Brutsaert-Parlange Symposium, Cornell 2012

Large Eddy Simulation Study of scalar transport in a wind turbine array atmospheric boundary layer)

Marc Calaf (EPFL), Charles Meneveau (JHU),
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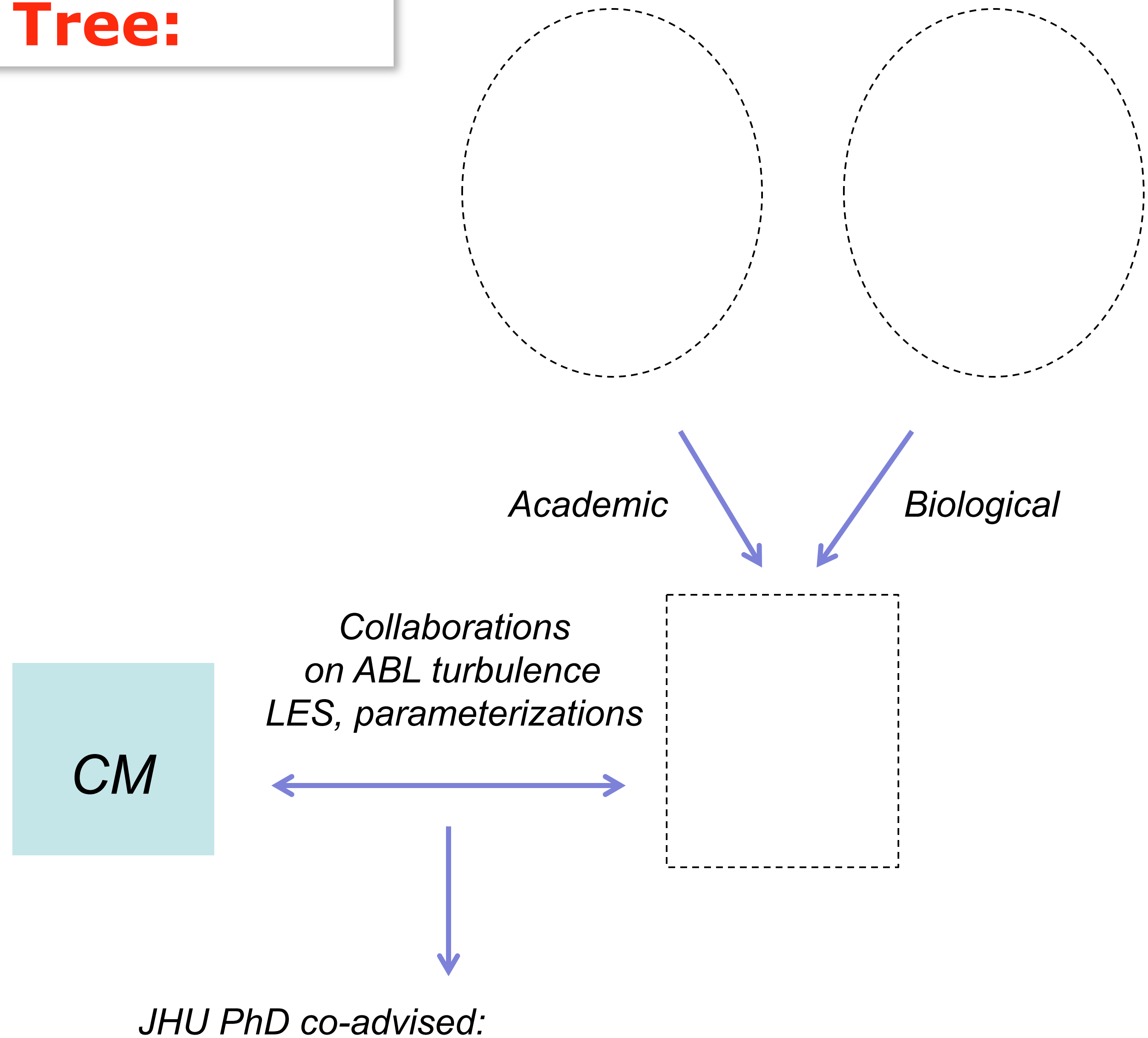
JHU Mechanical Engineering

idies Institute for Data Intensive Engineering and Science

JOHNS HOPKINS UNIVERSITY

Family Tree:



Academic
Biological
Collaborations
on ABL turbulence
LES, parameterizations
CM
JHU PhD co-advised:

Family Tree:

Academic

Biological

Collaborations
on ABL turbulence
LES, parameterizations

CM

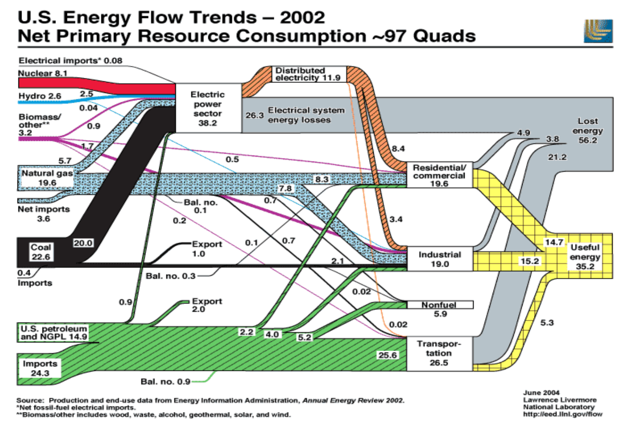
JHU PhD co-advised: Fernando Porte-Agel
Elie Bou-Zeid, Chad Higgins, Vijayant Kumar,
Jan Kleissl, Marcelo Chamecki, Marc Calaf (EPFL)

Some thoughts on how much we (USA) consume:

(i.e. "a few solar collectors or little wind-mills simply won't do")

- *Consider 3 TW US power consumption*

- *$3 \times 10^{12} / 300 \times 10^{6}$ = 10 kW per person in US*



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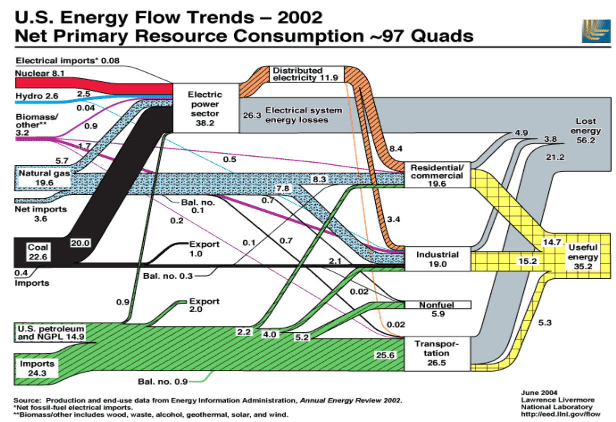
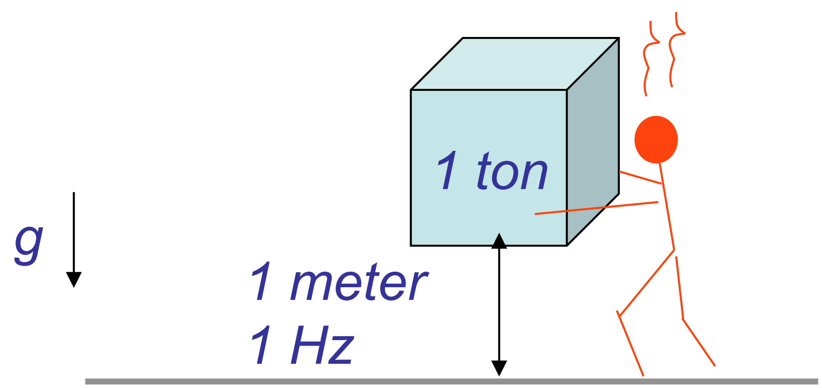


