Assessing the role of sub-grid landscape features in setting land surface-atmosphere exchange

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SCIENCE & IMPACT

Motivation: Mosaic landscapes in Land Surface Models

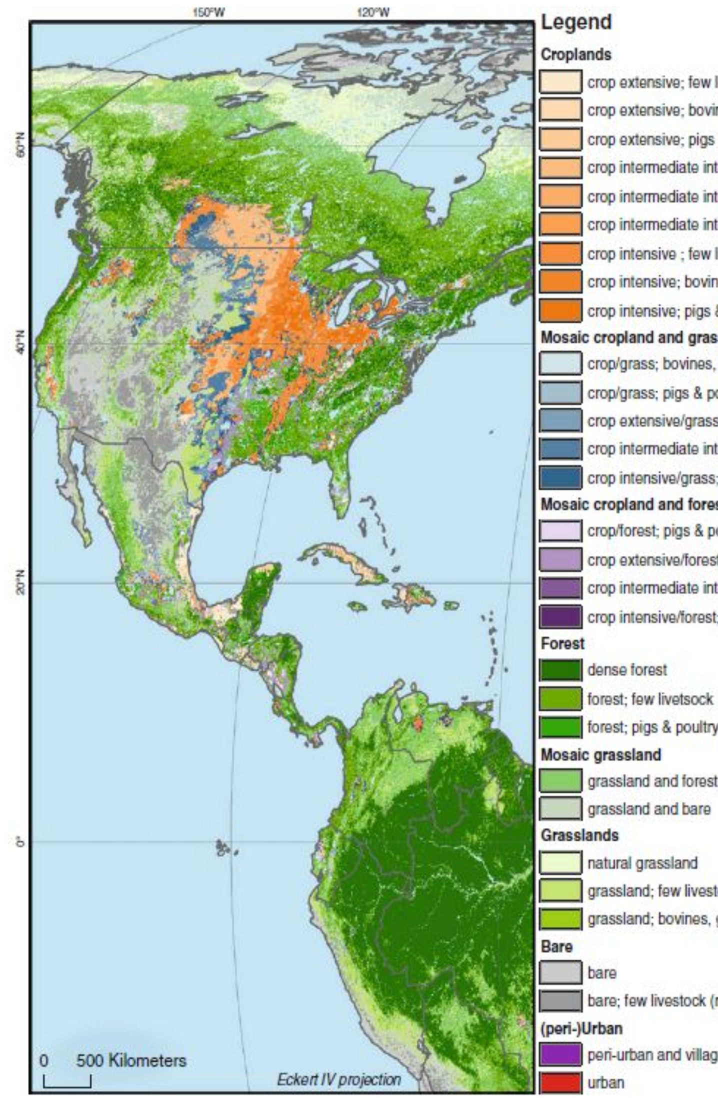
➢ 50% land surface is “mosaic”, occurs at multiple scales, both naturally and via management (e.g. Verburg 2007)

LSMs need to represent such landscapes within both NWP and climate models – at appropriate scales and complexity – in order to determine surface forcing, especially the turbulent fluxes, and near-surface atmospheric variables

Since 1990’s dominant approximation in LSMs has been tiling (e.g. Koster and Suarez, 1992).

