Scale dependence of atmosphere–surface coupling through similarity theory (Project HKU24)

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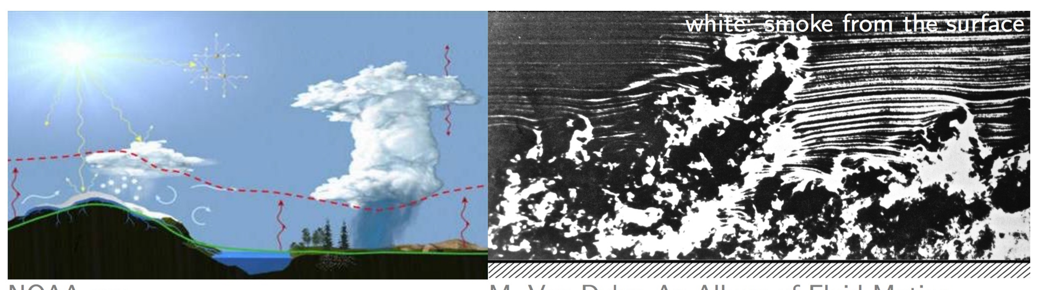
The planetary boundary layer

The PBL is the Atmospheric layer under immediate impact by the surface (typically $\mathcal{O}(100m)$ thick); it couples free atmosphere to underneath land/ocean.

⇒ cross-component transfer of energy, momentum, vapor

- vertically stratified
- always turbulent, but even in the entire domain
- propagates information about the boundary conditions into the atmospheric compartment

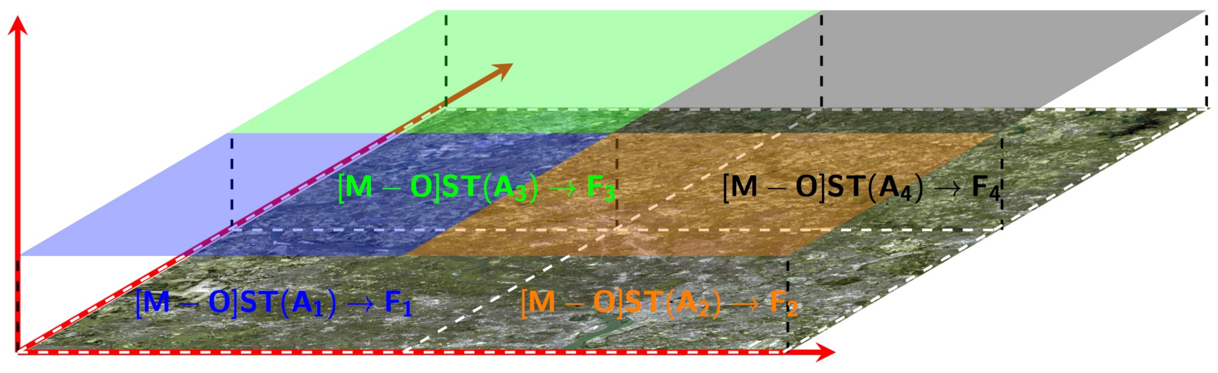


NOAA.gov M. Van Dyke: An Album of Fluid Motion

Monin–Obukhov similarity theory (MOST)

- surface acts as boundary condition of the atmospheric domain
- turbulence closure inside domain requires extension to the surface to provide gradients (fluxes) at the interface
- Monin–Obukhov Similarity theory exploits scale-similarity arguments in a non-dimensional framework and provides a flux–gradient closure at the surface:

$$U(z) = \frac{u_\star}{\kappa}\left[\log\frac{z}{z_{00}} + \Psi_U\left(\frac{z-z_{00}}{L_O}\right)\right] \quad (\text{for } z_{0,0} \ll z \ll \delta_{\mathrm{PBL}})$$



Limits of MOST

- Ψ perturbs neutral profile (requires $|z/L_O| \ll 1$)
- Ψ_U from observations is ambiguous (site-/process-specific issues as advection, imbalance, ...)
- equilibrated, homogeneous PBL required

⇒ heterogeneity of boundary of turbulence violate closure paradigms

How 'large' must a patch be to act as homogeneous for MOST?

