URBAN FLOW MODELING AND SOLAR FORECASTING USING HIGH-PERFORMANCE COMPUTING

Harish Gopalan, Venugopalan Raghavan , Senthil Kumar Selvaraj, Chin Chun Ooi, Arthur Teck-Bin Lim, George Xu, Pao-Hsiung Chiu, Su Yi, Poh Hee Joo and Lou Jing

Fluid Dynamics Department

Institute of High Performance Computing

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Table of Contents

FLUID DYNAMICS Department

Making a Splash in Fluid Flows

Mission:

To develop cutting edge modelling and simulation technology for fluid flow, thermal/mass transfer and fluid related multi-physics applications. The research focuses on insight of fluid physics, advanced flow solutions, and support industry innovation through simulation and design optimization.

FLUID DYNAMICS Research Foci

Coupled & multiphase flow

- Multiphase flow
- DEM + CFD coupling
- Climate model + CFD coupling
- Multiphysics coupling

Computational geometry, design & optimization

- Geometry & meshing
- Adjoint solvers
- Multi-fidelity control and design optimization
- Uncertainty quantification

Engineering fluids flow

- Viscoelastic flow
- Particle-laden flow
- Complex flow in advanced manufacturing

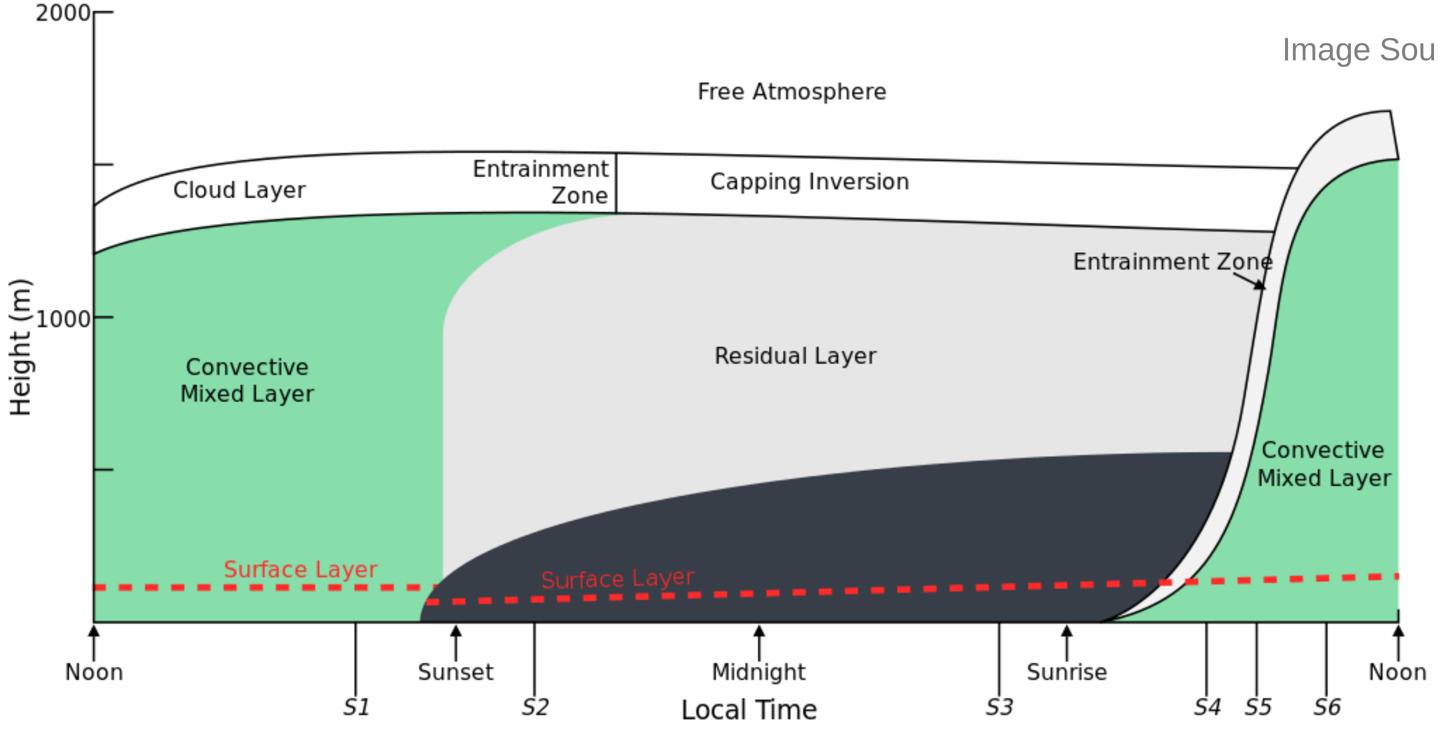
Physics-based data driven modelling of flow

- Data-driven surrogate modelling
- Physics-driven AI
- Model order reduction
- Inverse problem

Urban Flow Modeling – Physics

Atmospheric Boundary Layer

Image Source: Wikipedia



1. Climate models (Eg. WRF, SINGV, COAMPS, ECWMF, COSMO….)
2. ABL meteorological models (Eg. PALM - LES)
3. Somewhere in middle (Eg. Envi-Met)
4. Computational fluid dynamics (Eg. OpenFOAM, Fluent, starCCM,..)

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Computational Fluid Dynamics

- Applicable only within the surface layer
- Coriolis and geostrophic forcing neglected
- Monin – Obukhov similarity theory (MOST) can be applied

Image Source: Bing (Creative Common License)

Computational Fluid Dynamics Ingredients

1. Governing Equations
2. Inflow boundary condition
3. Wall boundary condition
4. Upstream and Downstream region
5. Representing structures
   a) Buildings
   b) Roads
   c) Water bodies
   d) Terrain
   e) Trees

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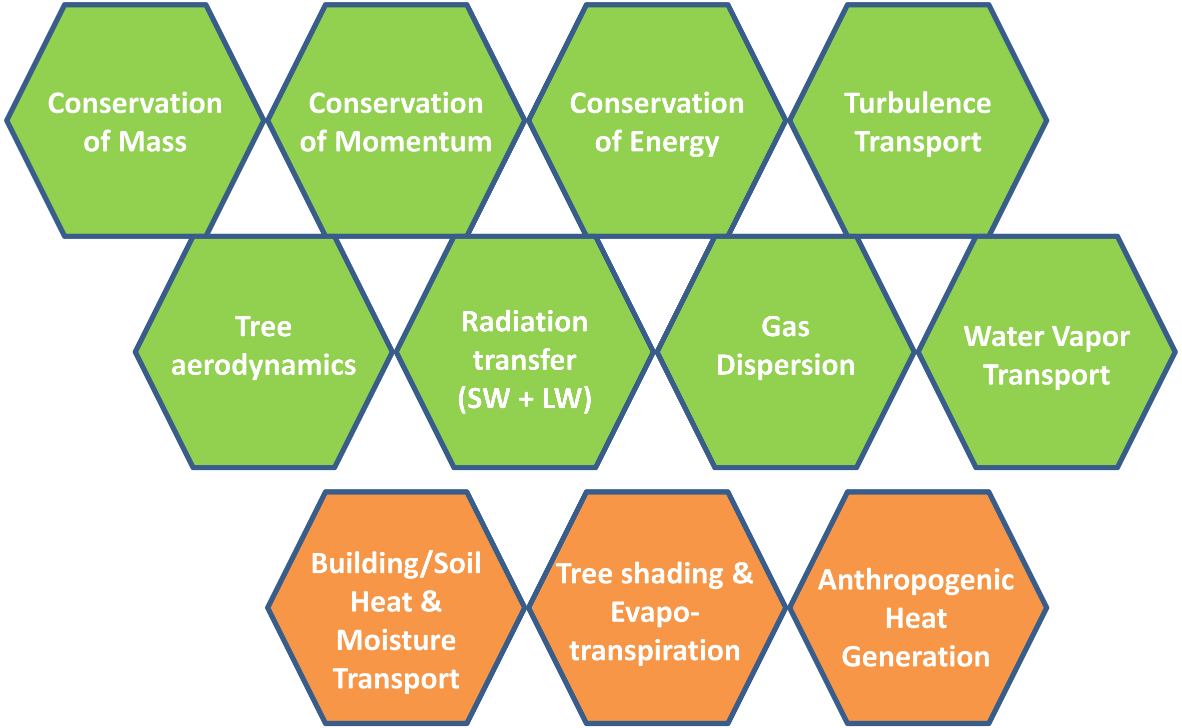
Governing Equations



