International Conference on Computational Science, ICCS 2017, 12-14 June 2017, Zurich, Switzerland

# Development of a new urban heat island modeling tool: Kent Vale case study

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**Abstract**

Urban heat island is intensified by anthropogenic activities and heat in conjunction with the built-up urban area, which absorbs more solar radiation during daytime and releases more heat during nighttime than rural areas. Air cooling systems in Singapore, as one of the anthropogenic heat sources, reject heat into the vicinity and consequently affect urban microclimate. In this paper, a new urban heat island modeling tool is developed to simulate stack effect of split type air-conditioners on high rise buildings and solar radiation induced thermal environment. By coupling the Computational Fluid Dynamics (CFD) program with the solar radiation model and perform parallel computing of conjugate heat transfer, the tool ensures both accuracy and efficiency in simulating air temperature and air relative humidity. The annual cycle of sun pathway in Singapore is well simulated and by decreasing the absorptivity or increasing the reflectivity and thermal conductivity of the buildings, the thermal environment around buildings could be improved.

*Keywords:* Urban heat island, stack effect, sensitivity analysis, solar radiation, thermal environment

# 1 Introduction

Urban heat islands (UHIs), together with urban noise and urban air pollution, are three of the major environmental challenges of future more livable cities. UHIs are described as the phenomenon that the air temperature in urban area is consistently higher than its rural area (Oke, 1973). While many causes of the urban heat island such as reduced evaporation, increased heat storage, increased net radiation, reduced convection and increased anthropogenic heat have been identified as in Gartland (2008), the contribution of each component strongly depends on the individual city and its geography. In a high-density mixed-used tropical city like Singapore, the urban microclimate varies from location to location and time to time. The prevalence of the use of air-conditioning in Singapore throughout the

year has posed heat-related stress and health issues (Kovats and Hajat, 2008; Lo and Quattrochi, 2003; Oikonomou et al., 2012), higher energy costs (Kolokotroni et al. 2012) and has downgraded urban living quality (Mavrogianni et al., 2011), as pointed out in Berger (2016). A comprehensive measurement of air temperature in earlier study (Wong and Chen, 2006) between 2001 and 2004 showed that the urban heat island in Singapore was about 4.5°C. A more recent study (Chow and Roth, 2006) found that the peak urban heat island intensity occurs approximately six hours after sunset at central business districts, high-rise residential estate, and low-rise residential area. Higher urban heat island intensities generally occur during the Southwest monsoon period of May – August, with a maximum of ~7°C observed at Orchard Road at approximately 9pm local time (Chow and Roth, 2006). A more comprehensive review of recent urban heat island studies in Singapore is conducted in Roth and Chow (2012).

In Singapore, the majority of installed air-conditioning systems on high rise residential buildings are split type air-conditioners, compact units rejecting heat from air-conditioning through a dry heat exchange. They affect and in turn exposed to the urban microclimate in their vicinity, with regard to capacity to provide cooling and the efficiency of their operation. One such microclimatic effect is the stack effect, a buoyancy-driven airflow fueled by the hot air rejected from condensing units. Stack effect of split type air-conditioners on high-rise buildings are simulated by CFD models as summarized in Bojic et al. (2008) and observed in Bruelisauer et al. (2014).

In the view of respective contributions from different aspects of anthropogenic heat and built-up area of a tropical city like Singapore, an integrated system needs to be established to identify the individual effects of major heat sources and sinks. Heat sources include air-conditioners on buildings at the small end of the scale and solar radiation at the large end of the scale. This paper discusses the development of a new urban heat island modeling tool at multiple urban scales, focusing on the stack effect induced by split type air-conditioners on high rise buildings and the effects of solar radiation on thermal environment around buildings.

## 2 Methods

Three universal conservation laws of mass, momentum and energy are taken into account by solving continuity equation (Equation (1)), Navier-Stokers equation (Equation (2)) and energy balance equation (Equation (3)). Conjugate heat transfer is simulated by solving heat convection (Equation (4)), conduction (Equation (5)) and radiation (Equation (6)) between fluid and solid regions. Turbulence is solved by $k - \varepsilon$ model. Solar radiation is simulated by accounting for the combined effects of the Sun primary hits, their reflective fluxes and diffusive sky radiative fluxes (Howell et al. 2010). The primary hit rays of solar radiation are calculated using a face shading algorithm. The reflected fluxes are considered diffusive and use a view factors method to deposit the energy on visible walls. The sky diffusive radiation for horizontal and vertical walls is calculated following the Fair Weather Conditions Method from the ASHRAE Handbook.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \tag{1}$$

$$\frac{\partial (\rho \boldsymbol{u})}{\partial t} + \nabla \cdot (\rho \boldsymbol{u} \otimes \boldsymbol{u} + p\boldsymbol{I}) = \mu \nabla^2 \boldsymbol{u} + \rho \boldsymbol{g} \tag{2}$$

