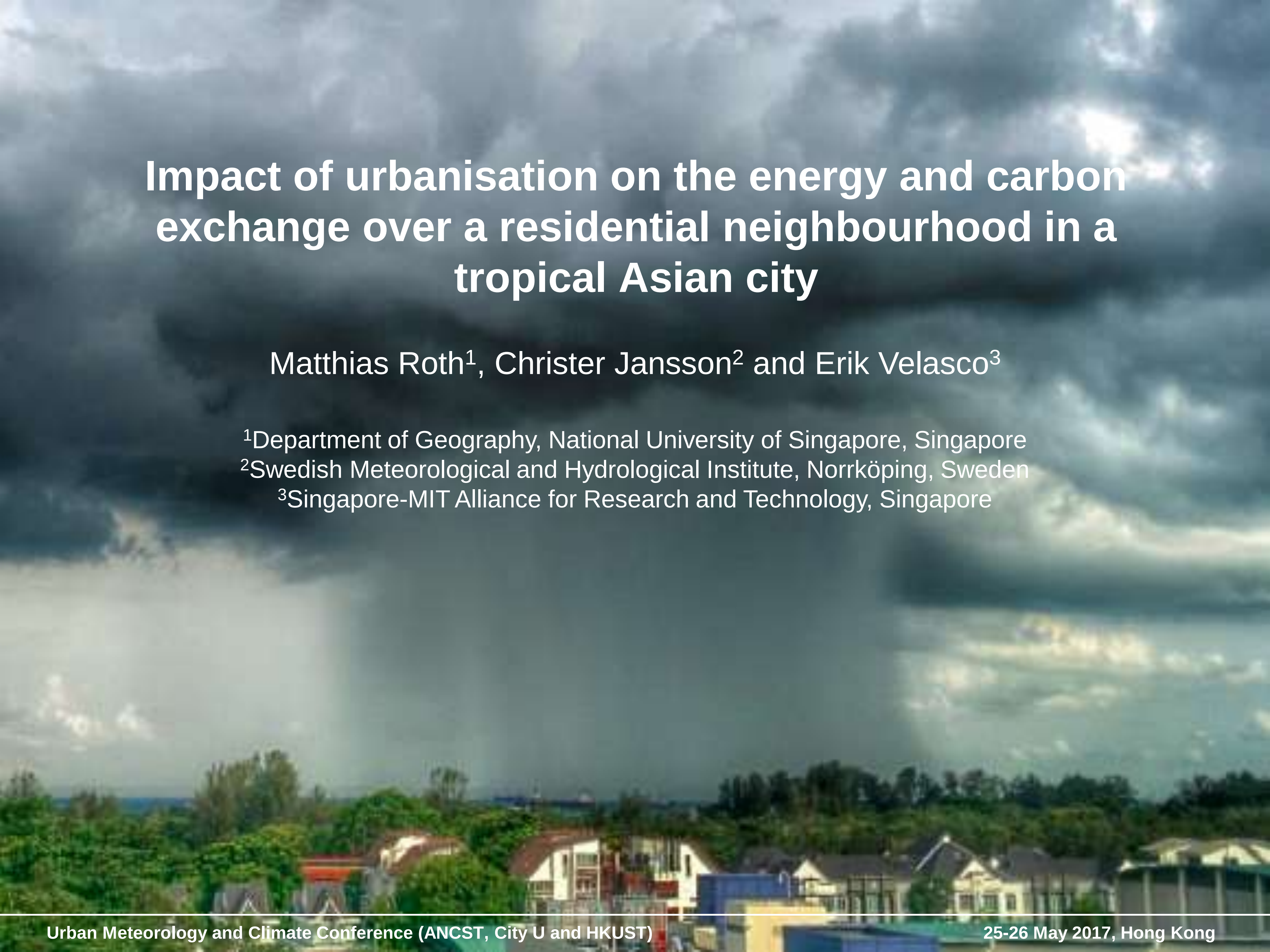

Impact of urbanisation on the energy and carbon exchange over a residential neighbourhood in a tropical Asian city

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Context

The energy balance and CO_2 exchange are two of the most important components of the surface-atmosphere exchange:

- The energy balance defines the energy partitioning at the surface and as such determines the microclimate of a location.
- The CO_2 exchange controls surface emissions of the most important GHG.

Knowledge gaps:

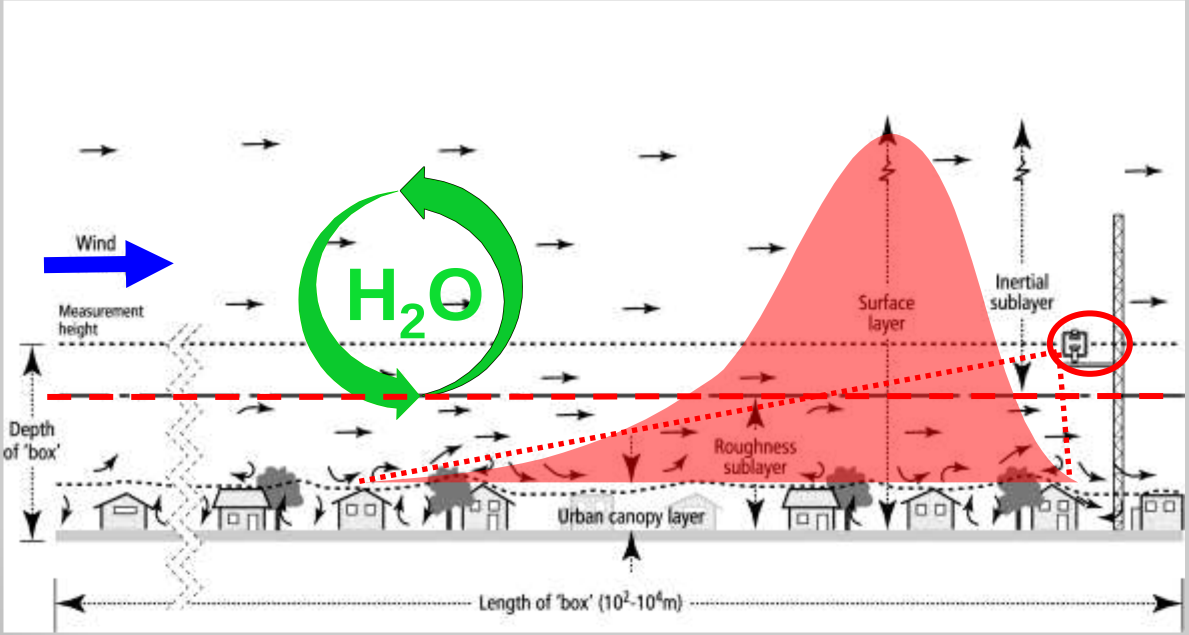
- Increasing amount of energy and carbon dioxide flux data are available for cities of the developed world located in the mid-latitudes, however they are notably absent in the (sub)tropics.
- Process-based models that simulate the physics of the urban atmosphere have not been tested against tropical data sets, while empirical models based on existing data sets are biased towards conditions found in mid-latitudes.

This presentation introduces a long-term data set of urban flux measurements in an understudied region, i.e. tropical rainforest climate, with a focus on temporal variability (diurnal, seasonal and inter-annual).

Reference: Roth M, Jansson C, Velasco E, 2017. Multi-year energy balance and carbon dioxide fluxes over a residential neighbourhood in a tropical city. *Int J Climatol*, 37, 2679–2698.

