TITLE: APPLICATION OF CFD IN ARCHITECTURE, URBAN PLANNING AND GREEN BUILDING DESIGN IN SINGAPORE

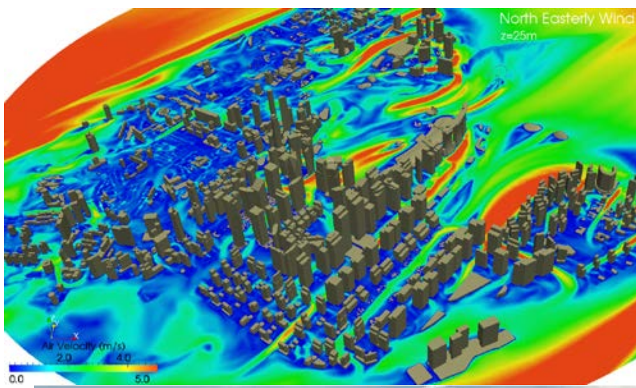
INVITED SPEAKER: DR. HEE JOO POH, SCIENTIST & MANAGER, IHPC, A-STAR, SINGAPORE

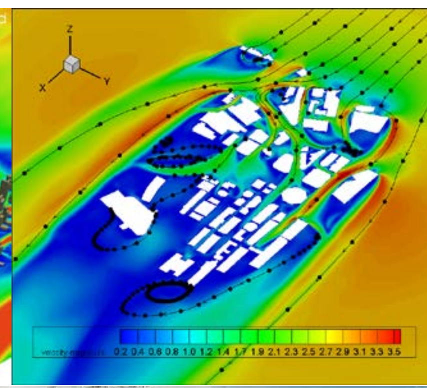
DATE & TIME: 19:00PM-20:00PM, 21 JAN 2015 (WED)

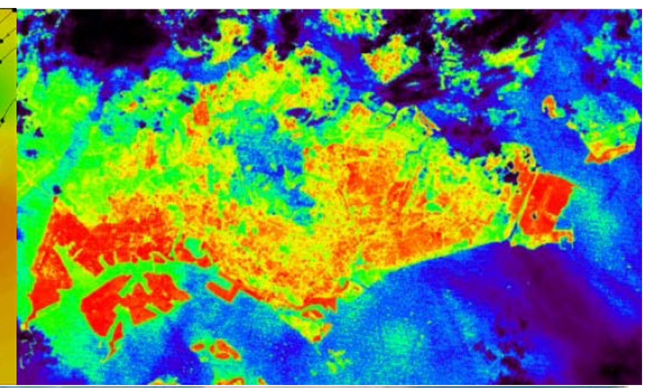
VENUE: DTLAB, 5/F, SCHOOL OF ARCHITECTURE, AITB, CUHK

Dr POH Hee Joo holds the position of Research Scientist and Manager (Environmental Flow) in Institute of High Performance Computing (IHPC), A-STAR. He is also an Adjunct Assistant Professor to both Mechanical Engineering Department and Building Department of National University of Singapore (NUS). He is the pioneer Adjunct lecturer for BCA Green Mark Professional course module for Computational Fluid Dynamics (CFD) Airflow Modelling for Green Buildings. He has over 15 years work experience in CFD research and consultancy jobs mainly focusing on system design and building ventilation simulation works. Since 2010, he has been appointed as external assessor for the BCA Green Mark CFD Natural Ventilation projects. In 2013, he was appointed by BCA Green Mark as member of the specialist committee for assisting BCA to chart the CFD criteria for Non-Residential Buildings. In recent May 2014, he had been nominated by Ministry of National Development (MND) Singapore to be honoured as a World Cities Summit Young Leader in recognition of his contribution to the field of urban liveability and sustainability in Singapore.

Abstract: In this lecture, he will first talk about the recent Singapore Green Building Master Plan to bring sustainable architecture design concepts and elements to the forefront of urban planning and green building, in particular for the application of CFD tools in passive building natural ventilation design as well as the development of the integrated urban microclimatic modelling work in common digital platform for master planning and environmental modelling. He will share IHPC research work in the development of CFD methodology Evaluation Parameters for Thermal Comfort, Indoor Air Quality (IAQ) and Wind Driven Rain (WDR) Modelling for Naturally Ventilated Spaces in Non-Residential Buildings (NRB) Under the Green Mark Criteria and Integrated Multi-physics Urban Microclimatic Modelling Tool. The research focus also includes using the meso-scale global climate model with micro-scale CFD to evaluate details of the urban climate environment, in particular the wind channel effect which results in tree failure. The lecture will be concluded with selective case studies of Singapore Green mark Platinum Buildings for Natural Ventilation Design with CFD assessment work.







Application Of CFD In Architecture, Urban Planning and Green Building Design In Singapore

Dr. POH Hee Joo
Scientist & Manager
Institute of High Performance Computing,
A-STAR

21 Jan 2014

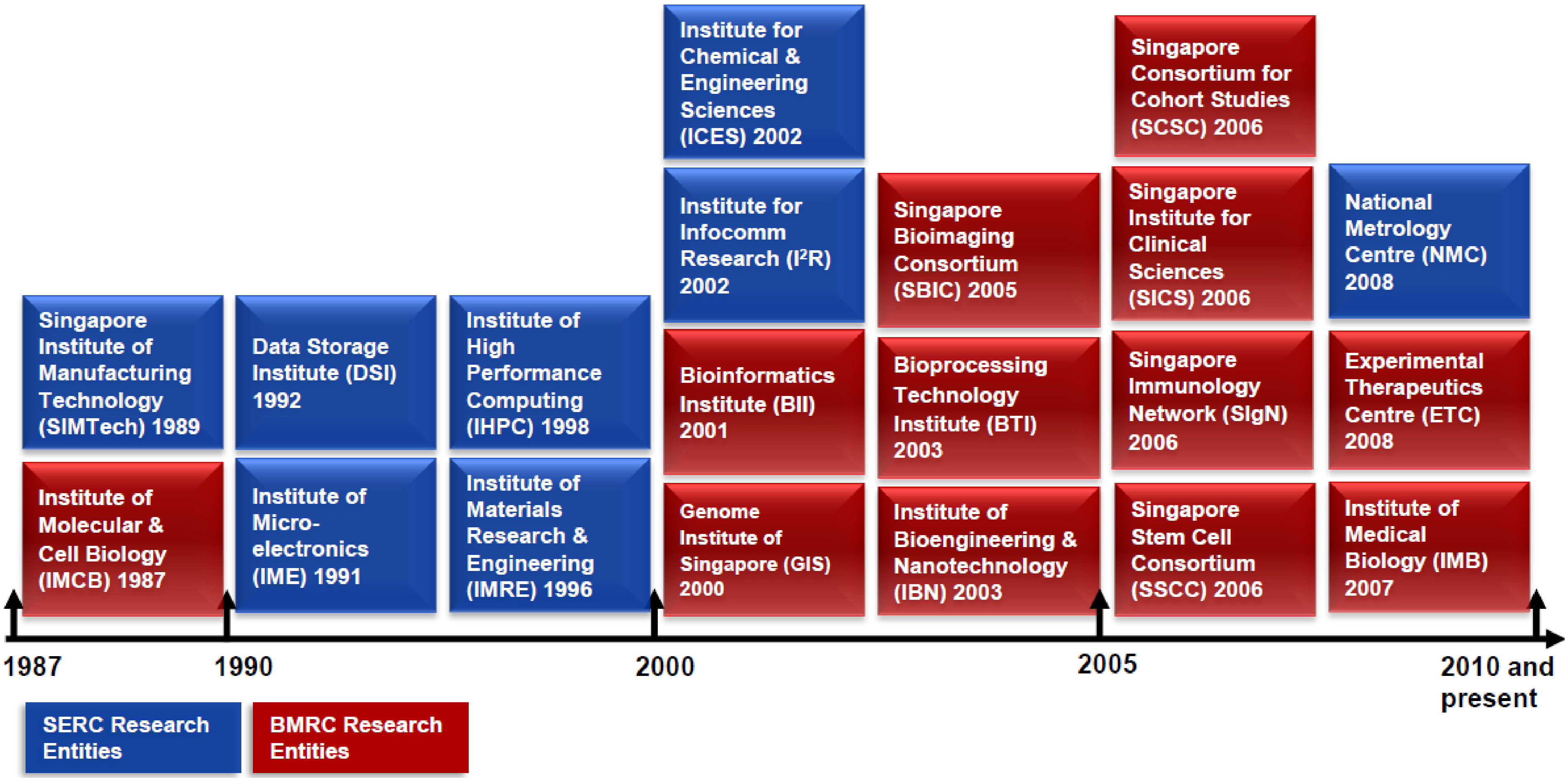
Outlines

- Introduction – Singapore Green Building Master Plan
- CFD & Urban Canopy Flow
- Case Studies
- Concluding Remarks

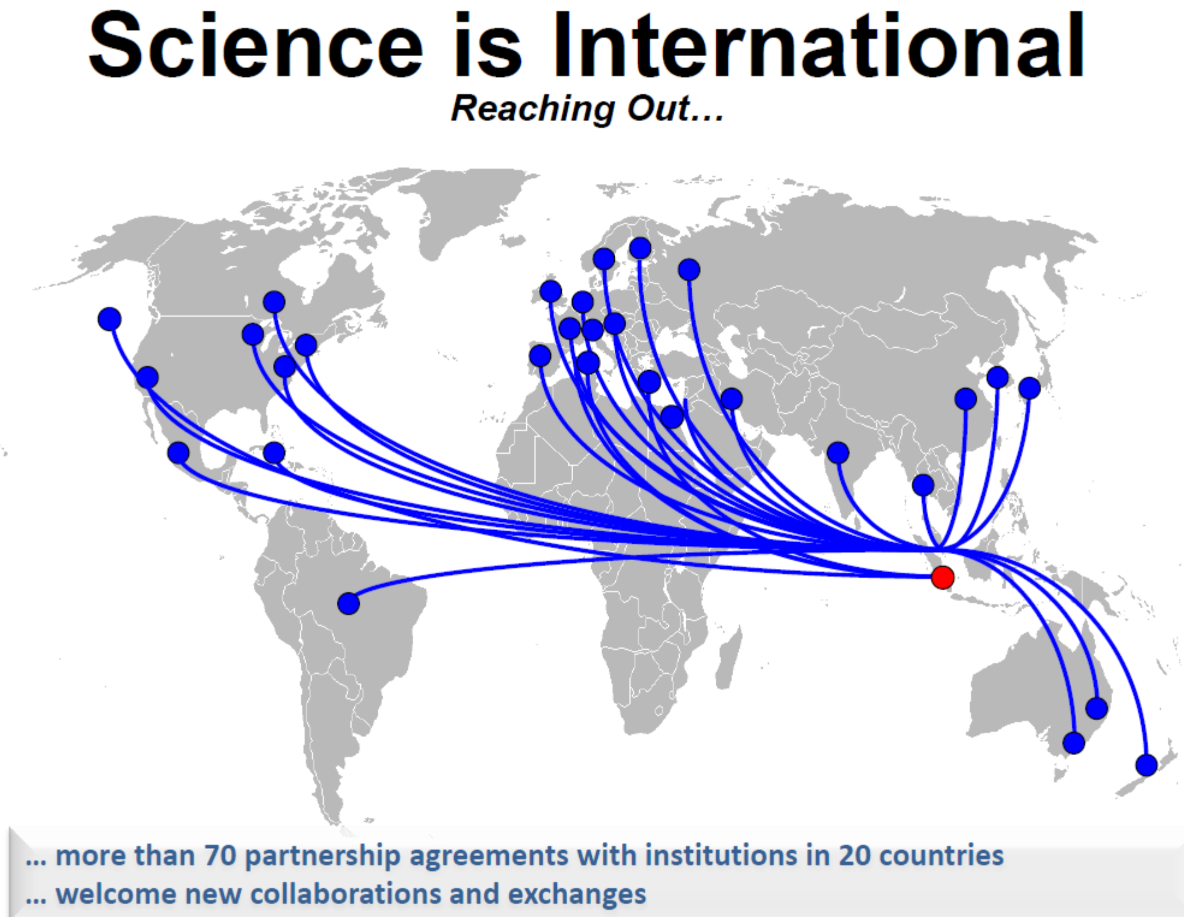
A-STAR Research Institutes

A*STAR has more than 2,900 RSEs

(More than 50% are international talent from some 60 countries)

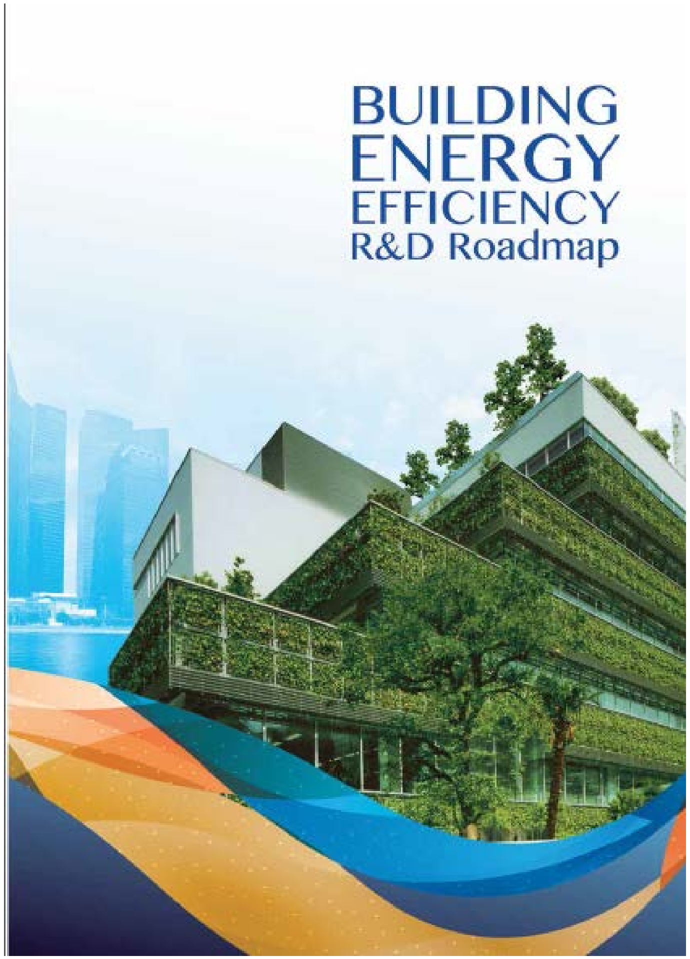


A-STAR Outreach



- IHPC ENV group host the following visiting professors:
  - Prof. Hazim Awbi, University of Reading, UK (2011)
  - Prof. Qingyan "Yan" Chen, Purdue University, USA (2012)
  - Prof. Ian Carmeliet, ETH Zürich, Institute of Technology in Architecture (2015)

Singapore Green Building Master Plan, 2014



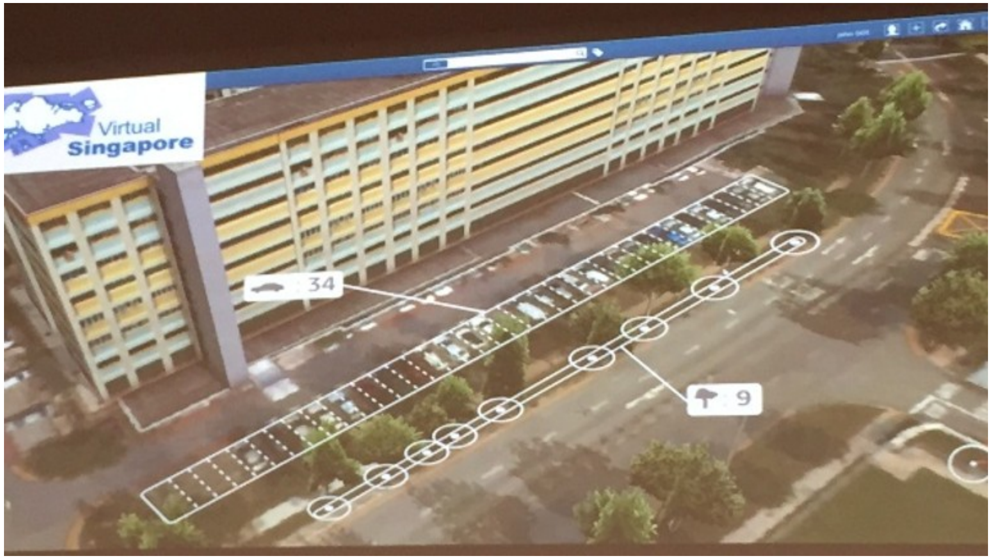
Outlines R&D pathways to improving energy efficiency within the building stock via technology improvements and policy recommendations

To share our aspiration and approach for Singapore to become **"A global leader in green buildings with special expertise in the tropics and sub-tropics, enabling sustainable development and quality living**

Sharing with Permission from BCA

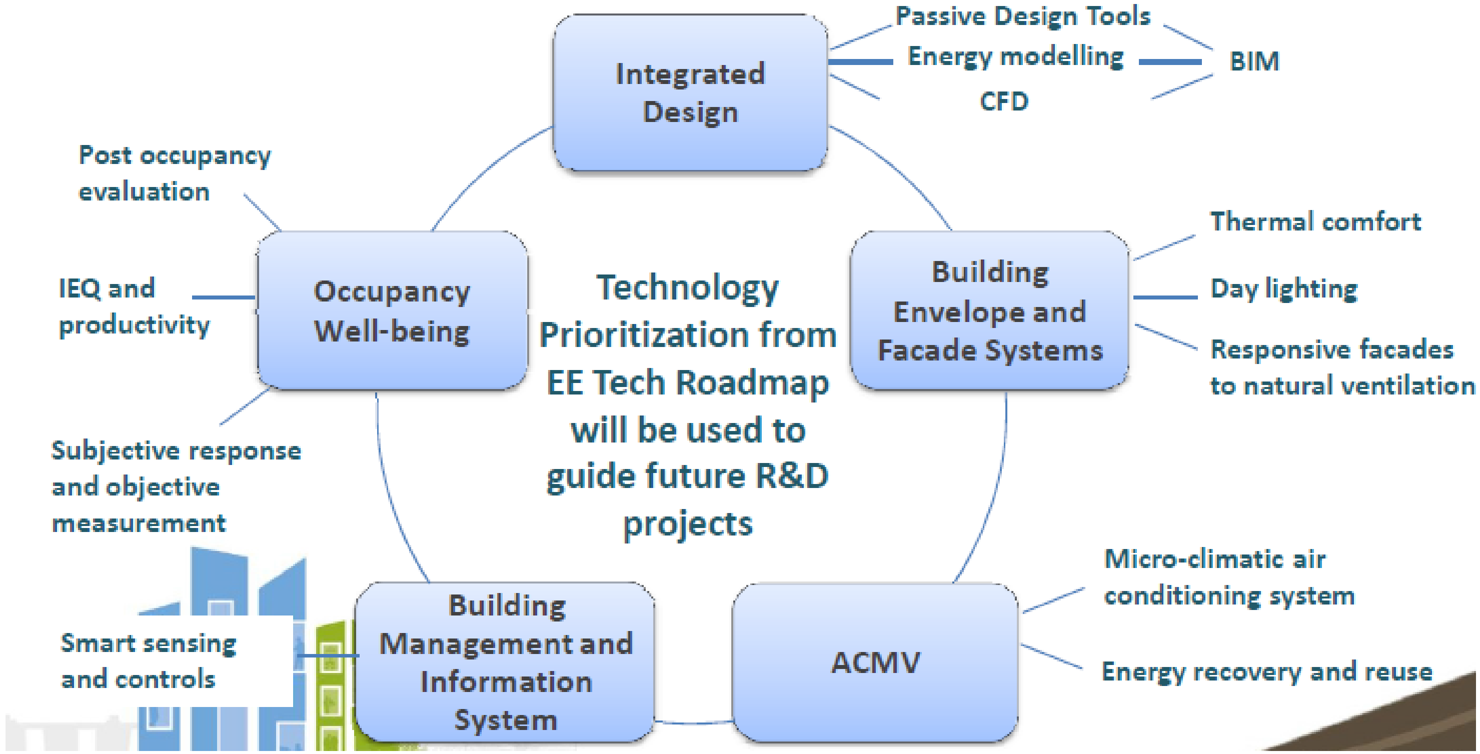
Singapore Smart Nation – Vision, 2014

- **The National Research Foundation says the S$73-million 3D city model platform will be owned and operated by the Singapore Land Authority when completed**
- The 3D map is intended for use by the public, private and research sectors. Its potential applications include locating facilities or amenities in the neighborhoods, sharing information and resource between the community, simulations of crowd and evacuation measures as well as enable planning and decision-making when it comes to delivering municipal services and analysing pedestrian flow.
- This can be done because the 3D model contains detailed information of physical Singapore. For example, models of buildings will include geometry and their components, right down to the building material.



Building Energy Efficiency Technology Road Mapping in Singapore, 2013

1. Air Conditioning & Mechanical Ventilation (ACMV)
2. Building Envelope & Façade System (BEFS)
3. Building Management & Information System (BMIS)
4. Integrated Design Approach and Tools (ID)
5. Occupancy Well-being (OW)



Green Building Technologies ZEB @ BCAA

Sharing with Permission from BCA

Green Buildings - Many Living Labs for Test Bedding

Residential

HDB Punggol Eco-Town (2010-2020)
Sustainable Waterfront Eco-Town for the Tropics.
Affordable & env sustainable public housing.

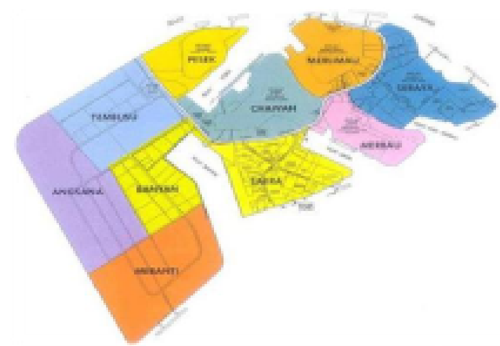
Business Park

JTC CleanTech Park (2010-2030)
First Eco-Business Park & the choice location & epi-centre for R&D & business activities in & supporting clean technologies, sustainable development & urban solutions.