Most existing codes include first 2 rows and some can all 3

Inflow Boundary Condition – MOST

$$\text{Wind Speed: } u = \frac{u_*}{\kappa}\left[\log\left(\frac{z+z_o}{z_0}\right) - \psi_m\left(\frac{z}{L}\right) + \psi_m\left(\frac{z_o}{L}\right)\right]$$

$$\text{Temperature: } T = T_w + \frac{T_*}{\kappa}\left[\log\left(\frac{z+z_o}{z_0}\right) - \psi_h\left(\frac{z}{L}\right) + \psi_h\left(\frac{z_o}{L}\right)\right]$$

$$\text{Relative Humidity: } \mathrm{w} = w_w + \frac{w_*}{\kappa}\left[\log\left(\frac{z+z_o}{z_0}\right) - \psi_h\left(\frac{z}{L}\right) + \psi_h\left(\frac{z_o}{L}\right)\right]$$

$$\text{Turbulence: } \nu_t = \frac{u_*\kappa z}{\phi_m\left(\frac{z}{L}\right)}$$

- u_* Friction velocity and calculated from reference data
- z_0 Davenport roughness length
- L Monin-Obukhov length
- $\psi_{m,h}$ and ϕ_m are well-known empirical functions

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Wall Boundary Condition

- Wind, turbulence and relative humidity: same boundary condition as inflow
- Temperature – Surface energy balance

$$SW + LW = SH + G + LH + A$$

  - SW – Direct, diffuse and reflected short-wave radiation
  - LW – Direct, and reflected long-wave radiation
  - SH – Sensible heat-flux due to turbulence
  - G – Ground heat-flux
  - LH – Latent heat-flux
  - A – Anthropogenic heat generation

$$SW + LW = -\rho_a c_p \frac{\nu_{tw}}{Pr_t} \frac{\partial T}{\partial n}\bigg|_w$$

- What if ν_{tw} is zero?

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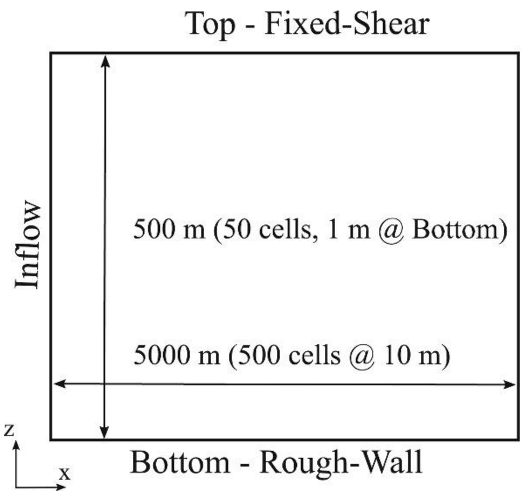
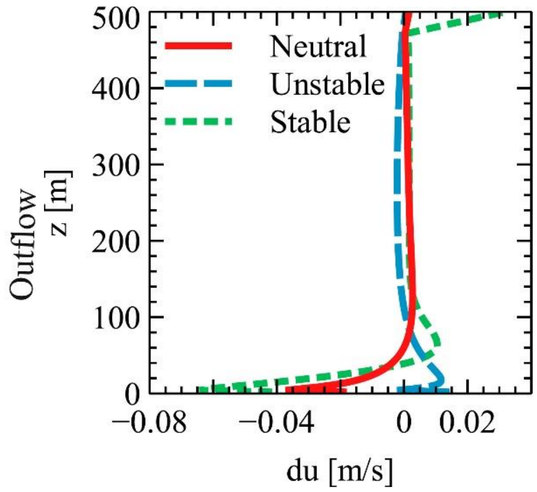
Upstream and Downstream Region

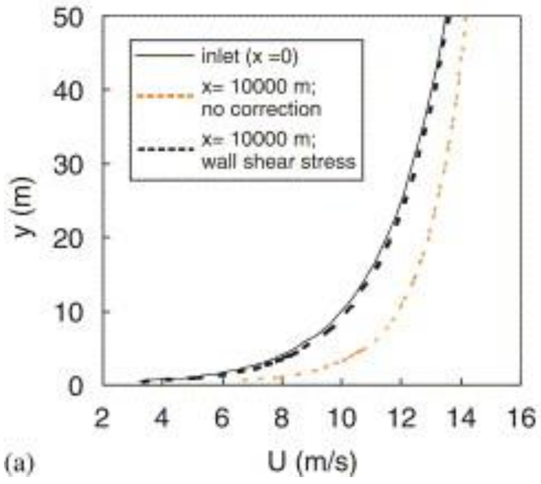
- Non-reflecting boundary condition in downstream
- Homogeneity in upstream
- Most codes cannot sustain homogeneity for long upstream regions
- Use MOST to avoid acceleration/deceleration of upstream wind



ABL Homogeneity Test



OpenFOAM – Using MOST



Blocken et. al

Representing Structures

- Buildings – 3D models
- Roads and water-bodies – 2D surface with modified roughness length
- Terrain – Usually neglected
- Trees – Aerodynamics, shading and evapotranspiration
  - Aerodynamics – Porous media model
  - Shading and evapotranspiration – Not available in most codes

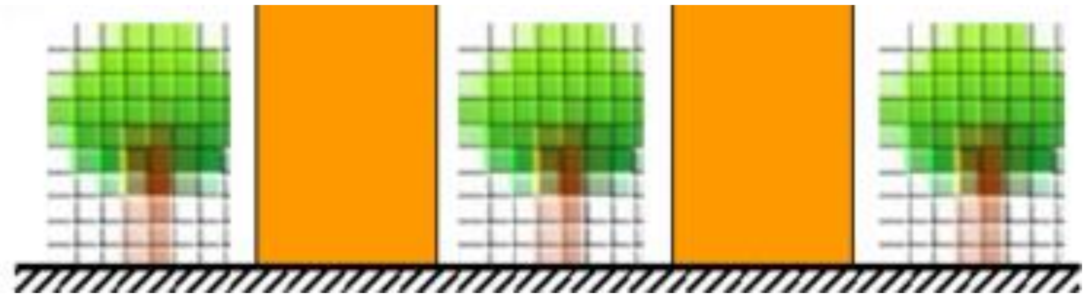


Image Source: Salim et. al (2015), JWEIA

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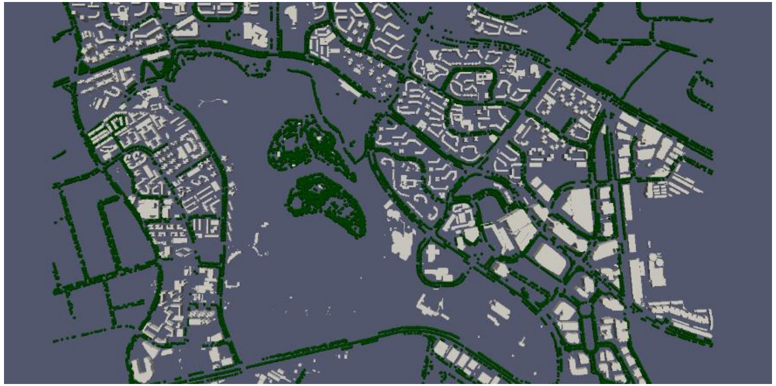
Tree Aerodynamics

