WRA in the ‘small wind’ regime

IEA Task 41 meeting:
Wind Resource Assessment and Obstacle Modelling

19 Feb. 2021

Mark Kelly, RAM section / DTU Wind Energy

WRA for ‘typical’ smaller turbines

(What was [not] addressed the first time around?)

- First generation of wind energy (~1970’s–80’s):
      » hub heights in the atmospheric surface layer
      » stall-regulation common
      » observations limited (though cheaper; more accessible?)
  – wind conditions
    - large velocity perturbations
      – nonlinear effects
      – ‘strange’ statistics: $P(u)$ form, directional dependence
    - bottom-up flow problem
      » many phenomena look like “turbulence”
    - measurement inadequacy
      – sample length
      – flow-distortion: instrument / externally
      – different turbulent environment than turbine

Task 41 research / end-user context

from 2020 research priorities survey

- [H] Standardize/open markets for WTG >55kW, >200 m^2
  - Increase upper limit for small/DW; adapt 61400-2 for this
    - Need data! → report data/validation?
- [H] Aeroelastic models & validation
- [H] Loads testing* & characterization: adapt 61400-13 for DW
- [H/M] Duration testing (USA)
- [M/H] turbulence prescription, characterization, classes*;
- [M] performance
- [M] tower dynamics/interaction
- [M] separate classification for micro-turbines

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Actual Power Curves
(reporting… c.f. -15)

WRA components for DW/SWT's…

WAsP-online/myWindTurbine.com :

- (small turbines)
- no extrapolation
- wind-atlas driven
- WAsP engine

WAsP-online: Uncertainty types/framework

Component	Input	Model: sensitivity	Model: representativity
Wind Atlas	(*.lib file)	Geostrophic Drag Law	GDL, *with* Wind Atlas
Orography	Map: $z(x,y)$	IB-z $(\partial z/\partial x)$	
Roughness	Map: $z_0(x,y)$	IBL(Δz_0) + horiz.extrapol'n(z_0)	
Obstacle	Missing? Location + dimensions	'model' = user input (+map?) + Pereira$(r,z,H,\ell\ldots)$	
Power Curve	$P(U)$ table	$P(U)$ + yaw error; Missing table	

DTU Wind Energy, Technical University of Denmark Mark Kelly, MET group Mar.2015

UQ for ‘simple, small’ wind turbines

Practical way from WAsP-online

Component	Estimate ($\delta U/U$)	Note
Wind Atlas input	$\sim (10\%) * f(z, \sigma_z)$	$2 \bullet RIX(\%) \frac{\Delta x}{90m}$
z map + flow-model	$f(\Delta x, \sigma_z) \sim f(\Delta x, RIX) \sim$	Flow-model unc.; complex terrain; can affect $dU(z_{0,bkd})$
z_0 map + model	$c_1 m_c(z/r_c)$	P(missing contour) m=Abs{ln($\Delta z_{02}/\Delta z_{01}$)} + bad $z_{0,land}$ at coastline
WindAtlas+GDL→Wasp	$\delta \ln z_0 * (z_0/z_{0,w})^p$	
Obstacle represent’n	$\propto P$(missed/bad)	Likely collapsable into Obst. model
Power Curve		Potential off-diagonals! (x-correl.’s)
Obstacle model	~ some % of Perera	Potential off-diagonals! (x-correl.’s)
User-entered thing…	…	…

Wind Energy, Technical University of Denmark | Mark Kelly, MET group | Feb-Mar.2015

UQ for ‘simple, small’ wind turbines

Practical way from WAsP-online

Uncertainty component	estimated form	worksheet form	p1	p2	p3	p4	p5	est.unc. in U
Wind atlas (.lib) input	$y\% + (x\%)\ \ln(1+RIX^* z_{ref}/z)$	$p_1 + p_2{}^*\ln(1+p_3{}^*p_5/p_4)$	5.0%	5.0%	5	21m.	10m.	11%
z map + flow-model	$c^*RIX(\%)^*Dx/dx0$	$p4^*p_1{}^*p_2/p_3$	5.0%	180	90	0.4		4%
z_0 map + model	$c^*\ \ln(z_0/z_{0w})(1-e^{-z/r})^*P\ (\text{coast})$	$p_5{}^*\ln(p_1/.0002)(1-e^{-p2/p3})^*p_4$	0.03	18m.	100m.	50%	0.20	8%
WindAtlas+GDL --> Wasp	$c\,(z_0/z_{0wr})^{0.3}\ [1+\delta z_0/z_0]^{0.3}$	$(p_1/.0002)^{0.3}\ {}^*[p_2]^{0.3}$	0.03	3				4%
Obstacle rep.+pos.+turb.pos.	...	p_1 %	5%					5%
Power Curve	...	p_1 %	10%					10%
Obstacle model	$c_1{}^*(\Delta U_{obs}/U_{obs})^*f(r/h,z/h)$	$p_1{}^*(p_2\%)^*[]$	0.3	6%				2%