- surface-layer closure (MOST) applied in most models of atmospheric flow
- assessment of the theory requires independent approach

Method: direct numerical simulation of a turbulent boundary layer

Fluid Mechanics approach

- smooth, homogeneous surface
- fixed boundary condition
- no micro-physical processes and radiation

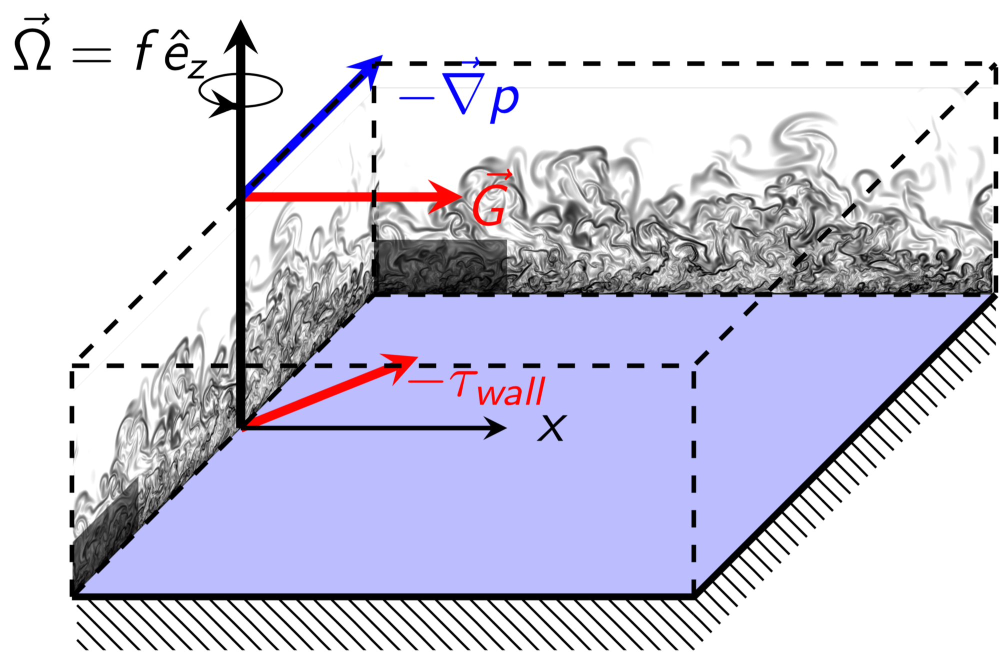
Numerics

- 6th-order compact spatial derivatives
- 6th-order collocated convective advection
- 4th-order low-storage Runge-Kutta time stepping
- Compact pressure-Poisson solver to machine accuracy
- MPI/openMP parallelized up to 262,144 threads/4 racks

Simulations

- $3072 \times 6144 \times 640 \approx 1.2 \times 10^{10}$ collocation points

$\approx 50,000$ iterations per case; $\approx 20 \times 10^6$ CPUh



Sketch of the Ekman layer that develops from the interaction between a flow in geostrophic balance $2\Omega k \times G\mathbf{i} = -\nabla p$ with the no-slip condition $u = 0$ at the boundary $z = 0$. Stable stratification is imposed by a negative surface buoyancy $B_{\mathrm{wall}} = -B_{\mathrm{ref}}$.

Statistical analysis

- Domain averages
- Convergence in time domain (→ virtual towers)
- Convergence in spatial domain (→ coarse graining)

3 directions: streamwise, spanwise, 2D (horizontally)