- Momentum equation includes an extra drag term $F_{di} = -C_d L(z) u_i |u_i|$
- Turbulence equations include turbulence production/dissipation terms due to wind-tree aerodynamics



- Results for Jurong Lake District
- Simulated for QUEST project*

* Development of Quantitative Urban Environment Simulation Tool (QUEST)

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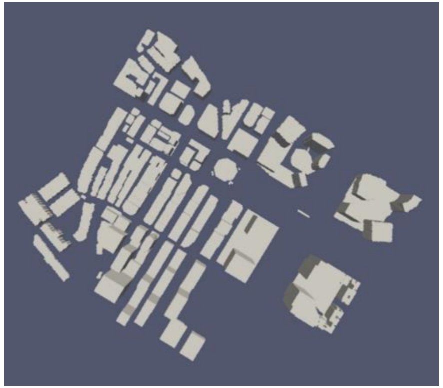
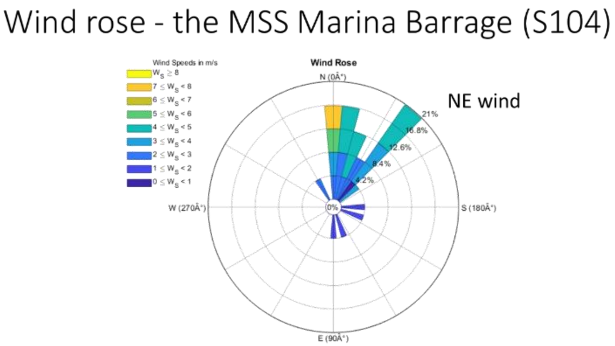
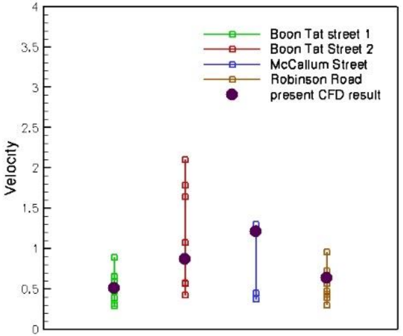
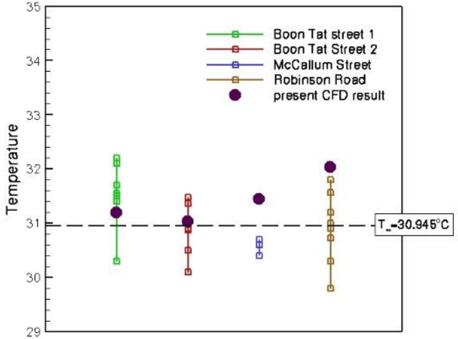
Validation and Verification (V & V)

- Many urban physical processes are simplified in simulations
- V & V helps to quantify the modeling errors*









* Cooling Singapore 1.5: Virtual Singapore Urban Climate Design

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Urban Flow Modeling – Enhancing Usability

Simulation of COmplex Urban Topology (SCOUT)

- Improving usability and functionality of existing open-source code OpenFOAM for urban flow modeling
- Development inspired from environmental assessment projects performed for URA (QUEST), and HDB (IEM)
- Backend frameworks
  - SCOUT – Core
  - SCOUT – Python: Python wrappers for SCOUT – Core
- Frontend frameworks
  - SCOUT – GUI (MPA, SMI)
  - SCOUT – Widget (MND, GovTech, NParks, HDB)
  - SCOUT – Cloud (Current in-house development) : Single platform for urban microclimate and energy forecasting framework

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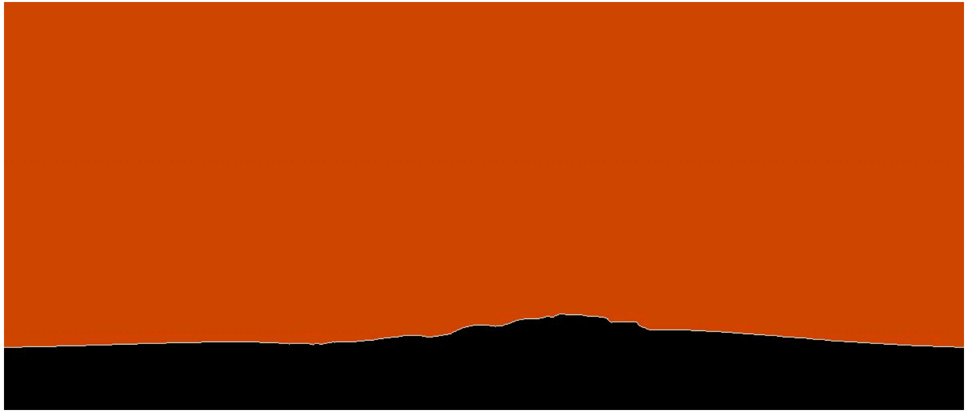
SCOUT – Core

- Enhancements to OpenFOAM or other open-source codes to improve usability
- Meshing
  - shapefile to STL converter
  - Parallel blockMesh (https://github.com/venugopalansgr/OpenFOAM)
  - Terrain mesher
  - surfaceSplitter
- Libraries
  - Radiance interface to OpenFOAM (https://github.com/hgopalan/RadianceToFoam)
  - MOST consistent boundary conditions and turbulence model
  - Tree aerodynamics
  - Tree shading and evapotranspiration
  - Building thermal storage
- Solvers
  - Improved steady solver
  - Multi-design solver
  - Unsteady nudged solver

