On specific nature of atmosphere-land/sea interaction in polar regions

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– TOWARDS A NEW MULTINATIONAL, MULTIDISCIPLINE CLIMATE, AIR QUALITY AND ENVIRONMENT RESEARCH EFFORT IN ARCTIC AND BOREAL PAN-EURASIA REGIONS

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CONTENT

***Energy and matter exchange at the Earth surface*:**

Current vision of roughness lengths especially for scalars (temperature, humidity, etc.) copied from engng fluid dynamics disregards real features of natural surfaces and yields big uncertainties in calculation of surface fluxes

***Turbulent transports in the surface layer*:**

Monin-Obukhov (1954) Similarity Theory (MOST) underlying universally recognised flux-profile relations disregards

- **self-control of turbulence in stable stratifications**
- **self-organised cells/rolls in unstable stratification**
- **strong effect of static stability in free flow on the surface fluxes in long-lived PBLs: POLAR DAY and POLAR NIGHT**
- **extra mixing over heterogeneous terrain**

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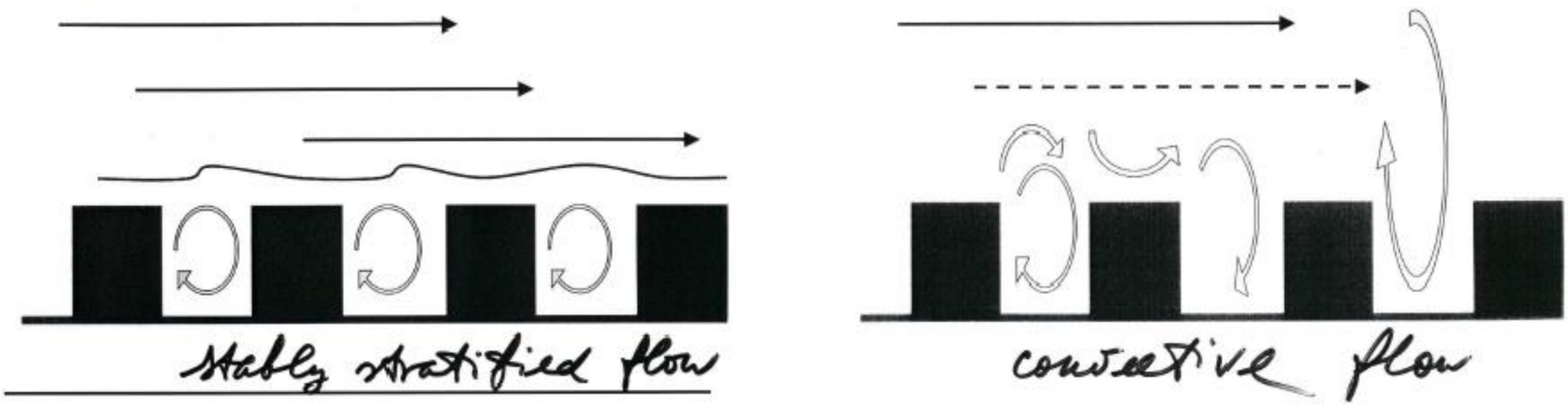
1. Stability dependence of roughness length for momentum