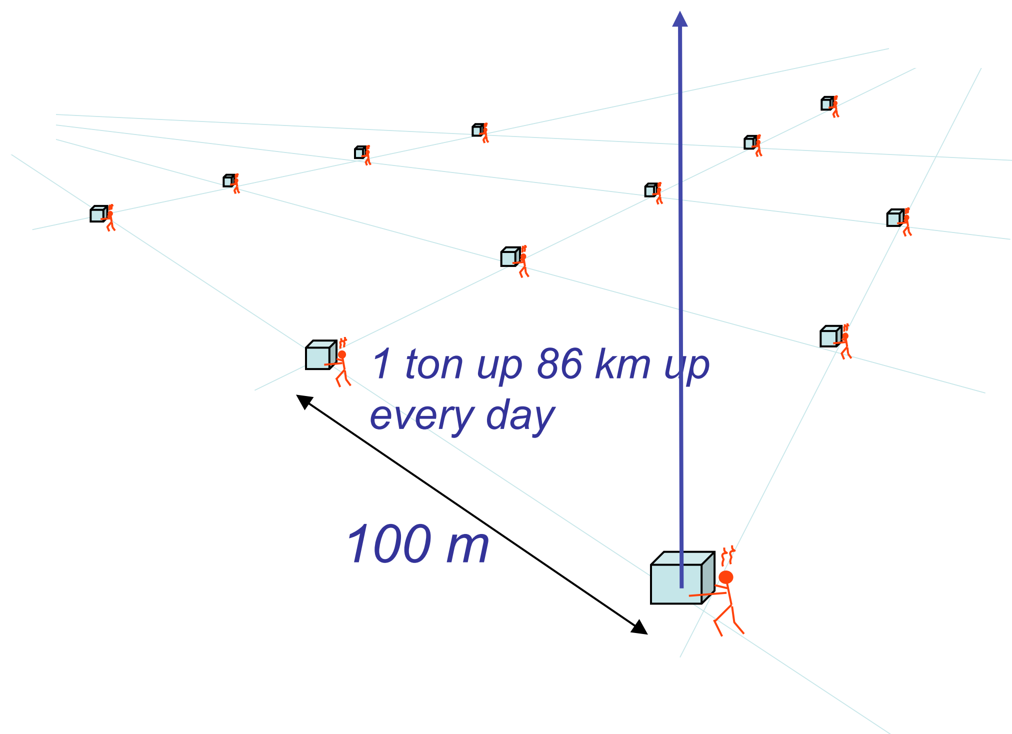
- *Consider 3 TW US power consumption*
- *$3 \times 10^{12} / 300 \times 10^{6}$ = 10 kW per person in US*
- *That is the same as lifting 1 ton by 1 meter every second!!*



Some thoughts on how much we (USA) consume:

(i.e. "a few solar collectors or little wind-mills simply won't do")

- *Back to entire US (lower 48): 3.7 Million km^2*
- $$\sqrt{\frac{3.7\times10^6\times10^6}{300\times10^6}} \approx 100\ m$$



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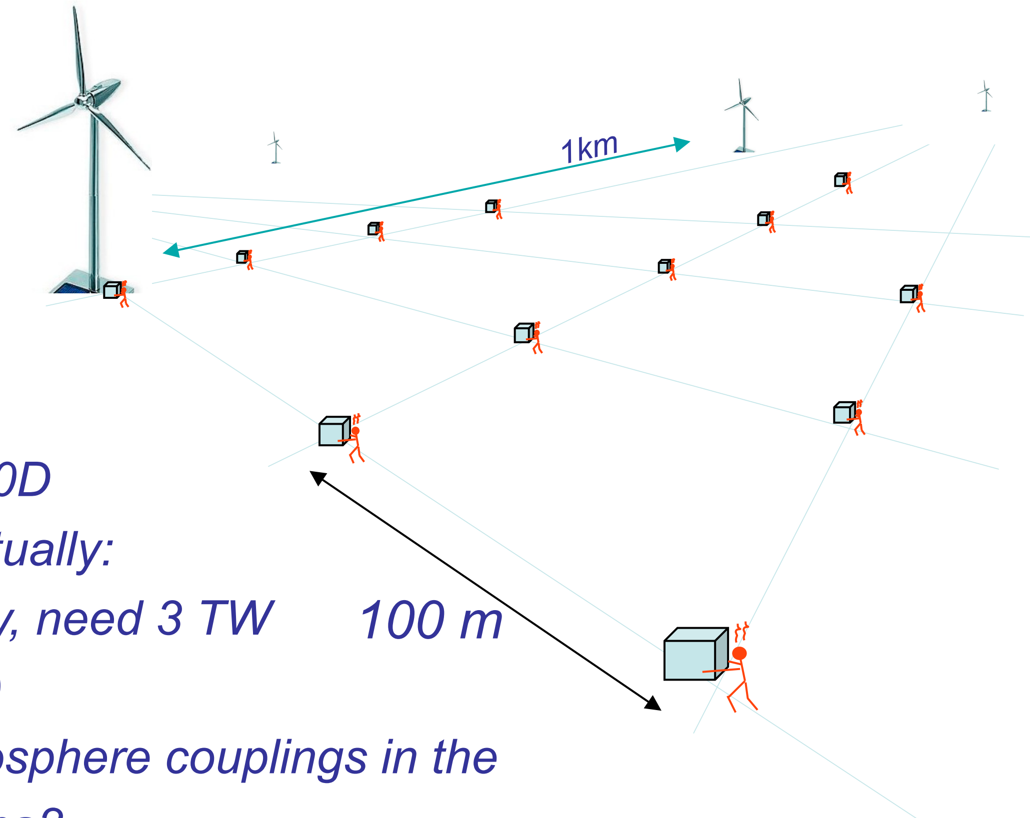


- *Need one 1MW WindTurbine for 100 people (100 x 10 kW)*
- *1 WindTurbine every 1km …. at 10D*
- *3 Million wind turbines (doable actually:*
  now US: 6 GW, av. power capacity, need 3 TW
  factor 500 = 2^9 - 9x3 = 27 years)
- *What can we say about land-atmosphere couplings in the presence of **very large wind farms**?*

