Assessment of a meteorological mesoscale model's capability to simulate intra-urban thermal variability in a tropical city

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Background

- The spatial heterogeneity of urban structures along with vegetated and open areas alter air temperature, radiation, moisture, and wind patterns creating distinct local climates within cities, which leads to significant spatial variability of air temperatures across the city.
- Mesoscale meteorological models are commonly applied over cities to analyze the urban-rural thermal contrast and explore heat mitigation strategies.

Can we rely on mesoscale simulations to predict the air temperature variability due *to the heterogeneous* urban landscape across the city?

Objective

- To investigate the model's capability (WRF coupled with BEP-BEM) to predict intra-urban thermal differences during different weather conditions in the tropical city of Singapore
- Two one-month long simulations representing different synoptic conditions:
  - (i) A wet period amidst SW monsoon (Jul 2013)
  - (ii) A dry period during NE monsoon (Feb 2014)

Observational data

Model results are evaluated against observations from

- A tall eddy covariance flux-tower located in a low-rise residential neighborhood
- 2-m air temperature sensors strategically located to represent diverse urban morphologies classified using Local Climate Zones (LCZ)

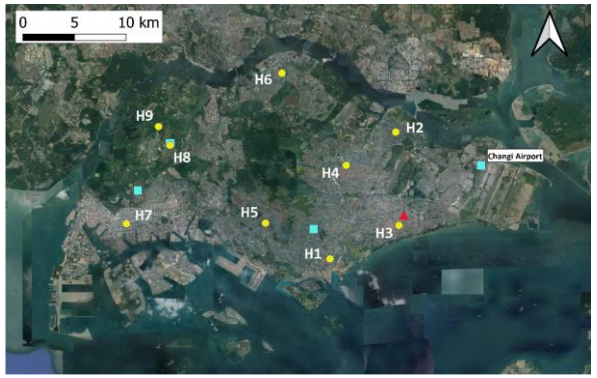


Fig. 1. Locations of the nine 2-m air temperature sensors, H1-H9 (yellow dots), flux tower (red triangle) and four MSS rain gauges (blue squares). Source of satellite image: Google Earth

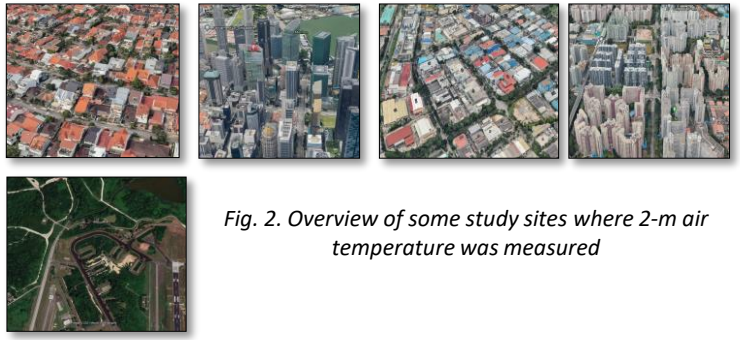


Fig. 2. Overview of some study sites where 2-m air temperature was measured

Model description

- WRF model with BEP-BEM
- Resolution d04: 1 km x 1 km
- Accurate spatial distribution of urban morphological parameters (mean building heights, urban fraction, building plan area density)

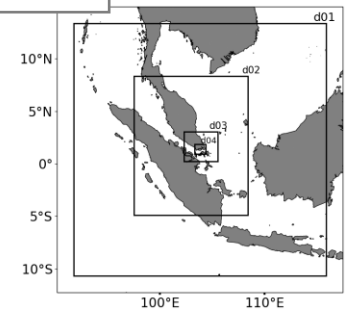


Fig.2 Model domains

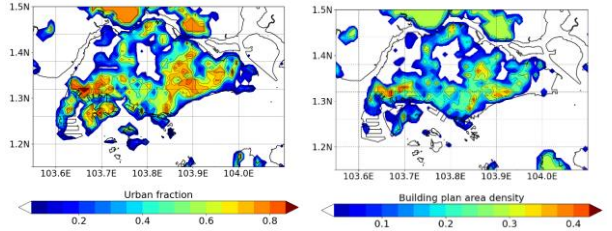


Fig 3. Spatial distribution of the urban morphological parameters implemented in the model: (left) urban fraction and (right) building plan area density

