School of Earth and Environment
FACULTY OF ENVIRONMENT
UNIVERSITY OF LEEDS

Heterogeneous surfaces - Flow over a canopy of variable density

Andrew Ross

Motivation

UNIVERSITY OF LEEDS

- 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

UNIVERSITY OF LEEDS

Roughness length parametrisation of surface

- Assume log profile at lowest grid point

$$u = \frac{u_{¿}}{\kappa} \log \frac{(z+d)}{z_0}$$

- 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

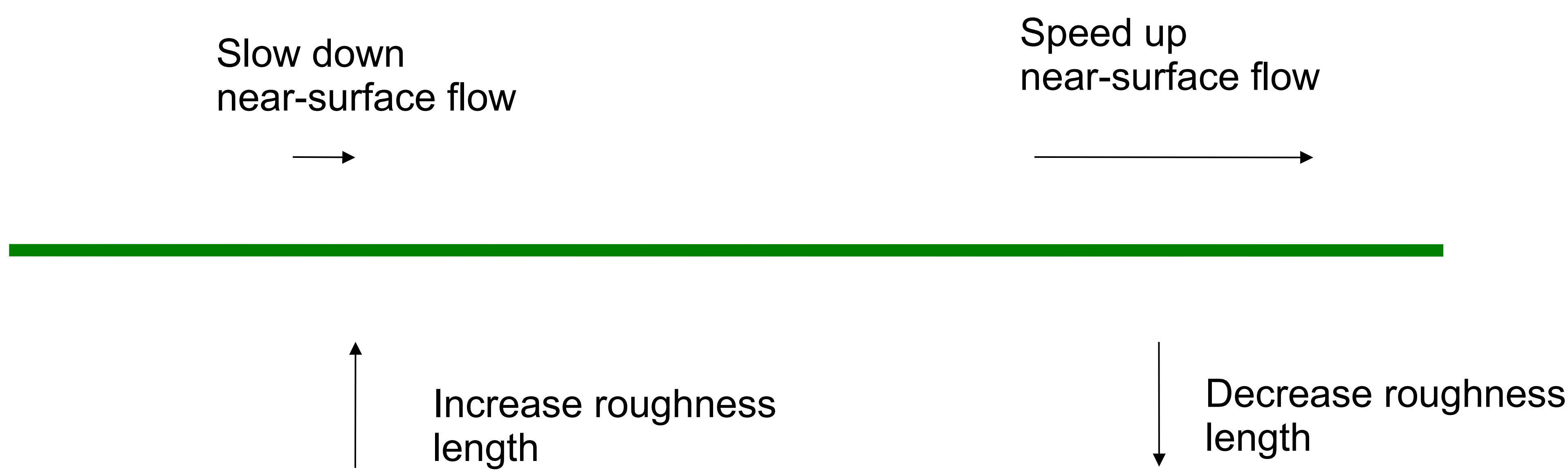
Includes distributed drag and modifications to the turbulence

