Multi-scale Urban System Modelling for Thermal Comfort Liveability Planning and Design

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A Multi-agency Initiative (Urban Redevelopment Authority, National Parks Board, Housing Development Board, Building Control Authority, Singapore Land Authority, Land Transport Authority, Jurong Town Corporation, Information Development Agency and Ministry of National Development/Ministry of the Environment & Water Resources)

Singapore - City in a Garden

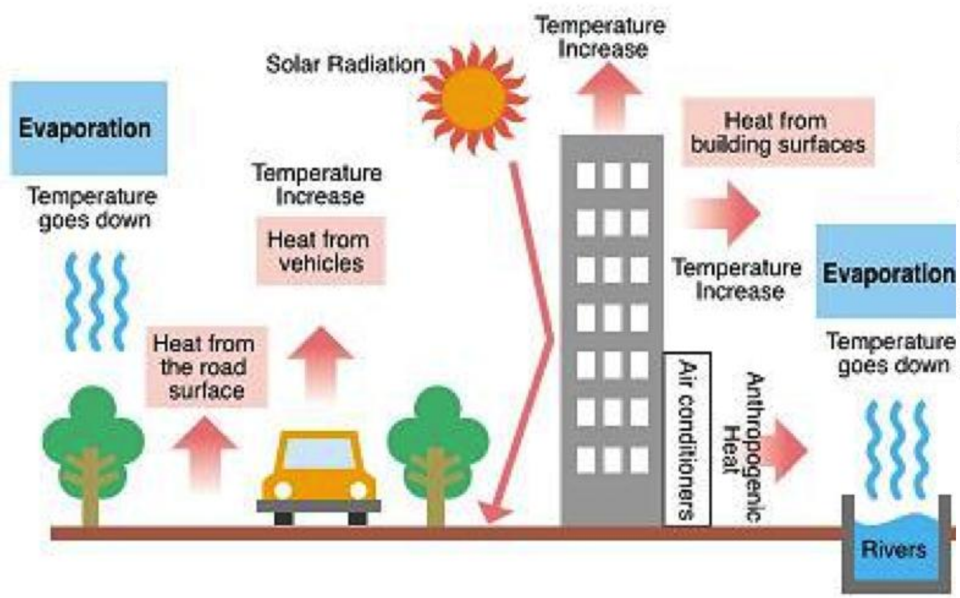
Highly urbanised city: Population: 5.2Million, Land Area: 714 sq km

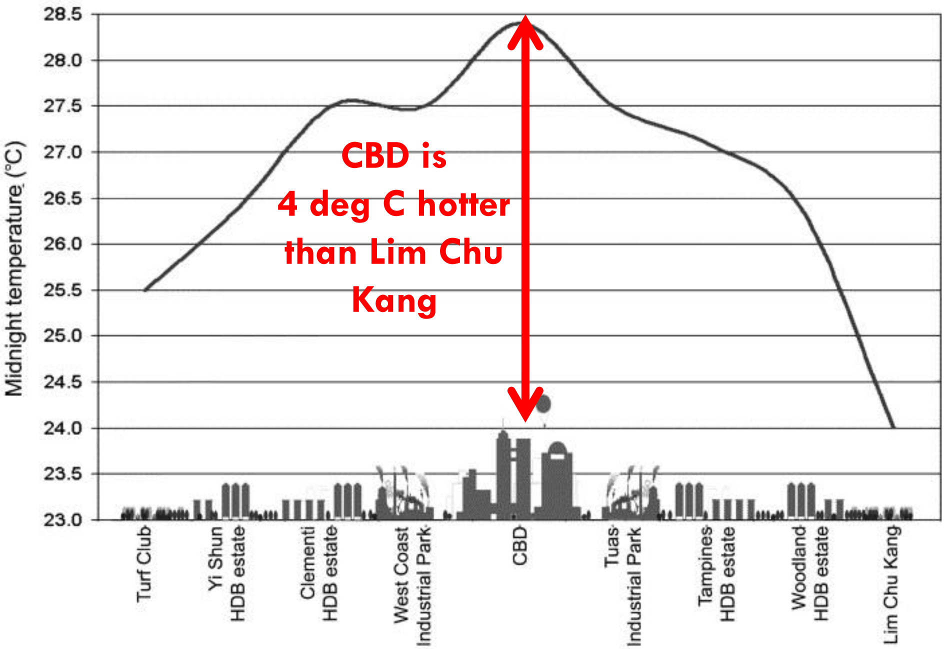
- Tropical weather, High-rise Buildings & Rich Urban Forestry

- Environmental Stresses & Climate Change Impacts, include: Global warming coupled with Urban Heat Island Effects

BACKGROUND: UHI- A CONSEQUENCE OF URBAN DEVELOPMENT

- Trapping of heat within urban canyons
- Increased heat storage from man-made materials
- Less vegetation and evapotranspiration
- Anthropogenic heat release
- Poor air movement and reduced heat transfer



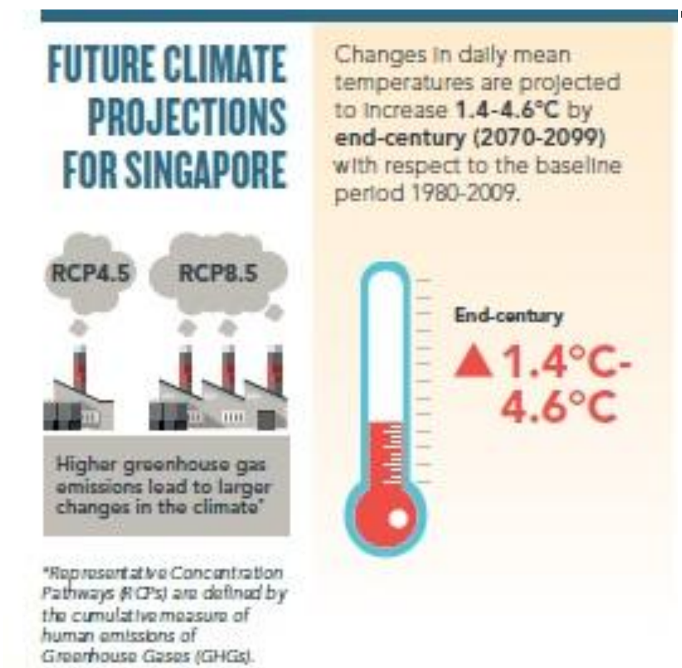


Source: Wong & Yu, 2005

BACKGROUND: UHI- A CONSEQUENCE OF URBAN DEVELOPMENT

- Due to combined effects of climate change (global warming) + further intensification of urban developments
- Negative impacts on thermal comfort, health and building energy use for cooling