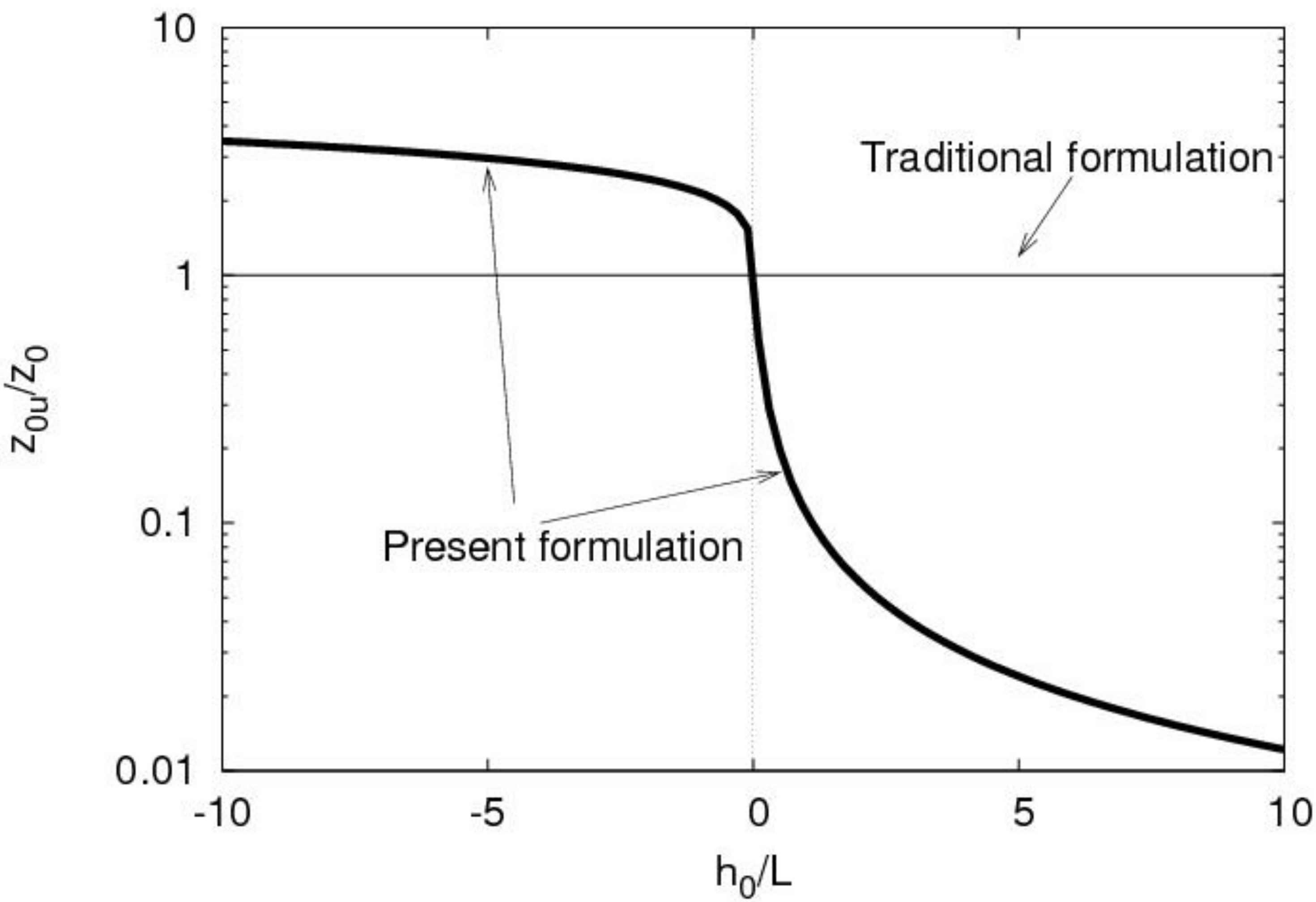
For urban and vegetation canopies with roughness-element heights (20-50 m) comparable with Obukhov length scale $L = u_*^3 / (-F_b)$ the surface resistance and, hence, roughness length must depend on stratification

Experimental data

Sodankyla Meteorological Observatory, boreal forest. Height of trees ~13 m; measurement levels: 23, 25, 47 m

BUBBLE urban BL experiment, Basel, (Rotach et al., 2004). Height of buildings h ~ 14.6 m, measurement levels: 3.6, 11.3, 14.7, 17.9, 22.4, 31.7 m

For deep canopies, roughness length for momentum strongly depends of stratification



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2. Roughness lengths for scalars