Terrain Mesher

- Terrain meshing two options: snappyHexMesh or moveDynamicMesh

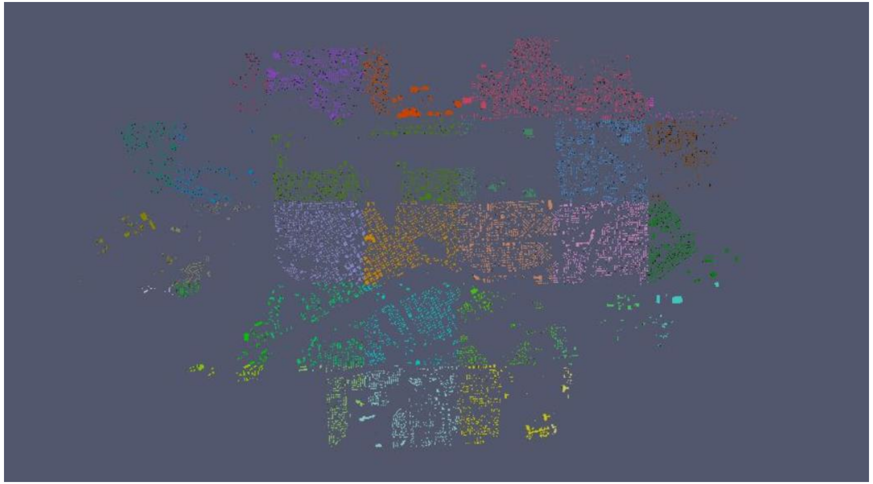
snappyHexMesh – no snapping

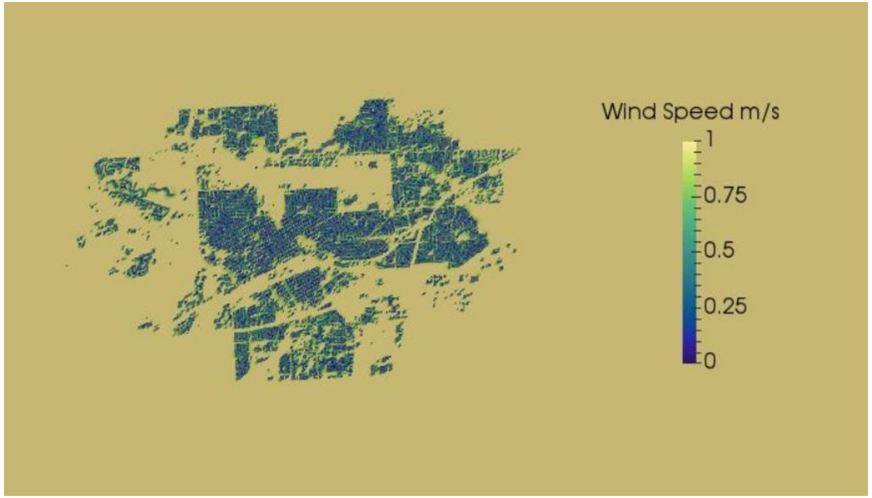


makeTerrain utility

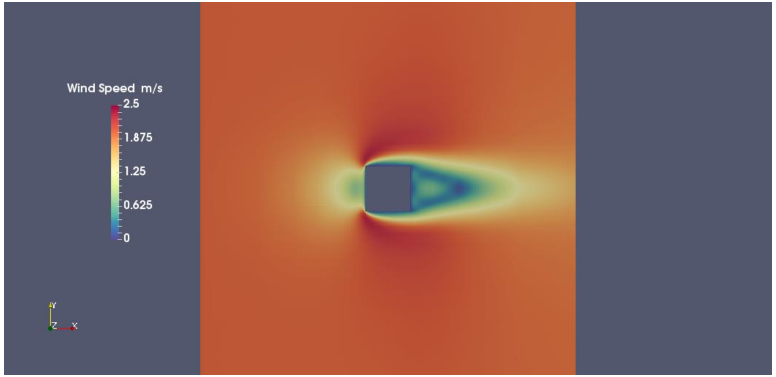
surfaceSplitter

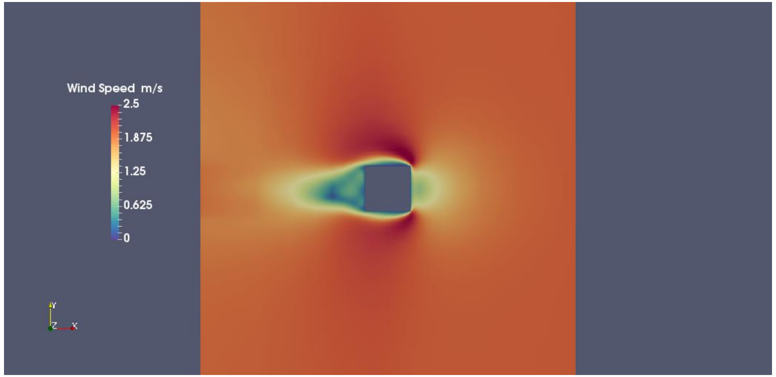
1. Shapefile to STL or import STL
2. Splitting and regrouping of STL based on Machine-learning classification techniques
3. Native OpenFOAM

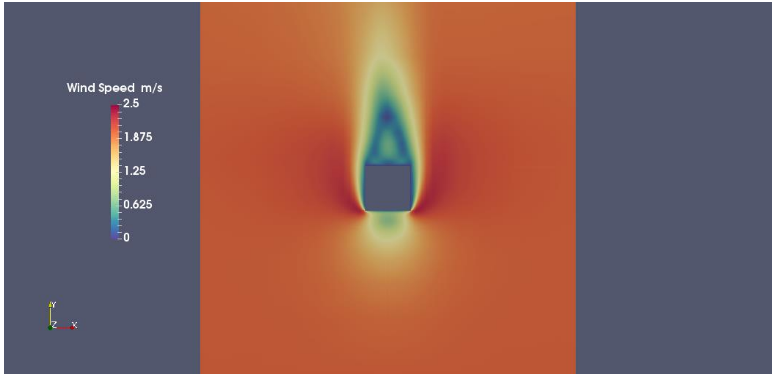




Multi-Design Solver







- Multiple design cases in one setup
- Automatic inflow/outflow
- Change – Wind speed, and direction ; temperature ; cloud condition
- Add/remove trees
- Add remove buildings (immersed-body)

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SCOUT – GUI*

- Design a Windows GUI for a solver designed to run on HPC system
- Windows client – Preprocessing, and user-interaction
- Linux server – Running simulations and post-processing
- Network folder – Samba
- Background solver execution and data transfer through TCP
- Features
  - Built-in preprocessor
  - Easy case setup
  - Intelligent mesher
  - Remote post-processing

* Modeling of Air Flow, Thermal and Chemical Gas Dispersion Towards Next Generation Port (Tuas Maritime Hub)

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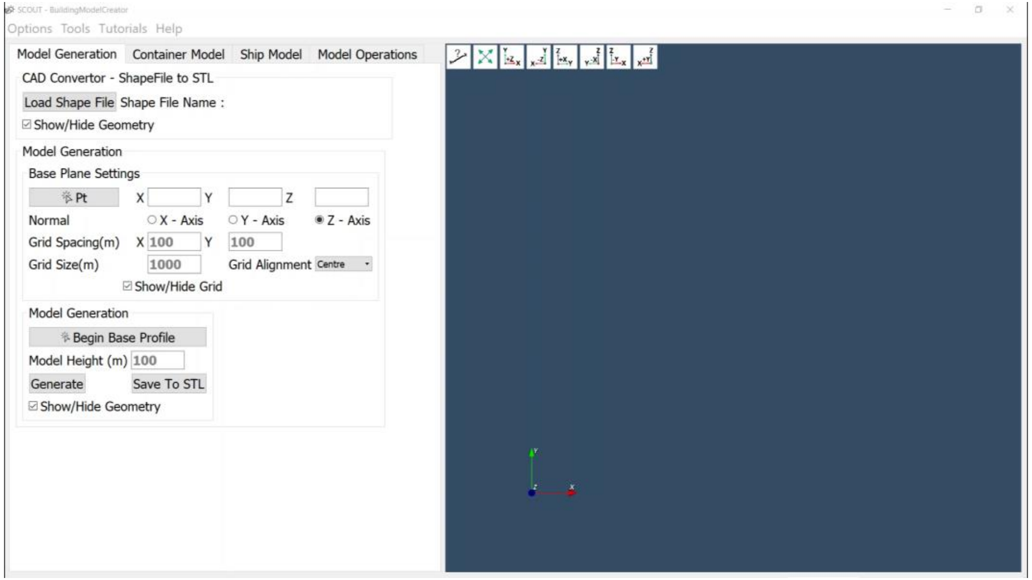
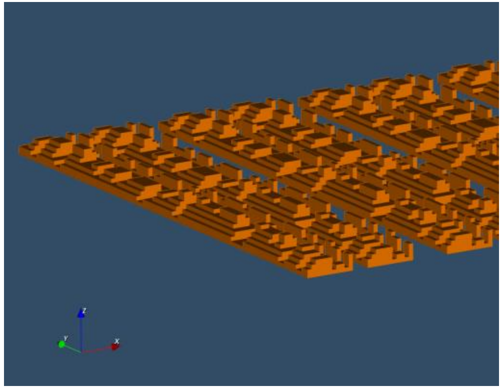
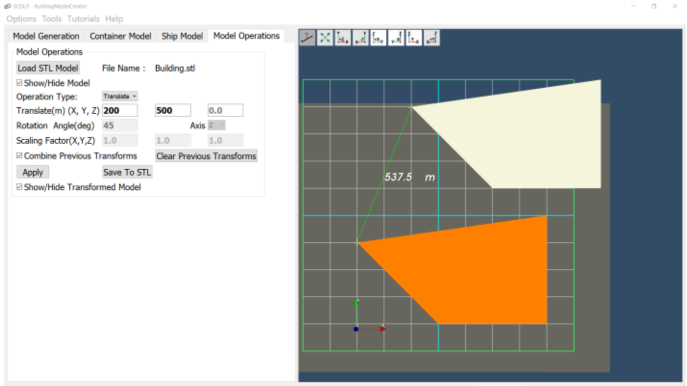
Preprocessor

