Spatial variability of building frontal area index and its relationship with urban heat island intensity

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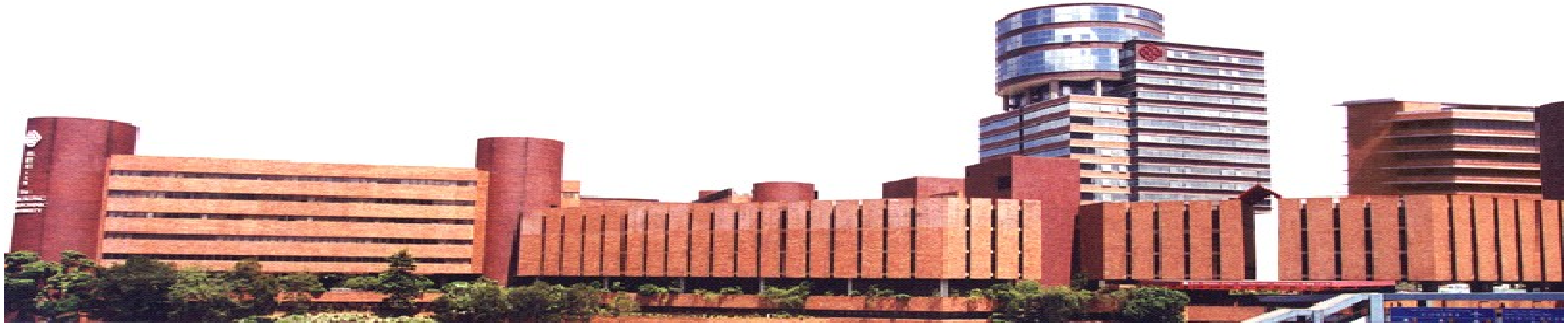

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Urban wind ventilation

- Significant **urban heat island** effects resulting from high building densities have been observed in temperate and tropical regions

- Air flow between rural and urban areas is one of the parameters governing urban heat island formation and the build-up of pollution

- But, most of the data included in **wind and air quality studies are from ground level instruments**. The gathering of data over large regions such as a city therefore is a major challenge

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Urban wind ventilation modeling

- **Wind tunnel model**

  Pros: model the local wind direction and pollutant dispersion at large scales over a district

  Cons: limited coverage, high cost

- **PSU/NCAR mesoscale model (known as MM5)**

  Pros: large area coverage

  Cons: at coarse resolution and it needs many input parameters

- **Computational Fluid Dynamics (CFD) model**

  Pros: over smaller areas in greater detail

  Cons: highly computer-intensive and generally inapplicable to large areas or whole cities

- **Remote Sensing + Geographic Information Systems?**

GIS ventilation modeling

- GIS techniques provide solutions with simplifying assumptions and numerical approximations

- GIS ventilation modelling at near surface condition can be **simplified through the estimating of roughness parameters**:

  – Roughness is a measure of the texture of a surface, if the roughness is large, the wind is difficult to pass through

  – zero-plane displacement height (z_d) and the roughness length (z_0) (Lettau, 1969; Counihan, 1975), plan area density (λ_p), **frontal area index (λ_f) (Grimmond and Oke, 1999; Burian et al., 2002)**, average height weighted with frontal area (z_h), depth of the roughness sub-layer (z_r) (Bottema, 1997; Grimmond and Oke, 1999) and the effective height (h_{eff}) (Matzarakis and Mayer, 1992) etc

Objectives

(i) To analysis the relationship between Frontal Area Index (FAI) and Urban Heat Island Intensity (UHII) at different scales,

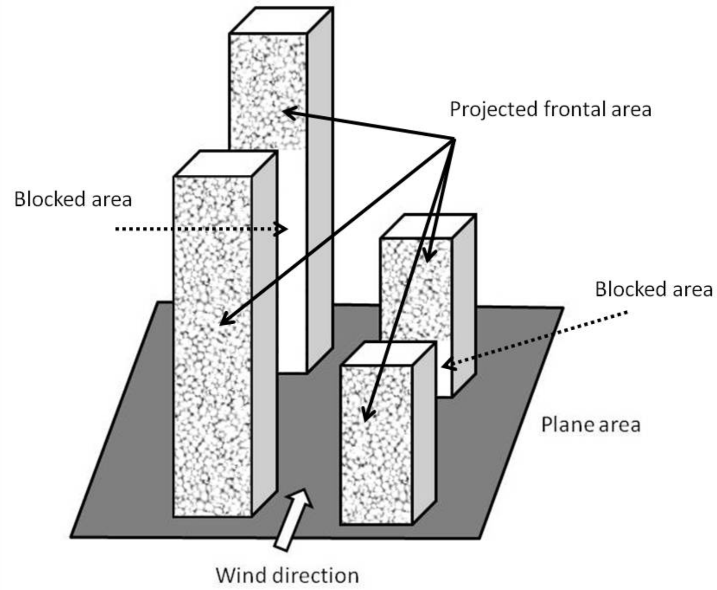
Definition of UHII:

UHII = T_a in city center – T_a in rural areas, where T_a is air temperature

(ii) To find the optimum operational scale and resolution of FAI, i.e. the scale and size at which it interacts most strongly with heat island intensity

Calculation of Frontal Area Index

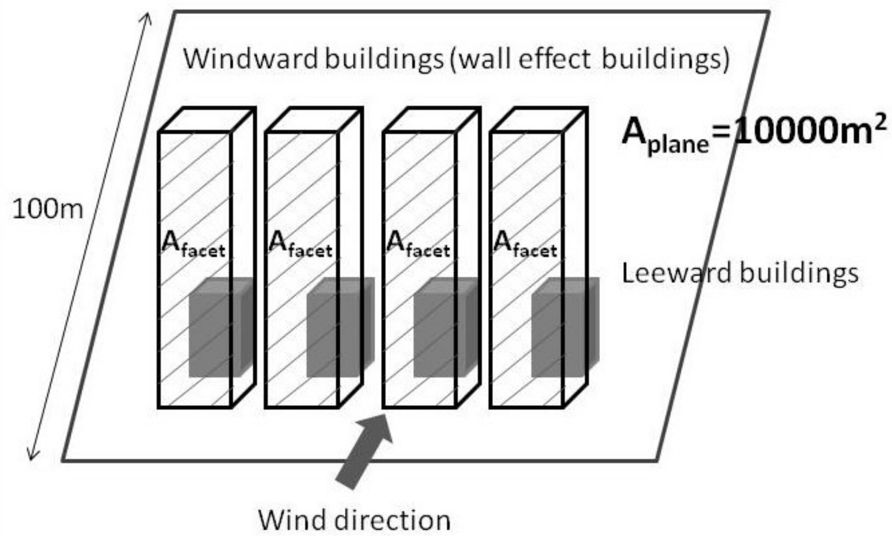
Equation: $\lambda_f = A_{facets} / A_{plane}$

