Challenges: large range of interacting scales

NWP models: large coverage but ...
Coarse Predictions + Unresolved Physics
Challenges: large range of interacting scales

Finer mode: enough resolution to capture environmental processes
only small time and space scales & unknown boundary conditions

Atmospheric Boundary Layer ~ 1 km

Surface Layer ~ 0.1 km
Challenges: large range of interacting scales

Modeling scale dictated by what you are interested in, what questions you seek to answer: e.g. understanding intricate details of urban environment, or its global impact?
Coarse Atmospheric/Land models need lower/upper BCs
Simple Urban models: urban area is a flat rough terrain with roughness $z_0$

\[ R_n = S_{down} + L_{down} - S_{up} - L_{up} = H + LE + G \]

\[ H = \rho c_p w' T' = -\rho c_p \frac{u_* \kappa (\theta_{air} - \theta_{surface})}{\ln \left( \frac{z}{z_{0,T}} \right) - \psi_h \{-z / L\}} \]

\[ LE = \rho L_v w' q' = -\rho L_v \frac{u_* \kappa (q_{air} - q_{surface})}{\ln \left( \frac{z}{z_{0,v}} \right) - \psi_v \{-z / L\}} \]

\[ G = -k_{soil} \frac{d\theta_{soil}}{dz_{soil}} = -k_{soil} \frac{\theta_{soil} - \theta_{surface}}{\text{depth}_{soil\ layer}} \]

\[ L_{up} = \alpha_L L_{down} + \epsilon \sigma \theta^4 \text{_{surface}} \]

\[ S_{up} = \alpha_S S_{down} \]

\[ S_{down}, L_{down}, \theta_{air}, q_{air}, u_{air} / u_* \text{ from previous time step of atmospheric model} \]

\[ \theta_{soil}, q_{surface} \text{ from previous time step of soil model} \]

This is one example of an algorithm

Solve iteratively (why?) for $T_s$

Need all $z_0$s, good urban representation to then update $\theta_{soil}, q_{surface},$ etc
Atmospheric/Land models need lower/upper BCs

Fluxes up $\rightarrow$ atmospheric stability $\rightarrow K_m, K_H$
Complex urban models: e.g. TUF3D
Complex urban models: e.g. computational fluid dynamics (CFD) simulations of flow over buildings
CFD example: what does it require?
Turbulent scales and Direct Numerical Simulations

\[ \Delta \]

- Dissipation range
- Inertial range
- Energy production range

\[ \eta \rightarrow L \]

\[ \Delta \rightarrow \]
Turbulent scales and Reynolds Averaged NS

No turbulence resolved, even if grid is smaller than some scales
Turbulent scales and Large Eddy Simulation

\[ \eta \quad \Delta \quad L \]

- **η**: Dissipation range
- **Δ**: Inertial range
- **L**: Energy production range

Diagram showing various scales of turbulence with arrows indicating the direction of energy transfer.
Large Eddy Simulation

Large scales carry most of the turbulent fluxes
Small scales in the inertial range are “easy” to model
Large Eddy Simulation

Large scales carry most of the turbulent fluxes
Small scales in the inertial range are “easy” to model

\[
\frac{\partial u_i}{\partial t} + \frac{\partial u_j u_i}{\partial x_j} = \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j} - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + F_i
\]

\[
\frac{\partial q}{\partial t} + \frac{\partial u_j q}{\partial x_j} = \nu_q \frac{\partial^2 q}{\partial x_j \partial x_j} + \ldots
\]
Large Eddy Simulation

Large scales carry most of the turbulent fluxes
Small scales in the inertial range are “easy” to model

\[ \frac{\partial u_i}{\partial t} + \frac{\partial u_j u_i}{\partial x_j} = \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j} - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + F_i \]

\[ \frac{\partial q}{\partial t} + \frac{\partial u_j q}{\partial x_j} = \nu_q \frac{\partial^2 q}{\partial x_j \partial x_j} + \ldots \]

\[ u \quad \text{Filter out small scales} \quad \tilde{u}(x,t) = \int G(r,x)u(x-r,t)d^3r \quad \tilde{u} \]
Large Eddy Simulation

