Quantify Effects of Traffic, Grasslands and Water Bodies on Urban Heat Islands: Kent Vale Case Study

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Abstract

Urban heat islands (UHIs) are quite common in megacities due to the built-up area and reduced greenery coverage of land surface, which highly affect urban livability. Effects of traffic, grasslands and water bodies on urban heat islands are investigated in this study by comparing results from two different scenarios with Computational Fluid Dynamics (CFD) models. In Scenario 1, all regions are set as concrete, while in Scenario 2, each region is set as its own property. It is found that

(1) The air temperature above Clementi Road is more than 2°C higher than surrounding air throughout the day time except during the early morning and can affect air even at 8m above the ground.

(2) Grasslands can cool down much larger area than their upright surface with capability of around 2°C decided by the size of grassland through intrusion into the hotter regions from gaps between three high-rise buildings and the verandah.

(3) The air temperature at the water surface of the swimming pool is found to be around 1.5°C cooler than the surrounding air and can go up to 1m above the water surface with temperature of around 0.5°C lower than the surrounding air.

By combing different urban heat islands mitigation strategies such as increase the greenery coverage with densely located grasslands and trees and have more suitable water bodies, better cooling effects can be achieved to improve the thermal environment in megacities.

Keywords: Effects of Traffic, Effects of Grasslands, Effects of Water Bodies, Urban Heat Islands, CFD Models

Introduction

Urban heat islands (UHIs) is one 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 [1]. 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 [2], 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.

Two comprehensive reviews of earlier urban heat island studies in [3,4] have identified the research gaps as illustrating mitigation effects of greenery and water bodies. Water availability and higher percentage of greenery could promote latent heat flux at the expense of surface heat storage, which will modulate energy partitioning. Without regarding the climate type, greenery and water bodies have strong influence on energy partitioning, which makes greenery an effective strategy to mitigate urban heat islands by reducing the uptake of heat storage, as pointed out in [3]. By comparing two satellite images of Singapore dated 13 years apart as in [4], the encroachment of high surface temperature areas into previously low surface temperature areas has illustrated the built-up of recent new low-rise residential areas and high-rise public housing estates.

As commented in [5], it is necessary to quantify the respective effects of major heat sources and sinks which contribute to urban heat islands in Singapore. [5] concludes that solar radiation is the predominant heat source in Singapore, whose effects and interactions with buildings and surrounding air is investigated in [6]. Other heat sources contribute to urban heat islands is mainly induced by anthropogenic activities [7], such as industrial activities, traffic system, commercial services and households.

The traffic system in megacities is found to be able to heat up surrounding air with waste heat ejected from vehicles and frictions between road surfaces and tires of vehicles [8-10]. While greenery is found to be able to cool down urban environment [11-14], there is still too little information of quantifying its contributions to mitigate urban heat islands. In addition, the effects of water bodies on urban heat islands [15] are still not clear.

In [16], a nice and comprehensive summary of urban heat island studies is made. It has concluded that urban heat island effect will exert a series of ecological and environmental effects on urban climate, urban hydrologic situations, soil properties, atmospheric environment, biological habits, material cycles, energy metabolism and residents’ health. Possible mitigation strategies are improvement of energy efficiency, urban landscape optimization, green roof construction, high reflective material utilization and green land cultivation. Earlier studies mainly focus on the effect of land use and land cover changes induced by urbanization on urban heat island effect [17-18]. As found in [17], urbanization in Shanghai is highly correlated with the increase of air temperature, hot days and the decrease of relative humidity, wind speed and vegetation normalized difference vegetation index, which is driven by continuous increase of buildings, paved roads, buses, population and gross domestic production, as well as the decrease of cultivated land. Similar phenomenon...
is also observed in Beijing, as presented in [18] that the moving direction of the urban heat island gravity center is basically in agreement with urban land sprawl and the encroachment of urban land on suburban land is the leading source of urban heat island effect. There are also interesting studies regarding future land cover changes and their effects on the land surface temperature, such as the study in Saudi Arabian Eastern Coastal City of Dammam presented in [19]. By projecting future land use and land cover change for 2026, it is found that the urban area is expected to encompass 55% of the city and 98% of the land cover is envisioned to have average land surface temperature over 41°C, which would make it difficult for the residents to live in the area.