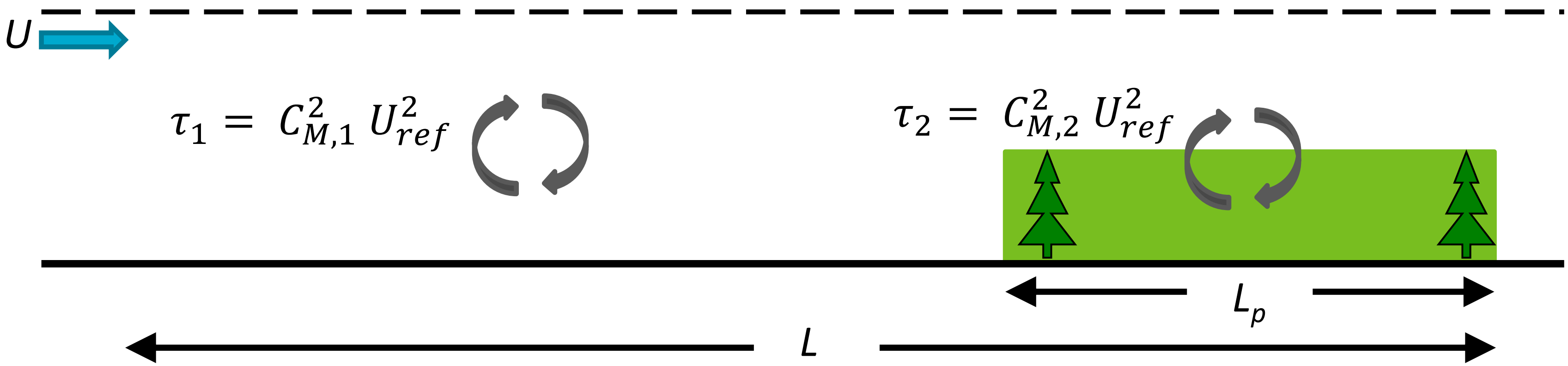
Many observation technologies and model-observation products invoke similar assumptions concerning the flow and landscape – these may not be appropriate in all contexts and at all scales.

One of the ‘nuts and bolts’ issues in LSMs that need reassessing as they evolve in resolution and application



van Asselen and Verburg (2012)

Tiling: (Kinematic) Momentum flux



Land Surface Model responsible for calculating grid-aggregate momentum flux, τ, for grid cell (*L*) given characteristics of the surface and a reference level wind speed, U_{ref}

Tiling assumptions

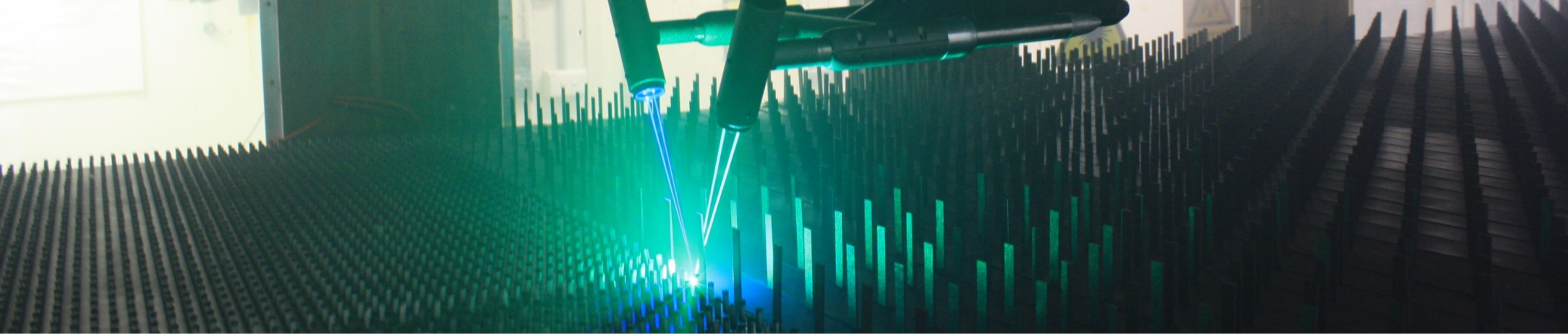
Transfer coefficients $C_{M,1}^2$ & $C_{M,2}^2$ prescribed as if surface were ***horizontally homogenous***

Flow and turbulence assumed statistically ***stationary*** and ***in equilibrium***

U_{ref} is uniform across all tiles (i.e. reference level above blending height)