- Not a CAD replacement
- Shapefile converter
- Building model
- Container model
- Ship model
- CAD operations

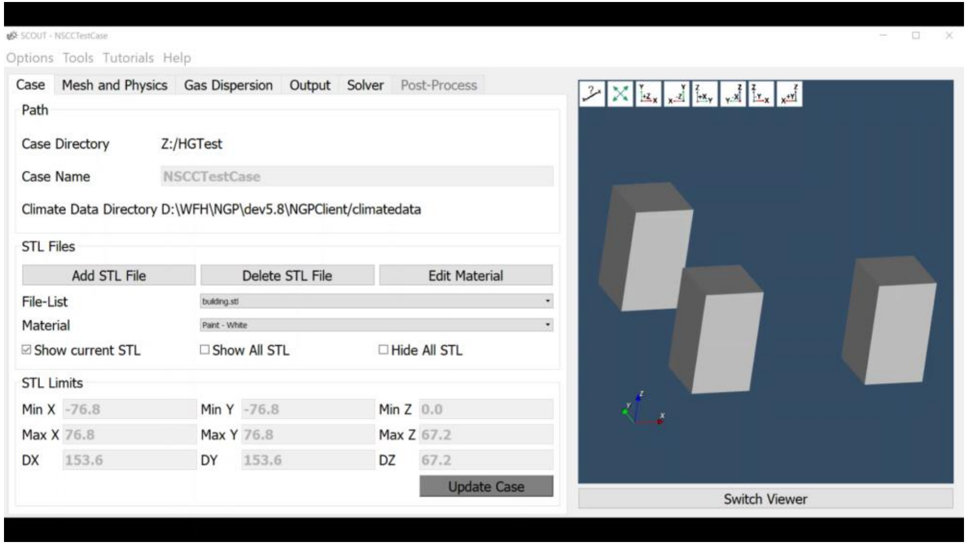






Case Setup

- Takes less than 10 minutes to setup case
  - Load CAD model and assign material property
  - Setup mesh requirement
  - Choose data, time and input data for simulation
  - Choose gas release point
  - Run simulations



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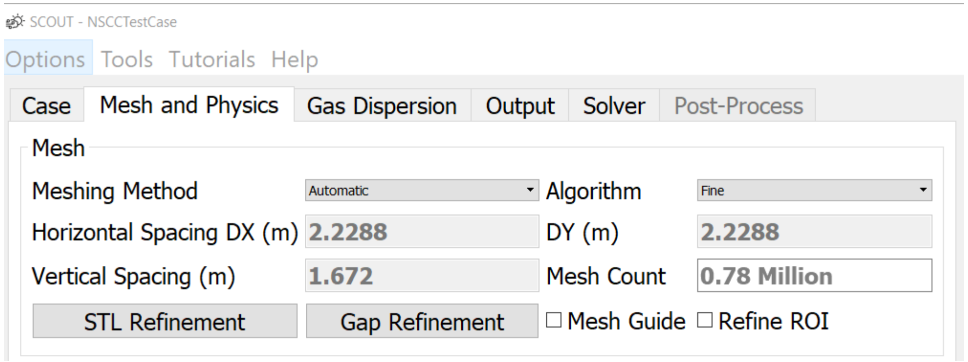
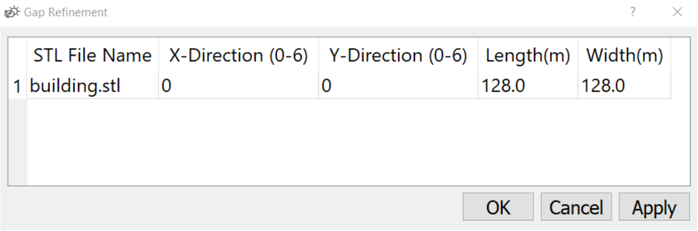
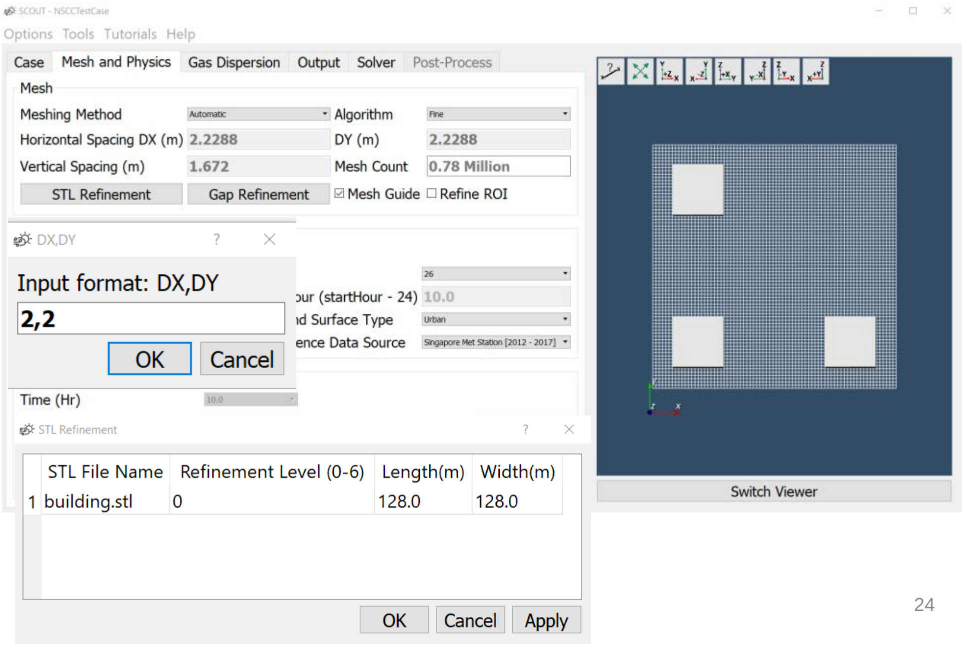
Intelligent Mesher

- Simple to use
- Keeps mesh count low
- Four step meshing
  - Step 1: Automatic mesher
  - Step 2: Mesh guide
  - Step 3: STL refinement
  - Step 4: Gap refinement