Measurement approach

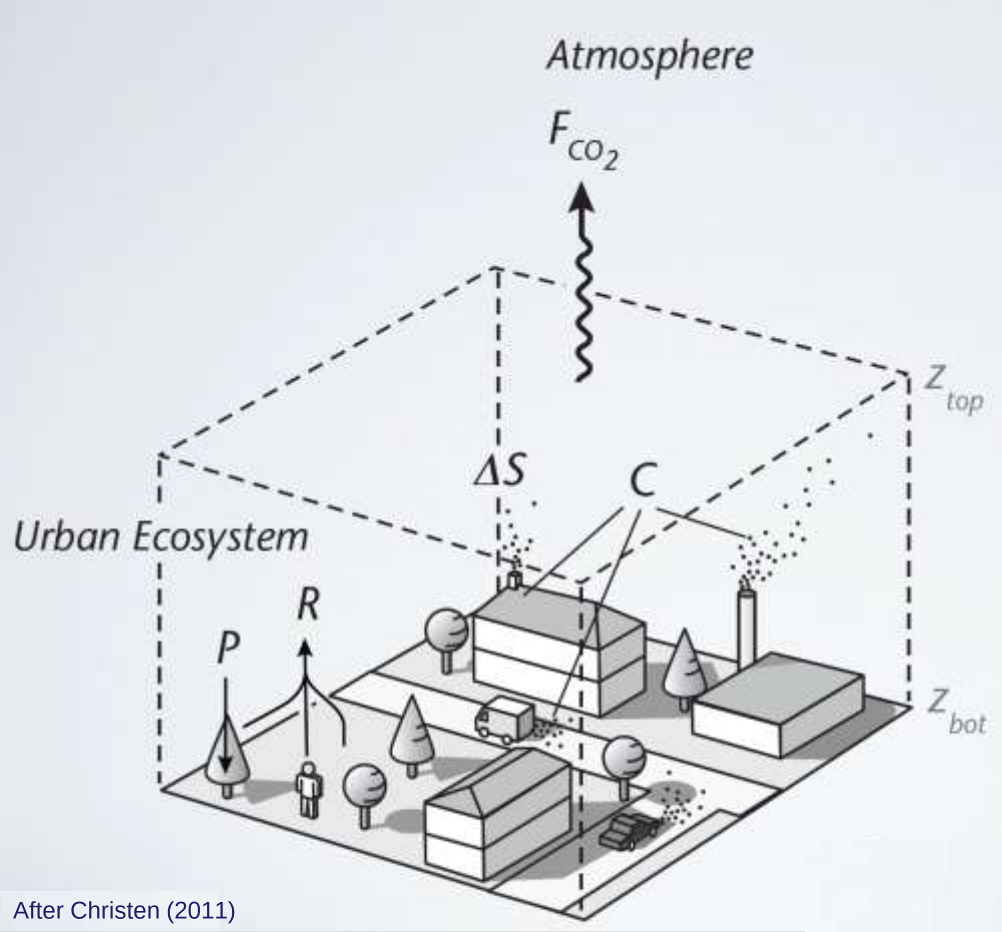
- Energy balance measurements are best made using eddy covariance (EC) approach. Sensors are installed above the blending height and results therefore integrate a mix of microclimatic effects and represent the climate of “neigborhoods”.
- Location should be optimal to represent urban ecosystem of interest for most wind directions or for prevailing winds.
- Only few observational studies exist that try to estimate the individual components from e.g. rooftops and canyons (scintillometery work in Basel).



(Modified from Oke, 1997, 2006)

Measurement approach

Eddy covariance (EC) approach - most direct and defensible way to obtain fluxes



After Christen (2011)

$$F_{CO2} = C + R - P + \Delta S$$

C - Combustion

R - Respiration

P - Photosynthesis

ΔS - Storage change in air within balancing volume

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

Q^* - Net allwave radiation

Q_F - Anthropogenic heat flux

Q_H - Sensible heat flux

Q_E - Latent heat flux

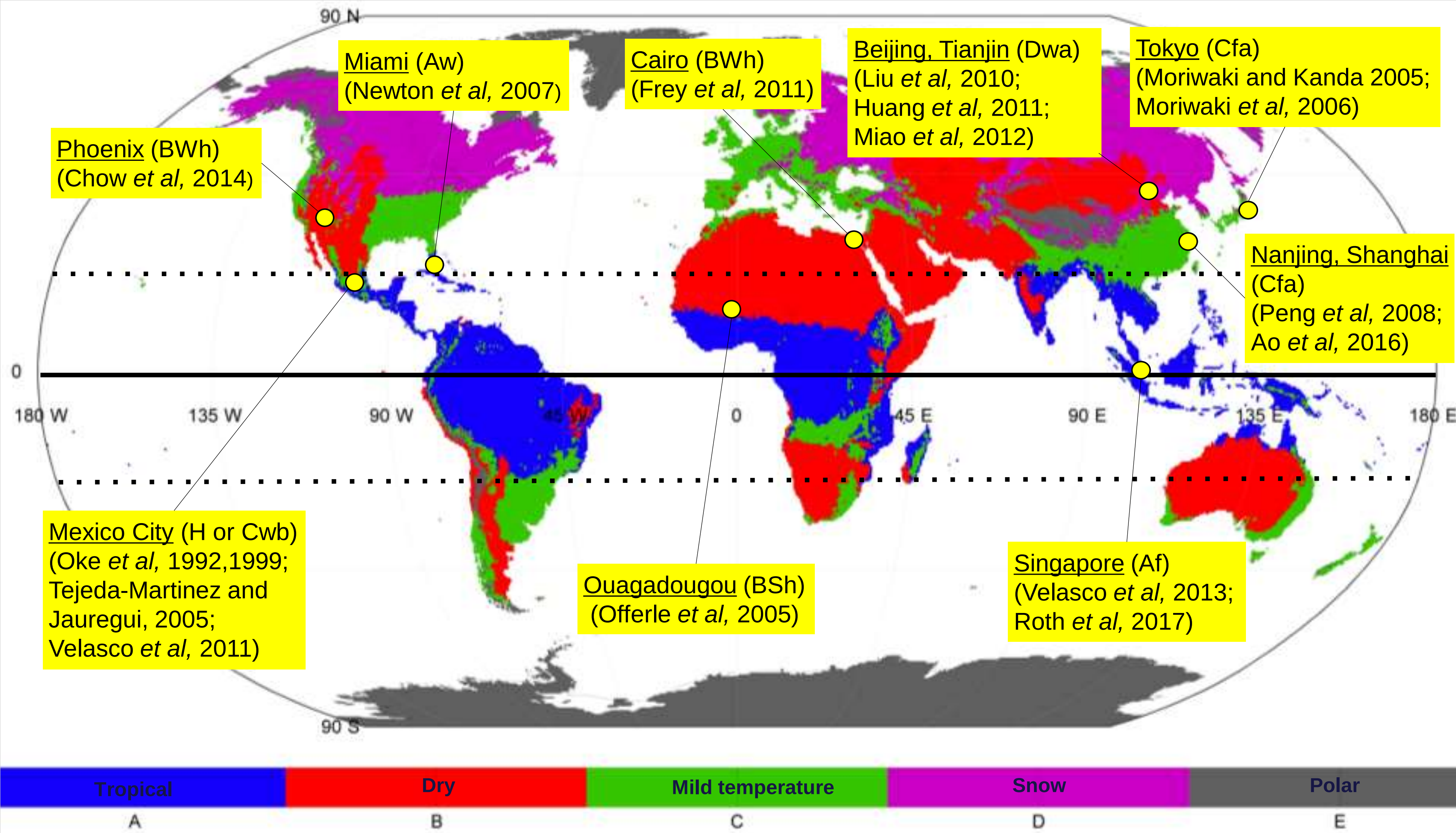
ΔQ_S - Storage heat flux (residual)

ΔQ_A - Advective heat flux (assumed 0)

Local-scale approach: Climate of neighborhoods with similar type of urban development; urban ecosystem of interest is represented within flux footprint

Measurement approach

Köppen and low-latitude/Asian urban flux studies



Phoenix (BWh)
(Chow *et al,* 2014)

Miami (Aw)
(Newton *et al,* 2007)

Cairo (BWh)
(Frey *et al,* 2011)

Beijing, Tianjin (Dwa)
(Liu *et al,* 2010;
Huang *et al,* 2011;
Miao *et al,* 2012)

Tokyo (Cfa)
(Moriwaki and Kanda 2005;
Moriwaki *et al,* 2006)

Nanjing, Shanghai
(Cfa)
(Peng *et al,* 2008;
Ao *et al,* 2016)