- Model urban features at the study sites:

ID	F_u	H/W	Description	LCZ class
H1	0.67	1.91	Compact high-rise (CBD)	LCZ 1
H2	0.68	0.60	Open high-rise (residential)	LCZ 4
H3	0.74	0.74	Compact low-rise (residential)	LCZ 3
H4	0.72	0.62	Compact low-rise (residential)	LCZ 3
H5	0.58	0.61	Open low-rise (residential)	LCZ 6
H6	0.51	0.32	Large low-rise (industrial)	LCZ 8
H7	0.82	0.56	Large low-rise (industrial)	LCZ 2/8
H8	0.28	0.11	Sparsely built	LCZ 9
H9	-	-	Scattered trees (rural)	LCZ B

Table 1. Urban morphological parameters used in the model at the location of each air temperature sensor (H1-H8).

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Model evaluation with flux-tower measurements

Micrometeorological variables, and radiative and turbulent fluxes obtained from the model are evaluated against measurements at the flux tower. This urban area is classified as LCZ 3 (low-rise buildings) with 74% urban fraction and 26% grass, and the mean height of buildings is 14.2 m.

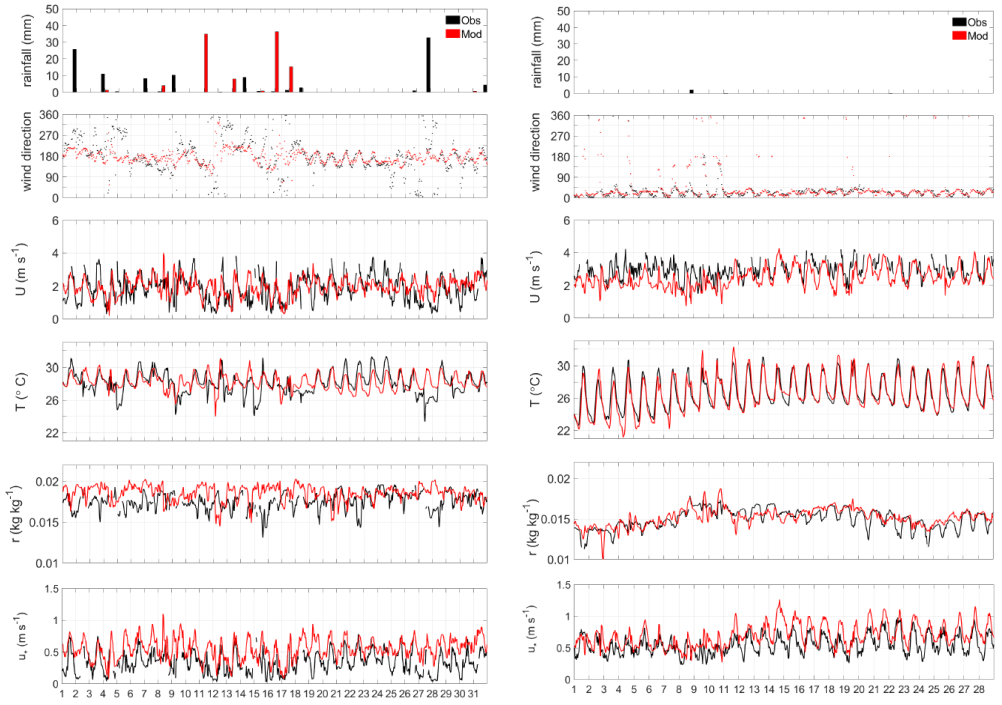


Fig. 4. Time series of meteorological variables and turbulence parameters measured (black) and modelled (red) at the flux tower during wet (left column) and (right) dry periods. From top to bottom: rainfall, wind direction, wind speed (U), air temperature (T), vapour mixing ratio (r) and friction velocity (u).*

