Atmospheric Planetary Boundary Layers (ABLs / PBLs) in stable, neural and unstable stratification: scaling, data, analytical models and surface-flux algorithms

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Part II: The role of large, organised eddied in the convective heat/mass transfer

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References

Zilitinkevich, S.S, Gryanik V.M., Lykossov, V.N., and Mironov, D.V., 1999: A new concept of the third-order transport and hierarchy of non-local turbulence closures for convective boundary layers. *J. Atmos. Sci.*, **56**, 3463-3477.

Elperin, T., Kleeorin, N., Rogachevskii, I., and Zilitinkevich, S., 2002: Formation of large-scale semi-organised structures in turbulent convection. *Phys. Rev.* ***E.*** **66**, 066305, 1-15.

Elperin T., Kleeorin N., Rogachevskii I. and Zilitinkevich S., 2006: Turbulence and coherent structures in geophysical convection. *Boundary-layer Meteorol.* **119**, 449-472

Zilitinkevich, S. S., Hunt, J. C. R., Grachev, A. A., Esau, I. N., Lalas, D. P., Akylas, E., Tombrou, M., Fairall, C. W., Fernando, H. J. S., Baklanov, A., Joffre, S. M., 2006: The influence of large convective eddies on the surface layer turbulence. *Quart. J. Roy. Met. Soc*. **132**, 1423-1456

Content

Large eddies (convective winds) enhance mixing

Homogeneous surfaces:

Shear-free convection → cells

Sheared convection → rolls

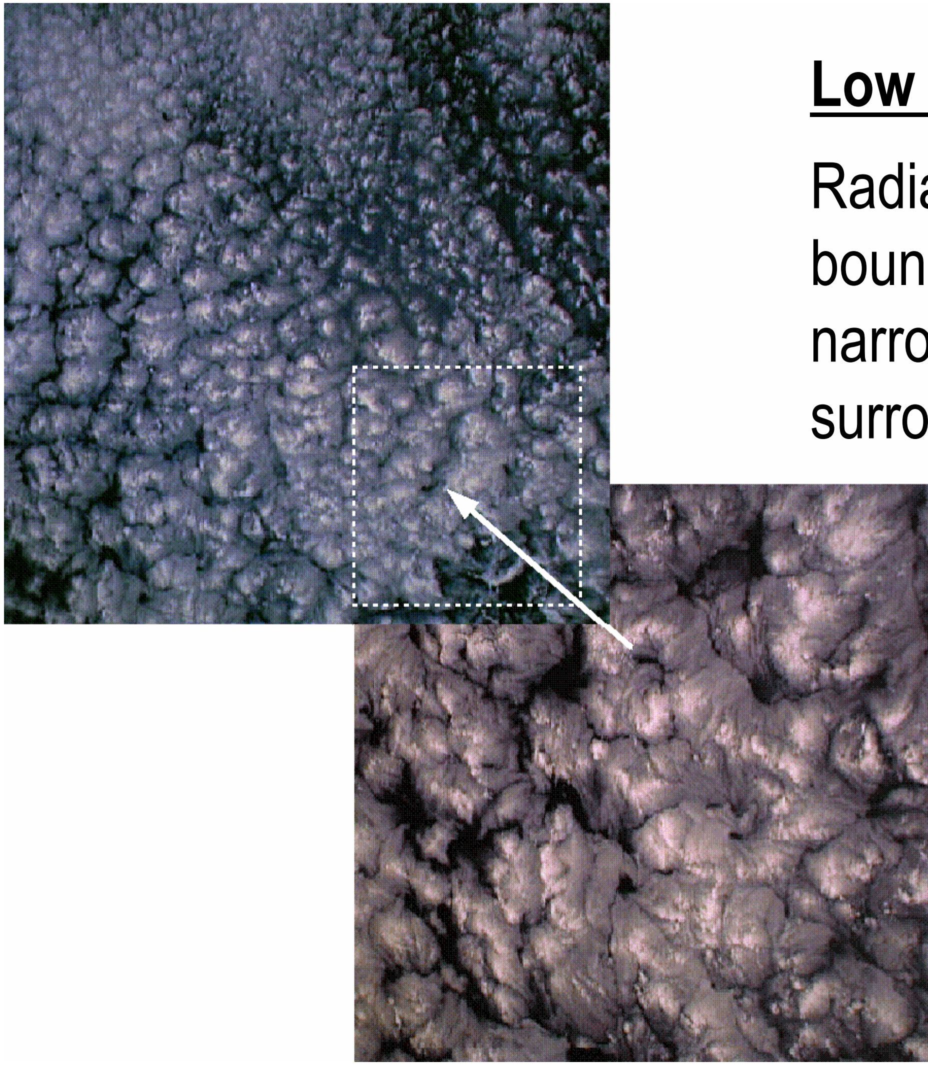
Heterogeneous surfaces and heat islands:

polynias / big cities

leads

Future work: improved CBL module and flux-parameterization

Closed cloud cells over the Atlantic Ocean



<u>Low wind convection</u>

Radiative cooling of the upper boundary of clouds causes narrow cold descending plumes surrounded by warmer updraughts

Open cloud cells over the Pacific Ocean

Low wind convection

Narrow warm uprising plumes surrounded by colder downdraughts, driven by the positive buoyancy flux over warm sea surface