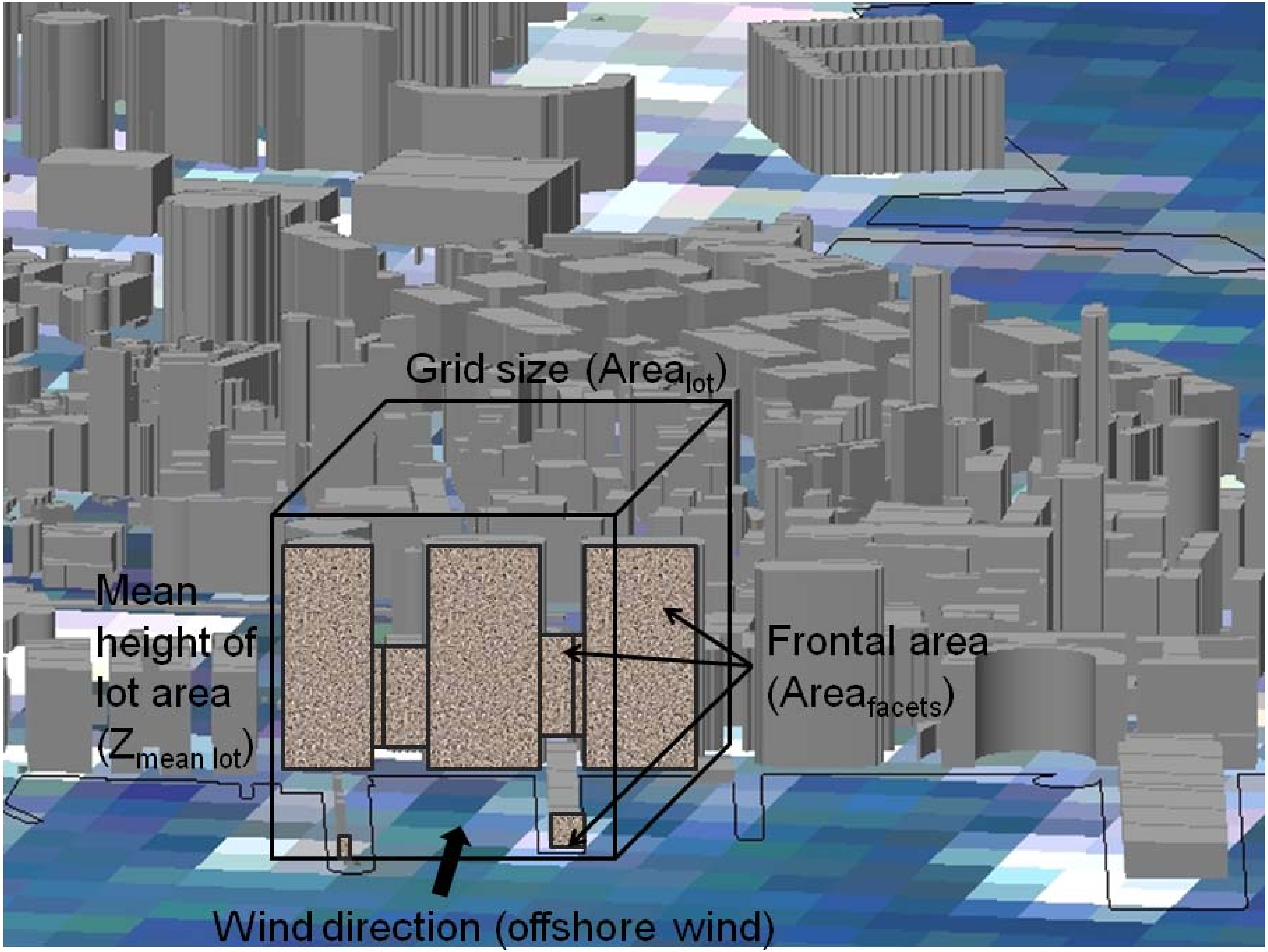


where λ_f is the frontal area index, A_{facets} is the total areas of building facets facing the wind direction, and A_{plane} is the plane area

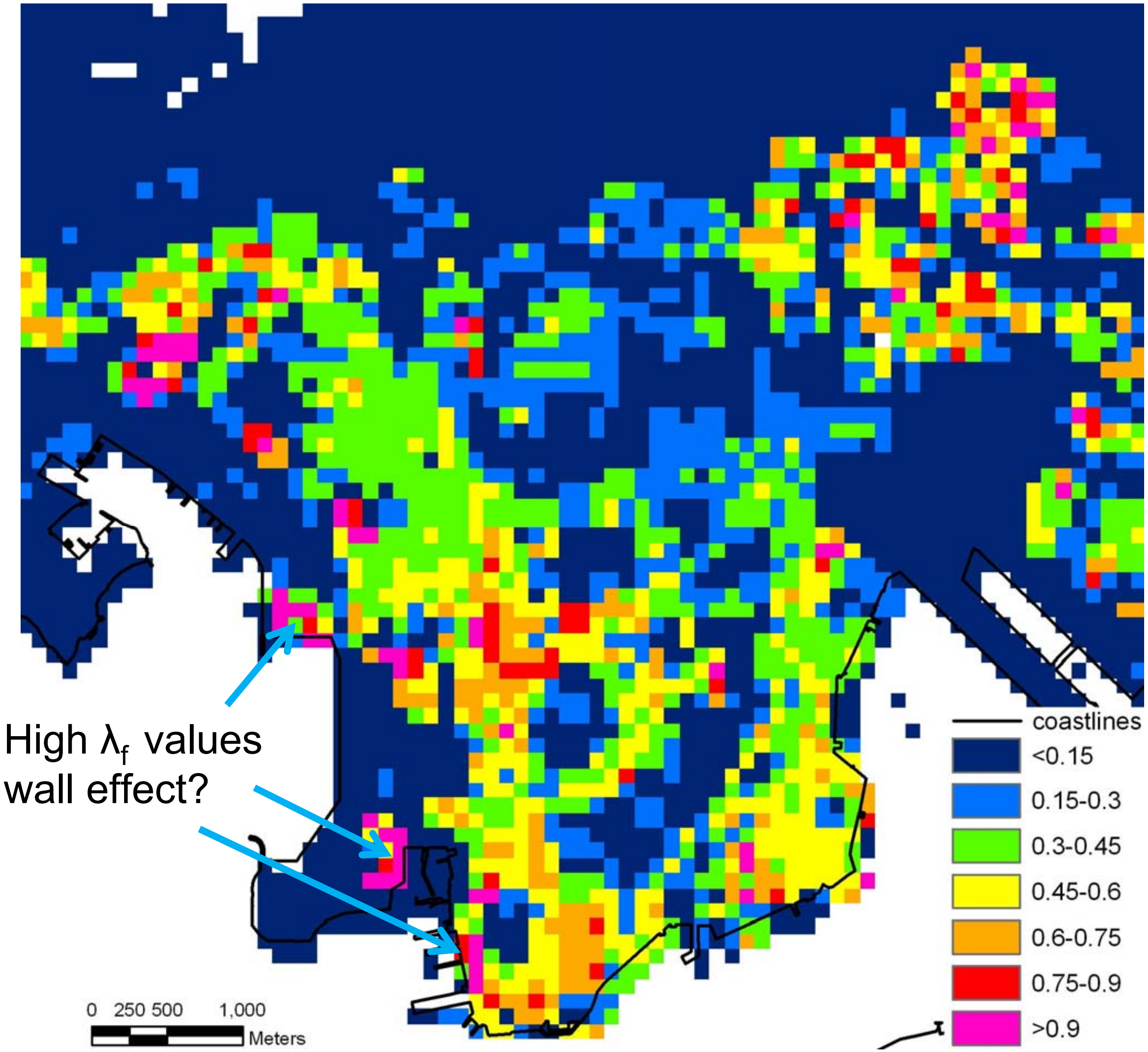
A customized program was written in ESRI® ArcGIS™ software

The scale of the LIC building digital data is 1:5000




Grid size (Area$_{lot}$)
Mean height of lot area ($Z_{mean\ lot}$)
Frontal area (Area$_{facets}$)
Wind direction (offshore wind)

Frontal area index map



Averaged λ_f in eight directions over study area

λ_f =>0.9 means that wind is mostly blocked by buildings within a selected plane region