While very few earlier studies have discussed the impacts of anthropogenic heat on urban thermal environment. A recent study of the impact of energy consumption on the surface urban heat island in China’s 32 major cities as presented in [20] has illustrated the importance of anthropogenic heat especially during night time. It has concluded that the cities with a larger urban-suburban difference in energy consumption intensity have a far greater impact on surface urban heat island during the night time. The main objective of this study is to quantify the effects of traffic, grasslands and water bodies on urban thermal environment with a case study. Kent Vale Buildings (Figure 1) is chosen as there are three 24-storey high-rise buildings, one verandah with a swimming pool on top, two grasslands at the ground floor in between the buildings and an arterial road Clementi Road at the back of the buildings.

### Model Details

#### Methods

Three universal conservation laws of mass, momentum and energy are taken into account by solving continuity equation (Equation (1)), Navier-Stokes 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.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{1}
\]

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

\[
\rho C_p \left( \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) = k \nabla^2 T + Q \tag{3}
\]

\[
q = h \left( T_a - T_{\infty} \right) \tag{4}
\]

\[
q = -k \nabla T \tag{5}
\]

\[
q = \varepsilon \sigma \left( T_s^4 - T_{b}^4 \right) \tag{6}
\]

where \( \rho \) is density, \( t \) is time, \( \mathbf{u} \) is flow velocity field, \( p \) is pressure, \( \mathbf{I} \) is the identity matrix, \( \mu \) is turbulent eddy viscosity, \( q \) is the gravity acceleration rate, \( T \) is temperature, \( C_p \) is the specific heat, \( k \) is the thermal conductivity, \( Q \) is the additional heat flux, \( h \) is the heat transfer coefficient, \( \varepsilon \) is the radiation factor and \( \sigma \) is the Stefan-Boltzmann constant, respectively. The meteorological effects are considered as calm wind situation in the model domain as boundary conditions, which is also the real situation of Kent Vale Buildings.

OpenFOAM (www.openfoam.com) is implemented in this study, 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. Parallel computing cases are running on the High Performance Computer (HPC) Salak in Future Cities Laboratory of Singapore-ETH Centre.

#### Model set up

The model domain for Kent Vale Buildings is selected as 250m × 250m × 200m in x, y and z directions, respectively. With snappyHexMesh of OpenFOAM, a high resolution of around 5cm is achieved for the smallest edges of buildings and the total number of cells is 1.27 million. The selected model resolution follows suggestions made in [21]. Two scenarios are simulated, namely Scenario 1: all regions are concrete (Figure 2) and Scenario 2: each region is set as their individual properties (Figure 3). The first scenario where all regions are concrete is the same as the model in [6], where the model validation of simulated solar radiation, air temperature

Figure 1: Front view of Kent Vale Buildings

Figure 2: Regenerated base case model domain in the CFD model where all regions are concrete. The air region is not shown here to better identify other regions

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Regenerated all regions in the CFD model. The air region is 200-
Thermo physical and radiation properties of different materials
Air

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Results and Discussion

Effects of traffic on urban heat islands

Heat induced by traffic system in megacities is one of the major anthropogenic heat sources. Estimations of major anthropogenic heat flux includes building energy consumption, traffic system and human metabolism are made in [7]. Time series of heat flux due to traffic system from 6am to 8pm during daytime (Figure 4) is adopted after part of Figure 3 in [7], which is employed as the forcing of traffic heat flux in the CFD model.

Effects of traffic on urban heat islands, or more specifically on the air temperature distribution patterns are identified by comparing the results of Scenario 2 where all regions are concrete with Scenario 1 where each region is defined with its individual properties. Air temperature distribution patterns at height of 0.5m above ground at 9am, 1pm and 5pm are shown in figure 5. 9 am is chosen as the morning situation the heat flux induced by traffic on Clementi Road is around 8.6 W/m². 1pm represents the peak hour of solar radiation as observed and indicated in [6], when the traffic induced heat flux is around 14 W/ m². While 5pm stands for the afternoon situation and the corresponding heat flux on Clementi Road is set as 15 W/m². Traffic induced heat flux starts to increase from 7am, peaks at around 1pm and remains until around 8pm before decreasing again.