$$\rho C_p \left( \frac{\partial T}{\partial t} + \boldsymbol{u} \cdot \nabla T \right) = \kappa \nabla^2 T + Q \tag{3}$$

$$q = h(T_a - T_\infty) \tag{4}$$

$$q = -k \nabla T \tag{5}$$

$$q = \epsilon \sigma (T_a^4 - T_b^4) \tag{6}$$

where $\rho$ is density, $t$ is time, $\boldsymbol{u}$ is flow velocity field, $p$ is pressure, $\boldsymbol{I}$ is the identity matrix, $\mu$ is turbulent eddy viscosity, $\boldsymbol{g}$ is the gravity acceleration rate, $T$ is temperature, $C_p$ is the specific heat, $\kappa$ is the thermal conductivity, $Q$ is the additional heat flux, $h$ is the heat transfer coefficient, $\epsilon$ is the radiation factor and $\sigma$ is the Stefan-Boltzmann constant, respectively.

OpenFOAM (www.openfoam.com) is implemented in this study as the core model, which is a free and open source Computational Fluid Dynamics (CFD) software developed primarily by OpenCFD Ltd since 2004 and distributed by OpenCFD Ltd and the OpenFOAM Foundation. The non-uniform thermal boundary condition was defined by considering the solar irradiance that enables to include the effect of shading and solar heating. Docker (www.docker.com) is employed to perform parallel computing on the 128-core High Performance Computer (HPC) in Future Cities Laboratory of Singapore-ETH Centre. Parallel computing together with the customized CFD program coupled with solar radiation model to simulate conjugate heat transfer ensured the high-performance of this tool in terms of both accuracy and efficiency. The total number of computational cells is 0.5 million and the model forcing is specified in Sections 3 and 4, respectively.

# 3 Stack effect of split type air-conditioners on high rise buildings

Stack effect of split type air-conditioners on high rise buildings are induced by the buoyancy-driven airflow coming out from the condensing units with rejected heat. The increasingly hotter air accumulated at higher levels of the same building will reduce the energy efficiency by increasing the ambient air temperature, the heat sink for the air-conditioners. This effect has been modeled before with ANSYS FLUENT (Bojic et al., 2008) with the same governing equations and more detailed set up for the work process of air-conditioners. The effect was confirmed in field measurements in Bruelisauer et al. (2014). The model uses the measurements of its case study to verify the tool.

The 24-storey Kent Vale Block H is chosen to study the stack effect of split type air-conditioners, which is a staff housing unit of the National University of Singapore. The thermal picture, which identifies the location of split type air-conditioners in the semi-column, together with the built CFD model are shown in Figure 1.
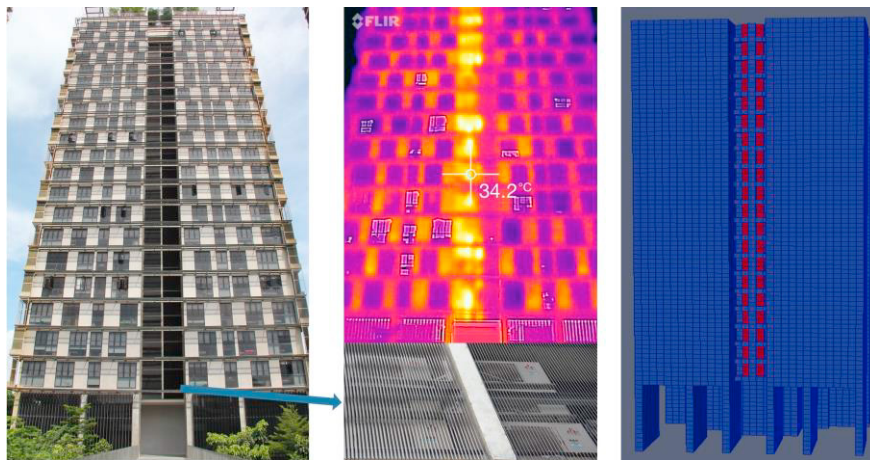


Figure 1: Kent Vale Block H (left), thermal picture of Block H (upper middle), split type air-conditioners (lower middle) and the 3D CFD model (right).