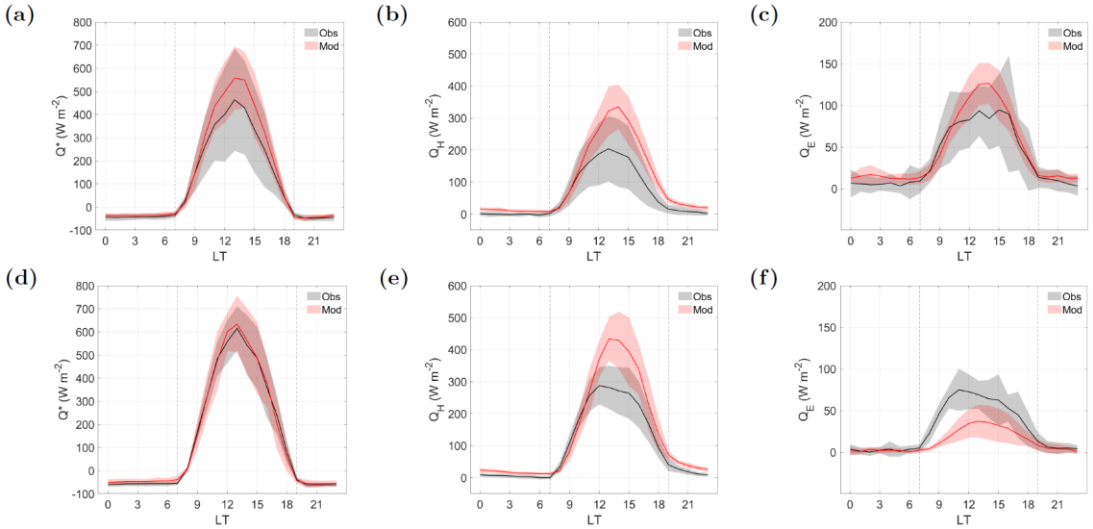


Fig.5. Mean diurnal variation and standard deviation (shaded areas) of modelled (red) and measured (black) values at the flux tower of: (a) Q, (b) Q_H, and (c) Q_E during the wet period. (d)-(f) same as (a)-(c) but during the dry period.*

- The model predicts the main ***meteorological variables*** reasonably well during both periods, and is able to capture their distinctive wind regimes. Moreover, the good agreement of modelled u_* demonstrates the model's ability to simulate the vertical turbulent transport of momentum, which is, however, slightly overestimated during the dry period.
- Model evaluation of ***surface energy balance*** shows better performance for net radiation (Q^*) during the dry compared to the wet period. The difficulty to predict the large day-to-day variability given by intermittent cloudiness during the latter, results in larger errors compared to the former, when relatively clear days prevail. The higher modelled Q_H during daytime suggests that no enough energy is channeled into the ground and buildings. The daytime underestimation (overestimation) of Q_E during dry (wet) conditions resulting in reflects the model's challenge to accurately predict soil moisture in this particular area.

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Spatial variability of 2-m air temperature

Modelled 2-m air temperature (T_{2m}) is separately for considering all weather conditions, days without precipitation, and clear-sky conditions during the two periods, respectively using the data from the urban sites (H1-H8) .

- Model tends to underestimate the minimum temperature ($T_{2m,min}$) in the most of built-up areas, in particular during the dry period.
- Significant influence of the street aspect ratio (H/W) on nighttime minimum temperatures is obtained in both observations and model results.