Distribution and size of tiles is irrelevant

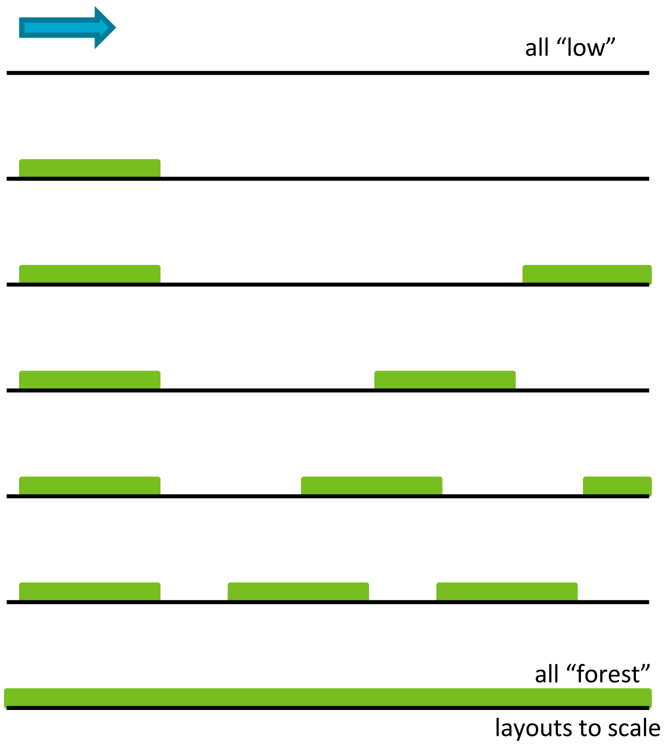
commonly: $$\frac{\mathrm{d}U}{\mathrm{d}z} = \frac{\kappa}{z-d}\phi_m \;\rightarrow C_M^2 = \kappa^2 \Big/ \left[\ln\left(\frac{z_{ref}-d}{z_{0m}}\right) - \psi_m\left(\frac{z_{ref}-d}{L_{mo}}\right)\right]^2$$



Wind tunnel experiments

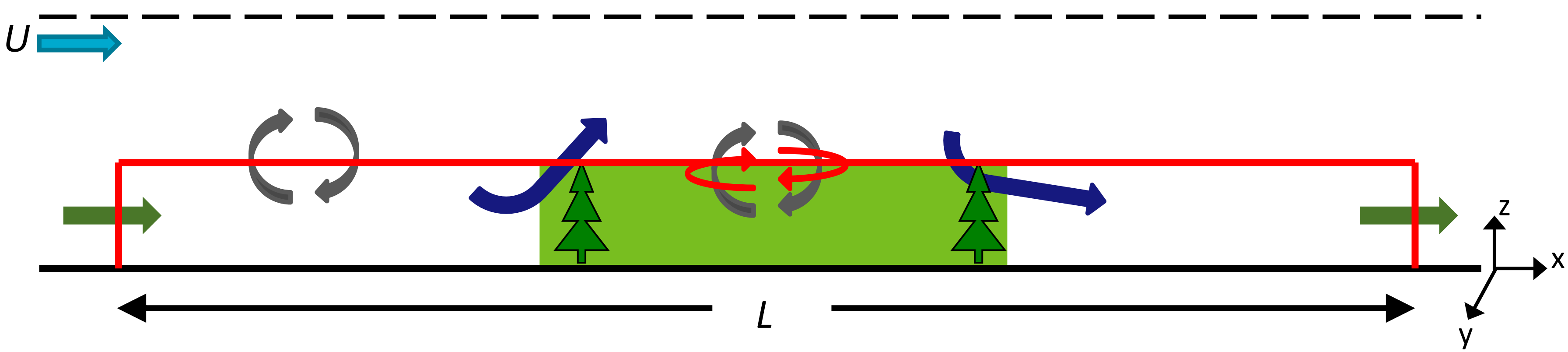
- 7 canonical experiments
- 2-dimensional edge flows
- alternating, repeating patches of low/high roughness
- zero pressure gradient, high Reynolds number flow
- low roughness – "grass", canopy height h_c=15mm, $z_0 \sim 2$ mm
- high roughness – "forest", canopy height h_c=60mm, $z_0 \sim 10$ mm
- 22 heights, 4 lateral positions, 17-27 streamwise positions
- > 2kHz and > 2 orders of magnitude in the inertial subrange

Analyse the furthest downstream patch of "forest" surface and "grass" either side