Commercial

URA Jurong Lakeside & Gateway (10-15years)
Largest Ecologically friendly lakeside destination for business & leisure in the Western Region of Singapore

Industrial Park

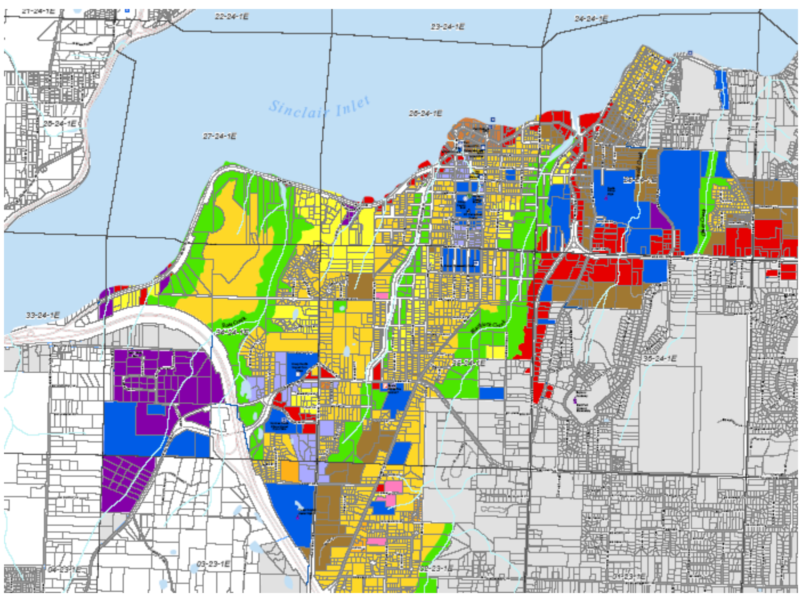


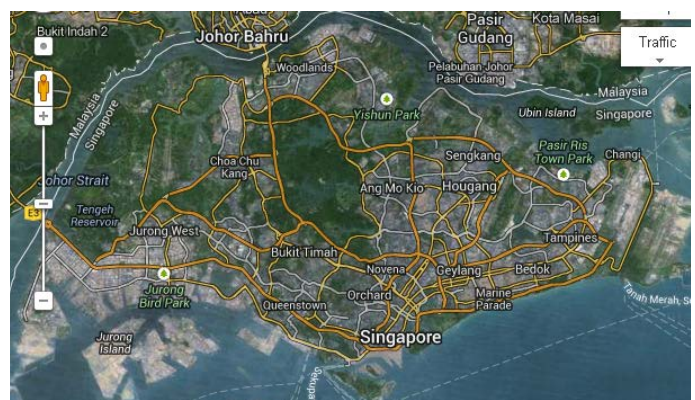
JTC Jurong Island Version 2.0 (10-15years)
Enhanced sustainability & competitiveness for the Integrated global energy & chemicals hub

Sharing with Permission from EDB

CFD in Built & Urban Environment

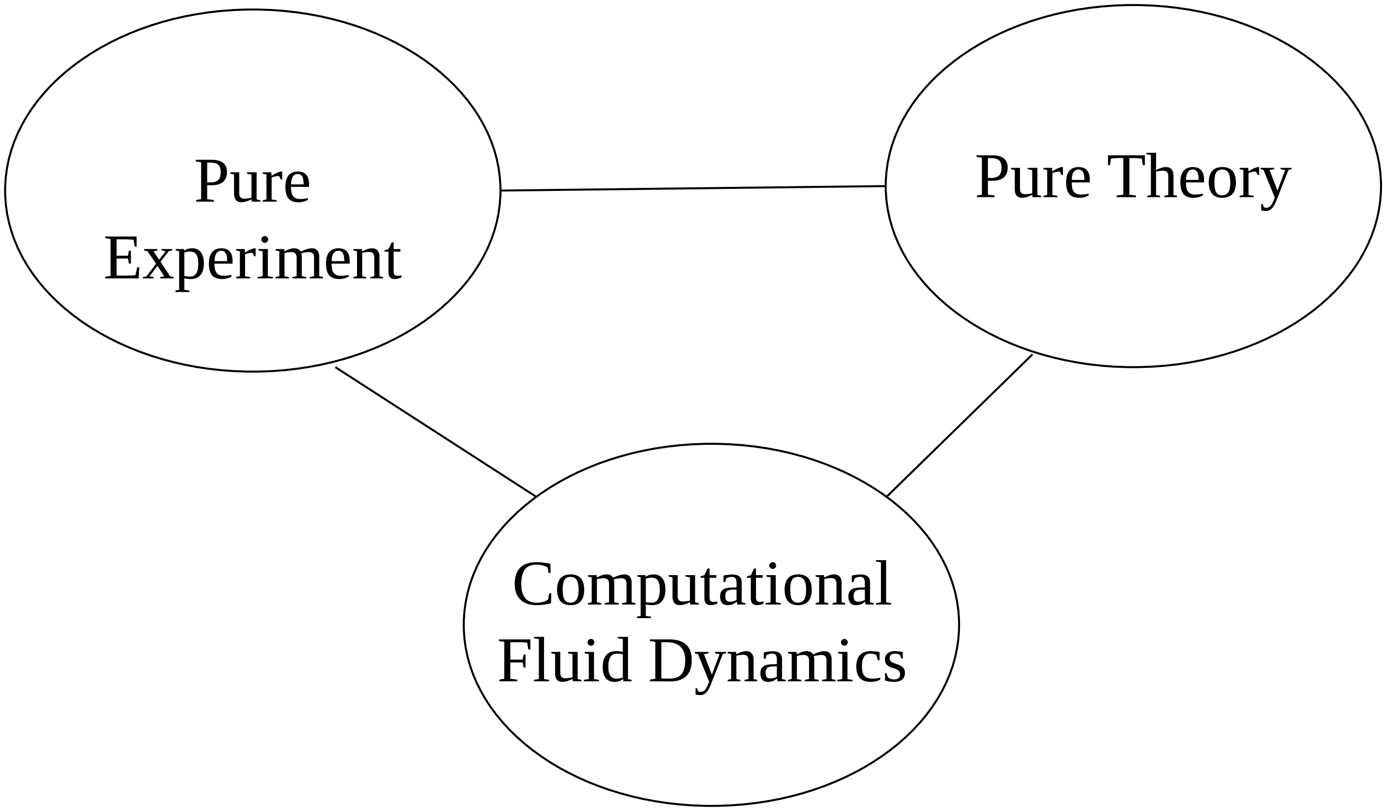
Research Capability	Research Opportunity/Impact
Urban Airflow Dynamics	Climate Change Impact & Urban Planning
Building Airflow Dynamics	Building Energy Efficiency & Integrated Design Tool
Fire Driven Flow Dynamics	Risk Analysis & Mitigation
Pollutant Dispersion Flow Dynamics	Air Quality & Health Assessment





Introduction to CFD

The "Three Dimensions" of Fluid Dynamics



- CFD provides new third approach – numerical experiment; and nothing more than that
- IHPC SAB 2014 Review – development of computational algorithms that incorporate **uncertainty quantification** is one topic that should be given attention

Introduction to CFD

Why to simulate industrial & environmental processes

- Expensive to experiment; often impossible
- Simulation can provide trends design/operation guidelines- must have validation to enhance confidence
- Useful for process control, optimization of processes
- Can help improve energy efficiency
- Can assist in reducing environmental impact
- Intensify innovation via numerical evaluation of novel concepts

Personal communication with Prof. Arun Mujumdar, Transport Process Research, 2000 – recent
http://www.arunmujumdar.com/

Time-Averaging of the Instantaneous Flow Equations

In order to model the random feature of turbulent flows, one can introduce into the governing equations of the flow field a time decomposition (also called ***Reynolds Decomposition***) of the instantaneous flow variables:

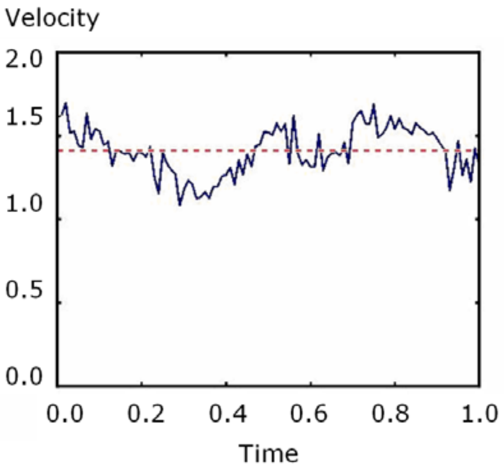
$$\phi(t) = \overline{\phi} + \phi'(t)$$

where $\overline{\phi}$ is the mean value of $\phi(t)$, $\phi'(t)$ is the instantaneous fluctuation of $\phi(t)$.

The mean value of $\phi(t)$ is obtained by integrating over a period of time, τ :

$$\overline{\phi} = \frac{1}{\tau}\int_{t}^{t+\tau}\phi(t)\,dt$$

However, the mean value of $\phi'(t)$ is zero, i.e. $\overline{\phi'(t)} = 0$



CFD - Mathematical Background

- General advection-diffusion equation

$$\frac{\partial(\rho\Phi)}{\partial t} + div\left(\rho\vec{V}\Phi\right) = div\left(\Gamma_\Phi \overrightarrow{grad}\Phi\right) + S_\Phi$$

The dependent variables (Φ), effective diffusion coefficients (Γ_Φ) and source terms (S_Φ) in the transport equations

Equation	Φ	Γ_Φ	S_Φ
Continuity	1	0	0
X momentum	u	μ	$-\frac{\partial P}{\partial x}$
Y momentum	v	μ	$-\frac{\partial P}{\partial y} - \rho g$
Z momentum	w	μ	$-\frac{\partial P}{\partial z}$
Energy	$c_p T$	k	Q
Species	c/ρ	d	Q_m

CFD - Mathematical Background

- Reynolds decomposition to the 2D, Newtonian, incompressible instantaneous flow equations

1. Continuity

$$\frac{\partial \overline{u}}{\partial x}+\frac{\partial \overline{v}}{\partial y}=0$$

2. X momentum

$$\frac{\partial \overline{u}}{\partial t}+\overline{u}\frac{\partial \overline{u}}{\partial x}+\overline{v}\frac{\partial \overline{u}}{\partial y}=-\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x}+\frac{\partial}{\partial x}\left(\nu\frac{\partial \overline{u}}{\partial x}-\overline{u'u'}\right)+\frac{\partial}{\partial y}\left(\nu\frac{\partial \overline{u}}{\partial y}-\overline{u'v'}\right)$$

3. Y momentum

$$\frac{\partial \overline{v}}{\partial t}+\overline{u}\frac{\partial \overline{v}}{\partial x}+\overline{v}\frac{\partial \overline{v}}{\partial y}=-\frac{1}{\rho}\frac{\partial \overline{p}}{\partial y}+\frac{\partial}{\partial x}\left(\nu\frac{\partial \overline{v}}{\partial x}-\overline{u'v'}\right)+\frac{\partial}{\partial y}\left(\nu\frac{\partial \overline{v}}{\partial y}-\overline{v'v'}\right)+g\beta_T\left(\overline{T}-T_o\right)$$

4. Energy

$$\frac{\partial \overline{T}}{\partial t}+\overline{u}\frac{\partial \overline{T}}{\partial x}+\overline{v}\frac{\partial \overline{T}}{\partial y}=\frac{k}{\rho c_p}\left(\frac{\partial^2 \overline{T}}{\partial x^2}+\frac{\partial^2 \overline{T}}{\partial y^2}\right)+\frac{\partial}{\partial x}\left(-\overline{u'T'}\right)+\frac{\partial}{\partial y}\left(-\overline{v'T'}\right)$$

Solve for primary variables, $\overline{u},\overline{v},\overline{p},\overline{T}$ turbulent stresses $\overline{u'u'},\overline{u'v'},\overline{v'v'}$ and turbulent heat transfers $\overline{u'T'},\overline{v'T'}$

CFD - Mathematical Background

- Analogy between laminar and turbulent stresses

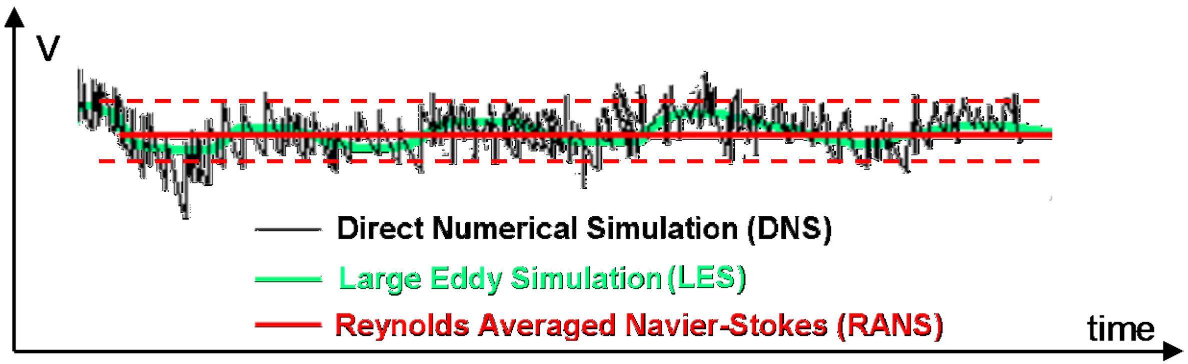
$$\tau_{ij} = \nu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \qquad -\overline{u_i' u_j'} = \nu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

- Analogy between laminar and turbulent heat fluxes

$$\varphi_j = k \left(\frac{\partial T}{\partial x_j} \right) \qquad -\overline{u_j' T'} = k_t \left(\frac{\partial \overline{T}}{\partial x_j} \right)$$

- Laminar kinematic viscosity (ν) and thermal conductivity (k) are the intrinsic properties of fluid, while turbulent viscosity (ν_t) and turbulent thermal conductivity (k_t) and are the local properties of flow
- Both analogies can reduce number of unknowns, but ν_t and k_t must be calculated everywhere in the flow

Flow Modelling – CFD Approach



LES

$$\frac{\partial(\rho \tilde{u}_i)}{\partial t} + \frac{\partial(\rho \tilde{u}_i \tilde{u}_j)}{\partial x_j} = -\frac{\partial \tilde{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \tilde{u}_i}{\partial x_j} - \rho\left(\widetilde{u_i u_j} - \tilde{u}_i \tilde{u}_j\right)\right)$$

Spatial Filtering

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial u_i}{\partial x_j}\right)$$

DNS

Time Averaging

$$\frac{\partial(\rho \bar{u}_i)}{\partial t} + \frac{\partial(\rho \bar{u}_i \bar{u}_j)}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \bar{u}_i}{\partial x_j} - \rho \overline{u_i' u_j'}\right)$$

RANS

CFD Modeling Tool

- To distinguish various type of modeling tool
  - White Box – theory based
  - Black Box – empirical based
  - Grey Box – theory-influenced empirical based
- CFD models are both theory-based and process (empirical)-based models (Blocken, 2012)
- CFD has been integrated as part of environmental modeling packages, e.g. Building Energy Performance, Urban Microclimatic model
- Environmental Fluid Mechanics CFD modeling is aimed at prediction and decision making – generally NOT AIMED AT DESIGN
- Model verification, quantification of uncertainties & model evaluation are necessary

B. Blocken, Environmental Modeling & Software 33 (2012) 1 - 22

CFD Modelling Techniques for NV

There are two approaches –

Internal flow simulation:

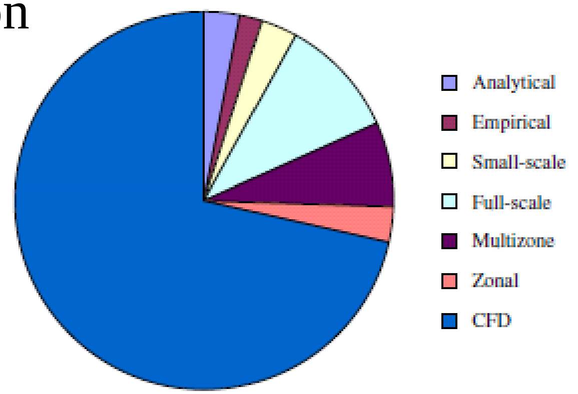
This requires boundary conditions at inlets & outlets which may be obtained from wind pressure data for the openings or CFD simulations for the whole site.

Coupled Internal and external flow simulation:

This requires climatic data, wind profiles and sheltering of surrounding structures.

Ventilation Performance Assessment Method: Review & Recent Application

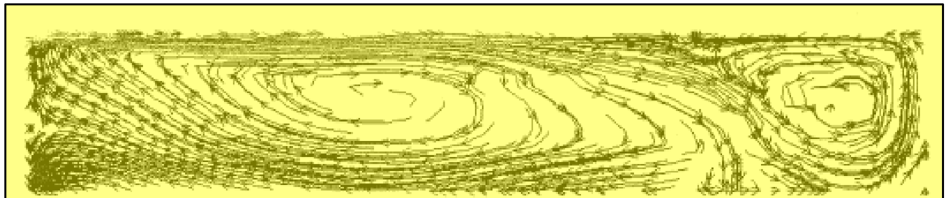
1. Analytical models – minimal contribution
2. Empirical models – minimal contribution
3. Reduced-scale experiments - generate data to validate numerical models
4. Full-scale experiments - generate data to validate numerical models
5. Multi zone models - main tool for predicting ventilation performance in an entire building; well mixing assumptions within the zone
6. Zonal models - limited applications and could be replaced by the coarse-grid fluid dynamics models; typically 1000 cells within the 3D space and solve the mass & energy balance equations
7. Computational Fluid Dynamics (CFD) models - <u>most popular (70%)</u>, trend to couple with other building simulation model, application is mainly for indoor air quality, natural ventilation, and stratified ventilation



Qingyan Chen, Building and Environment, 44 (2009) 848–858

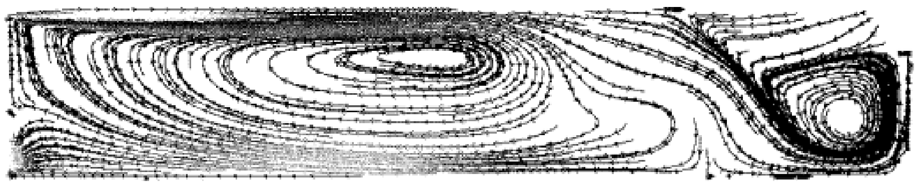
Different Turbulence Model

Turbulence Models



Experiment (3a)

LDV Measurements



RSM model (3b)

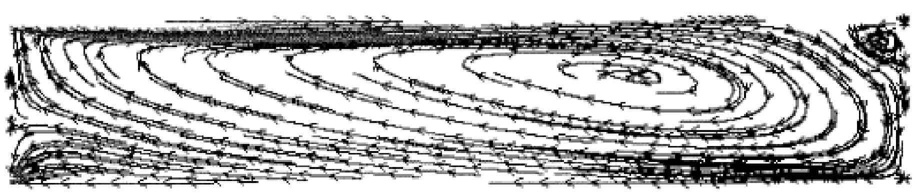
RSM
Fine grid:
624,000 cells

k-ε model (3c)

Standard
κ - ε

RNG k-ε model (3d)

RNG
κ - ε



RSM model with a coarse grid (3e)

RSM
Coarse grid:
240 000 cells

BCA GM – CFD Methodology

- To ensure computational domain length over development length – minimum 3 times
- Info on surrounding buildings
- Mesh size – to comply with GM criteria
- Clear geometry description (2D & 3D). Window schedule
- Unit level selection - proper tabulation of pressure differential data from estate level simulation result
- Turbulence model used? Atmospheric Boundary Layer implementation?
- Results converged? Show residual plot & time history of monitor point

BCA Green Mark Certification Standard for New Buildings, GM Version 4.1, 2012

CFD Result – Quality Control

- Steps of CFD simulation

CFD Simulation Steps	Group
Define the Problem	1. Problem Definition
Define the Geometry	
Generate Computational Grid	2. Grid
Choose Physical Modes	3. Models
Choose Turbulence Model	
Define Boundary Conditions	4. B.C.
Initial Conditions	5. Numerical
Select Solution Strategy	
Select Numerical Procedure	
Solve the Equations	6. Code
Check the Solutions	7. User
Post-Processing	
Analysis & Interpretation	
Documentation	

Errors

Uncertainties

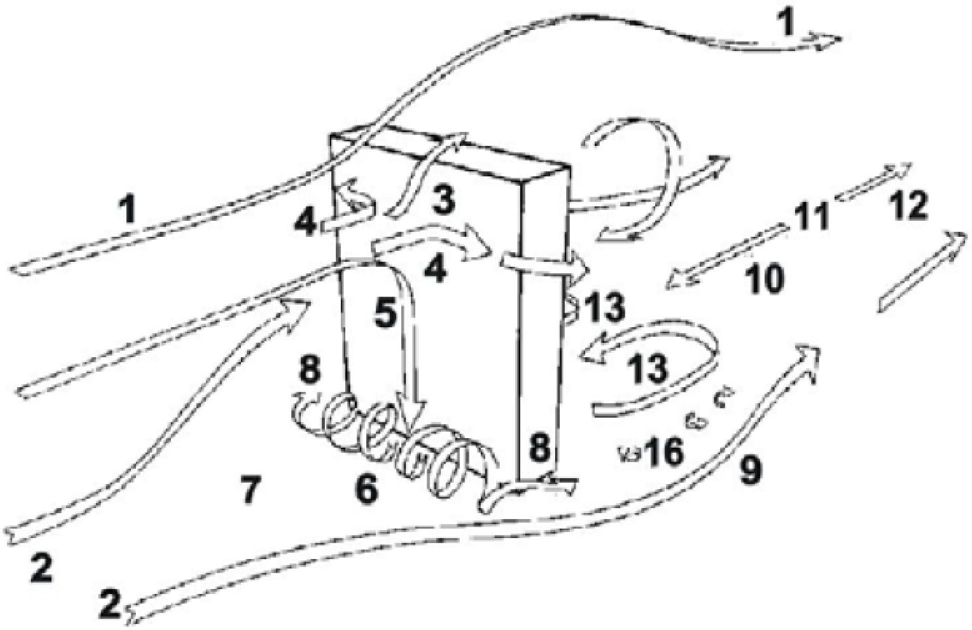
CFD Result – Quality Control

Check-List

Topic	Subtopic	Checks, advices
1. Problem Definition	Simulation method	Choose proper approach (2D/3D, steady/transient)
	Simplification	Choose proper solution domain
	Step-by-step approach	From coarse model to fine model
2. Grid	Number of cells	Hexahedral cells are better than tetrahedral cells
	Distribution	For simple room (5m x 5m x 3m), Coarse grid, 60^3~200K
	Cell quality	Medium grid, 100^3~1M, Fine grid, 200^3~8M
3. Models	Buoyancy	Boussinesq or variable density, check gravity direction
	Turbulence model	SST model best choice of 2 equation model for indoor flow
	Wall treatment	Wall functions, low Re-number wall treatment
	Radiation	Discrete ordinate, surface-to-surface
4. B.C.	Wall temperature	Check assumptions (obtained from BEPS)
	Air supply parameters	Realistic? Validated?
	Symmetry plane	Hides asymmetric phenomena?
	Wind situation	Boundary layer profile, check domain extent (10 times building size)
5. Numerical	Discretization scheme	2nd order
6. Code		Latest version, updates, user forums
7. User		Training, experience, ask expert
8. Documentation		Full documentation of parameters, readable scale

Urban Canopy Flow

- Wind flow around a single building

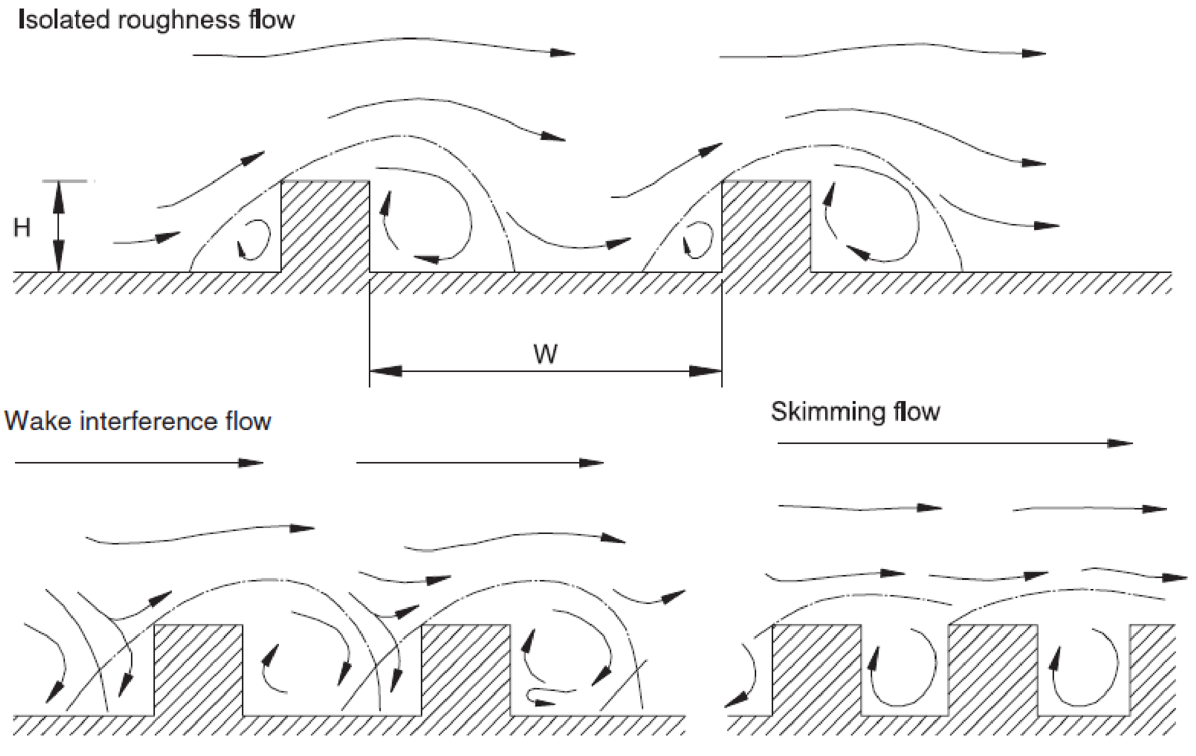


1. Flow over building
2. Oncoming flow
3. Flow from stagnation point over building
4. Flow from stagnation point around vertical building edges
5. Downflow from stagnation point
6. Standing vortex, base vortex or horseshoe vortex
7. Stagnation flow in front of building near ground level
8. Corner streams (vortex wrapping around corners)
9. Flow around building sides at ground level (adding to corner streams)
10. Recirculation flow
11. Stagnation region behind building at ground level.
12. Restored flow direction
13. Large vortices behind building
16. Small vortices in shear layer