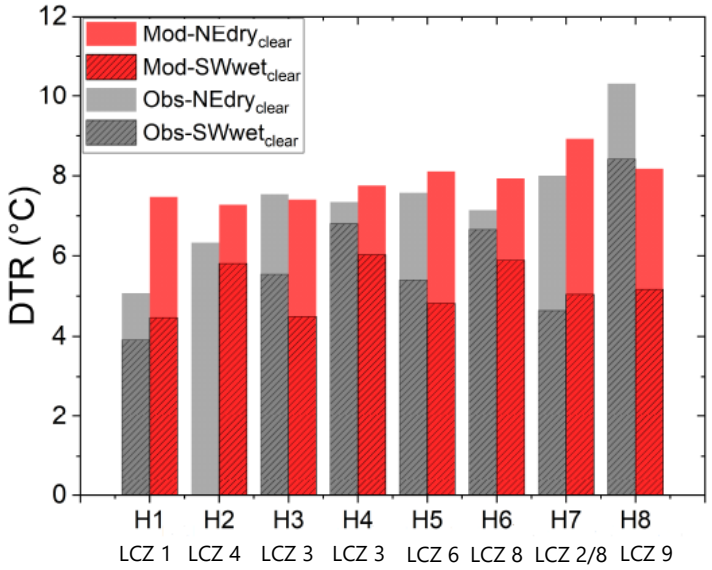


Fig. 7. Mean observed (black) and modelled (red) diurnal (DTR) at each site for the selected clear days during the wet (dashed) and dry periods.

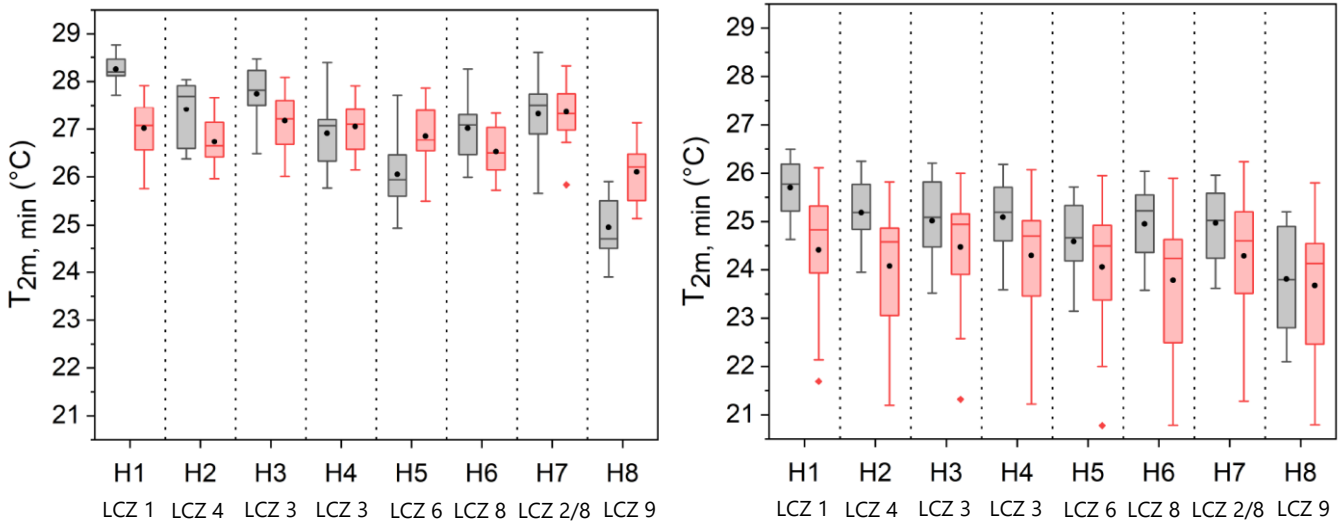


Fig. 6. Boxplots of observed (black) and modelled (red) T_{min} for days without precipitation during the (left) wet and (dry) period at eight urban sites (H1-H8).

The ability of the model to cool down and heat up the canopy layer is analyzed using the diurnal temperature range (DTR) during clear-sky days during the wet (SWwet$_{clear}$) and dry (NEdry$_{clear}$) periods.

- At the most vegetated site (H8$_{LCZ9}$) the model clearly fails to predict the cooling (heating) rate of the vegetation fraction, likely due to an overestimation of the thermal admittance of the natural surface and therefore, its ability to absorb and release heat.
- The model reproduces well the distinct thermal response representative of each urban configuration. However, it is unable to capture the lowest DTR observed at the high-rise urban sites (H1$_{LCZ1}$ and H2$_{LCZ4}$) during NEdry$_{clear}$.
- On the other hand, lower DTR is expected during SWwet$_{clear}$ compared to NEdry$_{clear}$ given a weaker thermal response due to higher surface moisture during the former period. The model indeed predicts the lower diurnal variation observed during SWwet$_{clear}$, and also reproduces the observed variability in DTR across the stations.