Requires very high vertical resolution to resolve canopy

Rough surface

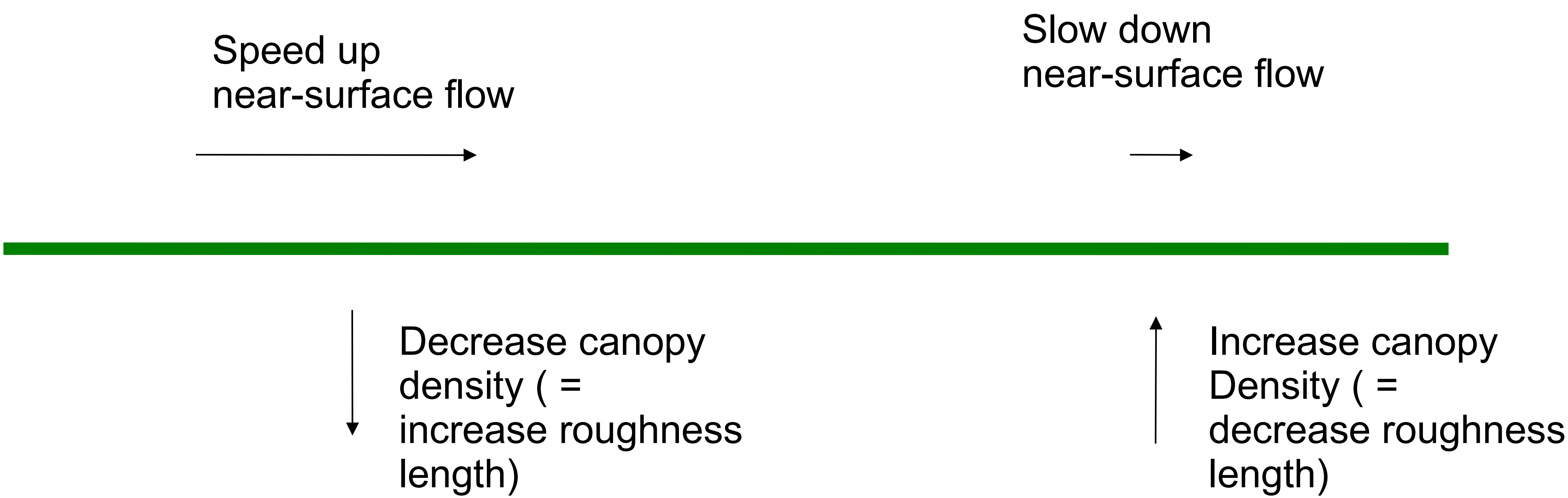
UNIVERSITY OF LEEDS

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



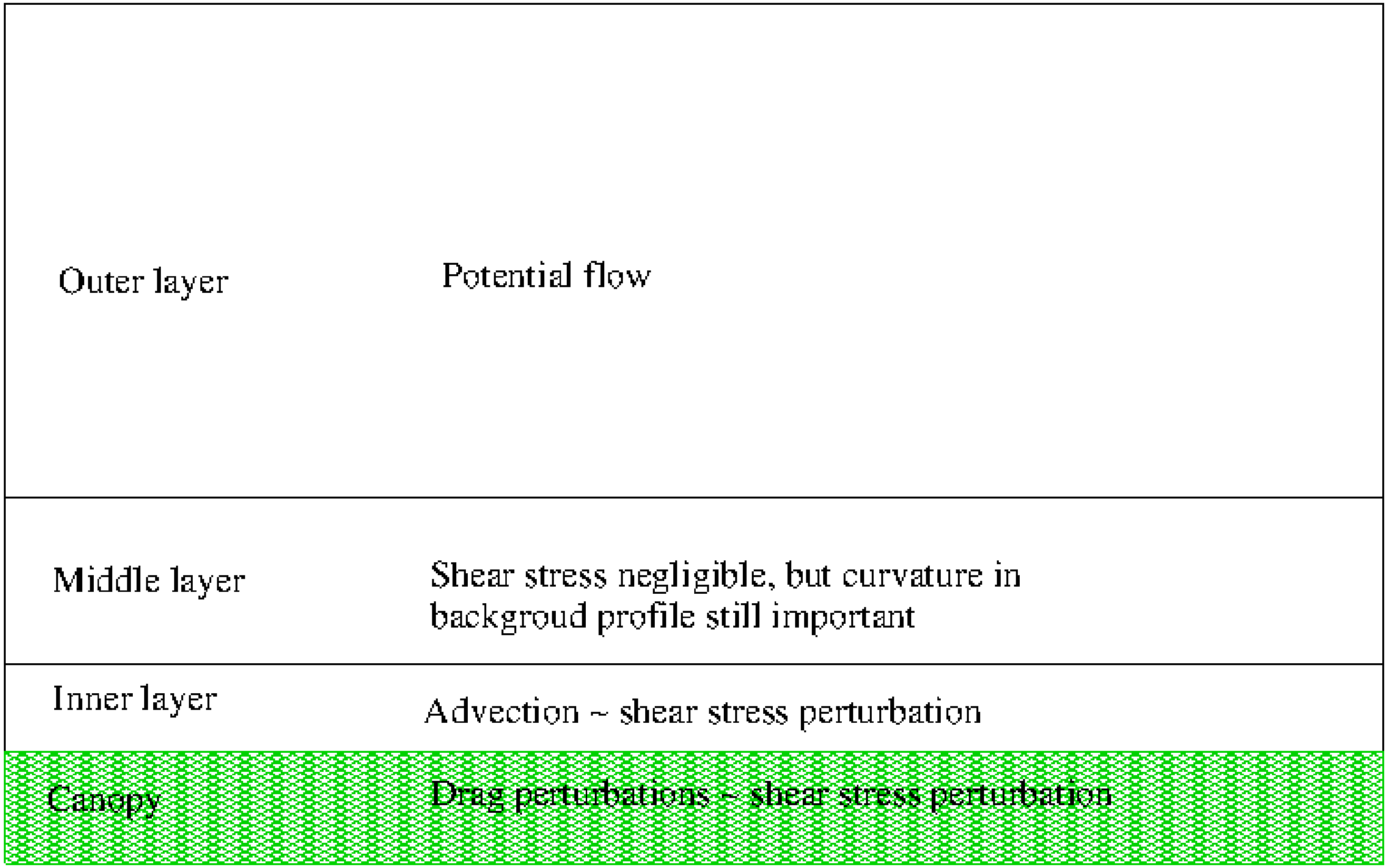
Canopy model

- 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).



Analytical model

UNIVERSITY OF LEEDS

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.

Canopy drag = $-C_d a U|U|$ 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.

Analytical model assumptions

UNIVERSITY OF LEEDS

In order to get analytic solution we require certain assumptions:

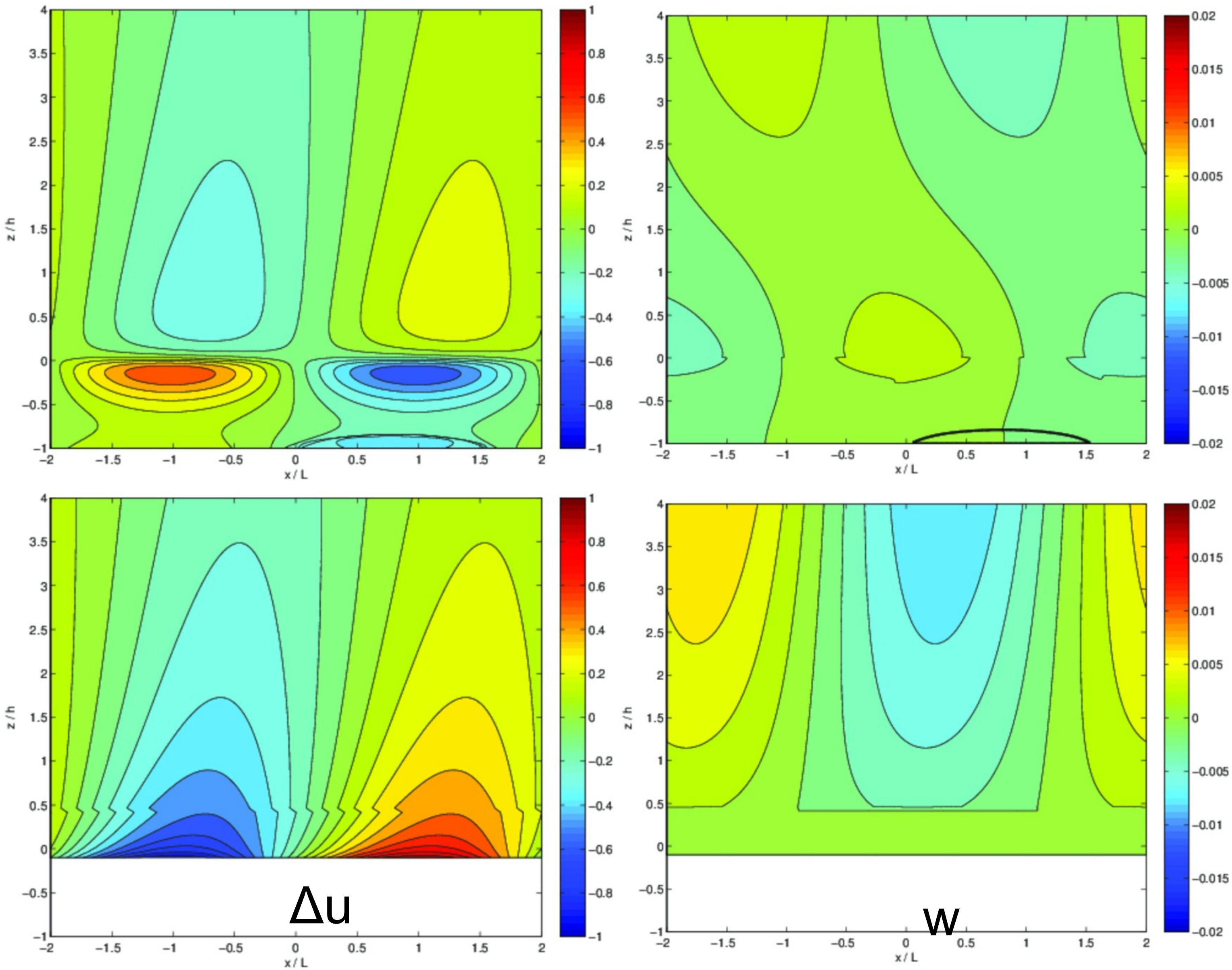
- Sufficiently deep canopy that the momentum is absorbed by the canopy, not at the surface.
- Small amplitude variations in canopy density to allow linearisation of the equations.
- Advection in the canopy is small compared to the perturbation drag term (i.e. $k L_c << 1$ where k is the wavenumber and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

