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Application of Grids, Clouds & High-Performance Computing in Research of Urbanization

Earth, Environmental Science & Biodiversity II: Urbanization
1400 to 1530; March 18, 2015 (Wednesday)
Conference Room 2, BHSS, AS
Chun-Ho Liu  廖俊豪
Department of Mechanical Engineering, The University of Hong Kong
Outline

• High-Performance Computers (HPCs)
  – In the last ½ decades.
• Grids, clouds & HPC in our daily lives.
• Multi-scales in atmospheric motions.
• Research of urbanization (small to large scales).
  – Building information modeling (BIM).
  – Digital maps.
  – Geographic information system (GIS).
  – Air ventilation assessment (AVA).
  – Meso-scale meteorology modeling.
  – Global-scale climatology modeling.
  – Our research effort.
    • Engineering approach to atmospheric pollution problems.
• Conclusion.
High-Performance Computers

Electronic Numerical Integrator And Computer (ENIAC)
First electronic general-purpose computer in the world
Daily Lives

Google map

Pipeline & facility management

Weather, flooding & snowing

Stock market

Hospital admission

Entertainment

Traffic report

Cloud banking

Business cloud
Scales of Atmospheric Motions

\[ \eta = \left( \frac{V^3}{\epsilon} \right)^{1/4} \]

The TKE dissipation scale

- Climate variation
- ENSO
- Seasonal cycles
- Intraseasonal (MJO)
- Planetary waves
- Tropical cyclones
- Fronts, squall lines
- Cloud clusters
- Thunderstorms
- Tornadoes
- Thermals
- Meso
- Synoptic

Global Temperatures

- Annual Average
- Five Year Average

\[
\begin{bmatrix}
\begin{array}{c}
\text{Temperature Monthly} \\
\text{Temperature Annual} \\
\text{Temperature Five Year} \\
\end{array}
\end{bmatrix}
\]
Building Information Modeling (BIM)

- Digital representation of physical & functional characteristics of a facility.
- A shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition.
  - Management of building information.
  - Construction management.
  - Facility operation.

- The Hong Kong Institute of Building Information Modelling
Building Information Modeling (BIM)

• Challenge
  – Increased coordination of construction documents.
  – Embedding & linking of vital information, such as vendors for specific materials, location of details & quantities required for estimation & tendering.
  – Improved productivity due to easy retrieval of information.
  – Improved visualization.
  – Increased speed of delivery
  – Reduced cost.

• Extension to building energy performance & green building.
• Enable the searching & use of massive datasets in m secs.
• Standardized & virtualized commodity infrastructure.
• Enable real-time continuous processing of open digital document/information flows.

https://www.youtube.com/watch?v=hgyhRk8smkk

Digital Maps/Orthophoto

- Derived from aerial photographs.
- Ground pixel $0.5 \text{ m} \times 0.5 \text{ m}$.
- Useful to architects, engineers & planners in development projects.
- Dataset for GIS & AVA studies.
Geographic Information System (GIS)

- A system designed to capture, store, manipulate, analyze, manage, & present all types of spatio-temporal or geographical data.
- Visualization of GIS data over the internet (or mobile devices).
- Uses spatio-temporal location as the key index for all other information.
- Survey data & remote sensing
  - Satellite images: MTSAT IR, EOS MODIS & NOAA/METOP, etc.
  - Underground utility services.
  - Atmospheric data?
Geographic Information System (GIS)

• **Challenge**
  – 3 product segments
    • Software, data & services.
  – Availability of low-cost GIS equipment.
    • Customized GIS applications/solutions in line with specific industry requirements.
  – Increased adoption of GIS application in mobile computing devices.
  – GIS, data mining & big data.
    • Findings from GIS datasets.
    • New algorithms for data infrastructure.
    • Collaboration among various parties
      – Machine learning & complex process modeling.
    • Quality & uncertainty in big data.
    • Analytic & visualization solutions.
  – Data network, stream-processing engines for real-time analysis, spatially-enabled databases & search engines.
  – Data consolidation from different parties.
Air Ventilation Assessment (AVA)

- Initiative to identify measures to improve the living environment.
- Effective airflow in the external macro built-up environment which would not lead to adverse or restricted conditions to cause human discomfort or be unfavorable for the predominant land use activities.
- Buildings in the (new) development project are solved explicitly.
- An indicator to ground-level ventilation.
- Reduction/enhancement of ground-level wind speed (compared with free-stream flow).
- Laboratory measurements or computer modeling (CFD).
- Mean wind speed & turbulent quantities.
Air Ventilation Assessment (AVA)