Singapore's UHI could worsen in future

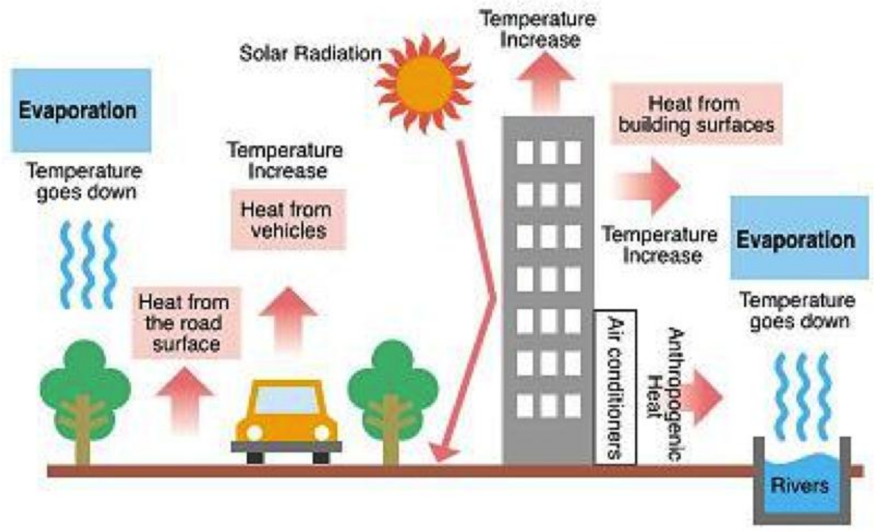


Need & Motivation

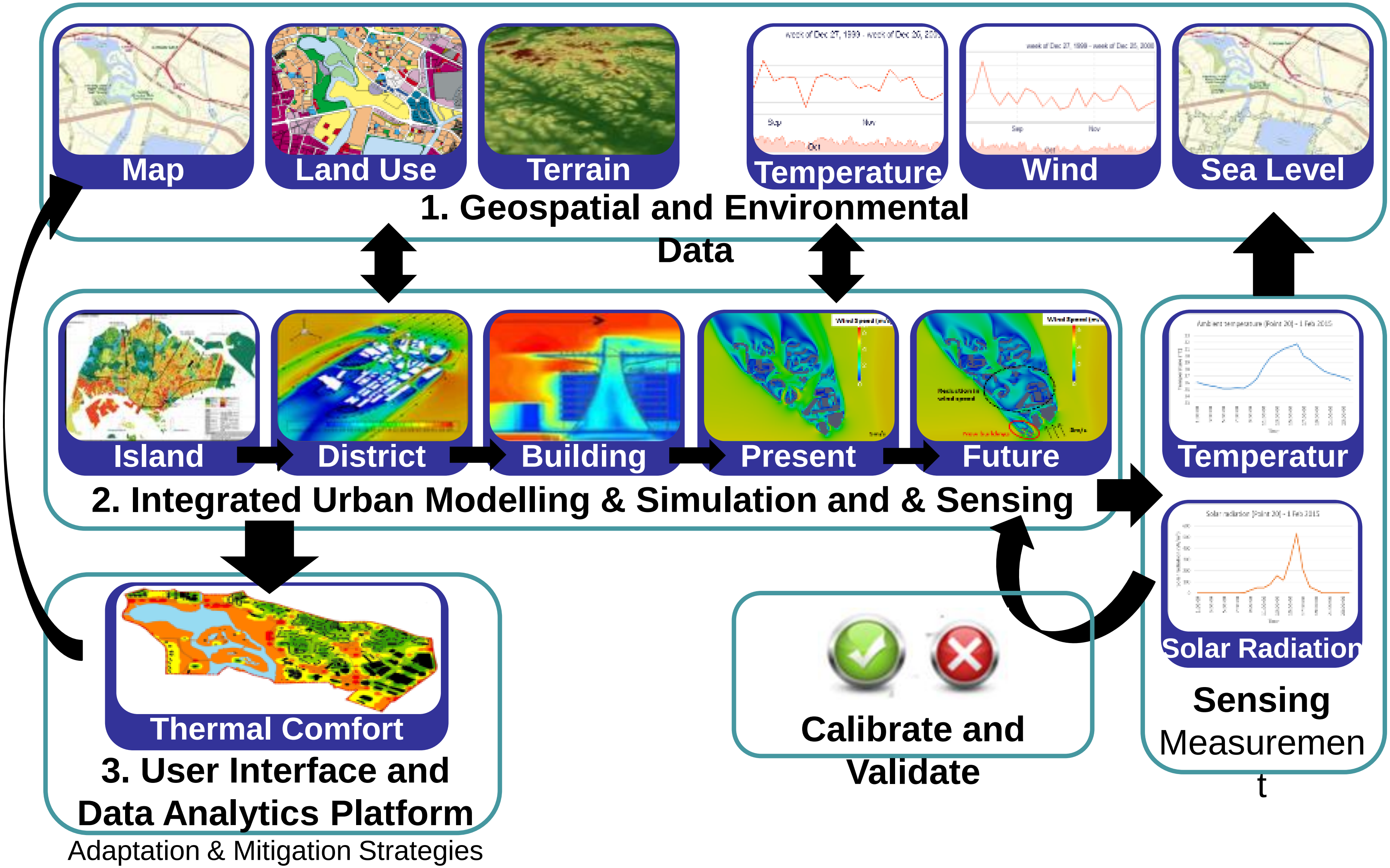
- **Singapore is susceptible to effects of climate change**
  - Rising global temperatures and sea level, with negative impacts such as affecting thermal comfort, energy use for cooling, coastal flooding & erosion, etc.. Need to develop adaptation measures and plans to tackle these impacts.

- **Need to exploit natural soft solutions and as first response to address Climate Change**
  - Using greenery (biodiversity) to mitigate heat stress and as well as natural defences such as using mangroves, etc. to mitigate the impacts of sea level rise and coastal erosion.
  - Cost effective approach: As first response to climate change, natural solutions can be altered and augmented by adding engineering solutions later.

- **Need to provide Modeling & Simulation (M&S) tools to exploit natural soft solutions**
  - To empower agencies to develop and assess the effectiveness of adaptation plans in addressing climate change impacts, in particularly global warming, exacerbated by UHI, and rising sea levels.



Integrated Adaptation Planning and Design
(Combined effects of UHI + global warming)



Thermal Comfort

The primary factors that must be addressed for thermal comfort can be categorised as:

- **Physical factors**: air temperature, solar radiation or radiant temperature, air speed, humidity;
- **Physiological, psychological, social, behavioral** such as metabolic rate, clothing insulation, acclimatization, etc.

Thermal Comfort Assessment Framework

Assessment	Factors		Approach
	Objective	Subjective	
Physical	Urban structures: Buildings, roads, etc; Microclimate: solar, temperature, wind speed, humidity.		Measurements/sensing & Modeling. (1) Integrated, coupled multi-scales urban model: Prognostic models based on the fundamental laws of fluid dynamics and thermo-dynamics to assess small-scale interactions between individual buildings, surfaces and plants.
Physiological, psychological, social, behavioral	Function of Space, Energy balance;	Past experience, preference, expectation, etc.	Measurements/sensing & Modeling, surveys, interviews. (2) Thermal comfort index (T_{min}, T_{max}, T_{avg}, Thermal Sensation Vote (TSV))

This is a **GIS-based** framework as it incorporates **location as an element for modeling & decision-making.**

Considerations for Thermal Comfort Assessment

- **Singapore-standardised thermal comfort diagrams.**

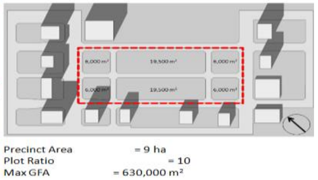
  - Multi-dimensional, to account for airflow, acclimatisation, and human activity.

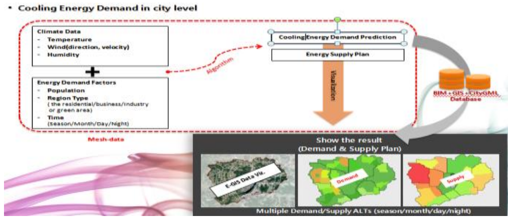
- **Thermal comfort diagrams for special populations (children; elders; professionals, etc.).**

  - In addition, there is a lack of parameterisation as a function of individual differences such as older people have entirely different physiological responses and needs – thus calling for an adjusted thermal comfort diagram.

- **Psychological aspects of human comfort.**

  - Previous research has shown that one could influence the perception of heat by employing low cost manipulations. Typical examples include the selection of colors, materials, texture and the inclusion of sound and lighting in the design.





Cooling Energy Demand

- **Social aspects of human comfort.**

  Use of social media and sensors to “nudge” people such as through real-time updates of energy costs for airconditioning or giving greater transparency to individual preferences for temperature in a workplace (diversity/choices).

Thermal Comfort Assessment Framework

(1) Integrated, Coupled Multi-scales Urban Model

Incorporates Location as an Element for Decision-making

Location-Specific Thermal Comfort Stress Assessment uses integrated, coupled multi-scales models:

(i) weather/climate & environment models (1~0.1 km resolution);

- **GSM/RSM/MSM**: Horizontal aspects 10km (regional domain) to (1~0.1 km resolution);

(ii) urban modeling (1~10 metre resolution)

Based on OpenFoam and CFD: Mass conservation and momentum equations were solved together with specific model equations, such as energy balance, turbulence such as Spalart Allmaras turbulence model, etc.

Thermal Comfort Assessment Framework

(2) Thermal comfort index

Outdoor thermal comfort prediction model

Field Survey

- Environmental Measurement & Sensing
- Questionaire

Thermal comfort modeling

- Multi-dimensional modeling such as regression analysis: T_{min}, T_{max}, T_{avg}, Thermal Sensation Vote (TSV)

Thermal Comfort Assessment Framework

(2) Thermal comfort index

Thermal comfort index map can be generated using the following formulae:

- $\mathbf{T_{min}}$ **(°C)** = F[***Ref*** $\boldsymbol{T_{min}}$ (°C), ***PAVE*** (%), ***GnPR, HBDG*** , **WALL** (m^2)]
- $\mathbf{T_{avg}}$ **(°C)** = F[***Ref*** $\boldsymbol{T_{avg}}$ (°C), ***SOLAR***$_{total}$ (W/m^2), ***PAVE*** (%), ***GnPR, HBDG, WALL*** (m^2), ***SVF***]
- $\mathbf{T_{max}}$ **(°C)** = F[***Ref*** $\boldsymbol{T_{max}}$ (°C), ***SOLAR***$_{max}$ (W/m^2), ***PAVE*** (%), ***HBDG, WALL*** (m^2), ***SVF, ALB***]
- **TSV** = F[***T, RH, V, rT***]