Cloud "streets" over the Amazon River

<u>Strong wind: shear-generated convective rolls</u>

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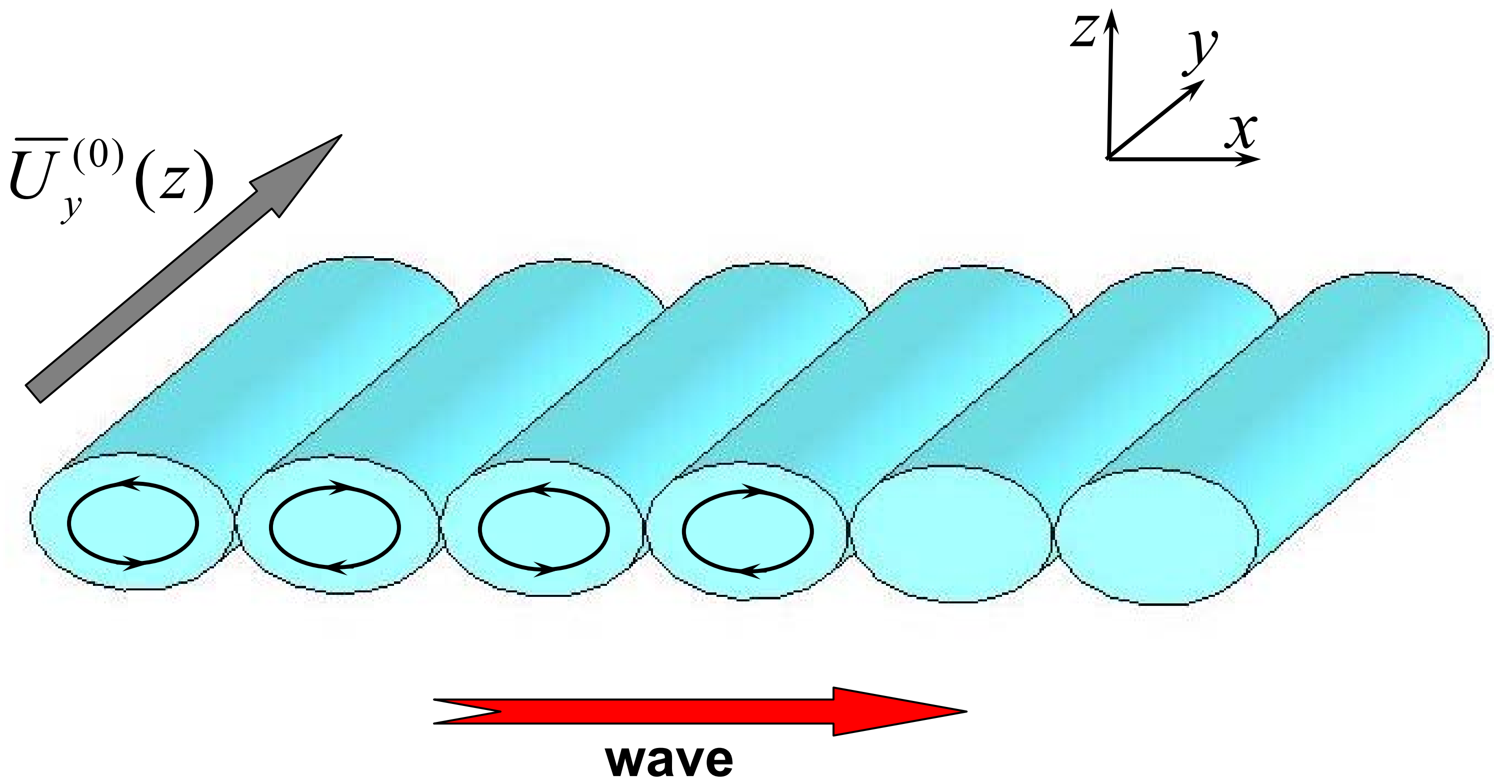
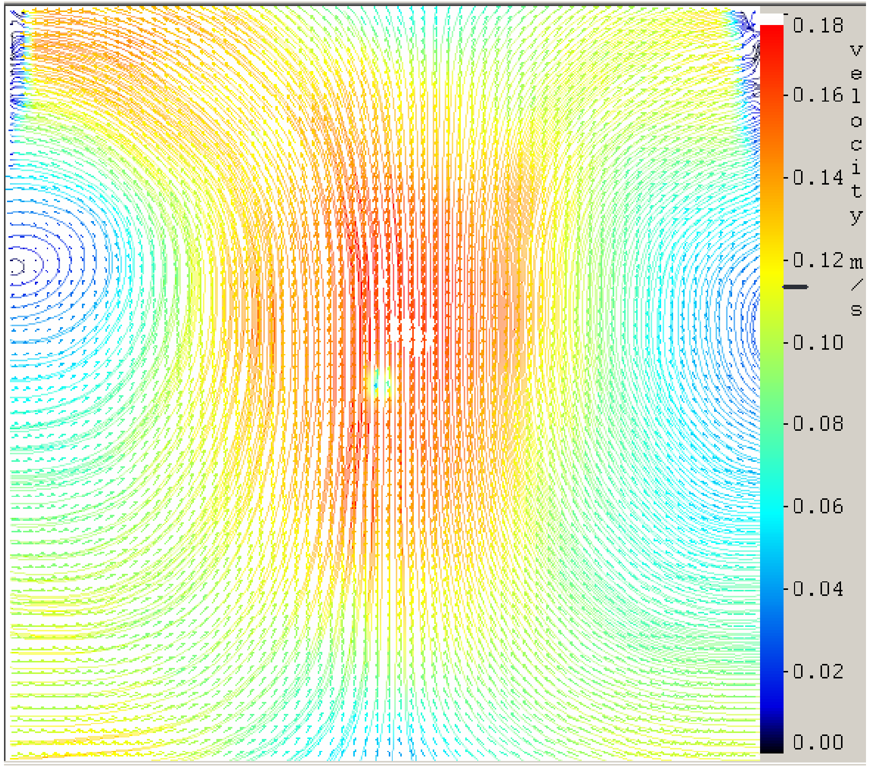
Convective-shear waves

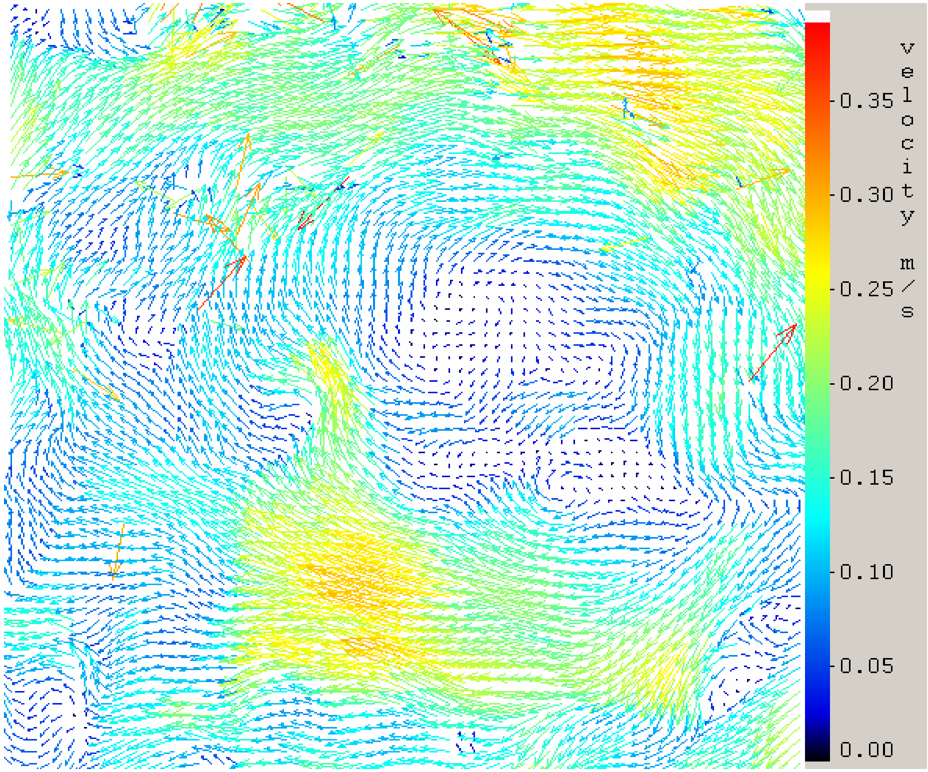


Perturbation analysis predicts generation of roll-type structures in the plane perpendicular to the mean wind (Elperin et al.)