Poette et al. (2017)

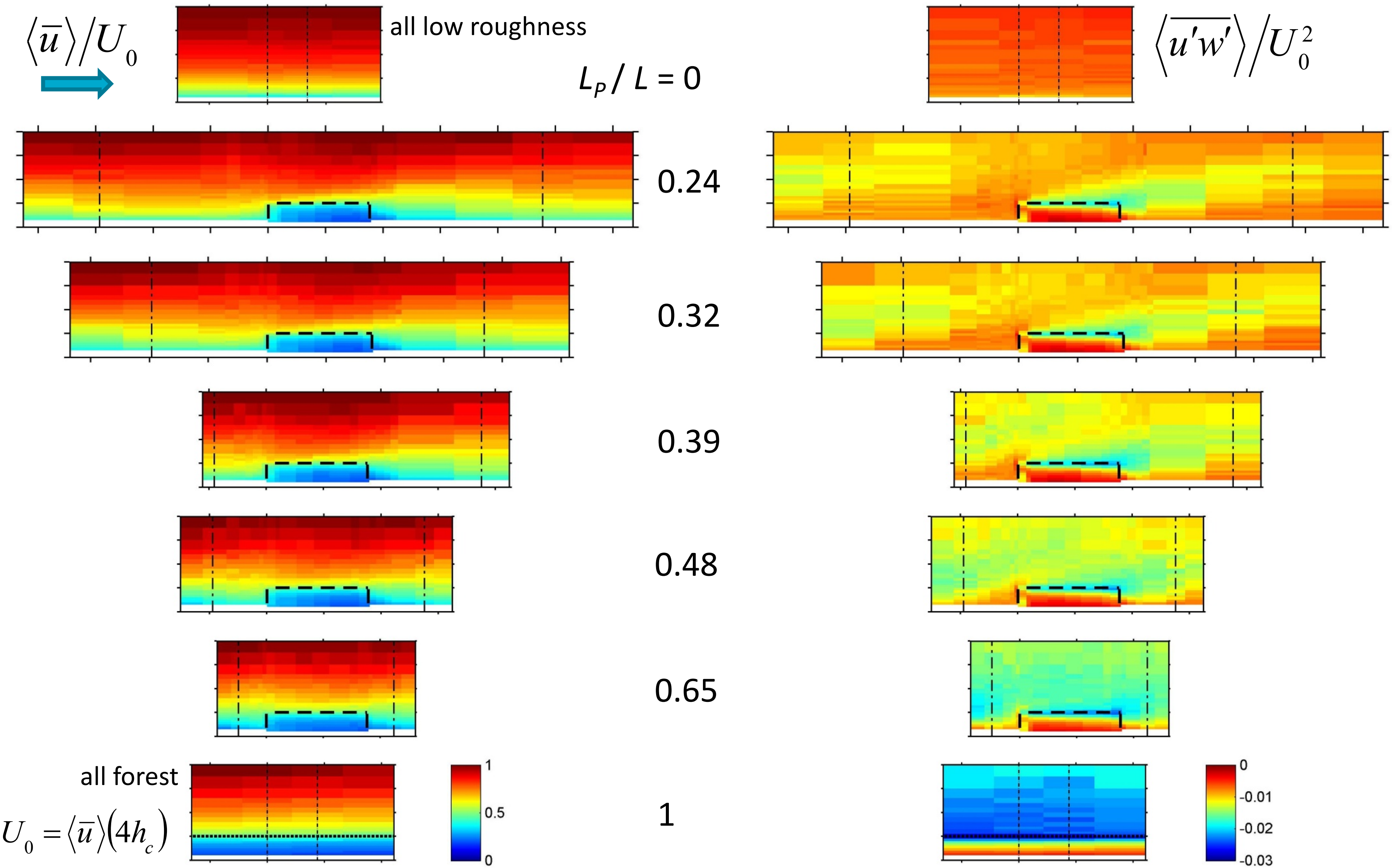
Momentum balance of a patch work landscape



