URBAN PBLs: SOME RECENT WORKS TOWARDS THEIR IMPROVED PARAMETERIZATION

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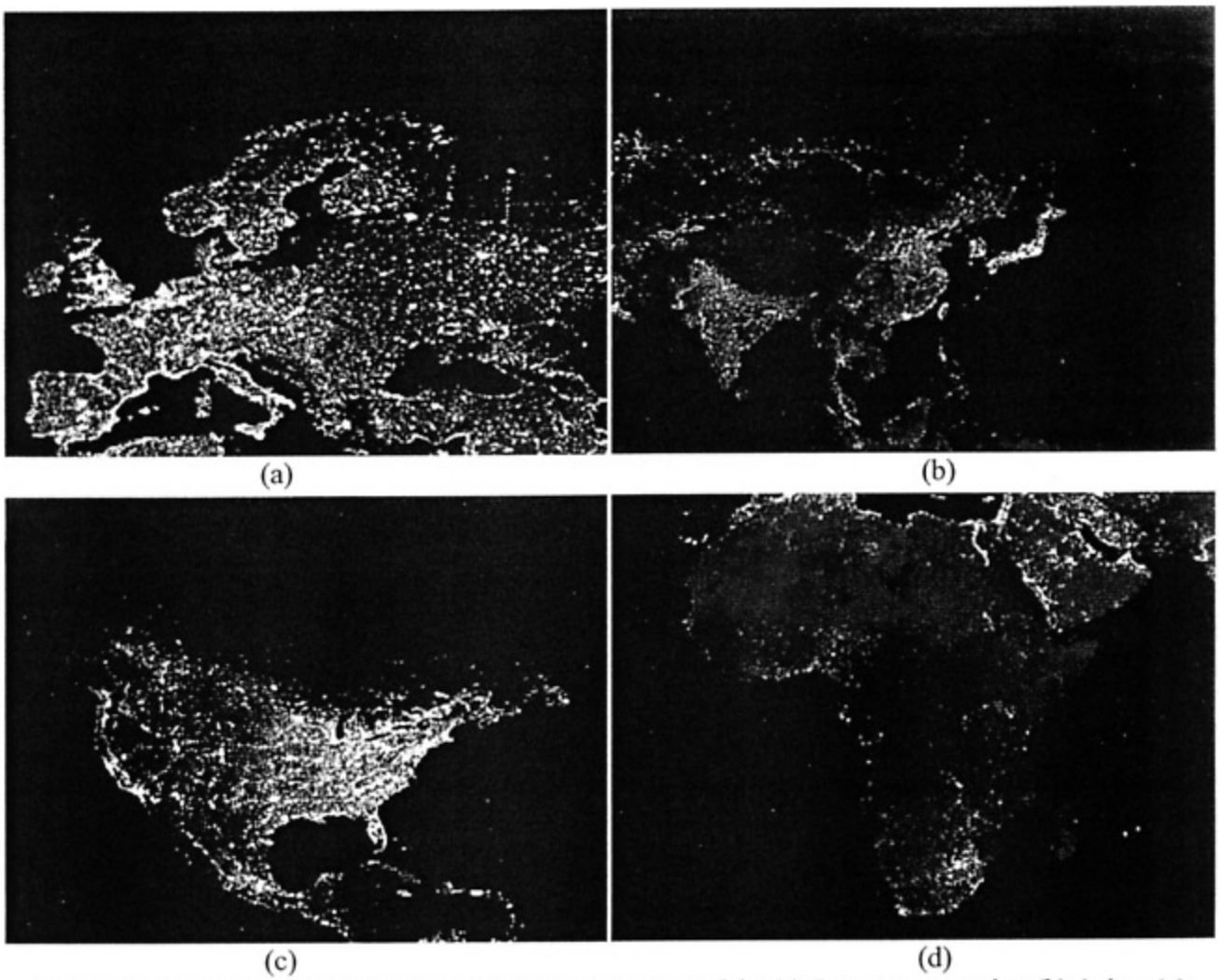
SATELLITE IMAGE MAP OF THE NIGHT LIGHTNESS OVER URBAN AREAS OF EUROPE



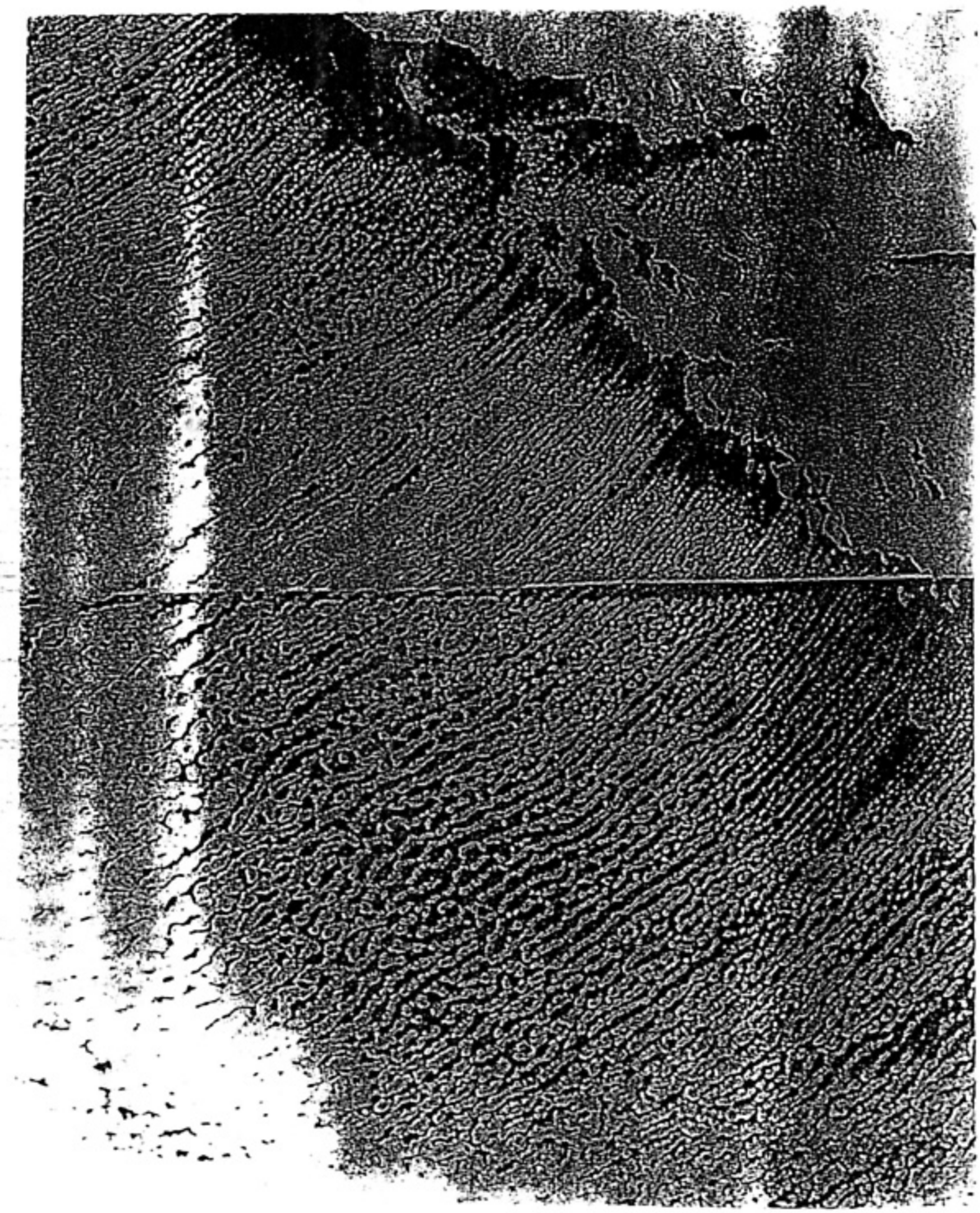
(a) (b)

(c) (d)

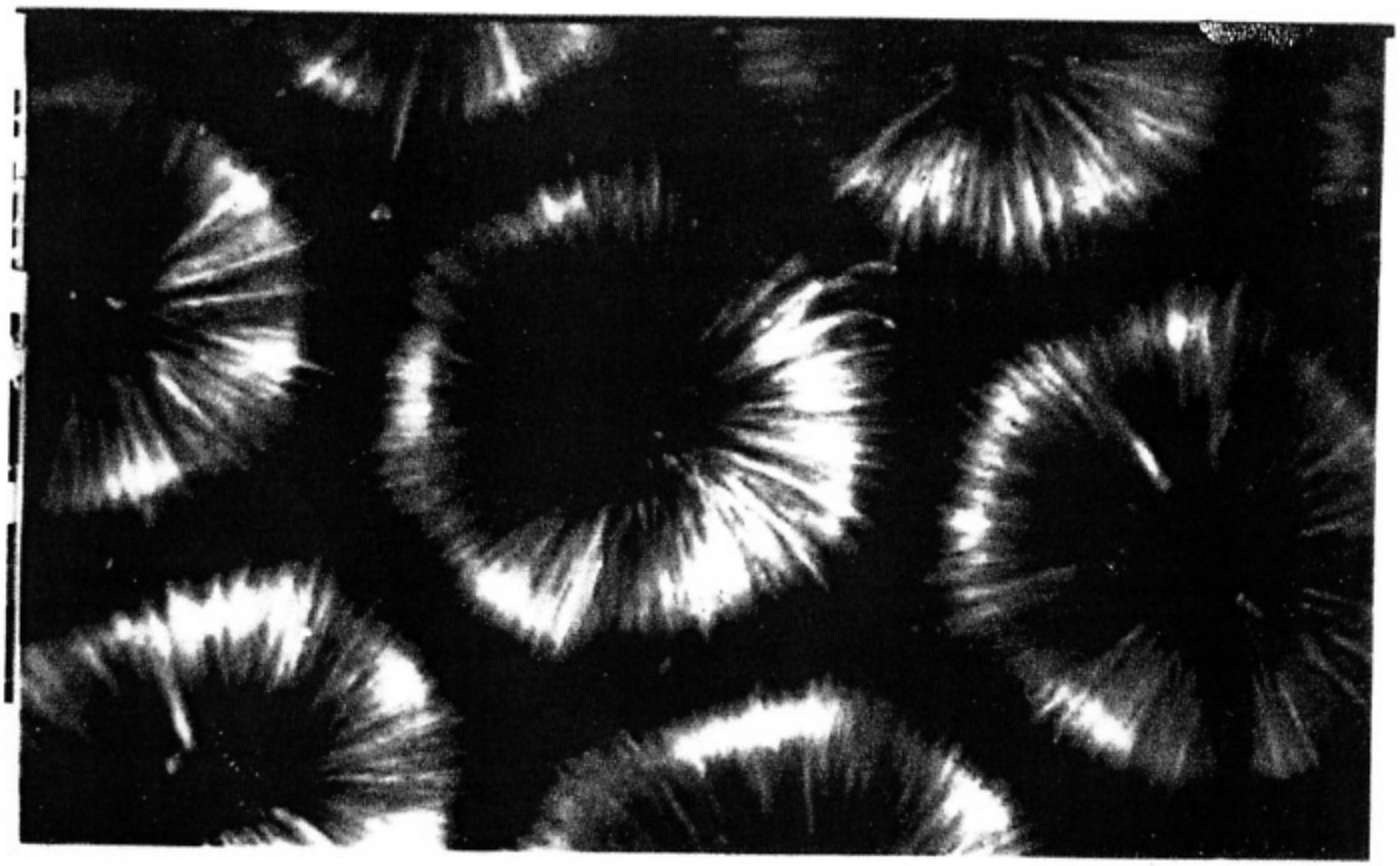
Satellite image maps of the night lightness over urban areas of the (a) European countries, (b) Asian, (c) North American, and (d) African continents (*NASA, 2004*). (from FUMAPEX ReportD4.4)