λ_f ~0.5 means that wind is half blocked

Frontal area index at different land use types

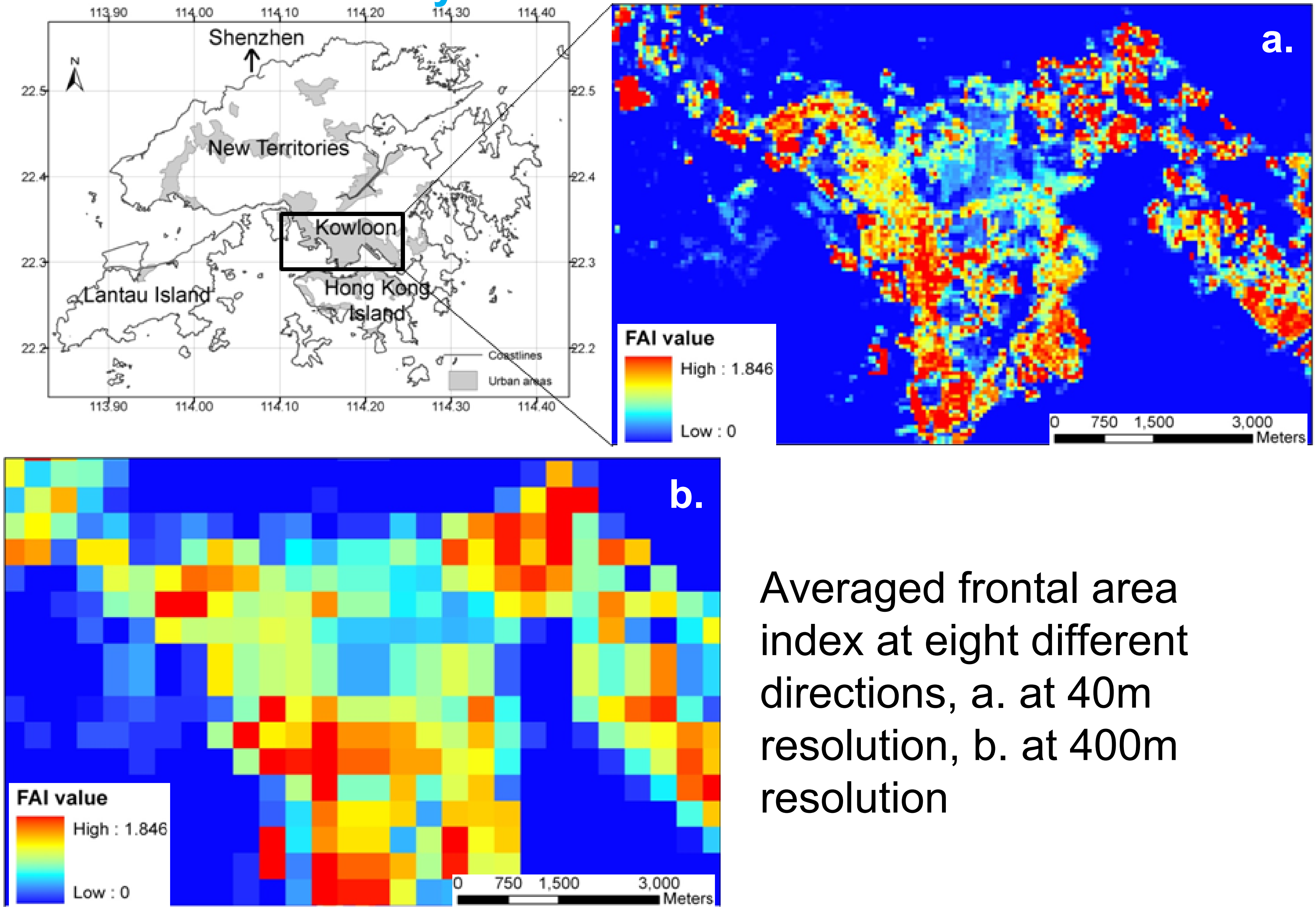
Landuse types	λ_f
Private Residential	0.267
Public Residential	0.241
Commercial/Business & Offices	0.305
Industrial	0.324
Warehouse & Storage	0.155
Rural Settlements	0.056
Vegetation	0.075
Public transportation	0.15
Vacant Development Land	0.191

Kowloon Peninsula have significantly **high λ_f values than** other countries and cities, i.e. **Los Angeles, Vancouver**…

Commercial and industrial areas have higher values as compared to others, primary because these areas have densely high rise buildings

Calculation of frontal area index at different resolutions

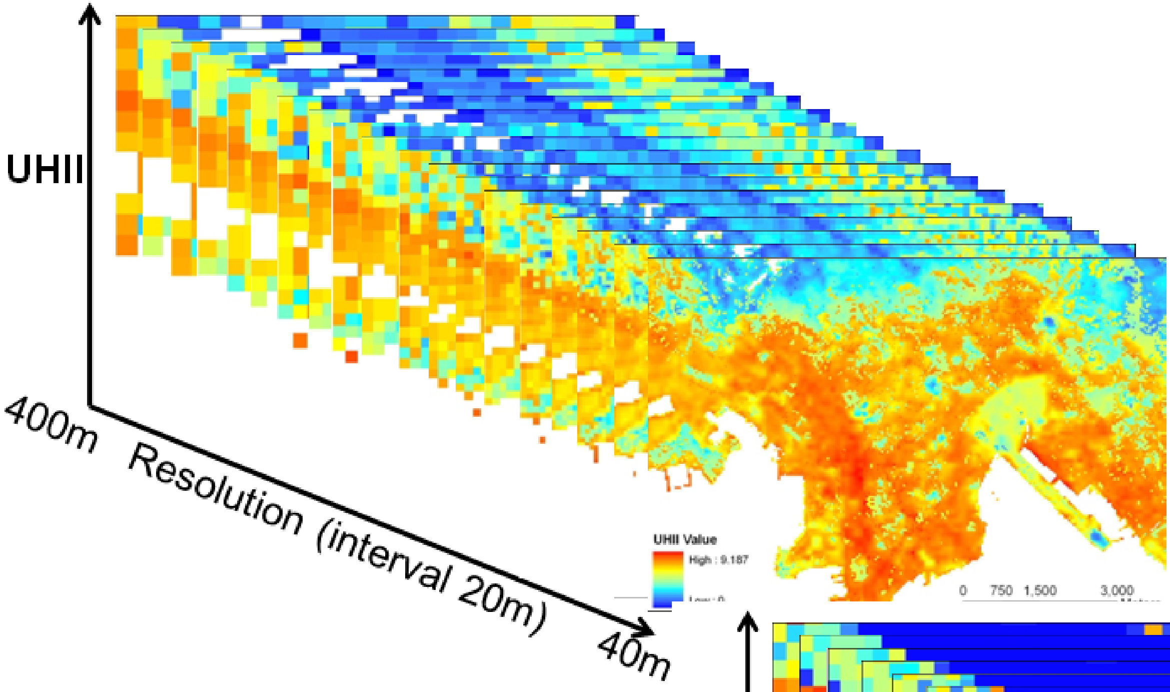
Study area – Kowloon Peninsula



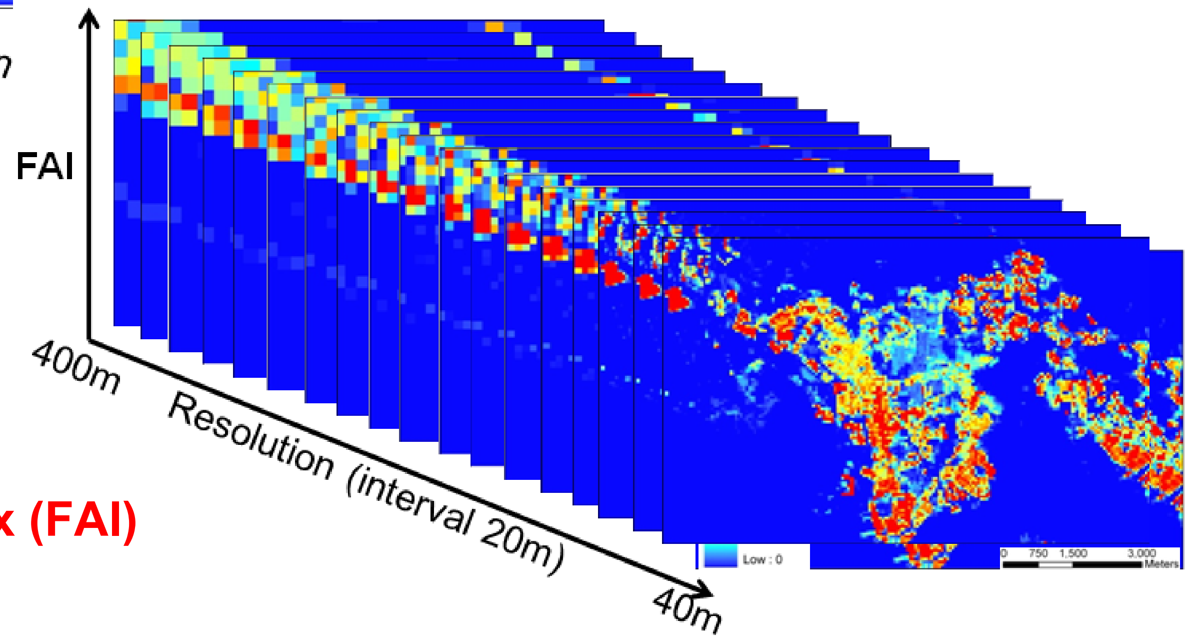
Averaged frontal area index at eight different directions, a. at 40m resolution, b. at 400m resolution

Calculation of frontal area index at different resolutions

What is the appropriate Grid Size?