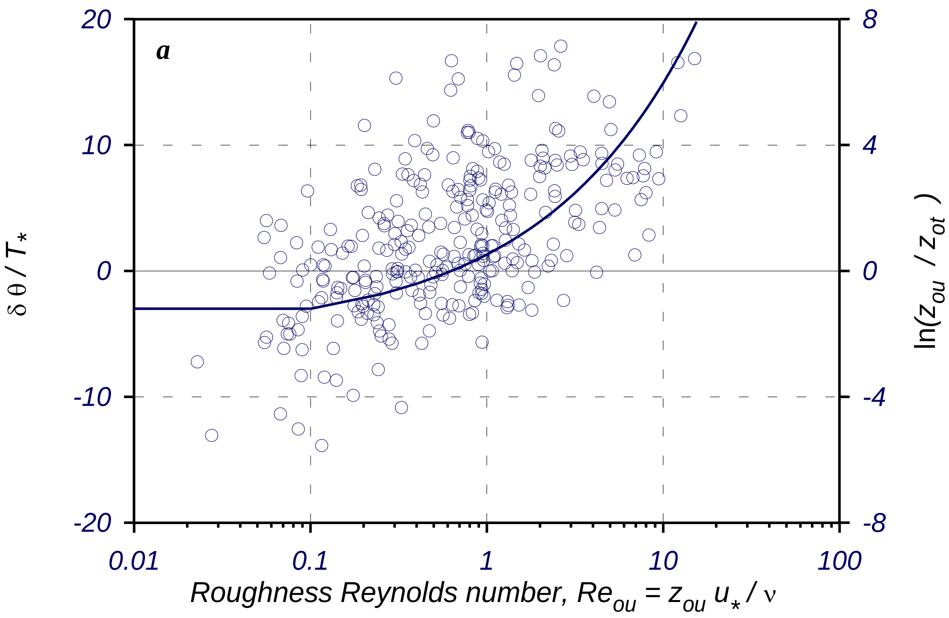
<u>Heat transfer</u> and **<u>heat roughness length</u>** Z_{0T} in contrast to the momentum roughness length Z_{0u} **<u>are controlled by molecular</u> viscosity and** conductivity, does not matter **how strong is turbulence** and **how deep are roughness elements**.

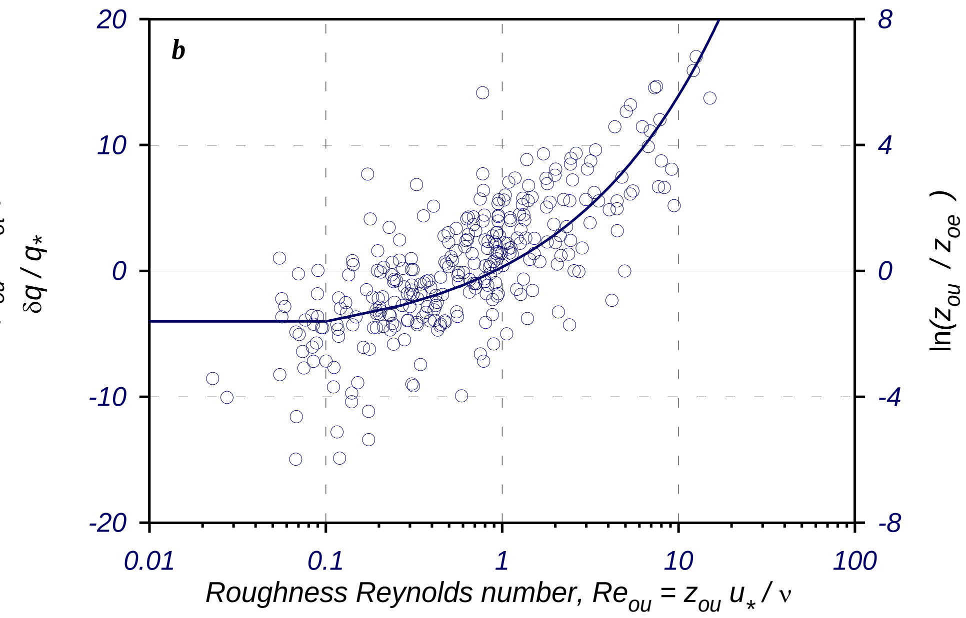
(Z et al., 2001) roughness length for scalars:

$$z_{0T} = z_{0u} \exp\left(-C_{0T} \sqrt{\frac{z_{0u} u_*}{\nu}} \right)$$

C_{0T} is empirical dimensionless universal constant

Empirical validation: temperature and humidity increments in the roughness layer over sea





Theoretical formulation:

$$\delta\theta / T_* = 6.3\,\mathrm{Re}^{1/2} - 5 \quad \text{at Re} \geq 0.1$$

$$\delta q / q_* = 6.3\,\mathrm{Re}^{1/2} - 6 \quad \text{at Re} \geq 0.1$$

agrees quite well with data, especially for humidity measured more accurately than very small aier-sea temperature increment