## 3.1 Model validation

The CFD model is forced by the real settings of initial air temperature and velocity of each split type air-conditioners on the north side of the Kent Vale Block H. The measurements of the stack effect was carried out on 23 November 2012. More details can be found in Bruelisauer (2014). Since the air-conditioners are located in the recessed area of Block H, horizontal wind is not considered in this simulation. The patterns of the simulated distributions of air temperature (Figure 2) match well the observed data in Bruelisauer et al. (2014). This indicates the tool is able to capture microclimatic effects induced by split type air-conditioners on high rise buildings.
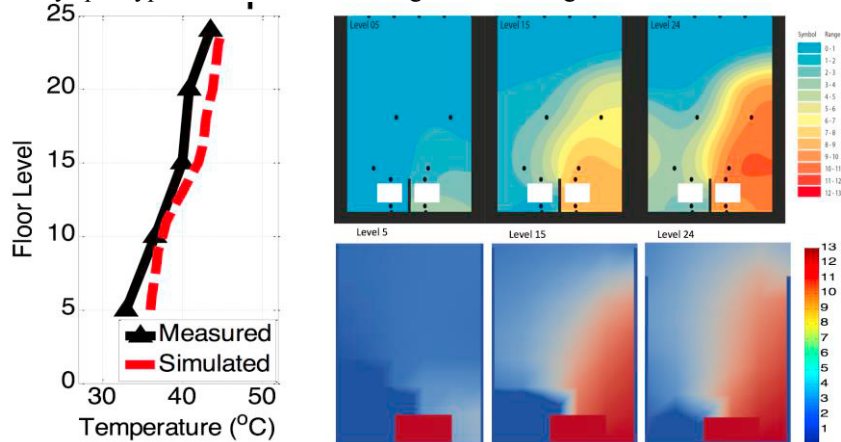


Figure 2: Validated simulated against measured data. Left: Validated vertical air temperature profile, indicating stack effect. Right: Horizontal air temperature distribution as temperature difference to ambient air temperature against measured data (top right image from Bruelisauer (2014))

## 3.2 Sensitivity analysis

Sensitivity analysis is performed by setting the indoor air temperature as 18 °C, 23 °C and 28 °C, and outdoor air temperature as 28 °C, 32 °C and 36 °C, respectively. It is found that a stronger stack effect can be observed with lower indoor (Figure 3) or higher outdoor air temperature (Figure 4), which indicates both are sensitive parameters in determining the air temperature distribution pattern outside split type air-conditioners.
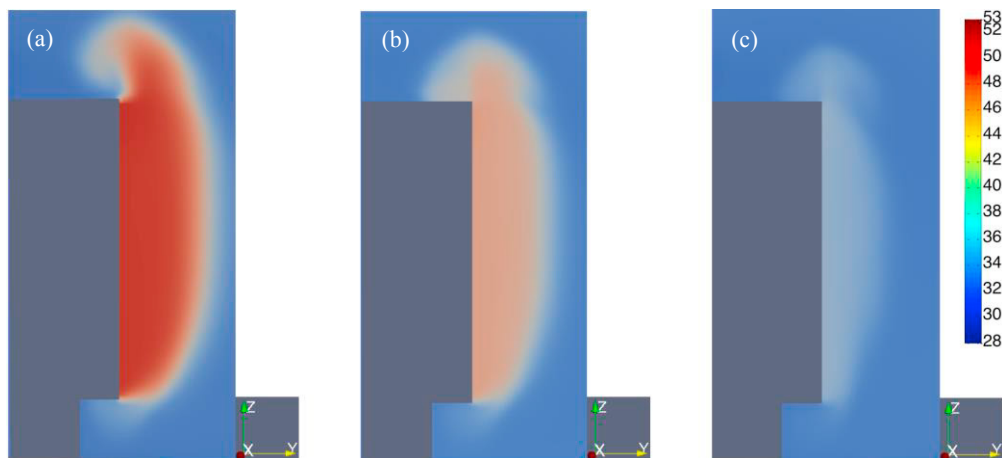
Figure 3: Sensitivity analysis of indoor air temperature on stack effect of split type air-conditioners with outdoor temperature of 32 °C. Case (a): $T_{indoor}$=18 °C, Case (b): $T_{indoor}$ =23 °C, Case (c): $T_{indoor}$ =28 °C.
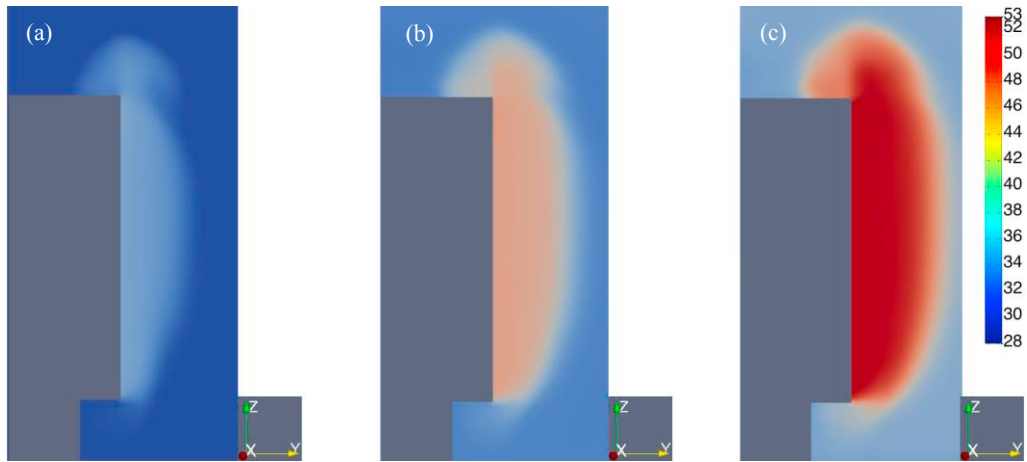


Figure 4: Sensitivity analysis of outdoor air temperature on stack effect of split type air-conditioners with indoor temperature of 23 °C. Case (a): $T_{outdoor}$=28 °C, Case (b): $T_{outdoor}$=32 °C, Case (c): $T_{outdoor}$=36 °C.