The windturbine-array boundary layer (WTABL)

Horns Rev 1 owned by Vattenfall.
Photographer Christian Steiness

Arrays are getting bigger: when L > 10-20 H (H: height of ABL), approach “fully developed” FD-WTABL

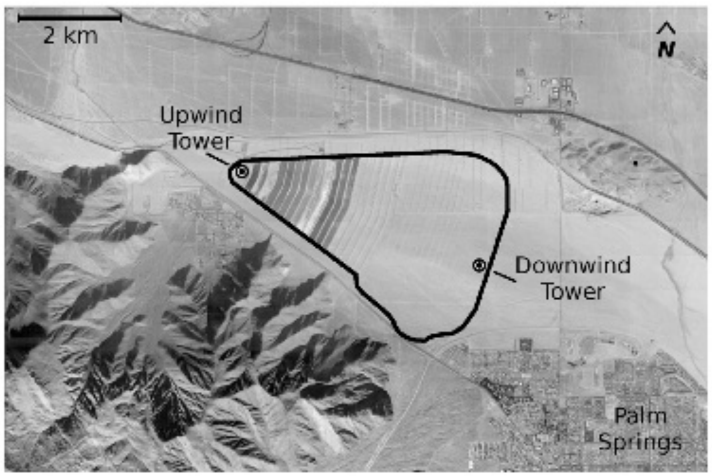
Effects of large wind farms on scalar fluxes: Heat and moisture

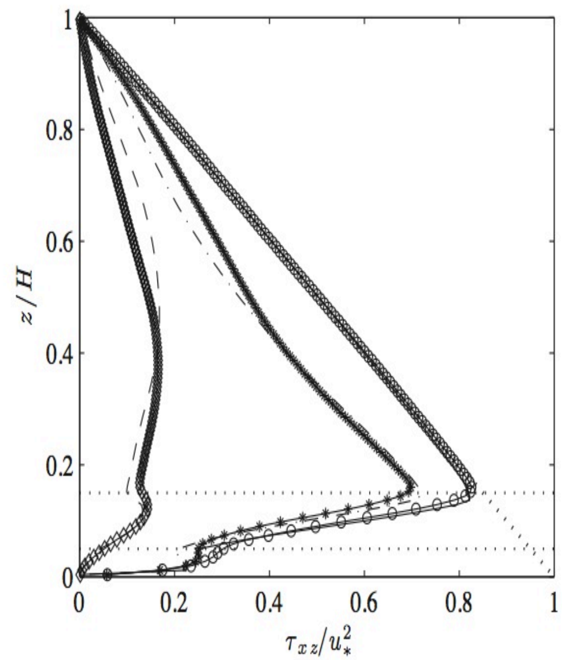
Observations: increased fluxes

(evaporation, drying, ??)

Baidya-Roy & Traiteur PNAS 2010

in San Gorgonio wind farm (CA)





But: Farm increases turbulence in wakes and $u_{*,hi}$ is increased, but $u_{*,lo}$ is DECREASED. Net effect?

Following in Brutsaert's footsteps (via Marc)

- We need to develop "macroscopic" understandings of such ABL's (WTABL), such as:
    - Effective roughness length z_0 for wind farms?
    - Universal structure of flow (stability corrections for velocity and scalars such as latent and sensible heat)
- Scalar transport in WTABL – increased or decreased fluxes?

Physics-based parameterizations for earth-system science

J. Atmos. Sci 1975

2028 JOURNAL OF THE ATMOSPHERIC SCIENCES VOLUME 32

The Roughness Length for Water Vapor, Sensible Heat, and Other Scalars

WILFRIED BRUTSAERT

College of Engineering, Cornell University, Ithaca, N. Y. 14853

12 August 1974 and 1 May 1975

ABSTRACT

An expression is presented for the roughness length of water vapor (or sensible heat, etc.) that is the surface value intercept of the straight line resulting from a semi-logarithmic plot of the mean specific humidity (or potential temperature, etc.) profile in the dynamic sublayer. The derivation is based on the standard assumption of continuity in the mean profile at the interface between the interfacial transfer sublayer and the fully turbulent surface sublayer. It is found that the resulting formulation yields similar results for a number of empirical and theoretical equations for the interfacial transfer that are available in the literature. The roughness length of any scalar admixture depends not only on the nature of the surface but also on the intensity of the surface shear stress and on the molecular diffusivity and the viscosity. In meteorological applications under rough flow conditions this roughness length may be considerably smaller than the aerodynamic roughness length z_0, whereas under smooth flow conditions it is usually somewhat larger.

The roughness length z_0 is a convenient measure of the hydrodynamic properties of natural surfaces. It may be defined as the fictitious level where the logarithmic wind velocity profile becomes zero when it is extrapolated down outside its actual range of validity.

In view of the analogy which may often be assumed to exist between the turbulent transfer of momentum and that of any other passive or inert admixture of the flow, it is very tempting to use this momentum roughness z_0 also to characterize the surface as regards its water vapor and heat transfer characteristics. Thus under this assumption the roughness length would also be the height where the specific humidity q defined by

$$(q_s - q_r) = \frac{E}{k u_* \rho}[\Phi_v(z_r/L) - a_v^{-1} \ln(z_{0v}/L)], \quad (1)$$

where q is the specific humidity of the air and E the rate of evaporation at ground level ($z=0$); k von Kármán's constant; $u_* = (\tau_0/\rho)^{\frac{1}{2}}$ the friction velocity; τ_0 the shear stress at $z=0$; ρ the density of the air; and a_v^{-1} represents a turbulent Schmidt (or Prandtl) number for neutral conditions, or the ratio of the eddy viscosity and the eddy diffusivity under neutral conditions; the subscripts s and r refer to the surface $z=0$ and to a reference level $z=z_r$ within the surface sublayer, respectively. The function $\Phi_v = \Phi_v(z_r/L)$ is

Physics-based parameterizations for earth-system science

GEOPHYSICAL RESEARCH LETTERS, VOL. 19, NO. 5, PAGES 469-472, MARCH 3, 1992

STABILITY CORRECTION FUNCTIONS FOR THE MEAN WIND SPEED AND TEMPERATURE IN THE UNSTABLE SURFACE LAYER

Wilfried Brutsaert
Cornell University, Ithaca, NY

Abstract. In accordance with a theoretical analysis by Kader and Yaglom, interpolation expressions are proposed for the Monin-Obukhov functions for the wind speed and temperature profiles under unstable conditions in the surface layer of the atmospheric boundary layer. The values of the parameters are adjusted to agree with earlier work under weak instability, as reviewed by Högström. The resulting formulations are valid for considerably larger values of their argument than those that were hitherto available. Their advantage is that they yield concise and closed-form stability correction functions which can be readily applied in profile analysis and model calculations.