Part 1

LARGE-EDDY ENHANSEMENT OF THE CONVECTIVE HEAT & MASS TRANSFER OVER VERY ROUGH SURFACES

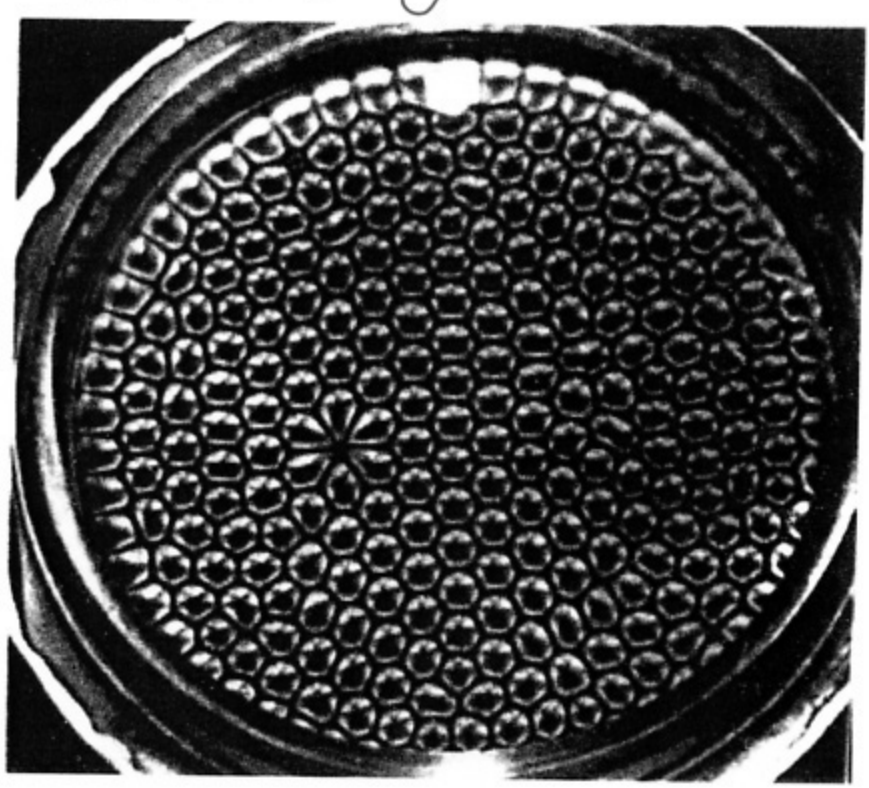


Convective rolls in the atmosphere: "streets" of cumulus clouds sitting atop of the convective boundary layer



141. Конвекция, создаваемая поверхностным натяжением (конвекция Бенара). Приводимый снимок, увеличенный примерно в 25 раз, демонстрирует гексагональную конвективную структуру в слое силиконового масла глубиной 1 мм при равномерном нагреве снизу и воздействии окружающего воздуха сверху. Если верхняя поверхность свободна, то течение создается главным образом неоднородностями поверхностного натяжения, а не плавучестью, как на фото 139 и 140. Свет, отраженный от алюминиевых хлопьев, демонстрирует подъем жидкости в центре каждой ячейки и ее опускание на краях. Время экспозиции составляет 10 с, тогда как время движения жидкости поперек ячейки от центра к краю равно 2 с. Фото M. G. Velarde, M. Yuste, J. Salan.

Viscous Convection in laboratory



142. Нерегулярности гексагональной структуры конвективной картины Бенара. Как видно на снимке, гексагональная структура ячеек, характерная для конвективной неустойчивости, вызванной главным образом поверхностным натяжением, приспосабливается к круговой границе. Алюминиевый порошок демонстрирует течение в тонком слое силиконового масла с кинематической вязкостью 0,5 см²/с на равномерно нагретой медной пластинке. Маленькая выемка на пластинке приводит к возникновению нерегулярности ячеек в области слева, где образуются ячейки в форме огранки бриллианта. Это показывает, насколько картина чувствительна к малейшим нарушениям регулярности. Koschmieder, 1974]

convective cells in lab. experiments

THE INFLUENCE OF LARGE CONVECTIVE EDDIES ON THE SURFACE LAYER TURBULENCE

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2. 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.

3. Akylas, E., Tombrou, M., Lalas, D., and Zilitinkevich. S., 2001: Surface fluxes under shear-free convection. *Quart, J. Roy. Met. Soc.*, 127, 1-15.

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5. Elperin T, Kleeorin N, Rogachevskii I. and Zilitinkevich S., 2004: Turbulence and coherent structures in geophysical convection. Submitted to *Environmental Fluid Mechanics.*

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Role of large eddies in the surface layer

Kolmogorov's turbulence and convective-wind instabilities

Turbulence closure

Motivation

- **Large buoyancy-driven eddies in CBLs**

  ⇓

  Cells include "convective winds" near the surface (convergence IBL-type flows towards plume axes)

  ⇓

  enhanced mixing controlled by non-local mechanisms

- **Flux calculation schemes based on the local surface layer theories still in use**

  Similarity theories
  Local closures

- **No consensus between prior non-local models**

- **Role of the surface roughness**

  → very rough surfaces

Content

1. Local theories
2. How large eddies act?
3. "Minimum friction velocity"
4. Early models
5. General large-eddy shear model
6. Its experimental and LES validation

TRADITIONAL CONCEPTS

M-O (1954) similarity theory

Scales

$$u_* = (\tau_s / \rho_0)^{1/2},\ L = u_*^3 / \beta F_{\theta s} = u_*^2 / \beta \theta_*,\ \theta_* = F_{\theta s} / u_*$$

Profiles

$$u(z) = k_u^{-1} u_* [\ln(z / z_{0u}) + \Psi_u(z / L) - \Psi_u(z_{0u} / L)]$$

$$\theta(z) - \theta_s = -k_\theta^{-1} \theta_* [\ln(z / z_{0\theta}) + \Psi_\theta(z / L) - \Psi_\theta(z_{0\theta} / L)]$$

- Given z_{0u}, $z_{0\theta}$, and measured/modelled $u(z)$, $\theta(z)$ and θ_s, the fluxes (u_*, θ_*) and L are found
- At small L, log interval ($30\, z_{0u} < z << L$) vanishes

Free convection Prandtl,1932; Obukhov,1946,60

$$\frac{\partial u}{\partial z} = \frac{C_U u_*^2}{F_{bs}^{1/3} z^{4/3}} \qquad u(z) = u_a - \frac{3 C_U u_*^2}{(F_{bs} z)^{1/3}}$$

C_U=1.7

$$\frac{\partial \theta}{\partial z} = -\frac{C_\Theta F_{\theta s}}{F_{bs}^{1/3} z^{4/3}} \qquad \theta(z) = \theta_a + \frac{3 C_\Theta F_{\theta s}}{(F_{bs} z)^{1/3}}$$

C_Θ=1.1

Prandtl scale: $W_c = (F_{bs} z)^{1/3}$

Classical heat transfer model
(Malkus,1954; Priestley, 1954)

Matching temperature profiles in the viscose $\sim \nu / W_c$ and the free-convection layer yields[1]

$$F_{\theta s} = C_{Conv} (\beta \kappa / \mathrm{Pr})^{1/3} \Delta\theta^{4/3}$$

Alternative rough-surfaces law
formally derived from the free-convection θ profile substituting z_{0u} for z and aerodynamic surface temperature θ_0 for $\theta(z)$:

$$F_{\theta s} = (3C_\Theta)^{-3/2} (\beta z_{0u})^{1/2} \Delta\theta^{3/2}, \quad \Delta\theta \equiv \theta_0 - \theta_a$$

Taking empirical value C_Θ=1.1 gives $(3C_\Theta)^{-3/2}$~0.2 (recommended e.g. by Louis, 1979). In reality, the coefficient is 10 times larger (Schumann, 1988)

[1] Equivalent form in terms of the Nusselt and the Rayleigh numbers is $\mathrm{Nu} = C_{Conv} \mathrm{Ra}^{1/3}$, where $\mathrm{Nu} \equiv \frac{F_{\theta s} h}{\kappa \Delta\theta}$, $\mathrm{Ra} \equiv \frac{\beta \Delta\theta h^3}{\kappa \nu}$

LARGE EDDIES IN THE SURFACE LAYER

Prandtl **&** Deardorff **scales:**

- $W_c = (F_{bs} z)^{1/3}$ and $W_* = (F_{bs} h)^{1/3}$

Businger **(1973a,b)**

- Scalar average $U_*^4 = < (u'w')^2 > + < (v'w')^2 >$
  $U_* \neq 0$
- Vector average $u_*^4 = < u'w' >^2 + < v'w' >^2$
  $u_* \to 0$
- U_* depends on the CBL parameters, F_{bs}, h, z_{0u}
- U_* / W_* is a decreasing function of h / z_{0u}

Wyngaard and Cote **(1974),** Panofsky **et al. (1977)**

- $\sigma_u^2 \equiv \overline{u'^2} = \sigma_v^2 \equiv \overline{v'^2} \sim 0.5 W_*^2$
- $\sigma_w^2 \equiv \overline{w'^2} = 1.1 W_c^2$

Large eddies in the CBL

Length scale = CBL depth h

Velocity scale (Deardorff, 1970) $W_*=(F_{bs}h)^{1/3}$

$F_{bs}=\beta F_{\theta s}+0.61gF_{qs}$ buoyancy flux at the surface; $F_{\theta s}$ and F_{qs} fluxes of temperature and humidity; g acceleration due to gravity; $\beta=g/T_0$ buoyancy parameter; T_0 reference temperature

Prior models

Schumann (1988) 1-layer model

- dominant role of buoyancy forces in IBL flows
- validated over rough surfaces $h/z_{0u}<10^5$
- inapplicable over smooth surfaces $h/z_{0u}>10^5$

Sykes et al. (1993) 1-layer model

- dominant role of large-eddy shears (log profiles)
- agrees with data over smooth surfaces
- inapplicable over rough surfaces

Zilitinkevich, Grachev, Hunt (1998)