It is found that the air temperature above Clementi Road is more than 2°C higher than surrounding air throughout the daytime except during the early morning. Before 9am when the traffic is not heavy, the air temperature above Clementi Road is almost as the same as other concrete regions. Since vehicles on the road consumes quite a large portion of total energy consumption in Singapore, the results imply that energy consumption in a megacity like Singapore during anthropogenic activities such as traffic system could bring huge impacts to urban thermal environment, which would worsen the situation of urban heat island in urban area, as found in [20].

As shown in figure 5, it is also noticed that the heating effects of Clementi Road reaches beyond its upright regions and also heats up other parts such as the region beside Block I through convection. Due to radiation effects of the hot road surface of Clementi Road, a gradually decreased heating effects are observed around the Clementi Road, especially towards Grassland 4 area.

The interesting air temperature distribution pattern around three high-rise buildings and the verandah is decided the interactions between building geometries, solar radiation and surrounding cool air, which will be investigated in another separate study.

Effects of grasslands on urban heat islands

As illustrated in figure 3, there are four grasslands in this model, namely Grasslands 1 and 2 at the ground level in between the three high-rise buildings and the verandah, Grassland 3 to the north of the verandah and Grassland 4 beside the Clementi Road located in the upper-left corner of the model domain. Cooling effects of grasslands are simulated by accounting for its evapotranspiration rate throughout the day with porous media technique of the region.

Both temporal and spatial effects of these four grasslands can be identified with figure 5. It is found that the cooling effects of grasslands are quite consistent throughout the whole day. The distribution pattern of

<table>
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Figure 4: Time series of heat flux from traffic adopted after part of Figure 3 in [7]
middle of the open space between Blocks G, H and I is mainly induced by the shading of Bridge H. Although the cooler zone above Grasslands 3 and 4 could also go up to 2m above the ground, the cooling effects are much smaller than those of Grasslands 1 and 2, especially combining with the shadings from the three high-rise buildings. While Grassland 3 still can cool down the hot air by less than 0.5°C, which is slighter stronger than that of Grassland 4. The results come from this study generally agree well with observations presented in [22]. As shown in [22], the observed effects of trees and grasslands could bring down both surface temperature and globe temperature in urban area, which could be a mitigation strategy of urban heat island effect.

Effects of water bodies on urban heat islands

Effects of water bodies on urban heat islands are identified by comparing air temperature distribution pattern above water surfaces with the situation that there is no water body. To simulate effects of water bodies on urban heat islands, evaporation rates of the water bodies in this model are set according to measured data. As illustrated in figure 3, there are five water bodies in this model, namely Pools 1-4 located at the ground floor beside Grasslands 1 and 2, and the swimming pool at the top of the verandah. Due to relatively smaller sizes of the ground water feature pools, effects of water bodies on urban heat islands are mainly focused on the swimming pool. Since the swimming pool is at the top of the verandah, air temperature distribution pattern at heights of 7m, 7.5m and 8m at 1pm are plotted in figure 7 for Scenario 1 and 2, respectively.

It is found that the air temperature at the water surface of the swimming pool is around 1.5°C cooler than the surrounding air, which is relatively smaller than the cooling capability of grasslands. The relatively cooler air can go up to 1m above the water surface with temperature of around 1.5°C cooler than the surrounding air, which is relatively smaller than the cooling capability of grasslands. The relatively cooler air can go up to 1m above the water surface with temperature of around

To quantify the cooling effects of grasslands along the vertical direction, air temperature distribution pattern at heights of 1m, 1.5m and 2m above ground at 1pm are plotted in figure 6 for Scenarios 1 and 2, respectively. Combining with figure 5, it is found that the cooling effects of grasslands can reach up to 2m above ground depends on their sizes. At the height of 2m above ground, Grasslands 1 and 2 can still cool down the surrounding hot air by more than 0.5°C. Figure 6 also indicates the cooling effects of shading from high-rise buildings does not change much throughout the day, as the simulation is carried out on 31st December when sun rises from Southeast and sets in Southwest. On this specific day, the open space between three high-rise buildings and the verandah is located in the shadow throughout the daytime. The relatively cooler zone in the
Effects of traffic, grasslands and water bodies on urban heat islands are investigated in this study by comparing results from two different scenarios. In Scenario 1, all regions are set as concrete, while in Scenario 2, each region is set as its own property.