Ref T^{min} = daily minimum temperature at reference point
Ref T^{max} = daily maximum temperature at reference point
$SOLAR^{total}$ = average of daily solar radiation total
PAVE = % of pavement area over radius of 50m surface area
WALL = total wall surface area
SVF = Sky View Factor
T= air temperature
V = wind

Ref T^{avg} = daily average temperature at reference point
SOLAR = average of daily solar radiation
$SOLAR^{max}$ = average of solar radiation maximum of the day
HBDG = average height to building area ratio
GnPR = Green Plot Ratio
ALB = average surface albedo
RH = relative humidity
rT = radiant temperature

Urban environmental quality, human's thermal comfort at pedestrian level is assessed by means of Thermal Sensation Vote (TSV)

Field Survey

Data Sampling Distribution

Study area (Singapore)		Sample Size		
		All	Male	Female
Park	East coast Park	152	75	77
	West coast Park	96	48	48
	Chinese Garden	102	51	51
	Botanic Garden	138	69	69
	Ang Mo Kio Town Garden	119	52	67
	Yishun Park	163	77	86
	Total	770	372	398
Square	City Hall Square	255	140	115
	Vivo City Square	148	74	74
	Total	403	214	189
Street or road	Orchard Road	191	91	100
	Chinatown Food Street	82	41	41
	Total	273	132	141
University	National University of Singapore	228	113	115
	Nanyang Technological University	174	85	89
	Total	402	198	204
Others	Clark Quay	188	94	94
Total		2036	1008	1028

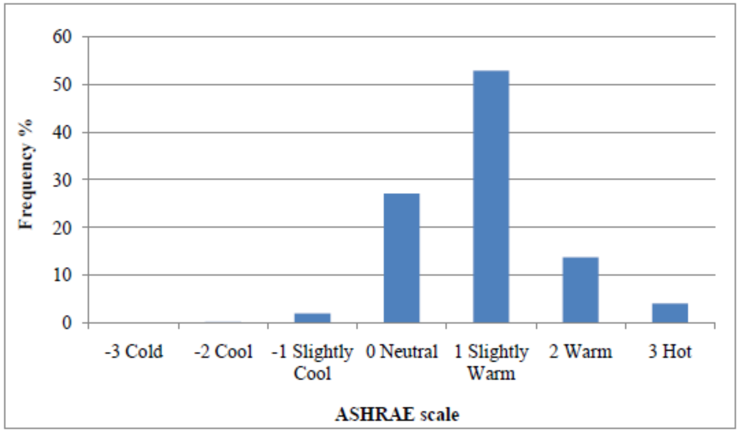
Background Characteristics of the Respondents

Sample size		2036
Gender	Male	1008
	Female	1028
Age (year)	Mean	30.1
	SD	14.9
	Minimum	10
	Maximum	72
Length of time living in Singapore (years)	Mean	7.8
	SD	14.7
	Minimum	0.5
	Maximum	46
CLO	Mean	0.30
	SD	0.06
	Minimum	0.15
	Maximum	0.56

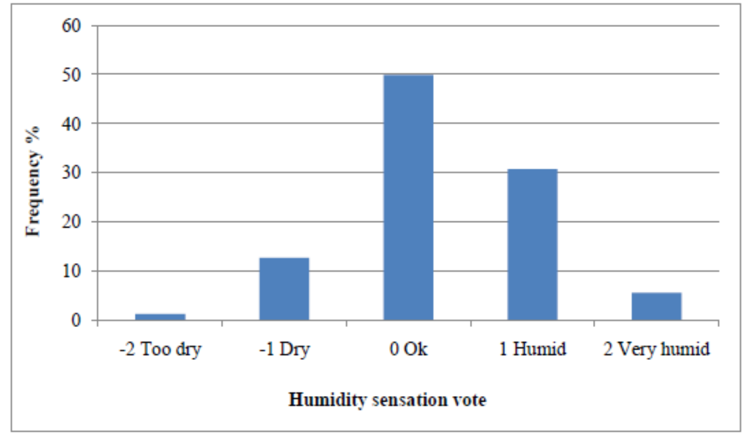
Field Survey- Information Gathered from Questionnaire

Section	Topic of investigation	Descriptions
1	Thermal comfort status	✧ Thermal perception of thermal environment, humidity, wind speed and sun (7-point scale for thermal sensation, 5-point scale for the perception of humidity, wind speed and sun) ✧ Thermal preference of thermal environment, humidity, wind speed and sun (3-point scale) ✧ Thermal acceptability of the overall thermal environment
2	Evaluation of adaptation factors and the use of urban spaces	✧ Reason to be in the place ✧ Time of exposure ✧ Previous environment ✧ Visiting frequency ✧ Adaptive behaviors
3	Demographic information	✧ Age, sex, race ✧ Activity ✧ Clothing level