Turbulent convection in laboratory

Semi-organised circulation in a box with heated bottom (Rayleigh-Benard apparatus): vertical (left) and horizontal (right) cross-sections (Elperin et al.)





SHEAR-FREE CONVECTION OVER WIDE HEATED AREAS: THE INFLUENCE OF SEMI-ORGANISED EDDIES ON THE HEAT / MASS TRANSFER AT THE SURFACE

Large buoyancy-driven eddies in CBLs

$\Downarrow$

"Convective winds": convergence IBL-type flows towards plume axes near the surface

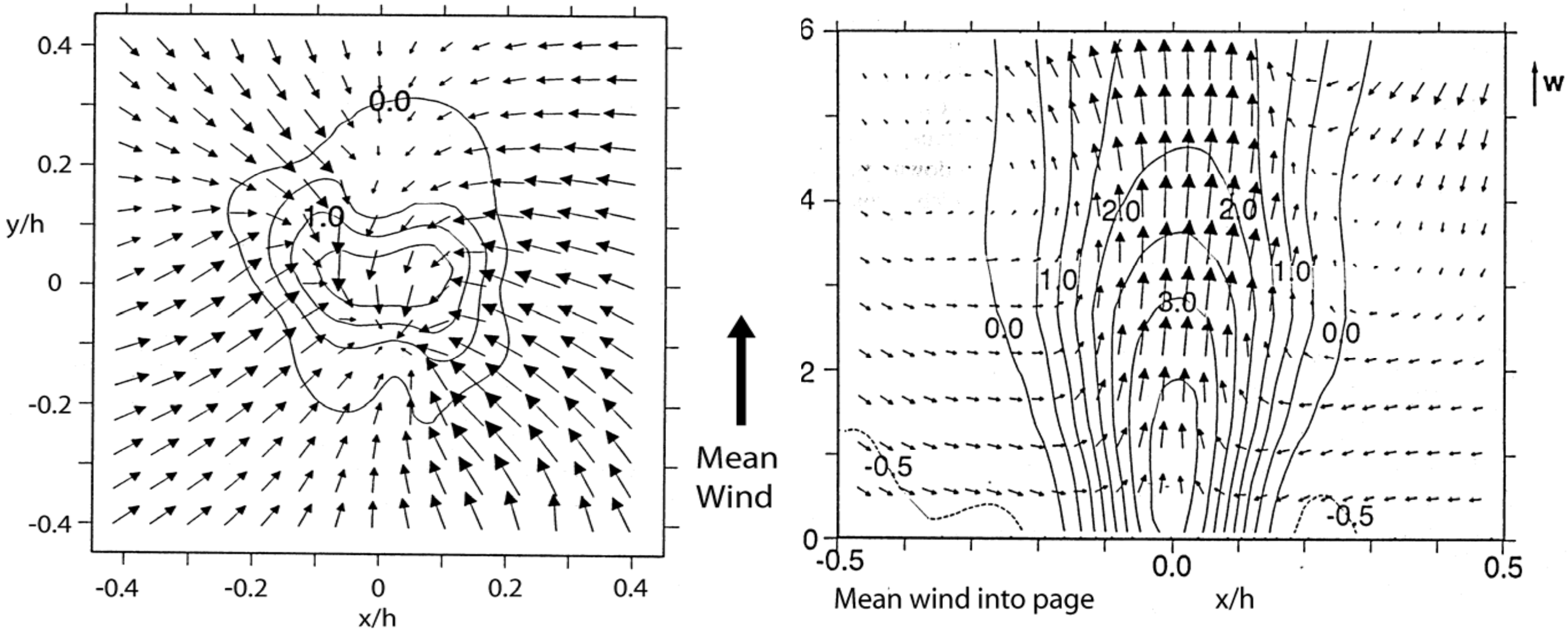
$\Downarrow$

Local sears in IBLs enhance mixing

$\Downarrow$

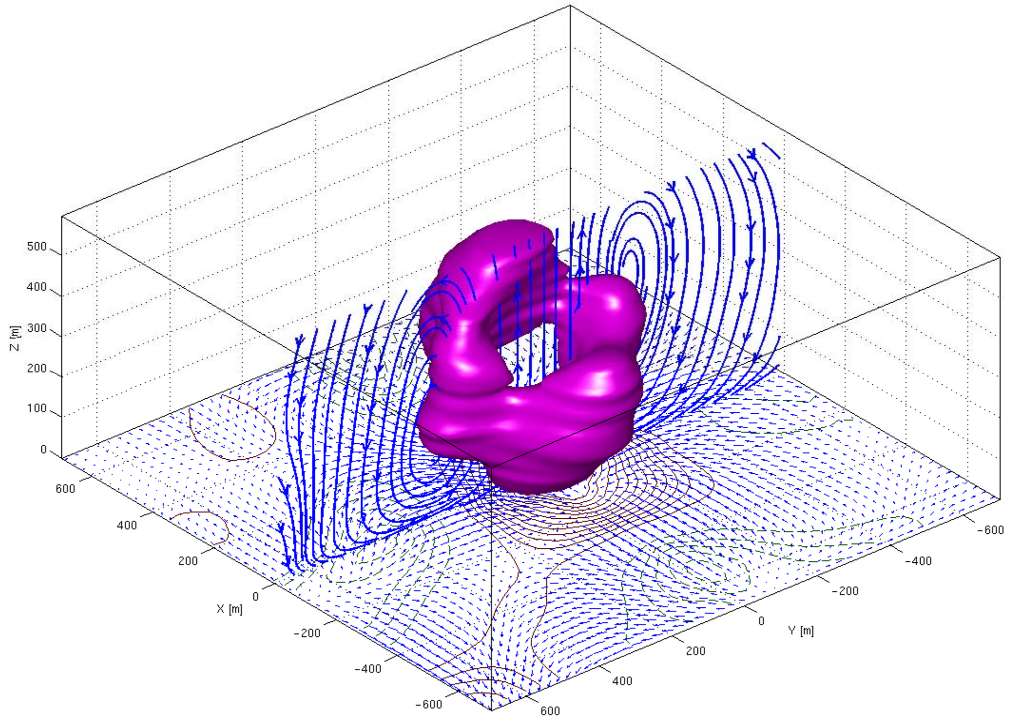
Stronger turbulent fluxes

Large convective eddy



Williams and Hacker (1992) airborne measurements: Arrows show the large-eddy velocity field (subtracting mean wind). Solid lines show deviations of potential temperature θ from its large-eddy averaged value $<\theta>$. The iso-surface $\theta-<\theta>=0$ marks the side walls of the updraught.