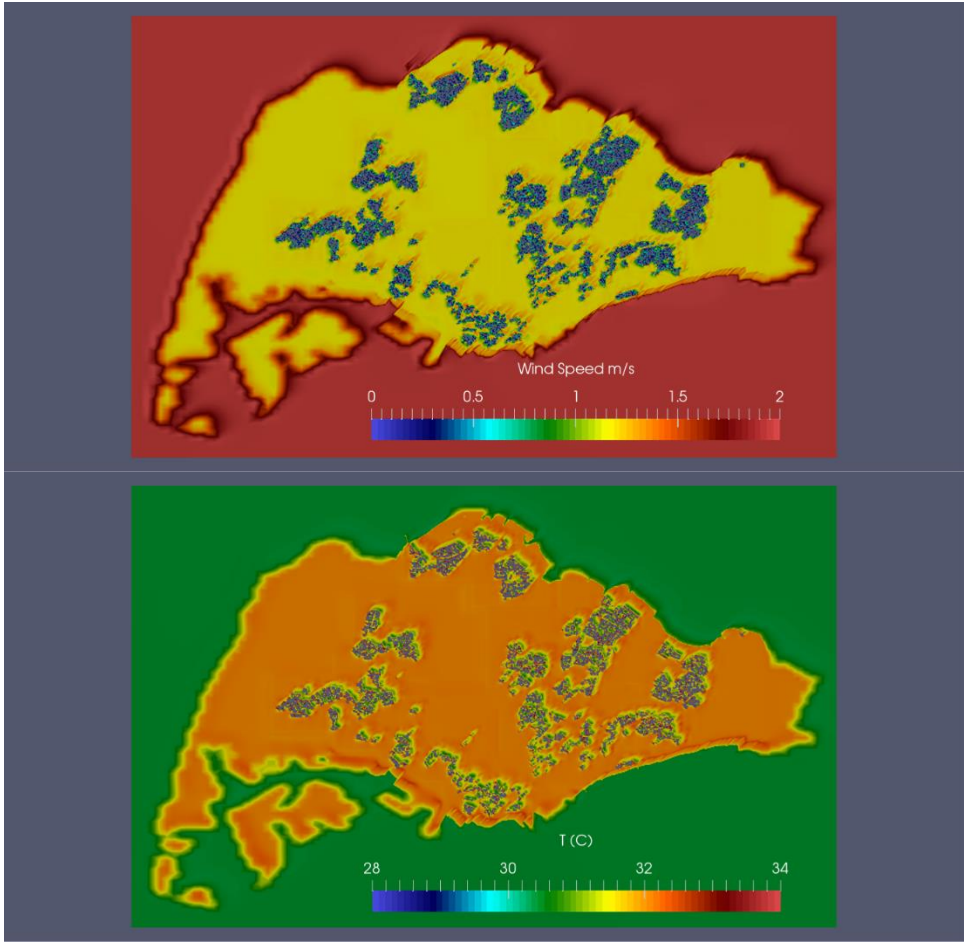


Intelligent Mesher

- Entire Singapore simulation with all HDBs included

[https://github.com/ualsg/hdb3d-data]

- 16 m near buildings
- Only 36 million grid points



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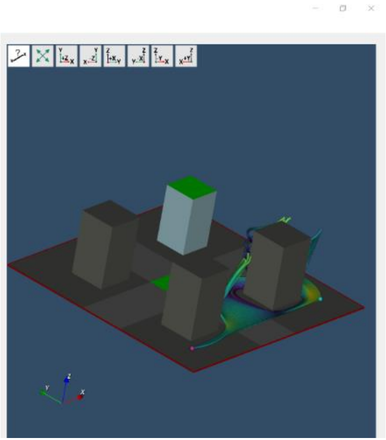
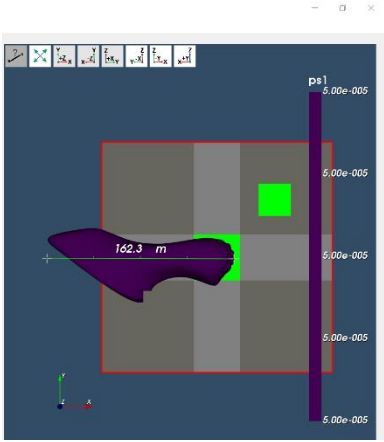
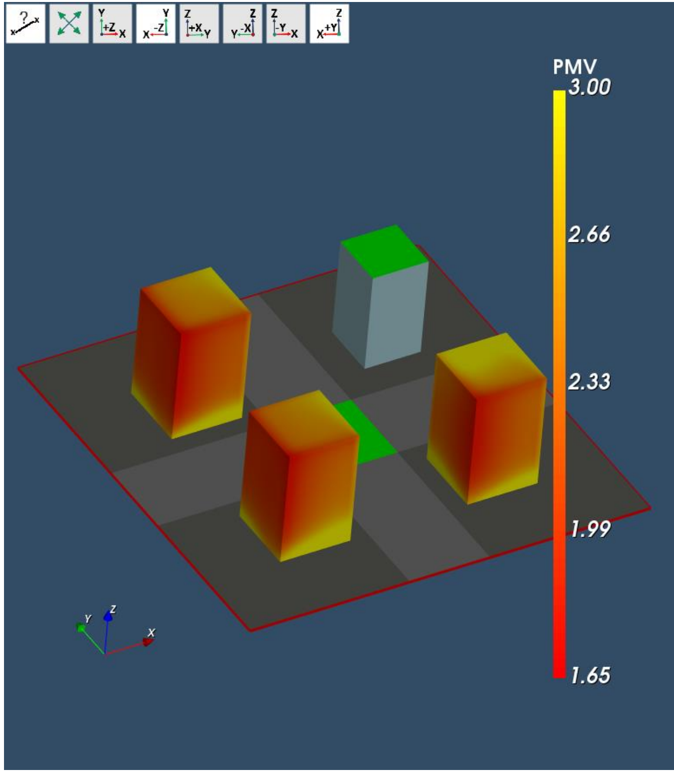
Postprocessing

- Quick built-in postprocessor
- Not a Paraview replacement
- Data processed on server and displayed on client
- Supports most basic plotting – Line, contour, wall, iso-surface and streamline
- Experimental support for postprocessing VTK/netCDF data on NSCC

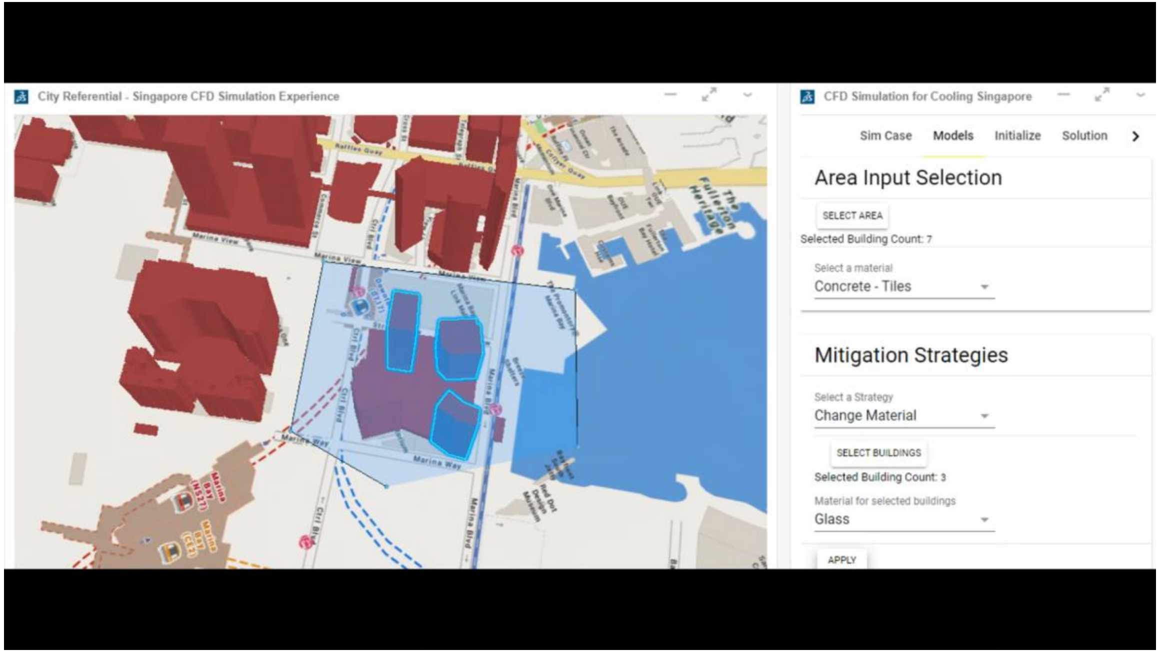






SCOUT – Widget [*,**]

- Integration of modules from IEM, VS – Tree** and SCOUT – Python
- CFD – Widget on Virtual Singapore platform