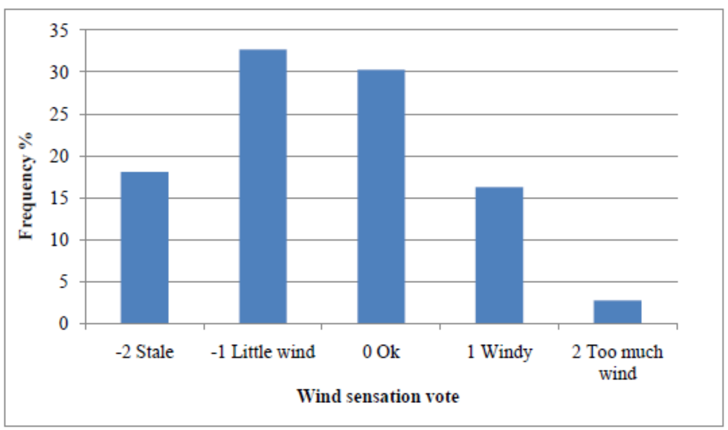
Subjective Thermal Responses



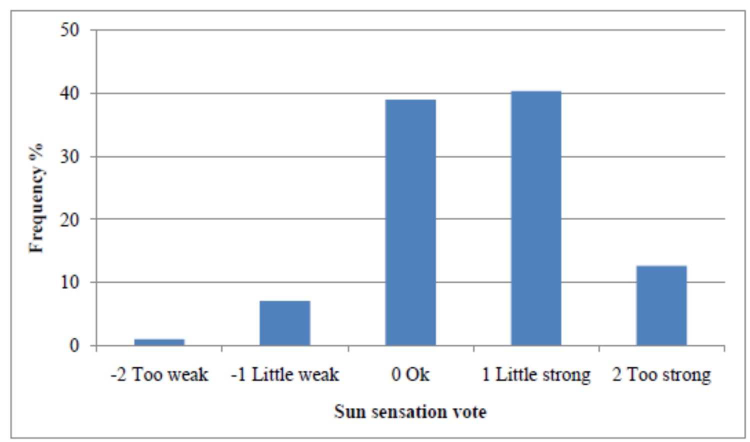
Distribution of thermal sensation votes



Distribution of humidity sensation votes

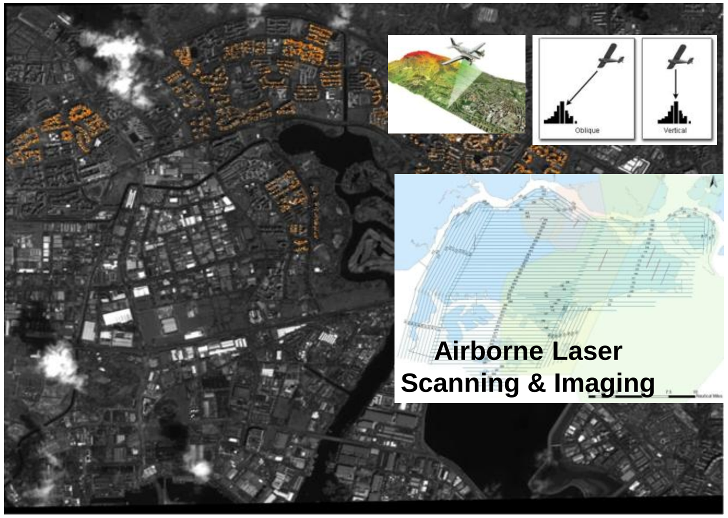


Distribution of wind speed sensation votes

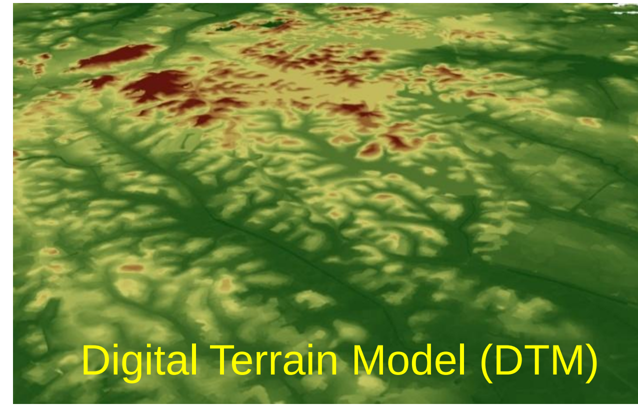


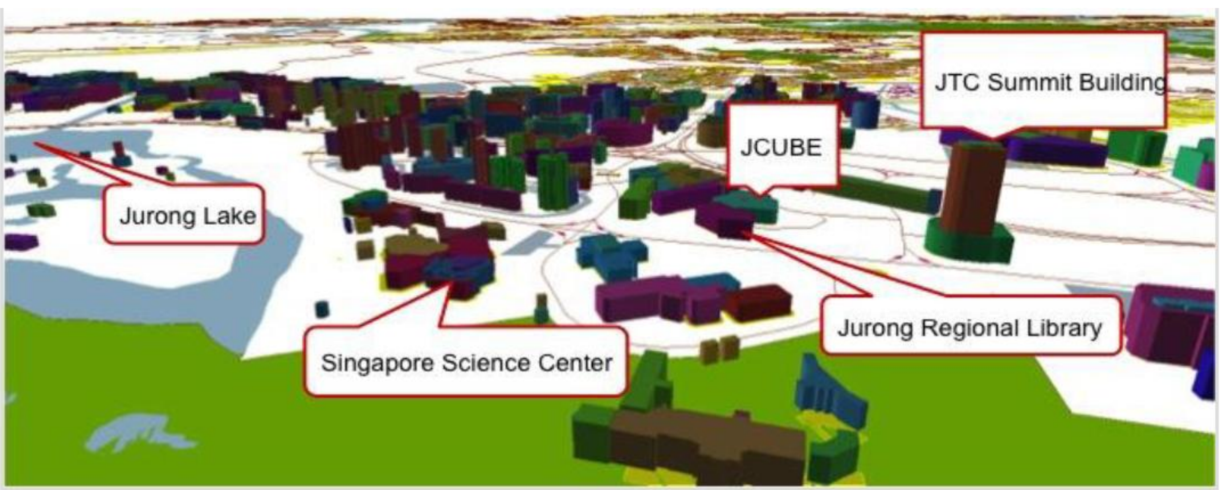
Distribution of sun sensation votes

CityGML 3D Models and Data



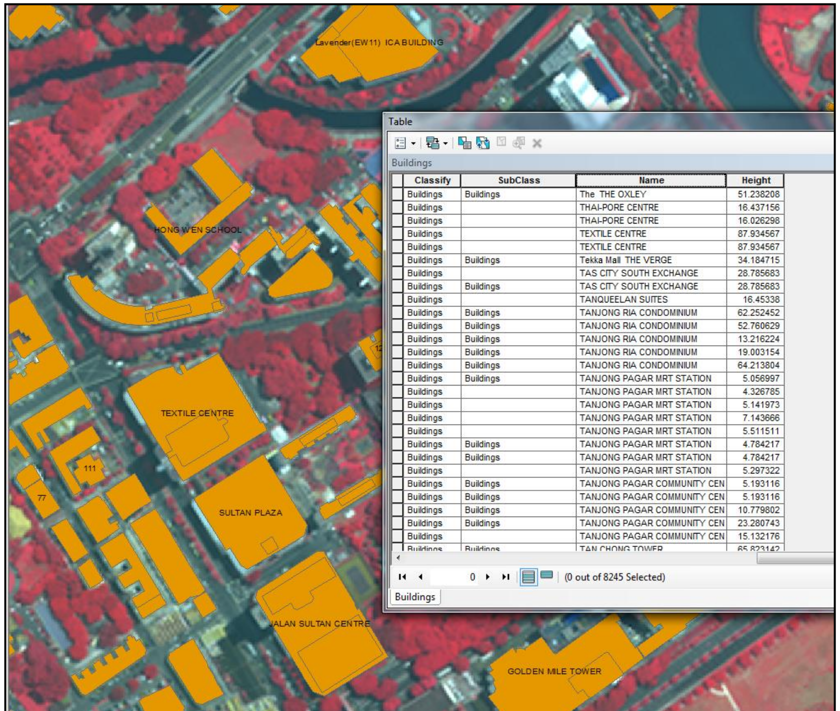
Satellite photogrammetry for 3D building



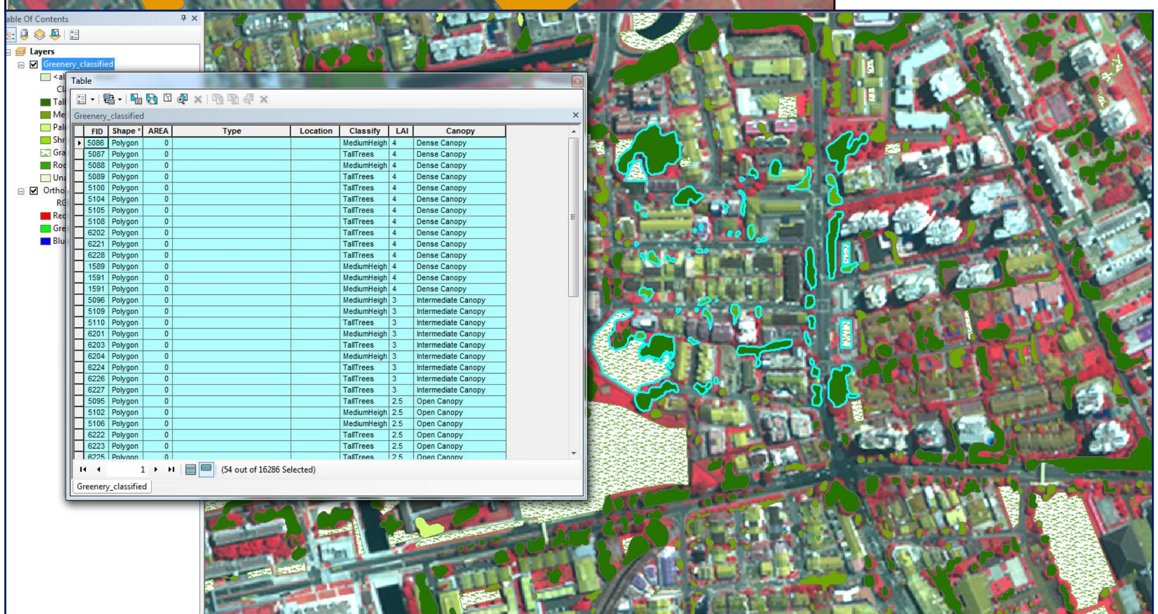


3D Buildings of Jurong Lake District, Singapore

Hard Surfaces - Buildings



- Buildings contain height information.
- Height information contains ± 1.5 meter error
- Most buildings also contain name information.