Mexico City (H or Cwb)
(Oke *et al,* 1992,1999;
Tejeda-Martinez and
Jauregui, 2005;
Velasco *et al,* 2011)

Ouagadougou (BSh)
(Offerle *et al,* 2005)

Singapore (Af)
(Velasco *et al,* 2013;
Roth *et al,* 2017)

- 25% of world’s population lives in *A* climates (~16% of land area; ~10% of GDP)
- Singapore only city with true *Af* climate

http://hanschen.org/koppen
Oxford Handbook of Economic Geography, 2000

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US Dept of State Geographer
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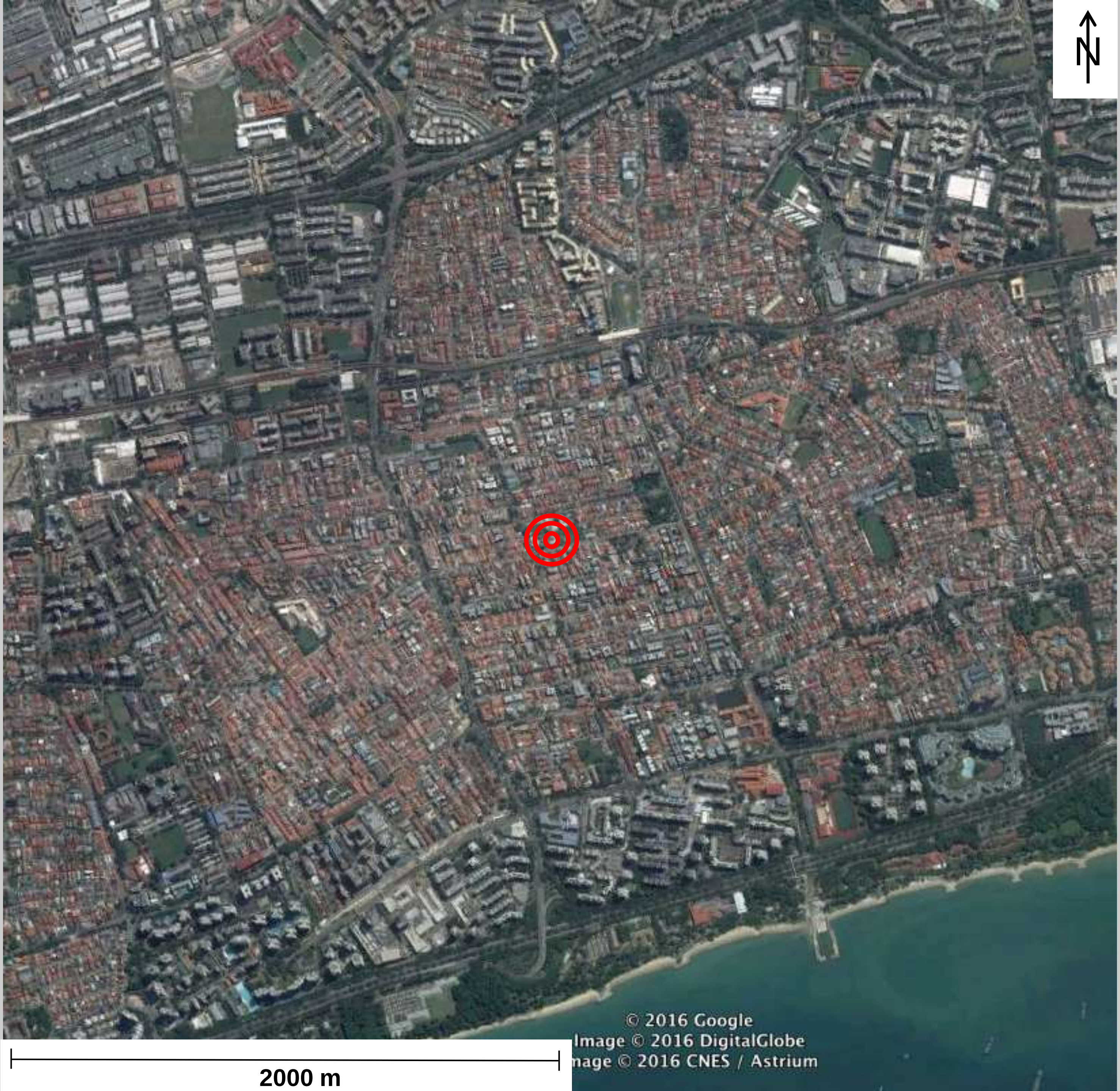

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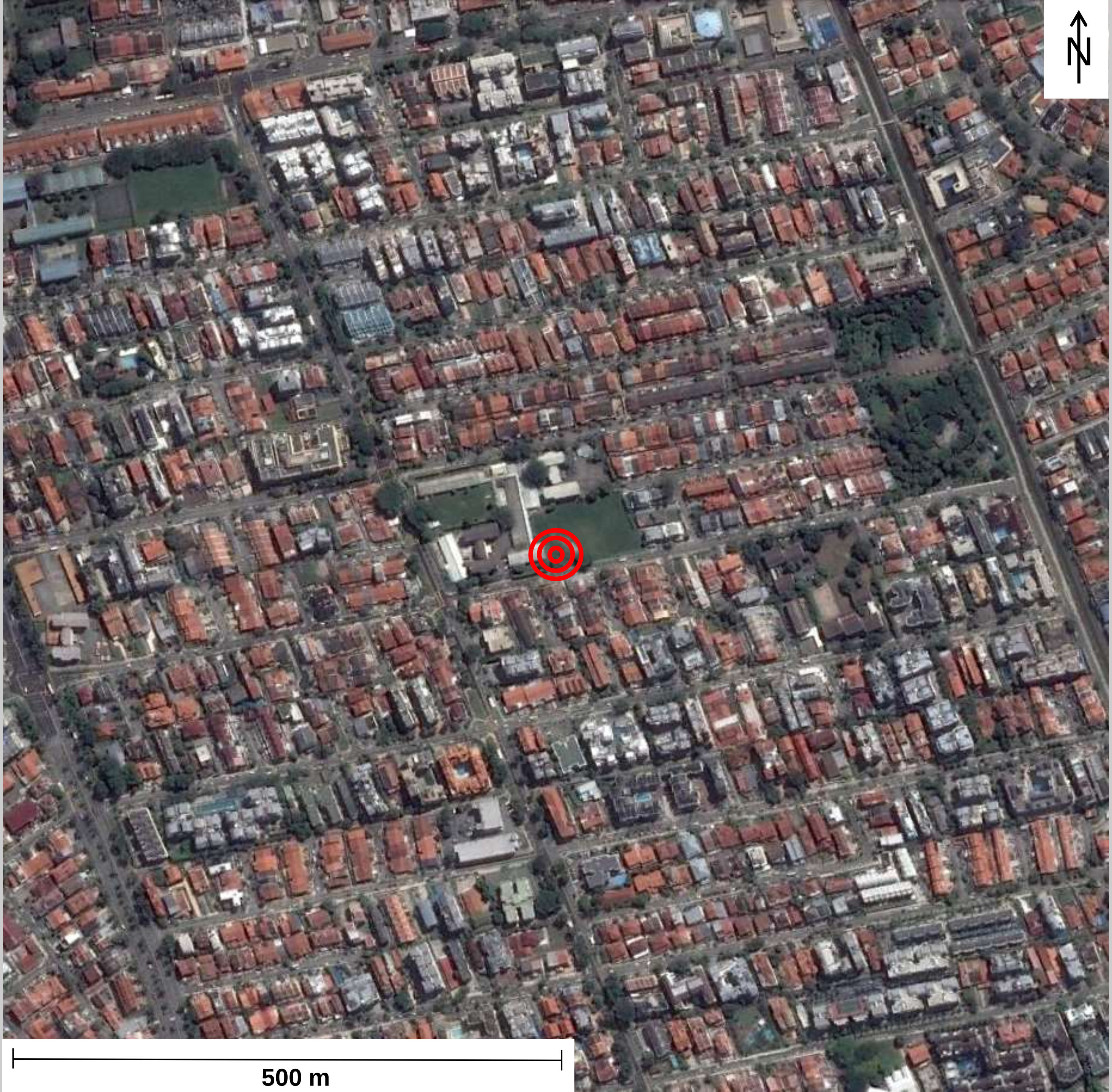
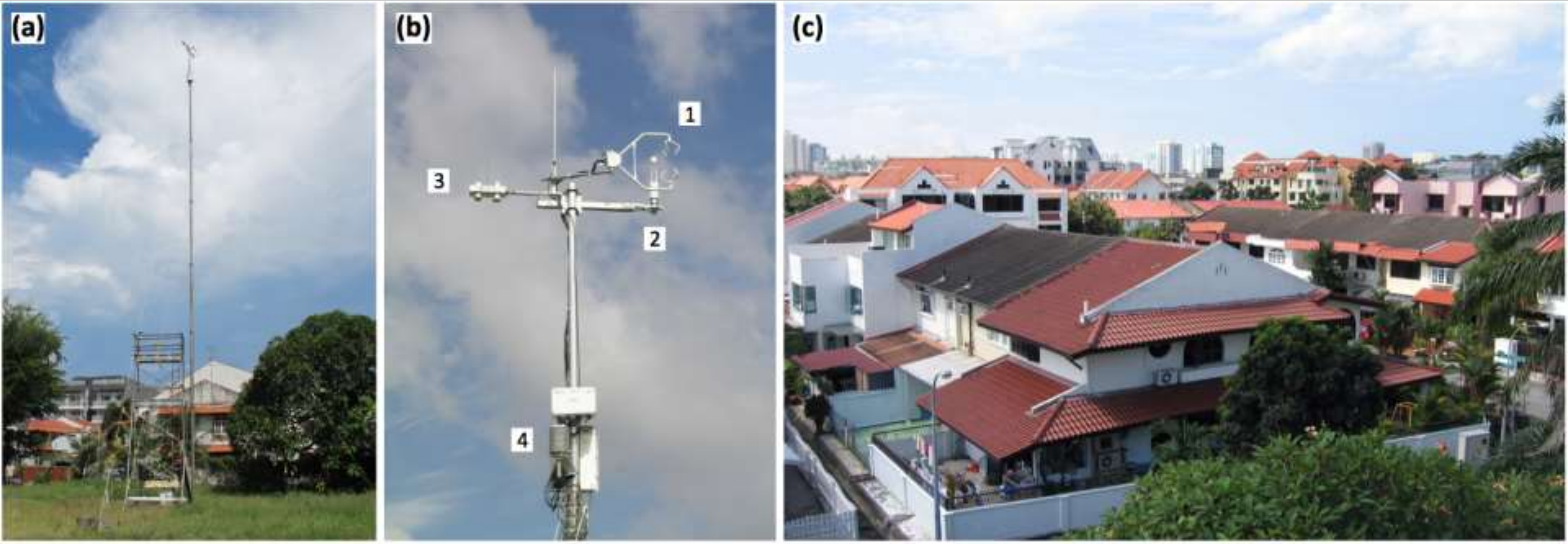

