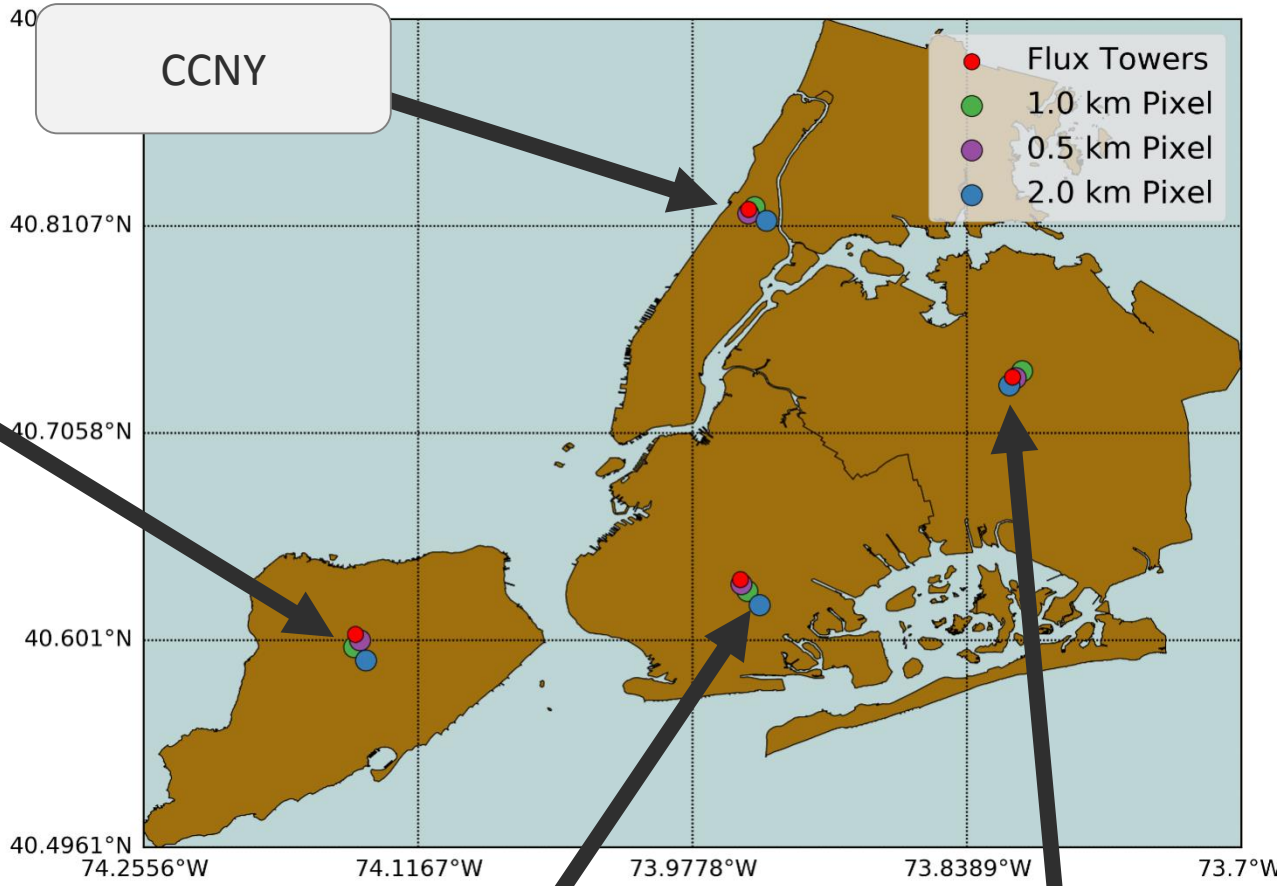
training

$$\Delta Q_s = \sum_i \sum_j \left(a_{1,i,j} L_{\lambda_j} + a_{2,i,j} \frac{\partial L_{\lambda_j}}{\partial t} + a_{3,i,j} \right)$$

ΔQ_s

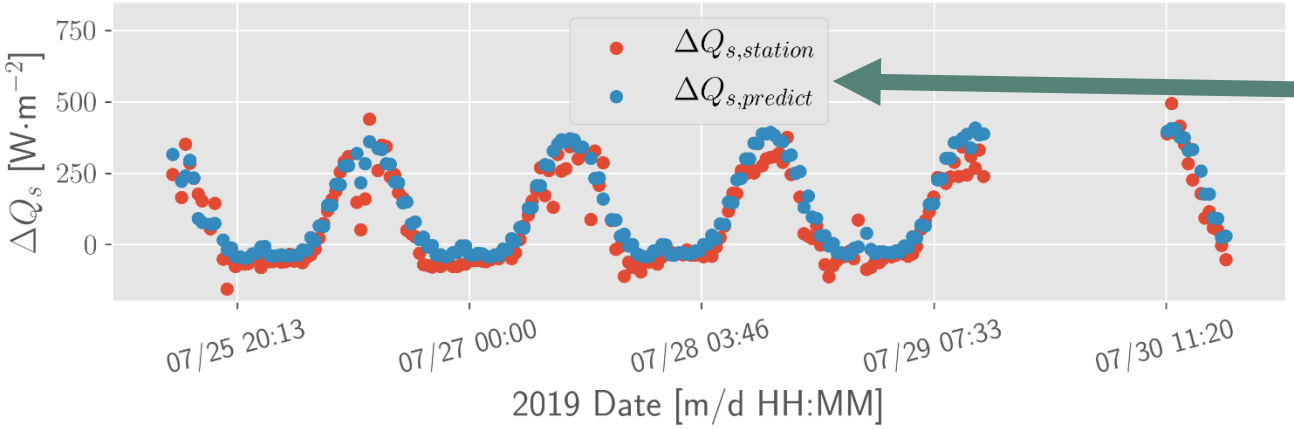


Analysis Locations

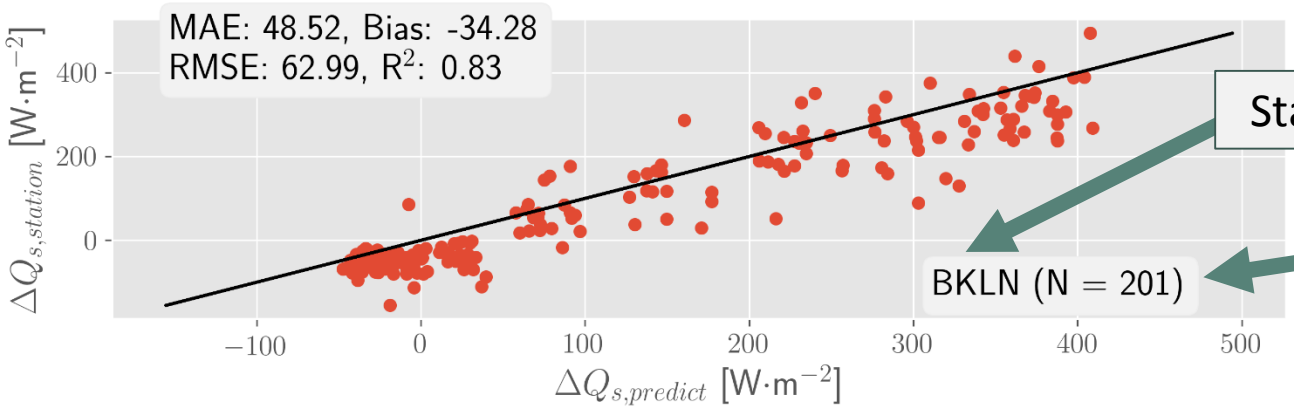


The four urban stations are used for comparison against other literature

Analysis Metrics



Prediction (blue) vs Ground-Truth (red)