Courtesy by Prof. Blocken, Eindhoven University of Technology

Urban Canopy Flow

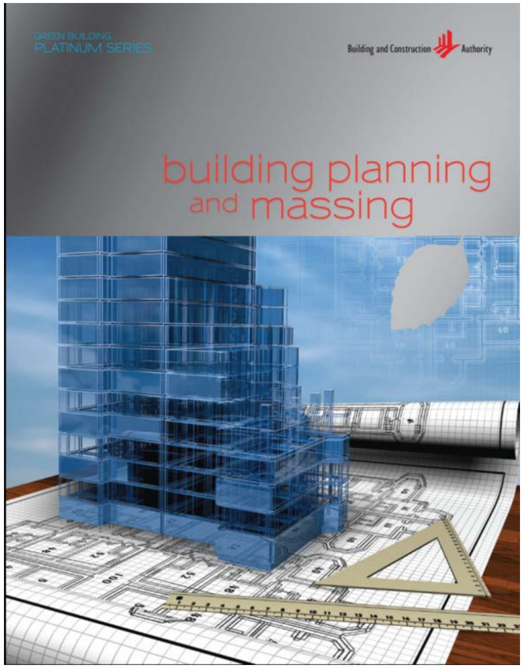
- Wind in the urban canopy – wind flow regimes
  1. Isolated Roughness Flow (IRF) → H/W<0.3
  2. Wake Interference Flow (IRF) → 0.3<H/W<0.7
  3. Skimming Flow (SF) → H/W>0.7



Reference : Boundary Layer Climates, T.R. Oke (1987)

Strategies At Estate Level To Achieve Good Natural Ventilation

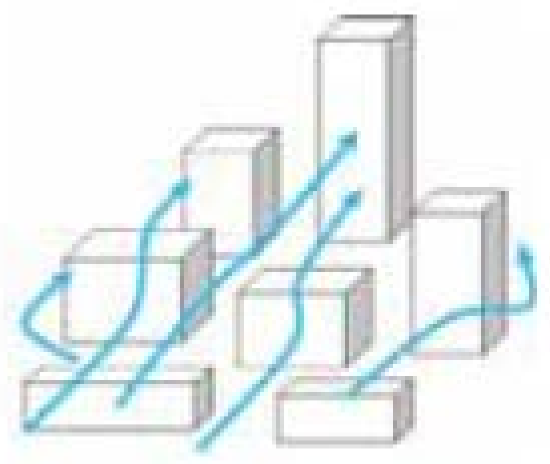
1. Create flow paths.
   - Link open spaces
   - Create open plazas at road junctions
   - Low-rise structures along routes of prevailing wind
   - Greater road widths to increase overall permeability



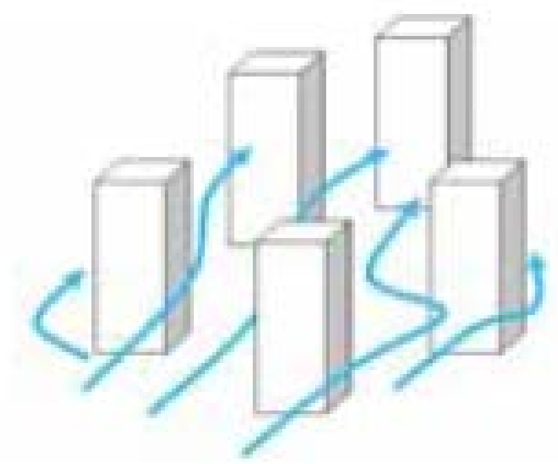
Reference : Building and Construction Authority, 2010, Building Planning and Massing

Strategies At Estate Level To Achieve Good Natural Ventilation

2. Arrange buildings according to ascending heights.
   – Lower rise buildings in front and towards direction of prevailing wind.



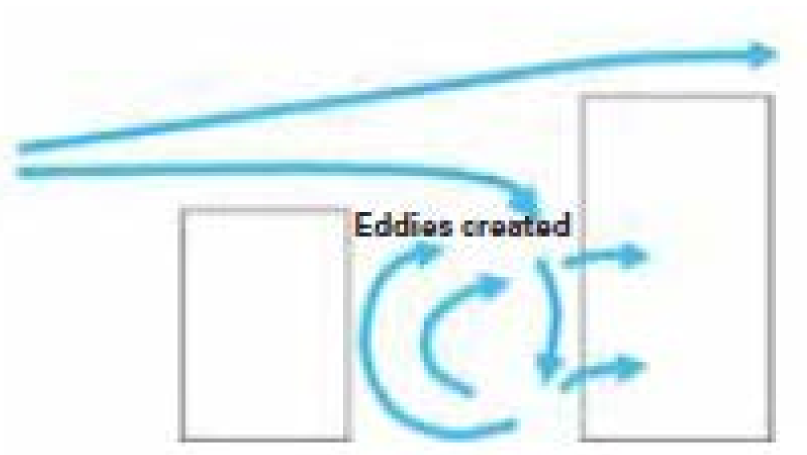
3. Stagger buildings.
   – Blocks behind should be able to receive the wind penetrating through the gaps between the blocks in the front row.



Reference : Building and Construction Authority, 2010, Building Planning and Massing

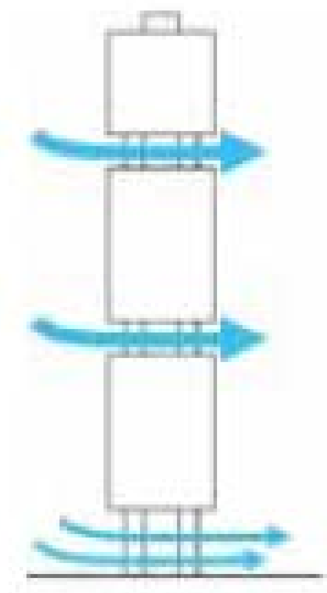
Strategies At Estate Level To Achieve Good Natural Ventilation

4. Create downwash wind.
   – Building design should consider capturing the downwash wind to reach the street level. Eddies may form in the canyon and this may assist in providing air movement within the canyon as well as into the buildings.



Reference : Building and Construction Authority, 2010, Building Planning and Massing

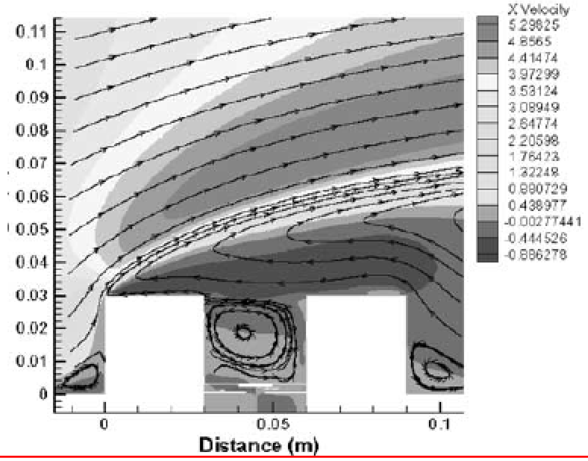
5. Improve building permeability.
   – Buildings should be as permeable as possible to channel airflow to the blocks in the back row. Sky gardens and double volume void decks can increase the permeability of blocks.



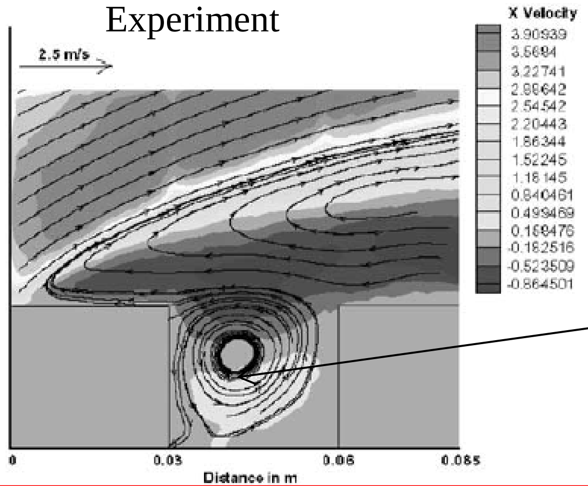
Urban Canopy Flow

- Street canyon with different building height

Simulation

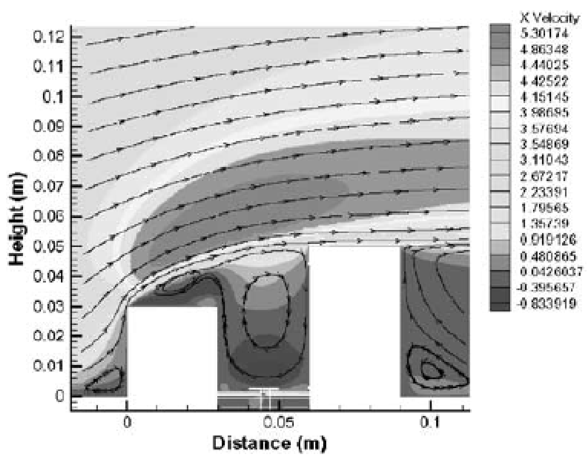


Experiment

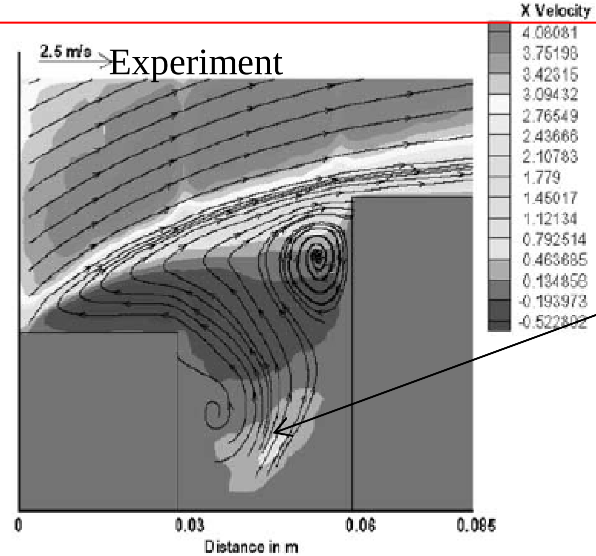


Flow recirculation/wake and trapping of pollutant

Simulation



Experiment



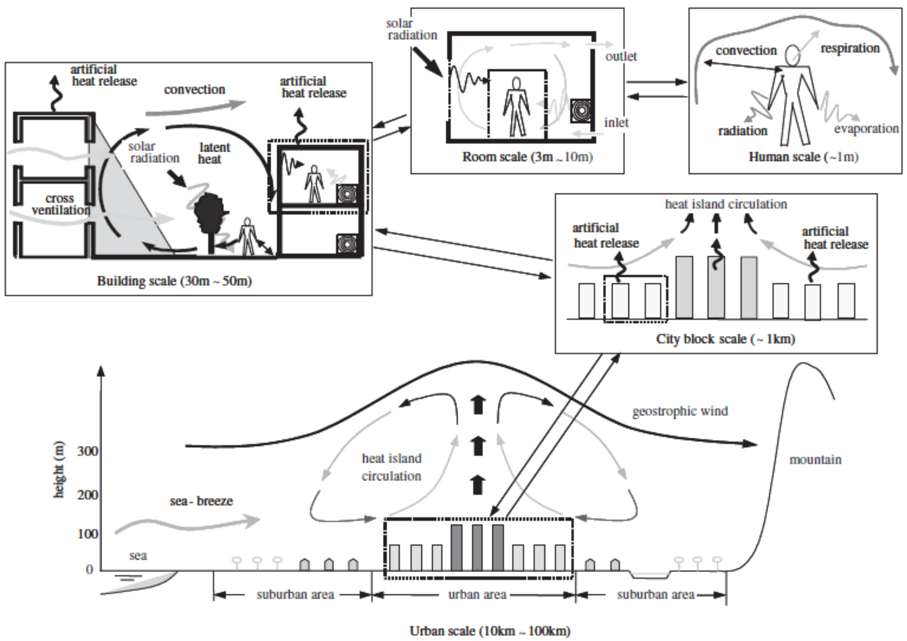
Low pressure regime is generated as "suction pump" to remove the pollutant

Reference : Jeroen van Beeck (2002)

Research Challenges

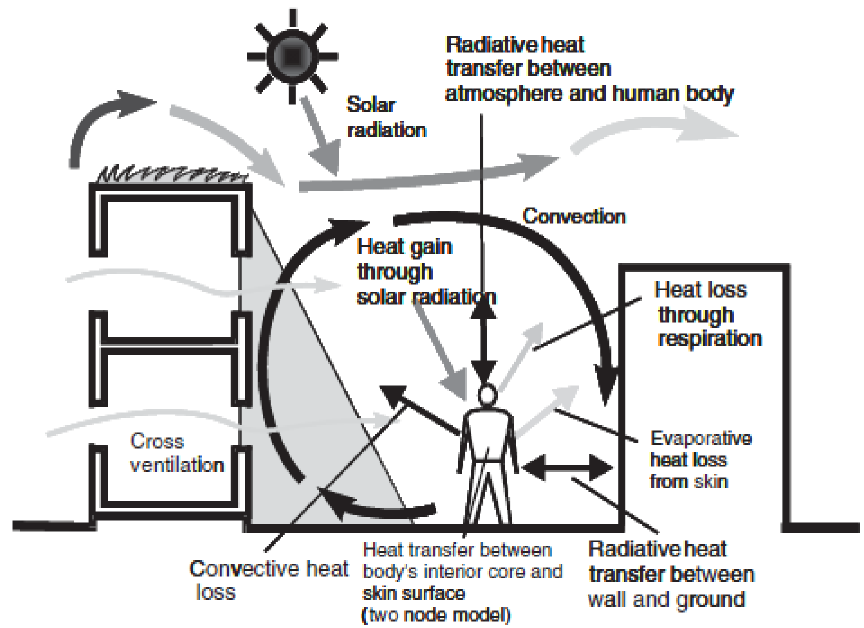
- Challenging issues – multi-scale & multi-physics

Multi-scale



Interaction of phenomena at various scales from indoor to urban

Multi-physics



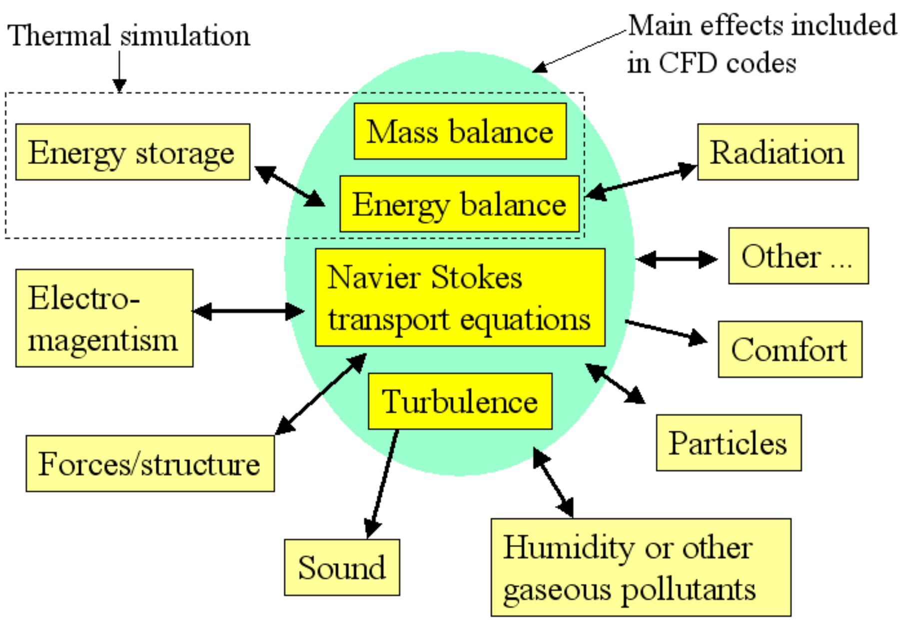
Complicated mechanism of heat exchange between the human body and the surrounding outdoor environment

Picture courtesy of Prof. Shuzo Murakami

Research Challenges

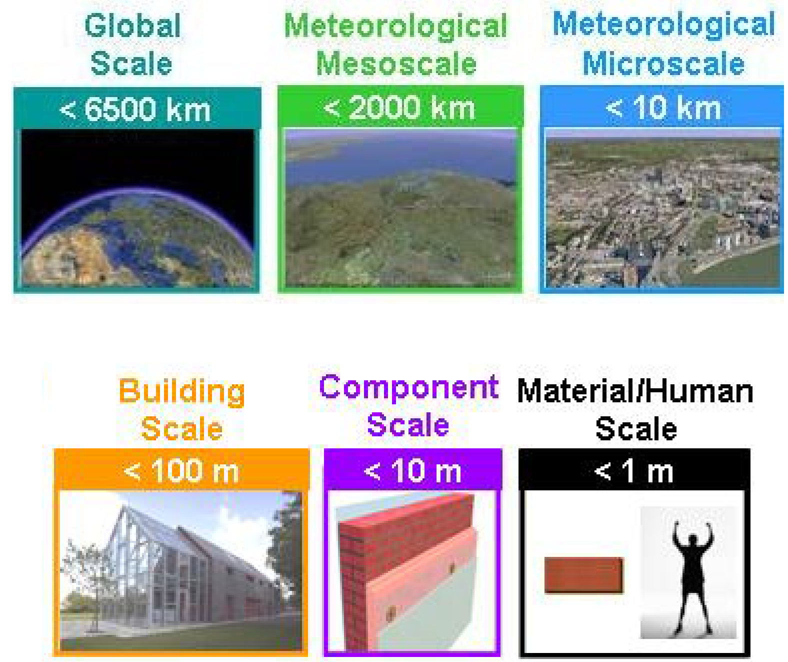
- Challenging issues – multi disciplinary

Multi-disciplinary – modeling methodology



CFD Combined with Other Prediction Models

Multi-disciplinary – urban physics

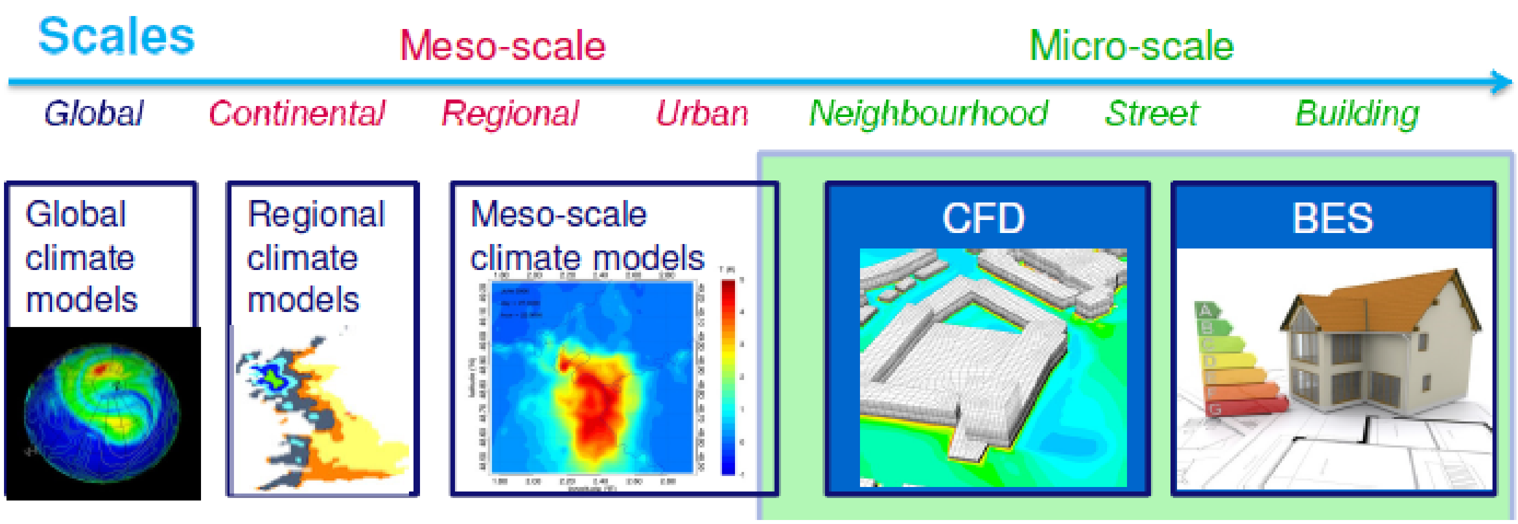


From macro-scale meteorology to human thermo physiology

Picture courtesy of Prof. Hazim Awbi

Research Challenges

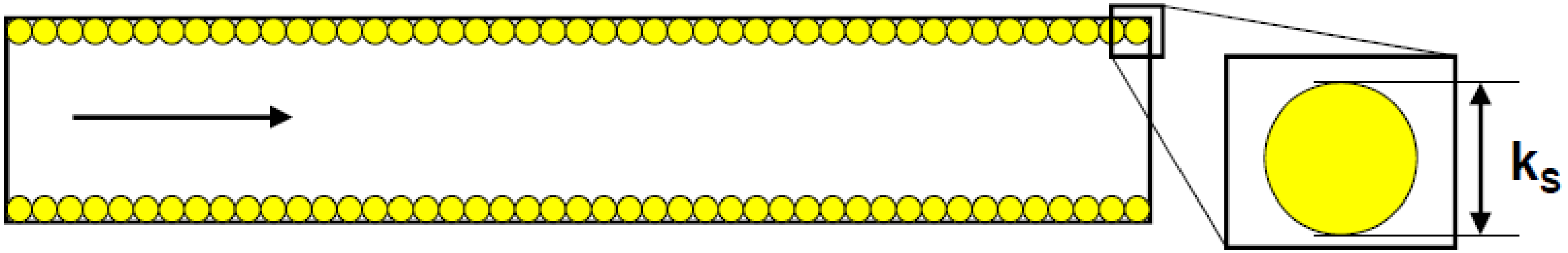
- A multi-scale analysis of the UHI effect: From city averaged temperatures to the energy demand of individual buildings
  - Computational Fluid Dynamics (CFD): Analysis of flow field for a computational domain.
  - Building Energy Simulations (BES): Analysis of energy use for individual buildings.