Introduction

In the turbulent surface layer above a uniform surface, the gradients of the mean wind speed V and of the mean potential temperature θ can be described well by similarity expressions proposed by Monin and Obukhov [1954]; these can be written in common notation as

$$\frac{dV}{dz} = \frac{u_*}{k(z-d)}\,\phi_m(y)\,,\quad \frac{d\theta}{dz} = -\frac{T_*}{k_h(z-d)}\,\phi_h(y) \qquad (1)$$

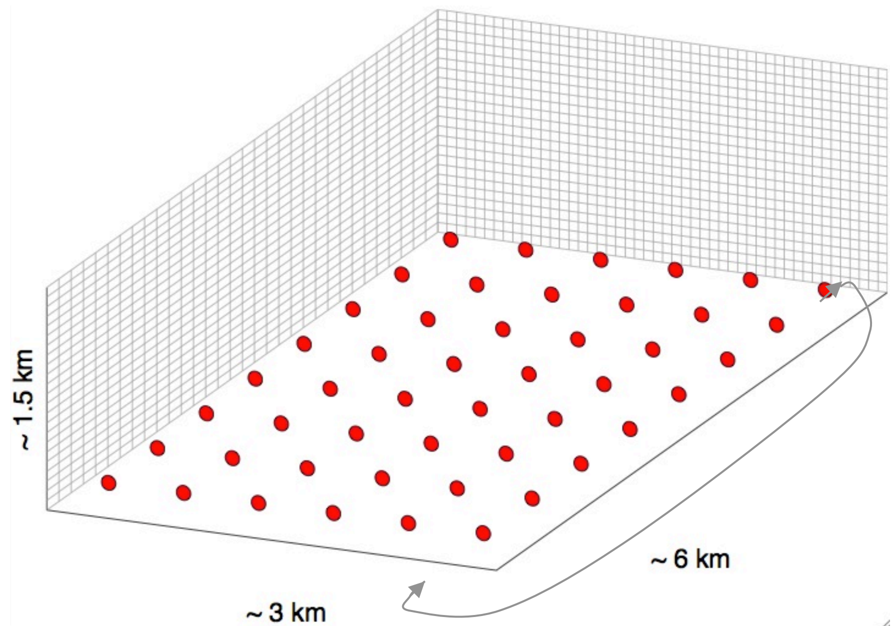
Over the past several decades many studies have been devoted to the determination of these presumably universal ϕ functions; because (1) are based on similarity considerations, most of this work was necessarily of an experimental nature. At the end of the eighties there appeared to be a broad consensus that the Businger-Dyer formulation [e.g. Dyer, 1974; Businger, 1988], albeit in a number of different but kindred versions [e.g. Högström, 1988], gave a good description of the available experimental data, and that it would be adequate for most purposes of analysis and model calculations. Subsequently, however, in a remarkable study Kader and Yaglom [1990] have reopened the issue of the proper similarity formulation of turbulence in the unstable surface layer. Through a reinterpretation of an earlier theory of Zilitinkevich [1971] and of Betchov and Yaglom [1971], and through a new analysis of available data, they provided strong evidence for the existence of 3 sublayers in the surface layer; these are a dynamic layer for $0<y\leq 0.04$, a dynamic-convective layer for $0.1\leq y\leq 1$, approximately, and a free convection layer for $y\geq 2$, approximately. For each of these sublayers they derived the functional dependency of both ϕ_m and ϕ_h on y (beside those for higher-order statistics). A novel feature of the results of Kader and Yaglom [1990] is the non-monotonic behavior of ϕ (y); for small y in the dynamic-

Generating data using Large Eddy Simulations (LES)

• LES code: horizontal pseudo-spectral (periodic B.C.), vertical: centered 2nd order FD. First version of LES code developed to study Brutsaert model of blending heights over patches by Albertson & Parlange 1999, - then Porté-Agel et al. 2000, Bou-Zeid et al. 2005, etc.

$H = 1000 - 1500m, \quad L_x = \pi H - 2\pi H, \quad L_y =$

$(N_x \times N_y \times N_z) = 128 \times 128 \times 128$



• Horizontal periodic boundary conditions (only good for FD-WTABL)

• Top surface: zero stress, zero w

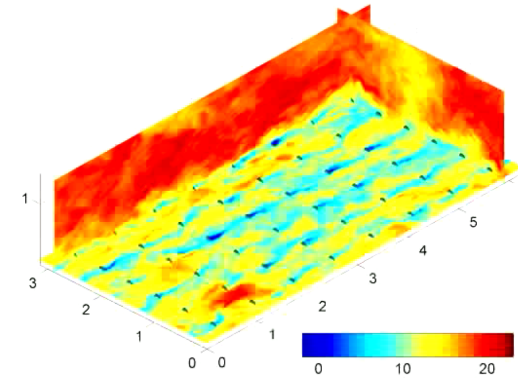
• Bottom surface B.C.: Zero w + Wall stress: Standard wall function relating wall stress to first grid-point velocity

• Scale-dependent dynamic Lagrangian model - eddy-viscosity closure but (no adjustable parameters)

• More details: Calaf, Meneveau & Meyers, “Large eddy simulation study of fully developed wind-turbine array boundary layers” Phys. Fluids. **22** (2010) 015110

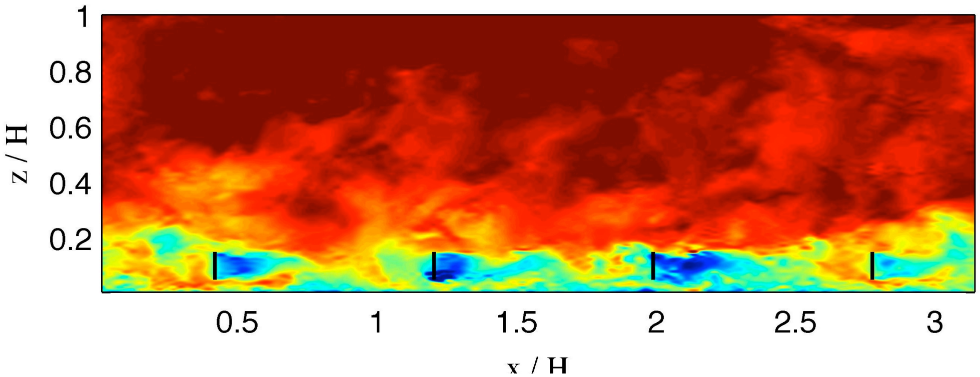
Suite of LES cases,

see Calaf et al. 2010, Phys. Fluids

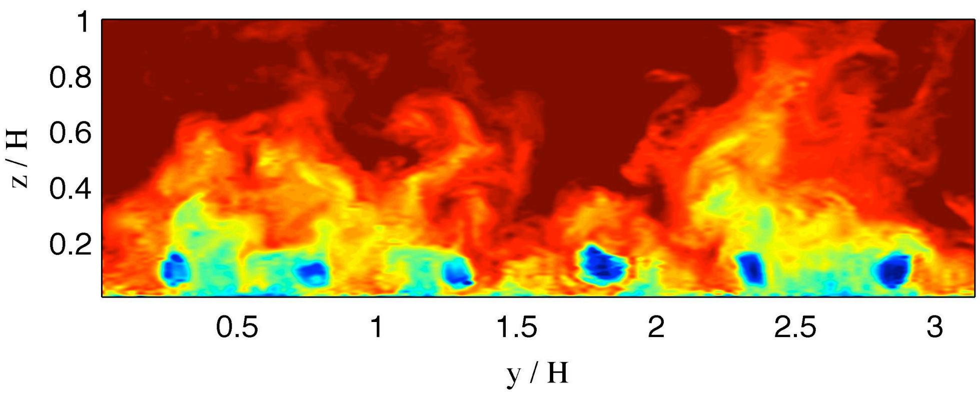


Instantaneous stream-wise velocity contours:

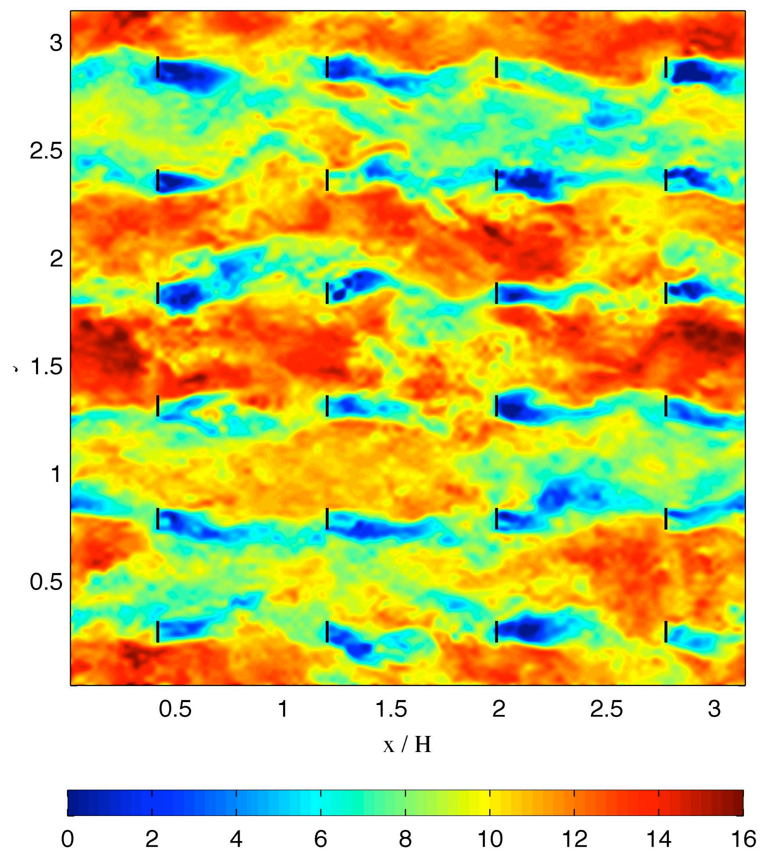
side-view



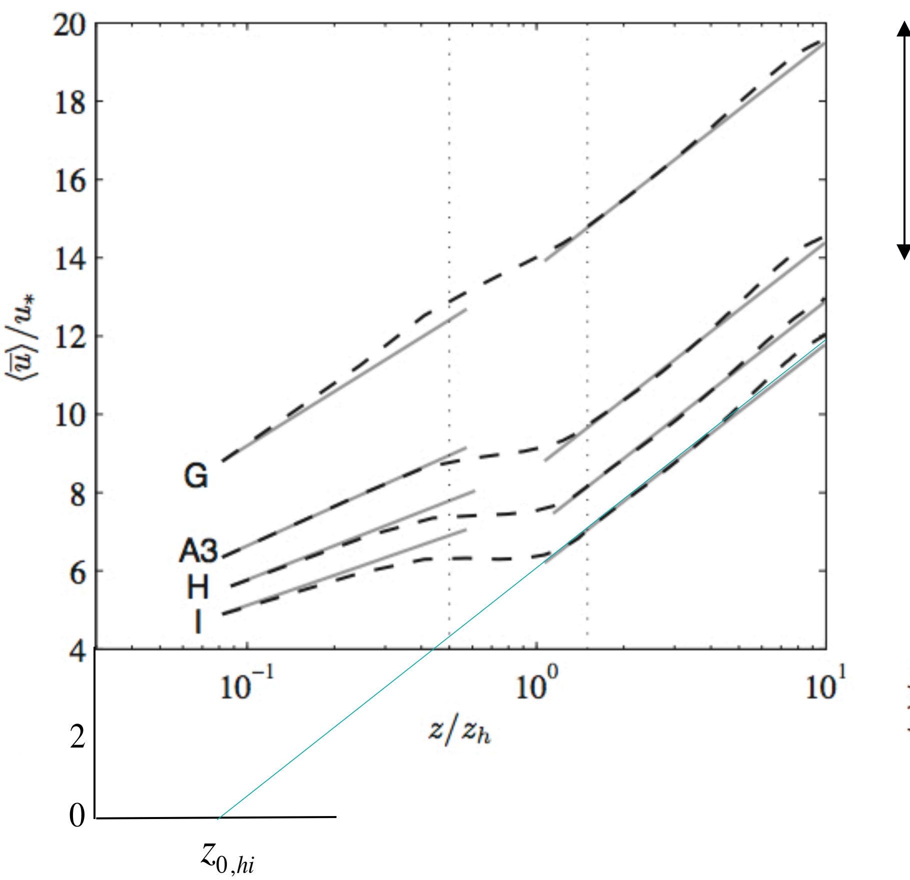
front-view



top-view



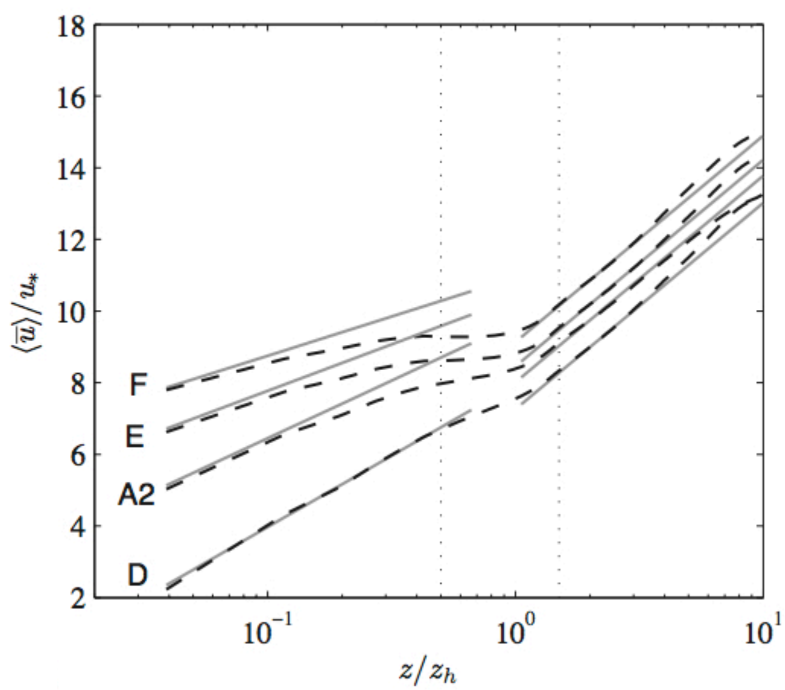
2 Log-laws! And measuring z_0 from LES (horizontally averaged)