Apply time and (double) space averaging on a control volume

$$\tau = \underbrace{\left[\left\langle \overline{u'w'} \right\rangle\right]}_{\text{turbulent flux}} + \underbrace{\left[\left\langle \overline{u}''\overline{w}'' \right\rangle\right]}_{\text{dispersive flux}} + \underbrace{\left[\left\langle \overline{u} \right\rangle^{\sim} \left\langle \overline{w} \right\rangle^{\sim}\right]}_{\text{patch flux}} + \underbrace{\int_0^{h_c} \left(\left\langle \overline{u^2} \right\rangle_{\mathrm{dn}} - \left\langle \overline{u^2} \right\rangle_{\mathrm{up}} \right) \mathrm{d}z \Big/ 2L}_{\text{streamwise change}} + \ldots$$

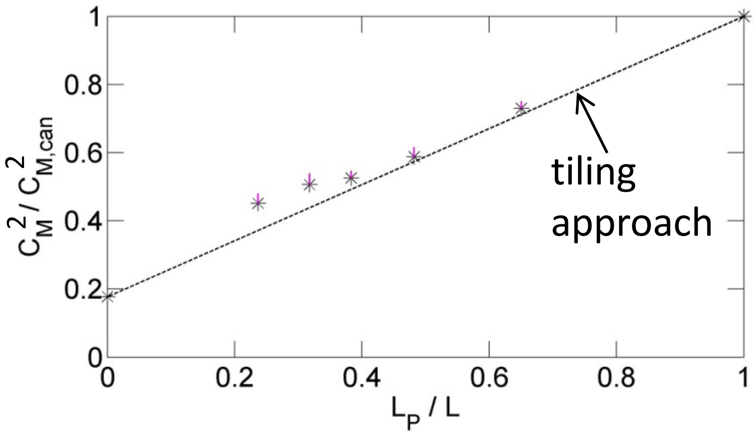
Derive $\tau = C_M^2 \, U_{ref}^2$ from the wind tunnel observations and compare with tiling approach wind speed | momentum flux



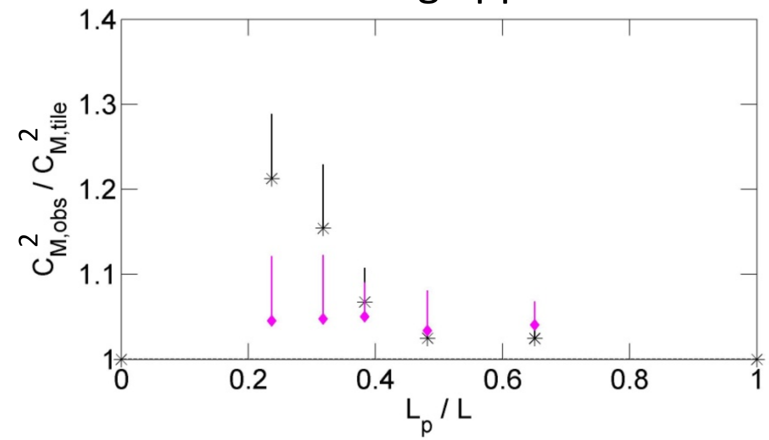
Theory exists for adjustment process for both mean flow and turbulence (e.g. Belcher et al. 2012)

Grid-Cell effective transfer coefficients (reference level at $2h_c$ of forest)

Relative to 'all forest'