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Spatial variability of 2-m air temperature

The model's capability to capture the observed spatial variability of T_{2m} across urban sites (H1-H8) is analyzed by comparing air temperature differences between all possible station pairs defined as,

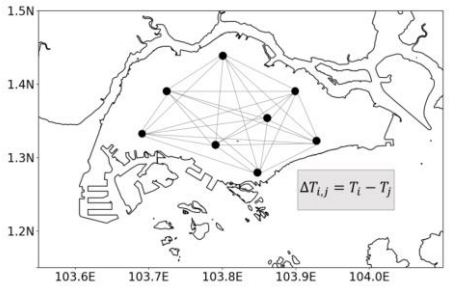


Fig. 8. Schematic representation of the methodology applied to compute $\Delta T_{i,j}$

$$\Delta T_{i,j} = T_i - T_j \quad i = 1, 2, ..., n-1 \ \ and \ \ j > i$$

where the indices *i* and *j* stand for the urban stations, and *n* the total number of stations.

- Temperature differences amongst urban station pairs show the lowest model agreement with observations for T_{max} of between 57%-65% during all weather conditions. This is probably because of the difficulty to accurately predict the intermittent cloudiness and the error in simulating the shading effects in the tallest urban areas.
- Agreement is better for both T_{mean} and T_{min}, with about 67-80% and 68-81% respectively for all studied weather conditions.
- During clear-sky conditions the model achieves the highest agreement for the spatial thermal variability for T_{min}, of 76-81% during both periods (Fig. 9).

The present results demonstrate the capability of the model to predict the observed trends in the intra-urban variability of air temperatures in a tropical city. However, the magnitudes of the nighttime temperature differences are consistently underestimated across all weather conditions investigated.

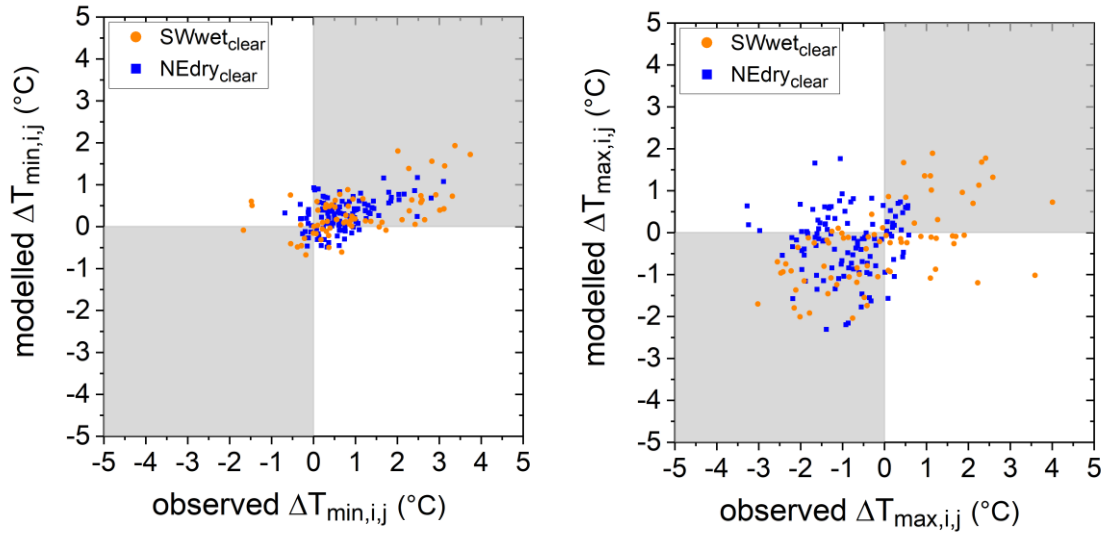


Fig. 9. *$\Delta T_{i,j}$ for (left) Tmin and (right) Tmax for four clear-sky days during the wet (orange) and (blue) dry periods.*

Long-term studies are also needed to more fully evaluate model performance under diverse synoptic conditions to account for the local climate and increase statistical reliability.

Future work: Improve the thermal characterization of natural and urban surfaces to better predict the thermal response in vegetated areas and accurately simulate the surface energy balance components, respectively.

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