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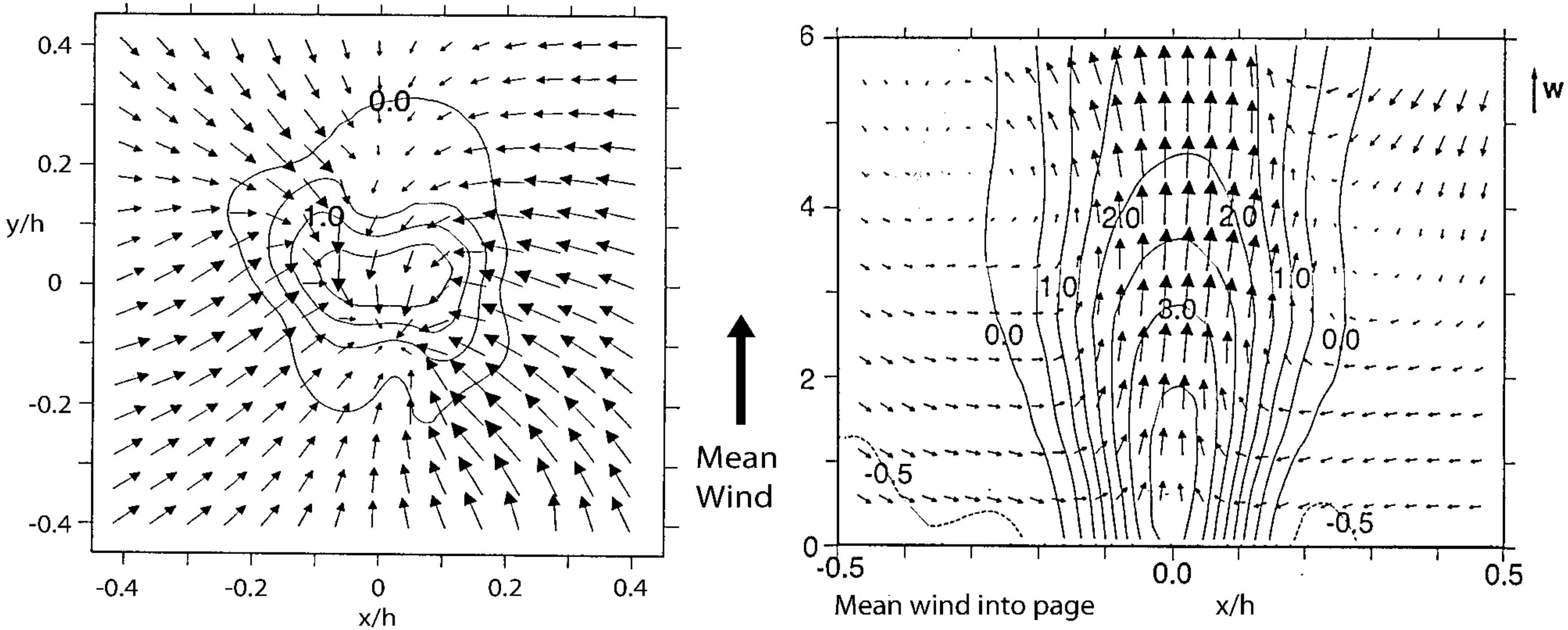
3. The effect of self organisation of convective turbulence on heat and mass transfer



Airborne measurements in the atmosphere (Williams, Hacker, 1992). Arrows show **self-organised wind pattern**. Solid lines show deviations of potential temperature θ from its mean value $<\theta>$; the lines $\theta - <\theta> = 0$ mark side walls of large buoyant plume.

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Enhanced heat/mass transfer in free convection

