Heterogeneous surfaces -
Flow over a canopy of variable density

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Motivation

• Parametrizations of vegetation are largely based on flat, homogeneous surfaces, but in reality surfaces tend to be highly heterogeneous.

• Previous work on forest canopies tends to focus on forest edges, i.e. sharp discontinuities.

• Recent high resolution modelling work suggests that correctly representing forest canopies is necessary for correctly predicting low level winds, for example for wind energy applications.

• Need to understand this in order to correctly parametrize effects of heterogeneity in large scale NWP / climate models.
Roughness length vs canopy model

Roughness length parametrisation of surface

- Assume log profile at lowest grid point
  \[ u = \frac{u_*}{\kappa} \log \left( \frac{z+d}{z_0} \right) \]
- Roughness length \( z_0 \), displacement height \( d \).
- Ignore the flow in the canopy
- Relatively easy and suitable for coarse resolution

Explicit canopy

- Model the flow within the vegetative canopy
- Includes distributed drag and modifications to the turbulence
- Requires very high vertical resolution to resolve canopy
Rough surface

- Belcher, Xu and Hunt (1990) in QJRMS
- Increased roughness = slow down near surface flow

Diagram:

- Slow down near-surface flow → Speed up near-surface flow
- Increase roughness length ↓ Decrease roughness length
Canopy model

• Decreased canopy density = increased roughness = speed up near surface flow
• Opposite effect to roughness length parametrisation!
Analytical model

Follows the work of Belcher, Xu and Hunt (1990), but with an explicit canopy layer similar to the model of Finnigan and Belcher (2004).

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer layer</td>
<td>Potential flow</td>
</tr>
<tr>
<td>Middle layer</td>
<td>Shear stress negligible, but curvature in background profile still important</td>
</tr>
<tr>
<td>Inner layer</td>
<td>Advection – shear stress perturbation</td>
</tr>
<tr>
<td>Canopy</td>
<td>Drug perturbations + shear stress perturbation</td>
</tr>
</tbody>
</table>
Analytical model

Linearise the equations of motion for small, sinusoidal changes in canopy density.

In the canopy it is a balance between changes in the canopy drag and shear stress.

\[
\text{Canopy drag} = -C_d a U |U| \quad \text{Shear stress} = l^2 \left( \frac{\partial U}{\partial z} \right)^2
\]

Acceleration / deceleration of the flow leads to horizontal convergence / divergence => vertical motion is induced.
In order to get analytic solution we require certain assumptions:

- Sufficiently deep canopy that the momentum is absorbed by the canopy, not at the surface.
- Small amplitude variations in canopy density to allow linearisation of the equations.
- Advection in the canopy is small compared to the perturbation drag term (i.e. \( k L_c \ll 1 \) where \( k \) is the wavenumber and \( L_c = 1 / (C_d a) \) is the canopy adjustment length.)
Analytical solution - canopy vs roughness length

Canopy

BXH

$\Delta u$

$w$
Analytical solution vs numerical model

Theory

Numerical model

Δu

w
• Solution for the pressure field depends on the parametrization of the turbulent stress term $\tau_{zz}$ above the canopy. Model this as $\tau_{zz} = \alpha_3 \tau_{xz}$ following Belcher, Xu and Hunt (1990).

• Observations suggest $\alpha_3 = 1.7$.

• First order mixing length model would give $\alpha_3 = 0$ to leading order.

• Hence, most models get this term wrong. What difference does this make?
Induced pressure field
Effect of displacement height

Canopy

Roughness length

Roughness length + displacement height
Analytical solution breaks down for shorter wavelength changes in canopy density.

More rapid changes => greater induced velocities => advection terms important in the canopy. Also induced pressure is larger and begins to be important deeper in the canopy.
Does this matter?

- If you are interested in the low-level winds over vegetation, particularly with small-scale heterogeneities, then it might well matter.
- If you interested in the large scale – probably not so much. For long wavelength (slow) changes in canopy density then the analytical canopy solution tends to the roughness length solution.
- Solutions are sensitive to the turbulence parametrization. In particular first order mixing length schemes get this wrong.
- Computation cost of including an explicit canopy representation of the vegetation probably rules this out for all but high-resolution simulations.
- Theory might help to develop improved parametrizations for the effects of heterogeneous vegetation in coarse resolution models. It also provides scaling arguments to determine when the canopy is important.
- These mechanisms might also be important for transport into / out of canopies.