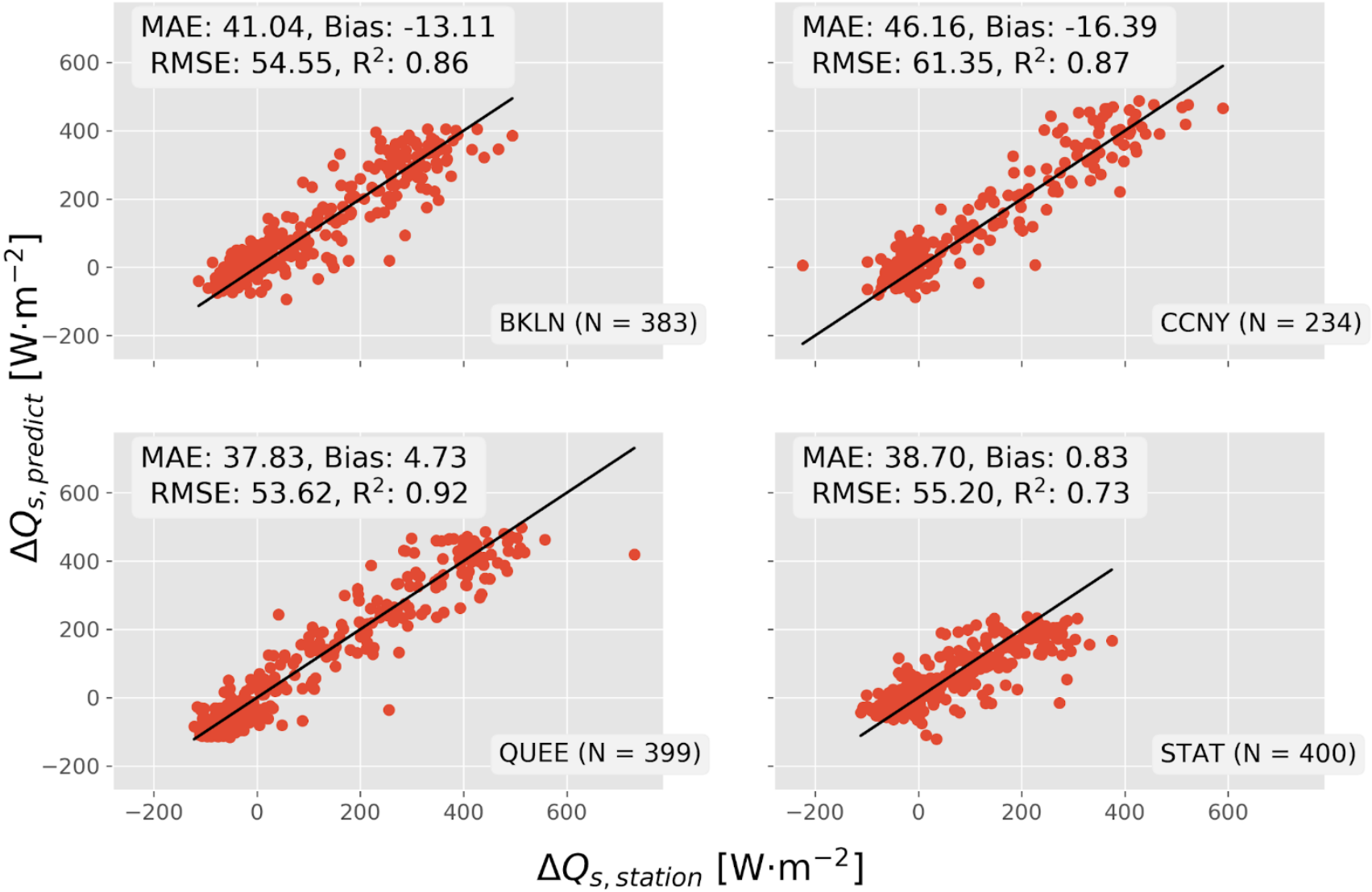
Station ID

Total # Points

$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n} \lvert \Delta Q_{s,station} - \Delta Q_{s,predict} \rvert$	$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (\Delta Q_{s,station} - \Delta Q_{s,predict})^2}$
$\text{Bias} = \frac{1}{n}\sum_{i=1}^{n} (\Delta Q_{s,station} - Q_{s,predict})$	$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} = 1 - \frac{\sum_i (\Delta Q_{s,station} - \Delta Q_{s,predict})^2}{\sum_i (\Delta Q_{s,station} - \overline{\Delta Q_{s,station}})^2}$

70% Data Training using multivariate linear regression and non-linear temporal spline

Validation Plots



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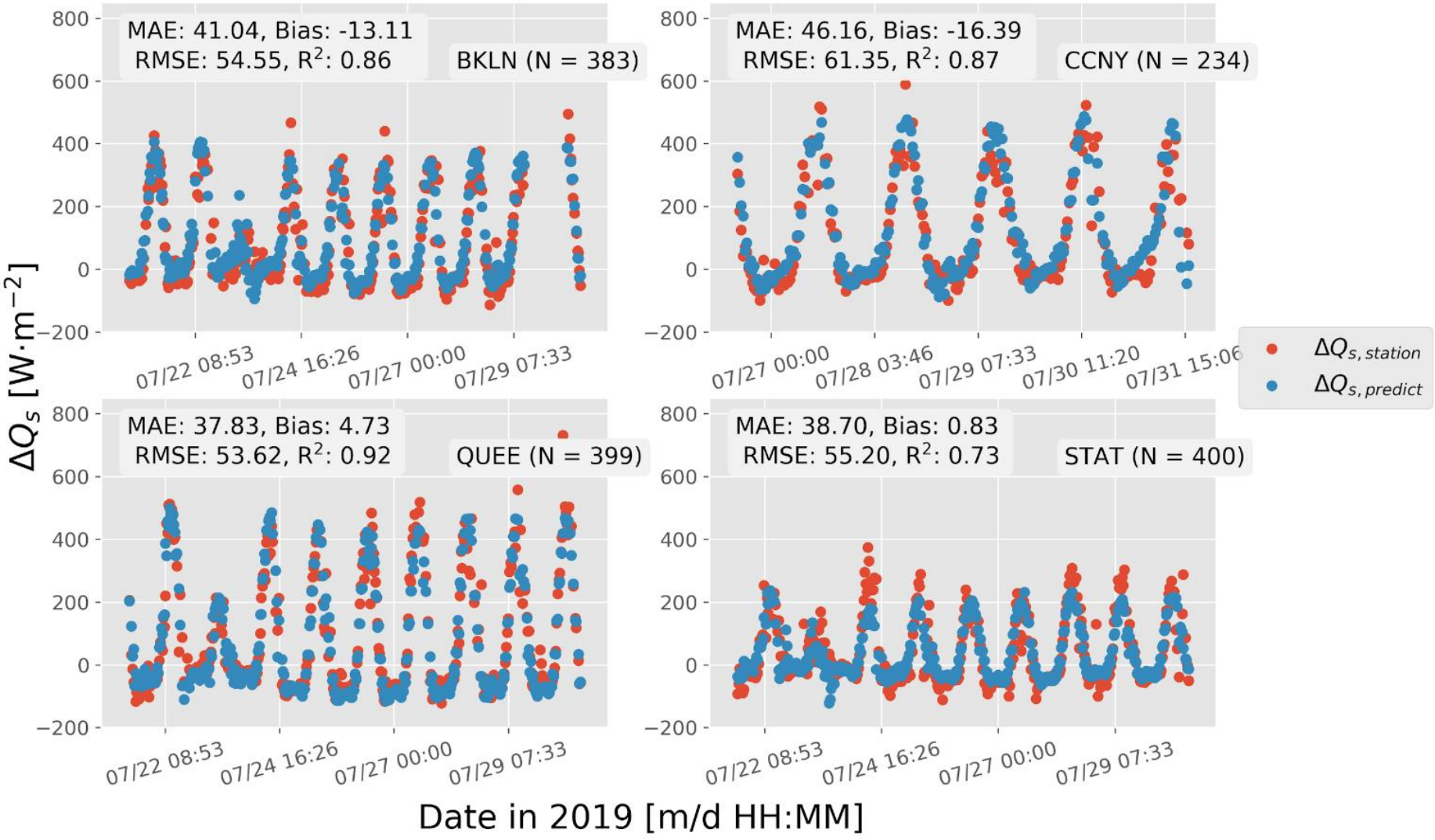

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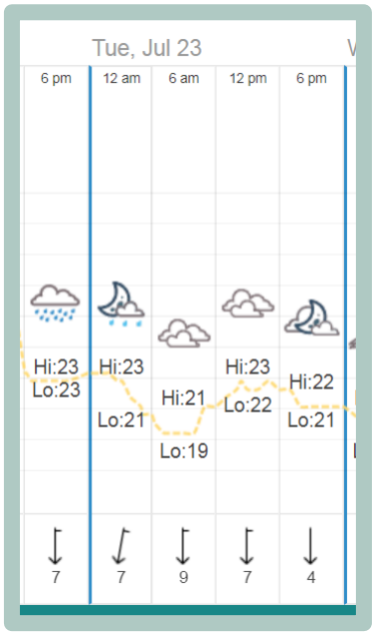