Obstacle represent’n	$\propto P(\text{missed/bad})$	Likely collapsable into Obst. model
Power Curve		Potential off-diagonals! (x-correl.’s)
Obstacle model	~ some % of Perera	Potential off-diagonals! (x-correl.’s)
User-entered thing…	…	…

Wind Energy, Technical University of Denmark Mark Kelly, MET group Feb-Mar.2015

WRA for 'modern' (multi-MW) wind turbines

uncertainty context :

- 'easier' measurements
- more models
  - flow: 'more terrain seen'
  - horiz. extrapolation
  - vertical extrapolation
  - power curves!
  - long-term correction

WAsP sub-models (ALL of them)

Component	Inputs [x]	Parameters/choices [θ]
(Weibull fit)	U, ϕ timeseries	(Weibull-fit algorithm)
flow-model (IBZ)	z map	Map size [Δr], $\Delta\phi$, h_{inv}
Δz_0 (IBL) model	Δz_0 map: [m_i, r_i]	$\Delta\phi$, $c1_{IBL}$, $c2_{IBL}$, $n_{\Delta z0}$,
GDL	$z_0, f, U, \left[r, z, \sigma_z, z_{0,\mathrm{eff}}\right]\vert_1^2$, ...	A, B
Profile modeling	z, z_0,	$H_{\mathrm{off}}, H_{\mathrm{rms}}, A, B, dA/d\mu, dB/d\mu$
Power Curve	P, C_T, ρ (+TI, shear)	IPC adj.(z)...
Obstacle model	r_i , $\{\Delta r, \Delta\theta\}_i, por_i , h_i$	A_P, a_P, b_P (Pereira)
Park Wake model	U, z	R, D, C_T, k_{exp}
(Long-term correction)	$U, U_{LT.\mathrm{ref}}, [T_{obs}, T_{ref}, \sigma_{1yr}, R_{LT-obs}]$	Interpolation method; Reanalysis set

Wind Energy, Technical University of Denmark   Mark Kelly, RAM   Aug.-Nov.2016

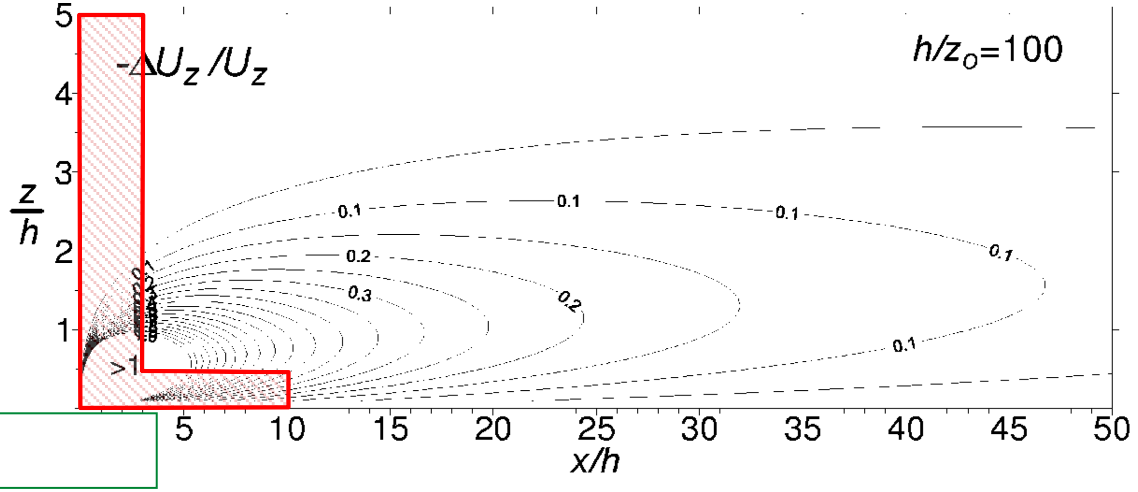
Obstacles…

Flow around bluff bodies is not easy, even for CFD

– In the ABL: multi-scale interaction, terrain, etc. make it harder !