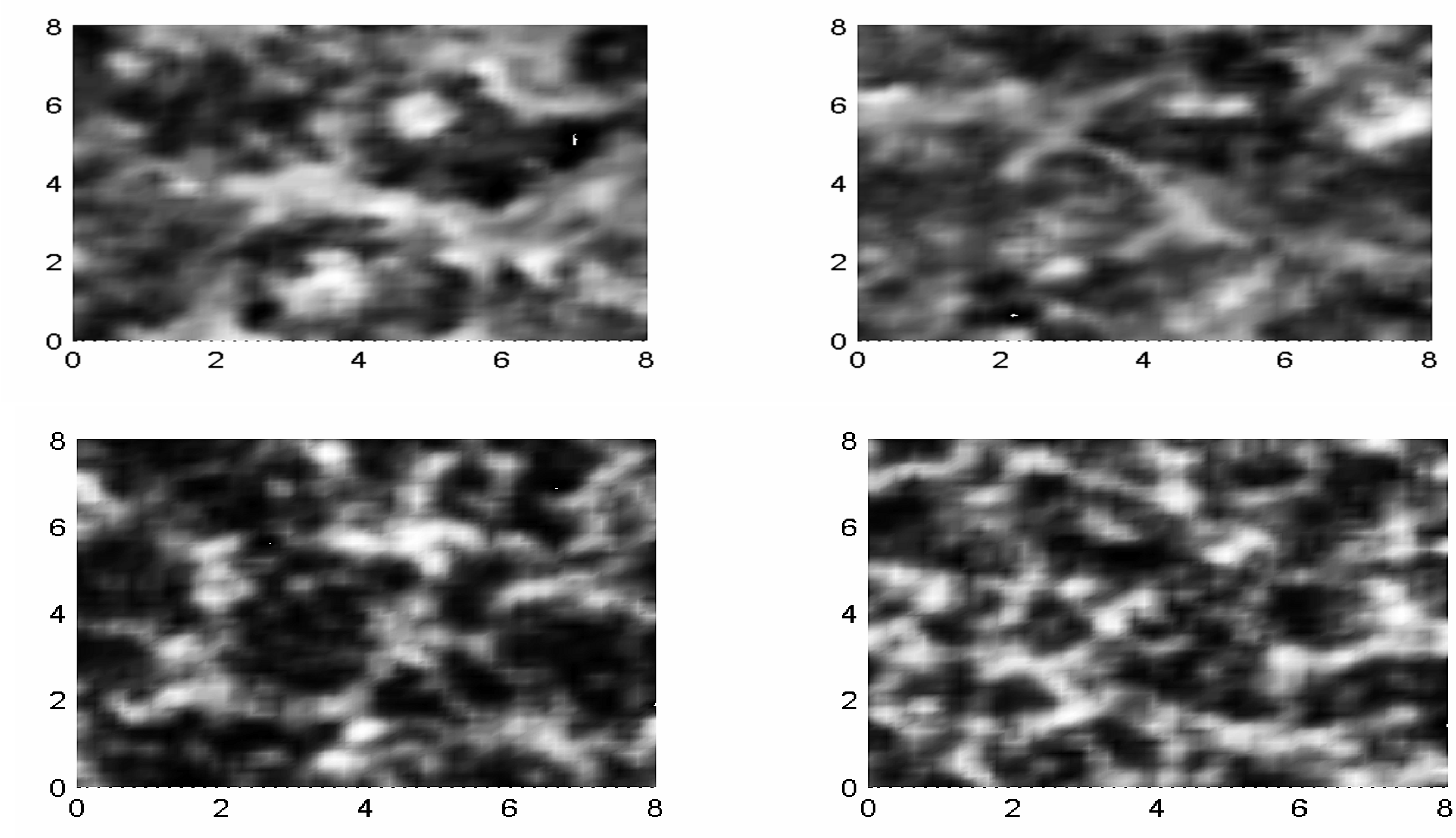
LES "portrait" of the 1st characteristic (most energetic) eddy in shear-free CBL



Solid contours in horizontal plane mark up-draughts with *w* from 0.14 to 0.84 m/s. The maximum updraught velocity is 1.2 m/s, maximum horizontal velocity is 2.8 m/s. Dashed contours mark down-draughts (varying from -0.16 to -0.8 m s-1). Bold curves with arrows in *y,z* plain show streamlines. The domain size is given in km.

Horizontal cross-sections of plumes and downdraughts over smooth and rough surfaces

upper snapshots – surface layer, below – upper CBL; left – smooth, right – very rough



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Prior large-eddy shear models

Deardorff´s scaling: CBL depth *h*, convective velocity $W_* = (\beta F_{\theta sx} h)^{1/3}$

Resistance coefficients: U_*/W_* , $F_{\theta sx}/(W_* \Delta\theta)$ versus h/z_{0u}

- **Schumann (1988) 1-layer model, dominant role of buoyancy forces**
- **Sykes et al. (1993) 1-layer model, dominant role of large-eddy shears**
- **Zilitinkevich, Grachev & Hunt (1998) 2-layer buoyancy + shear model**

Limited applicability; insufficient accuracy over very rough surfaces

New model

Large eddy life time considerably exceeds $h/W_* \sim$ 20 min

Large-scale convergence flows are internal boundary layers (IBLs):

$$W_* dh_I/dx = 0.24 W_c(z = h_I)$$

Locally equilibrium turbulence determines x-dependent values of

$\tau(z) = u_*^2(x)$, $F_{\theta sx}(x)$, large-eddy MO length: $L(x) = \tau^{3/2}(\beta F_{\theta sx} h)^{-1}$

Eddy viscosity / conductivity $K \sim z[u_* + Constant\ W_*(z/h)^{1/3}]$

Solution for area-averaged fluxes: $U_*^4 = \langle \tau^2 \rangle$, $F_{\theta s} = \langle F_{\theta sx} \rangle$