# 4   Urban microclimate around high rise buildings

The built environment will absorb more solar radiation during daytime and emit more heat during nighttime than rural area, which induces the diurnal cycle of urban heat island. Understanding the interactions between buildings and solar radiation is fundamental for studying the UHI effect. The whole of Kent Vale Residence (Figure 5) is simulated by forcing the model with solar radiation.
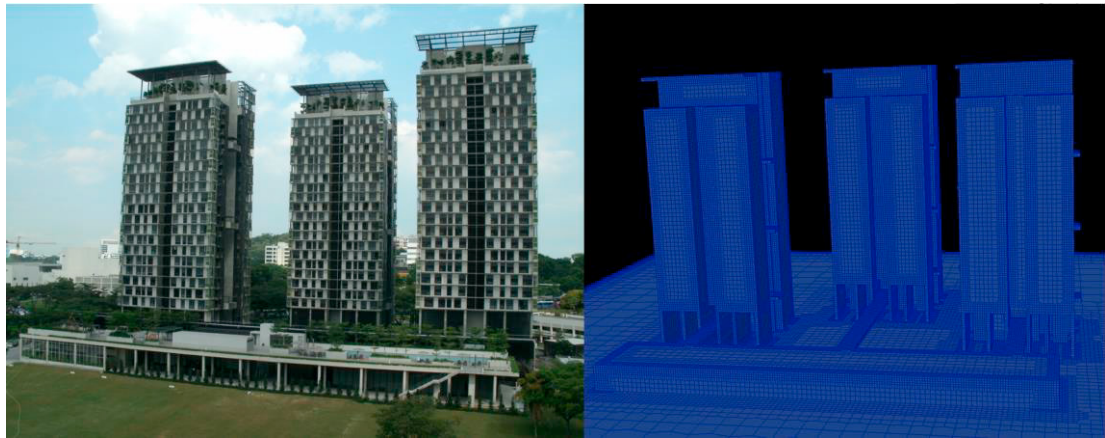


Figure 5: Kent Vale Block G, Block H, Block I, Verandah (left) (source: new.designsingapore.org/pda) and the 3D CFD model (right).

## 4.1   Model validation

Simulated solar radiation and air temperature on a typical day of each month are validated against observed data provided by National University of Singapore Meteorological Station (Figures 6-8,

Tables 1-3). Statistical evaluations are performed by calculating the correlation coefficient (r) and the mean absolute error in percentage (MAE (%)).

$$r = \frac{\sum(X_{model} - \overline{X_{model}})(X_{obs} - \overline{X_{obs}})}{\sqrt{\sum(X_{model} - \overline{X_{model}})^2 \sum(X_{obs} - \overline{X_{obs}})^2}} \tag{7}$$

$$MAE\ (\%) = \frac{\sum|(X_{model} - X_{obs})|}{(max(X_{obs}) - min(X_{obs}))N} \tag{8}$$

where $X_{model}$ and $X_{obs}$ are simulated and observed quantity, respectively. $\overline{X_{model}}$ and $\overline{X_{obs}}$ are the mea values of simulated and observed quantities, respectively. $N$ is the total number of quantities involved in the calculation. $max(X_{obs})$ and $min(X_{obs})$ are the maximum and minimum observed data among all involved quantities in the calculation, respectively. The calculation of observed solar radiation in each month throughout the whole year around Kent Vale buildings can be found in Xu (2016).

It is found that the simulated radiation, air temperature and air relative humidity generally agree well with observations, with r of 0.99, 0.98, 0.98 and MAE(%) of 2%, 4%, 6%, respectively. This shows that the modeling tool developed by coupling CFD model with the solar radiation model could capture most portion of air temperature and air relative humidity. Much smaller solar radiation, lower air temperature and higher air relative humidity in November and December are observed due to the heavy rainfall during the Northeast monsoon season. Heavy rainfall will diffuse more solar radiation, enhance evaporation of water on the group which low down the air temperature and increase the air's moisture. Since the atmospheric pressure in Singapore doesn't change so much during one day, the air's relative humidity is found be to highly negatively correlated with the air temperature. Errors are mainly from the neglected local effects such as trees, grasslands and swimming pools around buildings, which affect the small scale dynamics of the time series of air temperature and air relative humidity. In near future, the cooling effects of trees, grasslands, rivers, swimming pools and coastal seas will also be taken into account in this modeling tool.