- Belcher *et al* (1993): $F \sim \rho u_*^2 (h^2/L)(U_1/U_2)^4$
- Pereira formula: $\frac{\Delta U(z)}{U(h)} = -a(1-P)\frac{zh}{x^2}\eta' e^{-(\eta' z/x)^{3/2}}$; $\eta' \equiv 0.77 \left[\frac{\ln(h/z_0)}{2\kappa^2 (x/h)}\right]^{1/(\alpha+1)}$

– deviations from Pereira depends on many things…

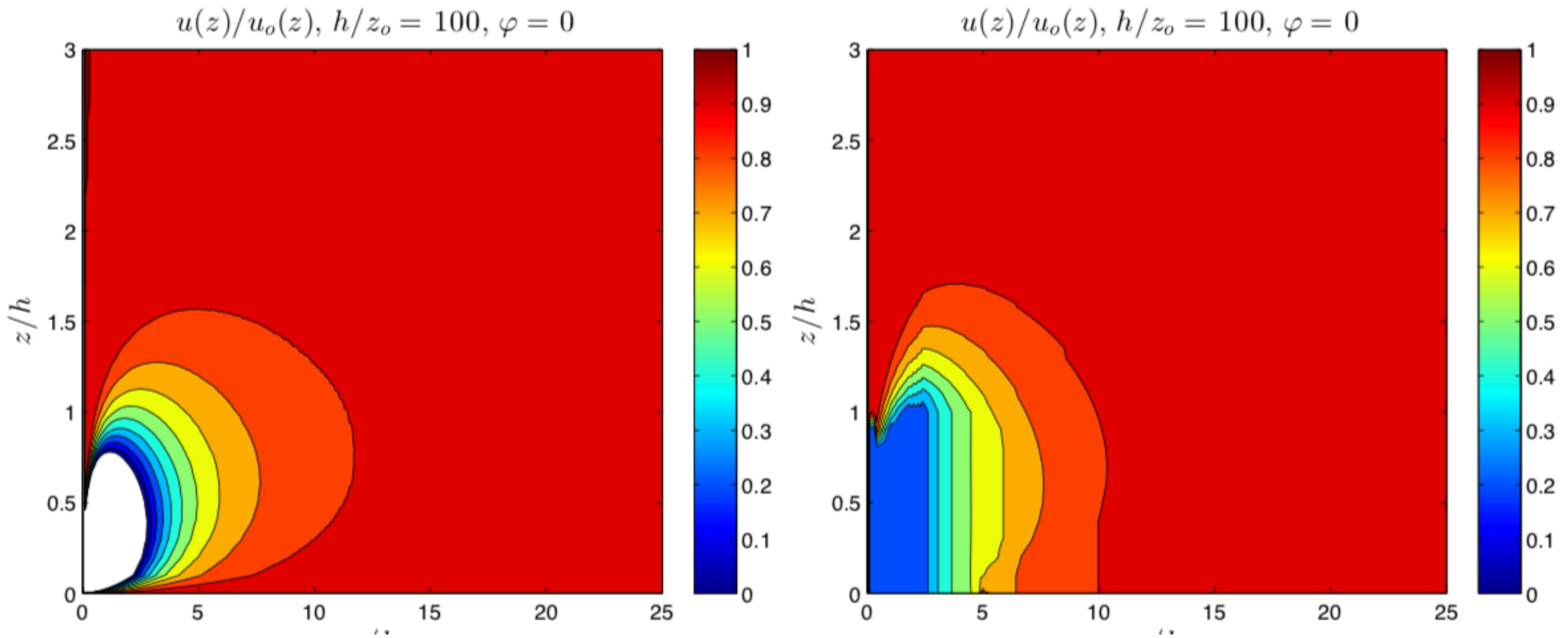


Obstacles…

- Modelling
  - Pereira parameterization long used (e.g. WAsP, AWS)
    - updated in 2015 based on lidar & fence experiment
  - Mass-consistent models also efficient
  - RANS used in WRA already, but…
    - more expensive for obstacles; boundary condition requirements
    - difficulty with steep faces; k-ε trouble with lengthscales
    - statistics problematic