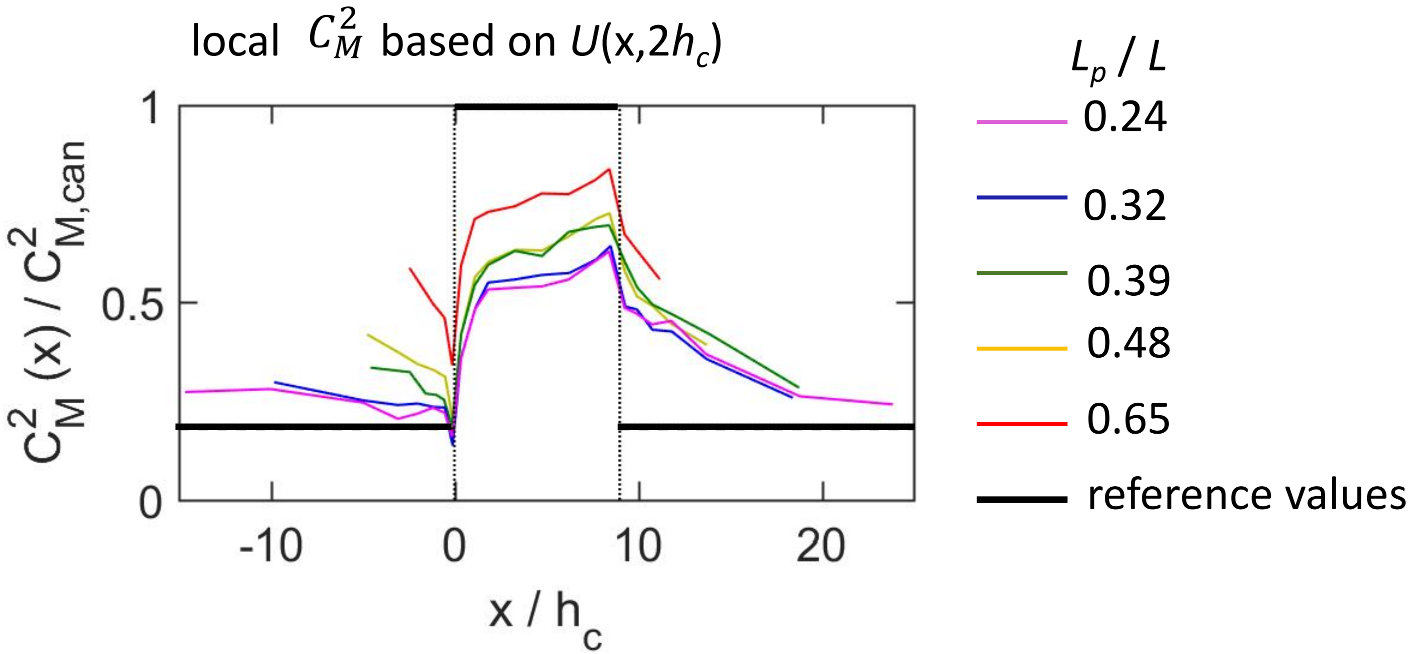


Relative to tiling approach



◆ non-turbulent component
Error bars: range of dispersive contribution

- Tiling approach captures the overall (factor 5) trend of C_M^2 with L_p / L
  - appreciable errors in some cases
  - due to perturbations to turbulent flux-mean flow relationship
  - **both** momentum flux and wind speed vary with L_p / L
  - 'novel' terms are small in aggregate (although these can be significant locally)