Large-scale self-organised structures

↓

Convective winds towards the plume base

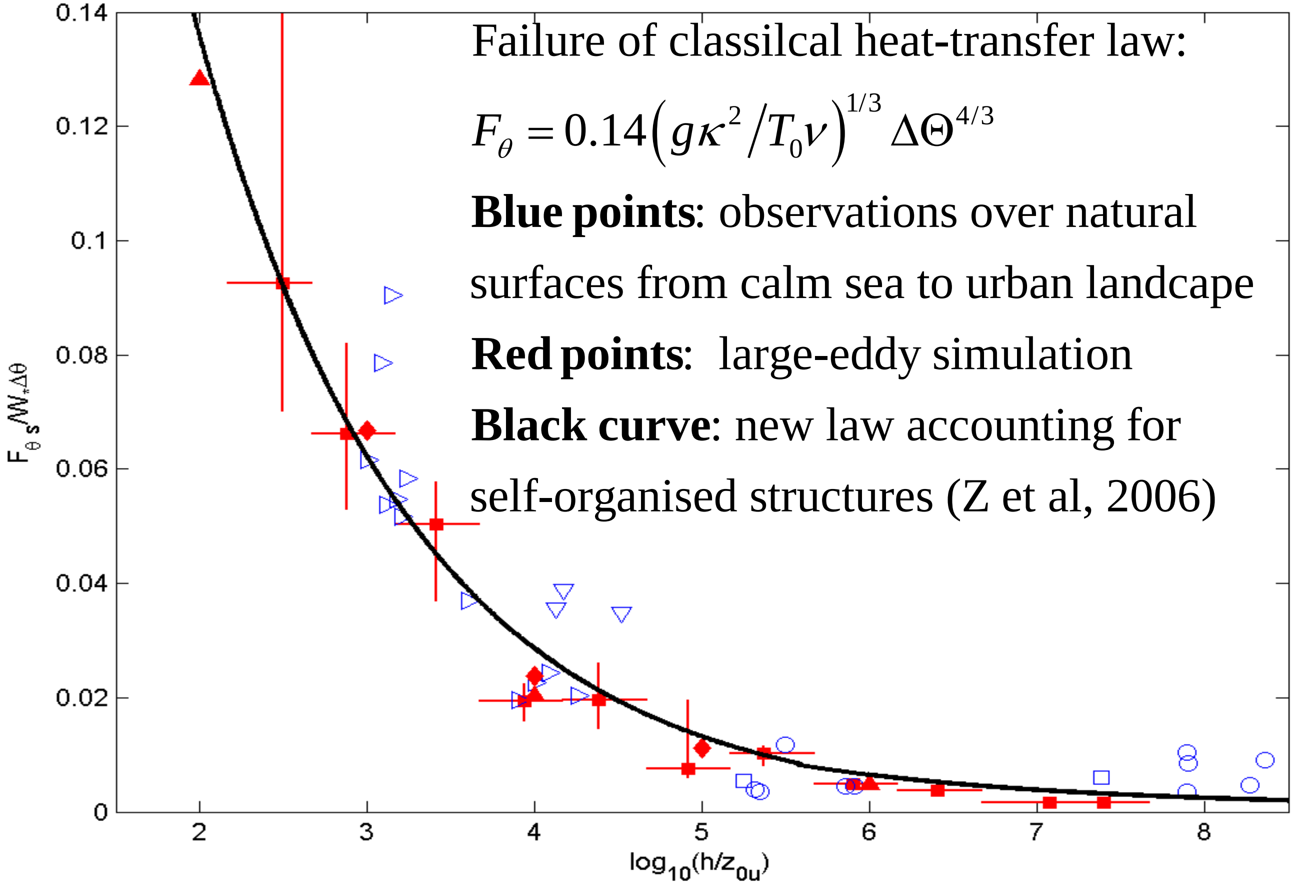
↓

Internal boundary layer → mechanical turbulence (**overlooked in conventional theories**)

↓

Strongly enhanced heat/mass transfer

Heat-transfer in calm-weather convection



Heat transfer is much stronger than traditional theory predicts.

It <u>depends on PBL height</u> (*h*) and <u>roughness length</u> (z_{0u}), both mossed in traditional theory

New law $F_\theta = f\left(h/z_{0u}\right)\left(gh/T_0\right)^{1/2}\Delta\Theta^{3/2}$ properly calculates the heat flux over rough surfaces **whereas traditional theory underestimates this flux by an order of magnitude**

4. Stably stratified turbulence: ***strong-mixing*** in PBL and ***weak-conductivity*** aloft ($Ri > Ri_c$)

Shallow PBL over Bergen seen due to water haze (courtesy I. Esau). Old theory confuses stable PBL and **supercritically** stable free flow. **EFB turbulence closure** (Z et al., 2007-2013) resolves the problem

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Self-control of turbulence in stable stratification via counter-gradient heat flux missed in K-1941, MO-1954