It is found that the air temperature above Clementi Road is more than 2°C and can be up to 20°C higher than surrounding air throughout the daytime except during the early morning. Before 9am when the traffic is not heavy, the air temperature above Clementi Road is almost the same as other concrete regions. The heating up effects of Clementi Road also extends to surrounding area through radiation and can affect air temperature even at 8m above the ground.

Cooling effects of grasslands are found to be quite consistent throughout the whole day. The distribution pattern of cooler zone is decided by the interactions of the cool air around grasslands, surrounding buildings and hotter air. Grasslands is found to be able to cool down much larger area than their upright surface through intrusion into the hotter regions from gaps between three high-rise buildings and the verandah. The cooling effects of Grasslands can be roughly estimated as 2°C, with larger values for larger grasslands. It is also found that the cooling effects of grasslands can reach up to 2m above ground depends on their sizes.

The air temperature at the water surface of the swimming pool is found to be around 1.5°C cooler than the surrounding air, which is relatively smaller than the cooling capability of grasslands. The relatively cooler air can go up to 1m above the water surface with temperature of around 0.5°C lower than the surrounding air. In addition, the cooled down region above the water surface does not expand much through radiation, which is slightly weaker than that of grasslands. The possible reasons for difference in cooling capabilities between grasslands and water bodies can be mainly attributed to the fundamental difference between evaporation and evapotranspiration. Evaporation of water from water bodies in urban area is mainly induced by the heating effects of solar radiation. Since small water bodies have relatively weaker total amount of water evaporated during daytime than huge water bodies such as lakes and reservoirs. When the water bodies in urban area are moving such as running rivers and active coastal seas, the cooling effects due to evaporation of water bodies will be much stronger than those of small water features such as swimming pools and landscape pools. While evapotranspiration of greenery includes grasslands and trees is the combined effect of both evaporation and transpiration. Due to photosynthesis activities of greenery when there is sufficient supply of sunlight, carbon dioxide, nitrogen and phosphorus, much cooler water vapor leaving the surfaces of leaves will enter the environment with initial momentum, which helps to magnify the cooling effects of greenery.

Other than cooling effects of water bodies, it is recommended to name the effects of water bodies as balancing effects, which will avoid the surrounding environment from being neither too hot nor too cold, as the specific heat capacity of water is 4.2 times that of air.

As shown in figure 7, it is also found that the air temperature in the whole domain is slightly lower with the existence of grasslands and water bodies in Scenario 2 than Scenario 1. This combined cooling effect through interactions between major heat sources and sinks, and the surrounding air can be as high as around 1°C at critical locations around the buildings even at the height of 8m above the ground. Judging from figure 7, the heating effects of Clementi Road can still weakly affect air temperature at the height of 8m above the ground. Similar slight cooling phenomenon are also observed in both numerical studies [23] and experimental measurements [24-25].

Conclusions

Effects of traffic, grasslands and water bodies on urban heat islands are investigated in this study by comparing results from two different scenarios. In Scenario 1, all regions are set as concrete, while in Scenario 2, each region is set as its own property.

It is found that the air temperature above Clementi Road is more than 2°C and can be up to 20°C higher than surrounding air throughout the daytime except during the early morning. Before 9am when the traffic is not heavy, the air temperature above Clementi Road is almost the same as other concrete regions. The heating up effects of Clementi Road also extends to surrounding area through radiation and can affect air temperature even at 8m above the ground.

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By combining different urban heat islands mitigation strategies such as increase the greenery coverage with densely located grasslands and trees and have more suitable water bodies, better cooling effects can be achieved to improve the thermal environment in megacities.

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