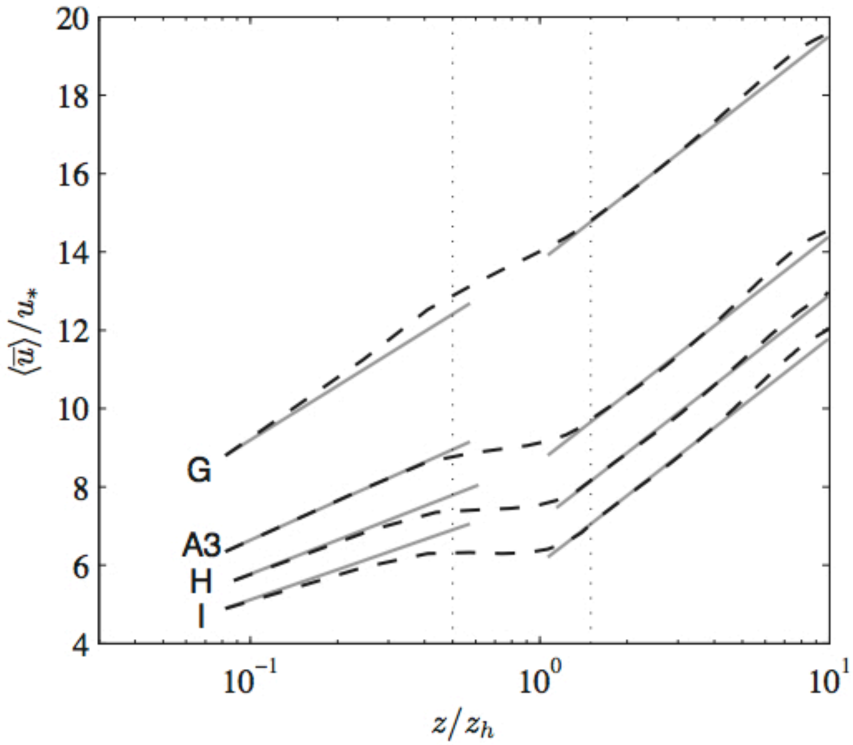
measure $z_{0,hi}$ from intercept

$$\langle \overline{u} \rangle_{xy} = u_{*\,hi} \frac{1}{\kappa} \log\left(\frac{z}{z_{0,hi}} \right)$$

(essentially the "Clauser plot" method)



"Effective roughness model" *(update to Frandsen, 1992, 2006)*



$$\left(\kappa u_* z_h + \nu_w\right)\frac{\partial\langle\overline{u}\rangle}{\partial z} = u_*^2$$

In wake, reduced slope:

$$\frac{\partial\langle\overline{u}\rangle}{\partial z} = \frac{1}{\kappa u_* z_h + \nu_w}u_*^2$$

$$\nu_w = \sqrt{\tfrac{1}{2}c_{ft}}\,\langle\overline{u}\rangle D$$

$$\nu_w^* = \frac{\sqrt{\tfrac{1}{2}c_{ft}}\,\langle\overline{u}(z_h)\rangle D}{\kappa u_* z_h} \approx 28\sqrt{\tfrac{1}{2}c_{ft}}$$

$$z_{0,hi} = z_h\left(1+\frac{D}{2z_h}\right)^{\beta}\exp\left(-\left[\frac{\pi C_T}{8\kappa^2 s_x s_y} + \left(\ln\left[\frac{z_h}{z_{0,ground}}\left(1-\frac{D}{2z_h}\right)^{\beta}\right]\right)^{-2}\right]^{-1/2}\right)$$

where $\beta = \dfrac{28\sqrt{\tfrac{1}{2}c_{ft}}}{1+28\sqrt{\tfrac{1}{2}c_{ft}}}$,

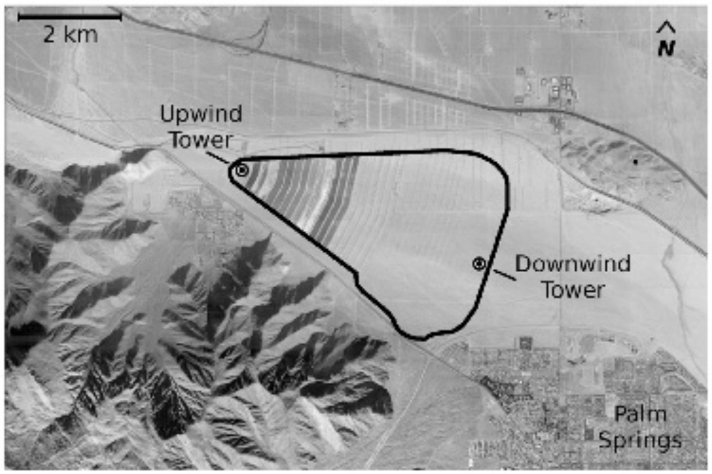
Effects of large wind farms on scalar fluxes: Heat and moisture

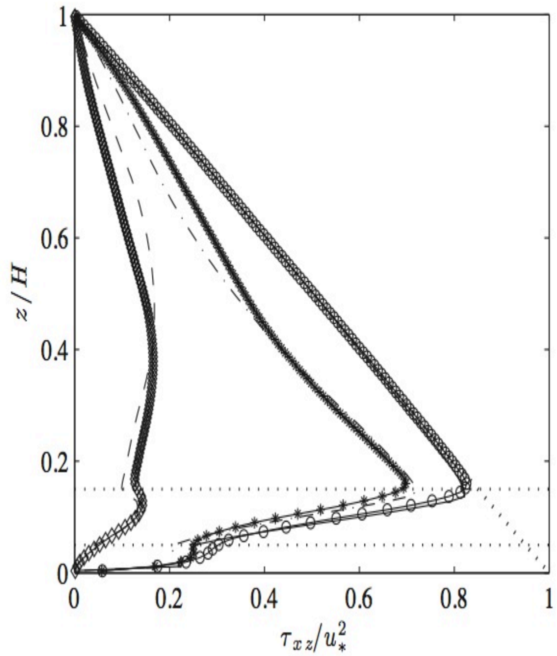
Observations: increased fluxes

(evaporation, drying, ??)

Baidya-Roy & Traiteur PNAS 2010

in San Gorgonio wind farm (CA)





But: Farm increases turbulence in wakes and $u_{*,hi}$ is increased, but $u_{*,lo}$ is DECREASED. Net effect?