- **Challenge**
  - Formulation of guidelines & standards.
  - Modeling
    - Turbulence models (RANS or LES?).
    - Necessity of transient simulation.
    - Energy from buildings.
    - Other than isothermal conditions
  - Computing
    - Details of the buildings.
    - Size of computational domain.
    - Spatial resolution requirement.
    - Coupling between difference scales.
  - Grid/Cloud
    - Update of building, terrain & meteorological information from various sources.
    - Post-evaluation of modeling results.
    - Large-scale computation using grids or clouds.
    - Results availability & user-friendly interface.
Meso-scale Meteorology Modeling

- Numerical weather prediction (NWP) models that have a horizontal grid spacing $1 \text{ km} \leq \Delta x \leq 15 \text{ km}$.
  - Weather Research & (WRF) Forecasting model.
  - Regional Atmospheric Modeling (RAM) System.
  - Meso-scale Meteorological Model (MM5).
  - Area-oriented Numerical Simulation & Environmental Assessment Modeling System (ANEMOS).
  - Meso-scale Compressible Community Model (MC2)
  - Met Office Unified Model (UM).
- Weather forecast, hurricane, tropical cycle, tornado, thunderstorm, mountain/valley/sea breezes & wind energy assessment.
- Parameterizations
  - Land surfaces.
  - Vegetation & built environment
  - Subgrid-scale (SGS) processes.
  - Convection.
  - Energy & water balance.
- Grid nesting for initial & boundary conditions.
  - Coupling with global models.
  - Data assimilation system.
Meso-scale Meteorology Modeling

• Challenge
  – Parameterizations & microphysics.
  – Coupling with other systems such as cities or sea wave.
  – Solar radiation.
  – Computing
    • Spatial resolution (hardly solves $< 5 \Delta x$) & grid nesting.
    • Able to resolve topographic but unlike buildings.
    • Surface roughness?

• Grids & Clouds
  • Initial & boundary conditions
    – Obtained from global models (e.g. ECMWF or NWS).
    – Global monitoring (data assimilation) via WMO.
  • Spin-up time.
  • Probabilistic forecasting & real-time simulation.
  • Community effort.
Global-scale Climatology Modeling

• Study of weather patterns related to the transport processes from the tropics to the poles & very large-scale oscillations (of time period months or years).

• A mathematical model based on the Navier–Stokes equations on a rotating sphere with thermodynamic terms for various energy sources (radiation & latent heat).
  – Navy Operational Global Atmospheric Prediction System (NOGAPS).
  – Community Earth System Model (CESM).
  – GEOS-Chem.
  – Model for Interdisciplinary Research on Climate (MIROC).
  – Meteorological Research Institute Atmospheric General Circulation Model (MRI-GCM).
  – Hadley Centre General Circulation Model (GCM)

• Understand the climate & predict climatic changes.

• Coupled with
  – Atmospheric model.
  – Oceanic & sea-ice model.
  – Land-surface model.
  – Solar radiation.
Global-scale Climatology Modeling

• Challenge
  – Atmospheric chemistry, constituents, ecosystems & climate.
  – Climate projections & forecasts.
  – Role of land surface in climatic change.
  – Ocean & climate.
  – Grids, clouds & computing
    • High-resolution atmospheric components.
    • Full coupling among various components.
    • Scalability & multi-core architecture.
    • Parallel I/O
  – Data sharing & assimilation.
  – Global observational data.
Research Interest

• Air Pollution Physics & Chemistry
• Geophysical Turbulence
• Scientific Computing

• Mathematical modeling of turbulence
  – Direct numerical simulation (DNS)
  – Large-eddy simulation (LES)
  – Reynolds-averaged Navier-Stokes (RANS) equations/turbulence

• Mathematical methods
  – Finite element method (FEM)
  – Finite volume method (FVM)

• Laboratory instrumentation
  – Wind tunnel
  – Water channel
Air pollution in the atmospheric boundary layer

Large-eddy simulation of the atmospheric boundary layer

10^3 to 10^4 m

10 to 10^3 sec

Atmospheric turbulence & stratification on pollutant transport

meteorology

Environmental fluid mechanics

Wakes & local turbulence production around buildings

Large-eddy simulation of the flows around buildings

1 to 10^2 m

10 to 10^3 sec

Nonlinear & tightly coupled chemistry among pollutants

Chemical species

Large-eddy simulation of the flows around buildings

Large-eddy simulation of the atmospheric boundary layer

Current Approach

Air pollution chemistry

Air pollution chemistry
In fact they couple with each other.