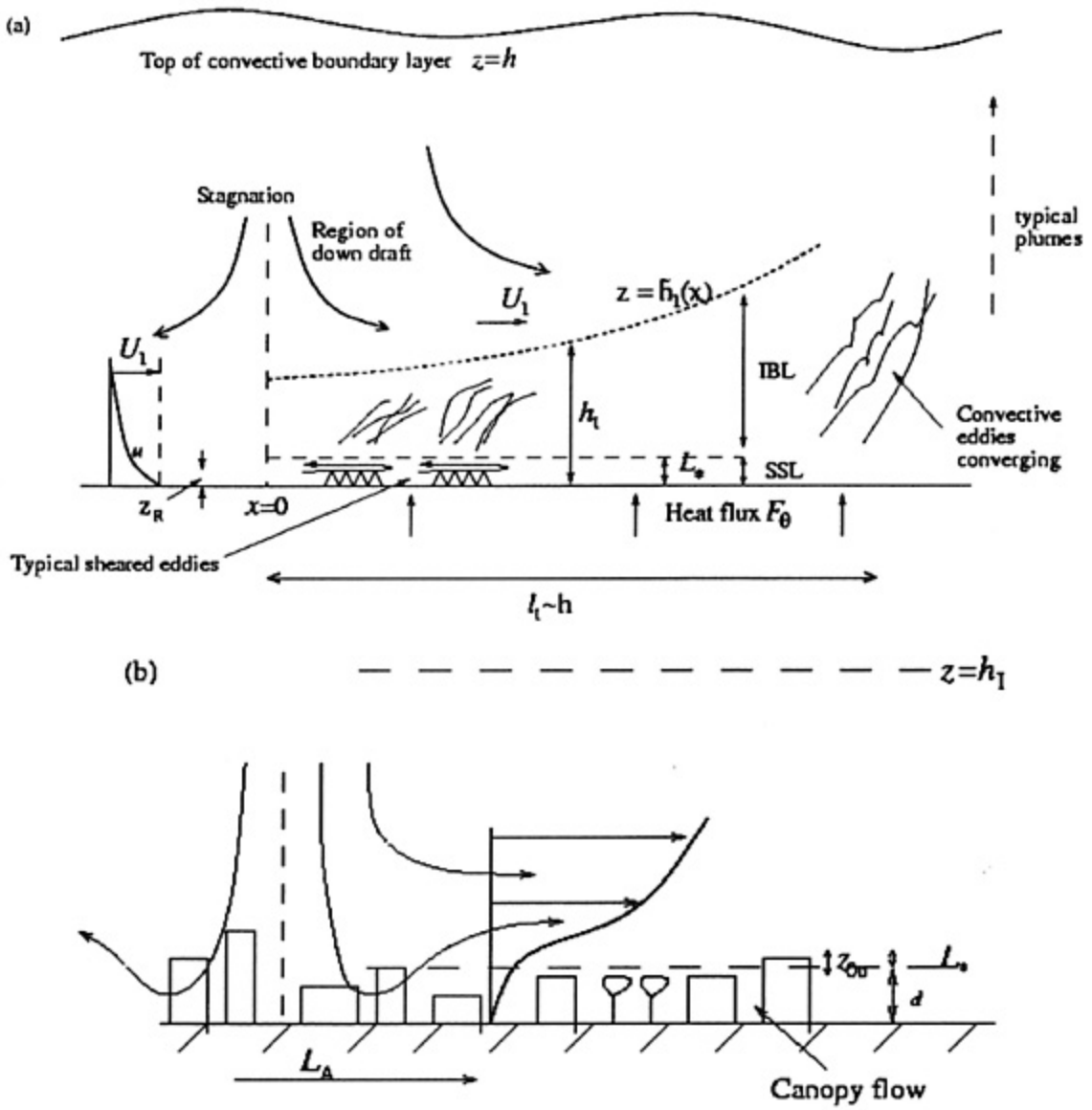
- 2-layer buoyancy&shear model "log + power law" profiles dependent on z/L_*, where $L_*=U_*^3/F_{bs}$ is based on the minimum friction velocity U_*
- inapplicable over very rough surfaces

Akylas et al. (2001, 2003) – ambient wind shear

GENERAL LARGE-EDDY SHEAR MODEL

Physical mechanisms and scales

- Life time of large eddies exceeds $h / W_* \sim 10^3$ s
- Large-scale convergence flows are IBLs
- Principal CBL length scales are
  its depth $h \sim 10^3$ m
  IBL depth $h_I \sim 10^{-1} h$
  large-eddy MO length L_*
  typical height of roughness elements $h_0 \sim 30\, z_{0u}$
- $h_I \sim 10^{-1} h$ – analysis of the momentum balance (Leibovich & Hunt, 1988; Zilitinkevich et al., 1998)
- Large-eddy MO length $L_* = \left(\frac{U_*}{W_*} \right)^3 h \sim 10^{-3} h << h_I$
- This allows approximating local mean profiles in the IBL flows using the MO theory with U_* and L_* substituted for u_* and L



Internal boundary layer within the large eddy structure of a convective shear free boundary layer

Note the internal surface layer with depth of the same order as the large-eddy Monin-Obukhov length

(a) Small roughness elements (less than the MO length)

(b) Large roughness elements (~MO length)

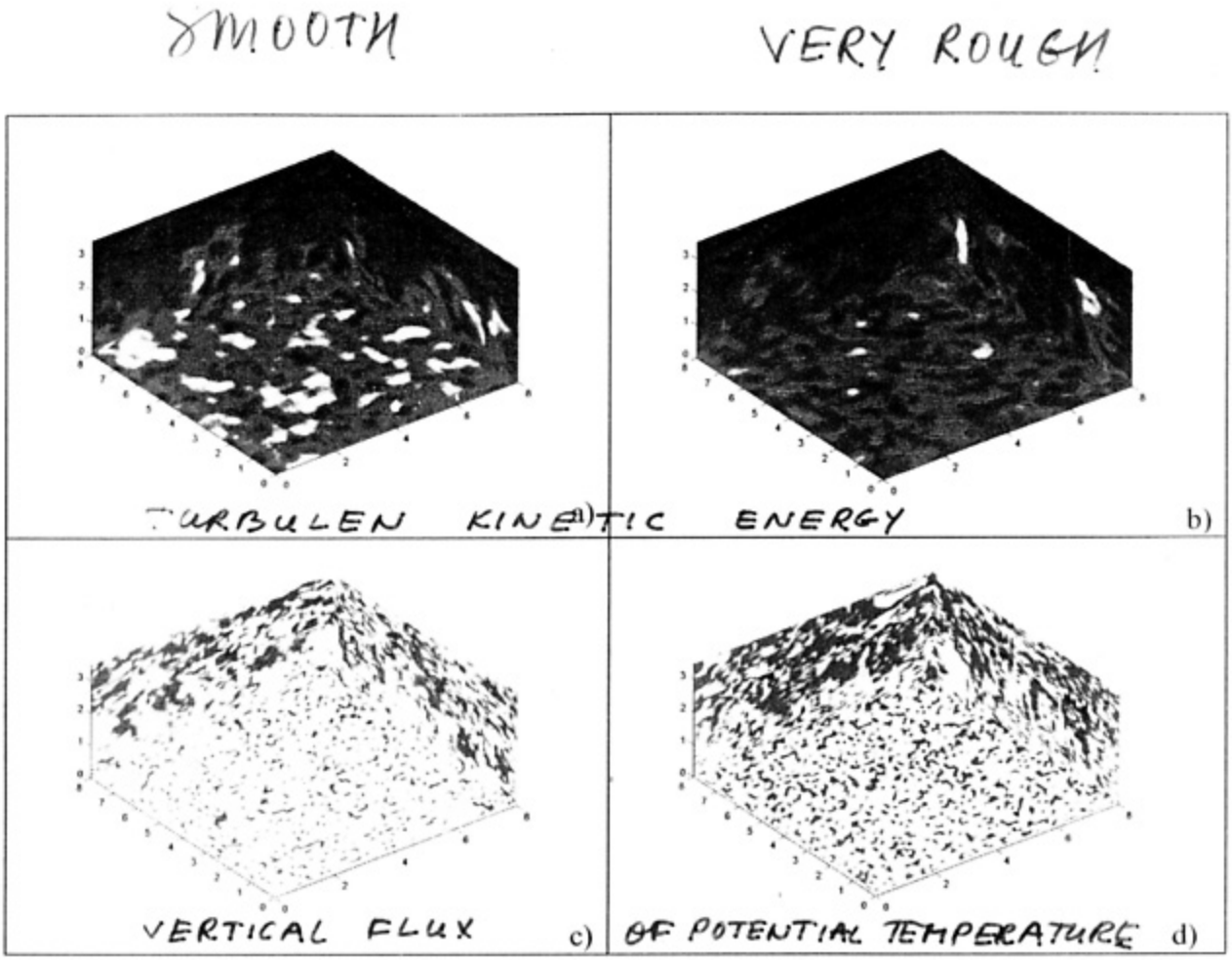


Figure 2. Snapshots of the turbulent kinetic energy (a, b) and the potential temperature flux (c, d) in the CBLs over very smooth surface (a, c – LES run 2 of Table 1) and very rough surface (b, d – LES run 29 of Table 1). Brighter areas correspond to more intensive transports of momentum and potential temperature. The domain sizes are given in kilometres.

Table 2: Summary of LES and field data, and corresponding symbols in Figures 3-4.

LES data	Red symbols	Reference
Present LES	◆	
Schmidt and Schumann LES	■	Schmidt and Schumann (1989)
Sykes et al. LES	◆	Sykes et al. (1993)
Sorbjan LES	▶	Sorbjan (1996)
Otte and Wyngaard LES	◀	Otte and Wyngaard (2001)
Noh et al. LES	★	Noh et al. (2003)
Field data	**Blue symbols**	**Reference**
SCOPE, September 1993, San Clemente Island, California	■	Fairall et al. (1996a, b, c), Grachev and Fairall (1997), Grachev et al. (1997, 1998)
TOGA COARE, 1992-1993, Western Pacific Ocean	●	
BOREX, July 1995, Borris site, Denmark	▼	Mikkelsen et al. (1996), Grachev et al. (1998)
PAFEX-1, January-February 1998, Phoenix, Arizona	◆	Grachev et al. (1999)
ATHENS, 1994-1999, Athens city centre and Attiki peninsula, Greece	▶	Batcharova and Gryning (1998), Akylas et al. (2003)

Table 2: Empirical dimensionless constants

Constant	Empirical value	In formula	Equation number
C_{U0} C_{U1} C_{U2}	6 0.3 -2.56	$\frac{U_*}{W_*} = C_{U1}\left(\ln\frac{h/z_{0u}}{(\ln(h/z_{0u}) - C_{U0})^3} + C_{U2} \right)^{-1}$, also in Eq. (35)	(34)
C_{U3} C_{00}	0.56 0.3	$\frac{U_*}{W_*} = C_{U3}\left[\frac{z_{0u}}{h} + C_{00}\left(\frac{z_{0u}}{h} \right)^{8/7} \right]^{1/6}$, also in Eq. (42)	(41)
C_1	0.25	$\frac{F_{\theta s}}{W_*\Delta\theta} = \frac{F_{qs}}{W_*\Delta q} = \frac{W_*^2}{(\beta\Delta\theta + 0.61g\Delta q)h}$	
C_2	-2.5	$= C_1\left(\ln\frac{h/z_{0u}}{(\ln(h/z_{0u}) - C_{U0})^3} + C_{U2} \right)^{-1} \left(\ln\frac{h/z_{0u}}{(\ln(h/z_{0u}) - C_{U0})^3} + C_2 \right)^{-1}$	(35)
C_3	0.8	$\frac{F_{\theta s}}{W_*\Delta\theta} = \frac{F_{qs}}{W_*\Delta q} = \frac{W_*^2}{(\beta\Delta\theta + 0.61g\Delta q)h} = C_3\left[\frac{z_{0u}}{h} + C_{00}\left(\frac{z_{0u}}{h} \right)^{8/7} \right]^{1/3}$	(42)