The tool could also be implemented to carry out design evaluation in terms of thermal environment. This 0.54 million cells and 7cm resolution model takes 36 cores HPC around one hour to finish a 24 hours diurnal cycle simulation, which is efficient enough to support design evaluation purpose.
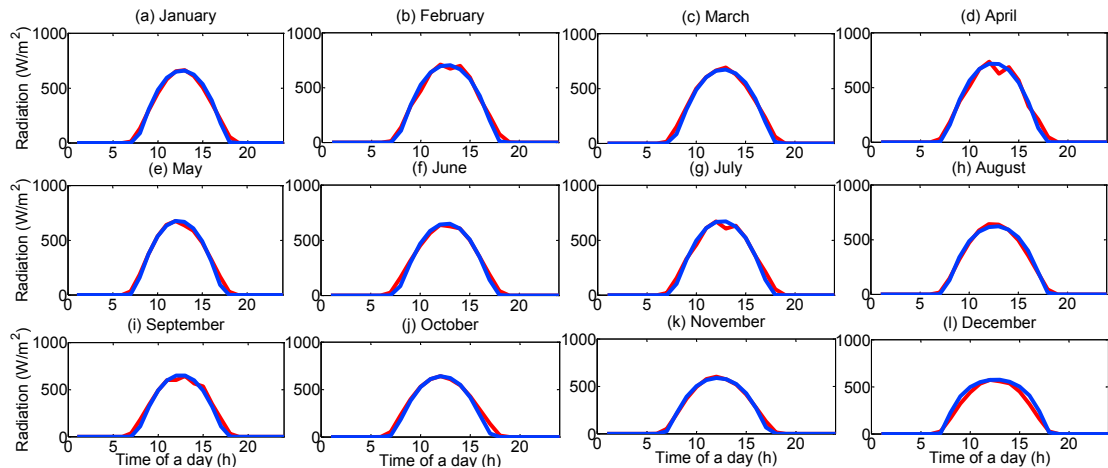


Figure 6: Validated solar radiation on a typical day of each month against measured data. Legend: measured data (red line), simulated results (blue line).

Table 1: Statistics of simulated solar radiation on a typical day of each month.

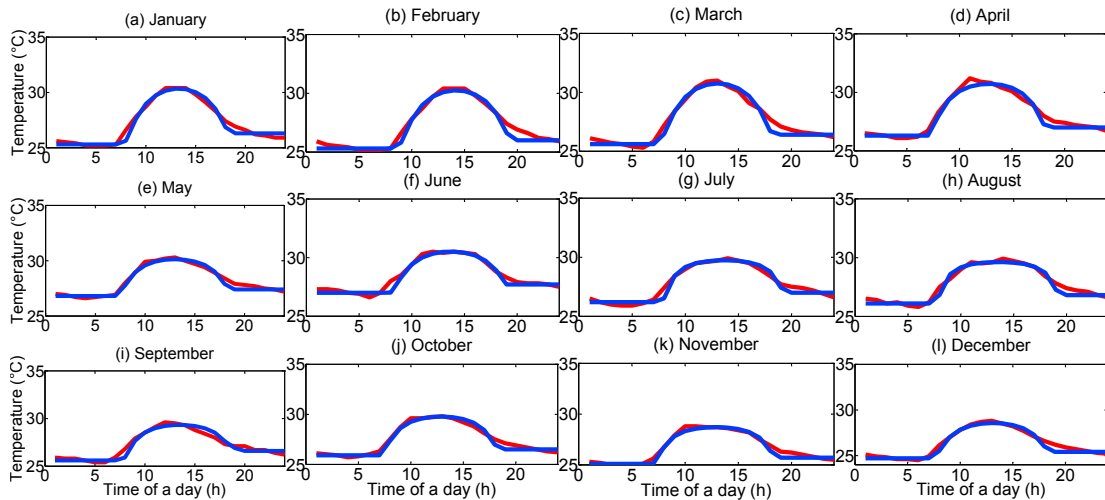|        | Jan  | Feb  | Mar  | Apr  | May  | Jun  | Jul  | Aug  | Sep  | Oct  | Nov  | Dec  |
|--------|------|------|------|------|------|------|------|------|------|------|------|------|
| r      | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 |
| MAE(%) | 1.67 | 1.97 | 1.66 | 2.48 | 1.55 | 1.78 | 2.02 | 1.78 | 1.72 | 1.40 | 1.39 | 1.22 |



Figure 7: Validated air temperature on a typical day of each month against measured data. Legend: measured data (red line), simulated results (blue line).

Table 2: Statistics of simulated air temperature on a typical day of each month.