First step: Passive scalar LES - NEUTRAL
(no Boussinesq term in momentum equations)
(M. Calaf, Parlange & M, Physics of Fluids December 2011)

Velocity (hub-height)

Temperature

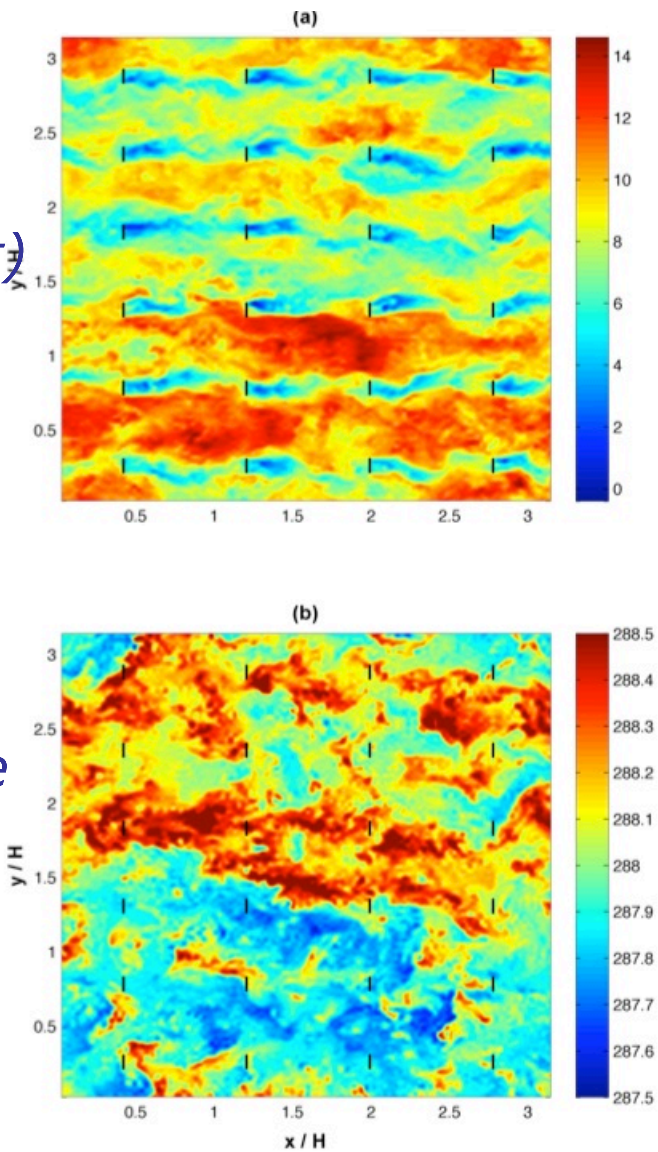
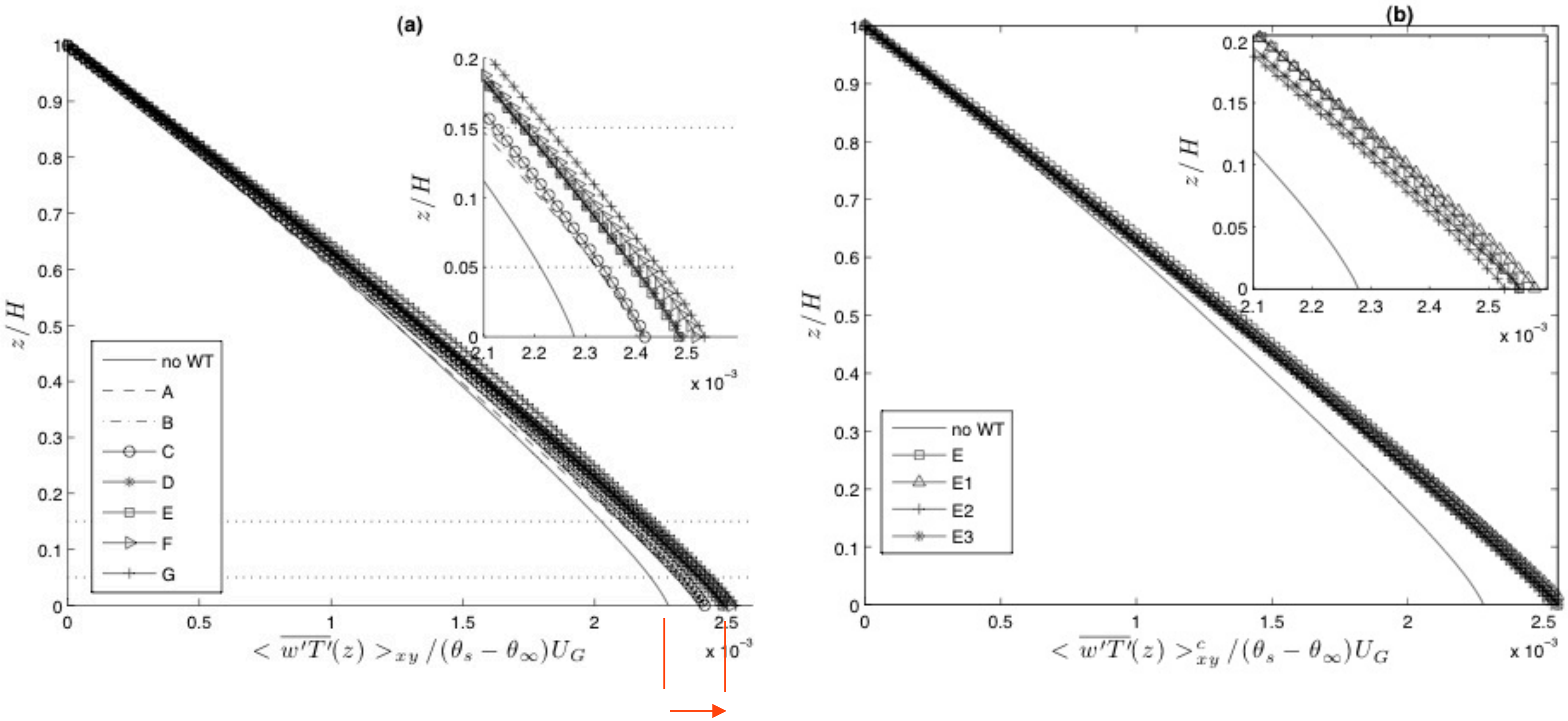


TABLE I: Table summarizing parameters of the various LES cases.

	s_x	s_y	$4s_xs_y/\pi$	N_t	C_T	C'_T	c_{ft}	c'_{ft}
A	7.85	$s_x/1.5$	52.3	4×6	0.45	0.6	0.009	0.011
B	7.85	$s_x/1.5$	52.3	4×6	0.52	0.7	0.01	0.013
C	7.85	$s_x/1.5$	52.3	4×6	0.6	0.88	0.012	0.017
D	7.85	$s_x/1.5$	52.3	4×6	0.68	1.13	0.013	0.022
E	7.85	$s_x/1.5$	52.3	4×6	0.75	1.33	0.014	0.025
F	7.85	$s_x/1.5$	52.3	4×6	0.82	1.63	0.016	0.031
G	7.85	$s_x/1.5$	52.3	4×6	0.88	2	0.017	0.038
$E1$	7.85/2	7.85/1.5	26.15	8×6	0.75	1.33	0.029	0.051
$E2$	7.85	$s_x/3$	26.15	4×12	0.75	1.33	0.029	0.051
$E3$	7.85/2	$s_x/1.5$	13.1	8×12	0.75	1.33	0.057	0.1