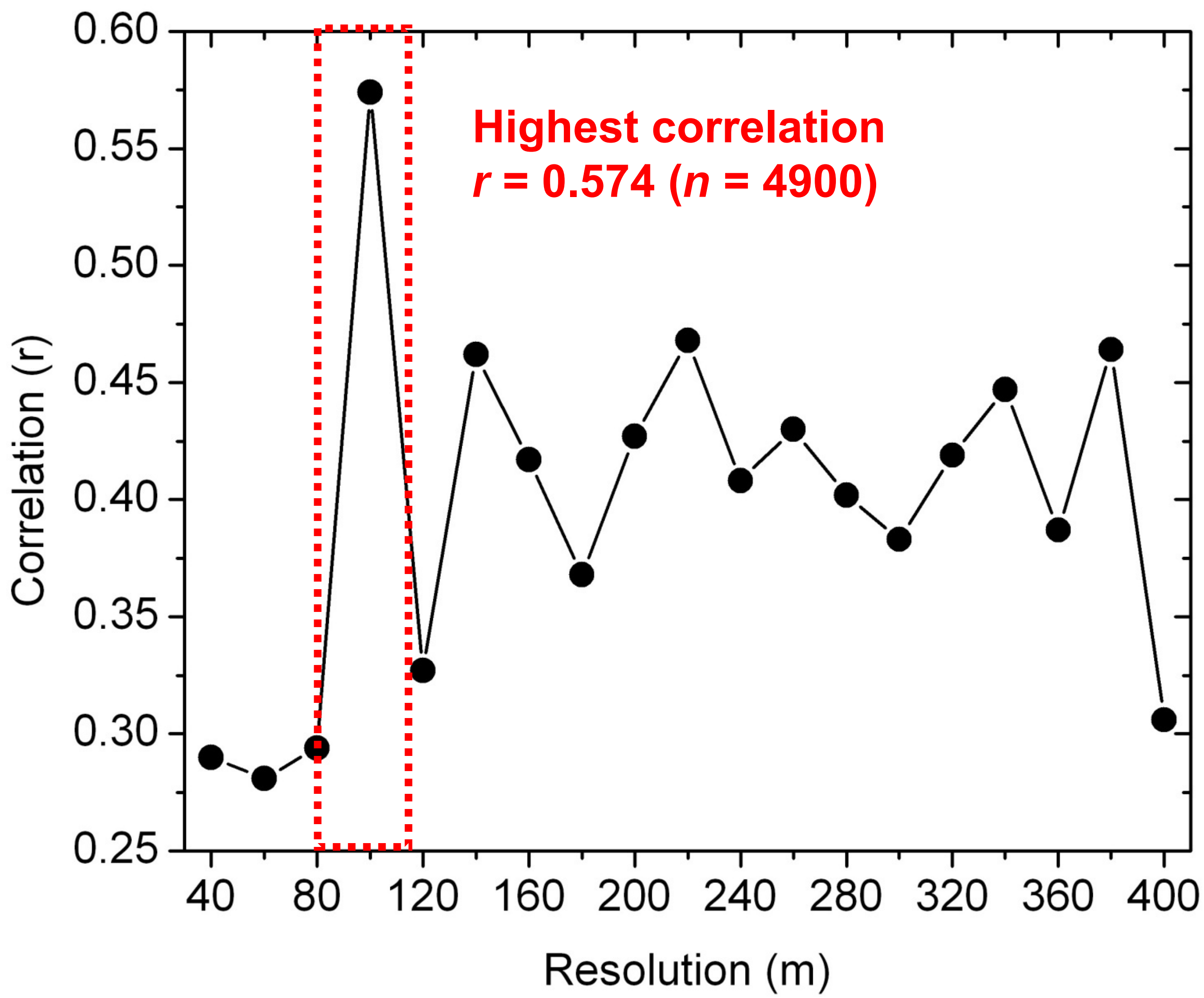
Urban Heat Island Intensity (UHII)
ASTER satellite image (winter night time)



Frontal Area Index (FAI)

Calculation of frontal area index

Grid size = 100m of plane area?



Statistical tests of the appropriate resolution

- **Mann–Kendall test**
  - to **examine whether there is a significant tendency/trend of increasing correlation** between FAI and UHII when the resolution is degraded (from 40m to 400m, with interval of 20m)

$$S=\sum_{j=1}^{n-1}\sum_{i=j+1}^{n}\operatorname{sign}(x_i-x_j)$$

$$\operatorname{sign}(x_i-x_j)=\begin{cases}1, \text{ if } (x_i-x_j)>0\\ 0, , \text{ if } (x_i-x_j)=0\\ -1, , \text{ if } (x_i-x_j)<0\end{cases}$$

$$Z=\begin{cases}\dfrac{S-1}{\sqrt{\operatorname{Var}(S)}} & \text{if } S>0\\ 0 & \text{if } S=0\\ \dfrac{S-1}{\sqrt{\operatorname{Var}(S)}} & \text{if } S<0\end{cases}$$

where *n* is the number of observations (e.g. 19 resolutions in this study), x_i and x_j are two sequential data values (i.e. when x_i = correlation at 60m, x_j = correlation at 40m, when x_i = correlation at 80m, x_j = correlation at 60m)

The ***Z* value is used to test the presence/absence of the trend**

Results of statistical tests

$Z = 0$ when no trend is observed

Significant level in hypothesis test (α)	**Mann–Kendall generated *Z* value**	**Accept/Reject**
1.645 (90%)	1.609	Reject (no significant trend)
1.960 (95%)	1.609	Reject (no significant trend)
2.576 (99%)	1.609	Reject (no significant trend)
n (number of samples)	19	

Hypothesis of having a significant tendency/trend from 40m to 400m resolution is rejected

➔ Imply that 100m resolution has the highest correlation between FAI and UHII

Applications

1. Identify and locate the ventilation paths across the Kowloon Peninsula using FAI and least cost path analysis

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A simple method for designation of urban ventilation corridors and its application to urban heat island analysis

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A B S T R A C T

This paper describes urban wind ventilation mapping, using the concept of "building frontal area index", and uses the Kowloon peninsula of Hong Kong as an example of a dense, sub-tropical urban environment where ventilation is critical for human health. The frontal area index is calculated for uniform 100 m grid cells, based on three dimensional buildings in each cell, for eight different wind directions. The frontal area index is then correlated with a land use map, and the results indicate that high density commercial and industrial areas with large building footprints had higher values than other urban land use types. Using the map of frontal area index, the main ventilation pathways across the urban area are located using least cost path analysis in a raster GIS. Field measurements of urban winds confirmed the significance and functionality of these modelled ventilation paths. Comparison of the pathways with a map of the urban heat island suggests that ventilation is a key parameter in mitigating heat island formation in the study area. Planning and environmental authorities may use the derived frontal area index and

Applications

2. Investigate the impact of "wall effect" buildings on air ventilation within densely built districts

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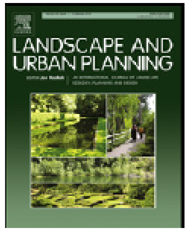

A study of the "wall effect" caused by proliferation of high-rise buildings using GIS techniques