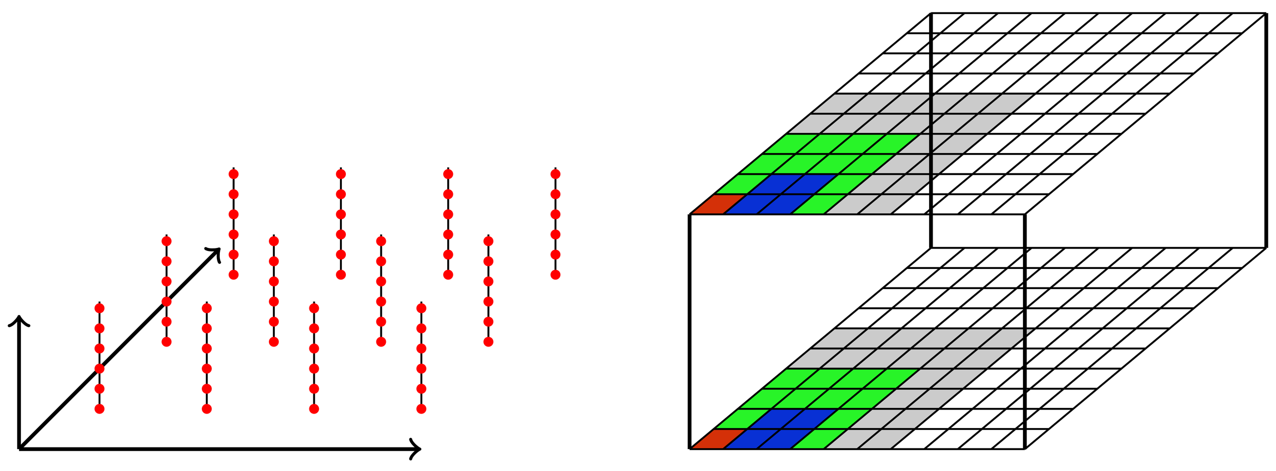
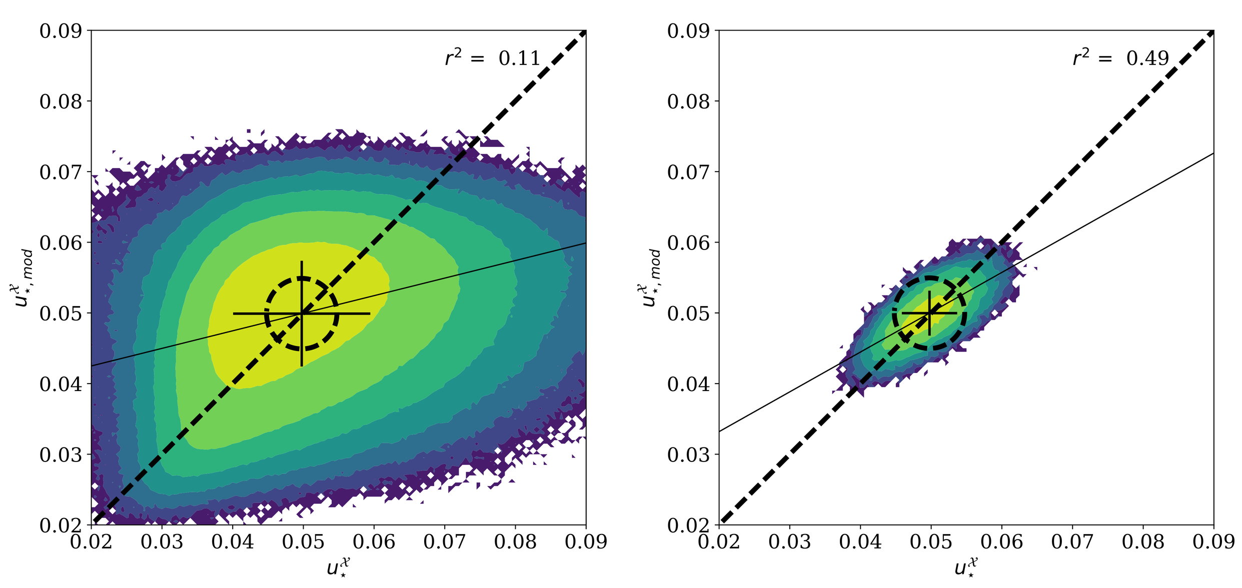


Illustration of the data employed in the convergence study. Left: individual towers distributed on a regular grid subsampling the flow in space. Right: coarse-graining procedure for a two-dimensional horizontal convergence (1D along the streamwise and spanwise directions is not shown

Convergence of individual samples to MOST in neutral conditions



Joint probability density function (pdf) of MOST-estimated friction $u_{\star,\mathrm{mod}}$ and actual friction $u_\star$ for filters F with different horizontal/temporal response ranging from instantaneous data to global averages. It is

$$u_\star^2 = \nu\sqrt{(\partial_z U_{z=0})^2 + (\partial_z V_{z=0})^2} \quad (1)$$