Obstacles…

- Modelling : rectangular obstacle
  - Pereira parameterization long used (e.g. WAsP, AWS)



WEMOD ‘old’ WAsP

(Peña *et al.*, 2015)

Obstacles…

- Modelling : rectangular obstacle
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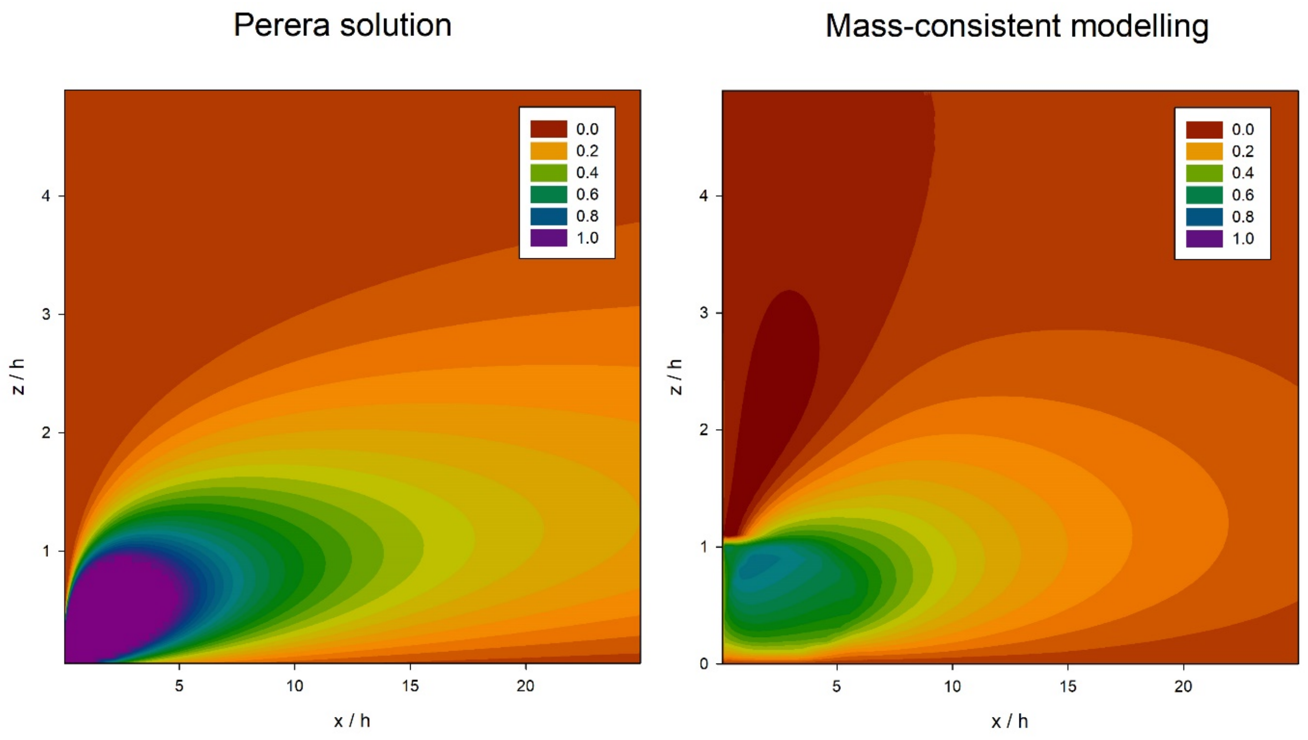
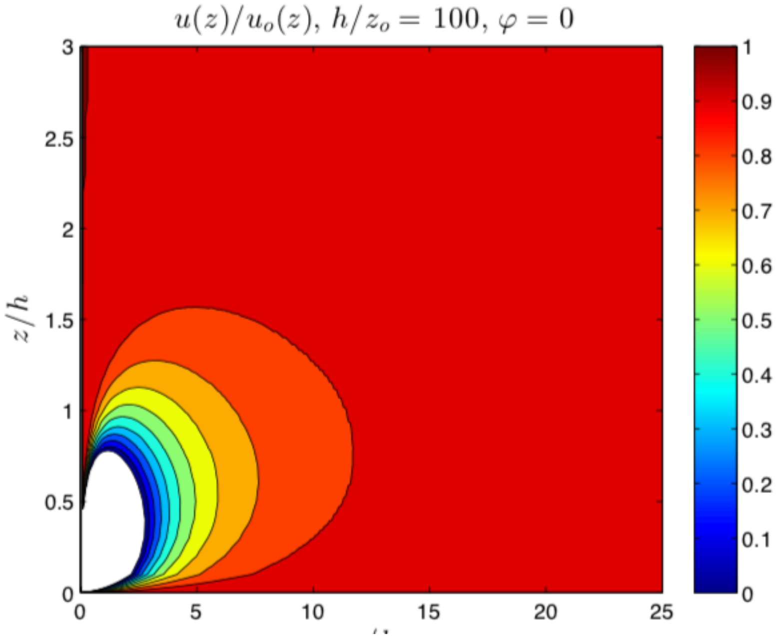