N
500 m

Measurements

Telok Kurau (TK) flux tower and EC sensor set-up:



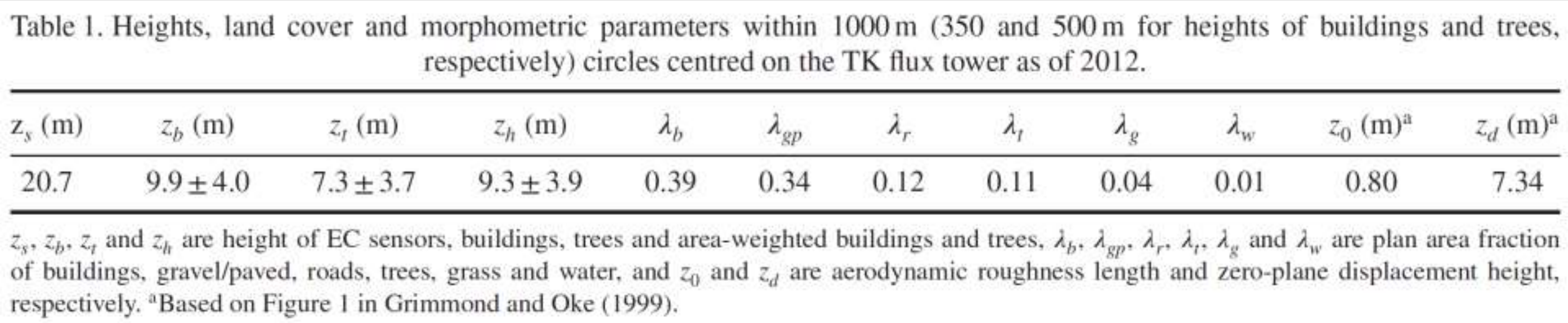


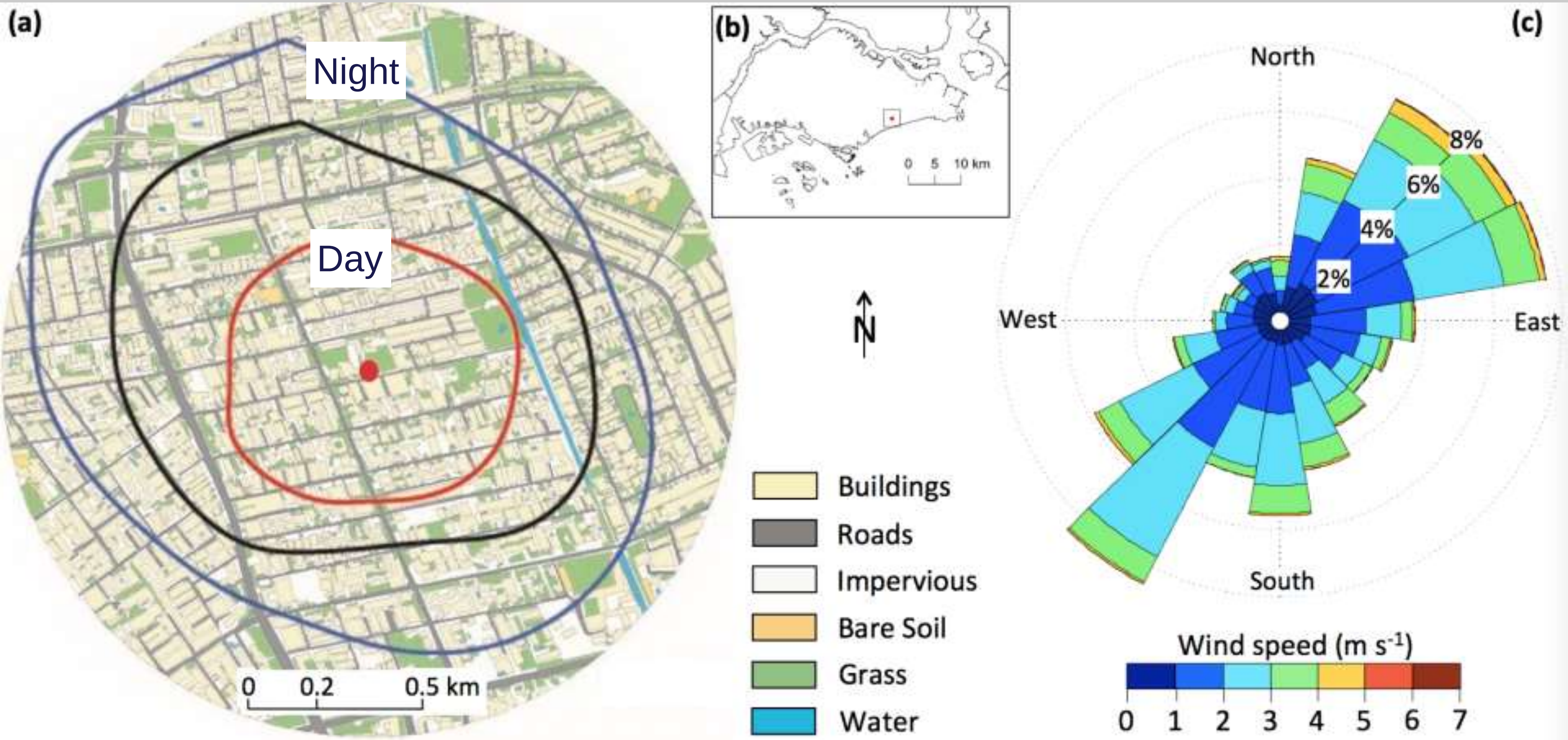
Table 1. Heights, land cover and morphometric parameters within 1000 m (350 and 500 m for heights of buildings and trees, respectively) circles centred on the TK flux tower as of 2012.