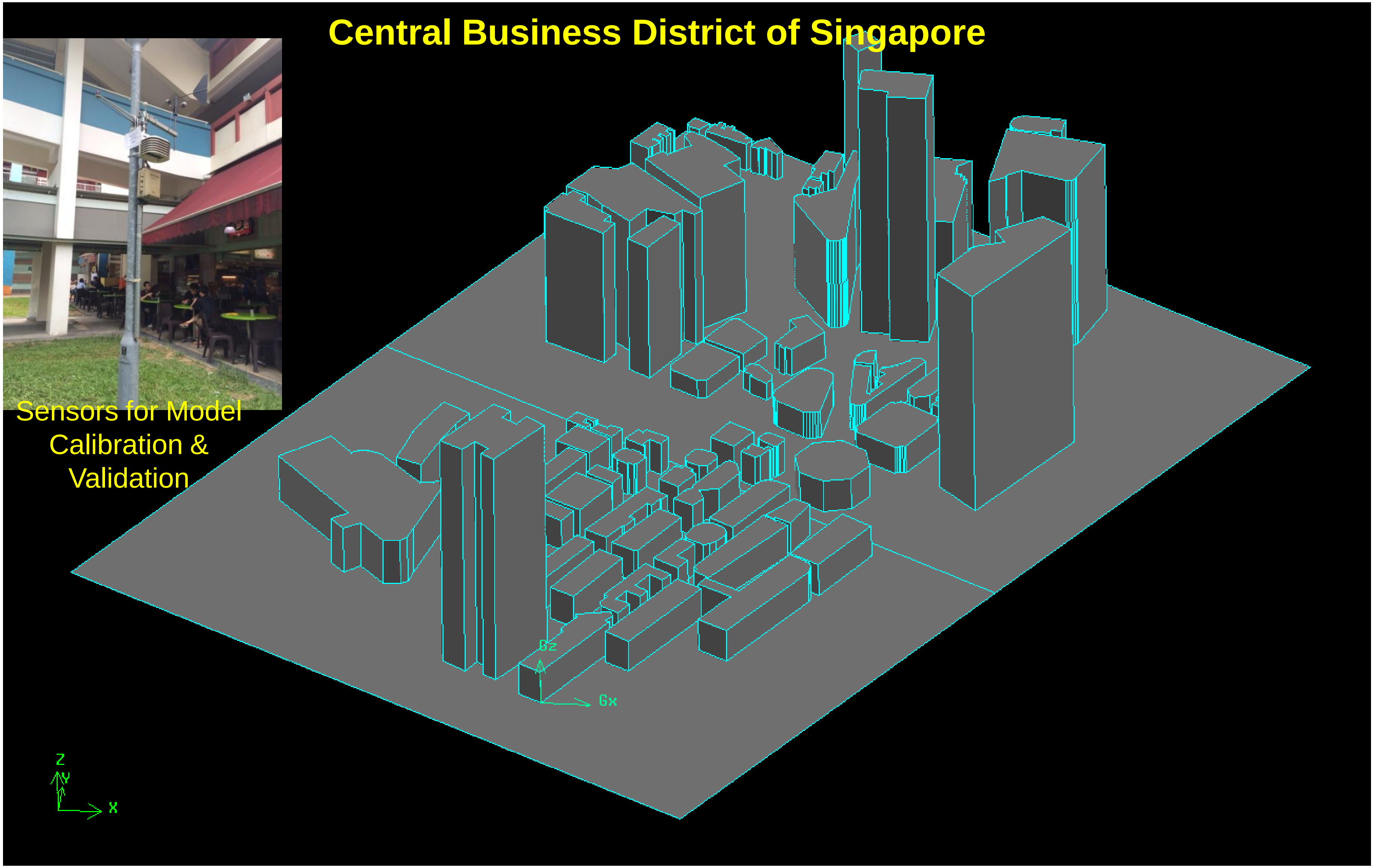


Leaf Area Index - GIS

Classification Details - Greenery

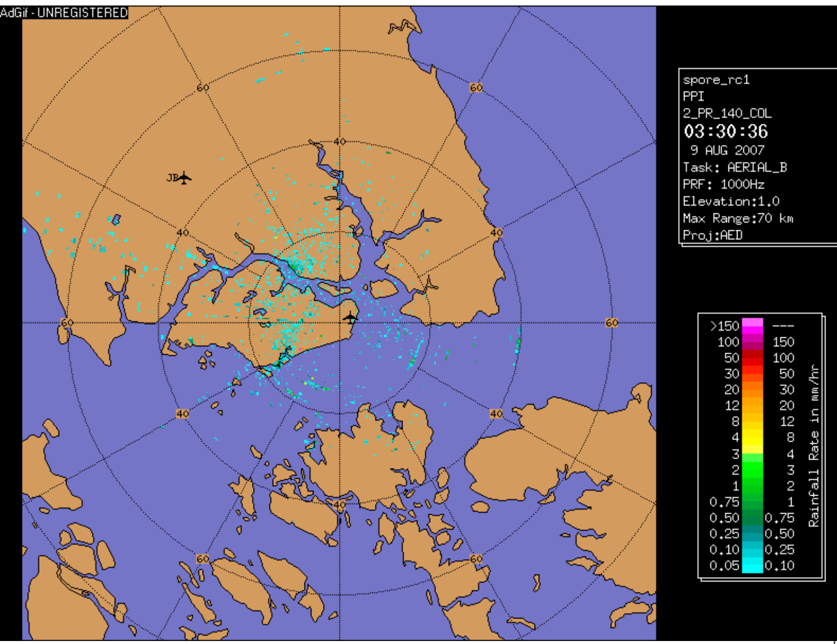
- Tall Trees (> 6-7 m)
- Medium Height Trees (< 6-7m)
- Palm Trees
- Shrubs
- Grass
- Roof Top Greenery

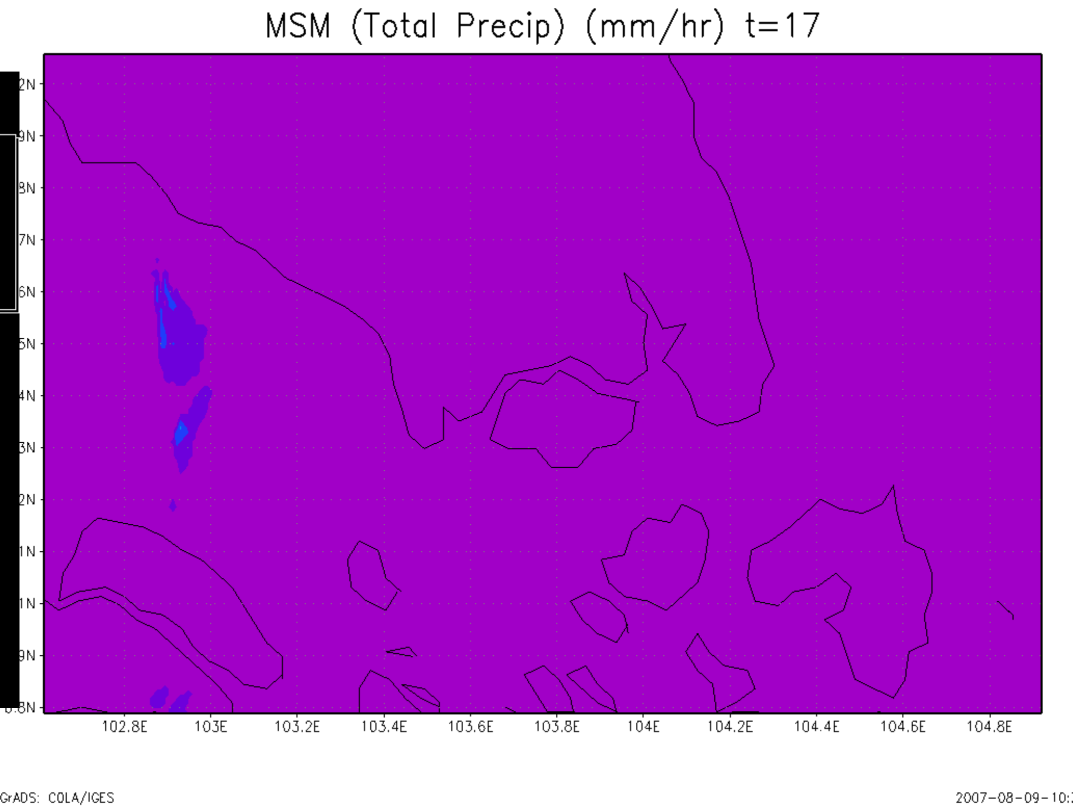
Integrated Coupled Multi-scales Urban Model



Integrated Coupled Multi-scales Urban Model

‘Sumatras’ Weather (Squalls)