Analytical solution - canopy vs roughness length

UNIVERSITY OF LEEDS

Canopy

BXH

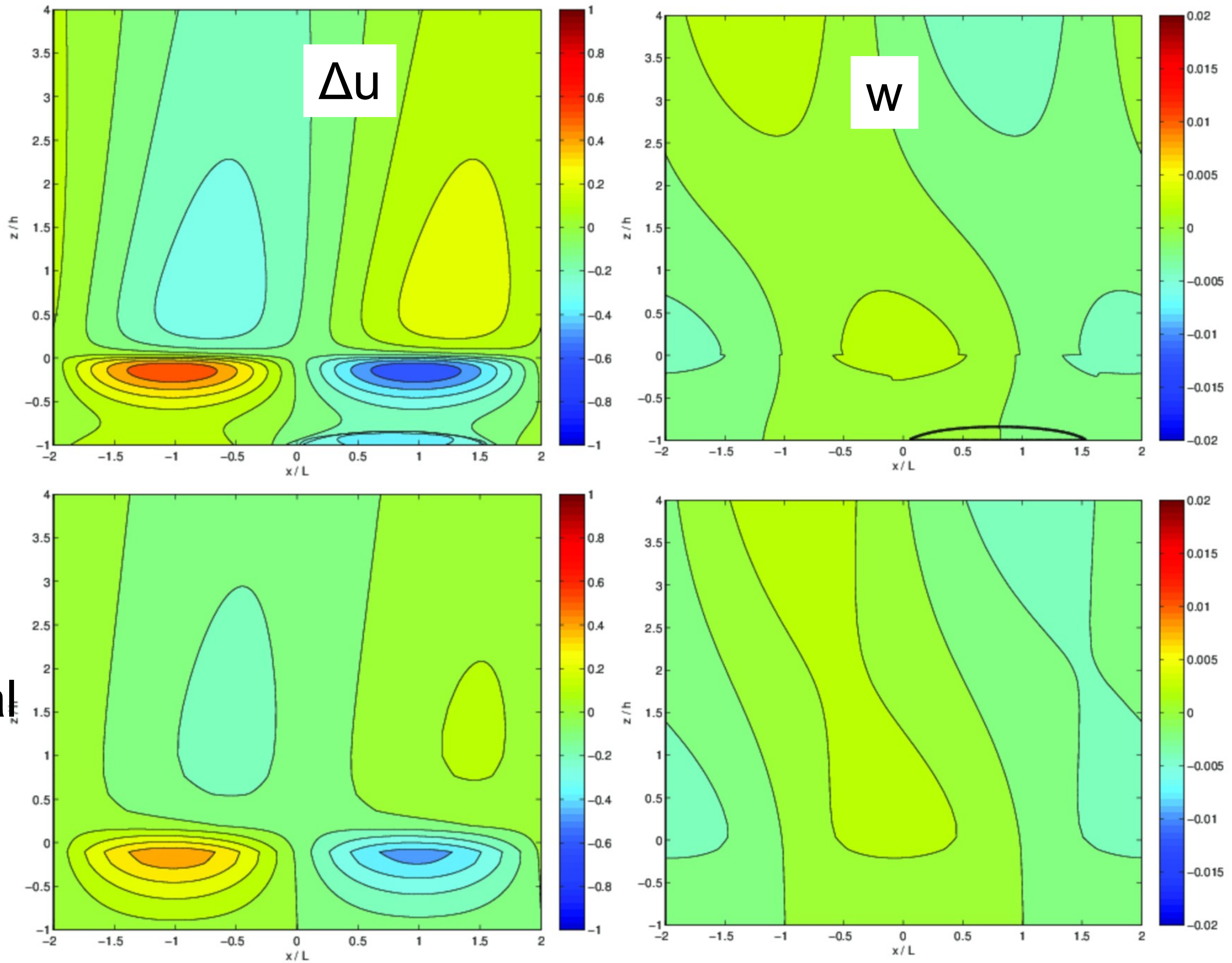


Analytical solution vs numerical model

UNIVERSITY OF LEEDS

Theory

Numerical model



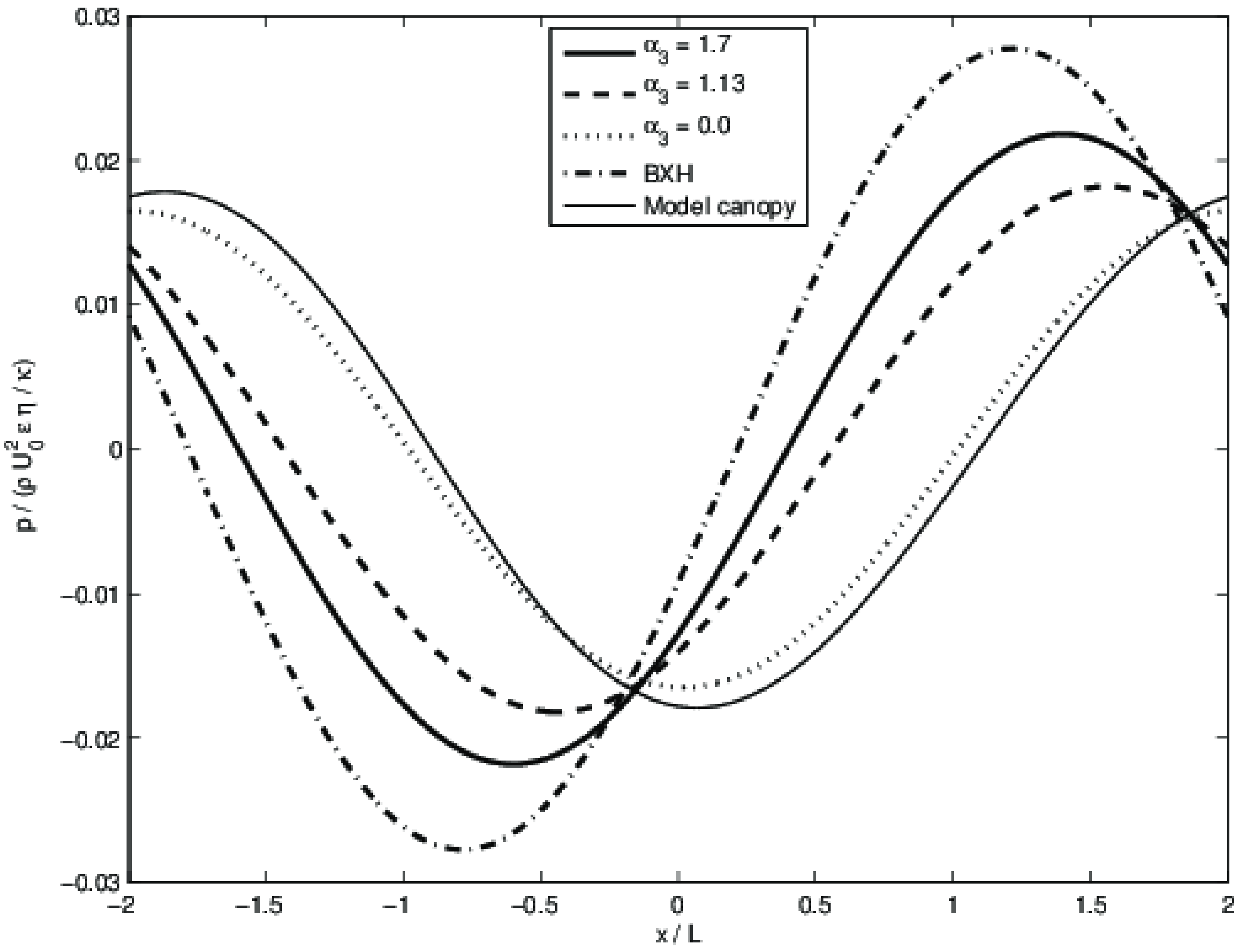
Sensitivity to turbulence parametrisation

UNIVERSITY OF LEEDS

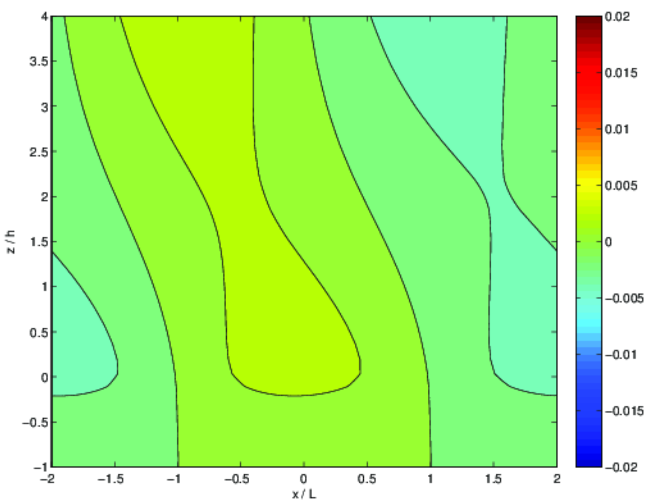
- Solution for the pressure field depends on the parametrization of the turbulent stress term τ_{zz} above the canopy. Model this as $\tau_{zz} = \alpha_3 \tau_{xz}$ following Belcher, Xu and Hunt (1990).
- Observations suggest $\alpha_3 = 1.7$.
- First order mixing length model would give $\alpha_3 = 0$ to leading order.
- Hence, most models get this term wrong. What difference does this make?