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ABSTRACT

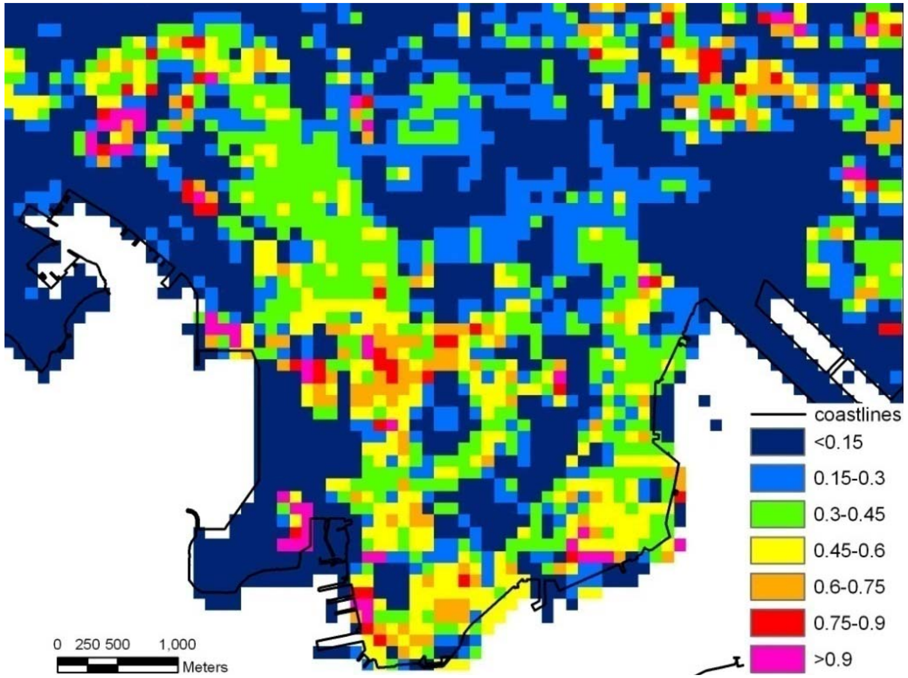
This paper describes a novel method using Geographic Information Systems (GIS) to investigate the "wall effect" caused by proliferation of high-rise buildings along the coast in Kowloon Peninsula of Hong Kong. The research utilises the concept of building frontal area index which is calculated based on three dimensional buildings in 100 m grid cells. The main ventilation pathways across the urban area are located using Least Cost Path analysis in a raster GIS and validated by field measurements. Field measurements were also taken in front of windward and leeward buildings. Results show that winds are forced by high

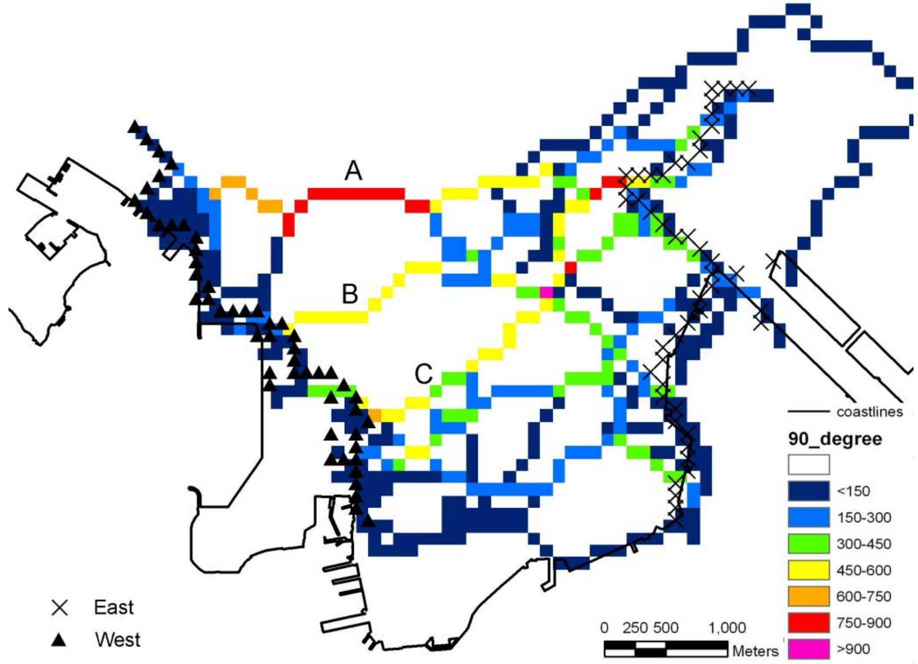
Least Cost Path Analysis

- Plots path of least resistance across a cost surface
- Grid cell value weighted by friction value according to degree of wind resistance
- 50 starting and ending points
- Many paths overlap – high occurrence frequencies indicate important ventilation corridors