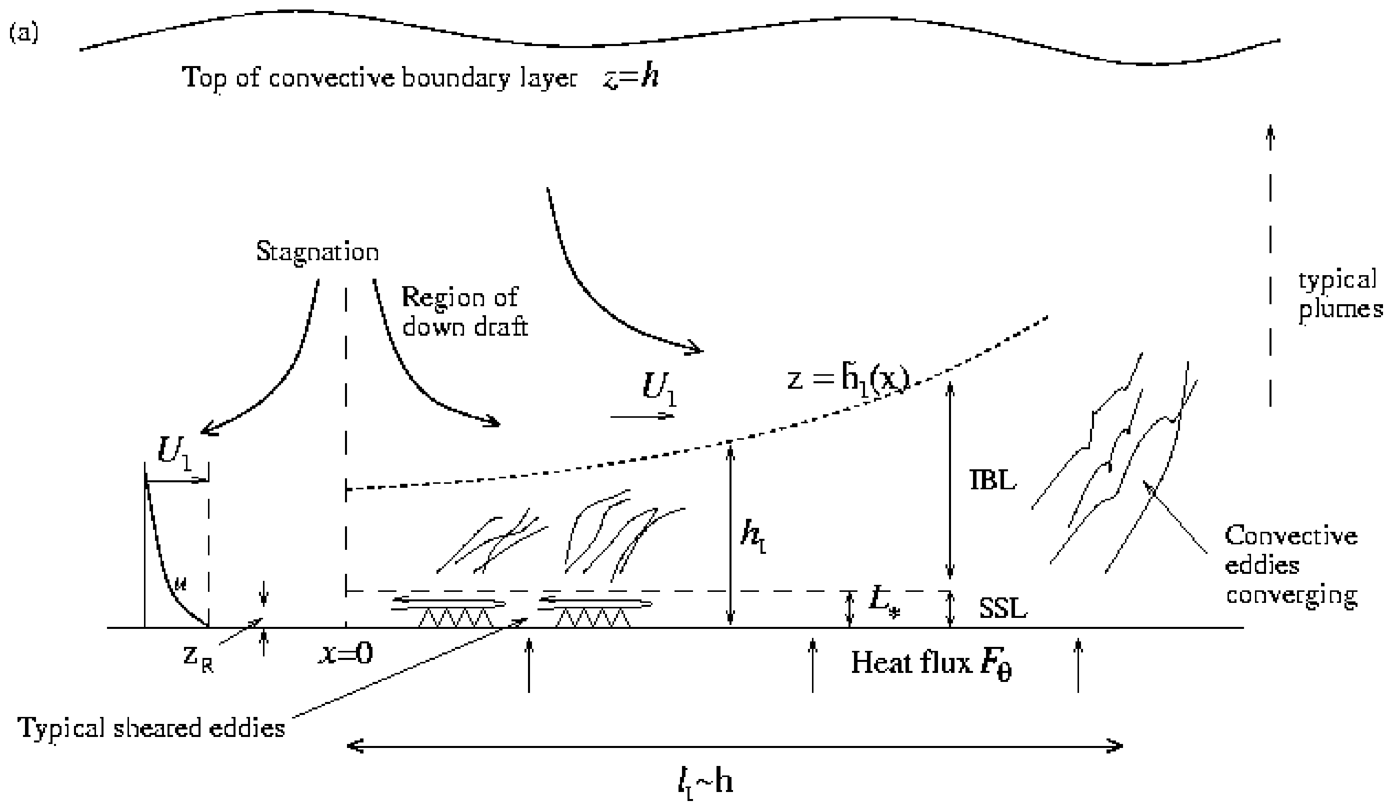
<u>Very rough surfaces:</u> surface shear layer diminishes

effective roughness length: $z_0/z_{0u} = 1 + C_{0C}(z_{0u}/L)^{1/3}$

IBL within the large eddy: (a) low roughness

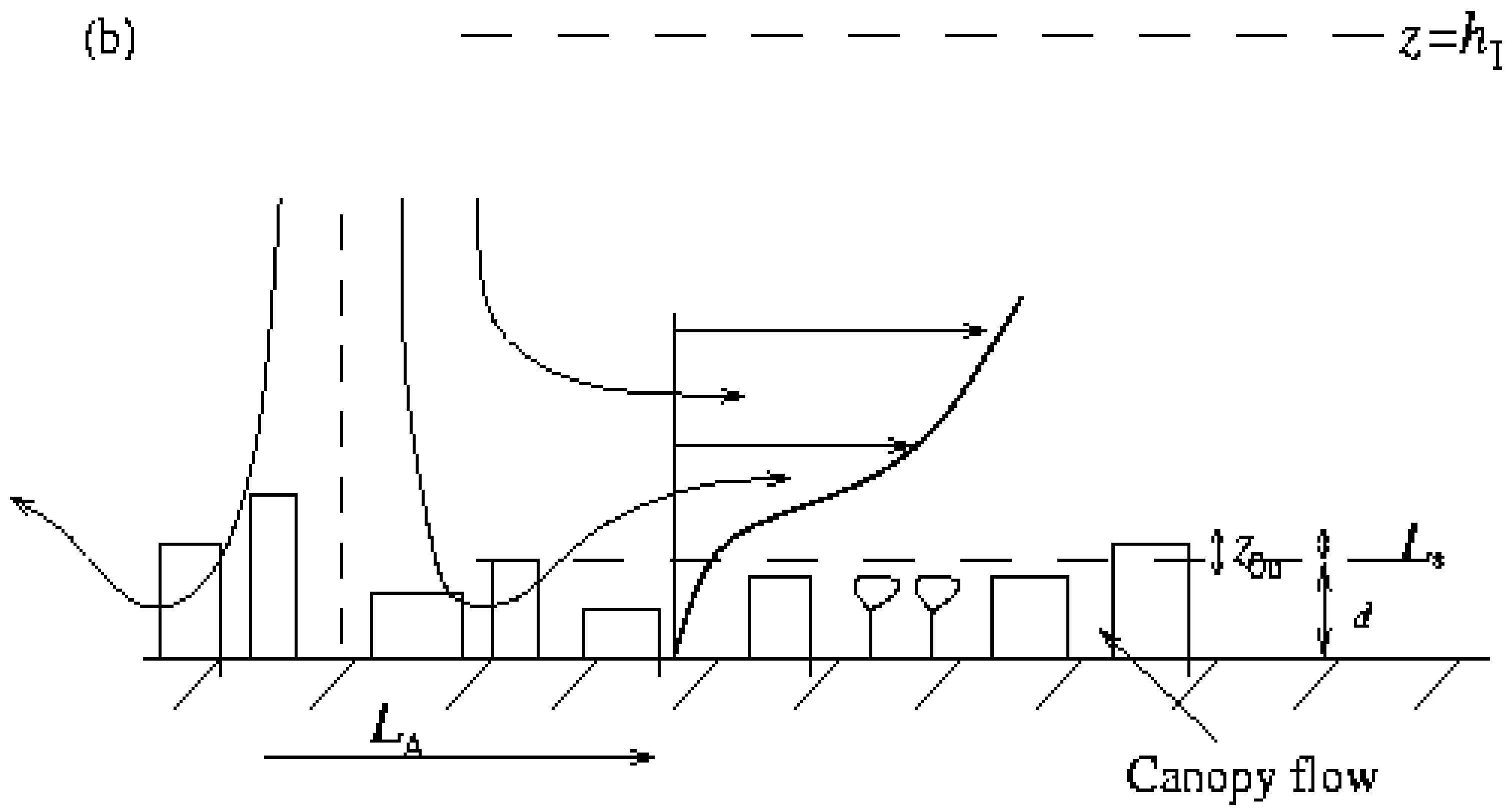
Typical height of roughness elements smaller than the MO length scale