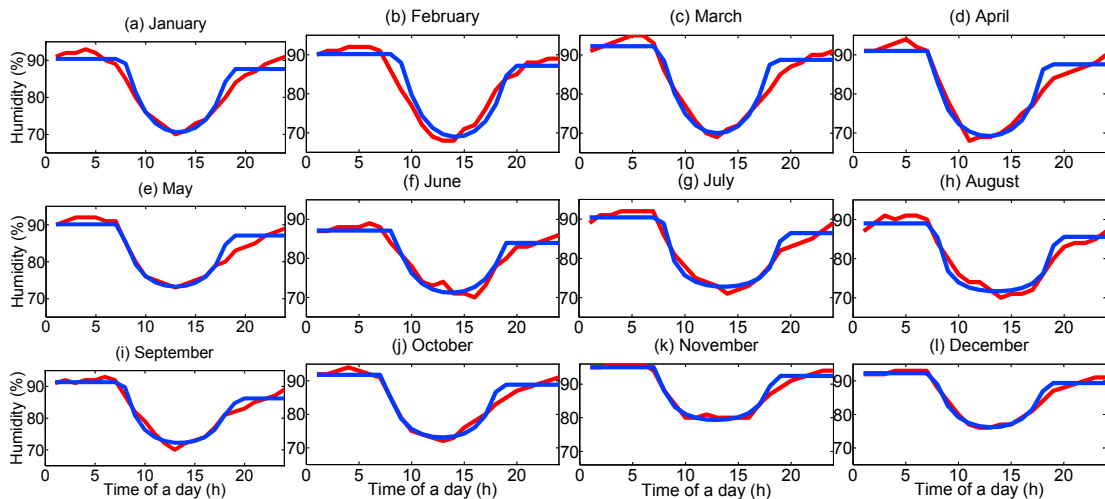|        | Jan  | Feb  | Mar  | Apr  | May  | Jun  | Jul  | Aug  | Sep  | Oct  | Nov  | Dec  |
|--------|------|------|------|------|------|------|------|------|------|------|------|------|
| r      | 0.98 | 0.99 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.97 | 0.98 | 0.99 | 0.98 |
| MAE(%) | 4.96 | 5.11 | 4.96 | 5.02 | 5.03 | 4.94 | 5.59 | 5.79 | 6.59 | 5.24 | 5.11 | 5.63 |



Figure 8: Validated air relative humidity on a typical day of each month against measured data. Legend: measured data (red line), simulated results (blue line).

Table 3: Statistics of simulated air relative humidity on a typical day of each month.

|        | Jan  | Feb  | Mar  | Apr  | May  | Jun  | Jul  | Aug  | Sep  | Oct  | Nov  | Dec  |
|--------|------|------|------|------|------|------|------|------|------|------|------|------|
| r      | 0.97 | 0.96 | 0.97 | 0.98 | 0.97 | 0.96 | 0.97 | 0.97 | 0.98 | 0.98 | 0.98 | 0.98 |
| MAE(%) | 6.76 | 8.26 | 6.17 | 5.49 | 6.39 | 6.44 | 6.85 | 7.39 | 5.06 | 5.06 | 5.89 | 5.01 |

## 4.2 Solar radiation induced urban microclimate around high rise buildings

As Singapore is located slight north to the equator, sun rises from Southeast and sets in Southwest from around 23rd September to 22nd March, and rises from Northeast and sets in Northwest from 23rd March to 22nd September. This annual cycle of sun path phenomenon is well simulated with the modeling tool, as shown in Figure 9.
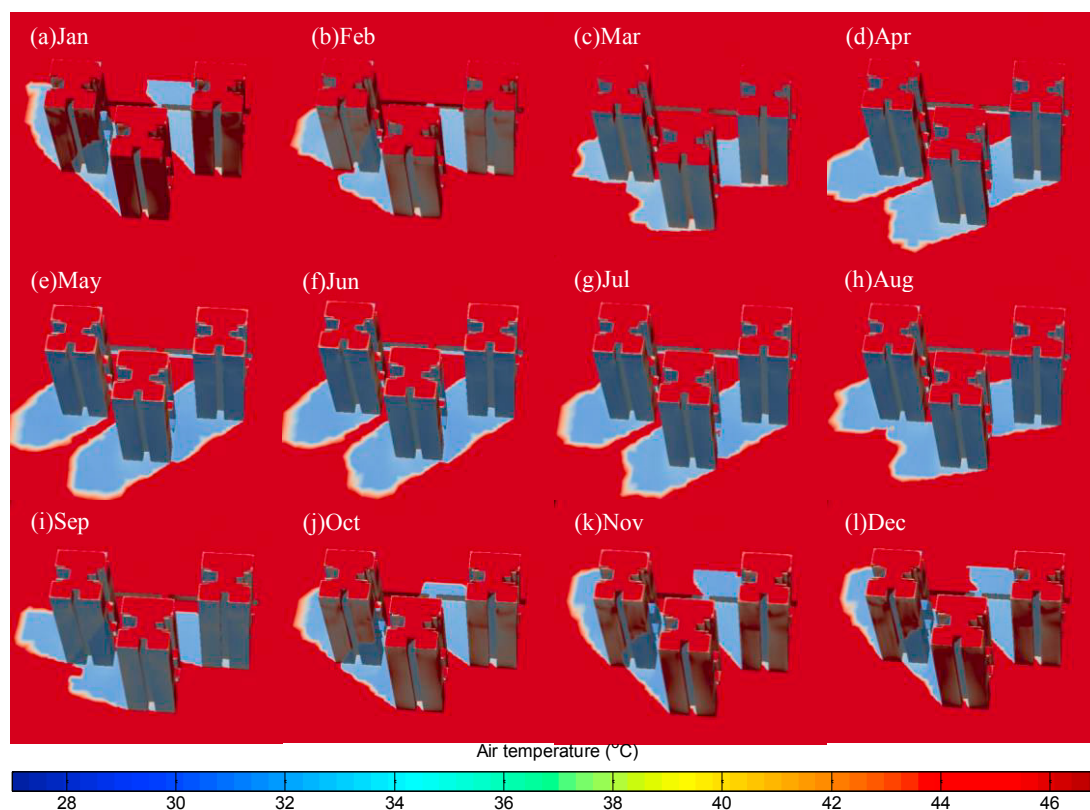