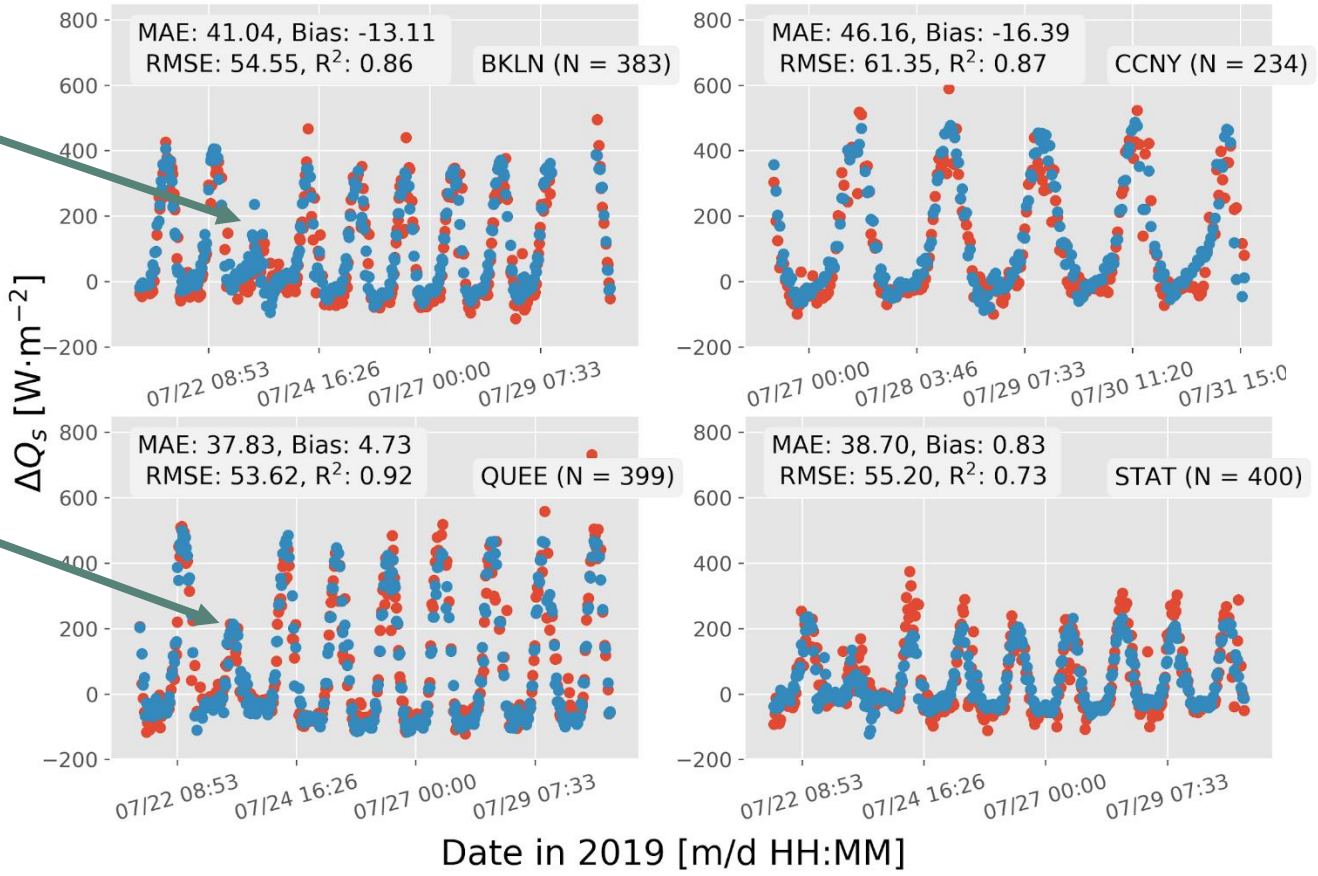

Our 16-band algorithm performs fairly well, even under rainy/cloudy conditions – robust for a satellite algorithm!

https://www.timeanddate.com/weather/usa/new-york/historic

Literature Comparison

Site/description	*N*	Slope	Intercept (W m^{-2})	r^2	Rmse (W m^{-2})
Los Angeles, California (residential suburb)	424	0.97	4.0	0.92	29.0
Mexico City (city center)	61	0.89	−6.8	0.96	33.6
Vancouver (light industrial)	312	0.96	−4.5	0.88	48.9
Miami, Florida (residential suburb)	204	0.98	22.9	0.79	61.9
Suburban Vancouver	464	0.75	30.8	0.67	62.9
Sacramento, California (residential suburb)	222	0.55	5.0	0.56	66.0
Chicago, Illinois (residential suburb)	163	0.81	38.8	0.56	83.3
Marseille (city center)	**192**	**0.49**	**31.0**	**0.70**	**94.8**
Tucson (residential suburb)	75	1.21	66.1	0.75	107.4

Site	N	R^2	RMSE
Brooklyn (100% Urban)	*383*	0.86	54.6
CCNY (91% Urban)	*234*	0.87	61.4
Queens (99% Urban)	*399*	0.92	53.6
Staten Island (57% Urban)	*400*	0.73	55.2

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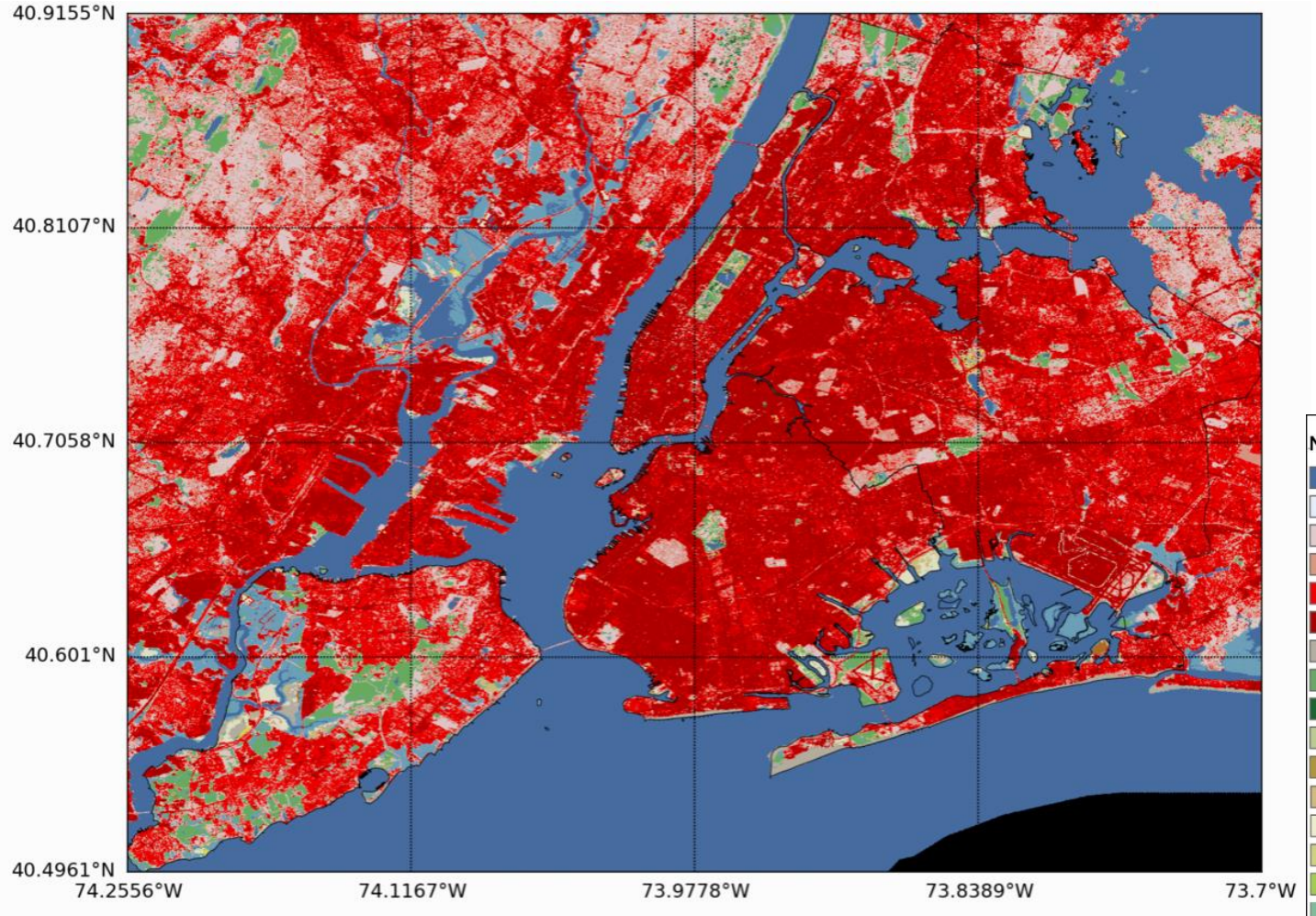
OHM average RMSE in literature: 65.3 [W· m^{-2}]