Two-layer structure: logarithmic + free-convection vertical profiles



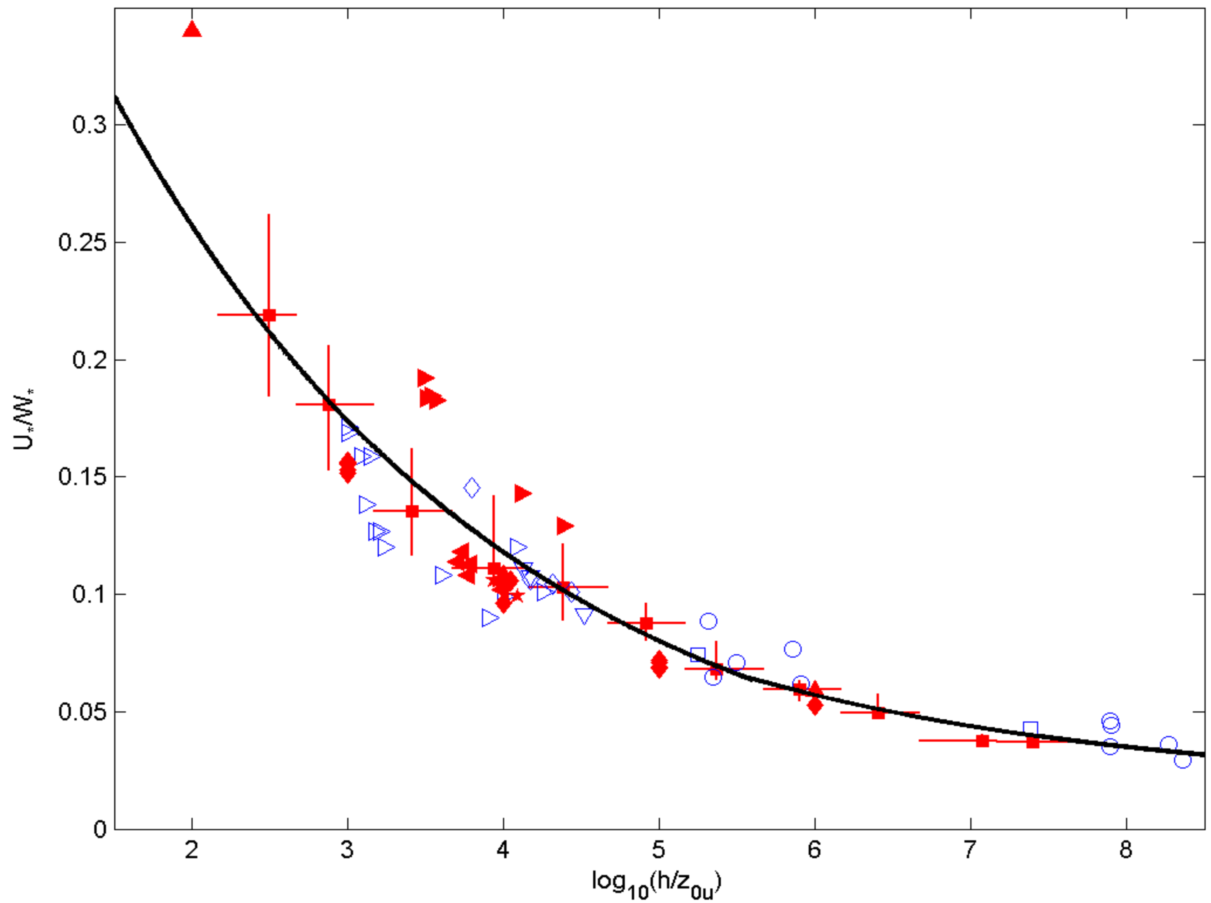
IBL within the large eddy: (b) large roughness

Typical height of roughness elements larger than the MO length scale
One-layer structure; essential stability dependence of the roughness length



Resistance coefficient U_*/W_* vs. h/z_{0u}

Blue symbols show field data; red symbols - LES (NERSC data with error bars)