F_θ-budget reveals downgradient and countergradient terms comprising the **factual** heat flux

$$F_\theta = C_1 t_T \beta \left\langle \theta^2 \right\rangle - C_2 t_T E_z \frac{\partial \Theta}{\partial z}$$

Key feedback assuring self-control (Z et al., 2007, 2013):

Increase in the temperature gradient $\partial\Theta / \partial z$ **enhances**

(1) total (**negative**) fluxes of heat F_θ and buoyancy $F_b = \beta F_\theta$

(2) hence mean squared temperature $\left\langle \theta^2 \right\rangle = -C_3 t_T F_\theta \, \partial\Theta / \partial z$

(3) and thus counter-gradient positive contribution to heat flux $C_1 t_T \left\langle \theta^2 \right\rangle$

This compensates for enhancing of negative heat flux and prevents collapse of turbulence in super-critical stratification

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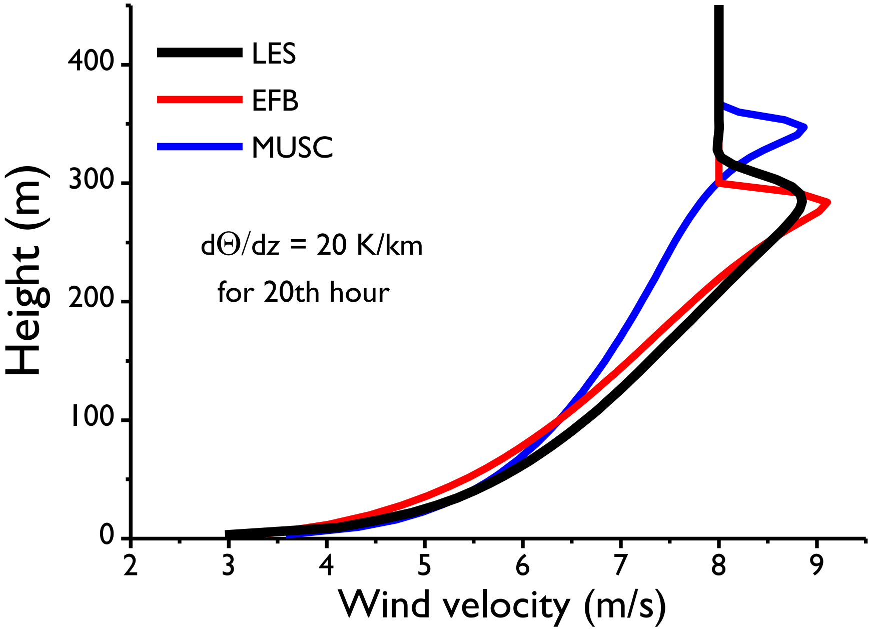
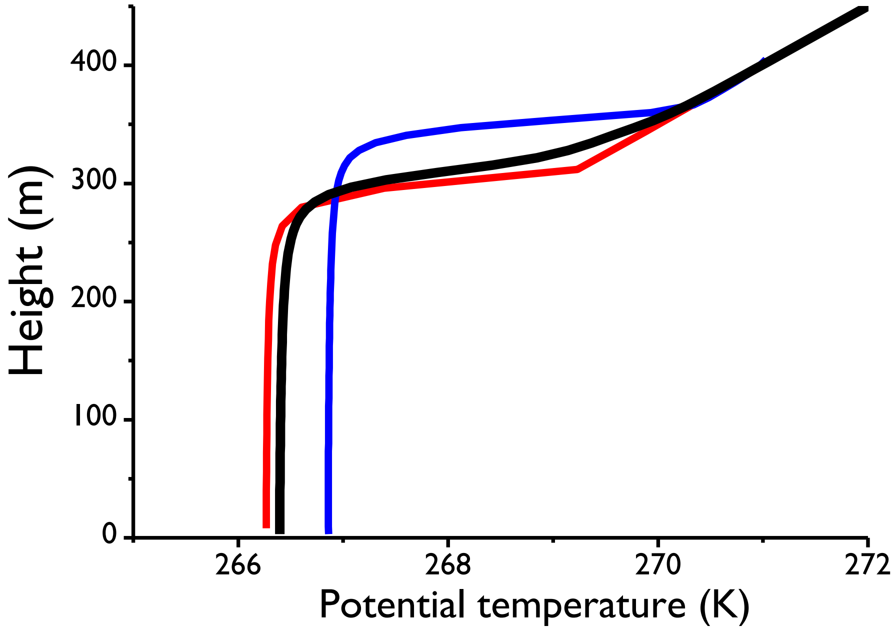
Conventionally Neutral PBL: EFB vs. LES