Horizontally averaged scalar flux from LES



10-15% increase, not strongly dependent on loading

Horizontally averaged scalar balance: constant flux

$$q_H^{WT} = \begin{cases} \frac{u_{*,lo}\kappa z}{Pr_T^{WT}} \frac{d[\theta_s - \tilde{\theta(z)}]}{dz} & (z_{0,s} < \mathrm{z} < z_h\text{-D}/2) \\ \frac{(u_{*,lo}\kappa z + \sqrt{c_{ft}/2}\langle\tilde{\mathrm{u}}(z_h)\rangle D)}{Pr_T^{WT}} \frac{d[\theta_s - \tilde{\theta(z)}]}{dz} & (z_h - D/2 < \mathrm{z} < z_h) \\ \frac{(u_{*,hi}\kappa z + \sqrt{c_{ft}/2}\langle\tilde{\mathrm{u}}(z_h)\rangle D)}{Pr_T^{WT}} \frac{d[\theta_s - \tilde{\theta(z)}]}{dz} & (z_h < \mathrm{z} < z_h + D/2) \\ \frac{u_{*,hi}\kappa z}{Pr_T^{WT}} \frac{d[\theta_s - \tilde{\theta(z)}]}{dz} & (z_h + D/2 < \mathrm{z} < H) \end{cases}$$

Horizontally averaged scalar balance: constant flux

For imposed geostrophic wind,
ratio of scalar flux with and without wind farm

$$\frac{q_s^{WT}}{q_s^0} = \underbrace{\frac{u_{*hi}}{u_*}\frac{Pr_T^0}{Pr_T^{WT}}}_{\text{Term 1}} \underbrace{\frac{\ln\left(\frac{u_{*hi}}{fz_{0,s}}\right)-\kappa C+\frac{u_{*hi}}{u_{*lo}}\ln\left[\frac{z_h}{z_{0,s}}\left(1-\frac{D}{2z_h}\right)^{\beta}\right]-\ln\left[\frac{z_h}{z_{0,s}}\left(1+\frac{D}{2z_h}\right)^{\beta}\right]}{\ln\left(\frac{u_*}{fz_{0,s}}\right)-\kappa C}}_{\text{Term 2}}$$

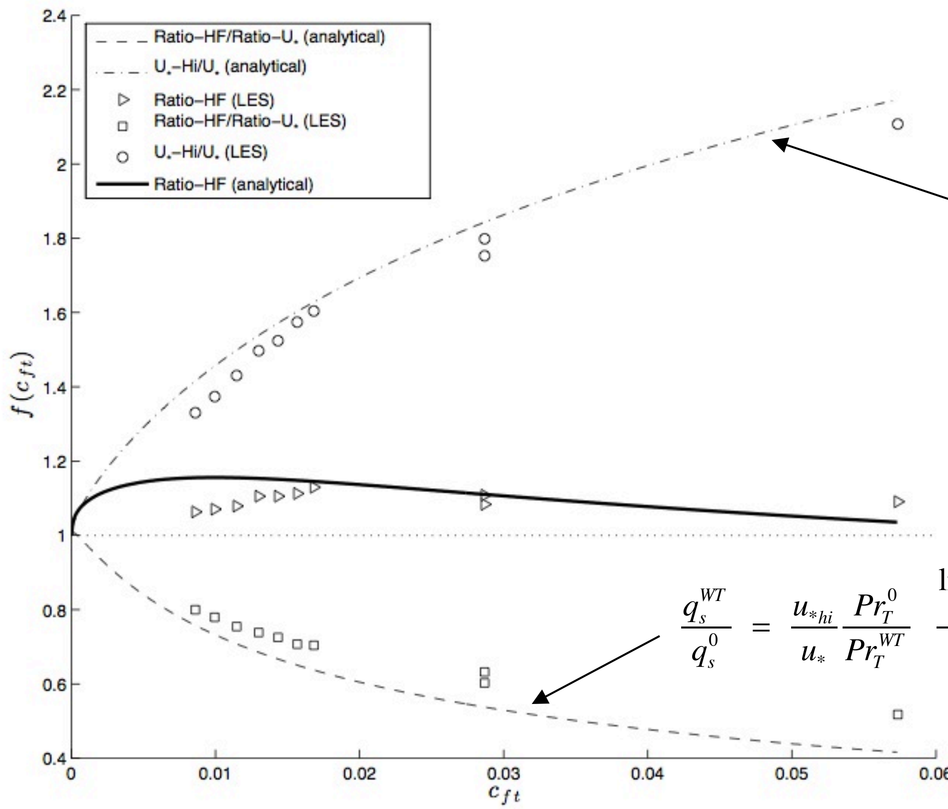
Term 1: increase due to increased turbulence in wake

Term 2: decrease due to "dead water region" below WT

$$\frac{u_{*hi}}{u_*} = \left[1-\frac{\ln\left(\frac{z_{0,hi}}{z_{0,lo}}\right)}{\ln\left(\frac{U_G}{fz_{0,lo}}\right)-C_*}\right]^{-1}$$

LES measured and model terms as function of loading
(neutral stratification)

For imposed geostrophic wind,
ratio of scalar flux with and without wind farm (symbols=LES)



$$\frac{u_{*hi}}{u_*} = \left[1 - \frac{\ln\left(\frac{z_{0,hi}}{z_{0,lo}}\right)}{\ln\left(\frac{U_G}{f z_{0,lo}}\right) - C_*}\right]^{-1}$$

$$\frac{q_s^{WT}}{q_s^0} = \frac{u_{*hi}}{u_*}\frac{Pr_T^0}{Pr_T^{WT}}\;\frac{\ln\left(\frac{u_{*hi}}{fz_{0,s}}\right) - \kappa C + \frac{u_{*hi}}{u_{*lo}}\ln\left[\frac{z_h}{z_{0,s}}\left(1-\frac{D}{2z_h}\right)^{\beta}\right] - \ln\left[\frac{z_h}{z_{0,s}}\left(1+\frac{D}{2z_h}\right)^{\beta}\right]}{\ln\left(\frac{u_*}{fz_{0,s}}\right) - \kappa C}$$

10-15% increase now
"better understood"

Thank you for welcoming me to the family and best wishes to you both, and to Eileen and Toyoko!

Academic

Biological

CM

Collaborations on ABL turbulence LES, parameterizations

JHU PhD co-advised: Fernando Porte-Agel
Elie Bou-Zeid, Chad Higgins, Vijayant Kumar,
Jan Kleissl, Marcelo Chamecki, Marc Calaf (EPFL)