Picture courtesy of Prof. Blocken

Research Challenges – Urban Canopy Flow

- Most commercial CFD codes were established for **mechanical engineering problems** rather than for **atmospheric flow problems**
- Wall function roughness modifications based on semi-empirical information for **sand-grain roughened pipes and channels (Nikuradse 1933).**



- Small-scale roughness (expressed by equivalent sand-grain roughness height k_S)

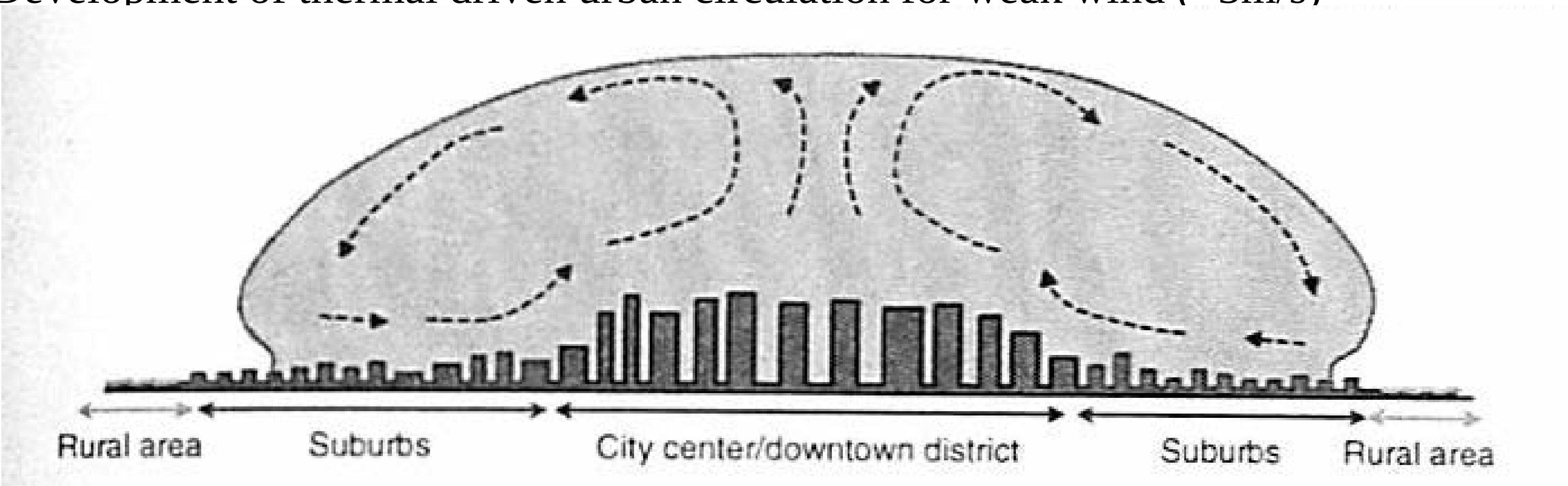
$$u = \frac{u^*}{\kappa} \ln\left(\frac{y}{k_s^+}\right) + 8.5$$

- Atmospheric flows: large-scale roughness (expressed by aerodynamic roughness length y_0)
- Many commercial CFD codes (Fluent, Ansys-CFX, …) provide only the first type of roughness modification.

Blocken B, Stathopoulos T, Carmeliet J. 2007. CFD simulation of the Atmospheric Boundary Layer – wall function problems. ***Atmospheric Environment 41(2): 238-252.***

Research Challenges – Atmospheric Stability Treatment

- Development of thermal driven urban circulation for weak wind (<3m/s)



- **Neutral** atmospheric stability does not always exist: often the atmosphere is either **stable** (causing air parcel to subside) or **unstable** (causing air parcel to rise)
- Atmospheric stability is characterized by
  1. Richardson number – buoyancy force/inertia force $$Ri = \frac{g}{\overline{T}} \frac{\left(\Delta T / \Delta z\right)}{\left(\Delta \overline{u} / \Delta z\right)^2}$$

  -0.01 < Ri < 0.01: convection is “fully forced”, and stability is neutral

  Ri > 0: stable condition

  Ri < 0: unstable condition

Reference : Mestayer, P.G., et al, The urban Boundary Layer field campaign in Marseille, Boundary Layer Meteorology. 2005. 114:315–365

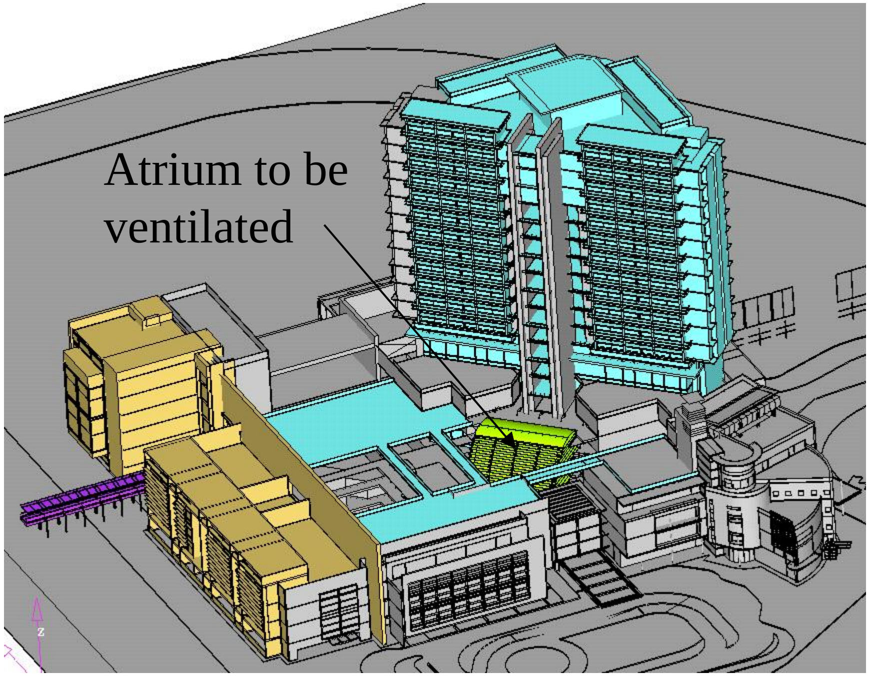
Environmental Fluid Mechanics Modeling

- EFM (Environmental Fluid Mechanics) – Scientific study of naturally occurring fluid flows of air and water on our planet earth, especially those affecting environmental quality of air and water
- Only concern with two bulk of fluids, air and water, under relatively narrow range of ambient pressure and temperature
- EFM is aimed at prediction and decision – generally not aims at design
- Multi-Physics, Multi-Scales & Multi-Disciplinary CFD and Urban Heat Island simulation

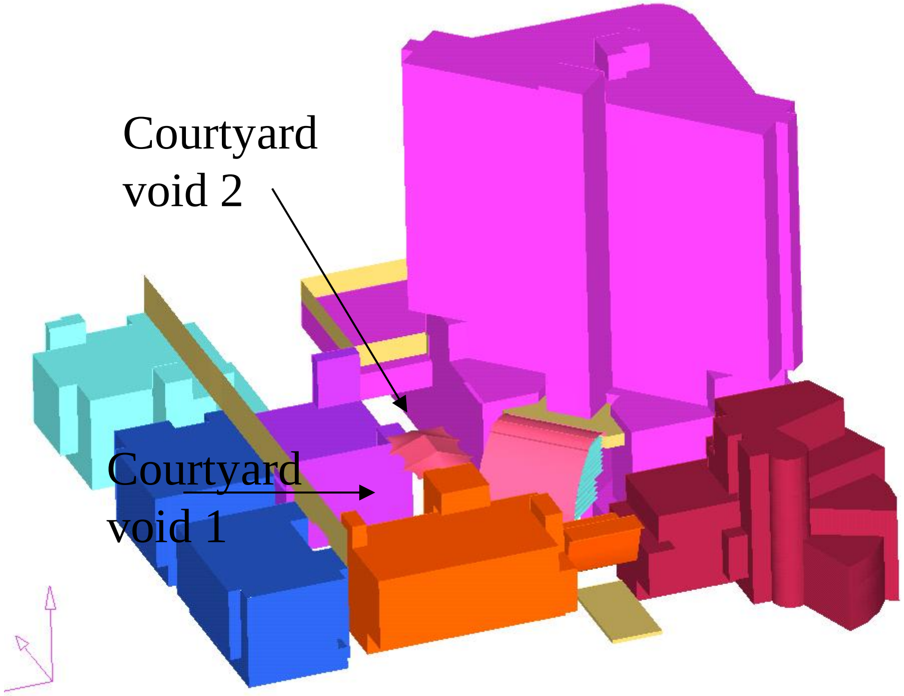
Cushman-Roisin, B, Fluid Mechanics of Environmental Interface, Chp. 1; Environmental Fluid Mech: Current Issue and Future Outlook, Taylor & Francis , 2008

Architectural Strategy For Public Podium Spaces Ventilation

- To reduce energy cost, only air-conditioning is planned for working spaces which necessitate full environmental control and to adopt naturally ventilation strategies where possible, in transition spaces, e.g. corridors and lobbies.



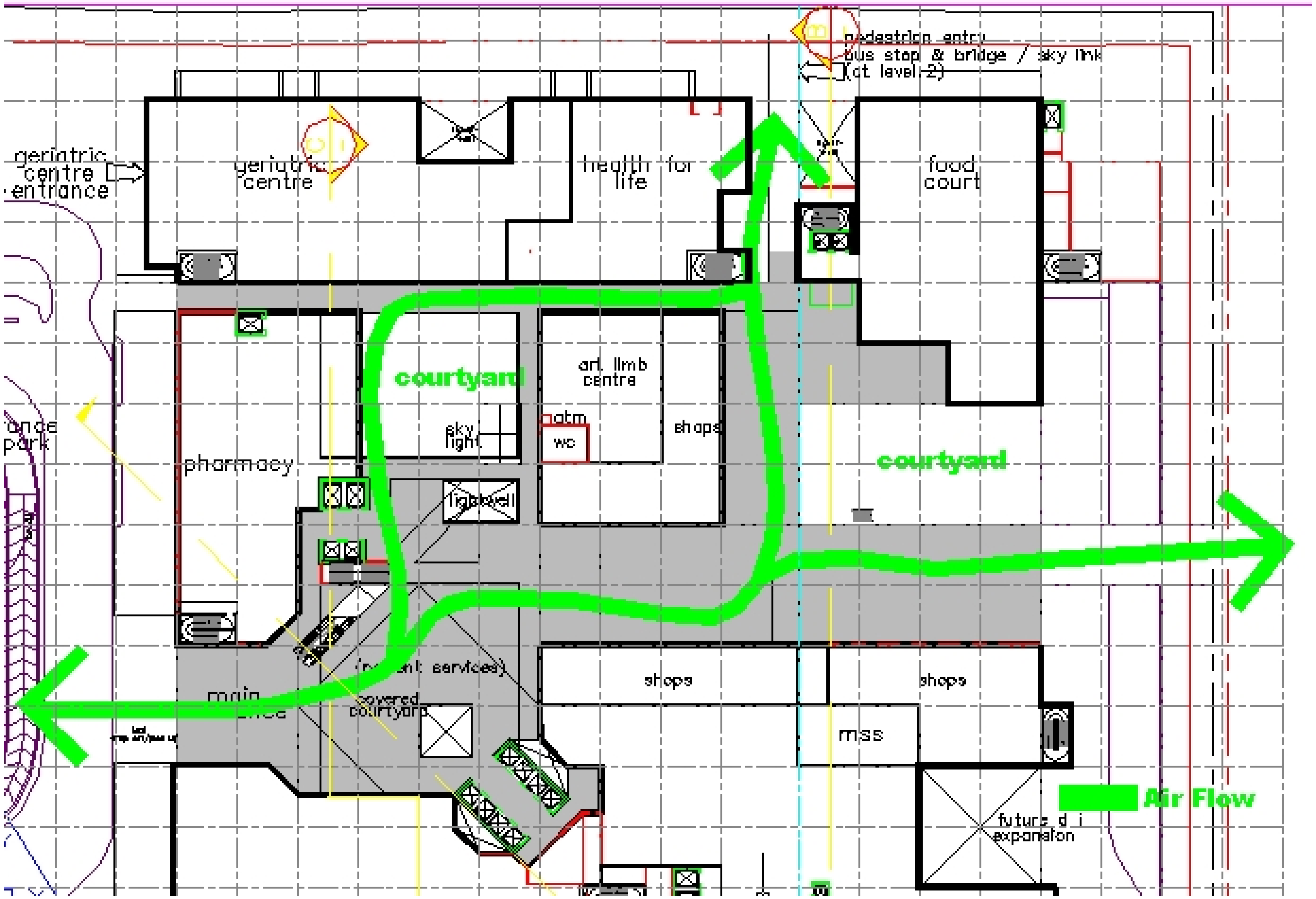
Artist Impression Drawing



Simplified CFD Model

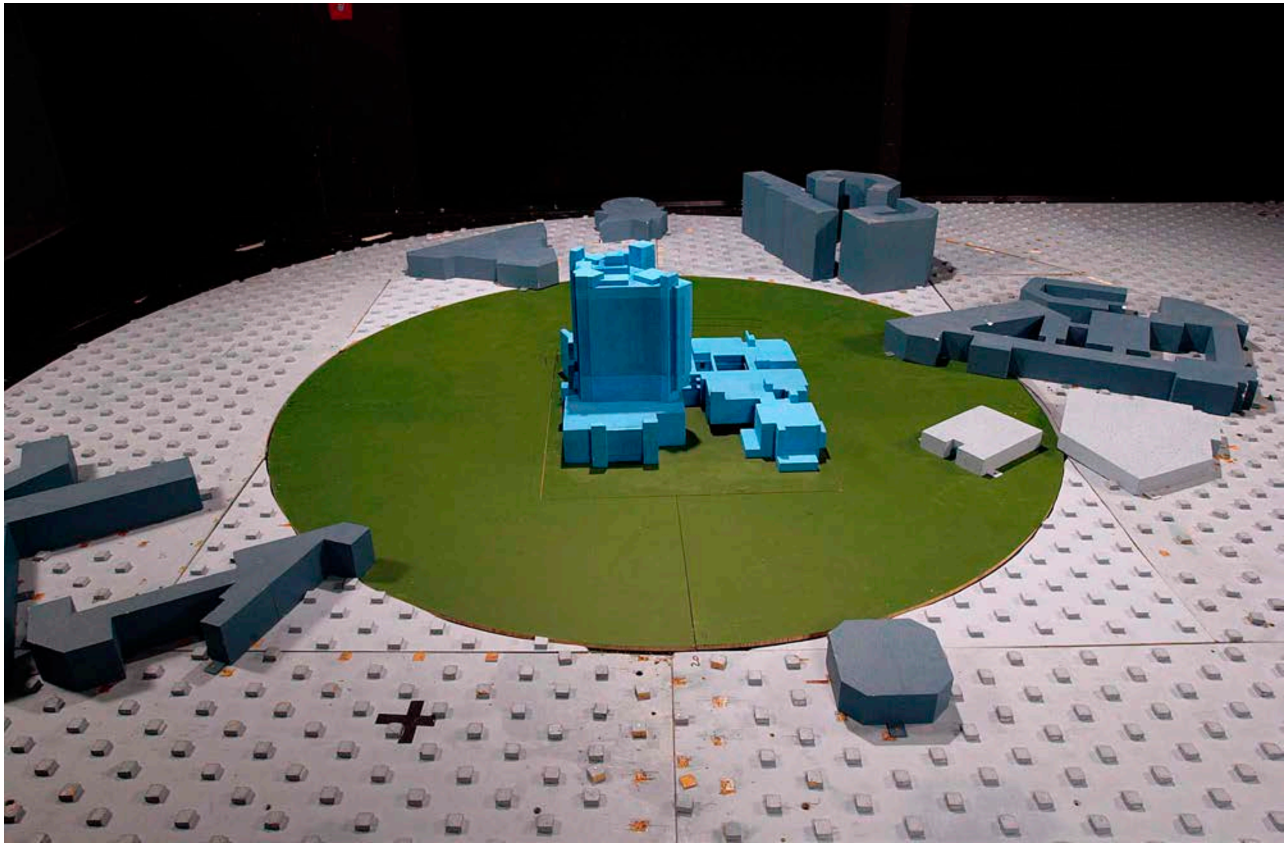
*Alex Lee, Joseph Lim Ee Man, **Hee Joo Poh**, George Xu Xiang Guo, Kurichi Kumar. Andrew Meier, Shane Amaratunga, CFD simulation in the architectural Strategy for the ventilation of public podium spaces in a local hospital building, CIB World Building Congress, 2 – 7 May 2004, Toronto, Canada*

Architectural Strategy For Public Podium Spaces Ventilation



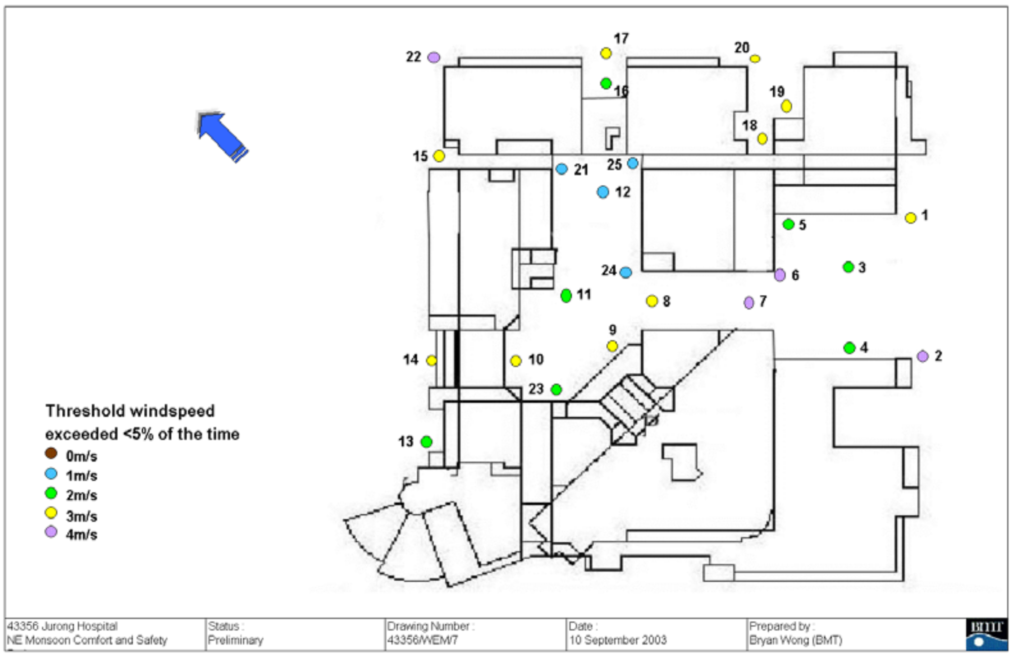
Desired Wind Path Direction

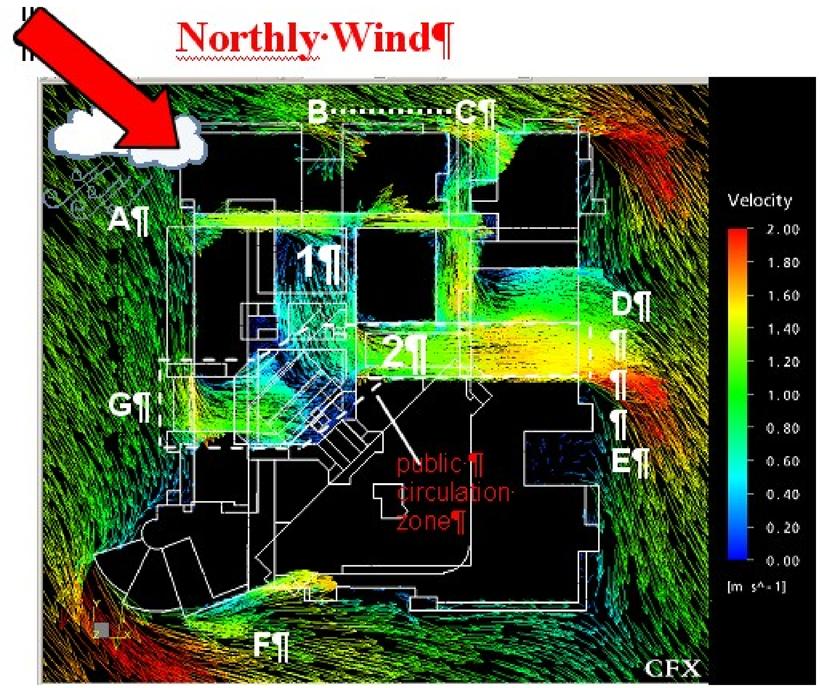
Architectural Strategy For Public Podium Spaces Ventilation



Wind tunnel model (Courtesy of BMT Fluid Mechanics Limited)

Architectural Strategy For Public Podium Spaces Ventilation



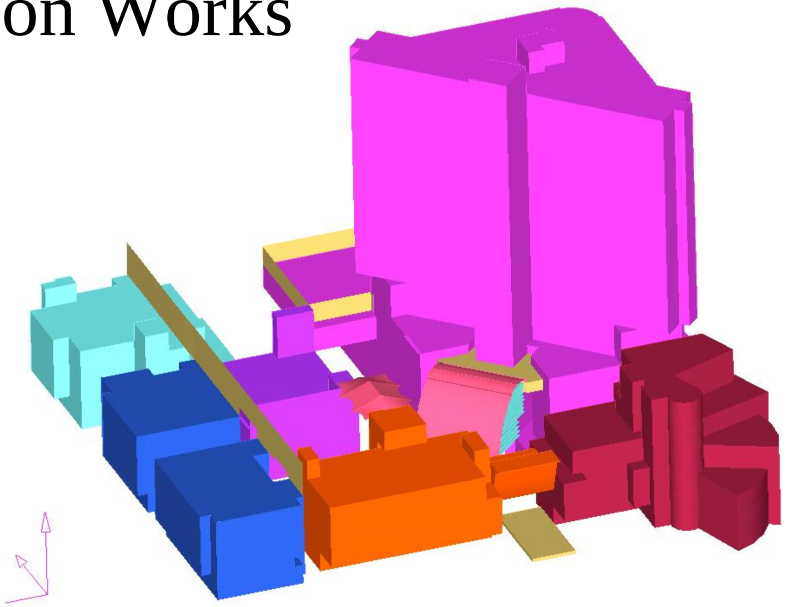


Experimental data (Courtesy of BMT Fluid Mechanics Limited)

Simulation results

Architectural Strategy For Public Podium Spaces Ventilation

Potential Extension Works



- More parametric studies on the factors affecting wind path through atrium space of the big buildings should be carried out in order to from the database for architect and building designers for further references

1) Relative position and opening size between inlet & outlet
2) Restriction of wind flow in the wind passage
3) Alignment of building opening to prevalent wind direction
4) Depth of atrium space between inlet and outlet
5) Size and shape of building adjacent of inlet & outlet
6) Positions and shapes of neighbouring blocks

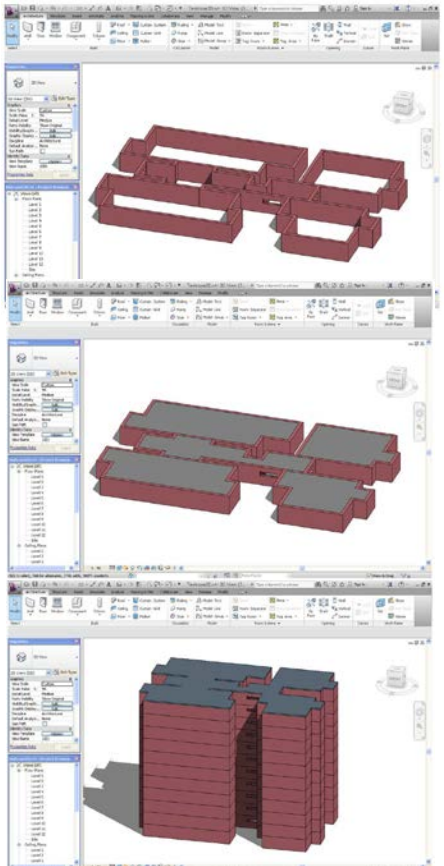
GrBEST Software – Introduction

1. To develop an easy to use and cost effective airflow modelling software for usage by green building industry.
2. An effective tool for usage by architect in the conceptual design stage
3. Used for analysis of detailed design by ESD consultants for Green Mark submission to BCA.
4. Modelling methodologies and techniques for CFD air flow simulations is verified.