PBL with zero surface heat flux (as in GABLS1) but developing **against stable stratification in free atmosphere**, which causes negative (downward) heat flux in the upper part of PBL





Traditional theories/models overestimate PBL height and overwarms CN PBL

Conclusions: Major failures of MOST

Unstable stratification

Wrong for all moments involving horizontal velocity fluctuations:
mean squared velocities, horizontal heat flux
Neglects effects of self-organised structures on ***surface fluxes***

Strongly stable stratification

Wrong for ***turbulent heat conductivity*** and ***Prandtl number***
Wrongly prescribes ultimate ***decay of turbulence at*** $Ri > 0.2$

Long-Lived (LL) PBL controlled by persistent stable stability in free flow (buoyancy frequency $N \sim 0.01$); **stable** in polar night / over cold ocean and **unstable** in polar day / over warm ocean
Incomplete scaling (missing N) → wrong ***flux-profile relations***

Heterogeneous terrain

Overlooks (i) **Extra TKE** generated by microcirculations;
(ii) **Extra heat flux >0** due to patchiness of surface temperature

Vincent van Gogh *The Starry Night*, June 1889, The Museum of Modern Art, New York

Thank you

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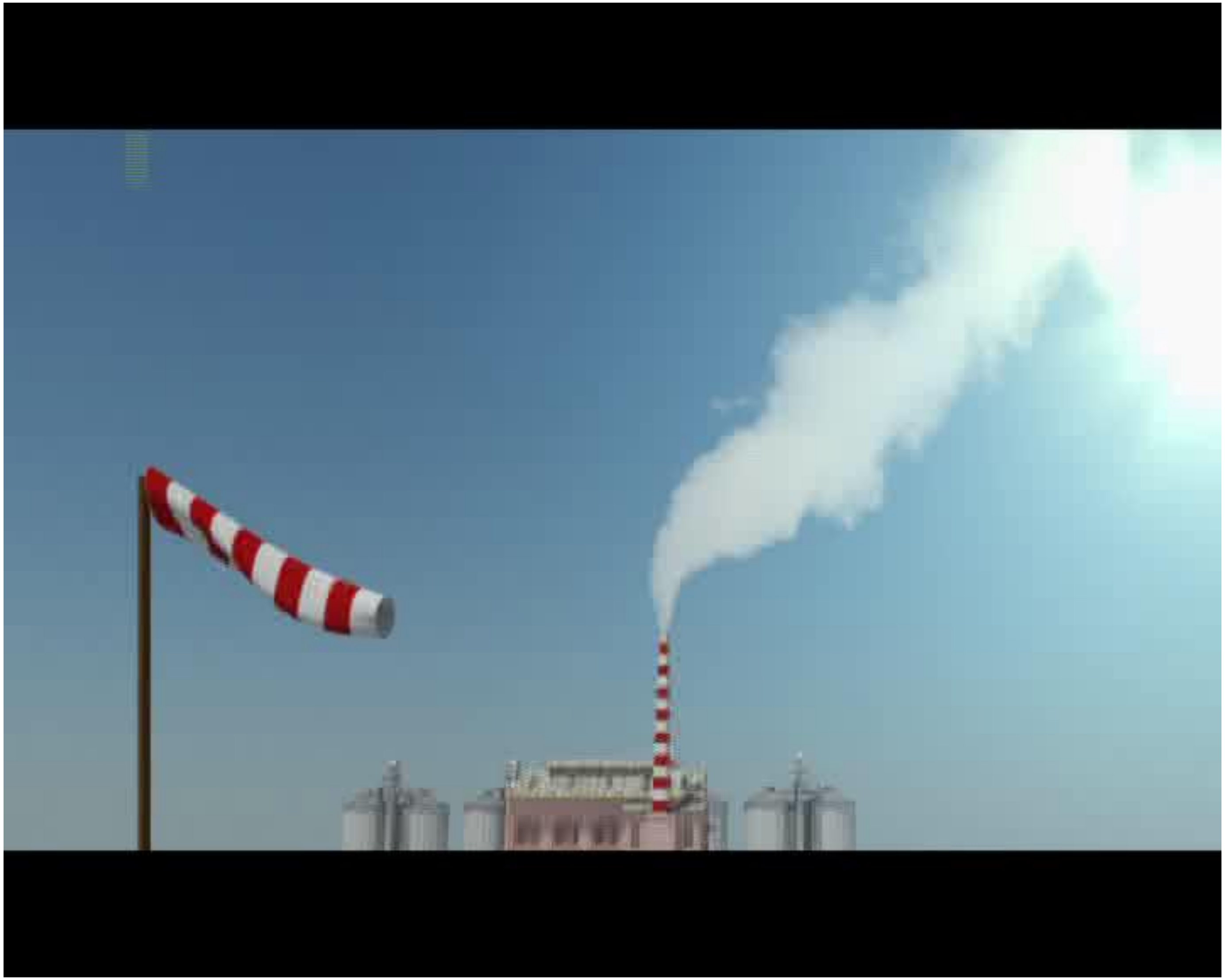
PBL height and air pollution.