Figure 9: Air temperature adjacent to building and floor surfaces at 10:30am on a typical day of each month throughout the whole year.

## 4.3 Sensitivity analysis

Sensitivity analysis is performed by setting a high and low value of building radiation properties (emissivity, absorptivity, transmissivity, reflectivity) and thermophysical properties (specific heat $C_p$ (in J/KgK), density (in Kg/m$^3$) and thermal conductivity Kappa (in W/mK)), as tabulated in Table 4. Comparison is made between these cases and the Base case. It is found that lower absorptivity, higher reflectivity and larger thermal conductivity of the buildings could bring down the surrounding air temperature and are sensitive parameters in determining thermal environment around buildings

(Figure 10). This could provide hints to architects and urban designers in drafting more environmental friendly designs to help mitigate urban heat islands.

Table 4: Settings of building radiation and thermophysical properties for sensitivity analysis.

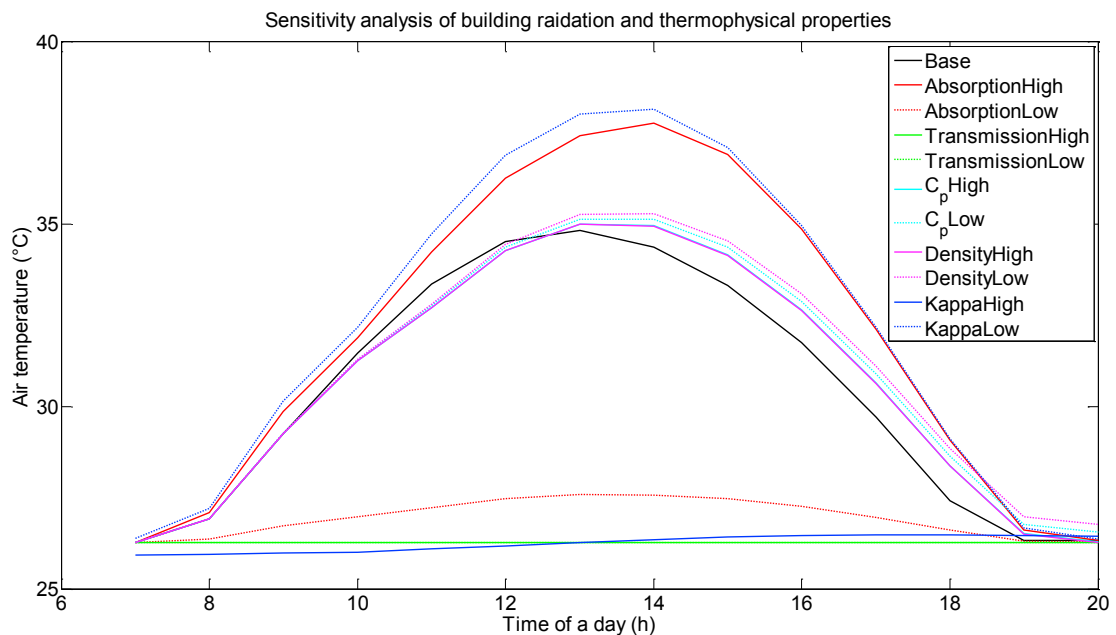| | Base | Absorption | | Transmission | | $C_p$ | | Density | | Kappa | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | High | Low | High | Low | High | Low | High | Low | High | Low |
| Emissivity | 0.7 | 0.9 | 0.1 | 0 | 0 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| Absorptivity | 0.7 | 0.9 | 0.1 | 0 | 0 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| Transmissivity | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Reflectivity | 0.3 | 0.1 | 0.9 | 0.1 | 0.9 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| $C_p$ | 750 | 750 | 750 | 750 | 750 | 1920 | 129 | 750 | 750 | 750 | 750 |
| Density | 2240 | 2240 | 2240 | 2240 | 2240 | 2240 | 2240 | 21450 | 200 | 2240 | 2240 |
| Kappa | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 429 | 0.09 |



Figure 10: Sensitivity analysis of building radiation and thermophysical properties on thermal environment around high rise buildings.