Large scales carry most of the turbulent fluxes
Small scales in the inertial range are “easy” to model

\[
\frac{\partial u_i}{\partial t} + \frac{\partial u_j u_i}{\partial x_j} = \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j} - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + F_i
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\[
\frac{\partial q}{\partial t} + \frac{\partial u_j q}{\partial x_j} = \nu_q \frac{\partial^2 q}{\partial x_j \partial x_j} + \ldots
\]

Filter out small scales

\[
\tilde{u}(x,t) = \int G(r,x) u(x-r,t) d^3r
\]

\[
\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial \tilde{u}_j \tilde{u}_i}{\partial x_j} = \nu \frac{\partial^2 \tilde{u}_i}{\partial x_j \partial x_j} - \frac{1}{\rho} \frac{\partial \tilde{p}}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}
\]

\[
\frac{\partial \tilde{q}}{\partial t} + \frac{\partial \tilde{u}_j \tilde{q}}{\partial x_j} = \nu_q \frac{\partial^2 \tilde{q}}{\partial x_j \partial x_j} - \frac{\partial \pi_j}{\partial x_j}
\]
EFM-LES: Log wind speed & energy spectra

\[ \langle \tilde{u} \rangle = \left( \frac{u_*}{k} \right) \ln\left( \frac{z}{z_0} \right) \]

Scale-dependent dynamic model, Lagrangian averaged | LASD
Scale-invariant dynamic model, Lagrangian averaged | LASI
Smagorinsky - Lilly model with wall damping of the mixing length | SMAG

Other validation for diurnal cycle, flow over cubes, etc.
EFM-LES: Simulations over built terrain: IBM

Integration of buildings into the domain: Immersed boundary method IBM (Tseng et al., EST, 2006)
Simulations over built terrain: EPFL campus

Simulations over the campus of EPFL: (Bou-Zeid et al., BLM 2009)
Mean flow

- Mean drag not sensitive to details of building representation

<table>
<thead>
<tr>
<th>Simulation</th>
<th>$z_0$ (m)</th>
<th>$d$ (m)</th>
<th>$C_d$ at 30 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-NS</td>
<td>0.4356</td>
<td>15.09</td>
<td>0.0256</td>
</tr>
<tr>
<td>M-NS</td>
<td>0.4347</td>
<td>15.39</td>
<td>0.026</td>
</tr>
<tr>
<td>S-NS</td>
<td>0.4316</td>
<td>15.53</td>
<td>0.026</td>
</tr>
<tr>
<td>C-WE</td>
<td>0.4196</td>
<td>14.42</td>
<td>0.0244</td>
</tr>
</tbody>
</table>

$H_{avg} = 23$ m

$d = 0.67 \, H$

$z_0 = 0.2 \, H$
Mean flow, sensitive to heterogeneity

- Mean flow varies between the upstream, over the campus, and downstream areas
Turbulence

- Turbulence and mixing rather sensitive to representation details over the campus, but not elsewhere
Turbulence

- Strong turbulence in the wake
Onto the “real world”: medium urban models

Can we perform “real-world” simulations of urban systems? What do we need?
“Real-World LES”

\[
\begin{align*}
\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial \tilde{u}_j \tilde{u}_i}{\partial x_j} &= \nu \frac{\partial^2 \tilde{u}_i}{\partial x_j \partial x_j} - \frac{1}{\rho} \frac{\partial \tilde{p}}{\partial x_i} + \tilde{F}_i - \frac{\partial \tau_{ij}}{\partial x_j} \\
\frac{\partial \tilde{q}}{\partial t} + \frac{\partial \tilde{u}_j \tilde{q}}{\partial x_j} &= \nu \frac{\partial^2 \tilde{q}}{\partial x_j \partial x_j} - \frac{\partial \pi_j}{\partial x_j}
\end{align*}
\]
“Real-World LES”