What about ecosystems?



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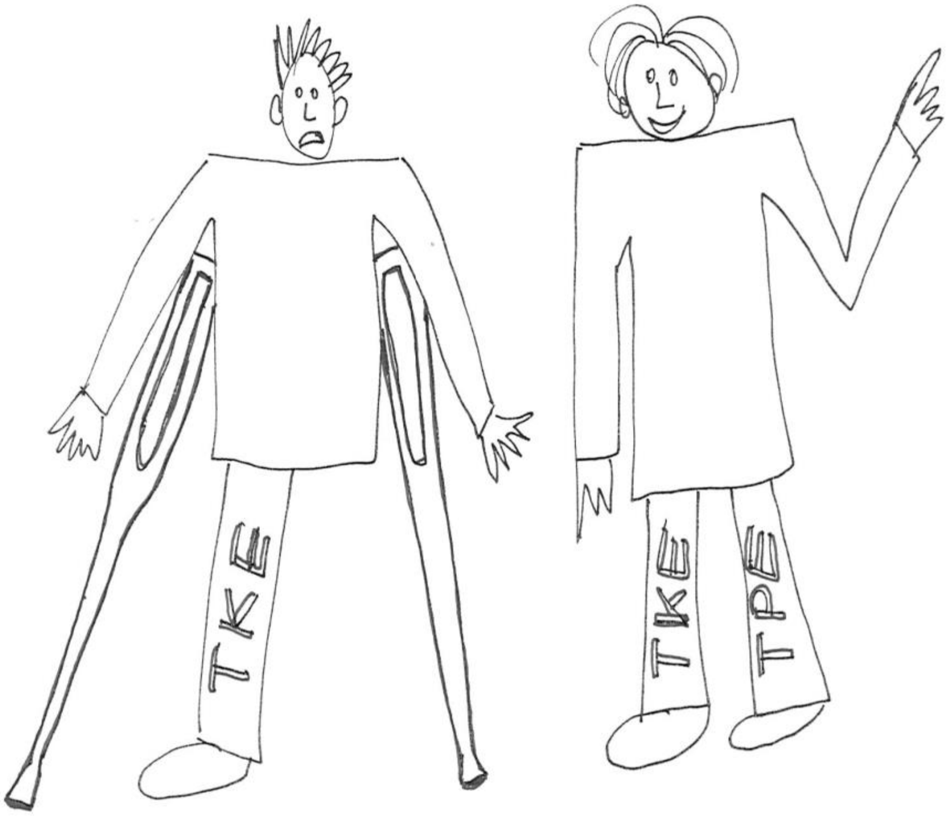
Remarks on turbulence in stable stratification

From hypothetical turbulent exchange coefficients and energetics limited to TKE



To EFB clsure (Z et al. 2007-18) flux-budget equations:

down-gradient and non-gradient transports,

TKE + TPE energy budget,

self-control of heat flux,

surviving of turbulence in supercritical stratification,

and many other features of real turbulence

We are capable to accurately calcualteing air-ecosystem interaction