z_s (m)	z_b (m)	z_t (m)	z_h (m)	λ_b	λ_{gp}	λ_r	λ_t	λ_g	λ_w	z_0 (m)[a]	z_d (m)[a]
20.7	9.9 ± 4.0	7.3 ± 3.7	9.3 ± 3.9	0.39	0.34	0.12	0.11	0.04	0.01	0.80	7.34

z_s, z_b, z_t and z_h are height of EC sensors, buildings, trees and area-weighted buildings and trees, λ_b, λ_{gp}, λ_r, λ_t, λ_g and λ_w are plan area fraction of buildings, gravel/paved, roads, trees, grass and water, and z_0 and z_d are aerodynamic roughness length and zero-plane displacement height, respectively. [a]Based on Figure 1 in Grimmond and Oke (1999).

(Roth *et al*, 2016)

Land cover, average 80% footprint and wind regime (30-min)



Observation period:
01/2006-11/2013

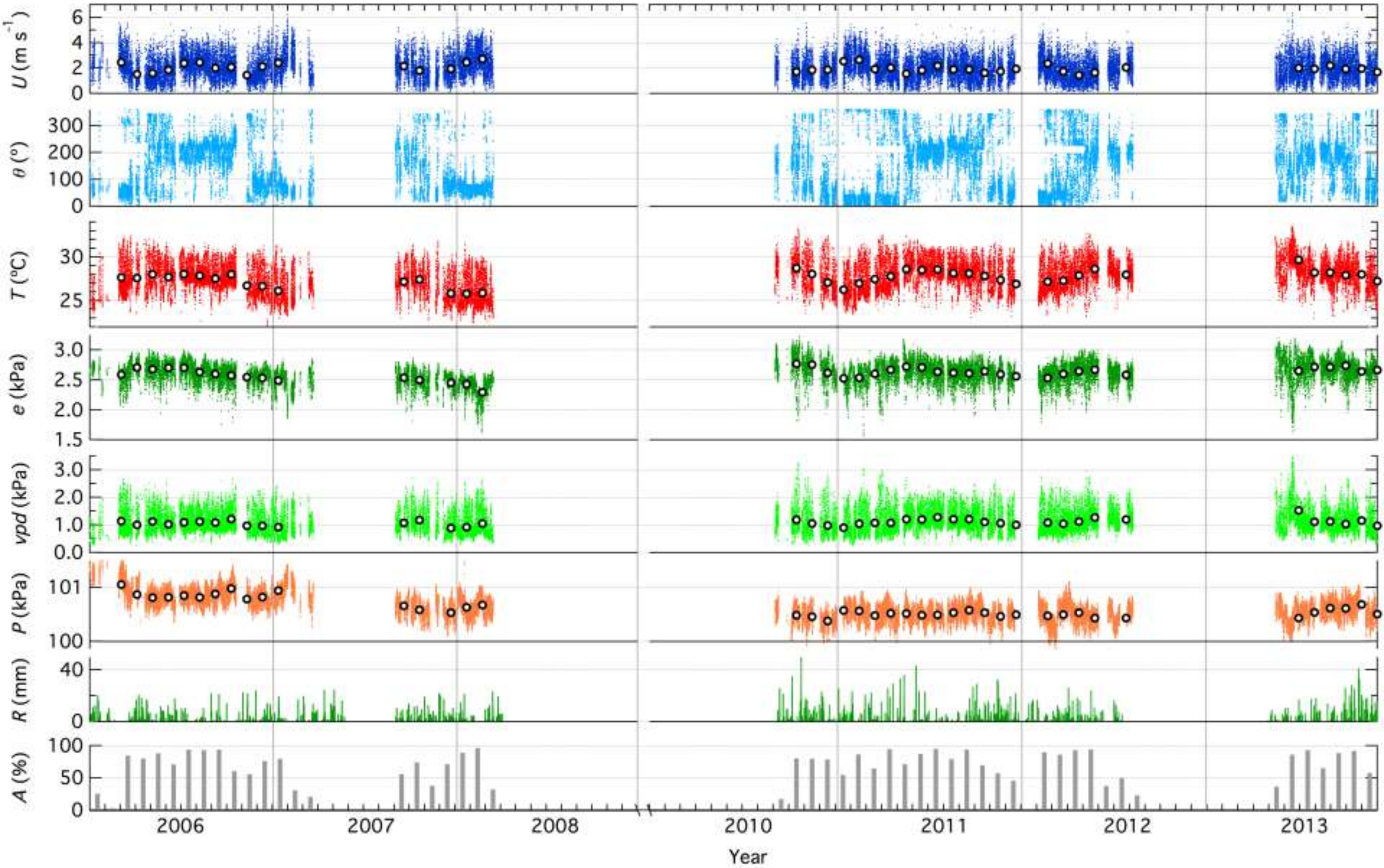
NE: 27%
SW: 34%
IM1/IM2: 19%/20%
Total: 100% (49,317 30-min runs)

NE_{wet}: 20%, NE_{dry}: 7%
Clear: 9%

* Calculated using analytical model by Hsieh *et al* 2000 (*Adv Water Res*)

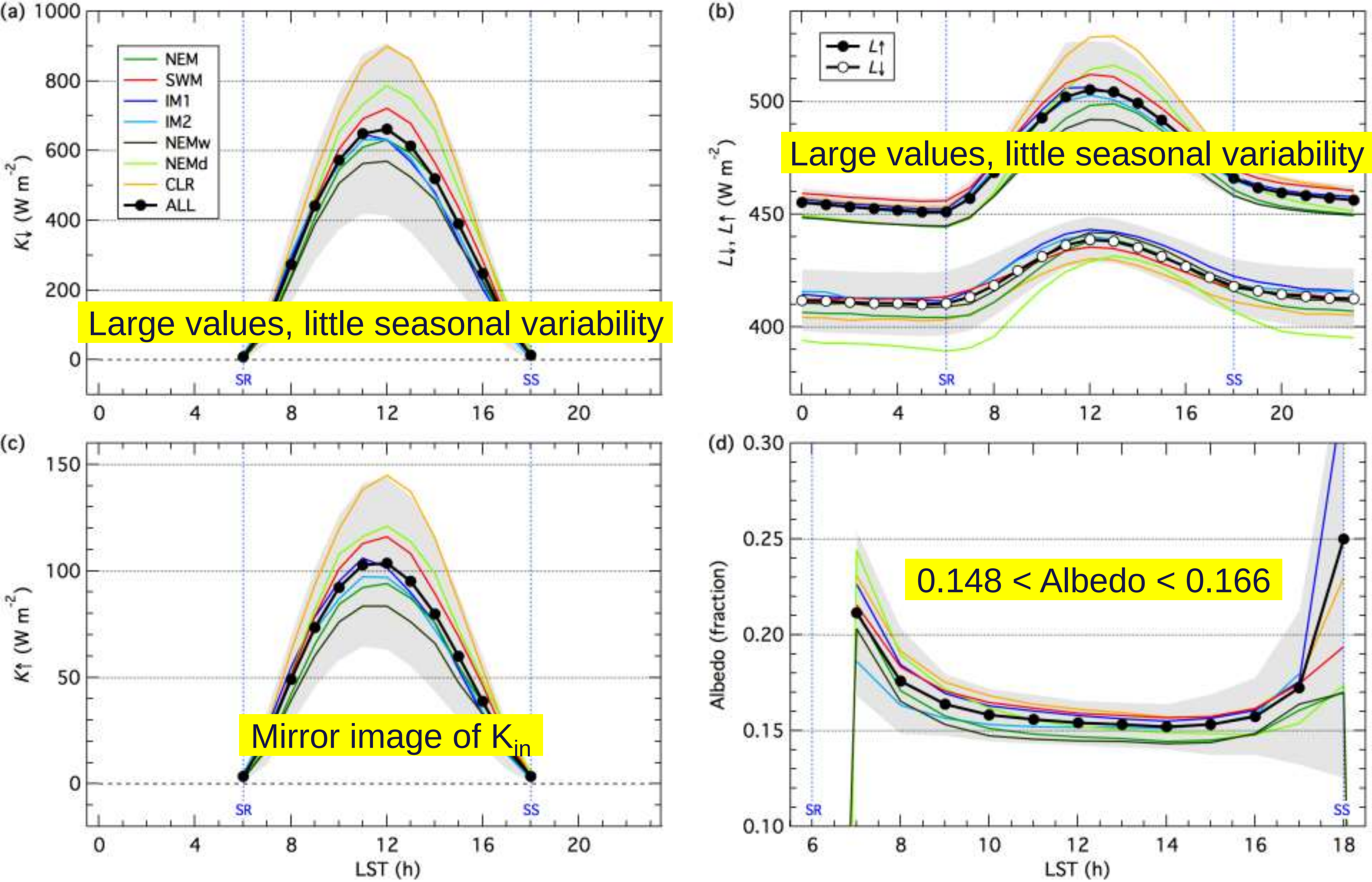
(Roth *et al*, 2016)