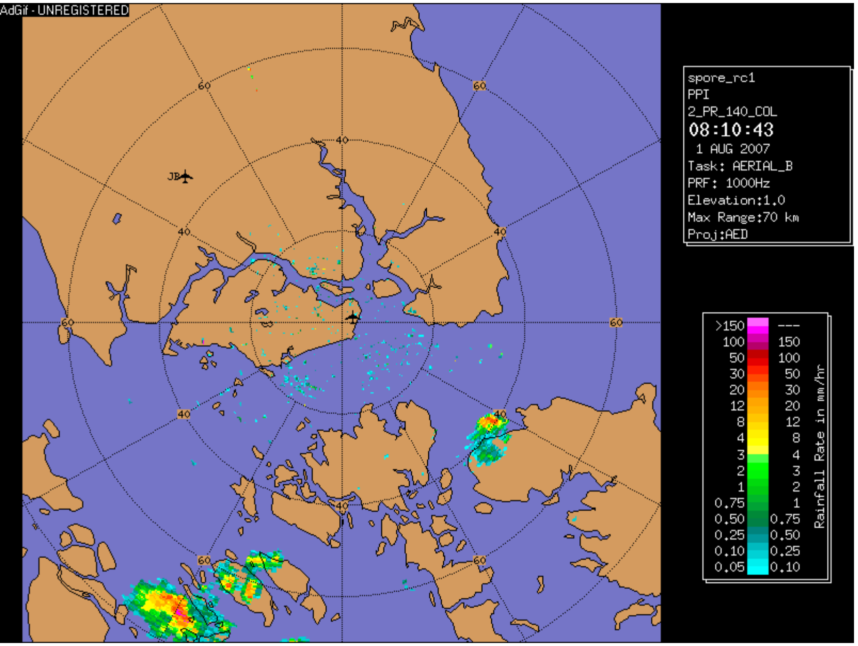


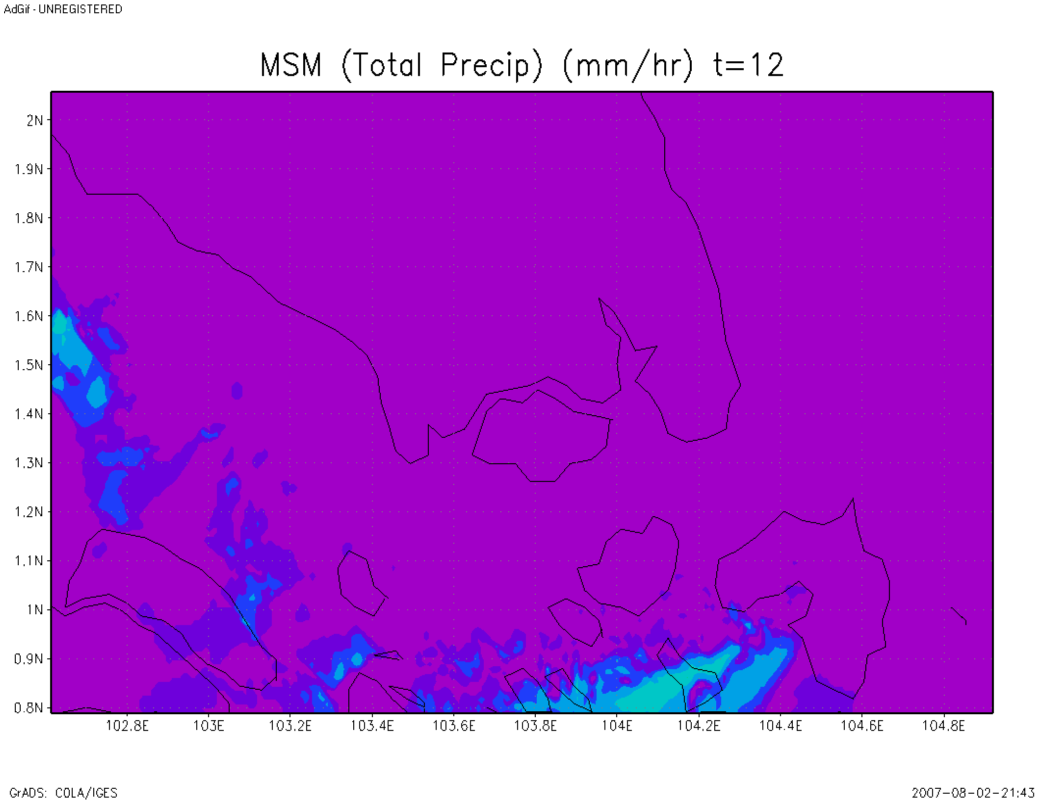


“Sumatras” Weather: 09 Aug 2007 (3am to 11am)

Integrated Coupled Multi-scales Urban Model

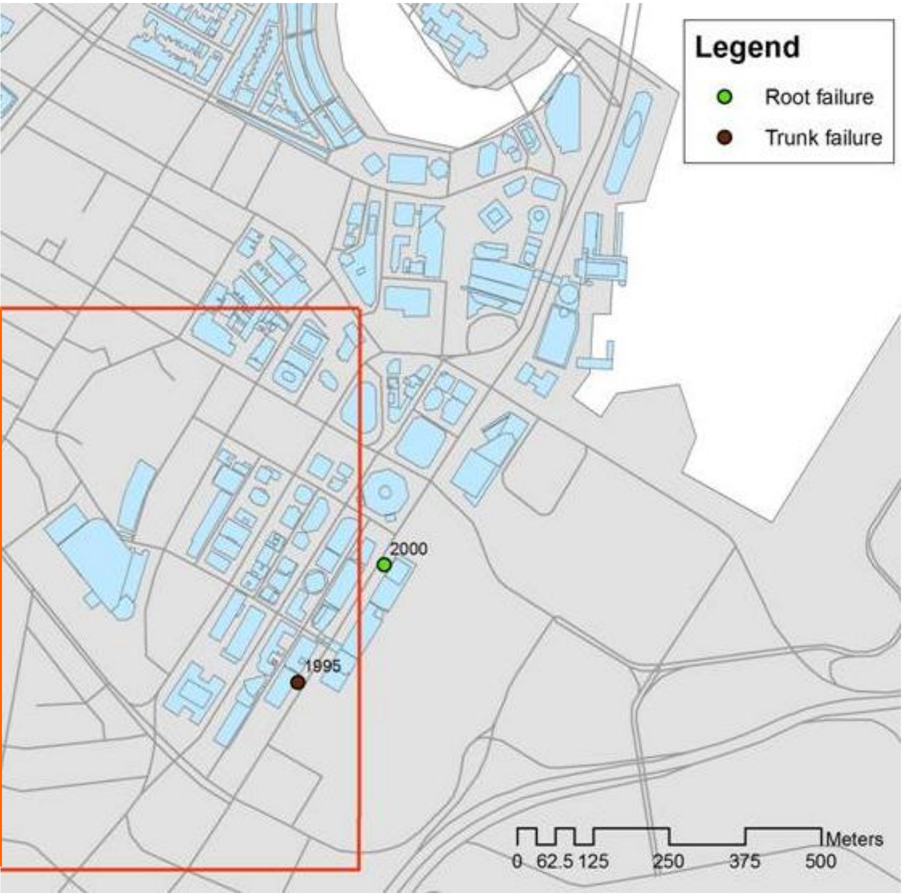
Southwest Monsoon

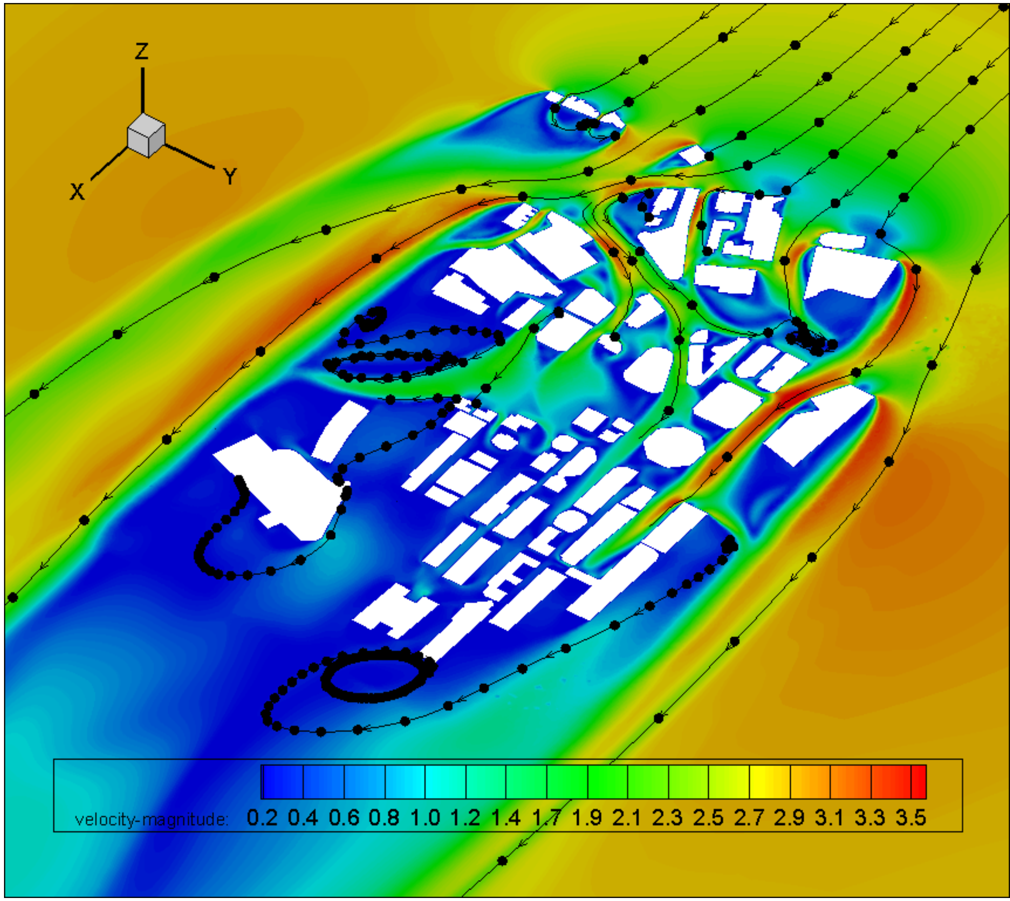




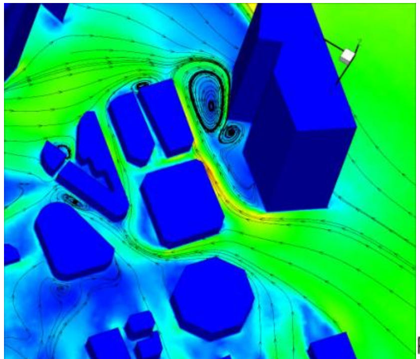
Southwest Monsoon Weather: 01 Aug 2007 (8am to 6pm)