$u_{\star,\mathrm{mod}}$ and $b_{\star,\mathrm{mod}}$ solve

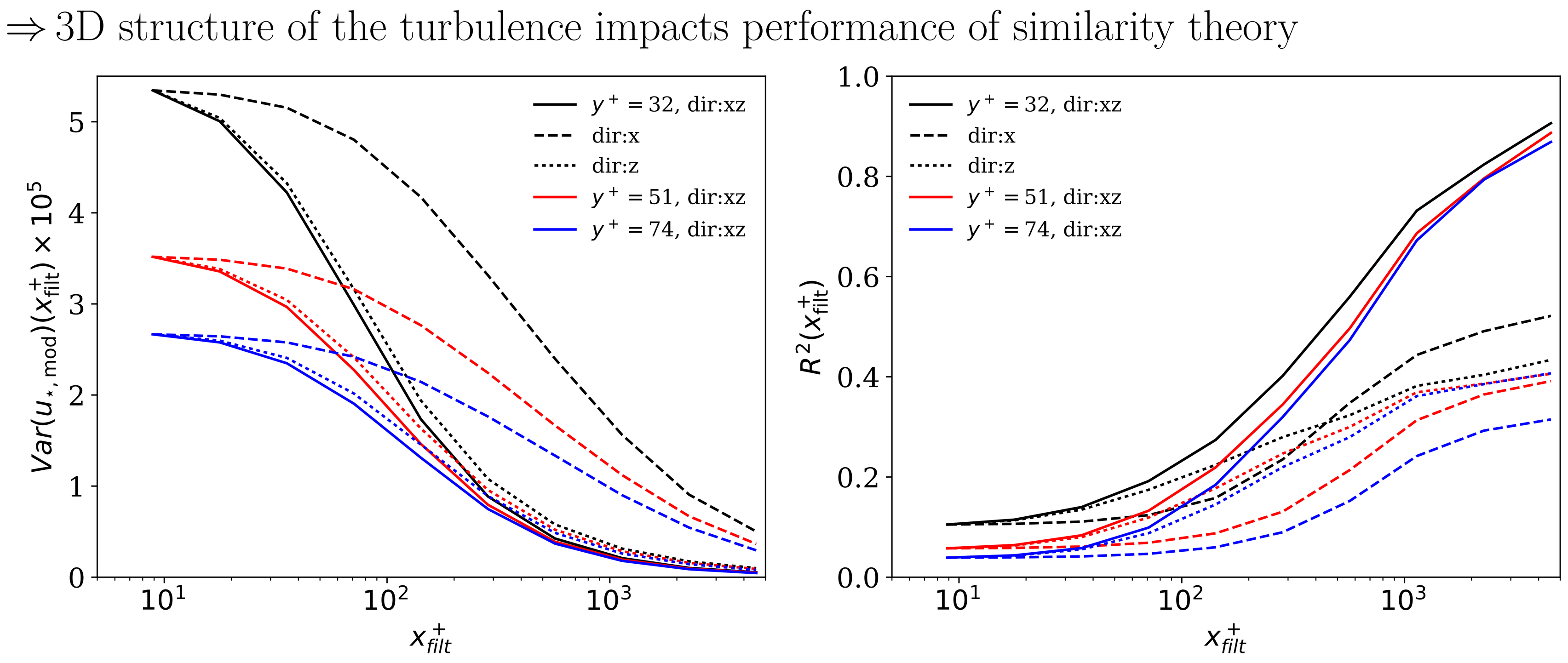
$$\kappa U = u_{\star,\mathrm{mod}} \ln\left(c_z u_{\star,\mathrm{mod}}\right) + c_M \frac{b_{\star,\mathrm{mod}}}{u_{\star,\mathrm{mod}}} \quad (2)$$

$$\kappa B = b_{\star,\mathrm{mod}} \ln\left(c_z u_{\star,\mathrm{mod}}\right) + c_H \frac{b_{\star,\mathrm{mod}}}{u_{\star,\mathrm{mod}}} \quad (3)$$

Left: Instantaneous data; right streamwise filtered along 2600 wall units ($\approx 1.5\delta_{\mathrm{PBL}}$); thick dashed line corresponds to perfect validity of MOST, thin solid line is least-square fit of all data.