Induced pressure field

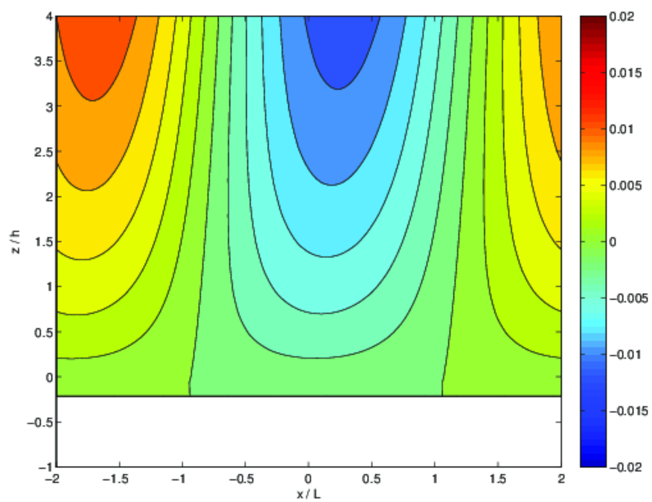
UNIVERSITY OF LEEDS



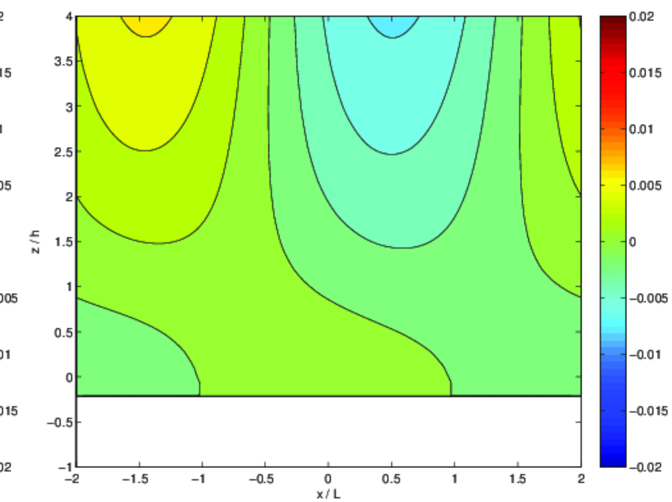
Effect of displacement height



Canopy



Roughness length



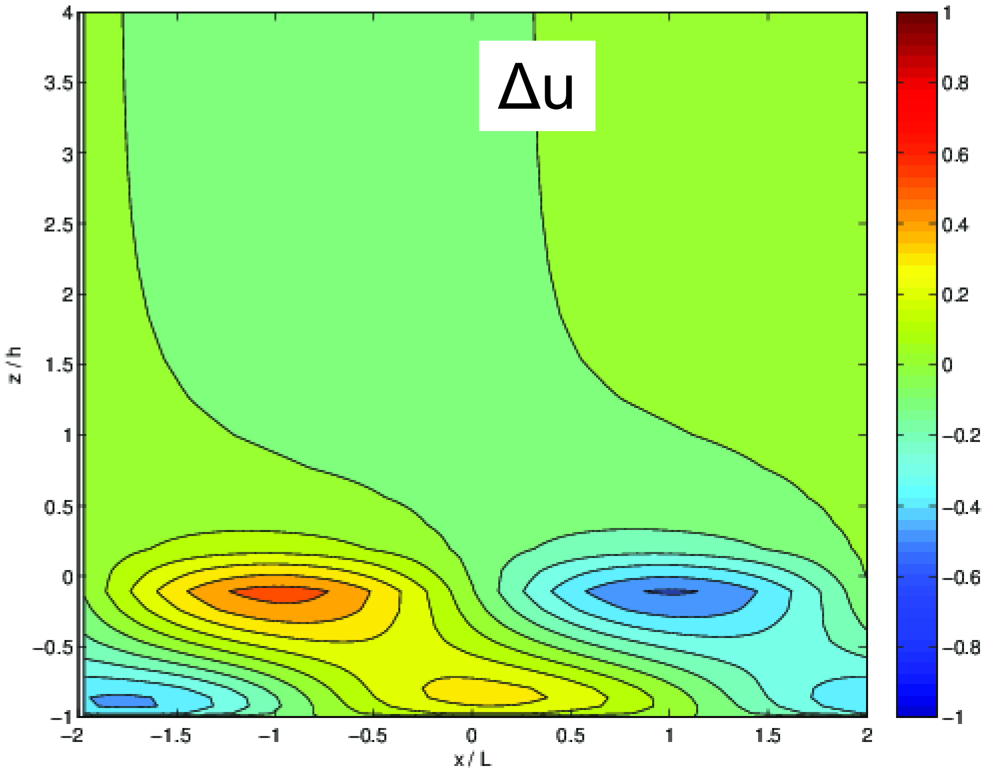
Roughness length+ displacement height