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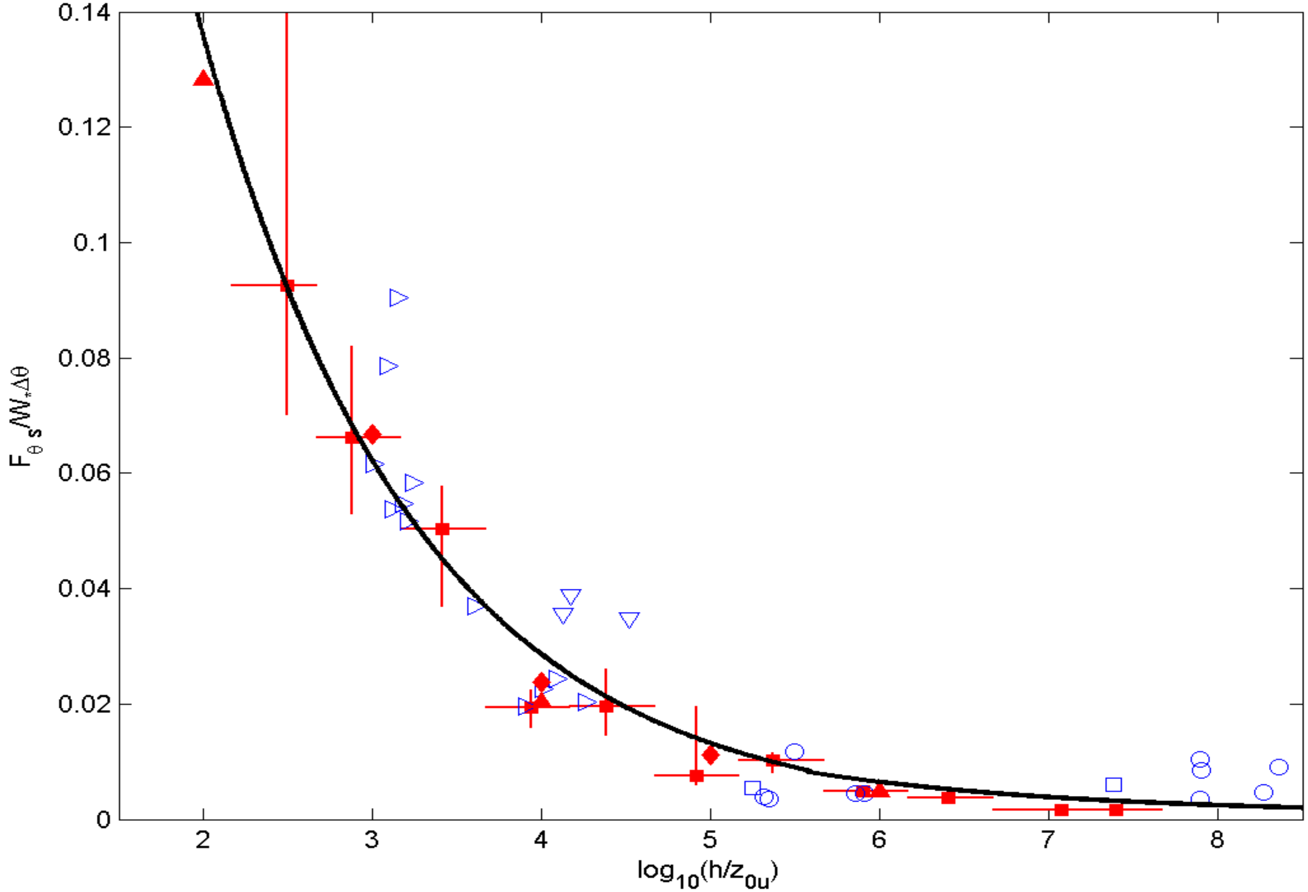
Heat transfer coefficient U_*/W_* vs. h/z_{0u}

Blue symbols show field data; red symbols - LES (NERSC data with error bars)



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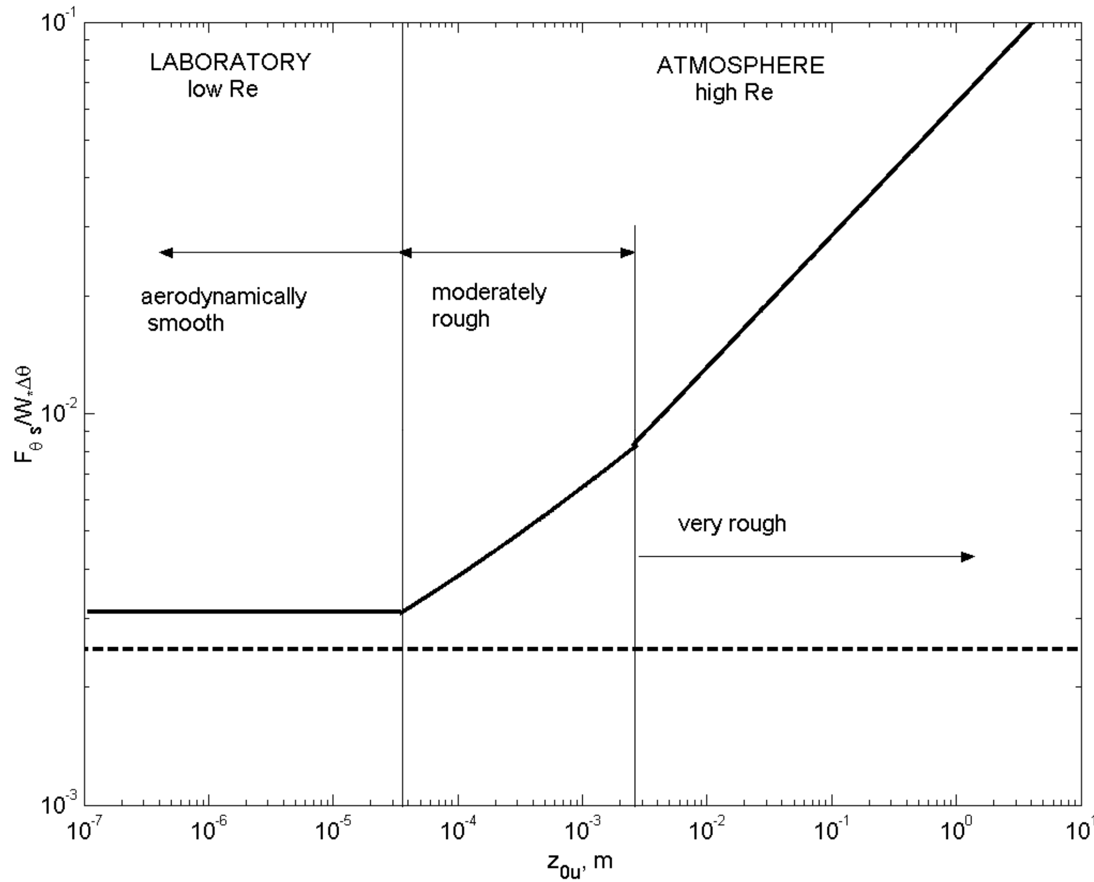
Comparison of heat transfer models

Solid line – our model validated against field data and LES (CBLs over natural rough surfaces); doted line – classical heat transfer law: Nu=0.14 $Ra^{1/3}$ (lab experiments)



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Conclusions and future work

Failure of the classical local theory

Key role of organised structures:

- not to be confused with largest turbulent eddies
- <u>notice inverse energy cascade</u>

New physics at large roughness:

- Diminishing logarithmic sub-layer
- <u>Stability dependence of the effective roughness length</u>

Future work

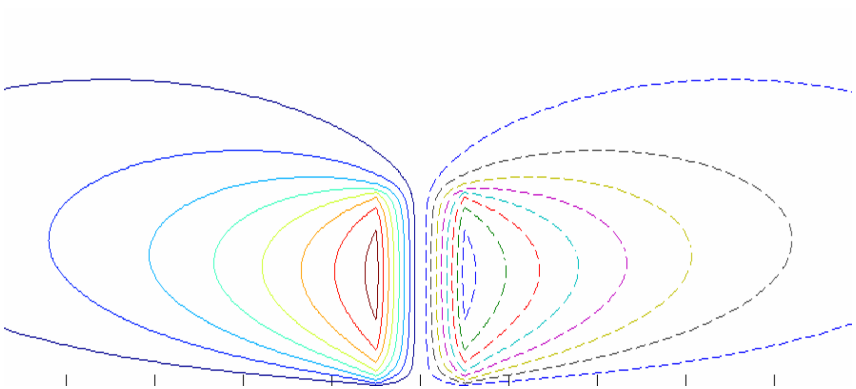
- Theory and its validation for sheared convection
- Improved parameterization of surface fluxes