\[ \frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial \tilde{u}_j \tilde{u}_i}{\partial x_j} = \nu \frac{\partial^2 \tilde{u}_i}{\partial x_j \partial x_j} - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \]

\[ \frac{\partial \tilde{q}}{\partial t} + \frac{\partial \tilde{u}_j \tilde{q}}{\partial x_j} = \nu \frac{\partial^2 \tilde{q}}{\partial x_j \partial x_j} - \frac{\partial \pi_j}{\partial x_j} \]

- Need realistic boundary conditions
- Need realistic flow forcing
“Real-World LES”

- Coupling LES (pushing the domain boundaries) with
  - Building model
  - Soil-canopy and subsurface model
  - Meso-scale model

**OR / AND**

- Measuring the boundary conditions
Multiscale simulations using WRF: Why WRF?
WRF real cases initialization

- Model top: 50 hPa (~20 km)
- Larger 3 domains: “mesoscale mode”
- Smaller 3 domains: “LES mode”
Questions

- Is WRF a good model/code for Large-Eddy Simulations?
  - Subgrid Scale models?
  - Numerics?

- Land-surface models and coupling to ABL?

- Can this nested modeling approach move us towards real-world LES?
Idealized WRF simulations: Improving LES capabilities


Numerics: numerous options, need careful simulation design
Multiscale simulations using WRF

- Model top: 50 hPa (~20 km)
- All simulations ~ 100^3
- 10km to 40m resolution
- Larger 3 domains: “mesoscale mode”

- Smaller 3 domains: “LES mode”
- September 24, 2007
- Cloud Free day
- NOAH land model
Finest Domain
Evolution and variability of fluxes

Problems: forcing is not always accurate
Questions

- Is WRF a good model/code for Large-Eddy Simulations?
  - Subgrid Scale models?
  - Numerics?

- Problems with forcing exist

- WRF does not represent individual building and exact canopies yet, it needs an urban surface model. "Simple Urban Model" options exist in WRF, but it also has "medium complexity" options → Land-surface models and coupling to ABL
The Urban Canopy Models in WRF

A spatially-analytical model for heat conduction

- Current UCMs use spatially discretized (finite-difference) method for conductive heat flux and surface temperature evolution.
- At least 3 layers required, temperature discontinuity occurs at interfaces.
- Spatially analytical scheme for surface temperature evolution uses Green’s function solution for homogenous IBVP
- Capable of predicting exact spatial variation of temperatures and fluxes, for multi-layer walls or grounds

\begin{align*}
T(x,t) &= T_i + \int_0^t q_1(t-\tau)dG_1(x,\tau) + \int_0^t q_2(t-\tau)dG_2(x,\tau) \\
Q_G(x,t) &= -k \frac{\partial T}{\partial x} = -k \left[ \int_0^t q_1(t-\tau)dG_1'(x,\tau) + \int_0^t q_2(t-\tau)dG_2'(x,\tau) \right]
\end{align*}
Temperature of the outer surface for a diurnal cycle

‘cheaper’ than discrete model
Temperature profile for a diurnal cycle

‘cheaper’ than discrete model
Comparison with SNOP data: Roof T

![Graph showing comparison between different measurement methods for roof temperature over UTC time. The graph includes lines for Semi-analytical (proposed), Fully discrete, EC measurement, and Sensorscope measurement. The x-axis represents UTC time in hours, and the y-axis represents roof temperature in °C. The graph illustrates the temperature variations over time.]
Comparison with field data: Ground T

UTC time (hour)

Asphalt, proposed method
Concrete, proposed method
Vegetated, proposed method
Asphalt, measured
Concrete, measured
Vegetated, measured

Ground temperature (°C)
ALL the important physics and NOTHING BUT the important physics?