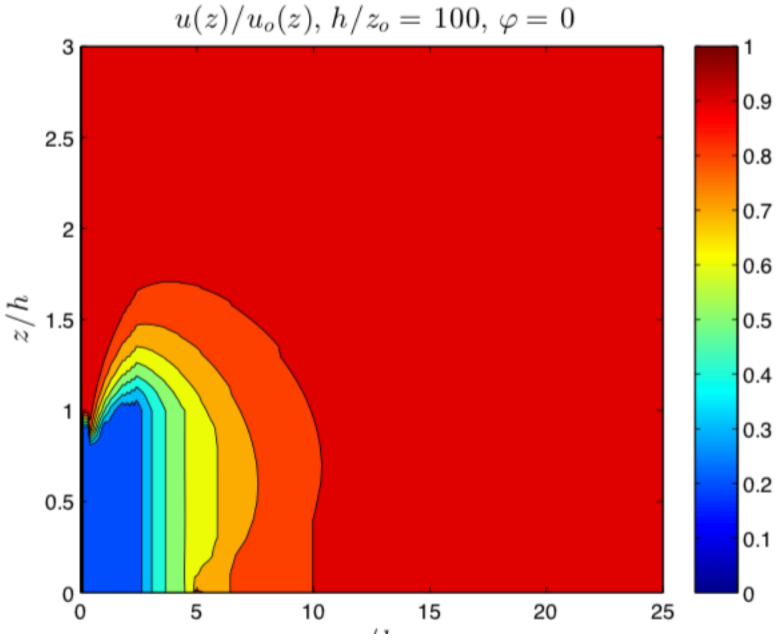
(Sogachev, 2020)

Obstacles…

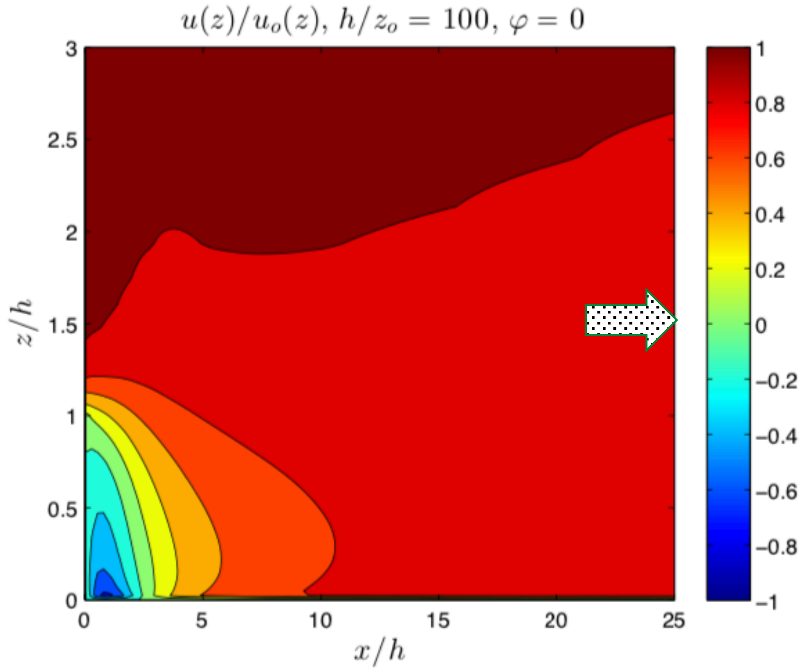
- Modelling : rectangular obstacle
  - Pereira parameterization long used (e.g. WAsP, AWS)
  - Mass-consistent models also efficient
  - RANS used in WRA already…



Pereira(WEMOD)