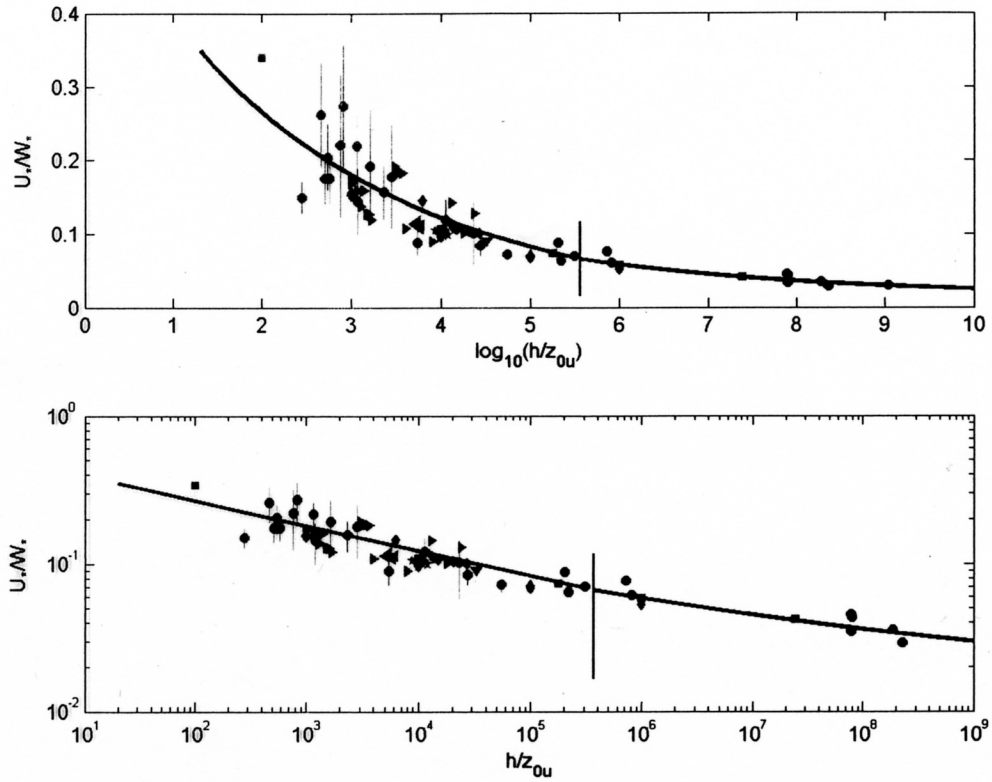


Figure 3. The resistance coefficient U_*/W_* versus h/z_{0u}. The solid curve shows our model: Eq. (34) for low-roughness surfaces $h/z_{0u} \geq 3.62 \cdot 10^5$, Eq. (41) for high-roughness surfaces $h/z_{0u} \leq 3.62 \cdot 10^5$, with empirical coefficients summarised in Table 3. Vertical line shows the matching point $h/z_{0u} = 3.62 \cdot 10^5$ between Eqs. (35) and (42). Symbols are given in Table 2. The lower panel (with logarithmic coordinates) demonstrates how the power law asymptote $U_*/W_* \sim (h/z_{0u})^{4/21}$, followed from Eq. (41) at large values of h/z_{0u}, fits data.

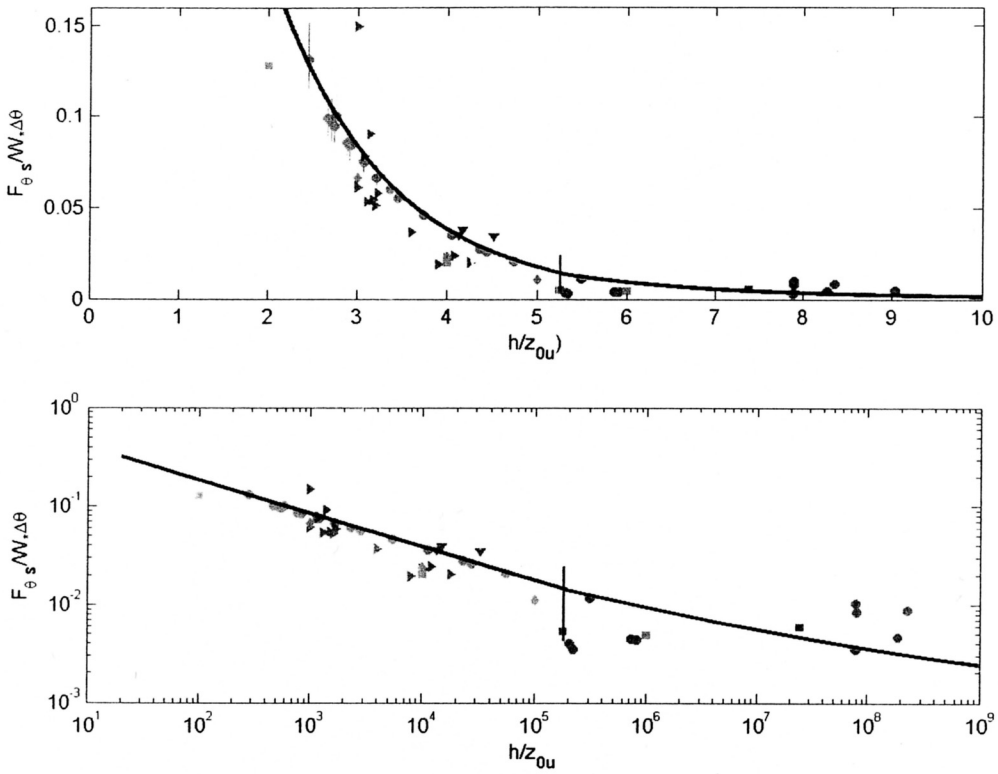


Figure 4. The heat transfer coefficient $F_{\theta s}/(W_* \Delta\theta)$ versus h/z_{0u}. Solid curve shows our model: Eq. (35) for low-roughness surfaces $h/z_{0u} \geq 1.8 \cdot 10^5$, Eq. (42) for high-roughness surfaces $h/z_{0u} \leq 1.8 \cdot 10^5$, with empirical coefficients summarised in Table 3. Vertical line shows the matching point $h/z_{0u} = 1.8 \cdot 10^5$ between Eqs. (35) and (42). Symbols are given in Table 2. The lower panel (with logarithmic coordinates) demonstrates how the power law asymptote $F_{\theta s}/(W_* \Delta\theta) \sim (h/z_{0u})^{8/21}$, followed from Eq. (42) at large values of h/z_{0u}, fits data.

CONCLUSIONS

Large convective eddies are semi-organised.

They are separated from the true turbulence by wide spectral gap.

Their typical length and velocity scales are: the CBL depth h and the D-velocity $W_* = (\beta F_s h)^{1/3}$.

Convective-wind/near-surface shears generate small-scale turbulence and "convective friction velocity" U_*. Mixing becomes strongly enhanced.

The theory gives U_*/W_* and heat/mass transfer coefficients as dependent on h/z_0.

Field-measurement and LES data are in excellent agreement with the theory at $10^2 < h/z_0 < 10^9$.

Classical theories overlook this mechanism and predict 10-fold smaller surface fluxes.

Applications: Warm-pool area in Tropical Ocean
Polynias in Polar Ocean
Forest fires
$\Rightarrow$ URBAN METEOROLOGY .....

Part 2

STABILITY DEPENDENCE OF THE ROUGHNESS LENGTH FOR URBAN AND VEGETATED SURFACES

Interaction of Atmospheric / Hydrospheric Flows with Rough and Complex Surfaces

Content

1. THE NEAR-SURFACE STRESS AND THE ROUGHNESS LENGTH FOR MOMENTUM
1.1 Classical concept of roughness lengths for momentum over smooth/rough solid surfaces and water
1.2 Simple models for very rough surfaces:
   - Stability dependence of the roughness length
   - Mean velocity and turbulent stress profiles in the roughness layer (urban canopy / rocky sea bottom)
1.3 A few words about aggregation of the surface-stress over complex terrain

2. THE NEAR-SURFACE SURFACE HEAT (SCALAR) TRANSFER
2.1 Roughness lengths for heat and other scalars: role of molecular conductivity (diffusivity); principal difference between the roughness lengths for momentum and scalars:
   - Smooth and moderately rough solid surfaces
   - Water surface
2.2 ~~Heat transfer over very rough and complex surfaces:~~
   - ~~Counter-gradient transports (roughness lengths inapplicable)~~
   - ~~Flux aggregation over ice-covered ocean with leads: LES + scaling analysis (I. Esau)~~

Roughness Lengths for Momentum

Neutral stability: z_{0u} is the level, at which $u(z)$ approaches zero when plotted versus $\ln z$

velocity profile $u(z) = \frac{u_*}{k} \ln \frac{z}{z_{0u}}$, eddy viscosity $K_M = k u_* z \quad (k = 0.4)$

SOLID SURFACES Physics: z_{0u} ~ typical vertical size of turbulent eddies in the roughness layer

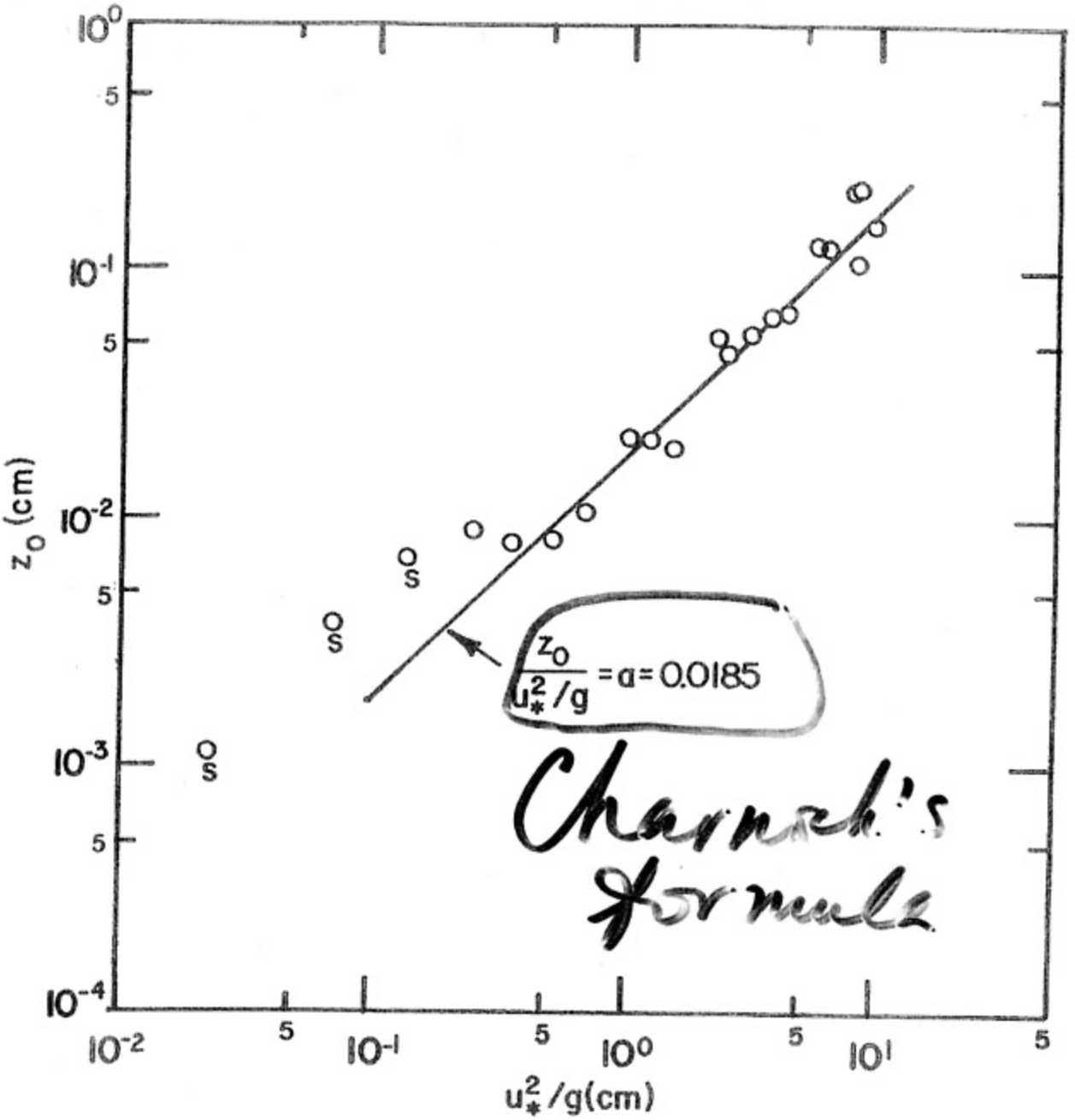
Smooth $z_{0u} = \frac{1}{10} \frac{\nu}{u_*}$; rough $z_{0u} = \frac{1}{25} h_0$; generally $\frac{z_{0u}}{h_0} = f_{0u}(\mathrm{Re})$ where $\mathrm{Re} = \frac{h_0 u_*}{\nu}$.