- MOST systematically underestimates the variance of fluxes; applicability is scale-dependent
  - MOST explains local variations for $[t,x]^-_{\mathrm{avg}} \gtrsim 0.1$
  - many models (LES/meso-scale) use $\Delta[t,x]$ below this range
- convergence depends on the direction along which the data is sampled
  - anisotropy of near-surface streaks causes slower along-flow convergence
  - variations are only governed by MOST when averaged along both horizontal directions

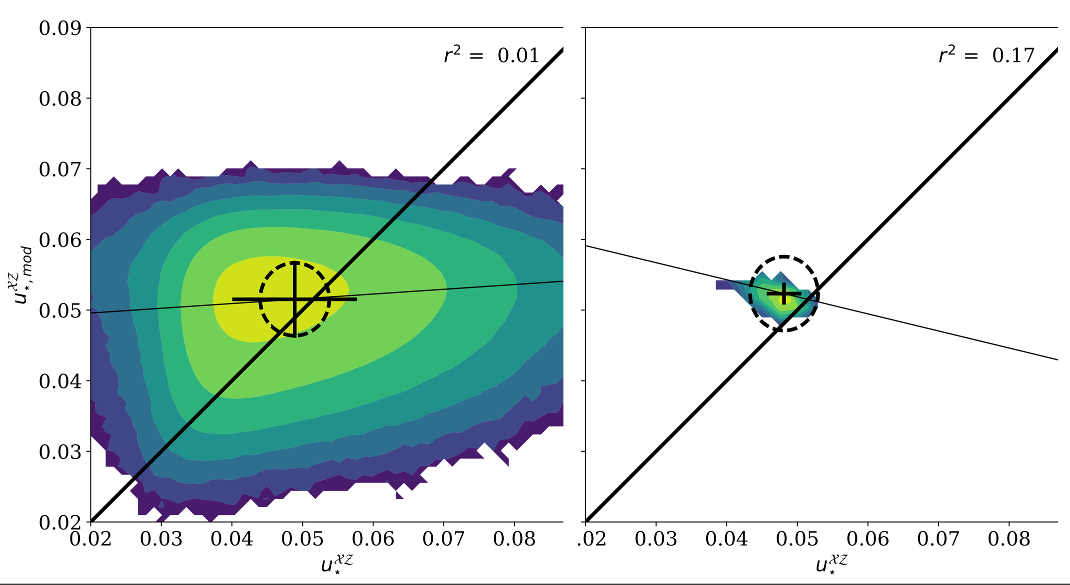
⇒ 3D structure of the turbulence impacts performance of similarity theory



Variance of the modelled friction (upper panel) and correlation of the modelled vs. actual friction (lower panel) as a function of the filter scale for the three ave raging directions considered at different heights within the surface layer.

Convergence in stable conditions

- local variation not captured by MOST (even at largest scales)
- MOST exhibits negative skill in explaining local variation
- large/small $u_\star$ values not captured by SL-wind bursts / intermittency
- friction–momentum coupling breaks down in stable conditions



Project-related publications

Ansorge C (2018): Scale dependence of Atmosphere–Surface coupling through similarity theory. *Bound-Lay Meteorol* (under review).

Hooijdonk I, Clercx H, Ansorge C et al. (2018): Parameters for the collapse of turbulence in the strongly stratified plane Couette flow. *J Atmos Sci* (under review).

Bou-Zeid E, Gao X, Ansorge C and Katul G. (2018): The role of return-to-isotropy in wall-bounded turbulent flows with buoyancy. *J Fluid Mech* (under review).

Ansorge C, Mellado JP (2014): Global Intermittency and Collapsing Turbulence in the Stratified Planetary Boundary Layer. *Bound-Layer Meteorol* 153(1):89–116

Ansorge C, Mellado JP (2016): Analyses of external and global intermittency in the logarithmic layer of Ekman flow. *J Fluid Mech* 805:611–635

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