WAsP

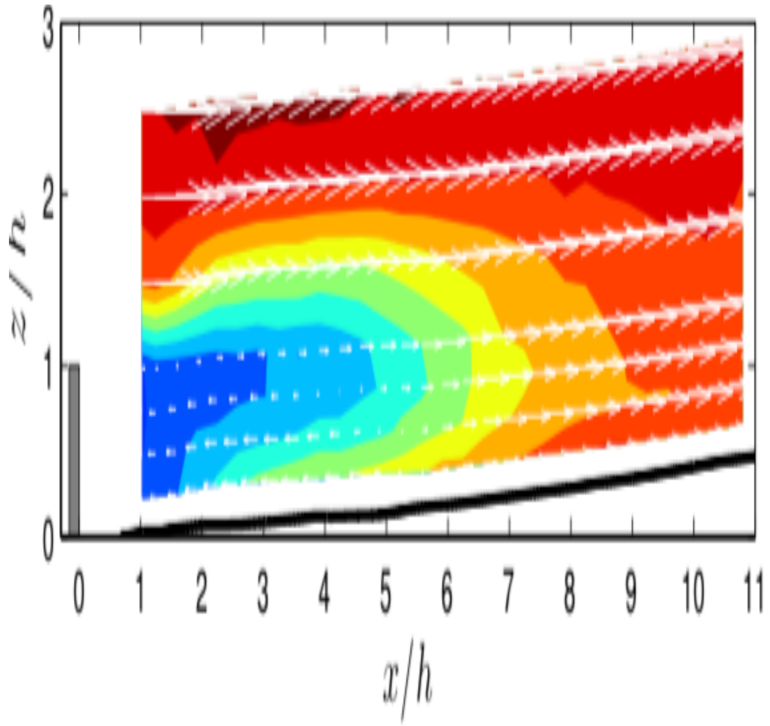


RANS

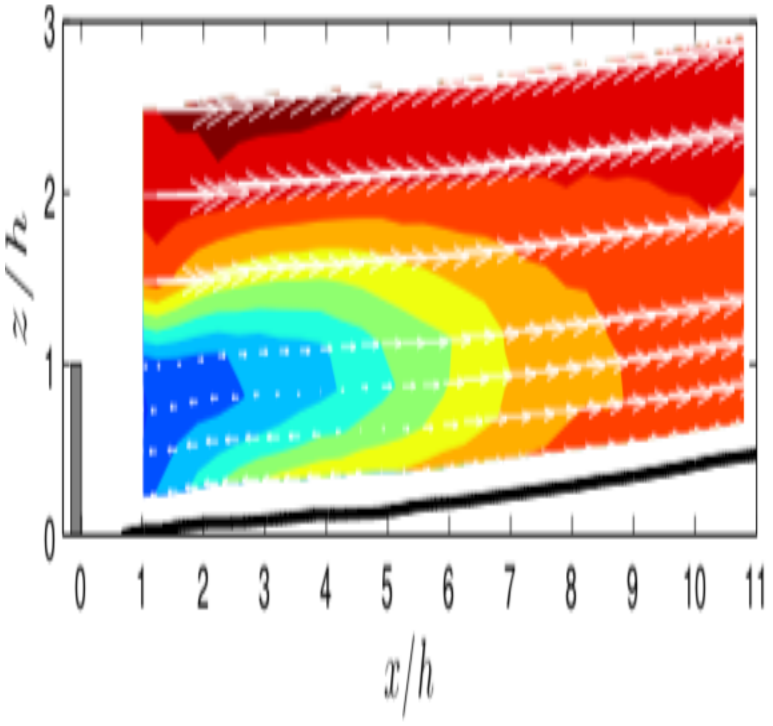
(Peña *et al.*, 2015)

Obstacles…

- Observation (lidar) : Risø 2014 **Fence** experiment
  - neutral conditions $\langle z/L\rangle \simeq 0.015$ $\langle z/L\rangle \simeq 0.021$