- MCMC analysis of the model
- "Important Physics" depend on the "monitored output"
Percentage sensitivity index

- In general, important parameters include geometry and roof properties, fraction of vegetation, $z_0$ for roof and canyon
- Ground properties not that important
Coupling a hydrologic model to UCM: soils

\[
\begin{align*}
\frac{\partial \theta_k}{\partial t} &= \begin{cases} 
\frac{1}{d_1} \left[ P - ET(\theta_1) - R - Q_{w,1} \right], & k = 1 \\
\frac{1}{d_k} \left[ Q_{w,k-1} - Q_{w,k} \right], & k > 1 
\end{cases}
\end{align*}
\]

\[
Q_{w,k} = D_D \frac{\theta_k - \theta_{k+1}}{0.5(d_k + d_{k+1})} + K_{k,k+1}
\]

\[
E_{p,nat} = \frac{\rho_a \left( q_{G,nat} - q_{can} \right)}{\text{RES}_a} \quad \text{for bare soil}
\]

\[
E_{p,nat} = \frac{\rho_a \left( q_{G,nat} - q_{can} \right)}{\text{RES}_a + R_s} \quad \text{for vegetation}
\]

\[
H_{can} = c_{pd} \rho_a \left( T_{can} - T_a \right) \quad \text{RES}_a
\]

\[
E = \beta_e E_p \quad \text{where}
\]

\[
\beta_e = \begin{cases} 
1 & \text{for } \theta > \theta_s \\
(\theta - \theta_r) / (\theta_s - \theta_r) & \text{for } \theta \leq \theta_s
\end{cases}
\]

\[
\theta_1 \quad \text{precipitation} \quad \text{evapotranspiration} \quad \text{surface} \quad \text{runoff}
\]

\[
\theta_2 \quad \text{infiltration}
\]

\[
\theta_k \quad \text{layer } 1
\]

\[
\theta_{k+1} \quad \text{layer } k + 1
\]

\[
\theta_N \quad \text{zero-flux boundary}
\]
Coupling a hydrologic model to UCM: soils

\[ \phi_{\text{eng}} \frac{\partial \delta_w}{\partial t} = P - E_p - R \]

\[ \phi_{\text{eng}} = \begin{cases} 
\text{porosity of gravel for roof} \\
1.0 \text{ for asphalt/concrete/brick}
\end{cases} \]
Urban surface temperatures

UTC time (hour)

Temperatures (°C)

- $T_{asp}$ measured
- $T_{con}$ measured
- $T_{veg}$ measured
- $T_{asp}$ UCM
- $T_{con}$ UCM
- $T_{veg}$ UCM
Total Urban Fluxes

(a) $H$ measured
$H$ UCM

UTC time (hour)
Heat flux (W m$^{-2}$)

(b) $LE$ measured
$LE$ UCM

UTC time (hour)
Urban Soil Moisture

![Graph showing soil water content over UTC time](image)

- Measurement
- UCM
Future developments

Large-Eddy Simulation over a fine grid

- Urban Canopy Model
- Radiative Trapping in the Urban Canopy Model
- Detailed Building Model
- Urban Canopy Model

Heat and momentum exchanges
But where did these measurements come from? Urban Sensing in Next Lecture

- **Speed:**
  - slow-response sensors $\rightarrow$ means
  - fast-response sensors $\rightarrow$ turbulent perturbations

- **Approach:**
  - Direct sensor: are “in touch” with what they measure.
  - Remote: measure from a distance
    - Active: emit something that is altered by the measured parameter (Radar)
    - Passive: look for signals caused by the measured parameter (IRgun)
Recommended Readings

- Oke: Boundary Layer Climates
- Pope: Turbulent Flows, chapters on numerical turbulence models
- Wang et al, JAMC, 2011