Site	*N*		
Brooklyn (100% Urban)	335	0.83	
CCNY (91% Urban)	200	0.83	
Queens (99% Urban)	347	0.90	
Staten Island (57% Urban)	350	0.73	

Satellite algorithm average RMSE: 56.2 [W· m^{-2}]

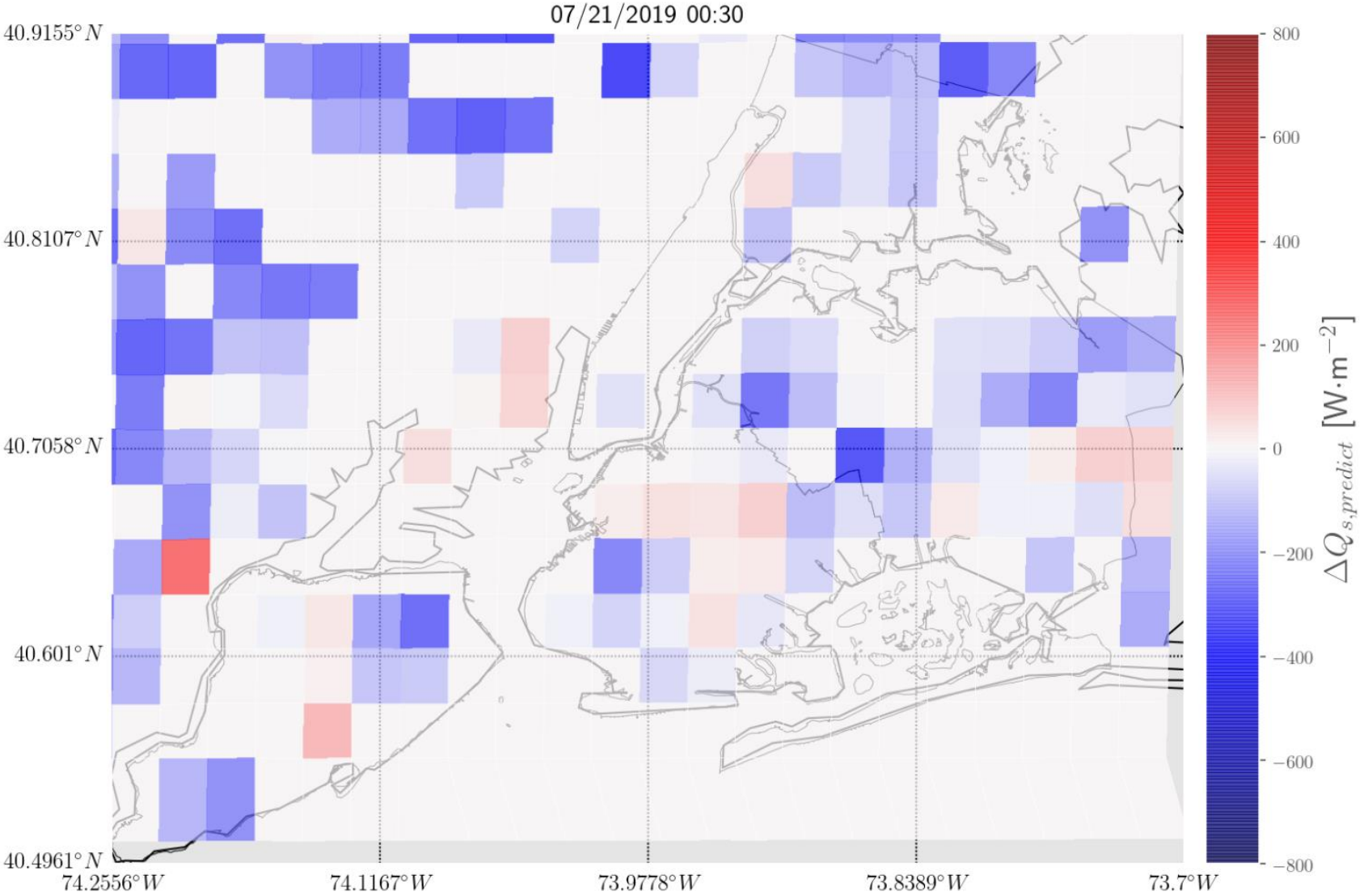
Roberts, S.M., T.R. Oke, C.S. Grimmond, and J.A.Voogt, 2006: Comparison of Four Methods to Estimate Urban Heat Storage. *J. Appl. Meteor. Climatol.*, **45**, 1766–1781.