Application 1: Ventilation path

East-west direction



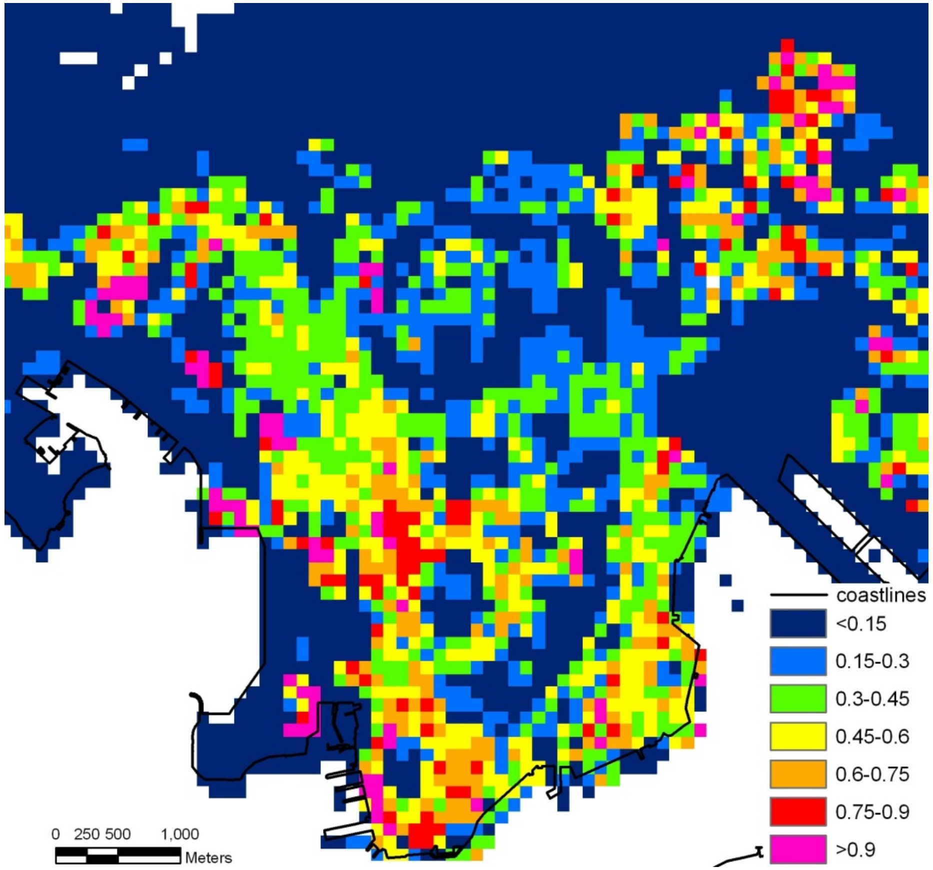


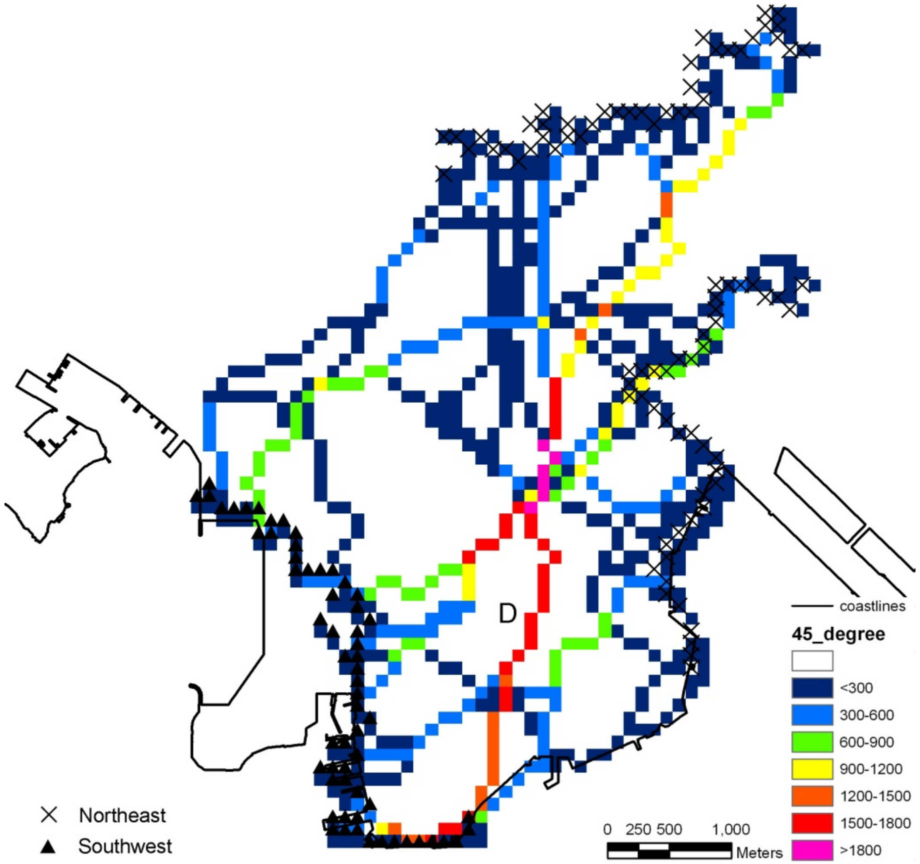
Left: Frontal area index map in east-west direction; Right: Occurrence frequency of ventilation paths in east-west direction (total number of paths is 2500)

Red and purple colour represent “high potential” contribution of wind ventilation
Orange and yellow represent “moderate potential” contribution of wind ventilation

Application 1: Ventilation path

Northeast-southwest direction



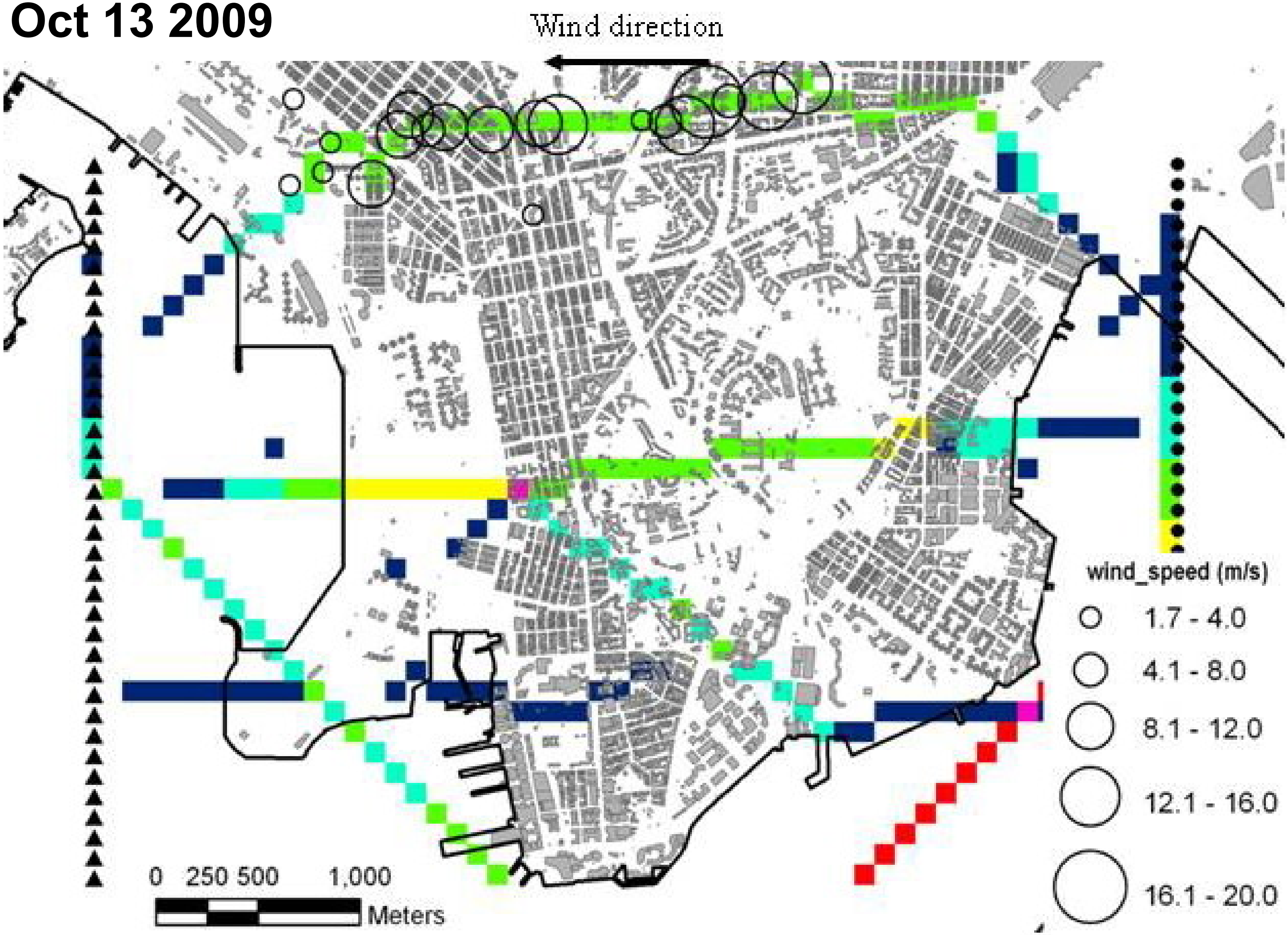


Left: Frontal area index map in northeast-southwest direction;
Right: Occurrence frequency of ventilation paths in northeast-southwest direction (total number of paths is 5186)