Roughness model $z_{0u} = \frac{\frac{1}{10} K_M|_{z=h_0}}{u_*}$ gives realistic estimate $z_{0u} = \frac{0.1 k u_* h_0}{u_*} = \frac{1}{25} h_0$

WATER SURFACE: Determine wave height h_0 and $z_{0u} \sim \frac{1}{25} h_0$. Taking $\frac{u_*}{u} \sim 0.05$, balance between wind kinetic energy $E_K \sim \rho_a u^2$ and surface waves potential energy $E_P \sim g \rho_w h_0$ gives

Charnock's formula

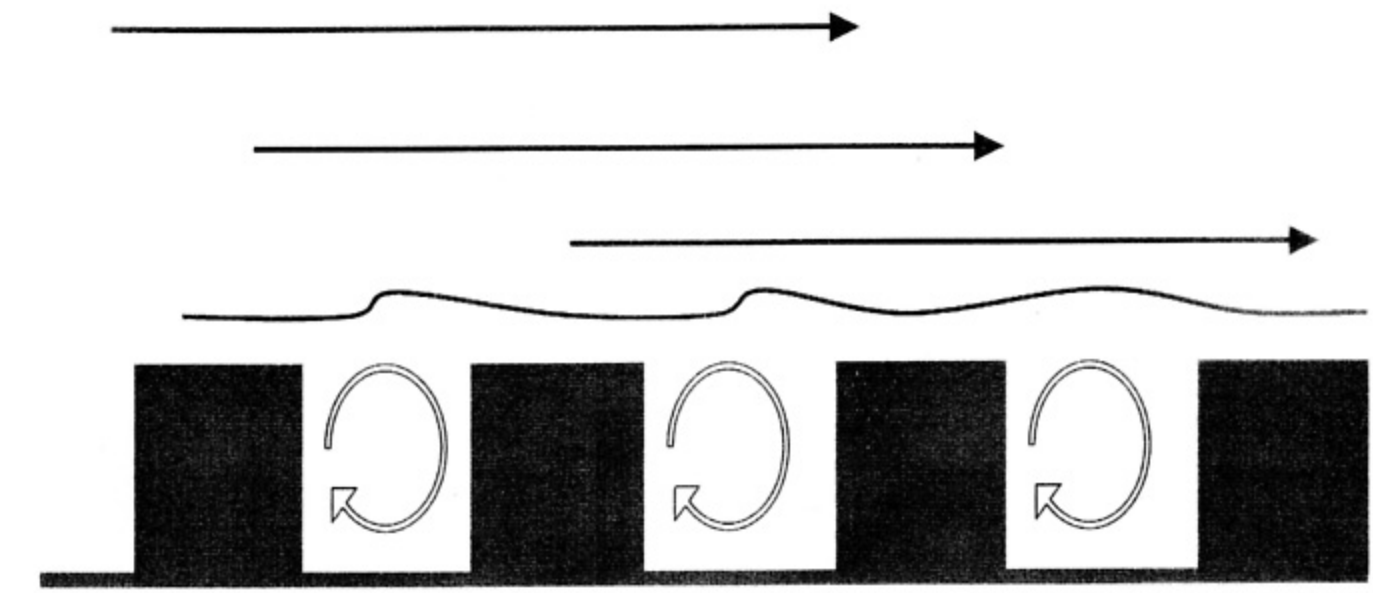
$$z_{0u} \sim \frac{16 \rho_a}{\rho_w} \frac{u_*^2}{g} \quad z_{0u} = \frac{u_*^2}{60 g}$$



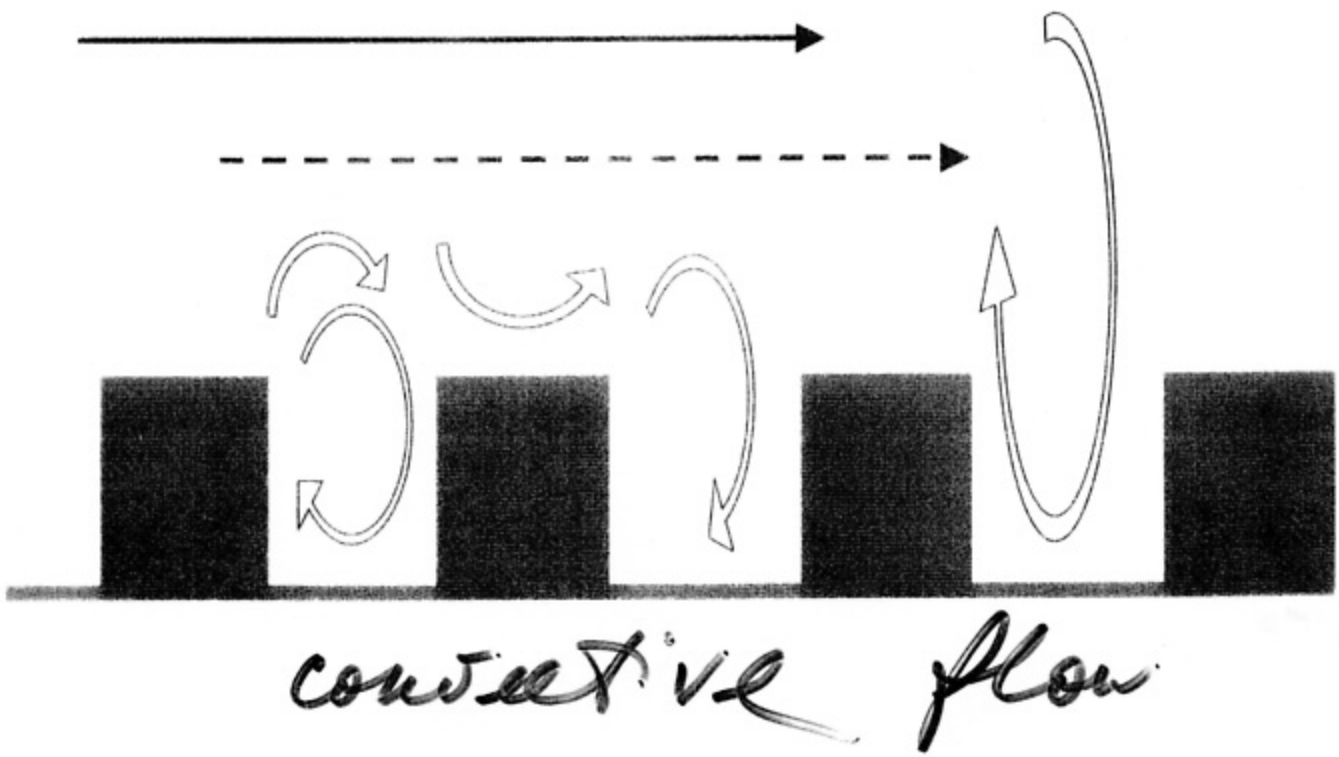
Observed roughness parameter of sea surface as a function of u_*^2/g

[After Wu (1980).]

STABILITY DEPENDENCE OF THE ROUGHNESS LENGTH



Stably stratified flow



convective flow

Very Rough Surfaces: a Model for Stability Dependence of the Roughness Length

STABLE STABILITY Turbulent eddies limited to roughness-layer height h_0 and MO length $L = \dfrac{-u_*^3}{\beta F_{\theta s}}$

Interpolation $1/z_{0u} = C_1/h_0 + C_2/L$

Consistent with Roughness model $z_{0u} = \frac{1}{10} K_M(h_0)/u_*$ taking $K_M = k u_* z (1 + C_u z/L)^{-1}$:

$$\frac{z_{0u}}{z_{00u}} = \frac{1}{1 + C_u h_0/L}$$ where z_{00u} is the neutral-stability roughness length, and $C_u \approx 2$

CONFIRMED BY OBSERVATIONS IN Sodankylä (I. Mammarella, 200

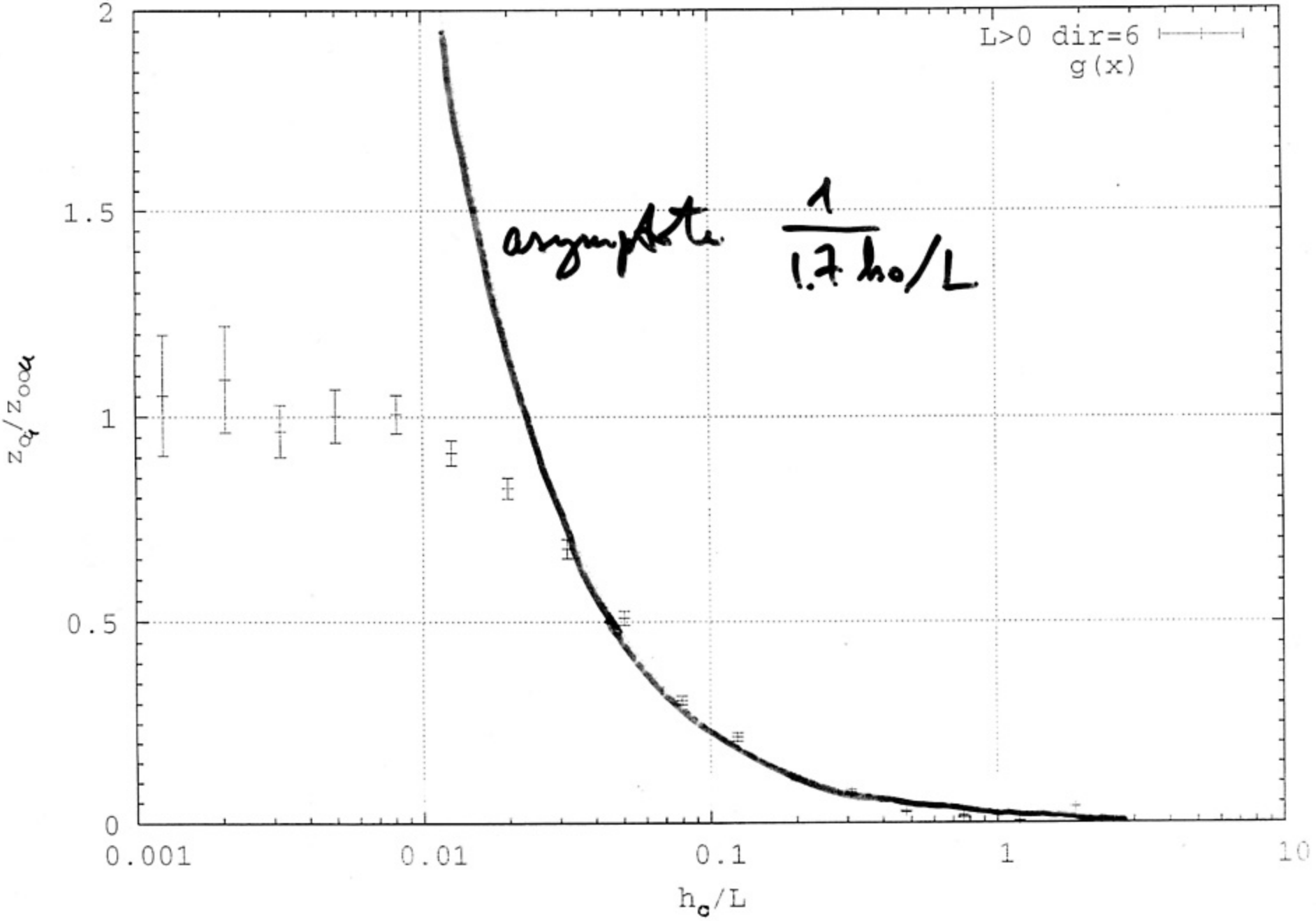
empirical 1.7

Velocity profile in this regime $u(z) = \dfrac{u_*}{k}\left(\ln\dfrac{z}{z_{0u}} + C_u\dfrac{z}{L}\right)$ Matching height $z_* = \dfrac{L}{C_u}$

Log layer $z_{0u} << z << z_*$ exists in any stratification because $z_{0u} = (0.1k/C_u)L << z_* = 25 z_{0u}$

No theory before present, but empirical evidence – lab data: Arya S.P.S., *J. Fluid Mech*, 1975, **68**, 321-343
field data over frozen sea: Joffre, S., *Boundary-Layer Meteorol.*, 1982, **24**, 211-229

Effective roughness length in stable stratification.
Comparison of the theory with Sodankylä data.