Spatial Reconstructions



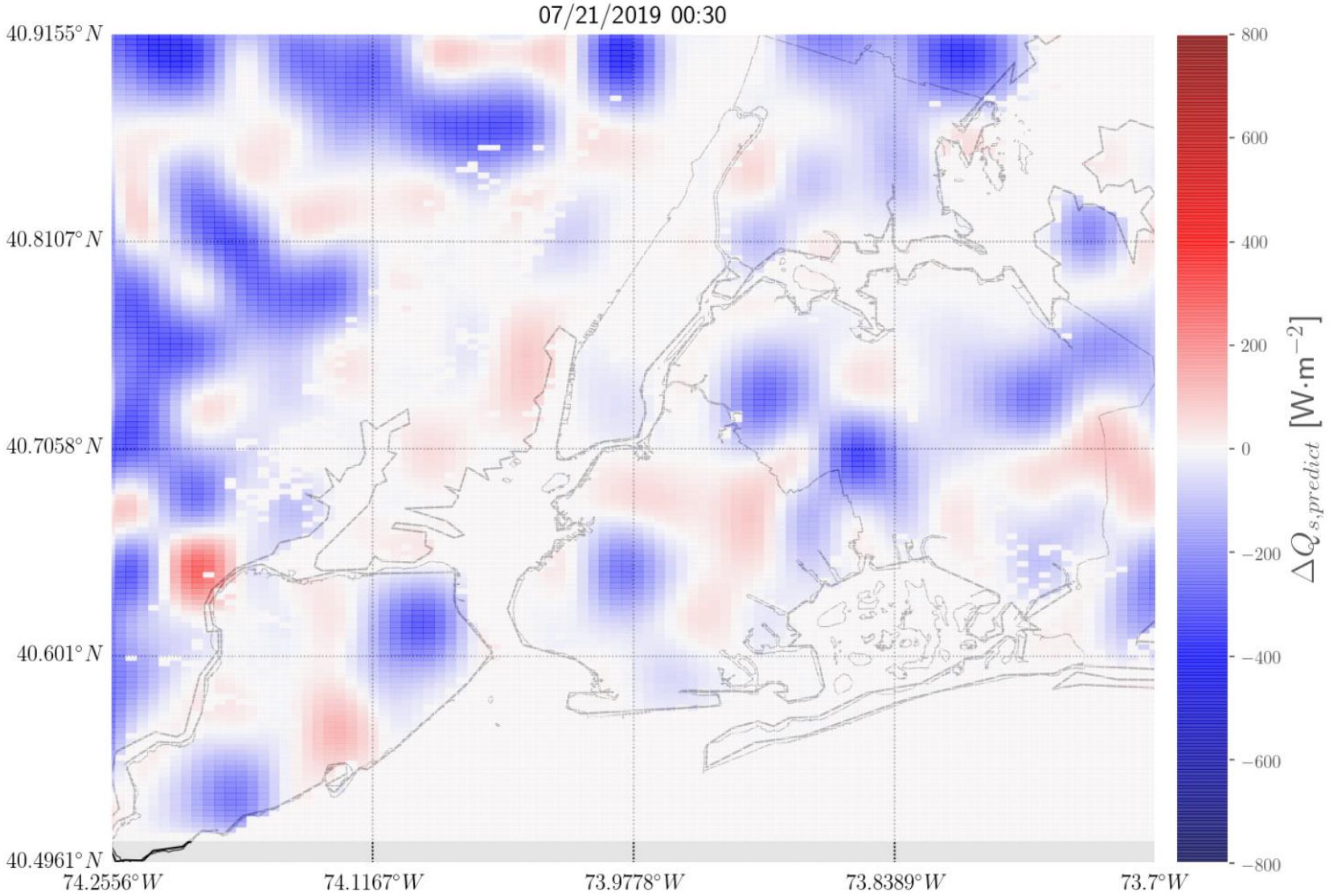
Spatial Reconstructions

Native GOES-16 2km Resolution



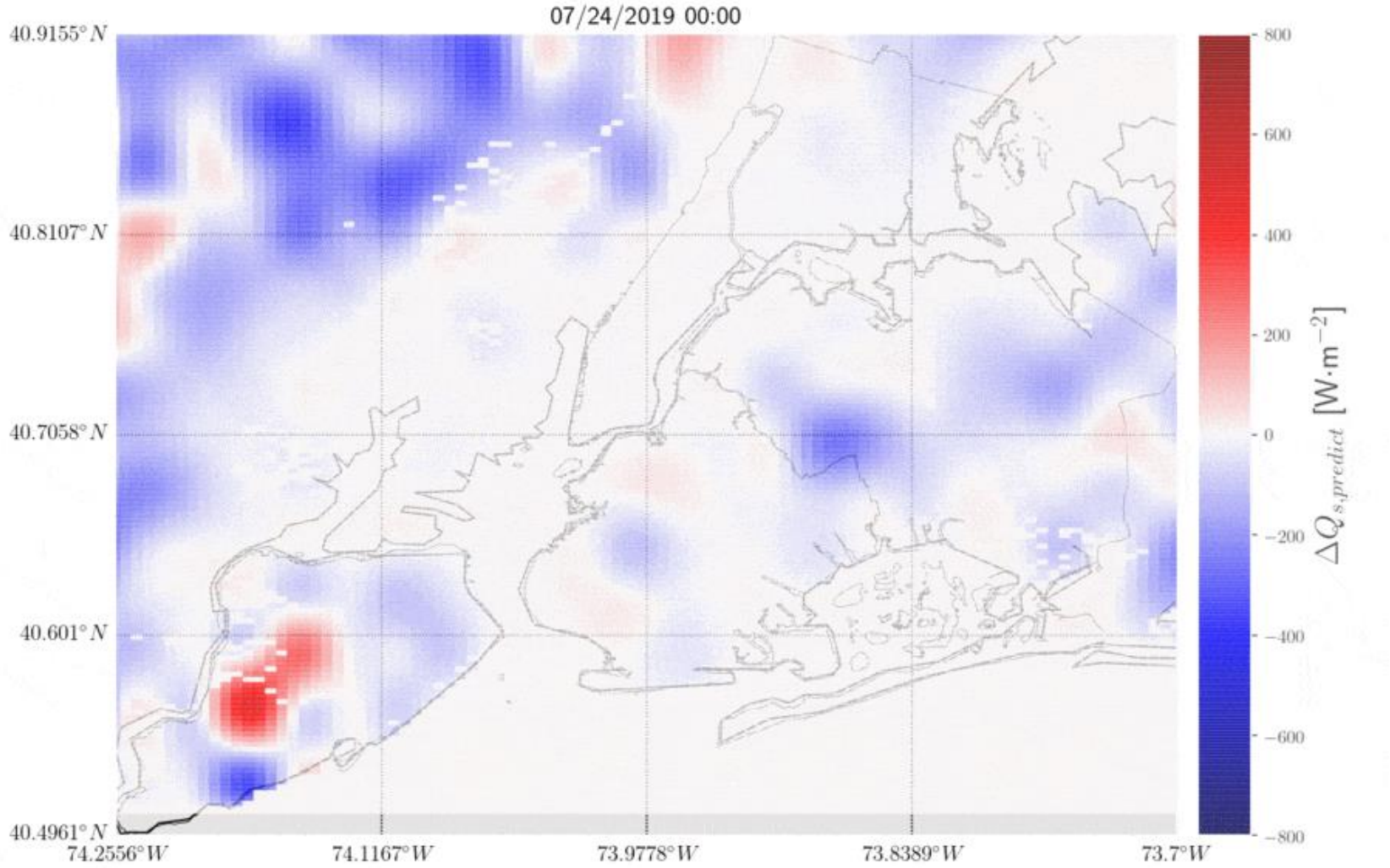
Spatial Reconstructions

Bicubic Interpolation (320m Resolution)



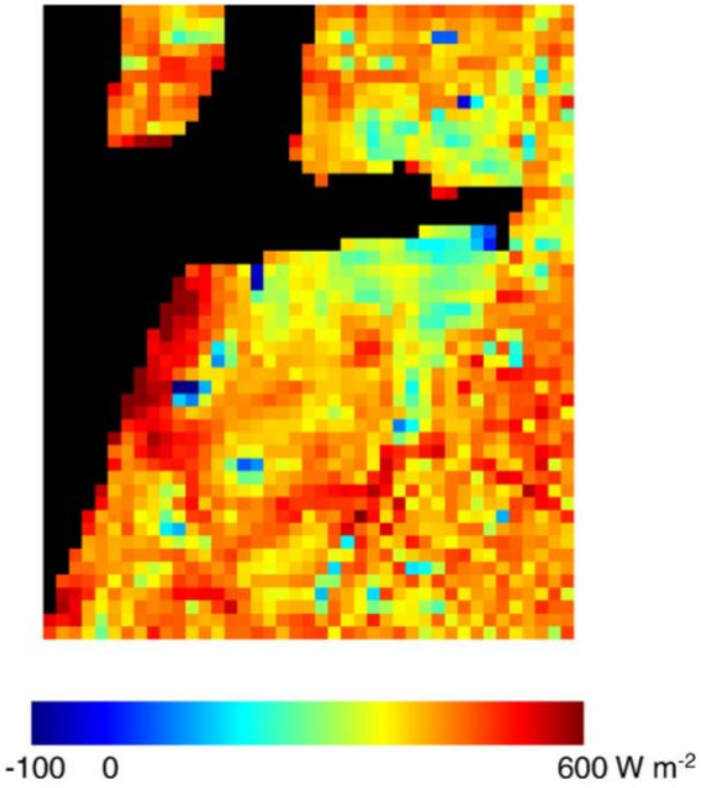
Spatial Reconstructions

Bicubic Interpolation (320m Resolution)