Meteorological conditions during measurement period



(Roth *et al*, 2016)

Ensemble mean diurnal variation of radiation components



Large values, little seasonal variability

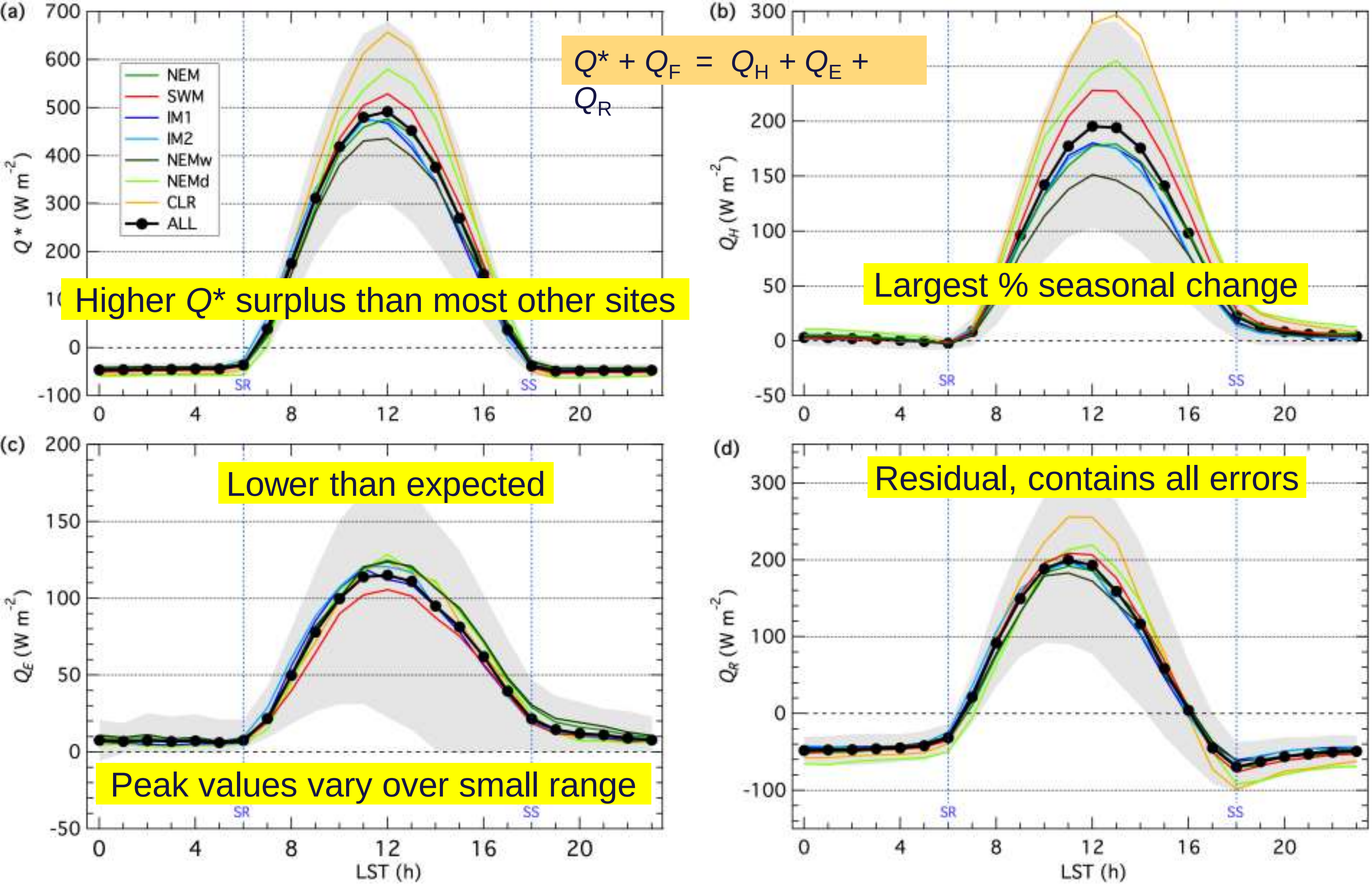
Large values, little seasonal variability

Mirror image of K_{in}

0.148 < Albedo < 0.166

(Roth *et al*, 2016)