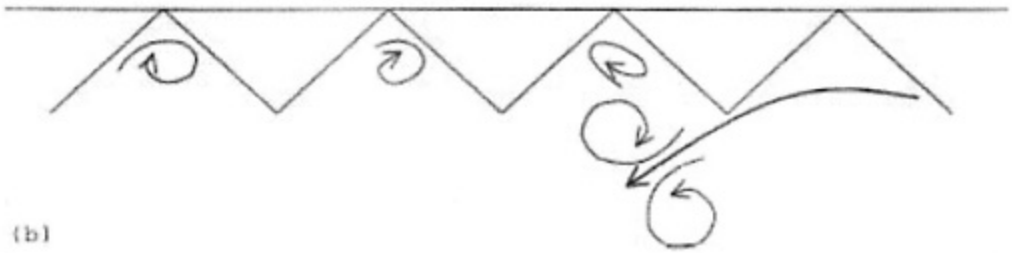


CONVECTIVE EDDIES UNDER COLD OBSTACLES

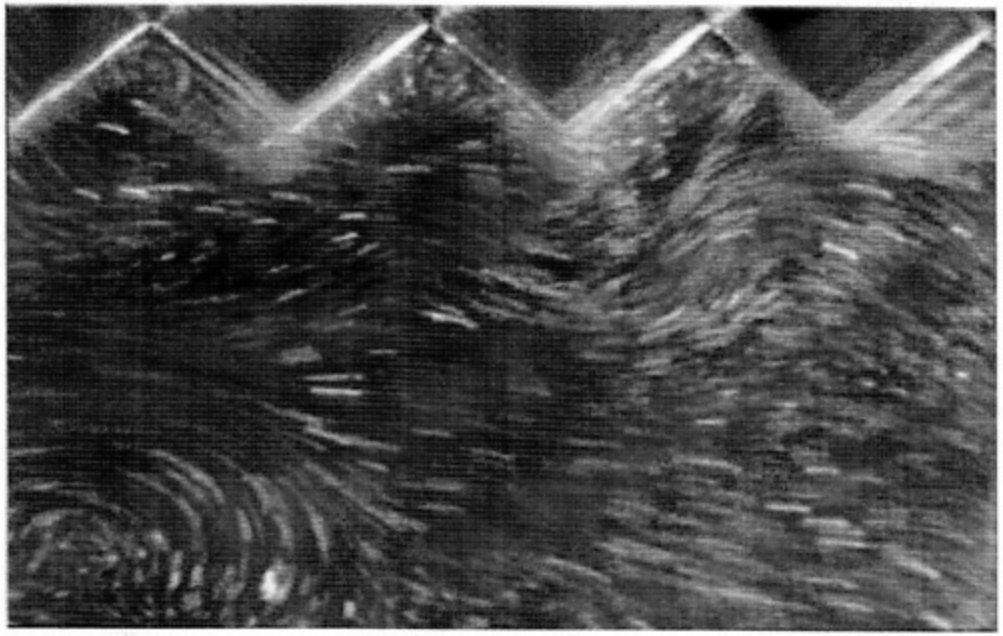
VOLUME 81, NUMBER 5 PHYSICAL REVIEW LETTERS 3 AUGUST 1998

Y.-B. Du and P. Tong, Enhanced Heat Transport in Turbulent Convection over a Rough Surface

(a)



(b)



CONVECTION Turbulent eddies over heated obstacles extend in the vertical causing $z_{0u} > z_{00u}$

Taking $K_M = ku_* z + C_U^{-1}(\beta F_{\theta s})^{1/3} z^{4/3}$ our Roughness model $z_{0u} = \frac{1}{10} K_M(h_0)/u_*$ gives

$$\frac{z_{0u}}{z_{00u}} = 1 + \frac{1}{kC_U}\left(\frac{h_0}{L}\right)^{1/3} \quad \text{where } C_U \approx 1.7$$

Velocity profile

$$u(z) = \frac{u_*}{k}\ln\frac{z}{z_{0u}} \quad \text{at } z << z_*$$

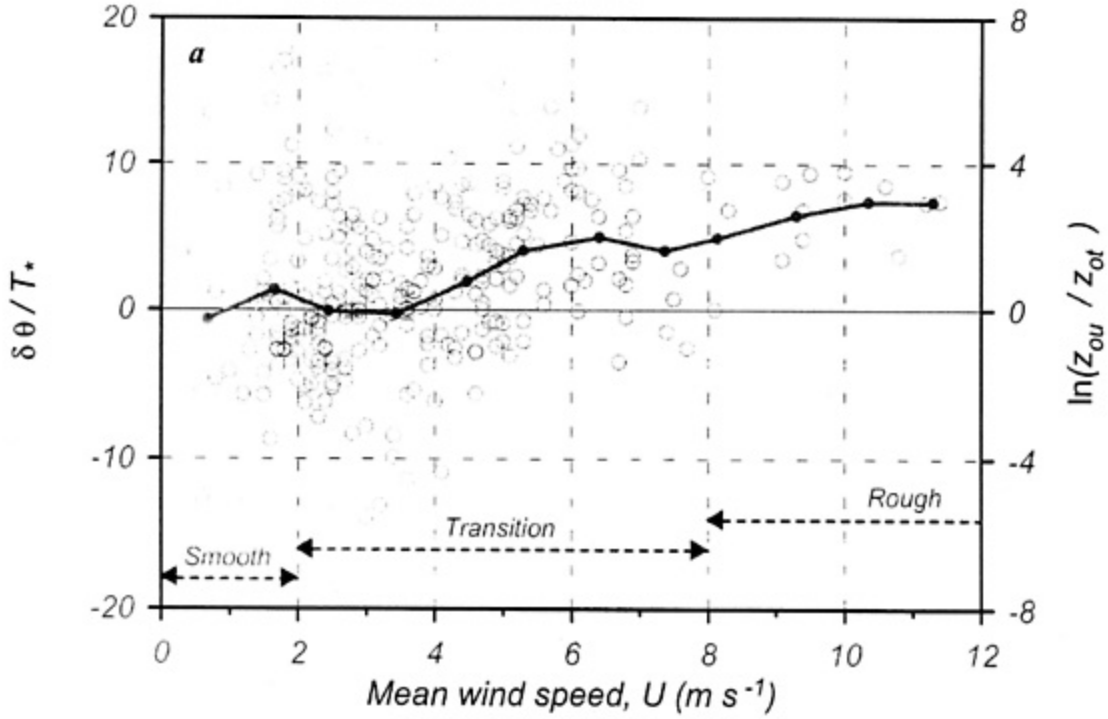
$$u(z) = u_\infty - \frac{3u_*^2}{C_U(\beta F_{\theta s} z)^{1/3}} \quad \text{at } z >> z_*$$

Matching height is $z_* \sim 0.1L$. In very strong convection, when $L < 0.7h_0$, the roughness length $z_{0u} \sim 0.06 h_0^{4/3}/L^{1/3}$ exceeds z_*. Then no log-layer –convective turbulence dominates throughout.

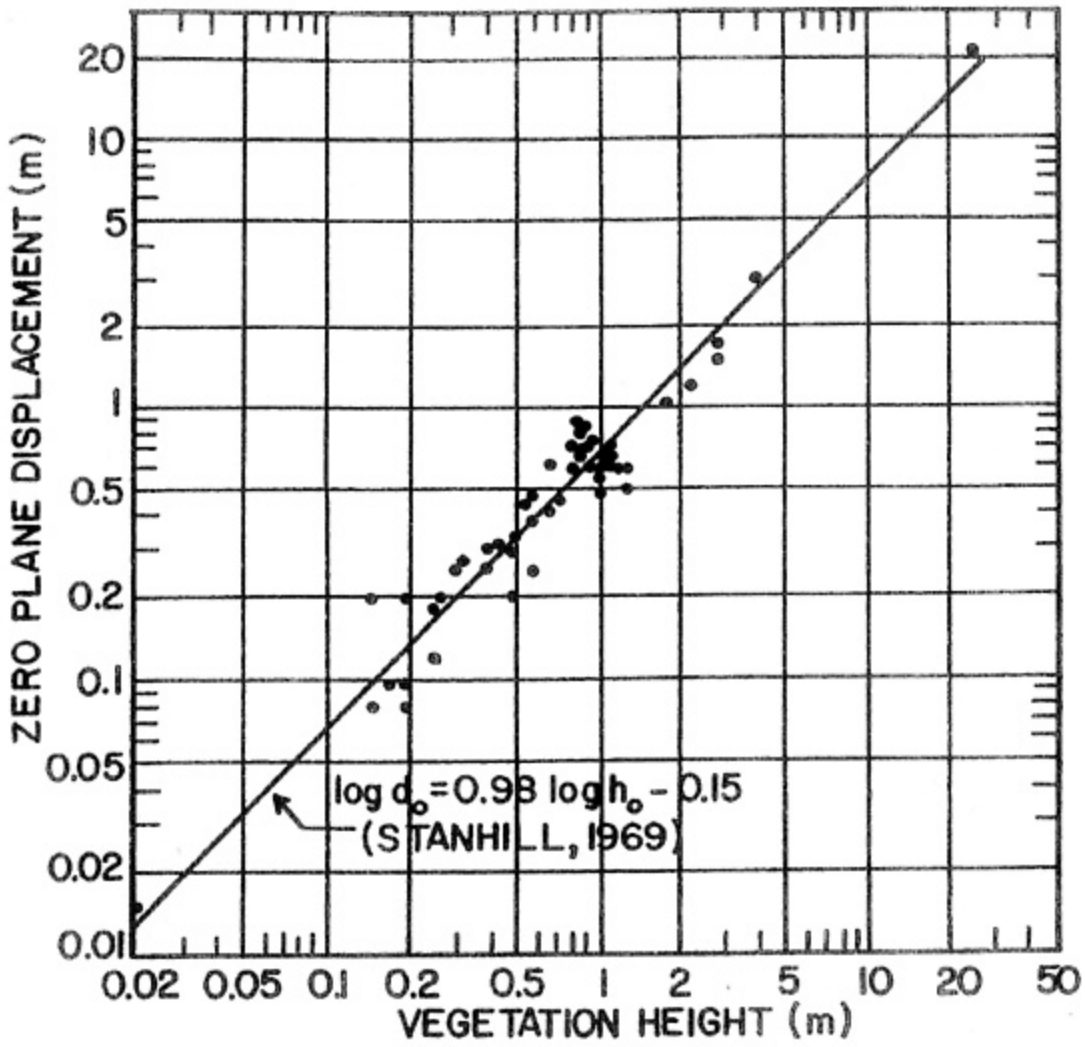
No theory before present; (indirect) empirical evidence from LES and field data over Athens (Z et al, *QJRMS*, 2005)

the same mechanism in Coelho & Hunt (1989)

EXPERIMENTAL ~~DATA~~ NEEDED (8) → $\frac{z_{0u}}{z_{00u}} = 1 + 0.2\left(\frac{z_{00u}}{L}\right)^{1/3}$?