–15°≤ φ ≤15°, $\langle\varphi\rangle$~5°

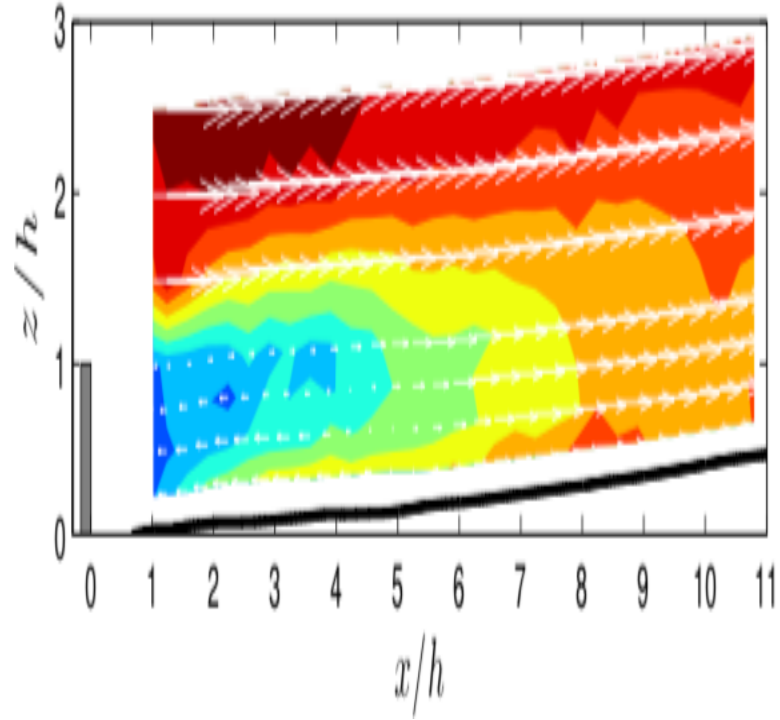


–30°≤ φ ≤30°, $\langle\varphi\rangle \approx -1°$

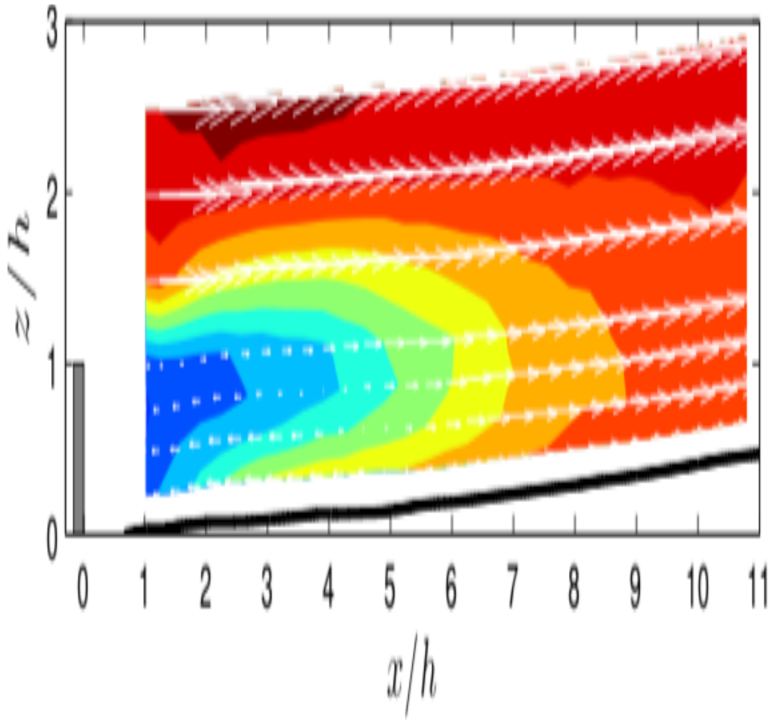
  - s

Obstacles…

- Observation (lidar) : Risø 2014 Fence experiment
  - bit stable $\langle z/L \rangle \simeq 0.044$ more neutral $\langle z/L \rangle \simeq 0.021$