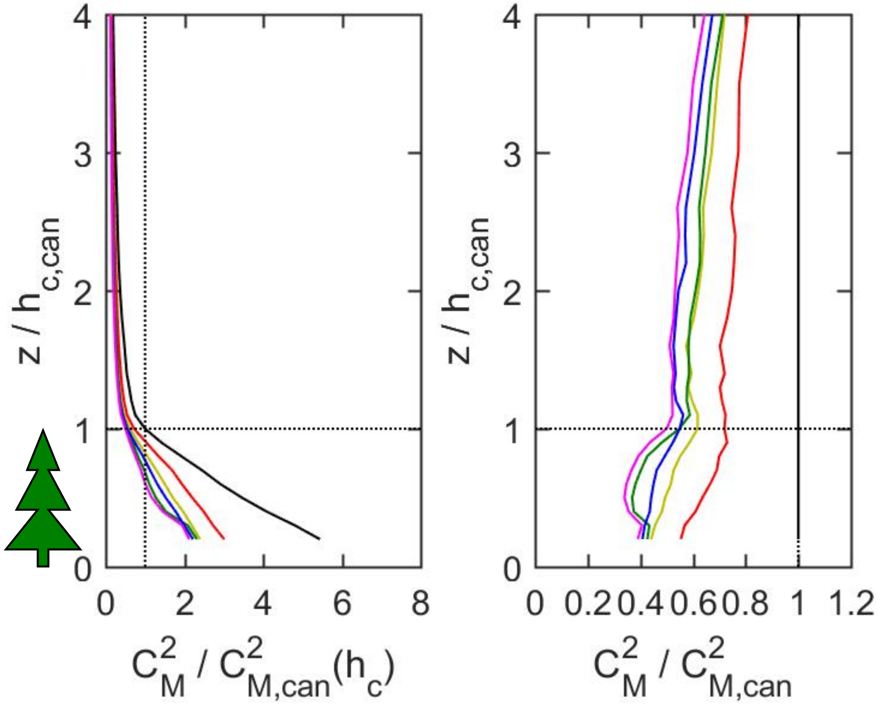


- C_M^2 differs from tile reference values at all locations
- Impacts centred on the edges – both upstream and downstream effects
- Asymmetric response in adjustment (see e.g. Bradley 1968)

- Tiling approach: C_M^2 under (over) estimated for “low roughness” (“forest”)
- Cancellation of errors occurring in the aggregate

Tile C_M^2 coefficients (based on grid cell wind speed)

'all forest' reference value is 1.5-3 times too large depending on reference height

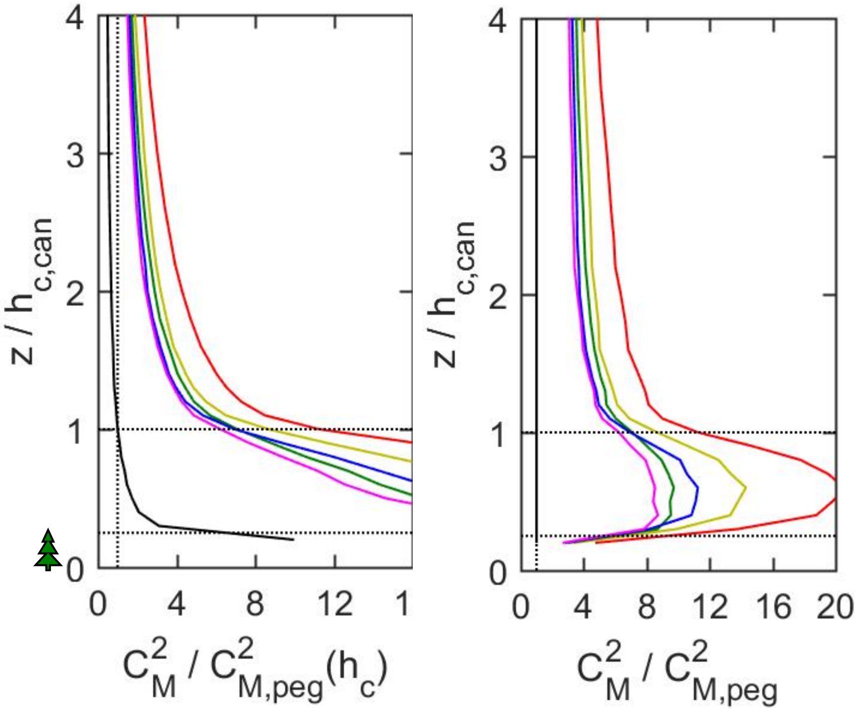


relative to reference case at h_c

relative to reference case at z

If tiling correct then = 1 at all *z*

'all low roughness' reference value is notably too small



Scalar transfer from mosaic landscapes

turbulent transfer is a determining factor for scalar transfer e.g. $H \propto C_M C_H U_{ref} \Delta\theta$

$\Rightarrow$ errors in tile momentum transfer efficiency impact tile scalar transfer

$\Rightarrow$ mechanism for direct aerodynamic interaction between tiles

unlike for momentum transfer

- turbulence is not the only determining factor for scalar transfer
- decreasing order of importance – momentum, heat, water (VPD)

unlike for momentum transfer

- errors in tile scalar transfer accumulate over time via the surface state variables