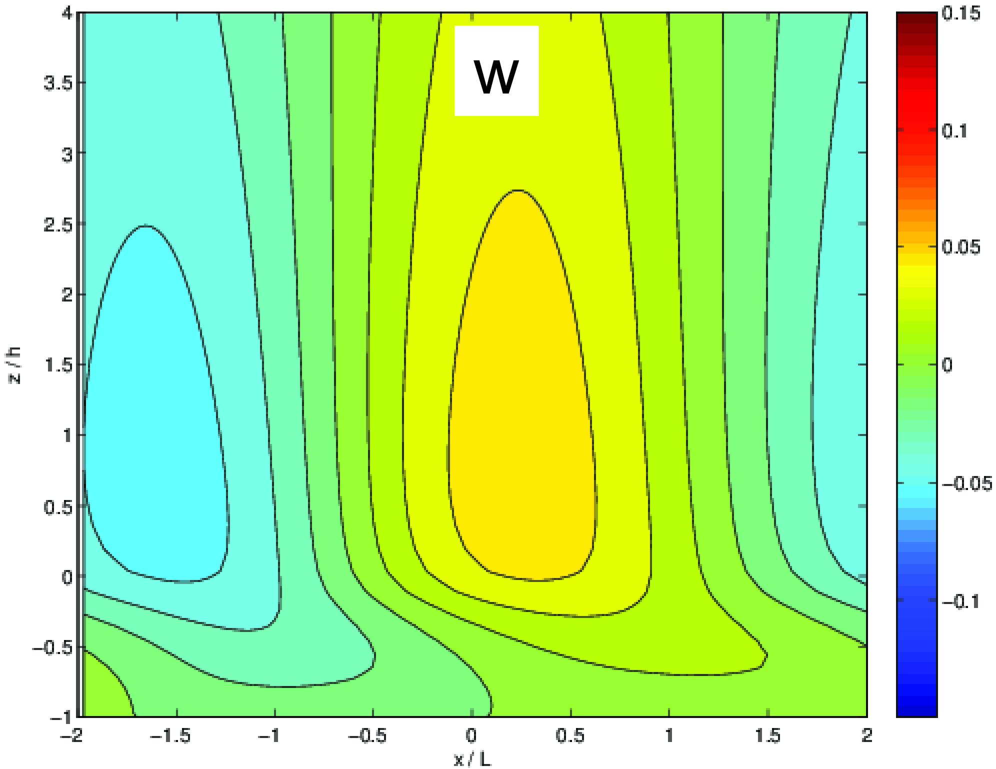
Short wavelength changes in canopy density

UNIVERSITY OF LEEDS

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?

UNIVERSITY OF LEEDS

- 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.
- Paper: Ross (2012) QJRMS **138** 1259-1272.