Ensemble mean diurnal variation of EB components



$Q^* + Q_F = Q_H + Q_E + Q_R$

Higher Q^* surplus than most other sites

Largest % seasonal change

Lower than expected

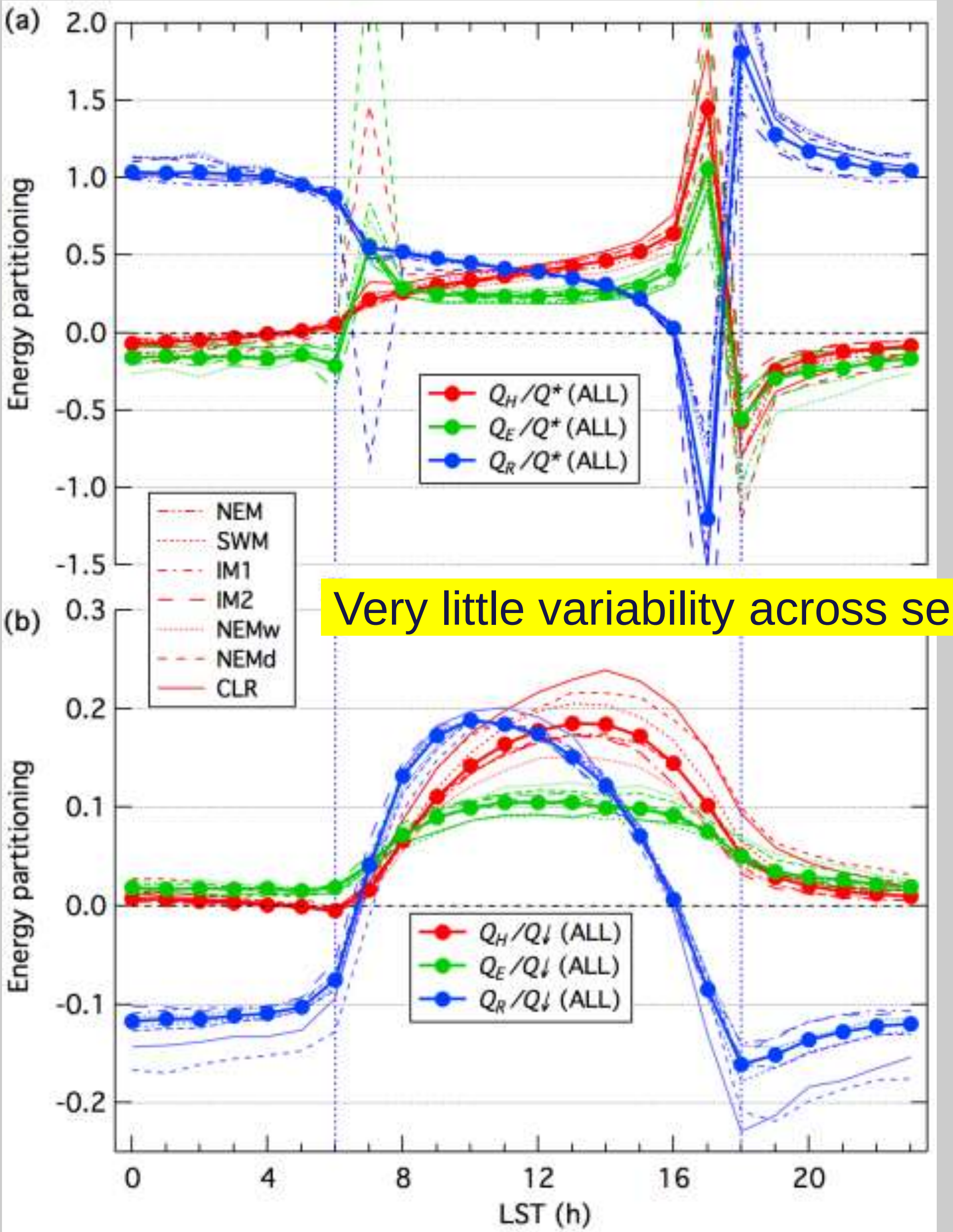
Peak values vary over small range

Residual, contains all errors

(Roth *et al*, 2016)

Ensemble mean diurnal flux ratios normalized by (a) net all-wave radiation and (b) total incoming radiation

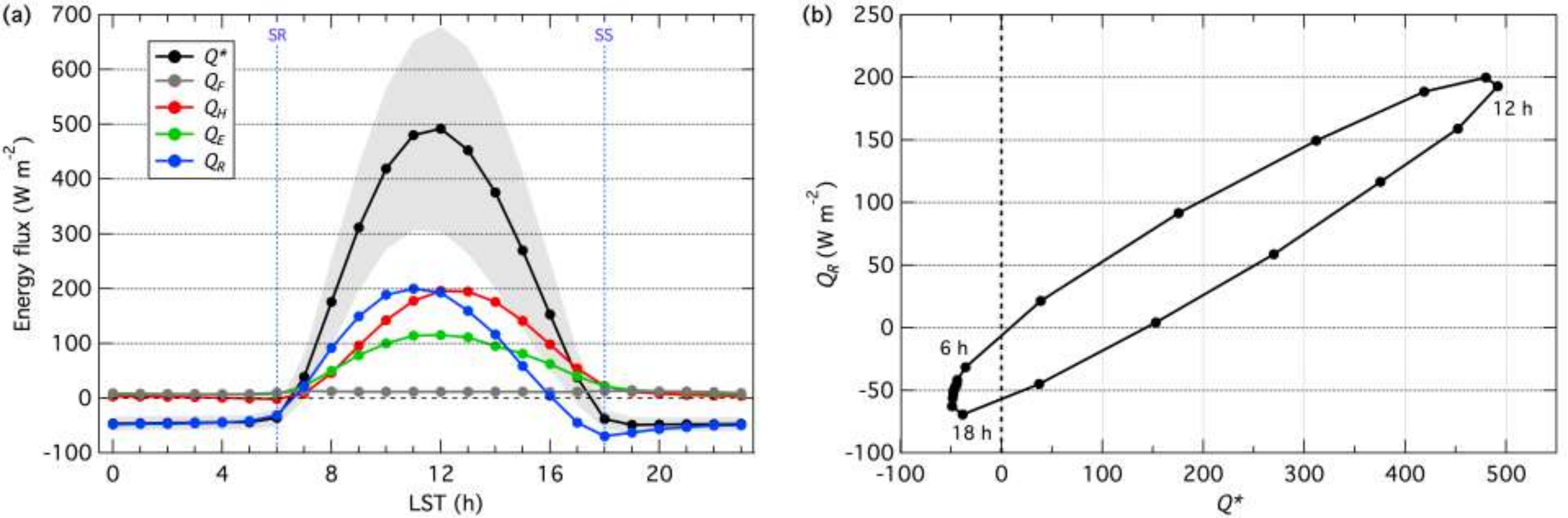
- Ratios allow the direct comparison of trends across different seasons and between cities, because they are not biased by the absolute magnitude of fluxes.
- Ratios are very similar to those observed over suburban areas across a range of climates.



Very little variability across seasons

(Roth *et al*, 2016)

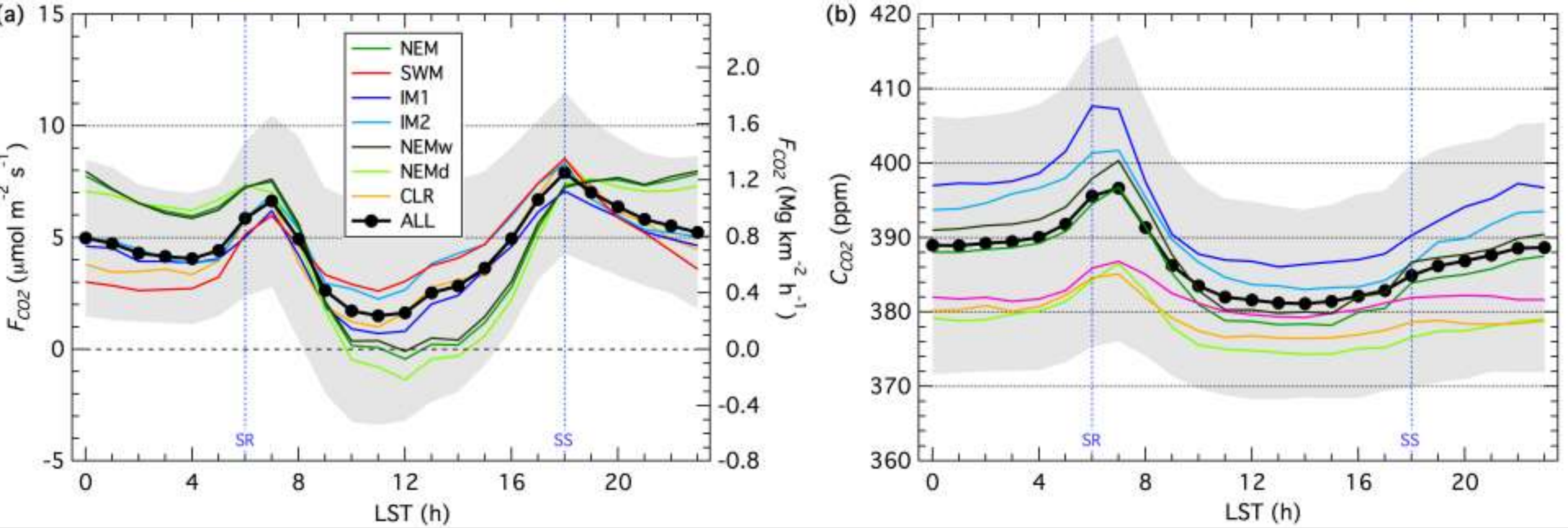
Long-term energy balance for entire study period



- General shape of the energy balance for the long-term average is similar to that measured over other suburban sites across a variety of latitudes and climate conditions.
- The phase of the individual fluxes is different with Q_R peaking 1 h before, Q_E at and Q_H 1 h after solar noon, respectively, resulting in a characteristic hysteresis pattern between Q^* and Q_R which is observed in most cities.