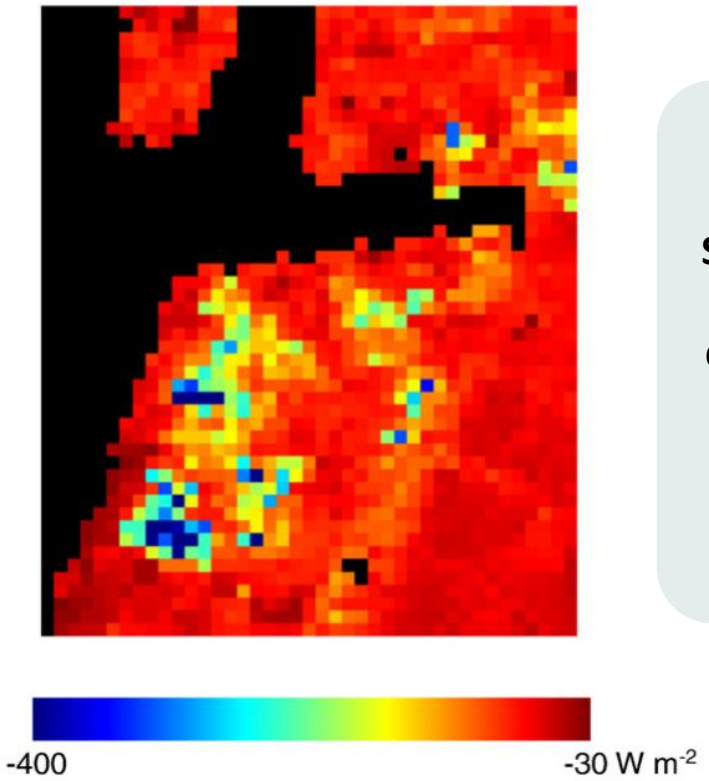


Literature Comparison

Storage heat flux in daytime on July 10, 2000



Storage heat flux at night on September 26, 2003

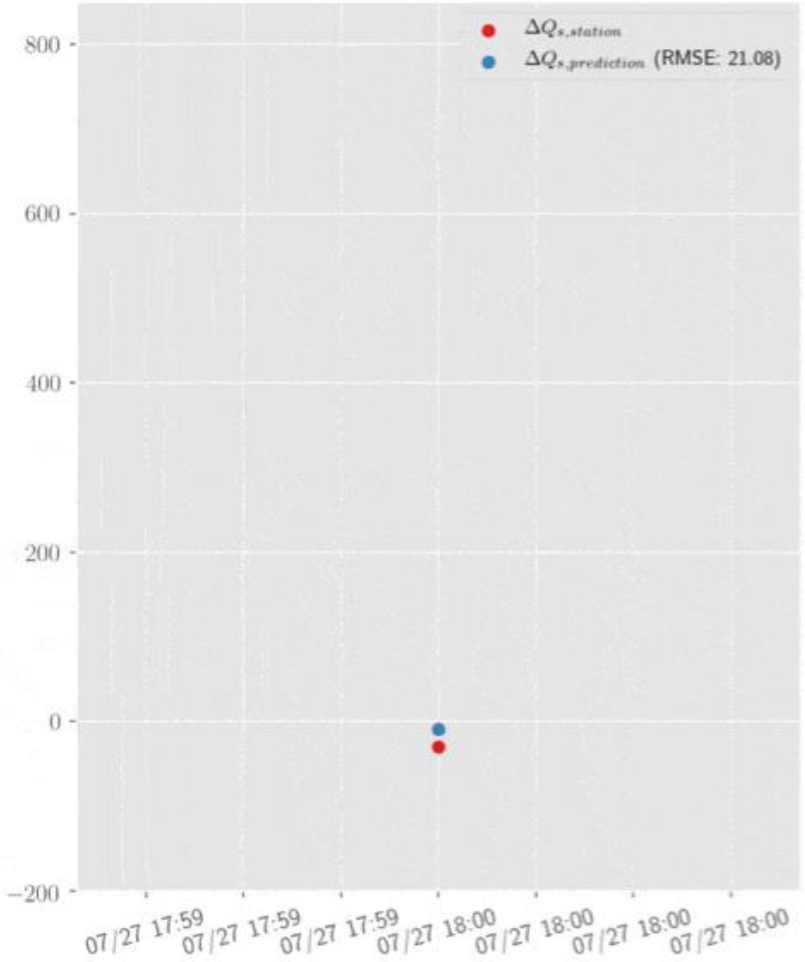


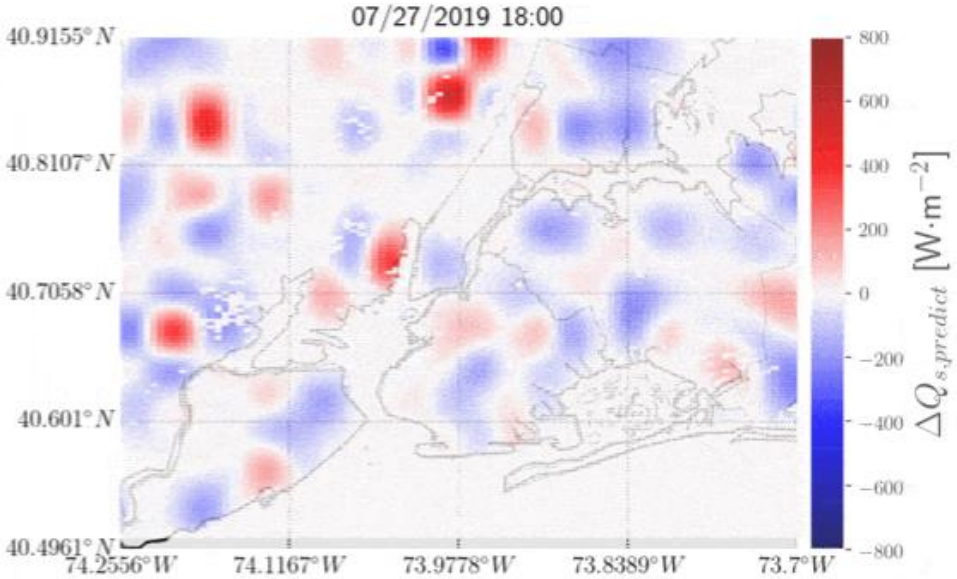
Similar spatial profiles for day and night in Nagoya, Japan

S. Kato, Y. Yamaguchi. Estimation of storage heat flux in an urban area using ASTER data
Remote Sens. Environ., 110 (2007), pp. 1-17

Interpolation Performance

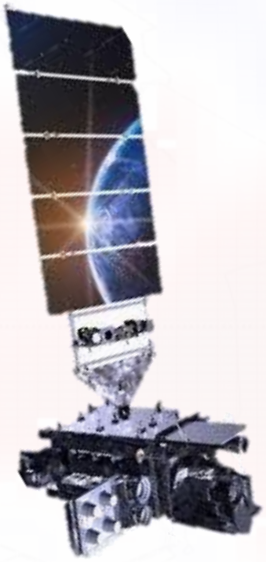
Bicubic Interpolation (320m Resolution), comparison with QUEENS Station (independent verification), July 27th-29th, 90% training





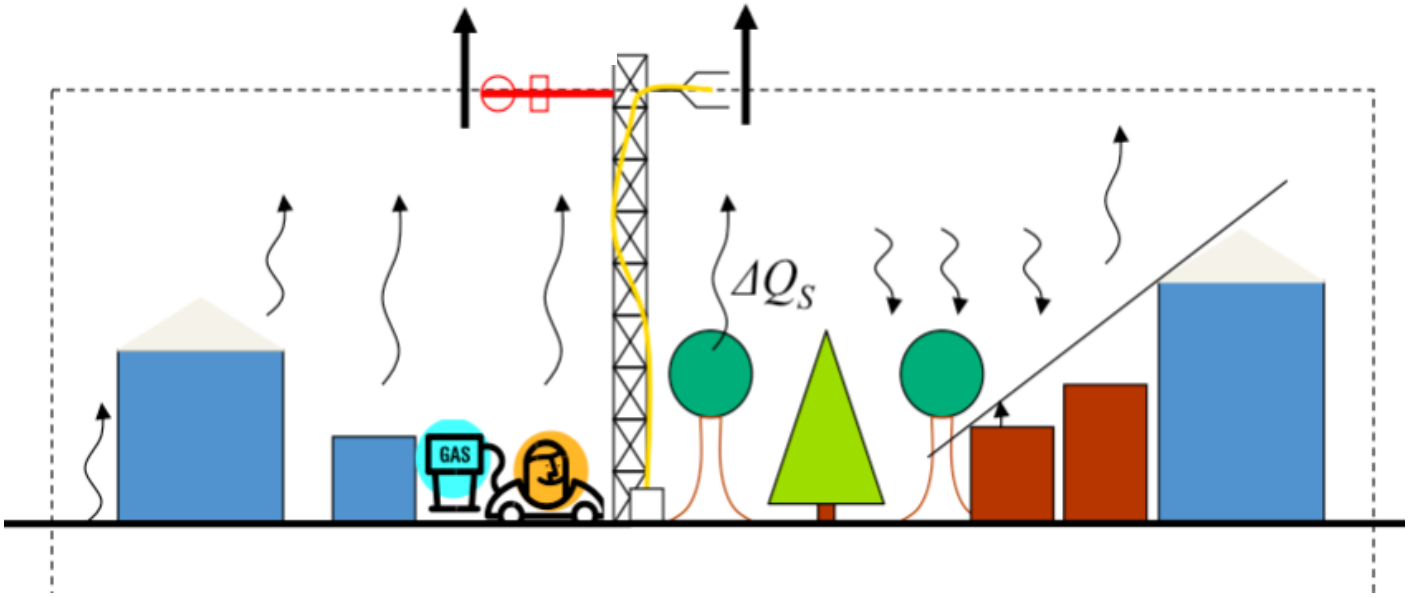
Key Takeaways:

1. The GOES-16 satellite Objective Hysteresis Model (OHM) is competitive with other storage calculation methods
2. The satellite OHM is able to capture the full diurnal cycle of heat storage
3. The spatial distribution of ΔQ_s is promising for calculation of a citywide heat storage product



Future Work:

- ❑ Thermal Mas Scheme (TMS) implementation using land cover
- ❑ Compare with urban numerical model



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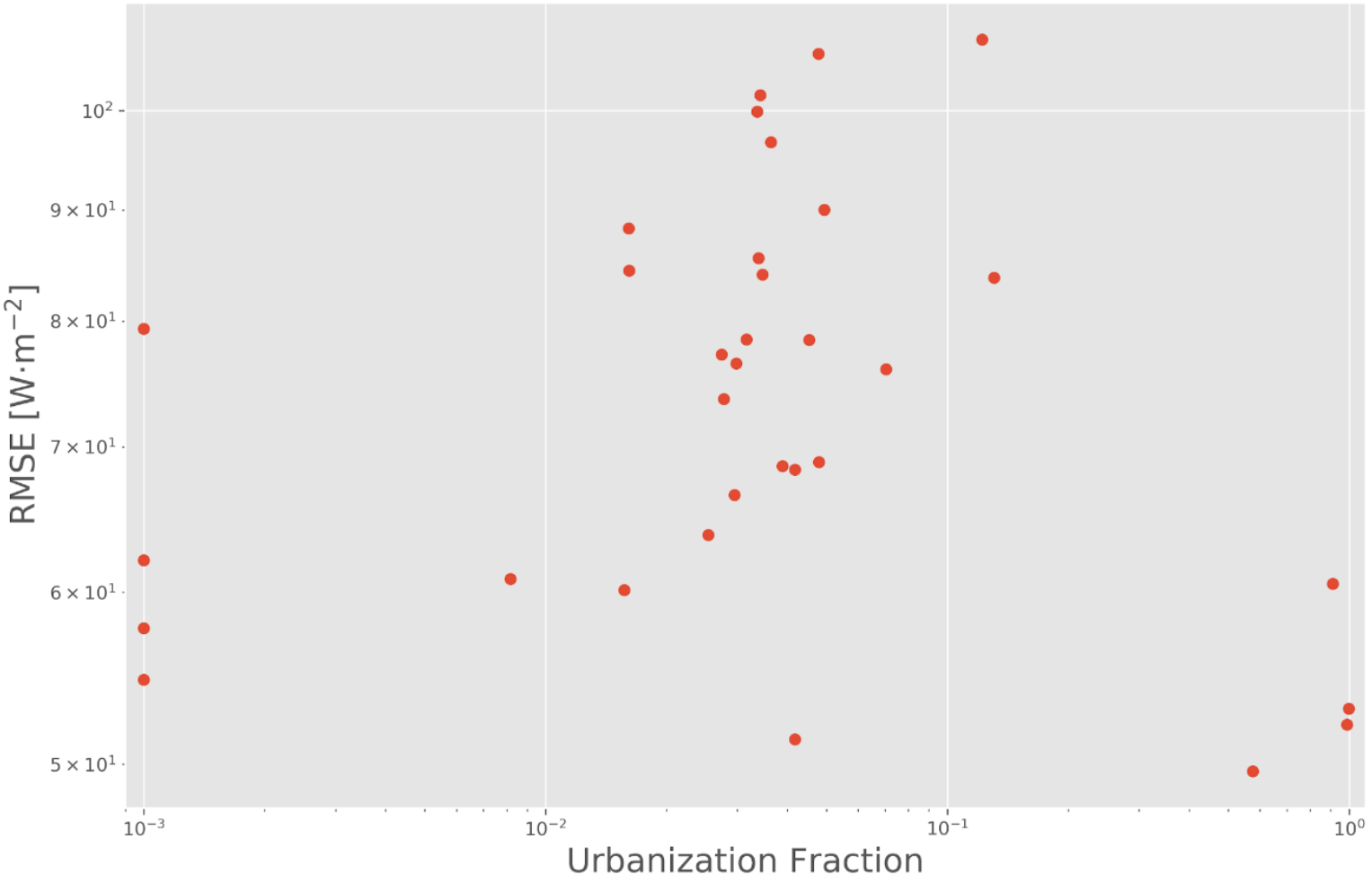
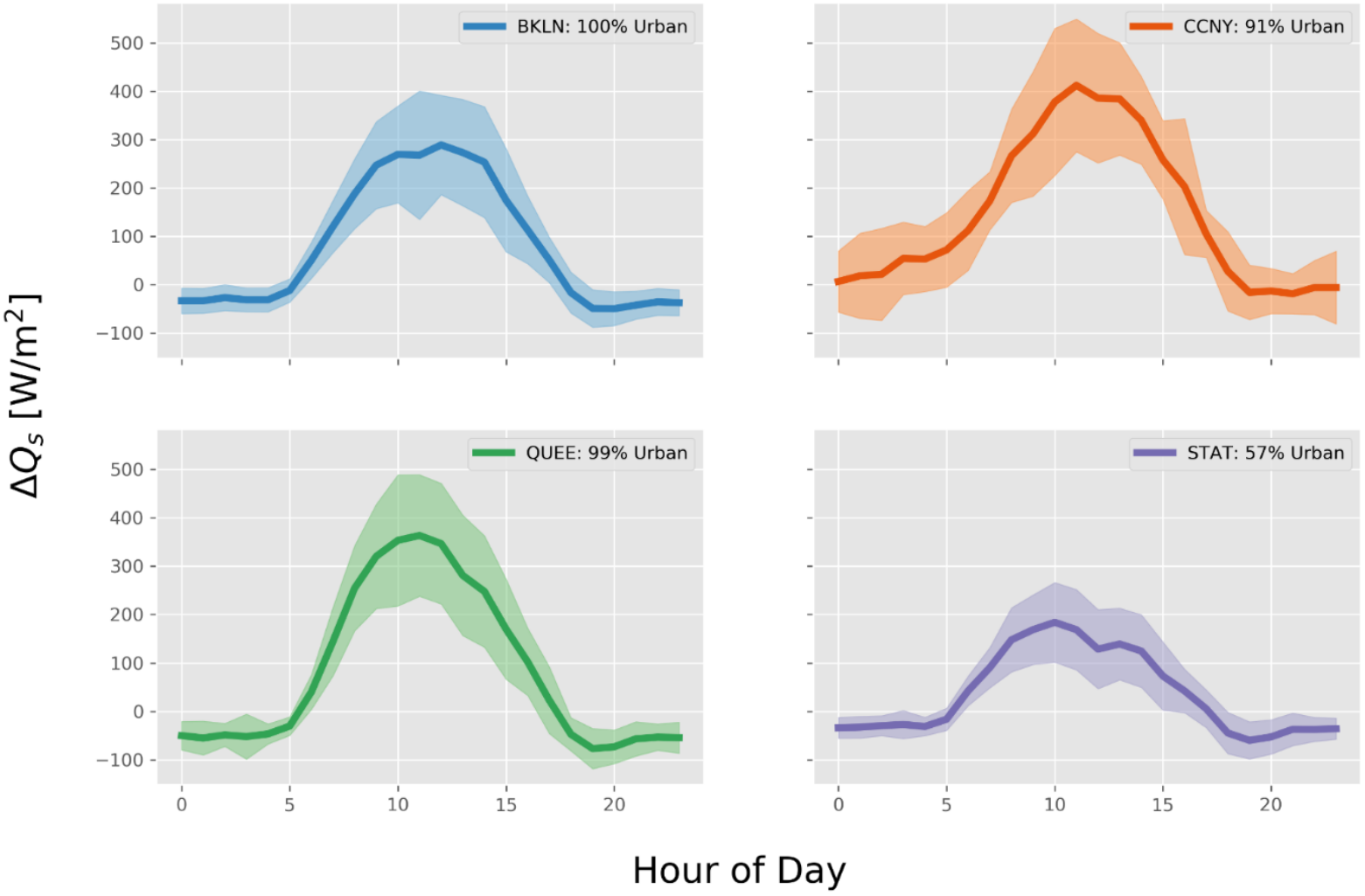
Thank you!

QUESTIONS?