Empirical wind speed dependence of the temperature increment across the roughness layer $\delta\theta$ and the temperature roughness length z_{0T} over the sea surface (data from SCOPE). The curve represents data averaged in wind-speed bins with 1 m s^{-1} width.



[After Stanhill (1969).]

displacement height

d_0

in neutral stratification

$d_0 \sim h_0$

Generally d_0 depends on stability

$$u(z) = \frac{u_*}{k} \ln \frac{z - d_0}{z_{0m}}$$

Roughness Lengths for Scalars

- Different physical nature of the roughness lengths for momentum (z_{0u}) and scalars (z_{0T} and z_{0q})
- Role of molecular conductivity / diffusivity never negligible: z_{0T} always depend on h_0, ν, χ ...
- Role of radiative heat transfer : z_{0T} ?

Temperature roughness z_{0T} is defined by extending log-profile down to approach surface temperature θ_s

$$\theta(z) = \theta_S - \frac{T_*}{k_T}\left[\ln\frac{z}{z_{oT}} - \Psi_\theta\left(\frac{z}{L}\right)\right], \quad \text{where } T_* = \frac{-F_{\theta s}}{u_*}$$

Using aerodynamic surface temperature θ_0 (determined from log profile extrapolated down to $z = z_{0u}$)

$$\theta(z) = \theta_0 - \frac{T_*}{k_T}\left[\ln\frac{z}{z_{0u}} - \Psi_\theta\left(\frac{z}{L}\right)\right]$$

but the temperature increment $\delta\theta \equiv \theta_s - \theta_0 = \frac{T_*}{k_T}\ln\frac{z_{0u}}{z_{0T}}$ should be determined !

BOUNDARY-LAYER SCALING In the well-developed-turbulence layer $(z >> z_{0u})$, the basic velocity scale characterizing vertical transports is u_*, hence the temperature scale is $T_* = -F_{\theta s} / u_*$

The thermal resistance of the roughness layer is controlled by molecular conductivity and viscosity, hence T_* is not a reasonable measure for the temperature increment $\delta\theta = \theta_s - \theta_0$

ROUGHNESS-LAYER SCALING Here, heat- and momentum-transfer depend on different mechanisms:

- τ consists of pressure part τ_p and molecular-viscosity part τ_ν
- The heat transfer within viscous layers over roughness elements is characterised by the transport velocity scale $\sqrt{\tau_\nu}$, whereas u_* becomes the mean-velocity scale
- Other scales are: u_* / z_{0u} for velocity gradient, $\tau_\nu \sim \nu u_* / z_{0u}$ for the viscous part of momentum flux, and $\theta_{*0} = -F_{\theta s} / \sqrt{\tau_{sv}} = -F_{\theta s} \sqrt{z_{0u} / \nu u_*}$ for the temperature increment. This gives

$$\delta\theta = k_T^{-1} A_0 T_* \mathrm{Re}^{1/2} \quad \text{and} \quad z_{0T} = z_{0u} \exp(-A_0 \sqrt{\mathrm{Re}}) \quad \text{where} \quad \mathrm{Re}_* \equiv z_{0u} u_* / \nu$$

A_0 is an empirical coefficient dependent on the Prandtl number $\mathrm{Pr} = \nu / \chi$ and the type of roughness

Lab experiments: **very good**, Sea surface: **fairly good**, Very rough or complex land surfaces: **very poor**

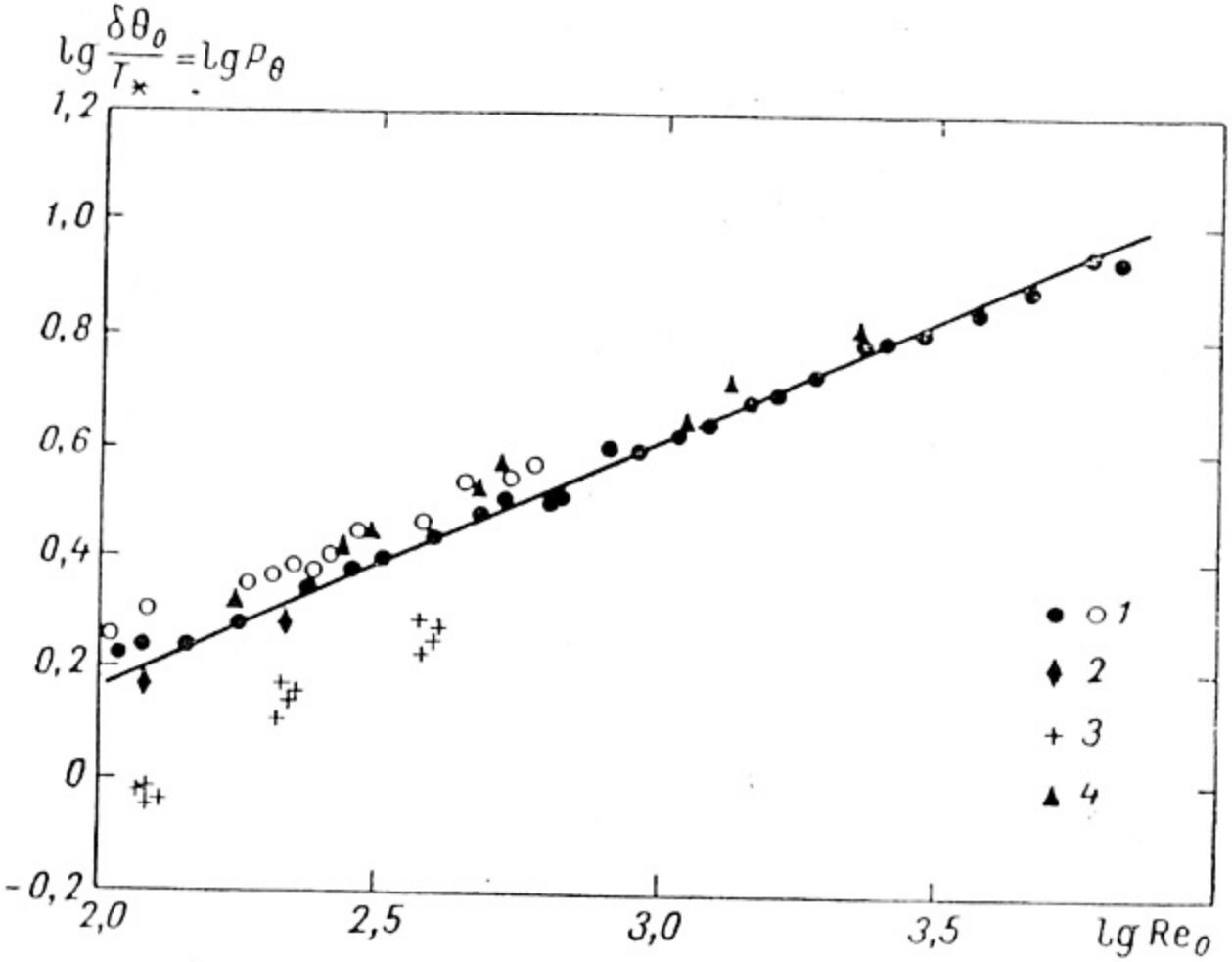


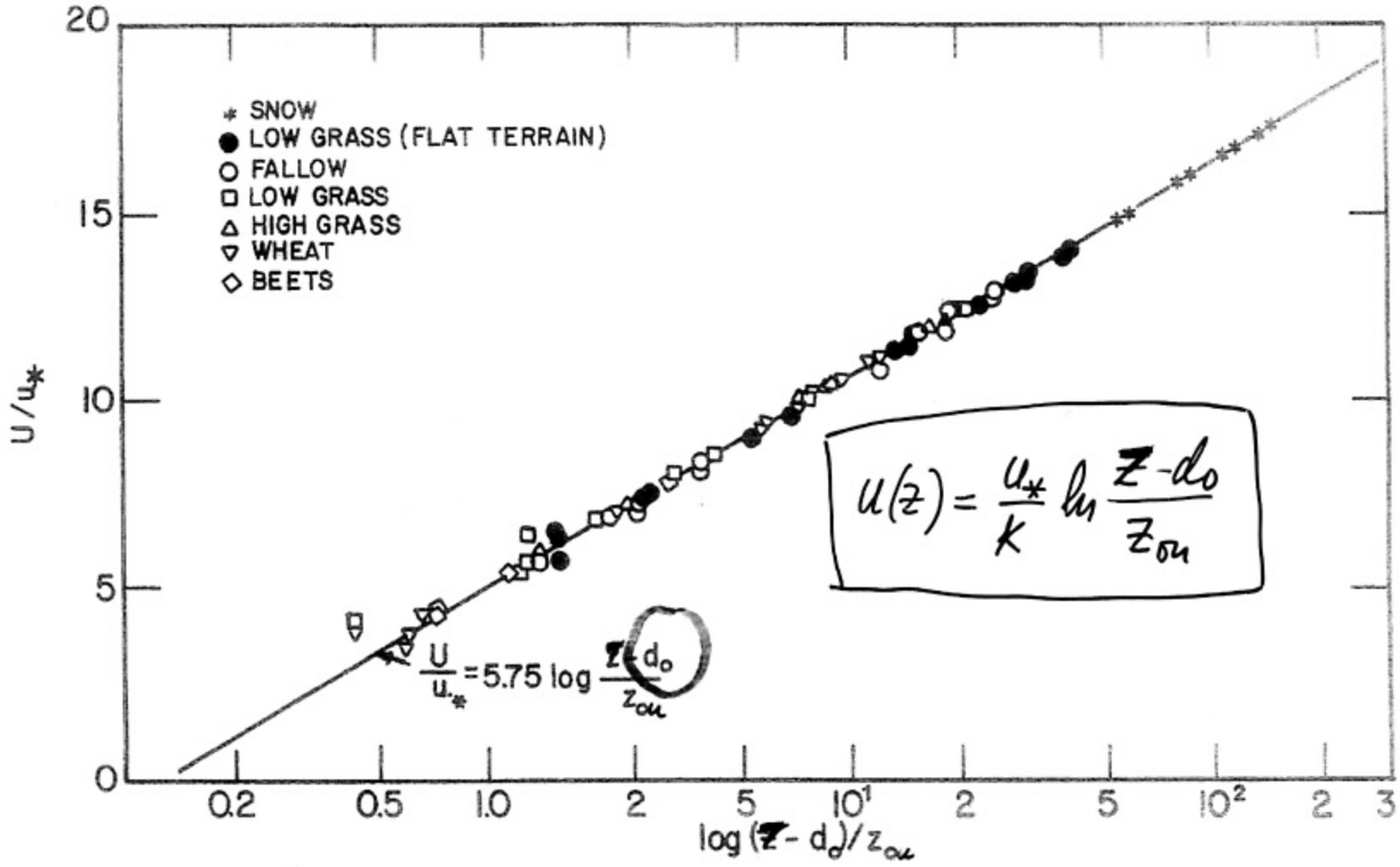
Рис. 1.5. Эмпирические данные о зависимости $\delta\theta_0/T_* = P_\theta(\mathrm{Re}_0)$