GrBEST - Developed Capabilities

BIM geometry preparation

Research into BIM geometry protocol for CFD water-tight



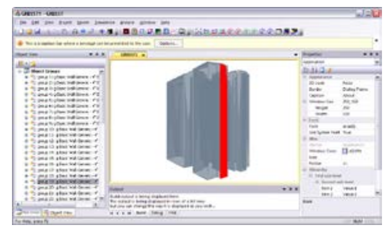
Geometry conversion to muSICS input file

Work with collaborator

Read in IFC and Visualize
↓
Simplification and substitution of geometry
↓
Boolean operation to extract internal & external surfaces
↓
Water tightness analysis
↓
Conversion to muSICS input file

Software Development

Geometry exploration

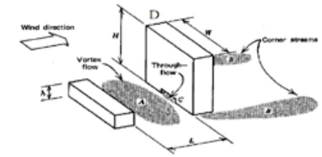


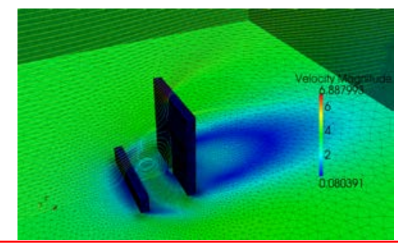
Project Manager (Windows)

Solver (Unix)

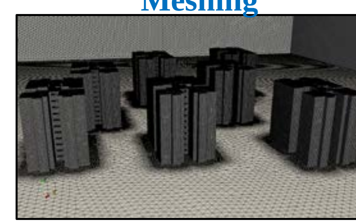
CFD simulation with GrBEST

Validation

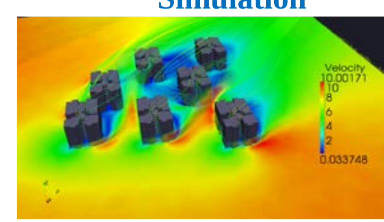




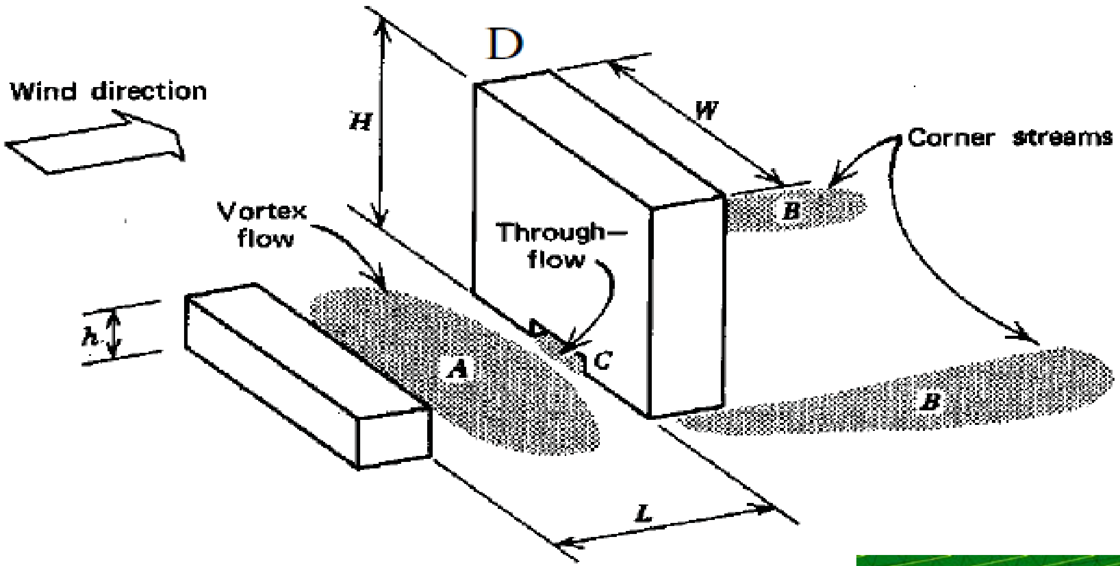
Meshing



Simulation

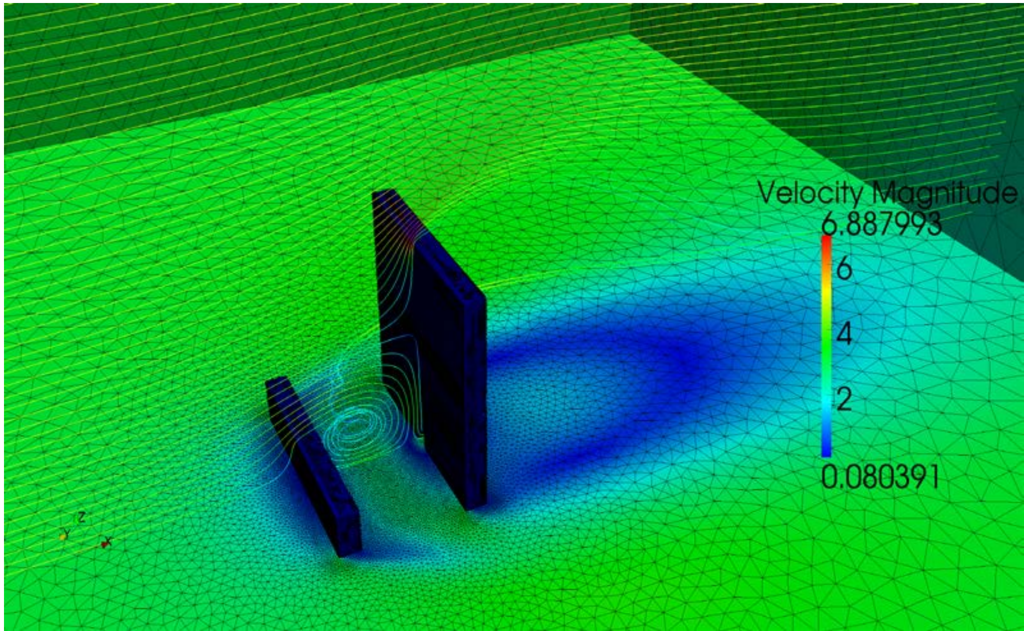


GrBEST – CFD Validation

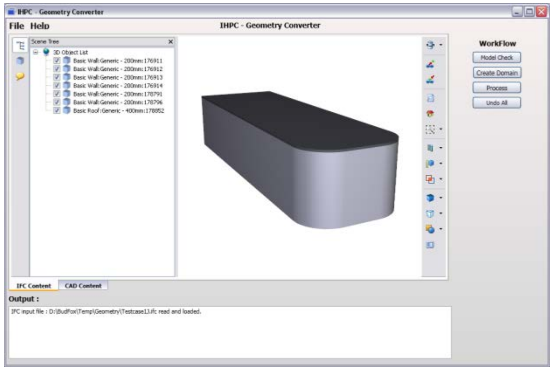


Ref: E. Simiu and R. Scanlan, “Wind effects on Structures”

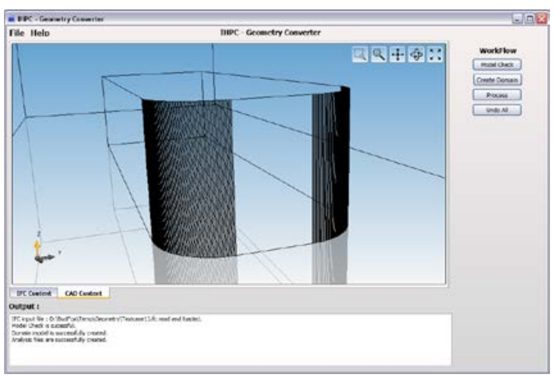
CFD simulation (mesh + streamlines)



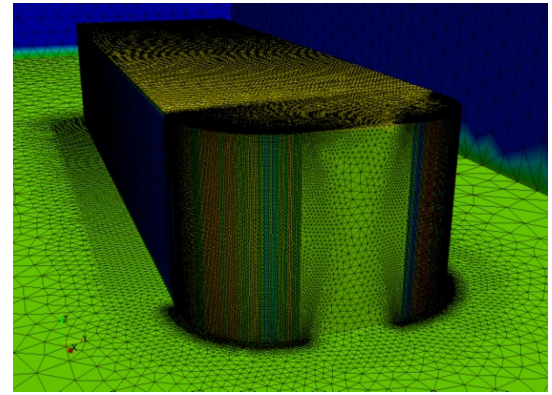
GrBEST – External Airflow



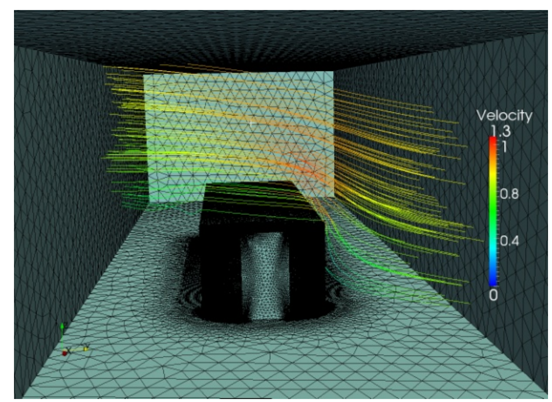
(a) IFC from REVIT



(b) IFC conversion

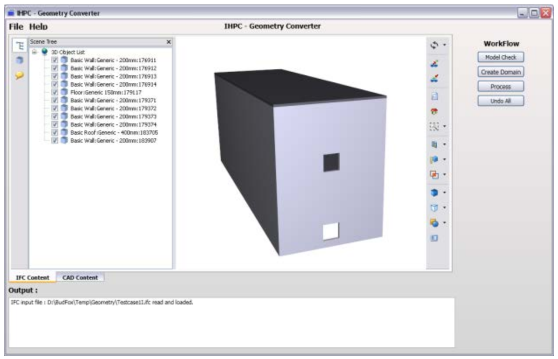


(c) CFD Meshing

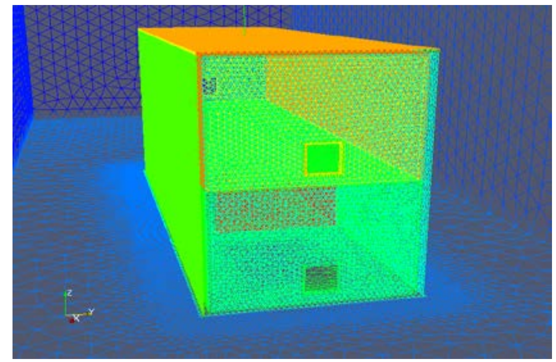


(d) Flow Simulation Results

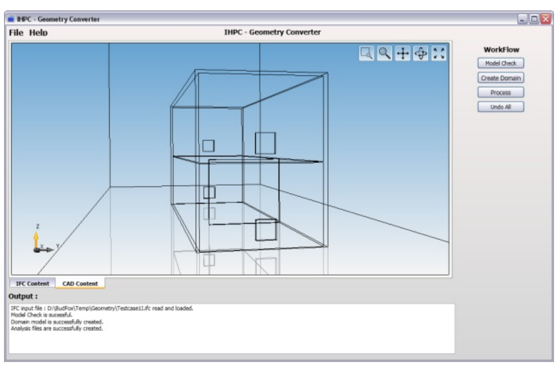
GrBEST – Internal Airflow



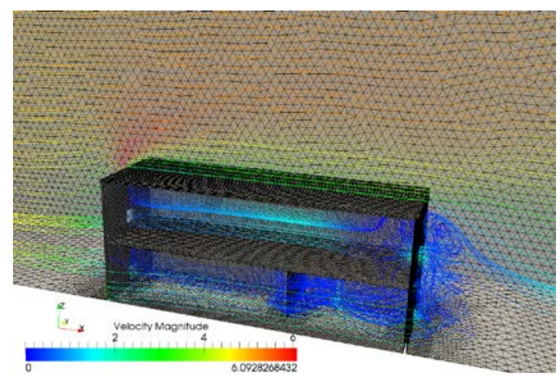
(a) IFC from REVIT



(c) CFD Meshing



(b) IFC conversion

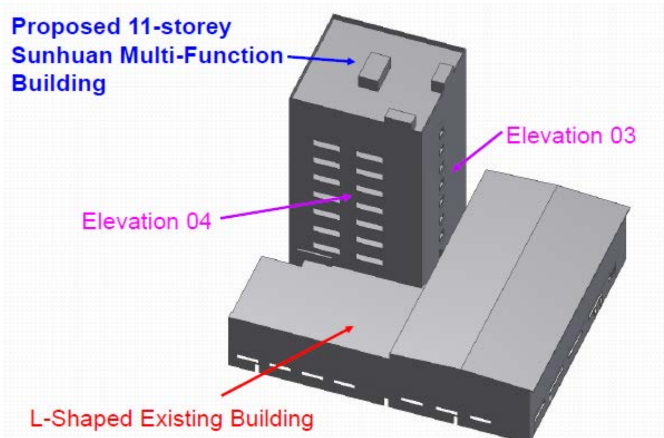


(d) Flow Simulation Results

GrBEST Software – Benefit

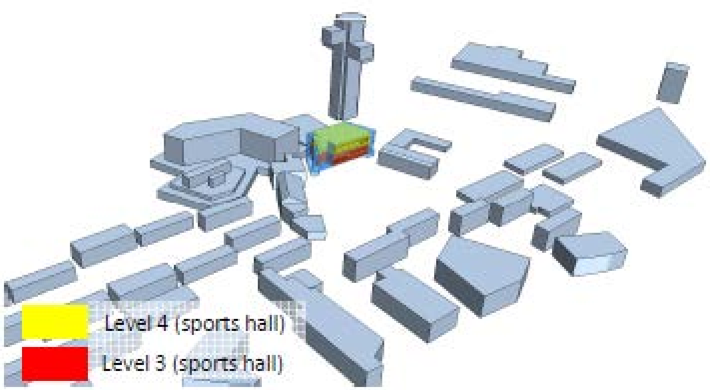
1. Time saving - reduce the CFD turnaround time
2. Cost saving – reduce initial capital cost to acquire a CFD license
3. Compute resource saving - allows users to run massively parallel computations