  $\Rightarrow$ introduction of compensating errors through choice of parameter values

non-linearity of adjustment occurs with energy, heat, water and other scalars (warm/cold, stable/unstable, wet/dry internal boundary layers)

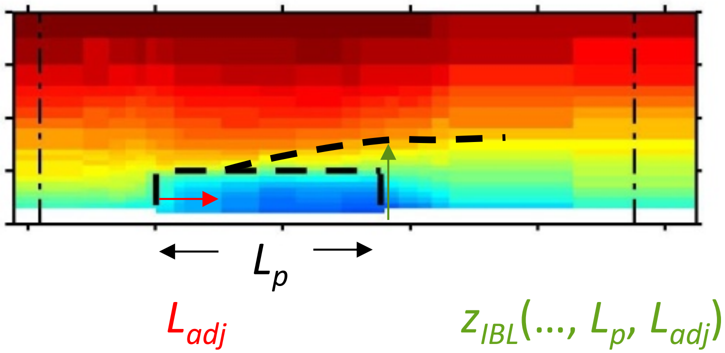
scalar transfer (including evapotranspiration) controlled by more than the local site conditions

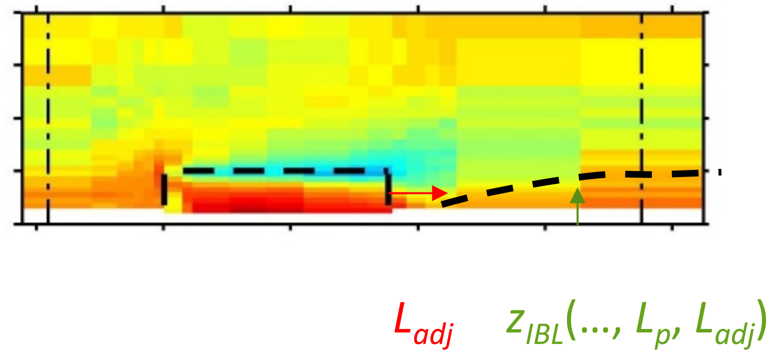
$\Rightarrow$ compounding factor when analysing multi-site data sets.

patch scale (L_p) for scalars would be impacted by plant species and land management

Way forward? Extended formulation for transfer coefficients

$$\frac{\mathrm{d}U}{\mathrm{d}z} = \frac{\kappa}{z-d}\phi_m \boxed{\phi_p} \rightarrow C_M^2 = \boxed{\psi_{p1}}\kappa^2 / \left[\ln\left(\frac{z_{ref}-d}{z_{0m}}\right) - \psi_m\left(\frac{z_{ref}-d}{L_{mo}}\right) + \boxed{\psi_{p2}}\right]^2$$





Heuristic model for ϕ_p dependent on one new variable

Patch scale / Patch size needed for equilibrium at reference level ($\gtrsim 1$)

\+ surface characteristics of surrounding tiles

$\rightarrow \tau_{patch}/U_{patch}^2$

$\rightarrow U_{patch}/U_{ref}$

\+ boundary layer depth and type (e.g. Raupach and Finnigan 1997)

\+ topographic length scales (e.g. Finnigan 1994)

\+ information from surrounding grid cells if needed

Concluding comments

- scale experiments can permit testing of some aspects of LSMs in ways that cannot be done through field observations or remote sensing
- Tiling of mosaic landscapes is a reasonable (30% error) approximation (for momentum transfer in this experiment) at the aggregate scale but notably incorrect at the tile scale [small patches of low C_M^2 surface downstream of high C_M^2 surface]
- (asymmetry/non-linearity of) adjustment is a missing process in LSMs. This permits spatial variation in efficiency of turbulent transfer (of momentum) to the surface (without the need to adjust the tile properties)
- errors in momentum transfer cascade onto predictions of the surface energy balance and surface state
- an extension of existing bulk aerodynamic formulation(s) (for the momentum flux) to incorporate sub-grid scale landscape features seems feasible
    - may need a change in LSM structure
    - may need a change in atmospheric model structure
    - quantitative impact of such a change is as yet unknown - this requires an assessment of the feedbacks