(Roth *et al*, 2016)

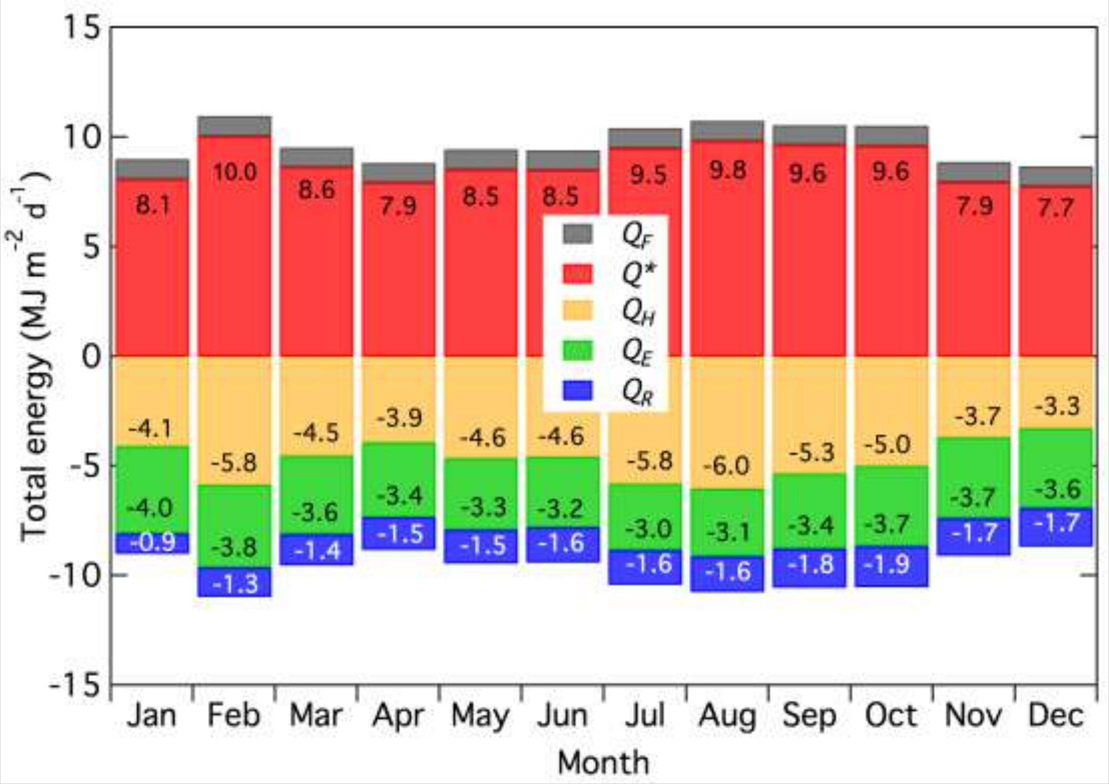
Ensemble mean diurnal variation of carbon dioxide



- Average fluxes are generally positive throughout the day with a clear diurnal pattern (morning and evening peaks in phase with rush-hour traffic).
- CO_2 uptake by vegetation lowers daytime fluxes, which occasionally can become negative around noon, producing lower net day- than nighttime fluxes.
- Given the absence of local CO_2 emissions related to space heating or cooling, changes across seasons are expected to be small.
- Mean carbon dioxide concentrations show characteristic morning peak related to traffic emissions, lower daytime values due to mixing layer growth.

(Roth *et al*, 2016)

Monthly mean energy totals for entire study period

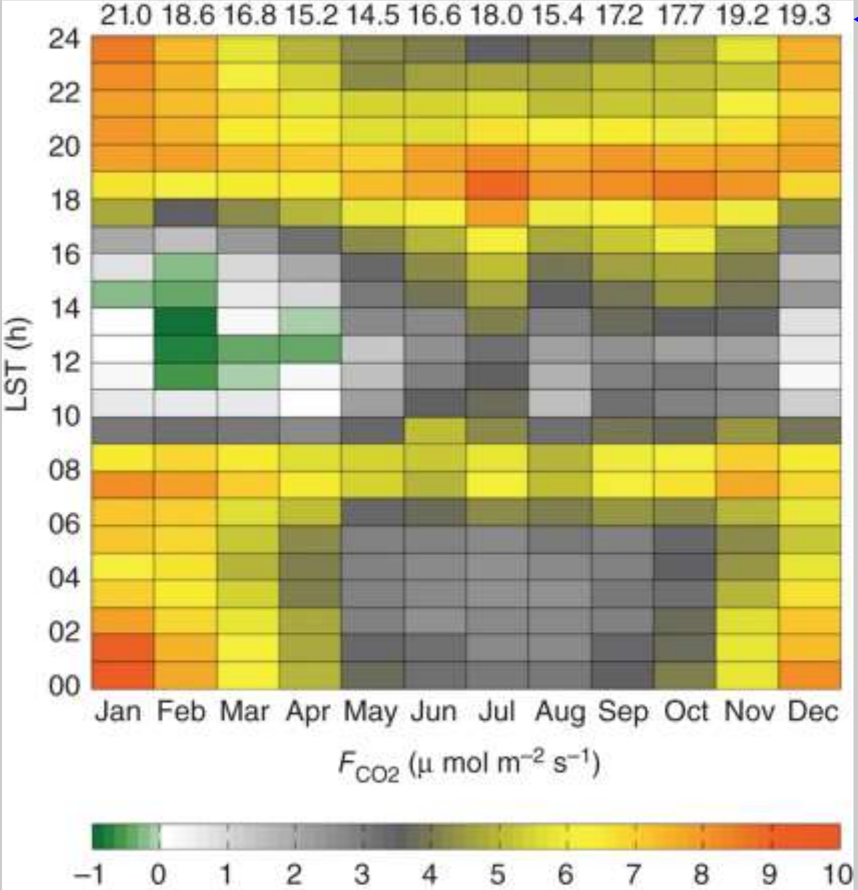


Calculated based on months with at least 50% data coverage

- Annual variation of monthly energy totals is much smaller compared to similar data from (sub)urban areas located in higher latitudes
- Q_R and Q_F are both small
- Year-round loss into substrate; artifact of energy balance closure?

(Roth *et al*, 2016)

Temporal variation of hourly CO_2 fluxes with month



Mean daily flux totals (Mg km^{-2} d^{-1})

- Strong diurnal variability, which is more pronounced than changes across months; latter is much smaller compared to other (sub)urban areas in mid-latitudes.
- Largest and lowest hourly fluxes are observed during NE monsoon months (December–March); potentially important role of nighttime respiration.
- Anthropogenic signal shows up as higher values during rush hours.

(Roth *et al*, 2016)

Urbanization dramatically influences the microclimatology

Comparison of annual energy and carbon fluxes with those from nearby natural ecosystems which may have existed before urban development occurred:

Rainforest (SE Asia)

Residential (Singapore)

0.15[1]	Q_H/Q^*	0.54
0.7[1]	Q_E/Q^*	0.39
0.76[2]	E/P	0.21
-124[3]	F_{CO2} (MgC km^{-2} y^{-1})	1737

([1]Hirano *et al*, 2015; [2]Takanashi *et al*, 2010; [3]Kosugi *et al*, 2008)

(Roth *et al*, 2016)

Summary

- Given the equatorial location (1º 19′ N) of the measurement site, annual changes in climate and energy/mass fluxes are much less than observed in cities located outside the tropics.
- The large radiative inputs produce a higher daytime *Q** surplus than observed at most other (sub)urban sites.
- The energy balance *partitioning* is nevertheless similar to that reported for subtropical and mid-latitude suburban sites.
- Annual variation of monthly energy totals is much smaller compared to similar data from (sub)urban areas located in higher latitudes.
- Significant variability exists in net radiation and sensible heat flux using a classification based on clouds and rainfall (unlike due to sun angle changes related to summer and winter seasons important in ex-tropical cities).
- The present site is an annual net CO_2 source of $6{,}368 \pm 5{,}867$ Mg km^{-2} y^{-1} with a mean daily emission of 17.4 ± 16.07 Mg km^{-2} d^{-1}.
- Singapore provides a unique climatic context and this study adds to the global data set of urban energy fluxes, which can be used to evaluate and adapt a range of ULSMs which investigate the urban heat island, improve the thermal comfort of residents, study extremes of urban weather, evaluate carbon mitigation options, etc.

Thank you!