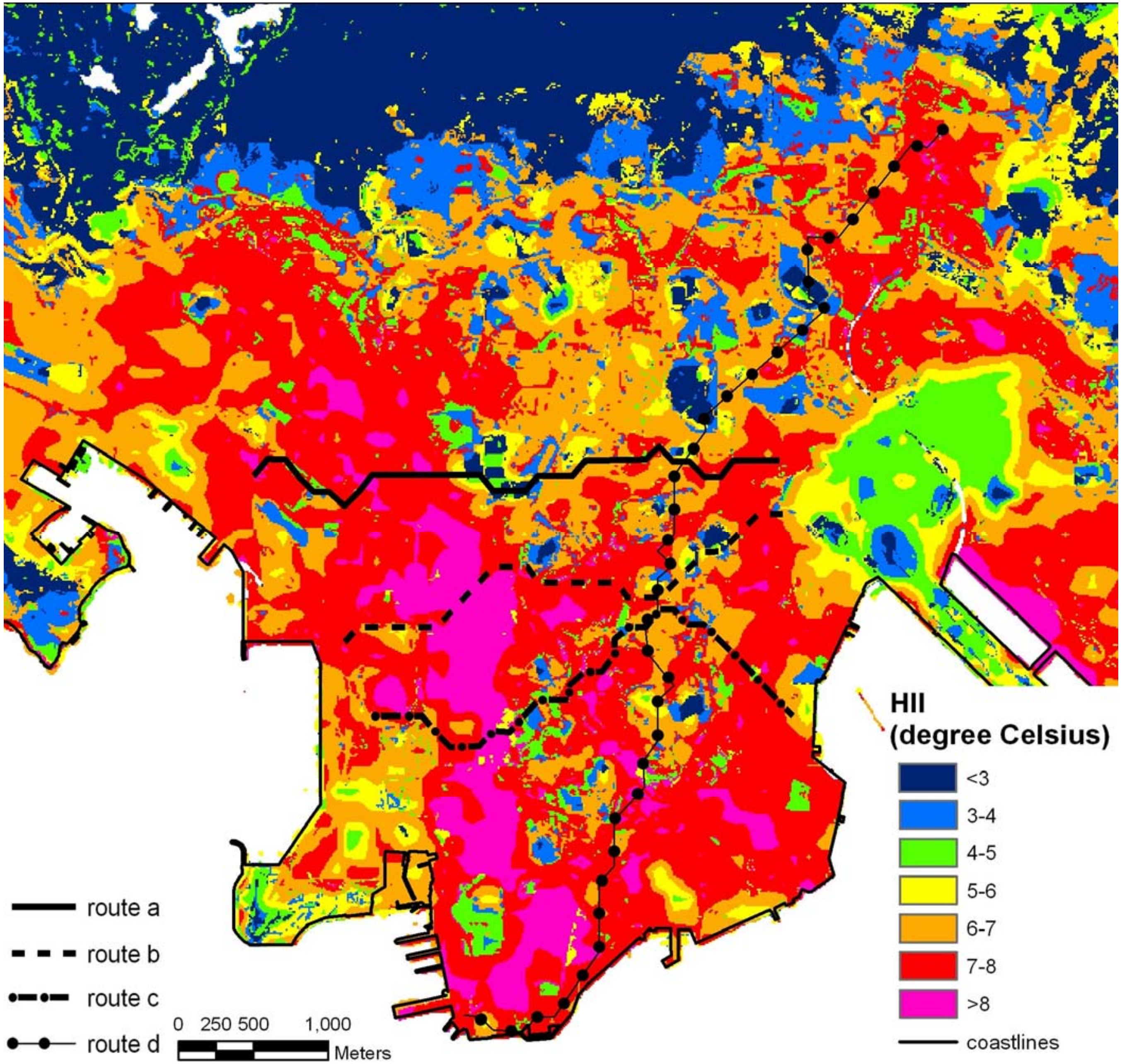
Application 1: Ventilation path

Validation strategy

Oct 13 2009



Application 1: Ventilation path



Designated ventilation paths overlaid on heat island intensity image at 10m resolution

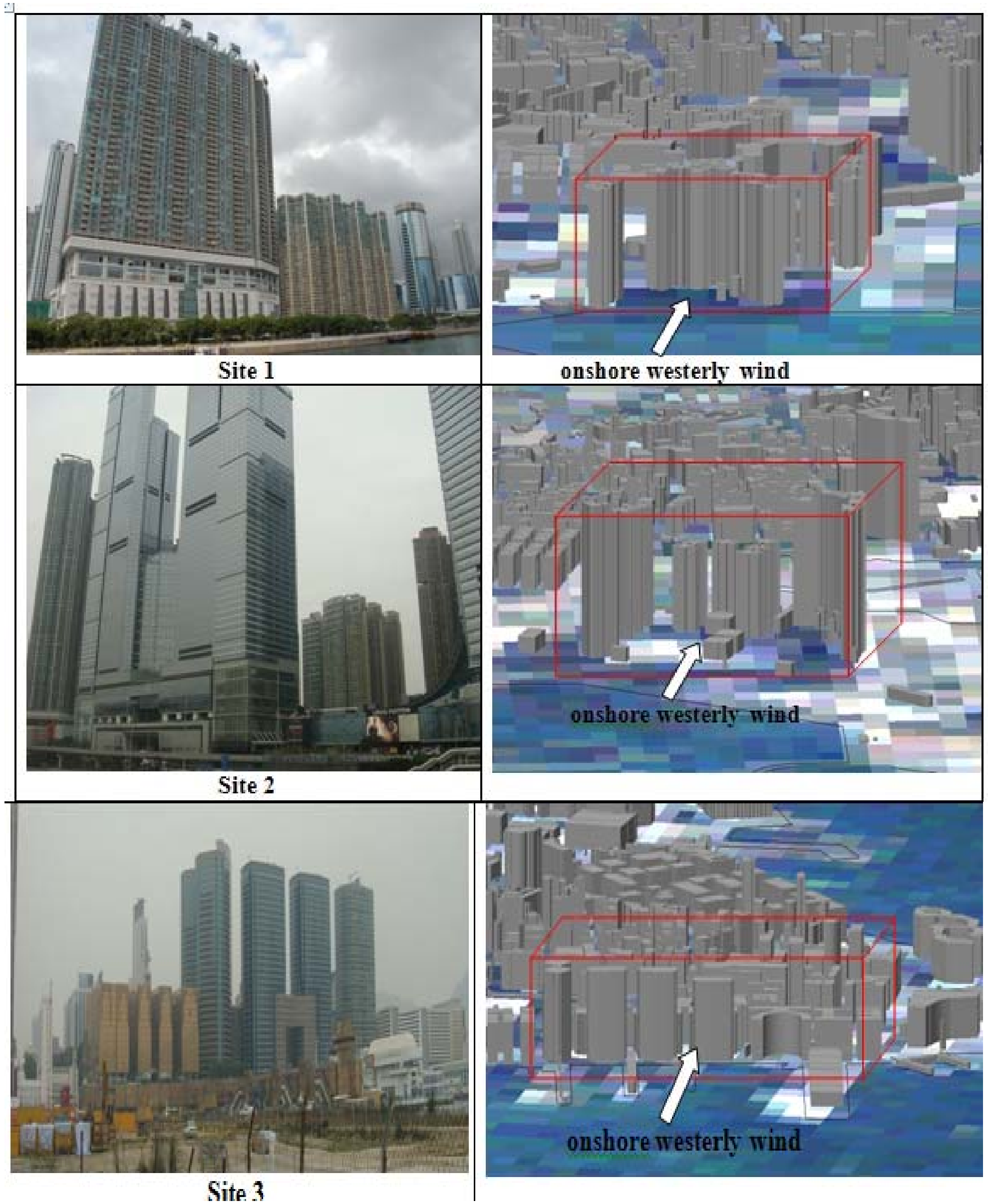
Red and purple areas indicate the core regions of the urban heat island