BCA Green Mark Assessment for Natural Ventilation Simulation

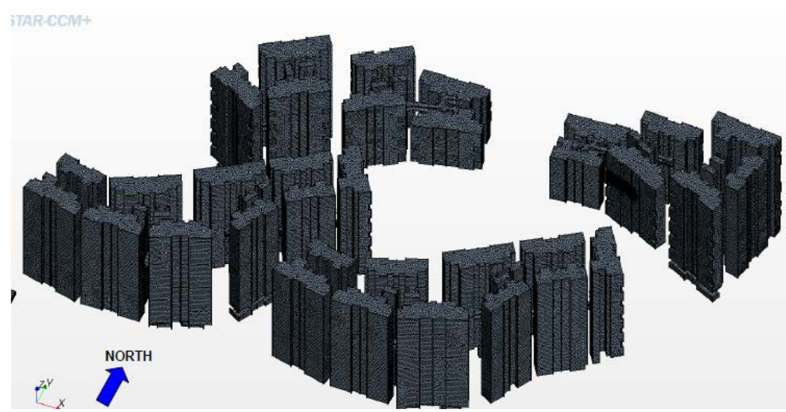


SunChuan Multi-Function Buildings

NTU North Hill Residential hall



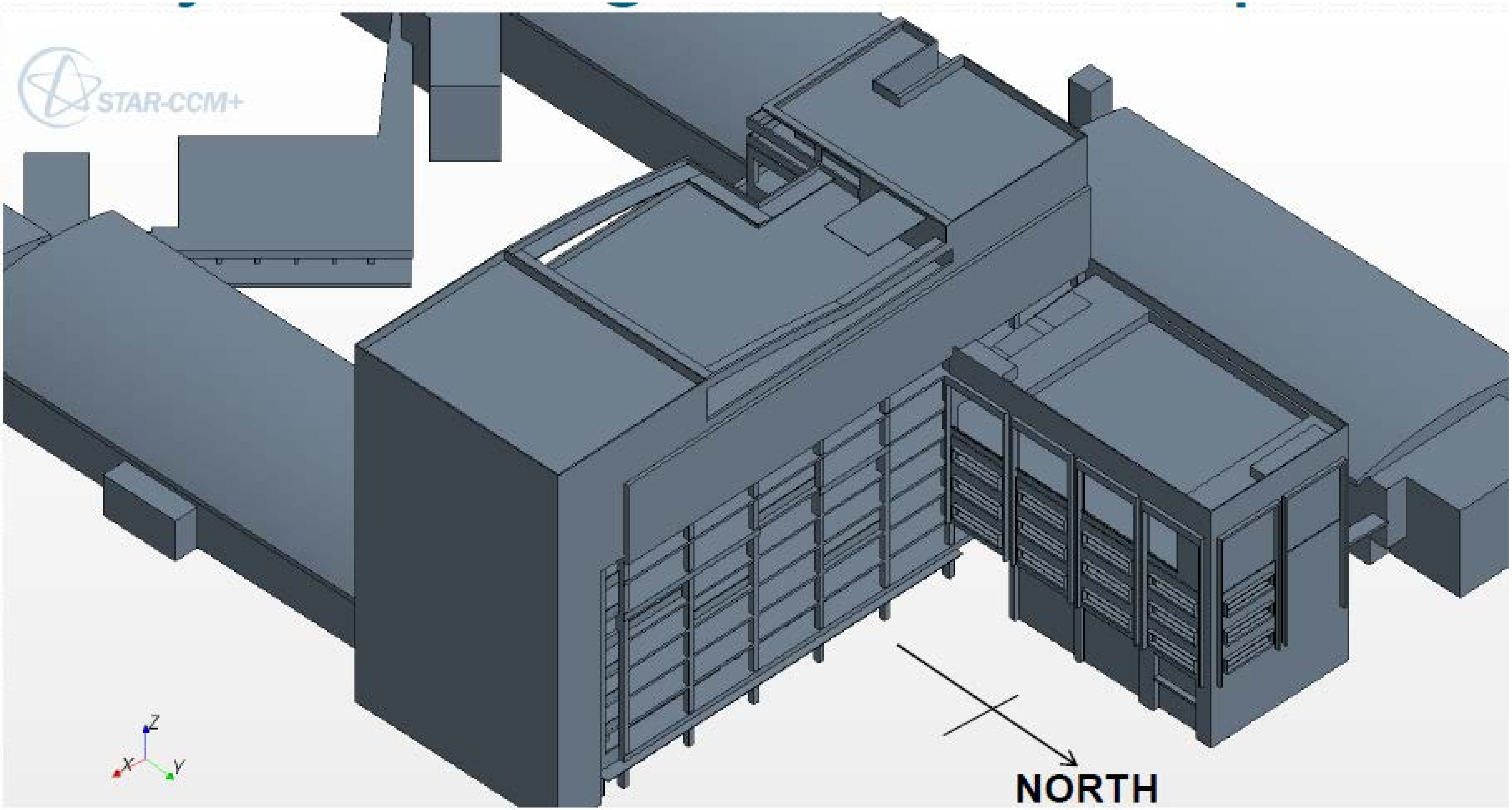
Singapore Polytechnics Sport Arena



HDB Water Cascadia

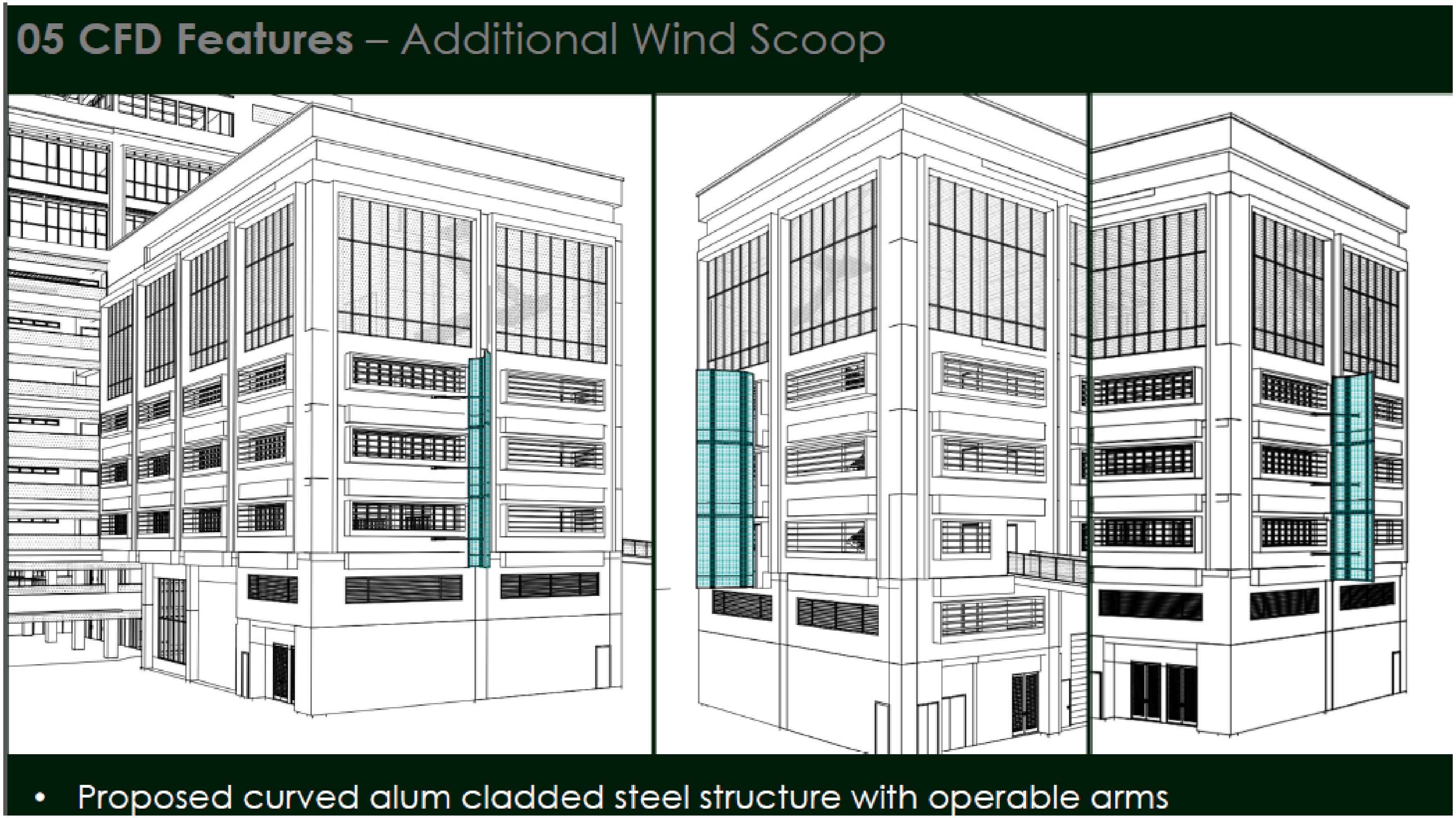
Case Study 1: BCA Academic Workshop

- Geometrical Description



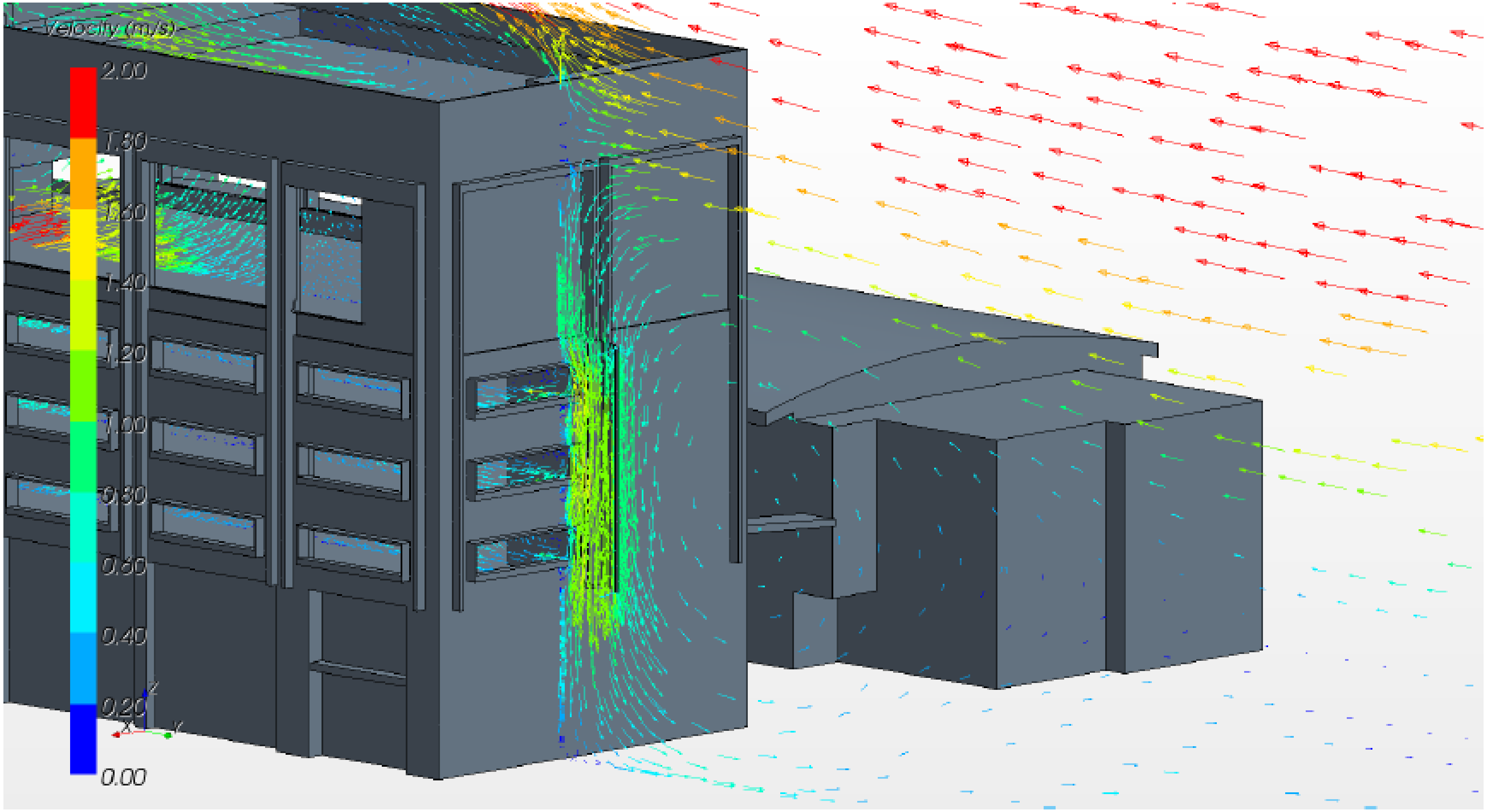
Case Study 1: BCA Academic Workshop

- Effectiveness of Incorporating Wind Catcher/Deflector



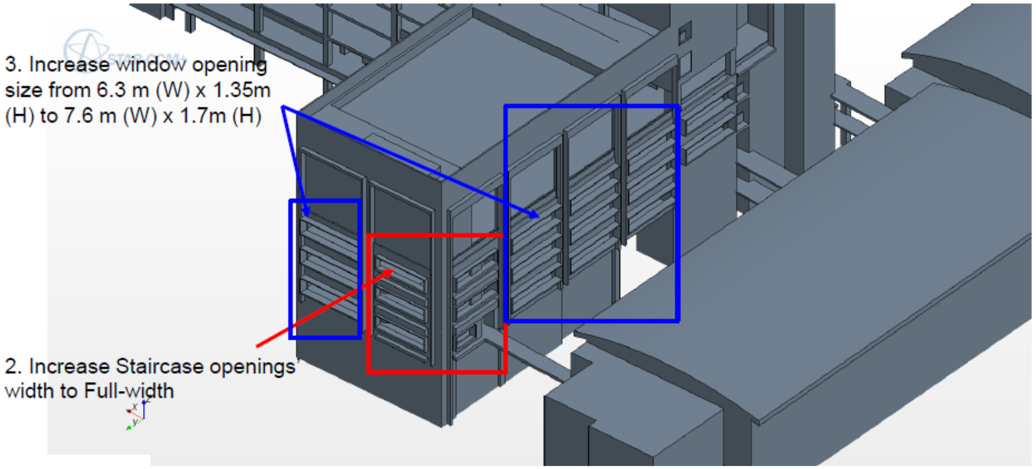
Case Study 1: BCA Academic Workshop

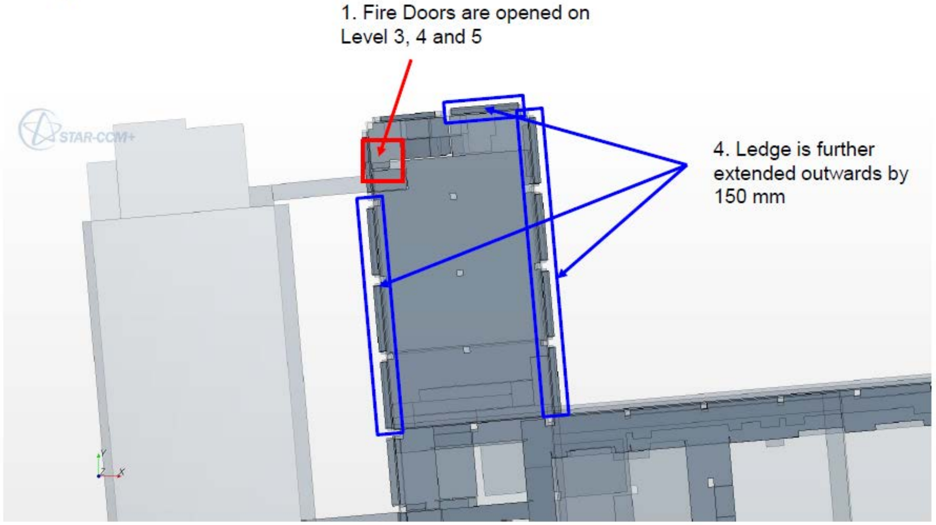
- Effectiveness of Incorporating Wind Catcher/Deflector



Case Study 1: BCA Academic Workshop

- Improvement of Natural Ventilation Performance of the Workshops, with the Proposed Design Changes





Remarks

- BCA Green Mark Platinum Series – CFD to drive design improvement for natural ventilation system is required
- Involve concerted effort from owner, architect and ESD consultants

The Development of **Computational Fluid Dynamic (CFD)** Simulation Methodology and Evaluation Parameters for **Thermal Comfort**, **Indoor Air Quality (IAQ)** and **Wind Driven Rain (WDR)** Modelling for Naturally Ventilated Spaces in Non-Residential Buildings (NRB) Under the Green Mark Criteria

GM –NRB – CFD, TC&IAQ, WDR

- BCA TD/GMD/ND & BCA RES - Project Management and Research Scientist
- Institute of High Performance Computing (IHPC), A-STAR -PI
- Department of Building, School of Design & Environment, National University of Singapore – co-PI
- Eindhoven University of Technology –co-PI
- BSD – Expert research collaborators
- Other relevant Institution/Agency (e.g. NEA, MOHH, MOE, JTC, HDB etc.) – industry partner

CFD, Thermal Comfort, IAQ & WDR for BCA Green Mark Criteria

- Project Objectives

1. To develop new CFD simulation methodology and evaluation parameters to cover a holistic range of application in NRB including
   1. *hospitals, commercial atriums and industrial facilities – Phase 1*
   2. *schools, hawker centres, sports facilities – Phase 2*

   Improved parameters for urban airflows that are *suitable for project simulated in densely-built -up city areas* shall be established as well.
2. To develop criteria for passing for an acceptable thermal environment in Non Residential Buildings (NRB). The alternative and more holistic evaluation methods shall cover both thermal comfort model and air quality index.
3. To develop Wind Driven Rain (WDR) simulation methodology based on Singapore's tropical rainforest climate and shall be established logically and economically feasible

CFD, Thermal Comfort, IAQ & WDR for BCA Green Mark Criteria

- Summary of Research Objective and Expected Outcomes/Deliverables

No.	Items	Outcomes/Deliverables
1	CFD frame work for NRB	• Methodology • Evaluation Parameters • Recommended Range/value of the Criteria for Passing
2	Thermal Comfort	• Methodology • Recommended Range/value of the Criteria for Passing
3	Air Quality	• Index(s) • Methodology • Recommended Range/value of the Criteria for Passing
4	WDR	• Survey (locations prioritization) • Methodology • Recommended Range/value of the Criteria for passing

Work Package 1 – CFD Evaluation Parameters

- Development of New methodology through JTC test case study

Parameters	Current Methodology	Proposed Methodology for NRB
Computational grid size	• Units: 0.1-0.2m • Buildings and ground level: 0.5-1.0m • Far field boundary: 10m with min. 50m away from ground.	• Determine an appropriate grid size to optimize computing resources and turnaround time. • Boundary layer/inflation layer elements are advisable to be used in "units"
Domain size	• Min. three times the length of the longest distance across development boundary.	• Propose blockage area proposal
Roughness factor setting	Nil	• Consideration to model trees/ greenery/ terrain/ topographical features. • Determine/ quantify surface roughness factor.
Component/ device modeling	Nil	• More precise descriptions of boundary conditions for louvers etc.
Selection of unit	• Mid-height level of development.	• Natural ventilated spaces in NRB may not start from the bottom. • To determine an appropriate level(s).
Pressure difference selection point	• Midpoint of opening measured at 0.5m away from surface area.	• Pressure difference taken only at midpoint is not representative. • To consider pressure differential over the entire surface.
Selection of units to determine area-weighted average velocity	• Five typical unit design layout for residential.	• Determine appropriate area-weighted average velocity method for industrial facilities.

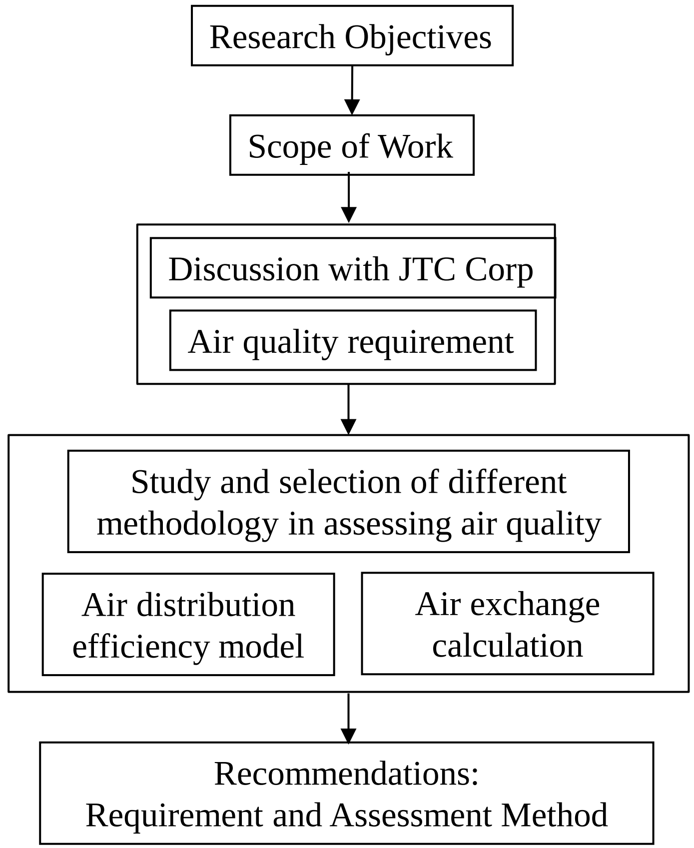
Thermal comfort methodology: thermal comfort field research

Measurement protocol:

- Measure all physical environmental variables (air temperature, mean radiant temperature, wind speed, relative humidity, clothing and metabolic rate)
- At one height of measurement (0.8-1 m)
- Data is sufficient to calculate PMV, PPD indices and at the same time and place (location) thermal questionnaires are ministered

Work Package 2

Air quality: research methodology



METHODOLOGY- DETAILS

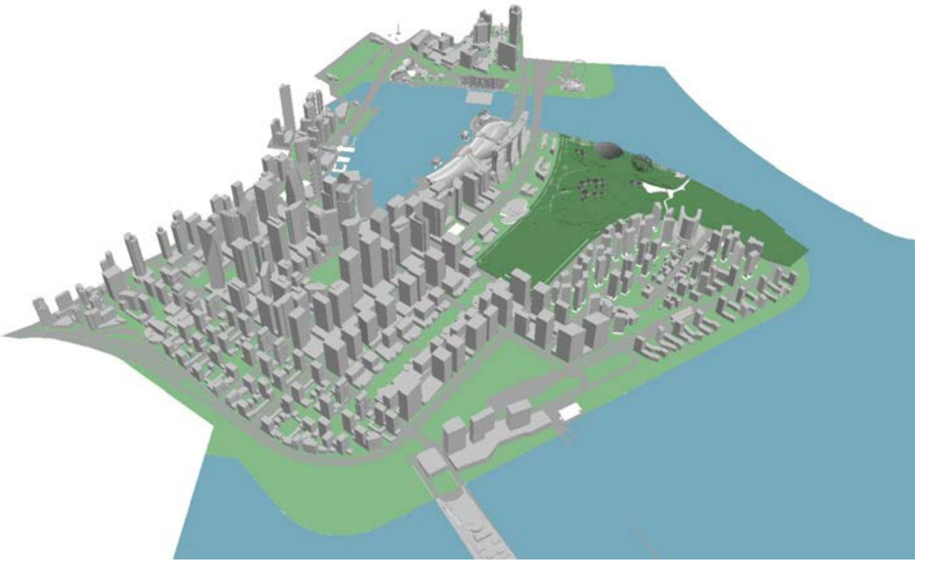
Item	Work item/ deliverable	By
1.	Identity building types, fenestration design (louvers, overhangs, etc) and spaces (hospital, industrial,). Consult BCA/ industry experts on selected building types/ fenestration design/ designs/ spaces.	BSD Reviewed by TU/e
2.	Develop a survey questionnaire to retrieve users' perception & acceptance on the WDR effects these spaces Conduct surveys and photographic evidence (no rain measurement) based on TU/e suggested criteria: 1. Very good (no noticeable penetration of WDR) 2. Good (some but acceptable degree of penetration of WDR) 3. Moderate (substantial penetration of WDR, barely acceptable) 4. Poor (unacceptable penetration of WDR) 5. Very poor (unacceptably large penetration of WDR). Once selected building types/ fenestration design/ designs/ spaces are agreed and confirm, collate/ retrieve building relevant data and drawings for CFD modeling (by TU/e)	BSD Reviewed by TU/e

METHODOLOGY- DETAILS

Item	Work item/ deliverable	By
3	Acquire Singapore meteorological data wrt rain and wind (volume, frequency, speeds, locations, etc) and group them into WDR typologies and determine their return period, etc: 1. Type 1 rain (no WDR risk) 2. Type 2 rain (low WDR risk) 3. Type 3 rain (high WDR risk)	BSD. Reviewed by TU/e
4	Define parameters for carrying out WDR CFD using the Eulerian-Lagrangian method – for industry application. Determine its relevance to WDR issues under tropical high rainfall with strong gusty wind scenario	TU/e Reviewed by BSD
5	Based on results, identify the recommended passing criteria for WDR and Green Mark assessment method and its score weightage. Determine how a typical building should be evaluated for its WDR: - Number of potential WDR locations. - Basis of selecting WDR simulation locations - Rain type to use. - Score weightage (eg. Under Type 3 rain, WDR was found to be Very Good- 3 points). Prepare a reader-friendly guideline detailing the methodology, parameter, result interpretation and presentation for industry use. Possibly develop good practice guidelines.	TU/e & BSD With BCA

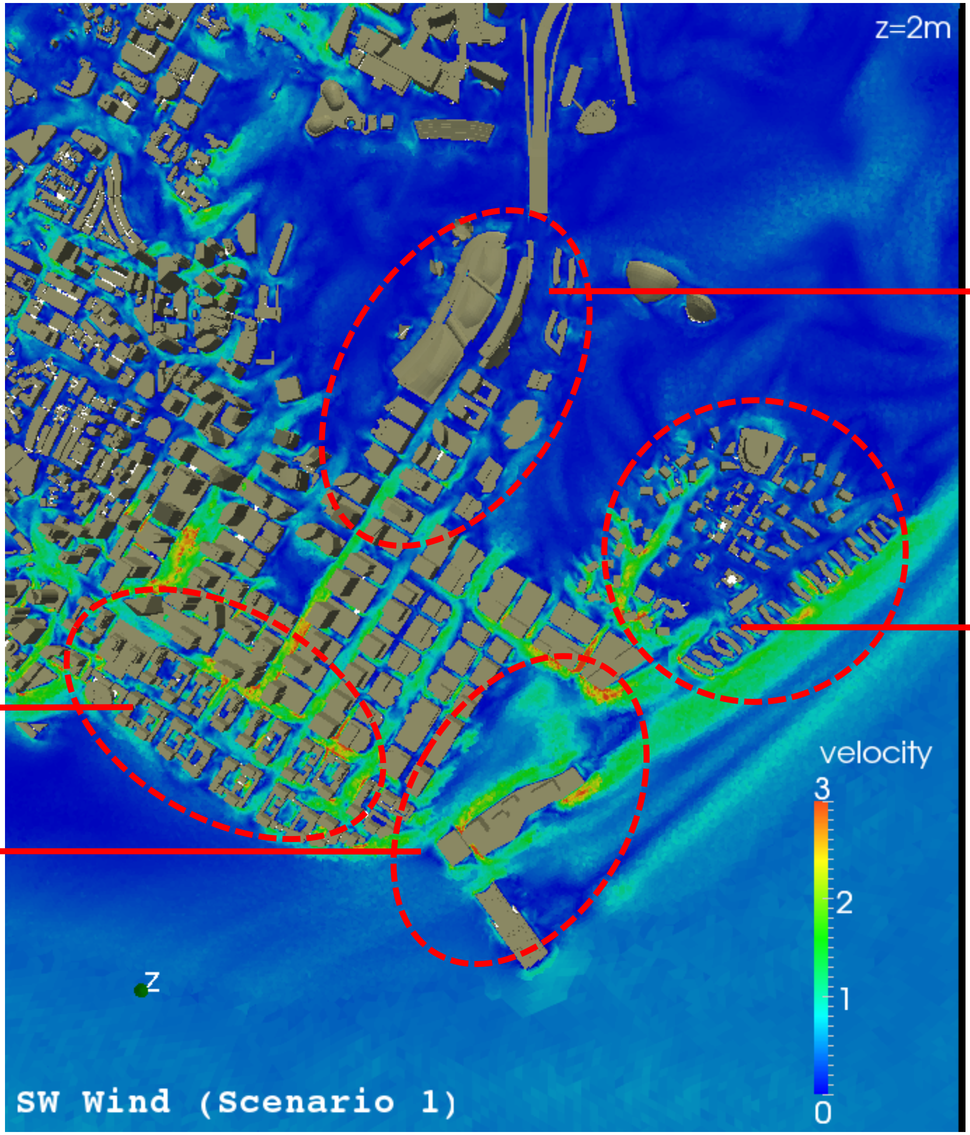
Urban Climatic Mapping Studies for Marina Bay, Singapore

- Objectives
  a. To provide inputs for land use planning that safeguard important environmental conditions from intensive urban development
  b. To reduce heat island effects and energy consumption and improve ventilation in high density environments
  c. To create more liveable and conducive life, work and play spaces in the city



Urban Climatic Mapping Studies for Marina Bay, Singapore

- CFD Wind Results – Scenario 1



Low wind velocity

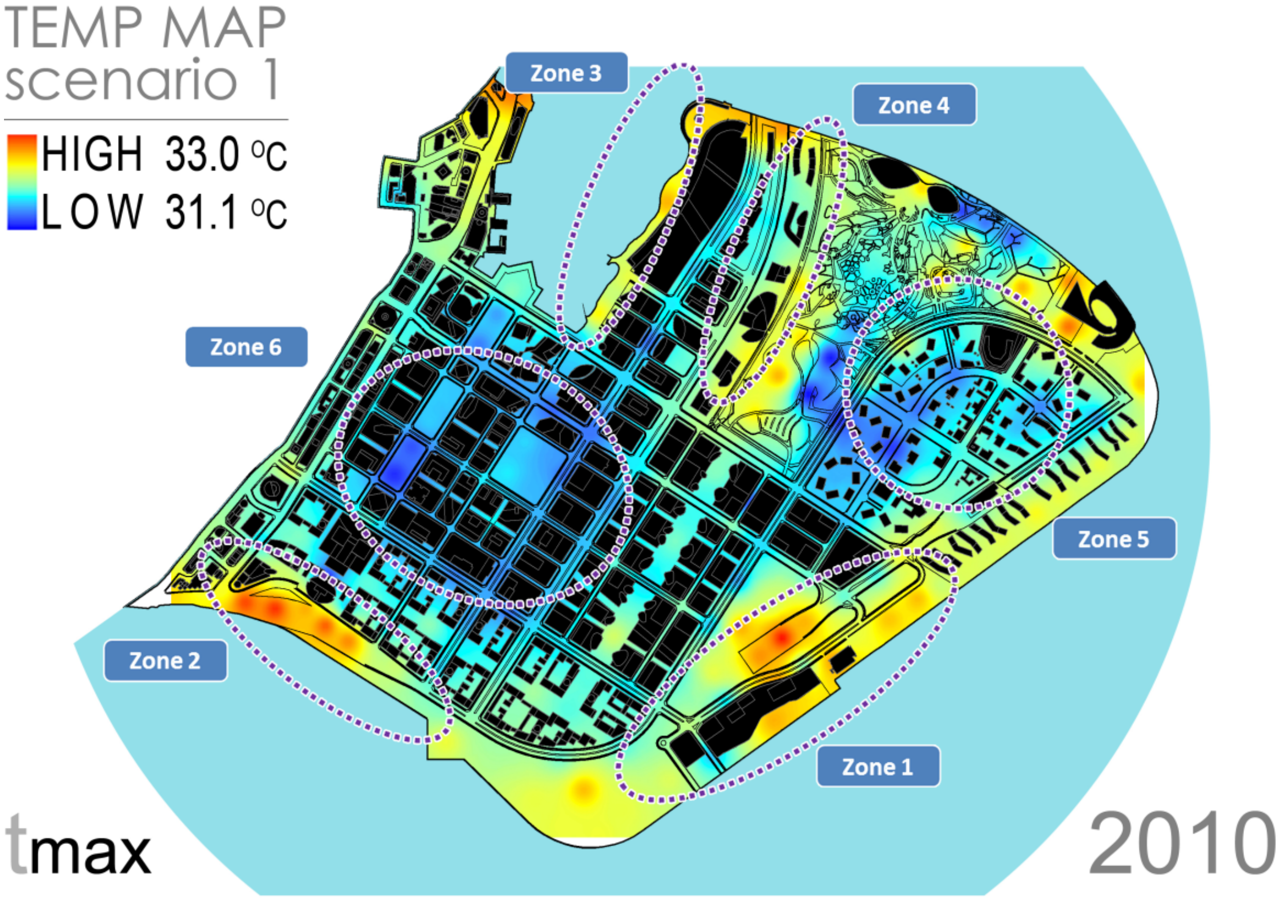
High & low wind velocity

High & low wind velocity

High & low wind velocity

Urban Climatic Mapping Studies for Marina Bay, Singapore

- Temperature mapping (NUS)



Scenario 1's climatic mapping findings highlight that **Zone 1**, **Zone 2** and **Zone 3** are identified to have **high air temperature and low wind movement**.

Urban Climatic Mapping Studies for Marina Bay, Singapore

Thermal Sensation Vote

Urban Thermal Comfort

TSV = 0.315Ta - 0.78V - 8.825

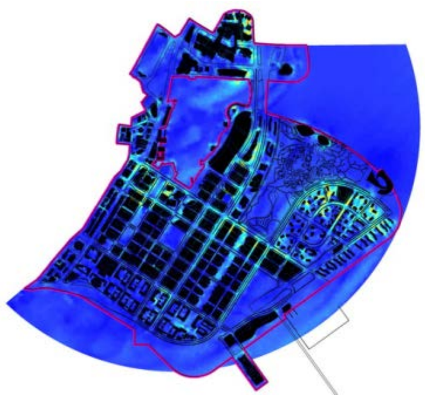
TSV = thermal sensation votes;

Ta = air temperature (degC);

V = wind speed (m/s).