Integrated Coupled Multi-scales Urban Model

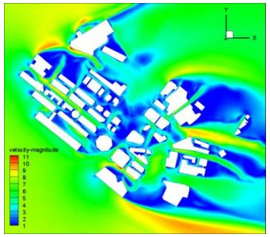




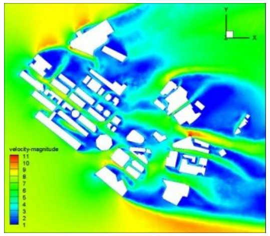
Integrated Coupled Multi-scales Urban Model



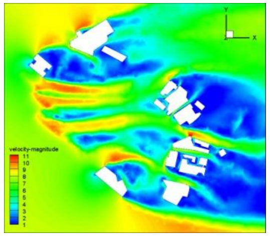
Central Business District of Singapore - *Urban Wind Risk Assessment*
(2 metre spatial resolution)



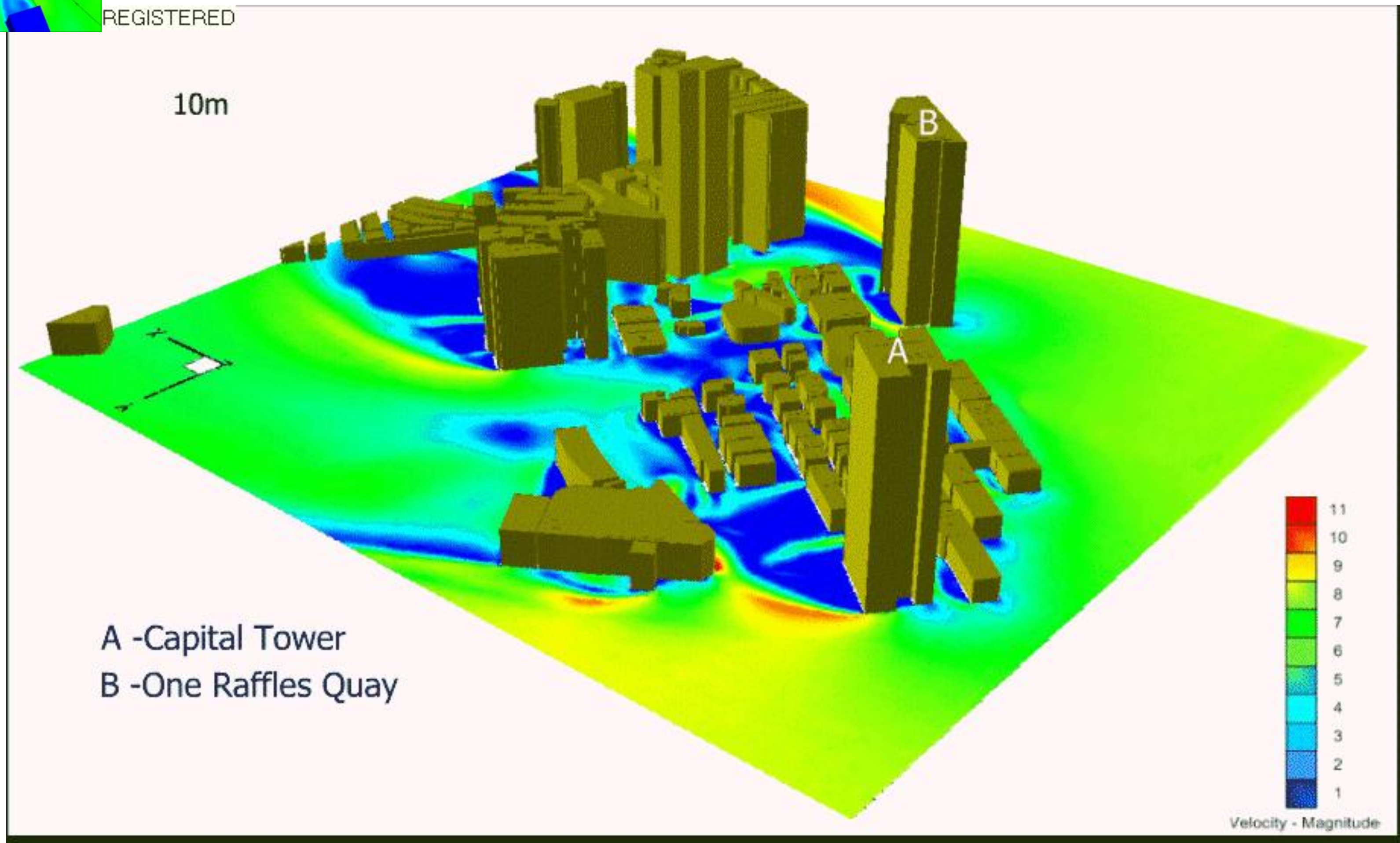
10 m



30 m



50 m



Thermal Comfort Assessment/Simulation

Temperature Map

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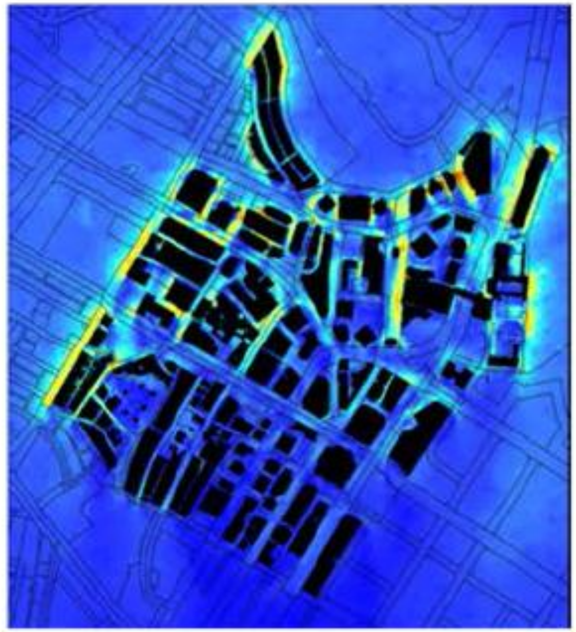

Wind Map (CFD)

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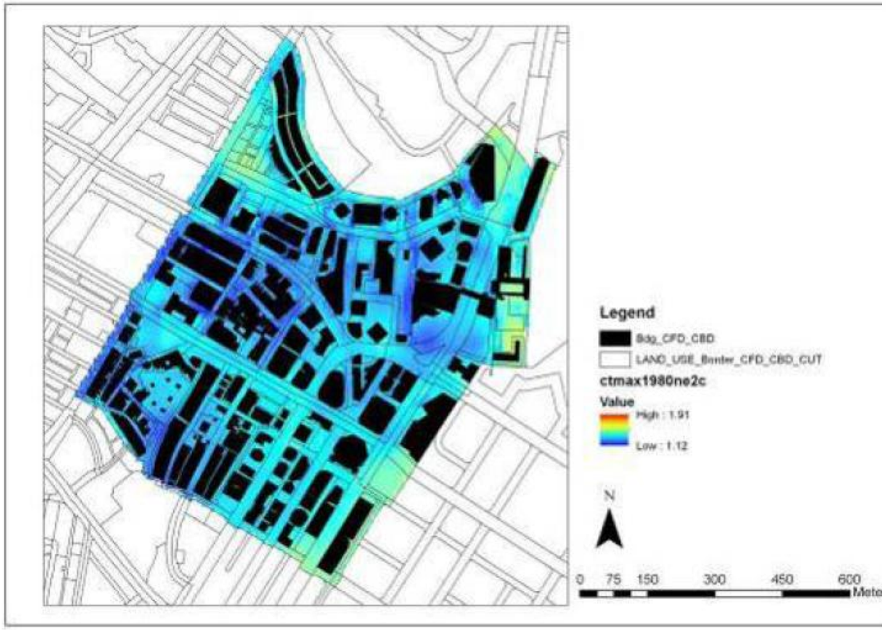
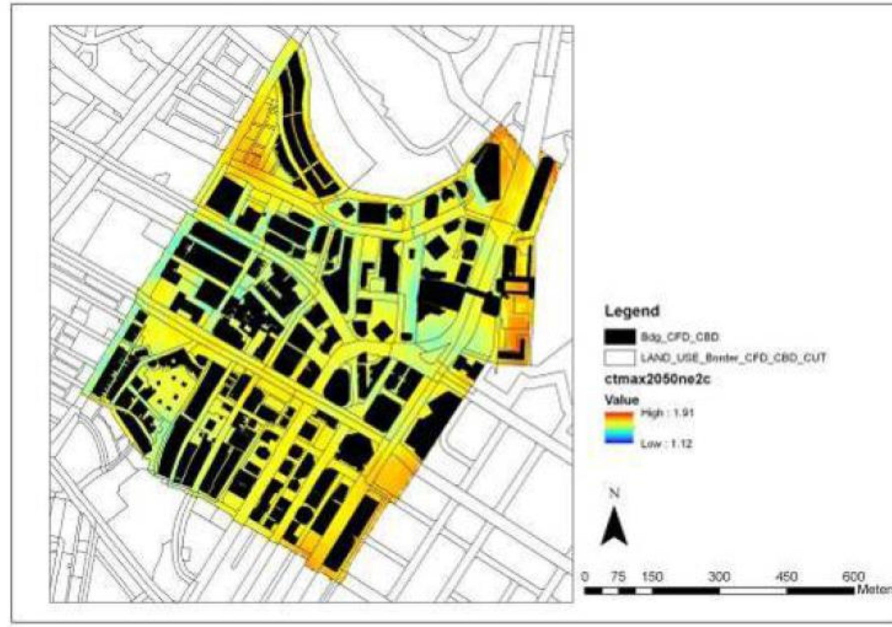
Thermal Comfort Map