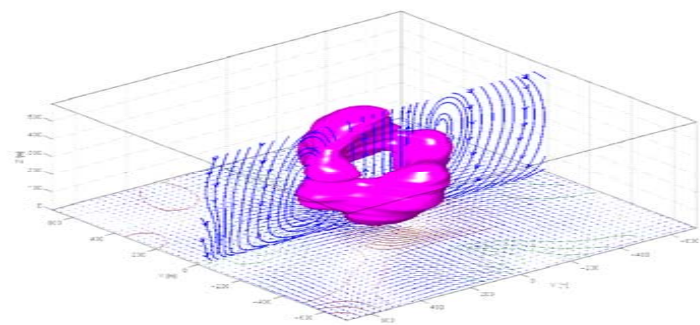
CHAOS GENERATES ORDER

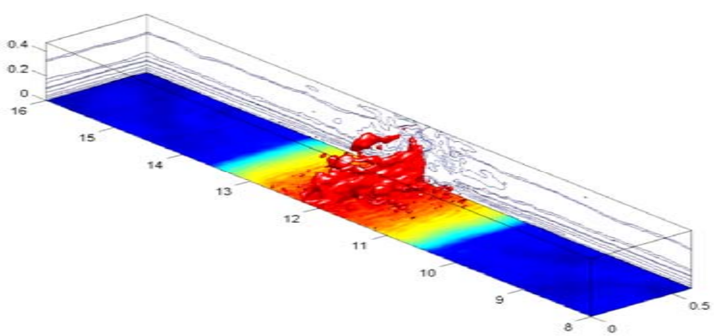
Large-scale convective structures are not turbulence: they are essentially regular motions fed by the convective energy production through the inverse energy cascade

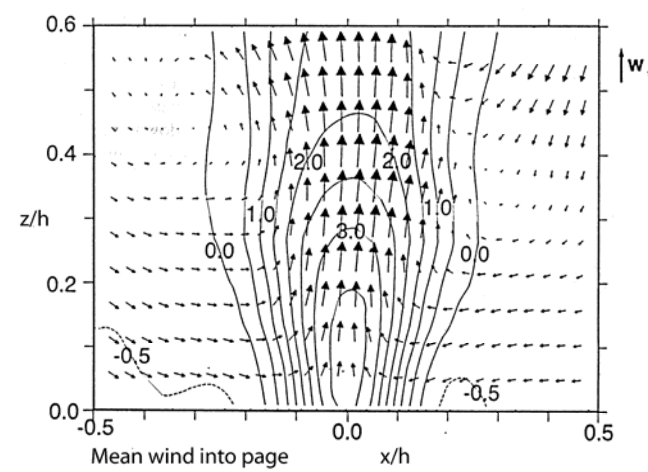
over heat island

over vide heated area









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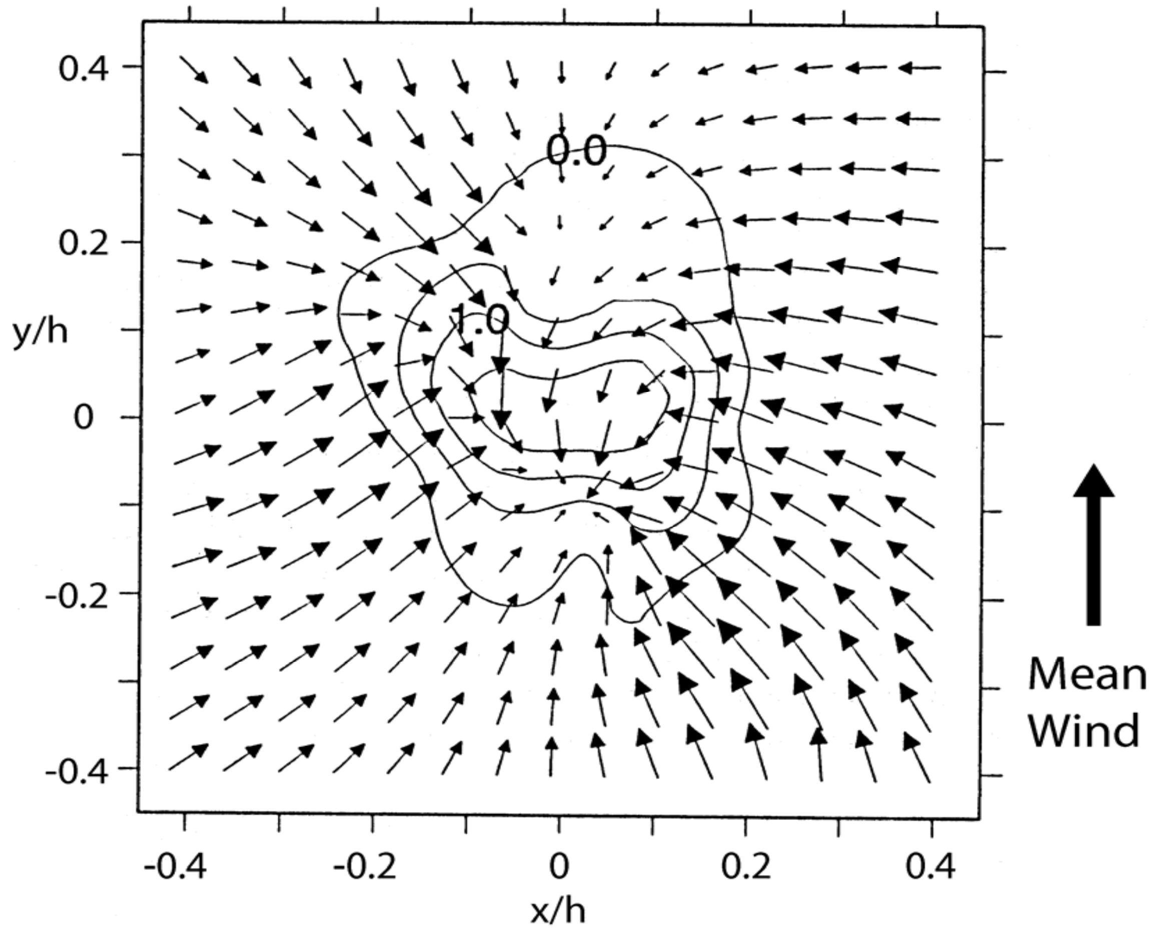

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