Temperature Map (**GIS**)

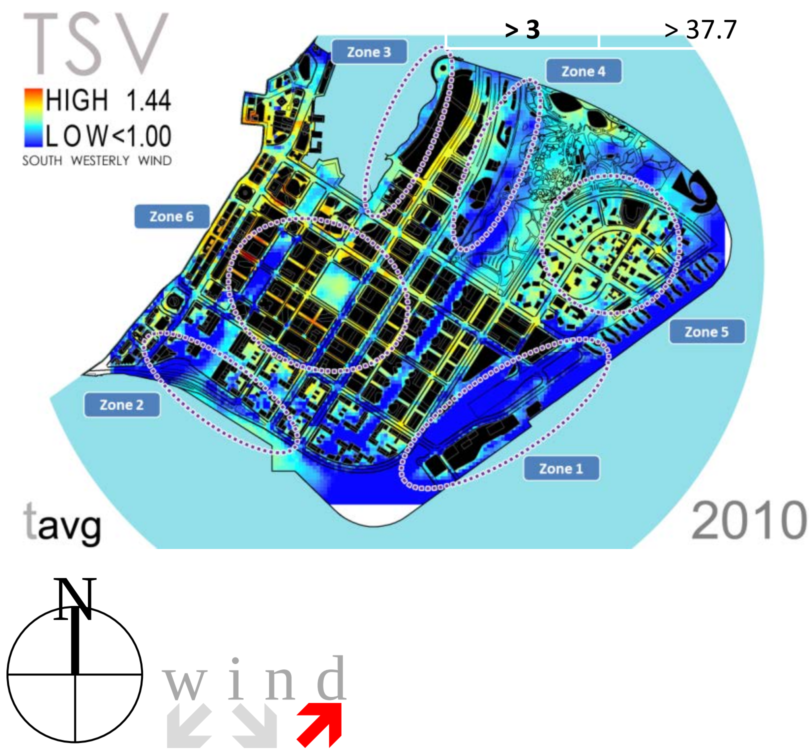
+



Wind Map (**CFD**)

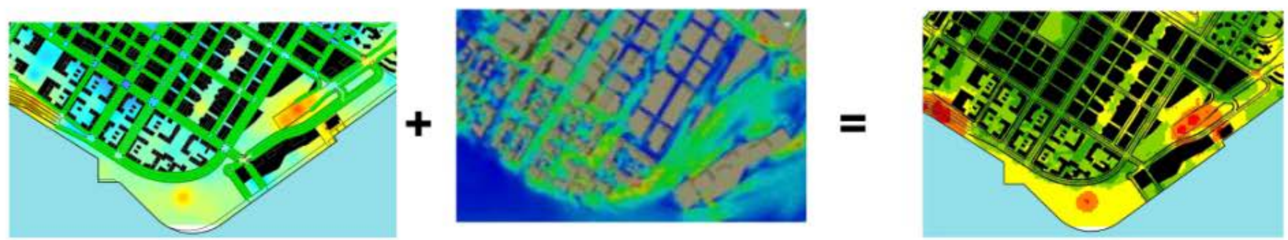
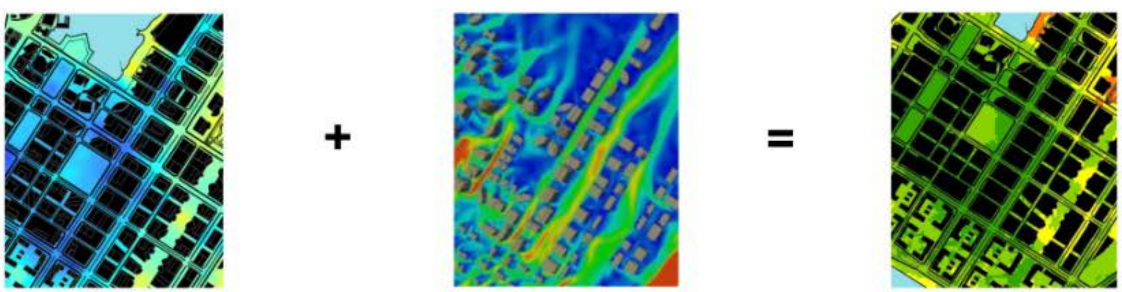
Acceptable TSV range for particularly for Singapore climate condition

TSV range	Ta range (°C)
-3 ~ -2	Not applicable
-2 ~ -1	22.4 ~ 25.4
-1 ~ 0	25.4 ~ 28.5
0 ~ 1	28.5 ~ 31.6
1 ~ 2	31.6 ~ 34.7
2 ~ 3	34.7~ 37.7
> 3	> 37.7



Urban Climatic Mapping Studies for Marina Bay, Singapore

- Urban Climatic Guides In Relation To Urban Geometry For Marina Bay Area

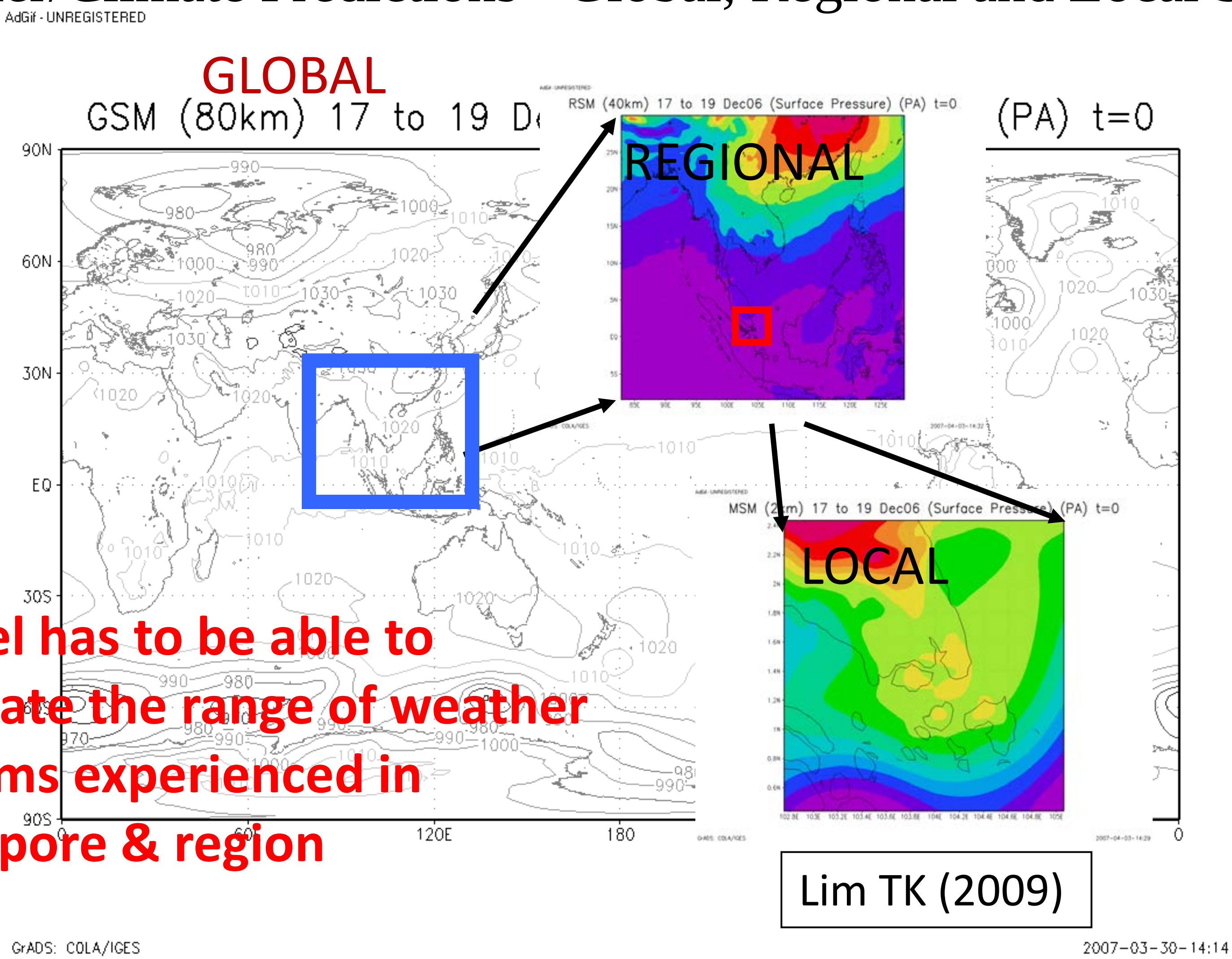
Urban morphology modifications and parameters	**Air temperature characteristics (in urban scale)**	**Wind ventilation characteristics (in urban scale)**	**Outdoor thermal comfort (in urban scale)**
Additional greenery at street level	Reduction of air temperature during daytime benefits from greenery effect	No significant changes. Requires micro-scale study.	Improve outdoor thermal comfort condition.
			
Landscape replacement scheme: -Additional sky garden and roof garden - Staggered building geometry - Increase building height	Reduction of air temperature during daytime benefits from greenery effect and building shading	Higher wind speed at and around the staggered level	Improve outdoor thermal comfort condition.
			

CFD Studies of Climate Change Impacts

- Methodology for Geospatial Risk Assessment of Wind Channels
  - Integrated GIS-based, coupled multi-scales models & data mining:
    - Weather/climate models (100m ~ 1km resolution)
    - Urban CFD modeling (1 ~ 10 meter resolution)
  - Case studies:
    - Northeast & Southwest Monsoons
    - Climate Change Effect
    - Severe Weather Impacts

CFD Studies of Climate Change Impacts

- Weather/Climate Predictions - Global, Regional and Local Scales

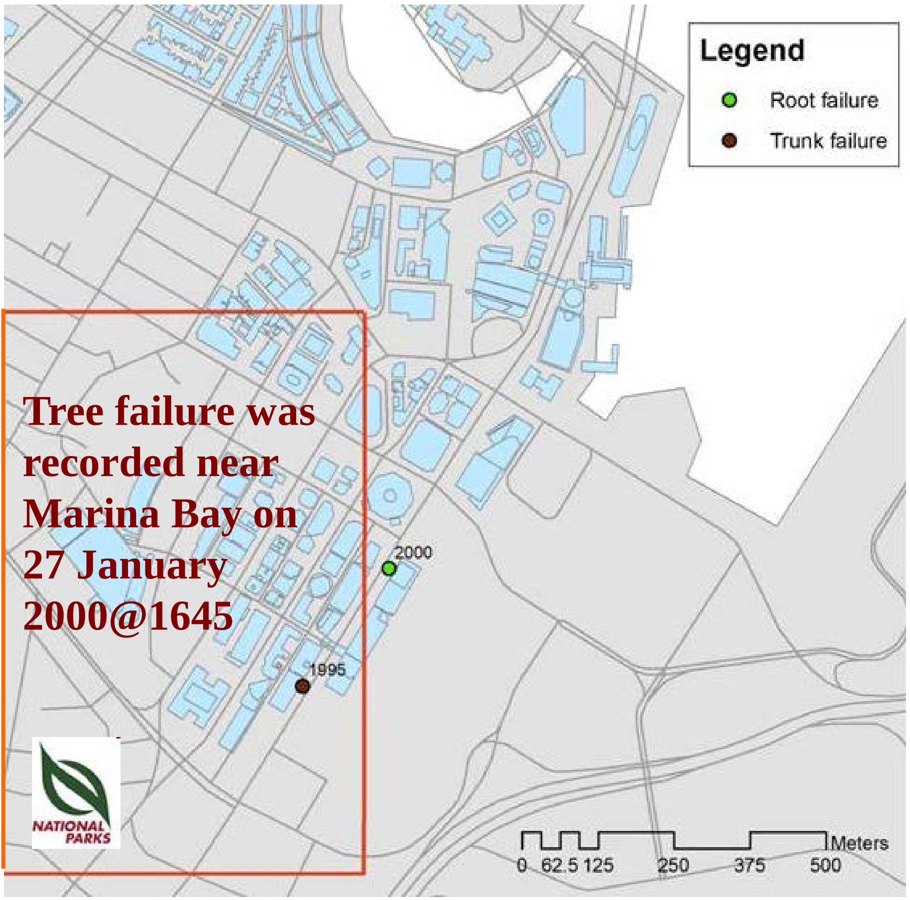


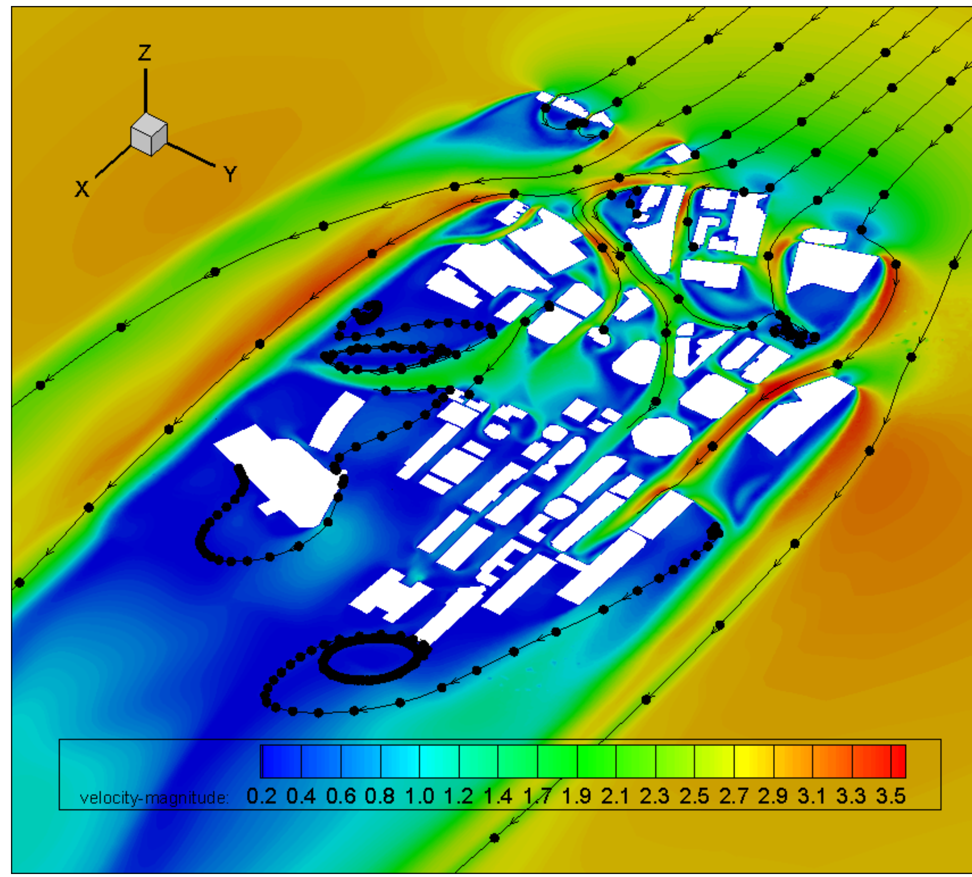
Model has to be able to simulate the range of weather systems experienced in Singapore & region

Lim TK (2009)

CFD Studies of Climate Change Impacts

- Computational Study on Impacts to Urban biodiversity

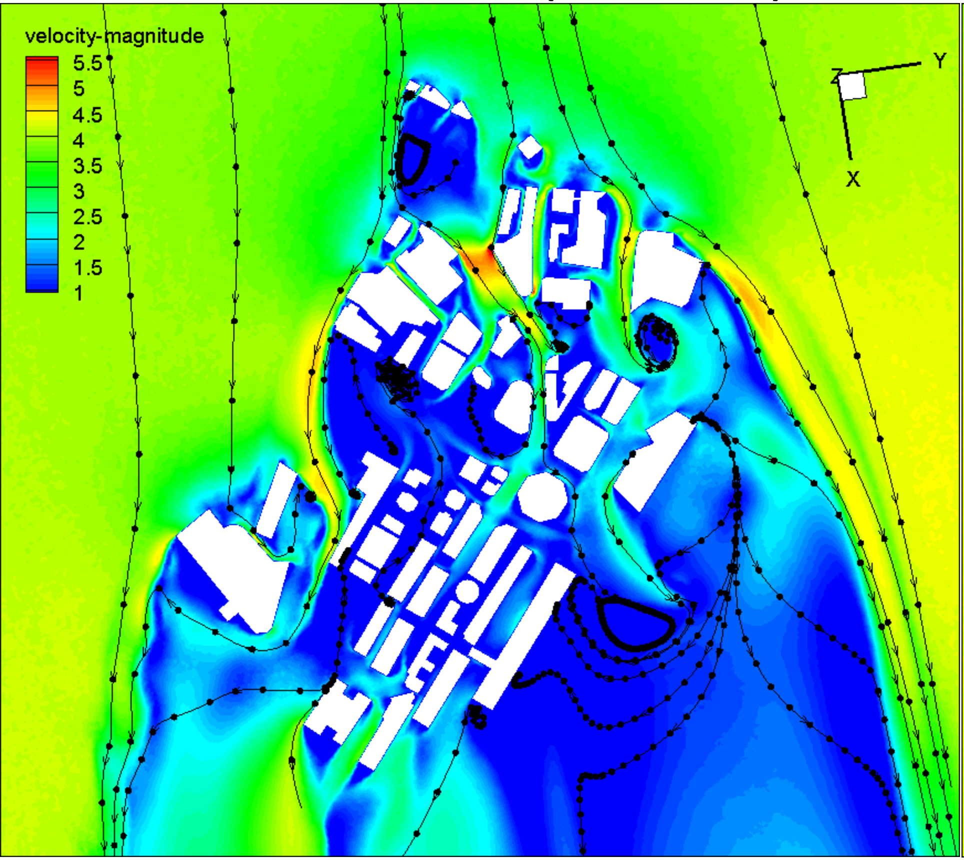




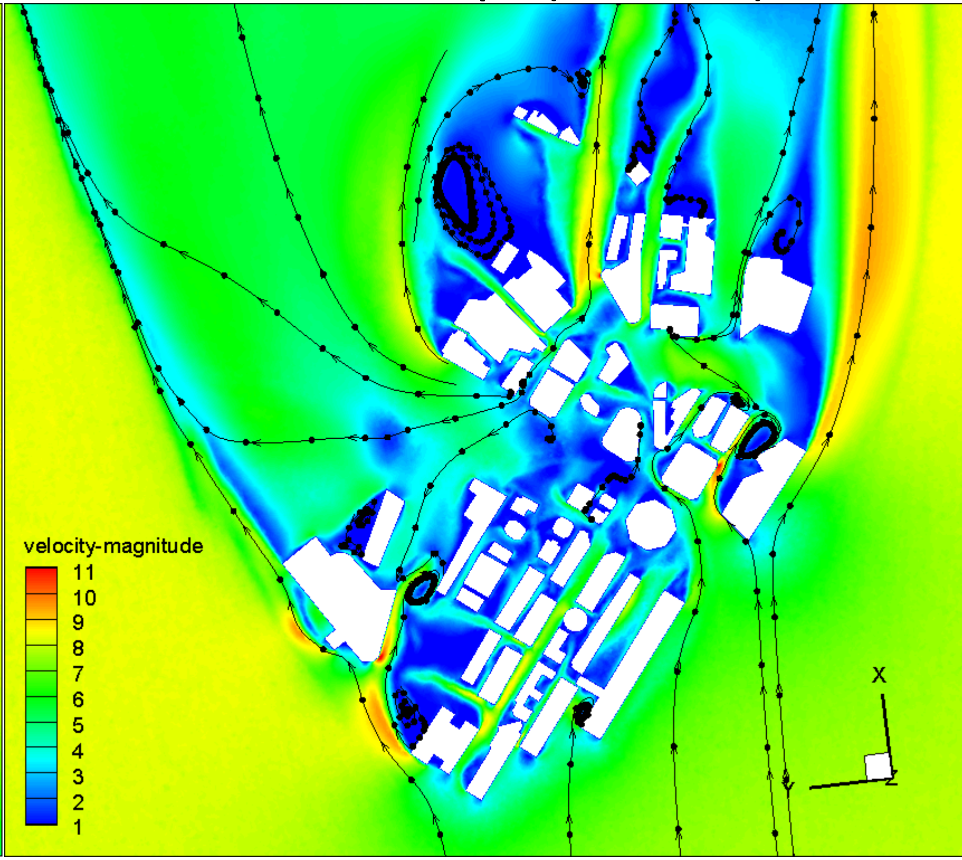
CFD Studies of Climate Change Impacts

- Severe Weather Impacts (Tropical Storm Vamei, Singapore, 27 Dec 2001) - Wind Flow: Before and After Storm

During the Approaching Phase of Vamei, 27 Dec 2001@ 5am (T=33 hours)



During the Receding Phase of Vamei, 27 Dec 2001, 10pm (T=50 hours)



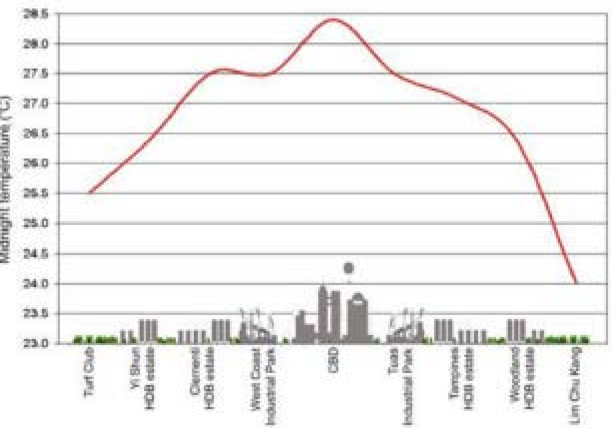
Downscaled wind flow (200km-1km-2m resolution) results from CFD model

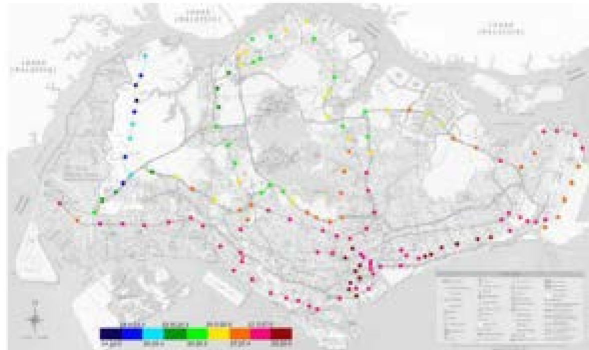
CFD initial wind condition: based on high resolution climate model (1km)

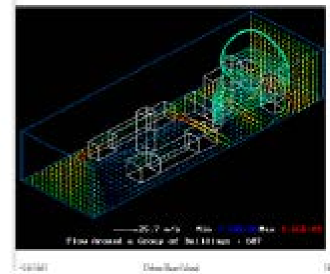
CFD Studies of Climate Change Impacts

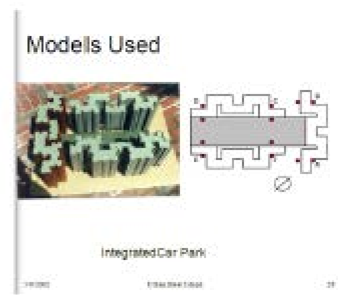
- Concluding Remarks
  - The local wind projections were conducted by employing various techniques, using available global monthly projection data (up to 2090), and local hourly historical data (1980-1999).
  - Coupling atmospheric models and CFD models provides an effective tool for urban wind risk assessment
    - of high wind speeds that may threaten tree failure, as well as understanding localised effects caused by climate change as well as severe storm events
    - of low wind regions that ventilation improvement may be required