All four paths cross these core areas at the shortest distance

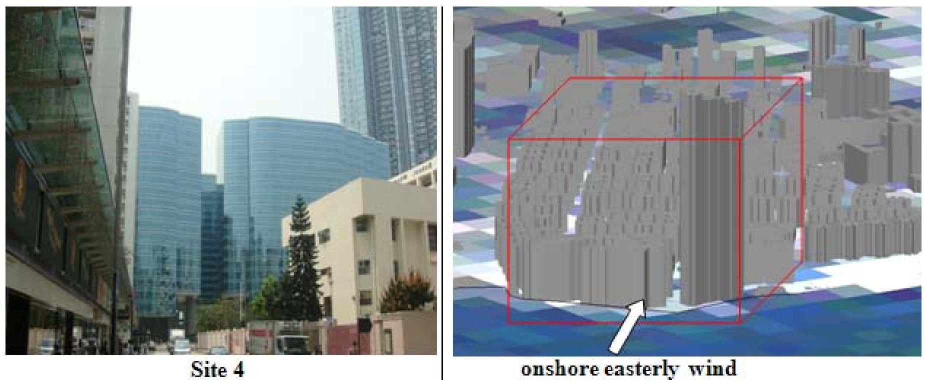
Application 2: "Wall effect" buildings

Olympic city

Union Square

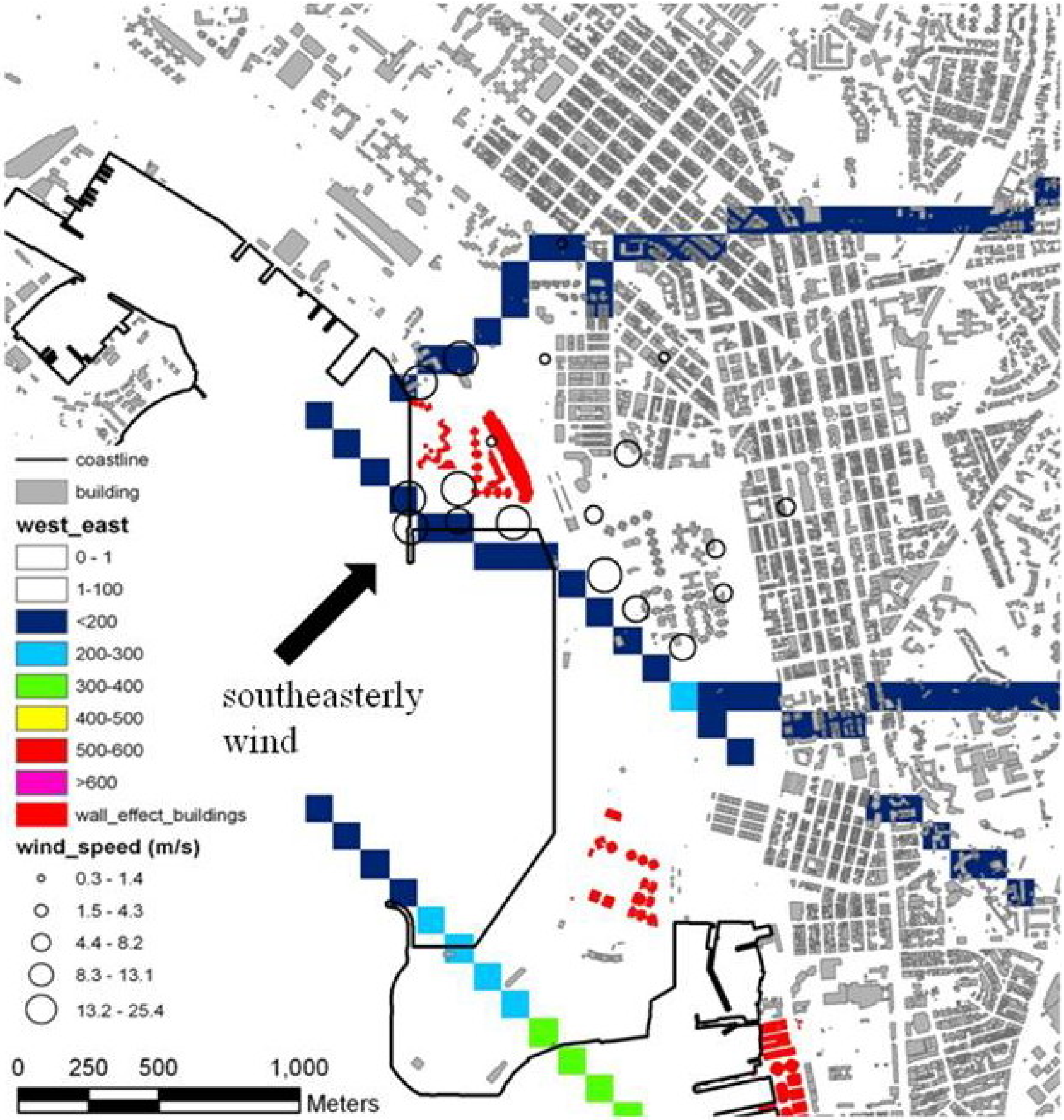


Harbor City



Harbor Plaza

Application 2: “Wall effect” buildings



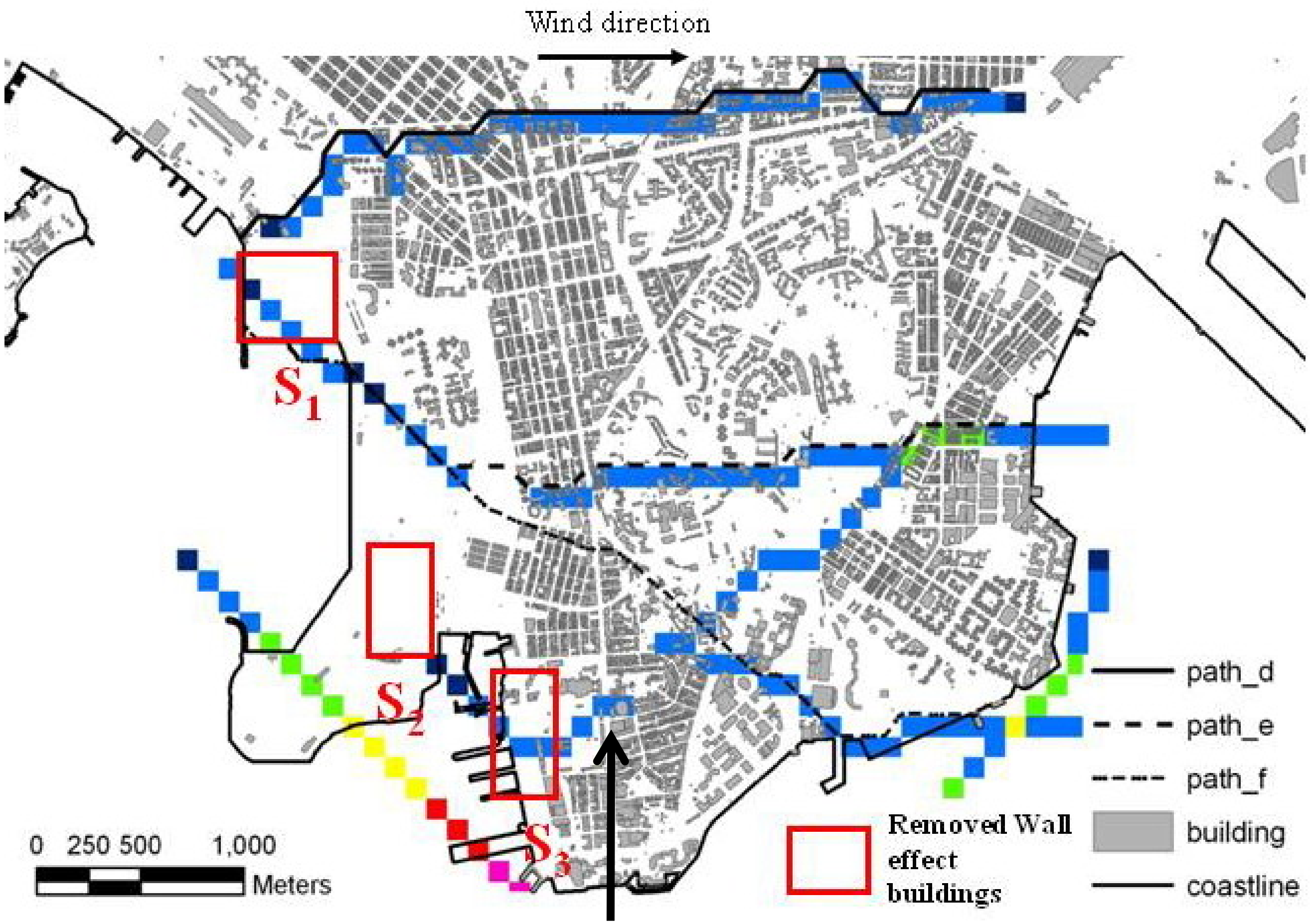
Measure wind speeds to leeward of “wall effect” buildings facing the southeasterly winds

Average and maximum wind speeds of **10.5ms^{-1} and 13.1ms^{-1}** were observed to the **windward** of the buildings

Leeward of the “wall effect” buildings and in inner areas was **four times lower (~2.5ms^{-1})**

Application 2: "Wall effect" buildings

Taken out the "wall effect" buildings (S_1, S_2, S_3, S_4), the λ_f and the LCPs were re-generated for the westerly wind direction



Removal of "wall effect" buildings has improved the ventilation in this inner district by 5%

16% → 21%

A new path provides fresh onshore air to the densely-built shopping and residential district of Tsim Sha Tsui

Conclusion

- This project studied **spatial variability** of building frontal area index and its relationship with urban heat island intensity, and it is a **first ever study using remote sensing technique with GIS modeling (frontal area index)** to (i) identify **ventilation corridor** and (ii) to investigate the impact of **"wall effect" buildings** on air ventilation within densely built districts

- The spatial resolution of **100m** is found to be statistically significant and with highest correlation (*r* = 0.574) between FAI and UHII

  – The optimal resolution 100m was able to **explain 57.4% of the variance in the heat island intensity map**

  – Building area footprints and heights, sky view factor are the causes of Urban Heat Island

  – **Remaining 42.6%** due to other factors e.g., variations in anthropogenic heat generated in the city and heat loss from different types of surface materials

- City planners and environmental authorities may use the derived models for pinpointing the key buildings which impede air flow to the urban core

Future Improvements

1. Considering the terrain elevation, since the study area is mainly flat
   – This could be allocating a DEM value weighting to the λ_f values in each cell

2. Considering different surfaces
   – Since winds traversing a vegetated surface have a greater cooling capacity than those traversing impervious surfaces

3. Considering different weightings on different elevations of facets
   – Ground level is more important than the tops of tall buildings, and a lower weight should be allocated to high level building facets

Thank you

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