TSV range	Ta range (°C)	Perception (reference to ASHRAE 7-point scale)
-3～-2	Not applicable	cold to cool
-2～-1	22.4～25.4	cool to slightly cool
-1～0	25.4～28.5	slightly cool to neutral
0～1	28.5～31.6	neutral to slightly warm
1～2	31.6～34.7	slightly warm to warm
2～3	34.7-37.7	warm to hot

Thermal Comfort Assessment/Simulation



TSV map during daytime (Tmax) (Current)



TSV map during daytime (Tmax) (2050, A2)

TSV range	Ta range (°C)	Perception (reference to ASHRAE 7-point scale)
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2～3	34.7-37.7	warm to hot

Summary

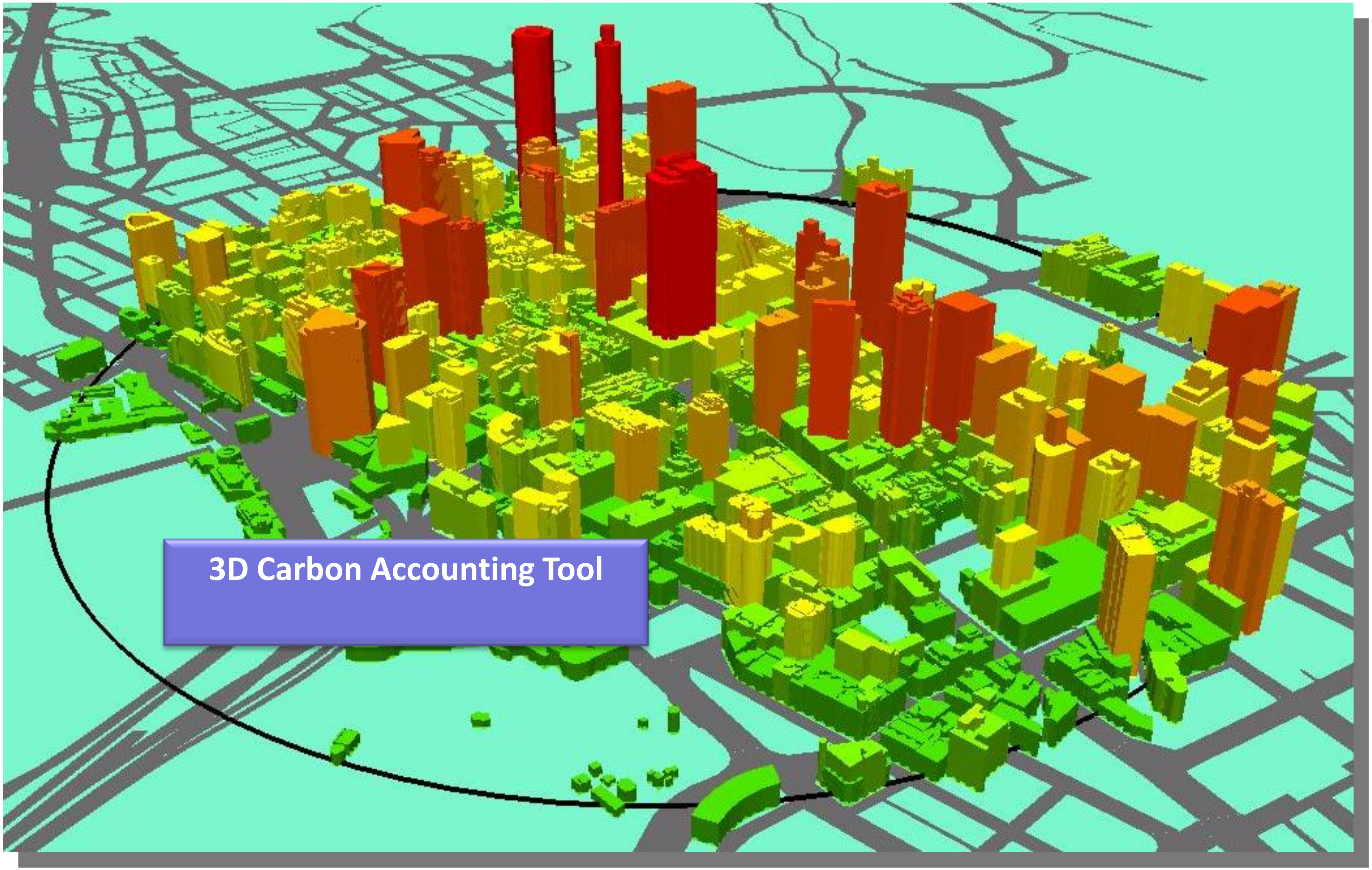
A GIS-based Thermal Comfort Assessment Framework (based on integrated coupled multi-scales atmospheric-urban-thermal comfort modelling) provides an effective platform to support climate-sensitive design and planning for Singapore

Areas for Development & Collaboration

Urban Planning

"driven by the vision of an **inclusive, highly liveable, economically vibrant and green home** for all Singaporeans"

An Assessment & Visualisation Tool



(I) Environmental Information

Study of climate change and climatic baselines on UHI/Thermal Comfort

(a) Access to oceanic, atmospheric, and geophysical data archives, which includes the a**rchive of Global Synoptic Observation Data from 1901-Present** of synoptic (hourly, 3-hourly, and 6-hourly climate data) from across the globe as well as global precipitation analyses (monthly, pentad, and daily) from surface and satellite measurements for 1979 onwards.

(NCEP/NCAR Reanalysis I: 1948-present (~200km); NCEP/DOE Reanalysis II: 1979-near present (~200km); NOAA-CIRES 20th Century Reanalysis version 2 (20CRv2): 1871-2012 (~200km); NCEP Climate Forecast System Reanalysis (CFSR) (~38km): 1979-present; Real-time NCEP Global Forecast System (GFS): 2015-present (~13km)

(b) Use of the datasets for the study of climate change and climatic baselines on UHI and thermal comfort; Sharing of research and studies on heat stress index.

(c) Customisation of the global/regional datasets and optimisation of integration of the downscaled global/regional climate data for the study of climate change and climatic baselines on UHI and thermal comfort for *ANY* typical city planning and design;

(d) Optimisation of GSM/RSM/MSM/Urban Model for urban planning and design.

(II) Modeling for Urban Environment

- NOAH (NOAH land surface model)
  - ✓ Developed in **N**CEP, **O**SU, **A**ir force, **H**ydrologic Research Lab
  - ✓ NOA1: maximum one-vegetation type considered in each cell

- Coupling of Land Surface Model to Urban Canopy Model – NCEP RSM/MSM

  The effects of land use type and anthropogenic heat (AH) and its diurnal variation on the thermal and wind environment such as coupling the Noah Land Surface Model (*Chen and Dudhia, 2001) to the Single-Layer Urban* Canopy Model (*Kusaka et al., 2001; Kusaka and Kimura, 2004) using a tile-approach (Tewari et al., 2006).*

(III) Use of Environmental Information for I*ntegrated* Planning & Design of Sustainable Cities

(a) Integration of Built and Natural Environment Datasets, incorporating environmental datasets, sensing and simulation such as urban materials; greenery types; scenario modelling (environment and climate) at various scales (island, precinct and building scales); 3D wind, temperature, thermal comfort;

(b) Analytical and 3D visualisation tools and services to support planners and managers in understanding the complex nature of urban development;

(c) Intelligent Disaster Decision Support System (IDDSS) for urban planning, integrating a smart geospatial information platform with an advanced optimisation and simulation engine to facilitate discovery and then integrate and analyse the data to develop simulation and optimisation models;

THANKS