28 Station Mean RMSE: 73.5 [W·m^{-2}]



EXTRAS


BKLN: 100% Urban
CCNY: 91% Urban
QUEE: 99% Urban
STAT: 57% Urban
500
400
300
200
100
0
−100
0
5
10
15
20
ΔQ_S [W/m^2]
Hour of Day

EXTRAS

Band #	Wavelength [µm]	Resolution [km]	Application
1	0.47	1	detects reflected visible solar radiation.
2	0.64	0.5	detects reflected visible solar radiation
3	0.86	1	Veggie band
4	1.37	2	Detect dust and cloud
5	1.6	1	Fire detection, snow, moisture from clouds
6	2.2	2	Clouds, aerosol optical depth
7	3.9	2	Low-level winds, clouds, fog
8	6.2	2	Winds and Total Precipitable Water
9	6.9	2	Mid-level water vapor, TPW, cloud mask
10	7.3	2	Lower-level water vapor, rain
11	8.5	2	Cloud-top phase and SO2
12	9.6	2	ozone
13	10.3	2	vertical temperature/moisture profiles, SST
14	11.2	2	Aerosol and Land Surface Temperature
15	12.3	2	LST & ash and dust
16	13.3	2	CO_2, pressure, temperatures

EXTRAS

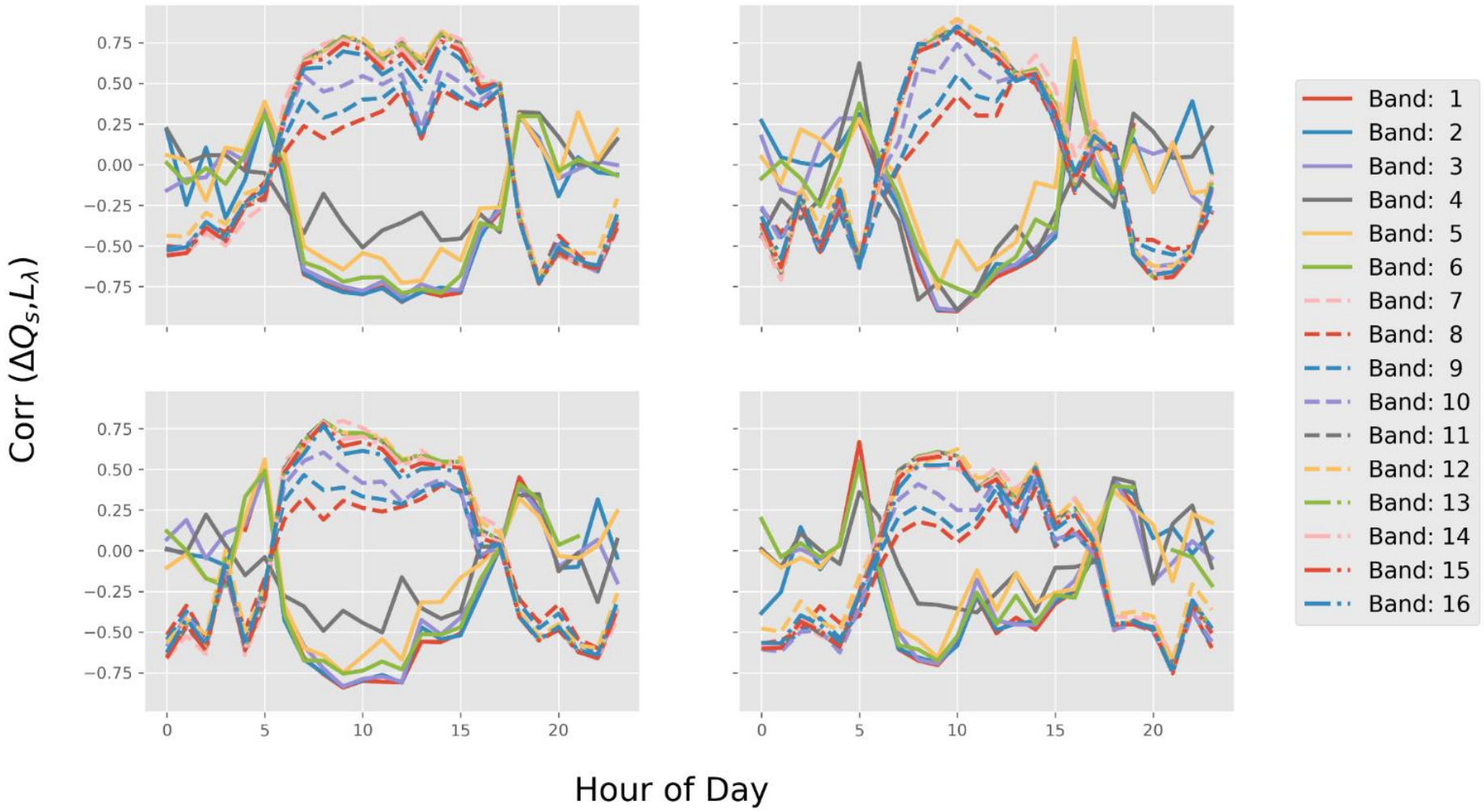

Corr (ΔQ_s,L_λ)
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
0
5
10
15
20
Hour of Day
Band: 1
Band: 2
Band: 3
Band: 4
Band: 5
Band: 6
Band: 7
Band: 8
Band: 9
Band: 10
Band: 11
Band: 12
Band: 13
Band: 14
Band: 15
Band: 16

Table 3. Absolute differences (bias) between in-situ and the modelled ground heat flux densities at six sites (**a**) with CAR, **b**) with NDVI and **c**) with OHM). Values in parentheses represent hypothetical rural differences for the CAR approach

Sites	Mean absolute differences (MAD) between modelled and measured ground heat fluxes in W/m^2						
	U1 Sperr.	U2 Spalen.	U3 Messe	S1 Allschwil	R2 V-Neuf	R3 L Erlen	MAD
a) LANDSAT 08.07.02	4	19	103		(44)	(15)	
a) MODIS day 08.07.02	1	32	96		(36)	(13)	
b) LANDSAT 08.07.02	3	26	1	18	2	69	20
b) MODIS day 08.07.02	1	25	3	9	3	74	19
c) MODIS night/MODIS day 08.07.02	15	4	11	22	20	5	13
c) MODIS night/LANDSAT 08.07.02	1	11	2	4	14	1	5
c) MODIS night/AVHRR 16 day 08.07.02	1	12	5	5	16	1	7
c) MODIS night/AVHRR 14 08.07.02	4	7	0	3	6	1	
c) MODIS night/AVHRR 16 night	6	5	2	7	1	3	4
c) MODIS day/LANDSAT 08.07.02	26	21	78	8	31	2	23
c) MODIS day/AHVRR 14 08.07.02	27	20	71	13	26	2	27
c) MODIS day/AVHRR 16 night 08.07.02	25	18	69	10	21	2	24
c) AVHRR 16 day/AVHRR 14 08.07.02	17	40	24	15	3	11	15
c) AVHRR 16 day/AVHRR 16 night	11	25	24	15	3	11	15
c) LANDSAT/AVHRR 14 08.07.02	5	17	8	10	5	3	8
c) LANDSAT/AVHRR 16 night 08.07.02	7	6	7	14	1	2	6
c) AVHRR 14/AVHRR 16 night 08.07.02	25	54	33	4	9	22	24
c) AVHRR 16/AVHRR 15 25.06.02	30	15	7	10	27	6	16
c) MODIS day/AVHRR 15 25.06.02	39	10	76	9	16	1	25
c) AVHRR16/MODIS day 25.06.02	15	28	19	36	44	9	25
c) AVHRR 16/MODIS day 26.06.02	14	37	7	40	37	12	25
c) MODIS night/AVHRR16 26.06.02	13	24	9	15	18	1	13
c) MODIS night/MODIS day 26.06.02	15	22	9	13	17	1	13
Site mean absolute difference	13	21	29	13	15	11	17
RMSE	11	12	34	10	13	21	17

Rigo, G., Parlow, E. Modelling the ground heat flux of an urban area using remote sensing data. *Theor. Appl. Climatol.* 90, 185–199 (2007)

"Net radiation gave a RMS error of 25 [W· m^{-2}]"

A similar satellite method uses MODIS/LANDSAT with MAD: 21.0 [$W \cdot m^{-2}$]

Our MAD: 40.9 [W· m^{-2}]

"shortwave upward radiation was derived using linear regression between in-situ measurements...and a channel computed from the visible and near infrared channels of LANDSAT ETM+"