**Meteorology**
- Surface roughness & drag force
- Anthropogenic & natural emission
- Wind shear & TKE production
- Momentum entrainment & subsidence
- Updraft/downdraft
- Natural terrain & building configuration
- Stratification & convective current

**Environmental fluid mechanics**
- Stratification & convective current on chemistry
- Weak pollutant dilution in stable stratification
- Pollutant concentrations on energy budget
- Phase change of H₂O
- Prolonged pollutant retention in the urban canopy layer
- Inhomogeneous pollutant distribution
- Enhanced pollutant dilution & mixing around buildings
- In the vicinity to ground-level pollutant sources
- Coupled pollutant mixing & chemistry
- Emission inventory

**Pollution chemistry**
- Air pollution in the atmospheric boundary layer
- Air pollution chemistry

**Large-eddy simulation of the atmospheric boundary layer**

\[ \text{CO}_x + \text{H}_2\text{O} \rightarrow \text{CO}_y + \text{H}_2 \text{O}, \quad K_c = 1.00. \]
Air pollution in the atmospheric boundary layer

How to handle the broad range of scales

Challenge in computational engineering & scientific computing

Large-eddy simulation of the atmospheric boundary layer

Meteorology

How the near-ground small scales interact with the large scales in the atmospheric boundary layer, & their collective effects on pollutant transport

Challenge in environmental fluid mechanics & atmospheric dynamics

Environmental fluid mechanics

Large-eddy simulation of the flows around buildings

Pollution chemistry

How urban morphology affects pollution chemistry, composition, & retention in the urban atmospheric/canopy layer

Challenge in urban climate & atmospheric chemistry

Integrated Approach
• **Long-Term Impact & Significance**
  – Improved understanding of air pollution physics & chemistry over urban areas.
  – Emission parameterizations for chemical species.
  – Recommendation for urban planning & environmental management.

• **International Scientific Community**
  – University of Reading, University of Birmingham, University of Southampton, Universität Hamburg, University of Oklahoma, Metro France, National Center for Atmospheric Research, & Central Research Institute of Electric Power Industry (Japan), etc.

• **Our niche research area**
  – Use Hong Kong as a platform to examine urban air pollution then apply the theory to elucidate the problems in other cities in the world.
  – On-going research projects in large-eddy simulation & air pollution chemistry over idealized urban areas.
Methodology

- Hypothetical rough/urban surfaces
- Horizontally homogeneous domain & cyclic boundary conditions (BCs).
- (Background) pressure gradient $\Delta P_x$ in the streamwise direction.
- Large-eddy simulation (LES) with the one-equation subgrid-scale (SGS) model.
- Change the aspect ratio ($AR = h/b$) to control the aerodynamic roughness.
Methodology
• Snapshot of chemically reactive pollutant (NO\textsubscript{x}-O\textsubscript{3}) plume dispersion over idealized urban street canyons. Nitric oxide is released from the 1\textsuperscript{st} street canyon into the urban canopy/atmospheric boundary layer.
• Nitrogen oxide concentration is high at the ground level, drops sharply at the roof level, then increases gradually in the streamwise direction.
Estimator

$ACH' = 0.35086 \pm 0.0001, R^2 = 0.9296$
Pollutant Dispersion Parameterization

- Advection-diffusion equation

\[ U \frac{\partial c}{\partial x} = K \left( \frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} + \frac{\partial^2 c}{\partial z^2} \right) + Q \delta(x, y, z) \]

\[ c(x, y, z) = \frac{Q}{4\pi Kr} \exp \left[ -\frac{u(r - x)}{2K} \right] \]

where \( r^2 = x^2 + y^2 + z^2 \)

- Advection-diffusion equation with chemistry

\[ U \frac{\partial c}{\partial x} = K \left( \frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} + \frac{\partial^2 c}{\partial z^2} \right) - Lc + Q \delta(x, y, z) \]

\[ c(x, y, z) = \frac{Q}{4\pi Kr} \exp \left[ -\frac{\left( u^2 + 4KL \right)^{1/2} r - ux}{2K} \right] \]

Parameterization of \( K \) over urban surfaces.
Collective effect of \( K \) & \( L \) on pollutant distribution & chemistry.
Preliminary Results

[NO₂] (ppb)

[NO] iso-surfaces: 10, 100 & 3000

[O₃] iso-surfaces: 0.2, 0.5 & 0.8 ppb
Conclusion

- A quick review on the use of grids, clouds & high-performance computing (HPC) in the research related to urbanization.
- Grids
  - Field observation monitoring, data assimilation & post-processing.
- Clouds
  - Analytic methods, big data sharing & community effort.
- High-performance computing
  - Modeling of atmospheric processes.
  - Multi-scale requirement, detailed multi-physics/chemistry & parallelism.

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