1 — Нуннер (1956), круглая труба, элементы шероховатости — шайбы различной формы и толщины. Pr =0,72; *2* — Пинкел (1954), круглая труба, спиральные шайбы, Pr =0,72; *3* — Ланцет (1969), канал, пирамидальные выступы, Pr =0,72; *4* — Дипри (1961), круглая труба, однородная песочная шероховатость. Pr=1,2

Old Empirical data on $\delta\theta_0/T_*$ (temperature increment across the roughness layer) on $Re_0 = \frac{z_{0m} u_*}{\nu}$

The curve like is $\sim Re_0^{0.45}$

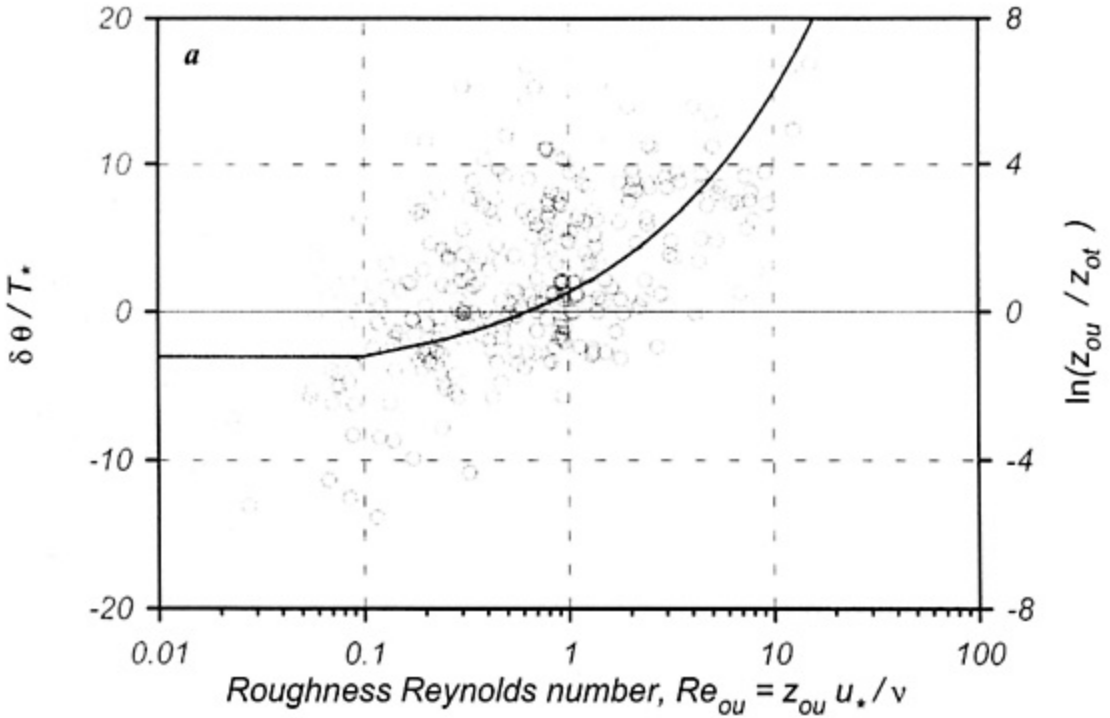
from Zilitinkevich



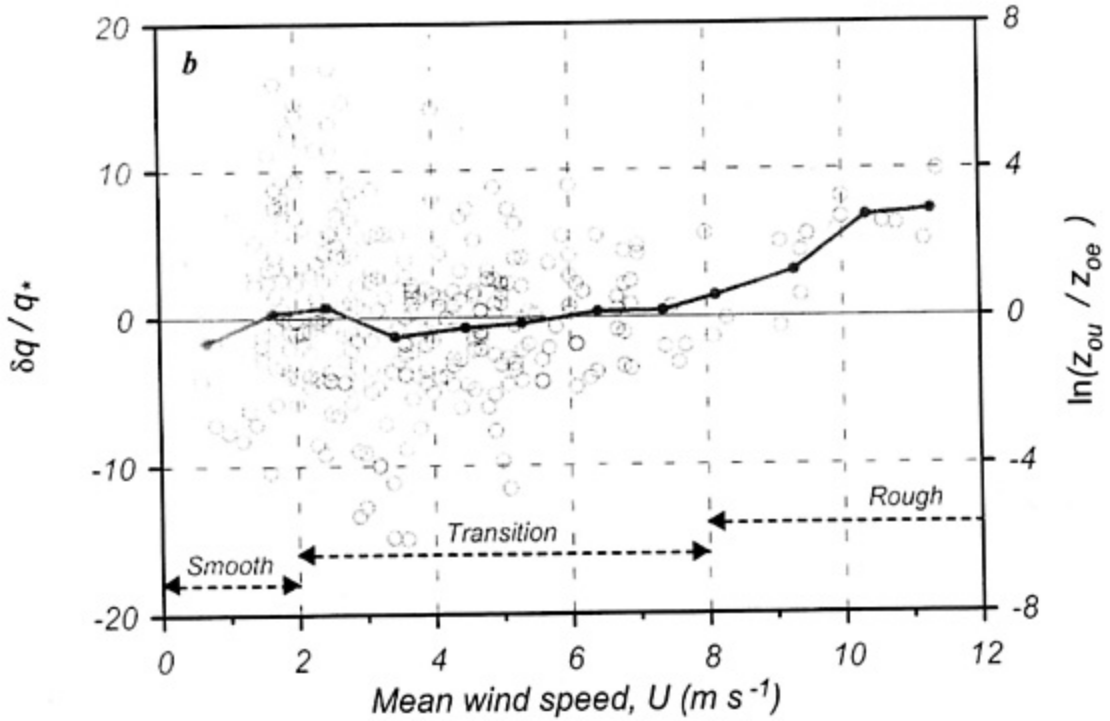
Comparison of observed velocity profiles over crops with the log law [From Plate (1971).]

Displacement height d_0

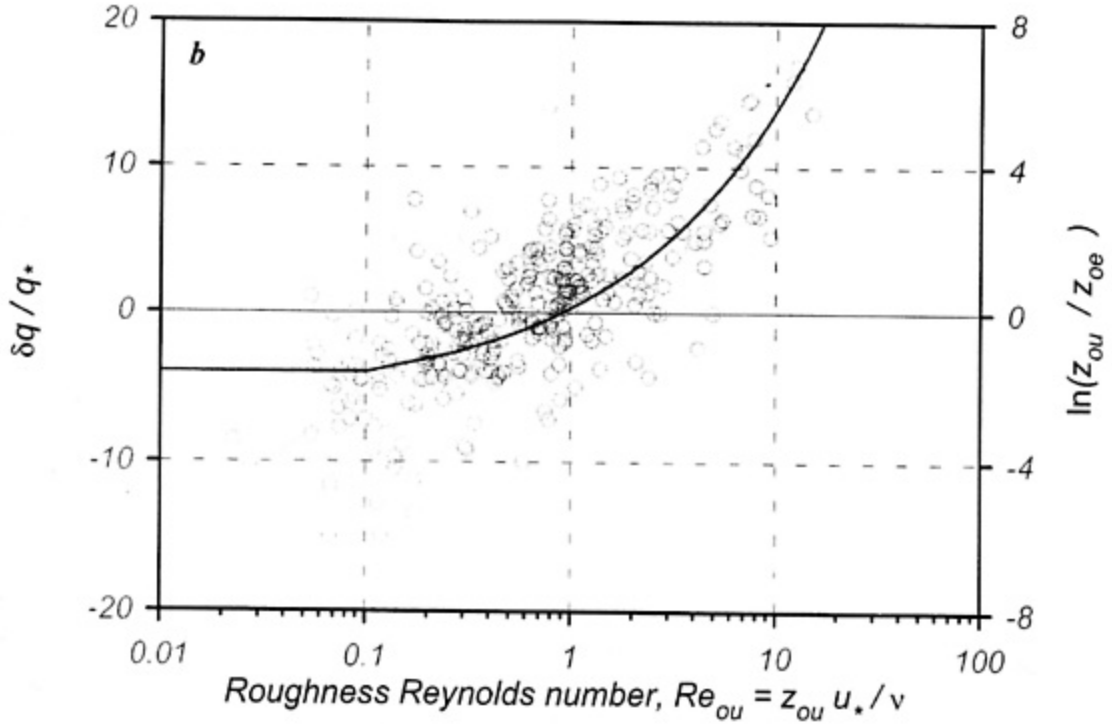
$\left(5.75 \log \frac{z-d_0}{z_-} = k \ln \frac{z-d_0}{z_-}\right)$



Theoretical dependence $\delta\theta / T_* = 6.3\,\mathrm{Re}_{0u}^{1/2} - 5 \quad at \quad \mathrm{Re}_{0u} \geq 0.1$ (the same data as before).



Empirical wind speed dependence of the humidity increment across the roughness layer δq and the roughness length for humidity z_{0q} over the sea surface (data from SCOPE).

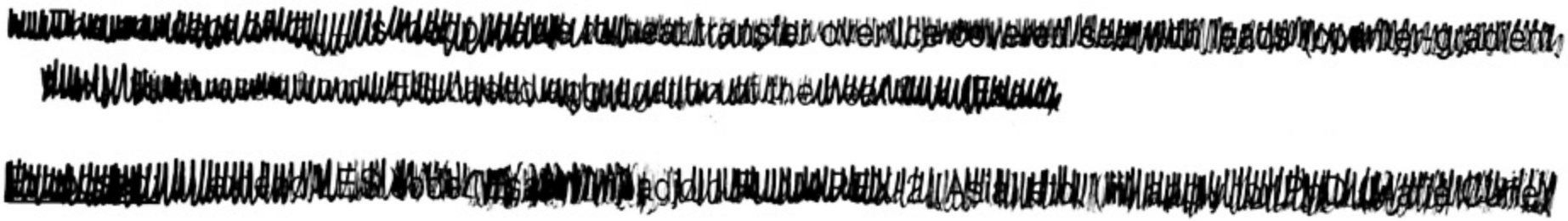


Theoretical dependence $\delta q / q_* = 6.3\,\mathrm{Re}_{0u}^{1/2} - 6 \quad at \quad \mathrm{Re}_{0u} \geq 0.1$ (the same data as before).

Concluding remarks

Solid surfaces (land surface, ice-covered sea, sea bottom)

- Over moderately rough, horizontally homogeneous surfaces $z_{0u} \sim h_0$; the roughness lengths for scalars z_{0T} and z_{0q} always depend not only on h_0, but on the surface Reynolds number $\mathrm{Re} = h_0 u_* / \nu$ ...
- For very rough surfaces, z_{0u} depends on stability: z_{0u} / z_{00u} increases with increasing h_0 / L. Proposed theoretical model needs further empirical validation (urban canopy, forest). CONVECTION ?
- An attempt is made to parameterise vertical profiles of the mean velocity and basic parameters of turbulence within roughness canopy. Proposed model needs verification (wind tunnel, urban canopy).
- Over very rough, complex and vegetated surface z_{0T} and z_{0q} are very uncertain or inapplicable. Alternative approaches are needed, e.g. LES of turbulent flows within roughness canopy.

Sea surface

- Because of surface waves, the roughness length for momentum z_{0u} is determined uncertainly
- Given z_{0u}, scalar roughness lengths z_{0T} and z_{0q} or scalar increments are calculated through Re