* Cooling Singapore 1.5: Virtual Singapore Urban Climate Design
** Wind Load Prediction on Trees in Virtual Urban Landscape for Greenery Management

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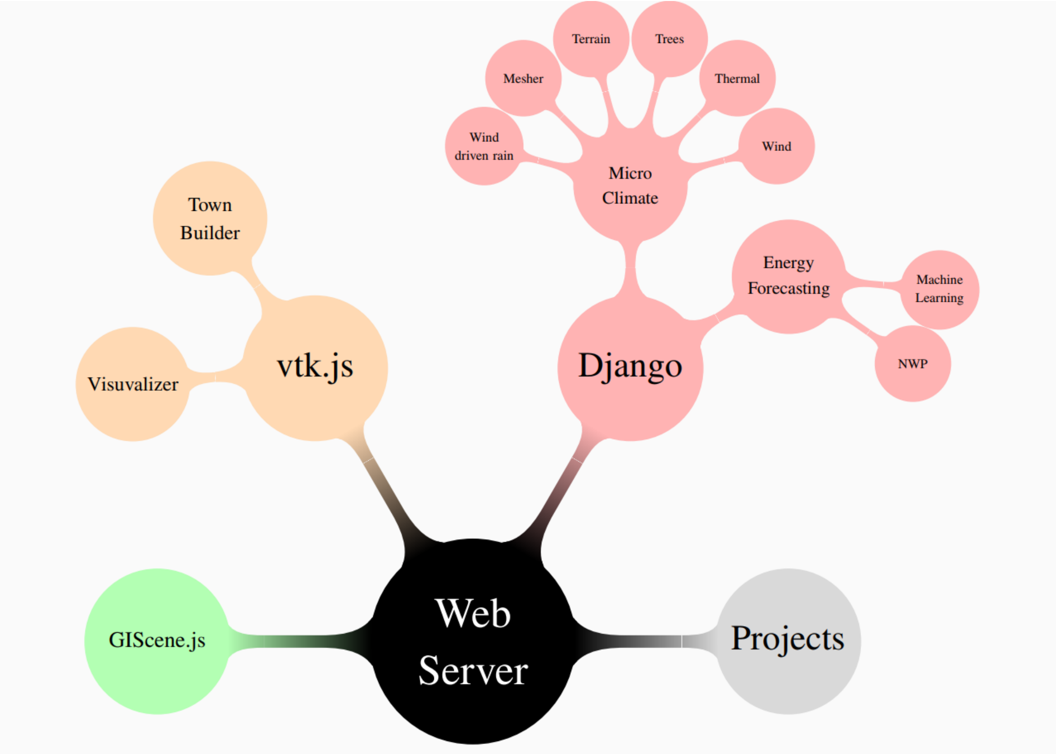
SCOUT – Cloud



- Secure computing server
- Urban microclimate modeling and renewable energy forecasting
- Support for WRF, OpenFOAM, Hybrid WRF and Machine learning, and coupled WRF – OpenFOAM-Energy Modeling simulations

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Solar Forecasting

- Local context
    - Low wind speeds
    - Narrow tidal range
    - Crowded sea space
    - No geothermal
    - Abundance of solar radiation
- Issues
    - Load fluctuations
    - Need to balance grid
    - High variability in cloud movement in tropics [Nobre et. al (2016)]
    - Commercial solutions – Not sufficiently tested for south-east Asia

In-house development to test our machine learning algorithms for non-linear processes

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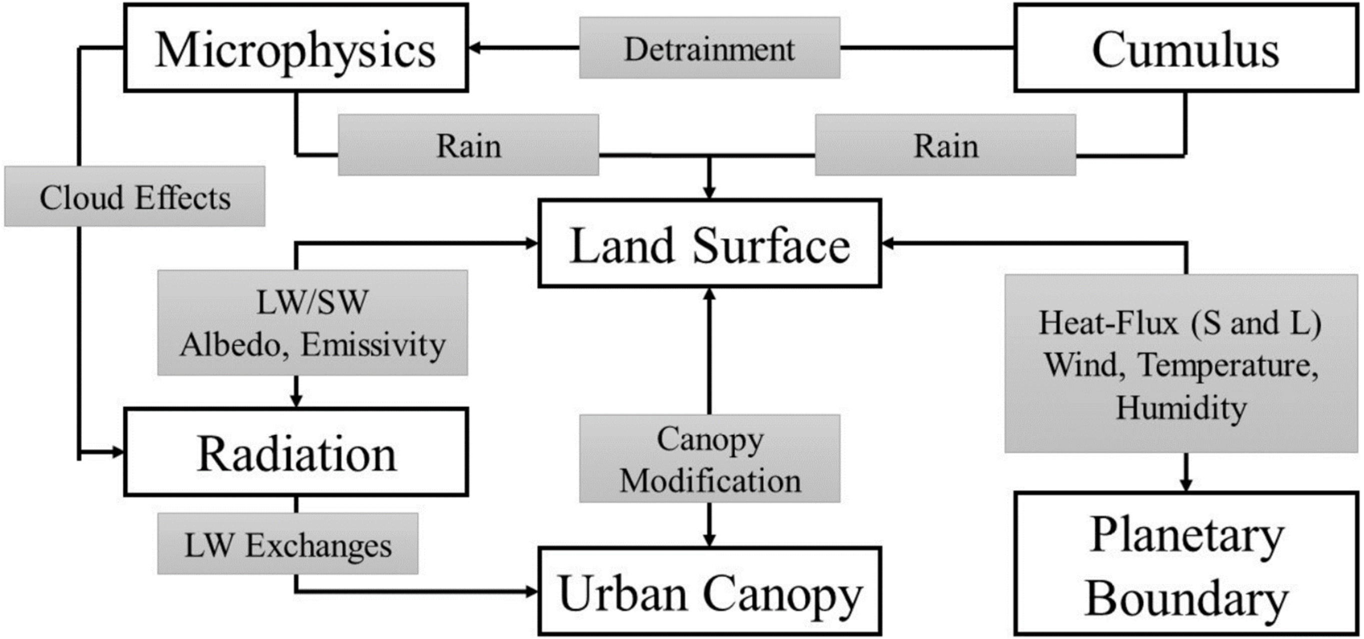
Solar Forecasting

- Very short term (< 15 minutes)
  - Statistical models
  - Persistence
  - ANN …
- Short term (< 4 hours)
  - Cloud imagery
  - Satellite data
- Long term (> 4 hours)
  - Numerical weather prediction

Climate Modeling – WRF



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WRF – Solar Radiation

- Multiple choices
  - Radiation schemes
  - Microphysics schemes
  - Cumulus schemes
  - How do we downscale?
- Day-ahead forecasting issues
  - Systemic biases
  - Variability in cloud motion
- How can we improve prediction?
  - Hybrid WRF – Machine learning approach