# 5 Conclusions and future work

A new urban heat island modeling tool is developed in this study to simulate stack effect of split type air-conditioners on high-rise buildings and their surrounding thermal environment induced by solar radiation. It is found that the tool can accurately simulate the stack effect of split type air-conditioners on high-rise buildings, an effect which will not influences the urban microclimate but has severe implications on the energy performance of the air-conditioners. The coupled CFD-solar radiation model can simulate air temperature and air relative humidity accurately and efficiently with conjugate heat transfer. The annual cycle of sun pathway in Singapore is well captured by this modeling tool. To improve thermal environment around buildings and mitigate urban heat island, it is suggested to use material of lower absorptivity, higher reflectivity and larger thermal conductivity for

buildings. Architects and urban designers can be supported by simulations from this tool to evaluate effects of different designs on the surrounding thermal environment.

Further sources of anthropogenic heat like traffic will be included in this modeling tool in the near future. In addition, heat sinks such as trees and grasslands, waterbodies like swimming pools, rivers and coastal seas will also be added into this integrated system to account for their cooling effects. Further work will consist of implementing this modeling tool to evaluate different design strategies to mitigate urban heat islands and urban microclimates, looking at new design of building facades, roofs and cooling systems.

# References

Berger, M., (2016). The Manifold Challenges for Modeling the Urban Heat Island. *Procedia Computer Science*, 80, 2000-2007.

Bojic, M., Savic, S. and Nikolic, D., (2008). Application of Computational Fluid Dynamics to flow next to high-rise buildings in Hong Kong due to air-conditioner heat rejection. *International Journal of Energy Technology and Policy*, 6(1/2), 159-177.

Bruelisauer, M., Meggers, F., Saber, E., Li, C. and Leibundgut, H., (2014). Stuck in a stack – Temperature measurement of the microclimate around split typecondensing units in a high rise building in Singapore. *Energy and Buildings*, 71, 28-37.

Bruelisauer, M., (2014). LowEx heat rejection systems in the tropics: Beyond energy efficiency, towards integrated multi-scale cooling system. Doctoral Thesis No. 22273, ETH Zurich.

Gertland, L., (2008). Heat Islands: Understanding and Mitigating Heat in Urban Area. London: Earthscan.

Chow, W.T.L. and Roth, M., (2006). Temporal Dynamics of the Urban Heat Island of Singapore. *International Journal of Climatology*, 26, 2243-2260.

Howell, J.R., Siegel, R. and Menguc, M.P., (2010). Thermal Radiation Heat Transfer. Fifth Edition. CRC Press.

Kolokotroni, M., Ren, X., Davies, M. and Mavrogianni, A., (2012). London's urban heat island: Impact on current and future energy consumption in office buildings. *Energy and buildings*, 47, 302-311.

Kovats, R.S. and Hajat, S., (2008). Heat stress and public health: a critical review. *Annual Review of Public Health*, 29, 41-55.

Lo, C. and Quattrochi, D.A., (2003). Land-use and land-cover change, urban heat island phenomenon and health implications. *Photogrammetric Engineering & Remote Sensing*, 69(9), 1053-1063.

Magrogianni, A., Davies, M., Batty, M., Belcher, S., Bohnenstengel, S., Carruthers, D. and Ye, Z., (2011). The comfort, energy and health implications of London's urban heat island. *Building Services Engineering Research and Technology*, 32(1), 35-52.

Oikonomou, E., Davies, M., Mavrogianni, A., Biddulph, P., Wilkinson, P. and Kolokotroni, M., (2012). Modelling the relative importance of the urban heat island and the thermal quality of dwellings for overheating in London. *Building and Environment*, 57(0), 223-238.

Oke, T.R., (1973). City size and the urban heat island. *Atmospheric Environment*, 7(8), 769-779.

Roth, M., and Chow, W.T.L., (2012). A Historical Review and Assessment of Urban Heat Island Research in Singapore. *Singapore Journal of Tropical Geography*, 33, 381-397.

Wong, N.H. and Chen, Y., (2006). Exploring the Urban Heat Island Effect in Singapore. In Tropical Sustainable Architecture, ed. Bay Joo Hwa and Ong Boon Lay, 10-1-10-23. London: Architecture Press, 23pp.

Xu, M., (2016). Towards a cooler Singapore. *Global Journal of Science Frontier Research*, 16(3), 32-35.