Urban Heat Island Study in Singapore









- Taking spatial temperature profiles

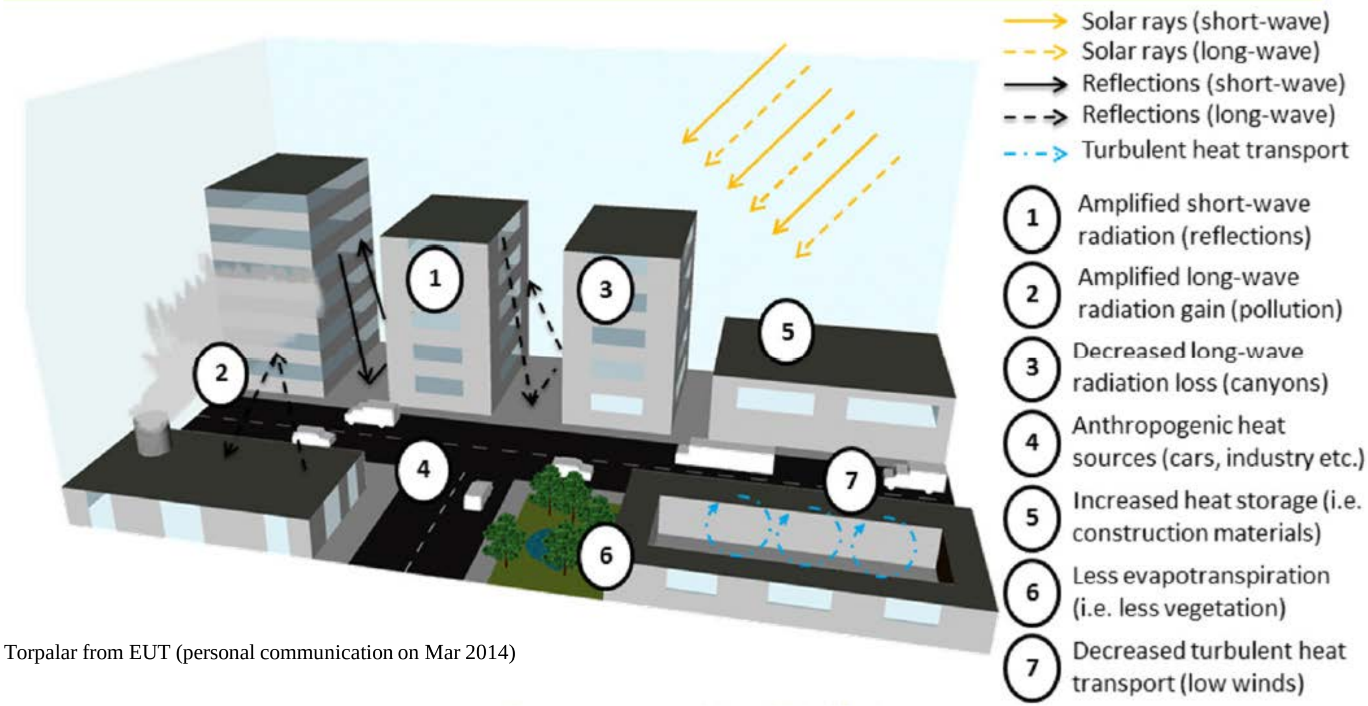
- Enhancing wind flow through wind tunnel and CFD studies
- Cooling surfaces by greenery and color change (albedo)
- Built artificial sun shading

- UHI effects:
  a. Increasing urban air temperature
  b. Deteriorating air quality and human comfort
  c. Increasing air conditioning cooling load and subsequently building energy consumption

Source: A study of Urban Heat Island (UHI) in Singapore *by Prof. Wong Nyuk Hien*

UHI – Causes

1. Canyon Radiative Geometry - multiple reflection of short-wave radiation between the canyon surfaces, decreasing the effective albedo of the system
2. Urban ‘Greenhouse’ - increased incoming long-wave radiation from the polluted and warmer urban atmosphere
3. Canyon Radiative Geometry - decreased long-wave radiation loss from within street canyons due to the complex exchange between buildings and the screening of the skyline
4. Anthropogenic Heat - heat released from combustion of fuels and animal metabolism
5. Thermal Properties - increased storage of sensible heat in the fabric of the city.
6. Evaporation - transpiration - reduction of evaporating surfaces in the city putting more energy into sensible, and less into latent heat.
7. Shelter - reduced turbulent transfer of heat from within streets



(Picture is courtesy of Torpalar from EUT (personal communication on Mar 2014)

T. R. Oke, et al, Simulation of surface urban heat islands under ‘ideal’ conditions at night part 2: Diagnosis of causation, Boundary-Layer Meteorology, Volume 56, Issue 4, pp 339-358, September 1991

UHI – CFD Research Opportunities

CFD Open-FOAM Multi-physics module

1. Simplified geometrical conversion to generate Water Tight 3D surface geometry
2. **Cut-cell meshing approach** to reduce computational burden
3. CFD modelling with coupling of the solar irradiance mapping **(building)**
4. CFD modelling of aerodynamic drag and cooling effect by **vegetation**
5. CFD modelling with **effect of land breeze & sea breeze**
6. CFD modelling with **anthropogenic heat** (manmade heat from commercial, industrial & **traffic**)
7. CFD modeling with **water body** effect
8. CFD modeling with **topographic terrain**
9. CFD analysis with **time dependent mode for reduced scale street level** with soil layer inclusion for two separated domain on built urban areas and rural hinterlands to capture the dynamic heat storage effect and hence the diurnal Urban Heat Island phenomena.

UHI- CFD Research Activities in Singapore

Quantitative Urban Environment Simulation Tool (QUEST) *(Led by A1)*

Climate Downscaling (WP1) (NEA, NOAA)
- Downscaled temperature, wind data etc for Singapore to 1km resolution.
- For baseline climate and future climate change scenarios

Geospatial Data (WP2) (SLA, NUS)
Prep geospatial data for whole Singapore from SLA's LIDAR survey for CFD

CFD Simulation Tool (ASTAR, NEA, NUS)

Thermal Comfort Index (WP4)
- Considers Singaporean's perceptions of thermal comfort (in relation to wind speed & temp)

Computational Fluid Dynamics (Version 1) (WP3)
- Uses available solar radiance inputs from existing Daylight Simulation software
- Generate wind and temperature data

Calibration and Validation with sensors @ Jurong Lake District (WP5)

Modelled Areas (by Q4 2015)
- Whole of Singapore (~700 sqkm)
- Temperature, wind and thermal comfort
- For baseline climate and future climate scenarios

Urban Microclimatic - Multi-Physics Integrated Simulation Tool (UM-MIST) *(Led by A2)*

Climate Inputs
Weather information from meteorological stations

Geospatial Data
Obtained from URA/HDB's 3D models

Integrated Multi-Physics Tool (ASTAR)

Computational Fluid Dynamics (Version 2) (WP1)
- Uses more detailed solar radiance inputs from improved daylight simulation software in WP2

Daylight Simulation (WP2&4)
- Improve daylight simulation software to model more complex lighting situations and behaviour
- Requires 2 years

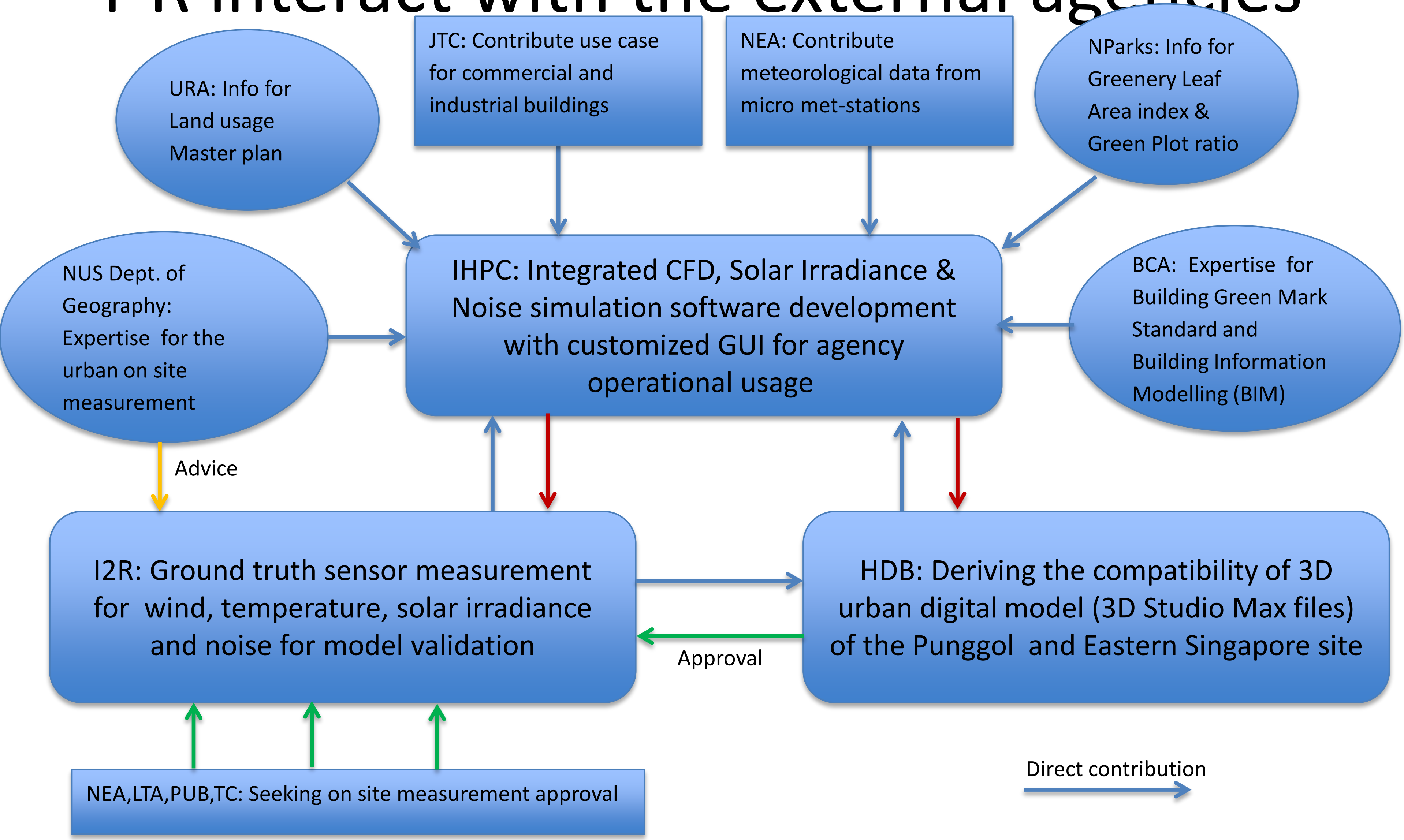
Sound Wave Simulation (WP3)
- Improve noise simulation methodology to model more complex sound behaviour

Calibration and Validation with sensors @ Punggol (WP5)

Modelled Areas (by Q4 2017)
- Quarter to half of Singapore (~400 sqkm)
- Temperature, wind, solar irradiance/shading, noise
- For baseline climate scenario

Common urban environment simulation tool used by agencies

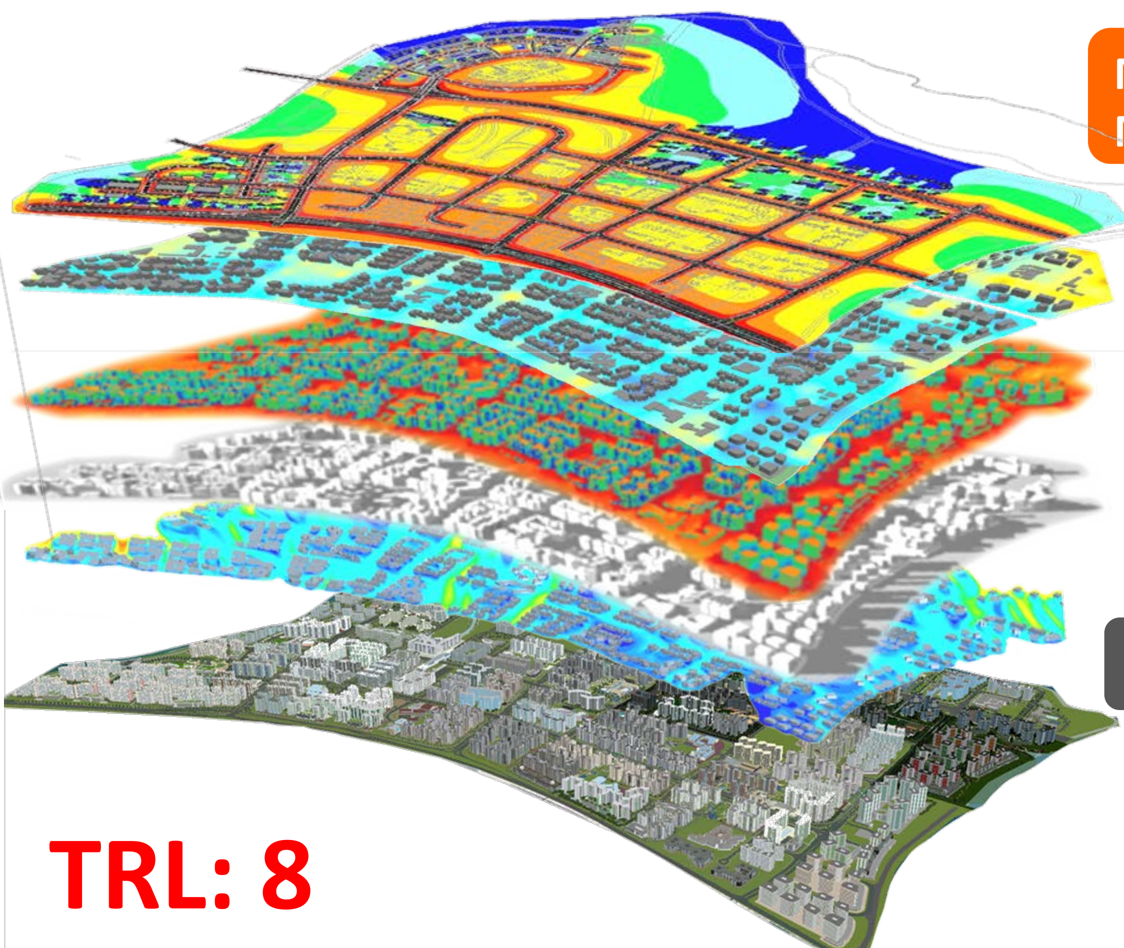
Workflow chart showing how IHPC and I^{2}R interact with the external agencies



UHI- CFD Research Activities in Singapore

Research Objectives

Integrate whole process(Master planning, urban design & environmental modelling)



Multi-Physics Modelling Platform

- Noise Map
- Thermal Map
- Solar Irradiance
- Shadow
- Wind Map

Iterative process

Urban Digital Model

- Planning & Urban Visualisation

TRL: 8

UHI- CFD Research Activities in Singapore

3D Digital Model

Research Methodology

Solar Irradiance & Shading

- Model Pre-processor
- Develop a surface mesh generation algorithm
- Develop hybrid (forward and backward ray-tracing) solver
- Validation with DIVA

Wind Flow & Temperature

- Conversion to Water Tight 3D surface geometry
- OpenFOAM Mesh Utility – Cut Cell Mesh
- Develop OpenFOAM Multi-physics CFD Solver
- Validation with STAR-CCM+

Noise Mapping & Propagation

- Model Pre-Processor
- Meshing
- Develop coupled numerical and geometrical noise modelling algorithm
- Validation with CadnaA

Coupling solar irradiance with CFD

Coupling CFD with Noise

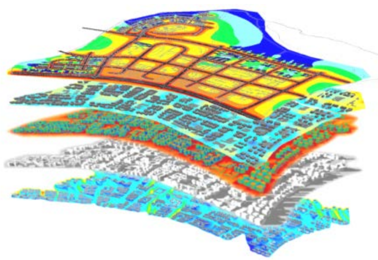
Validation with field measurement(Solar irradiance, wind, temperature, noise)

Integrated Modelling Tool

- Customized GUI for agency operational usage
- Scalable with potential to integrate more tools in future

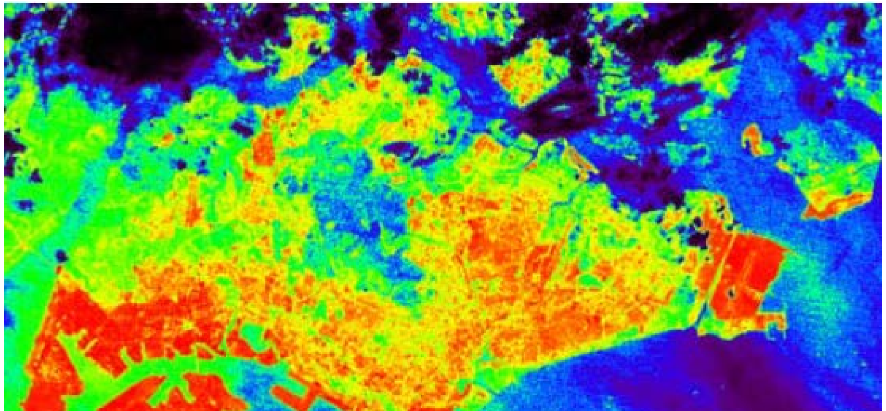
Results to GIS layers

- Impact of planning &UD on environment
- Develop mitigation guides upstream

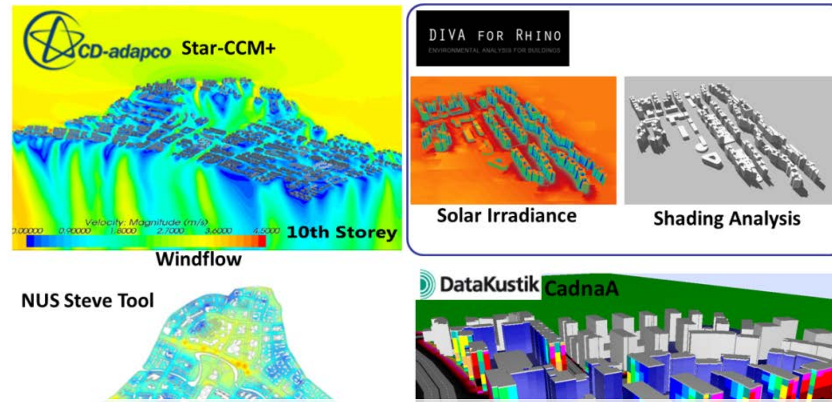


UHI- CFD Research Activities in Singapore

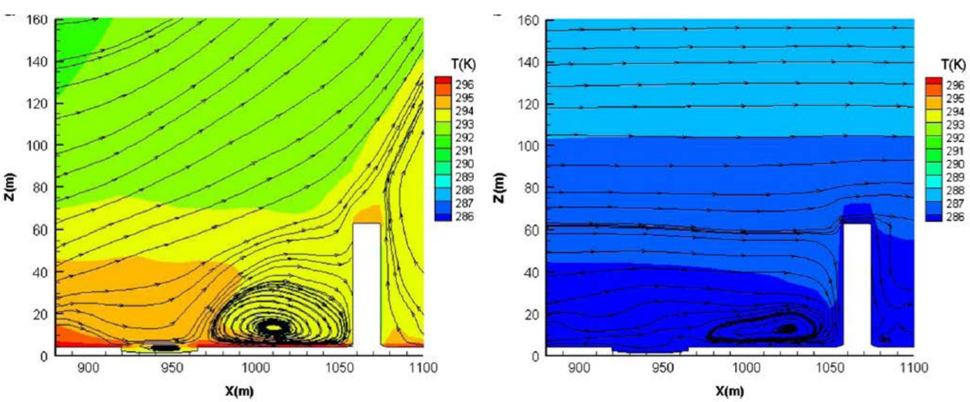
Novelty



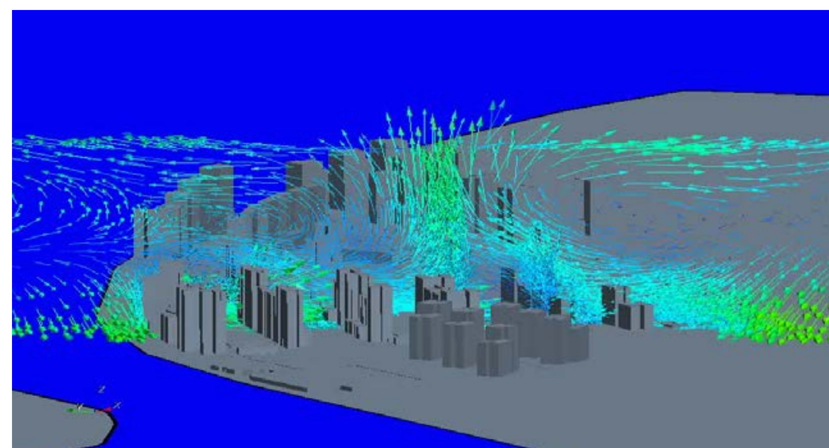
Account for vegetation, water bodies, anthropogenic heat sources



Integrated modelling platform developed based on open source code



Coupling wind flow (CFD) with solar irradiance simulation

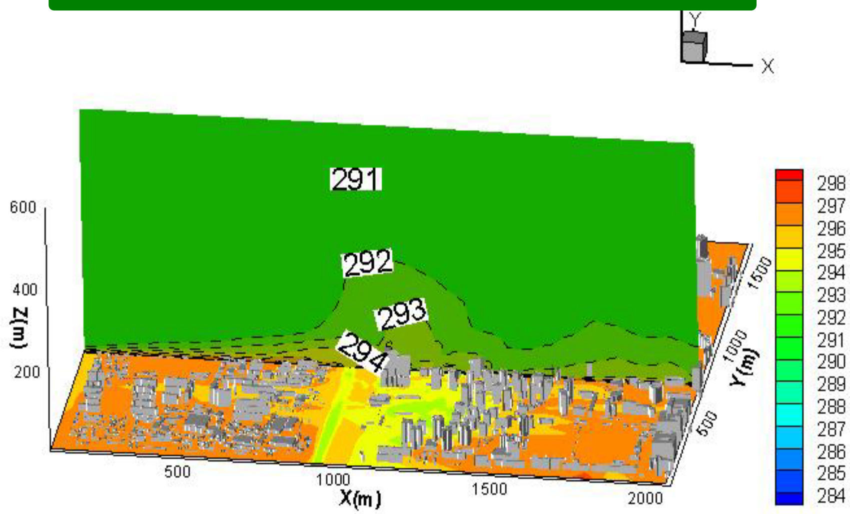


Land & sea breeze effect for coastal area

Urban Heat Island simulation

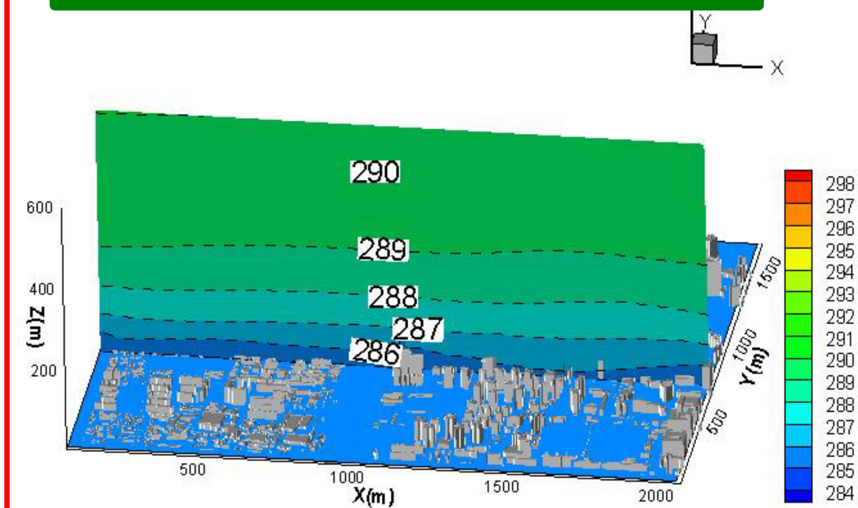
- Urban Thermal Environment with LES simulation

Temperature at daytime



Intense solar radiation

Temperature at night



Without solar radiation

Closure

- CFD application for Environmental Fluid Mechanics modeling has becomes increasingly important
- BCA Green Mark Platinum Series – CFD to drive design improvement for natural ventilation system is required - involve concerted effort from owner, architect and ESD consultants
- Good prediction and decision making for environmental fluid mechanics modeling to achieve urban planning and sustainability needs:
  – Bottom up approach : details urban geometry elements coupled with multi-physics CFD model
  – Top down approach : accurate weather prediction coupled with multi-scale CFD model
- Large scale super computing resources is required for billion cells environmental flow simulation for Singapore Island