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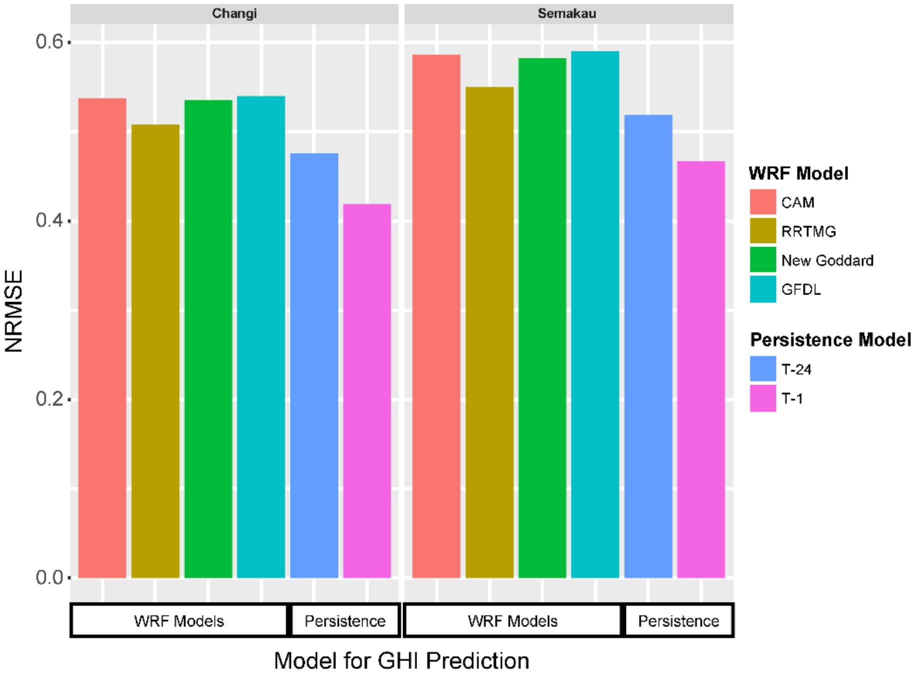
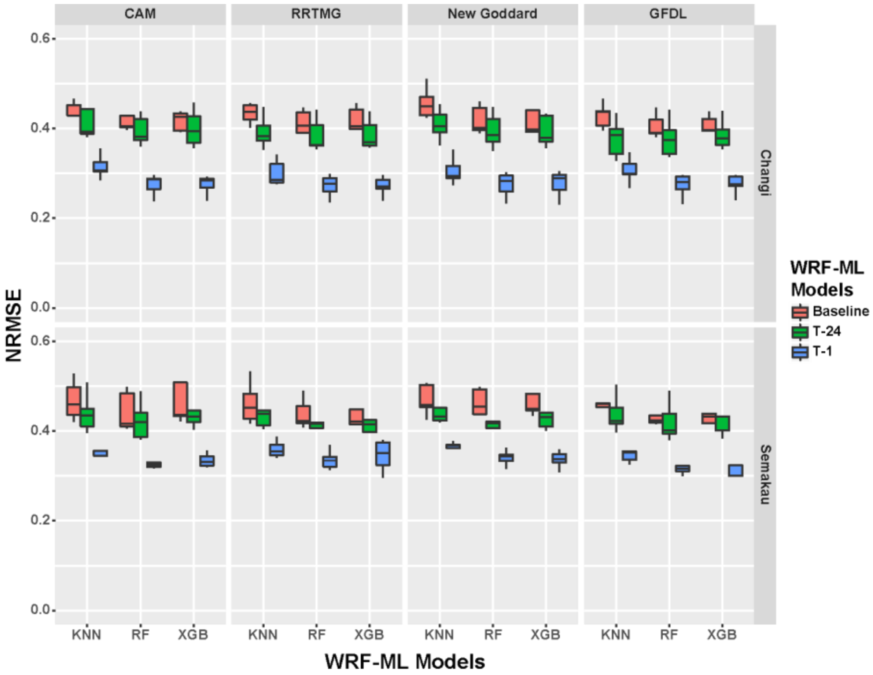
Initial Results





WRF Setting: One-way downscaling (81->27->9->3->1 km)
WRF Physics: PBL: YSU; Cumulus: GF; Microphysics: WSM 6; LSM: Noah-MP
Execution time: < 2 hours on 1 node of NSCC for day-ahead forecasting

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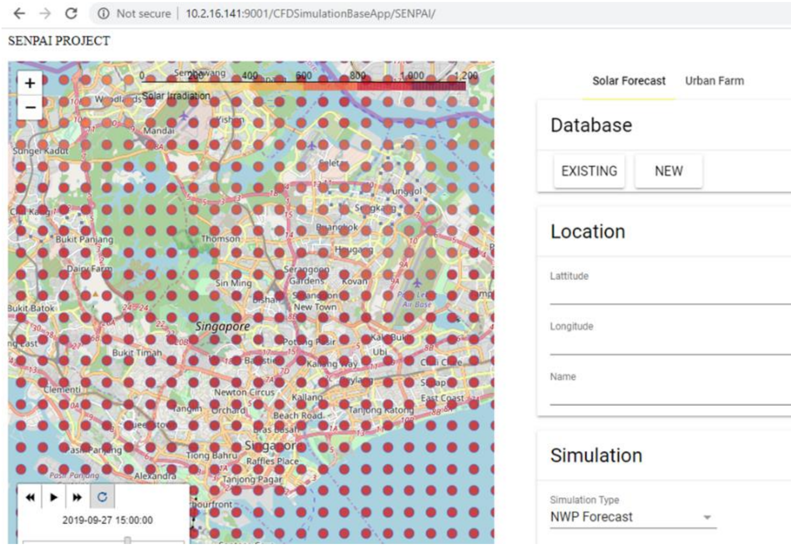
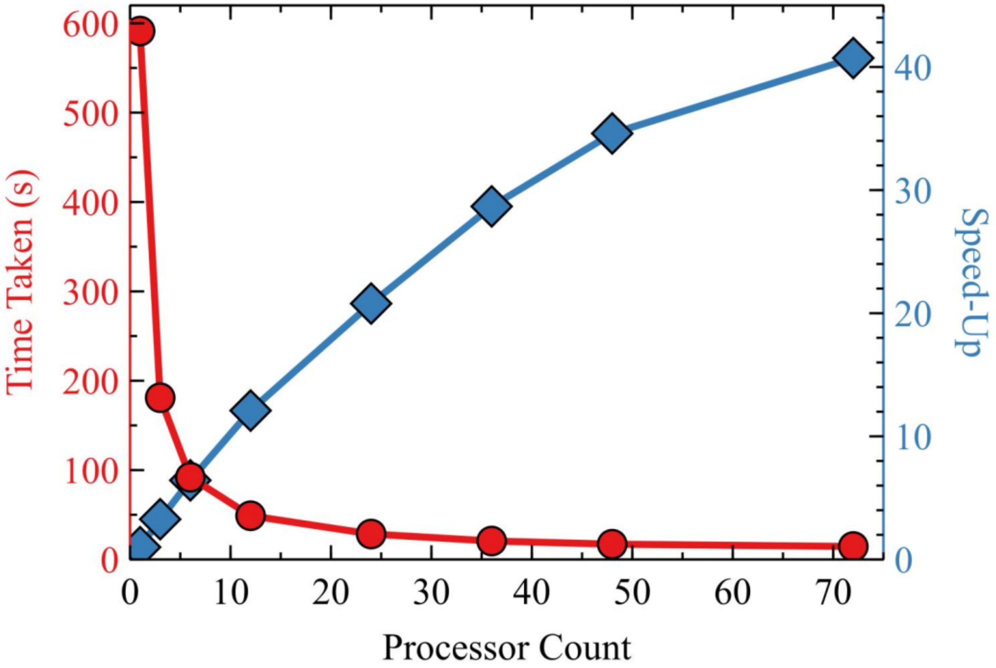
SENPAI – Forecasting Module in SCOUT – Cloud



- Scalable Environmental Planner using Artificial Intelligence (SENPAI) forecasting module in SCOUT – Cloud
- User selects Lat and Lon
- Day-ahead forecasting using WRF
- Machine learning correction if ground truth available
- Can be extended to rain forecasting or wind farm power forecasting
- Developed for enhanced usability of numerical weather prediction codes

Dark Knight – High Performance Computing



- Parallel blockMesh meshing scaling study on NSCC
- 500 million cells – Less than a minute on 512 processors [tested on NSCC]

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Contact:
Harish Gopalan
gopalanh@ihpc.a-star.edu.sg

THANK YOU

www.a-star.edu.sg

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HPC: NSCC