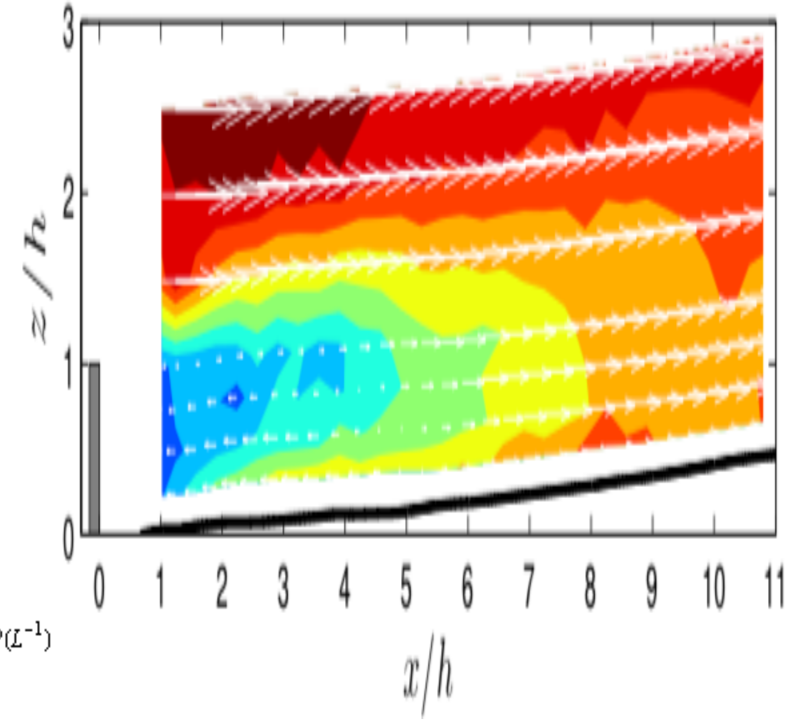
–30°≤ φ ≤30°, $\langle \varphi \rangle \approx -9°$ (bimodal)

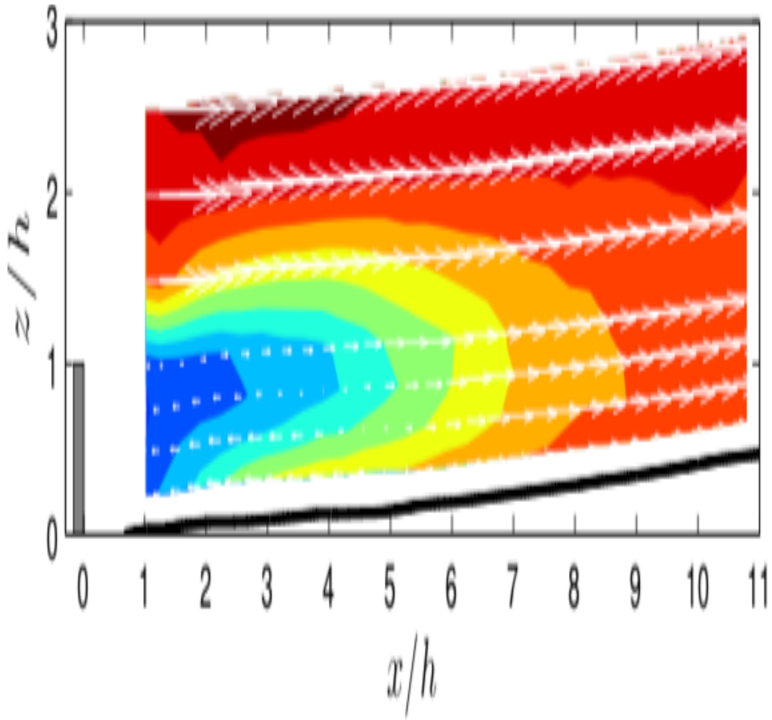


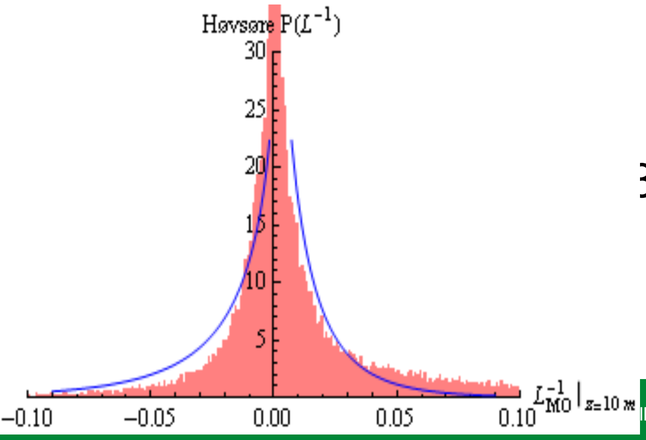
–30°≤ φ ≤30°, $\langle \varphi \rangle \approx -1°$

Obstacles…

- Observation (lidar) : Risø 2014 Fence experiment
  - bit stable $\langle 6\ \mathrm{m}/L \rangle \simeq 0.044$ more neutral $\langle z/L \rangle \simeq 0.021$







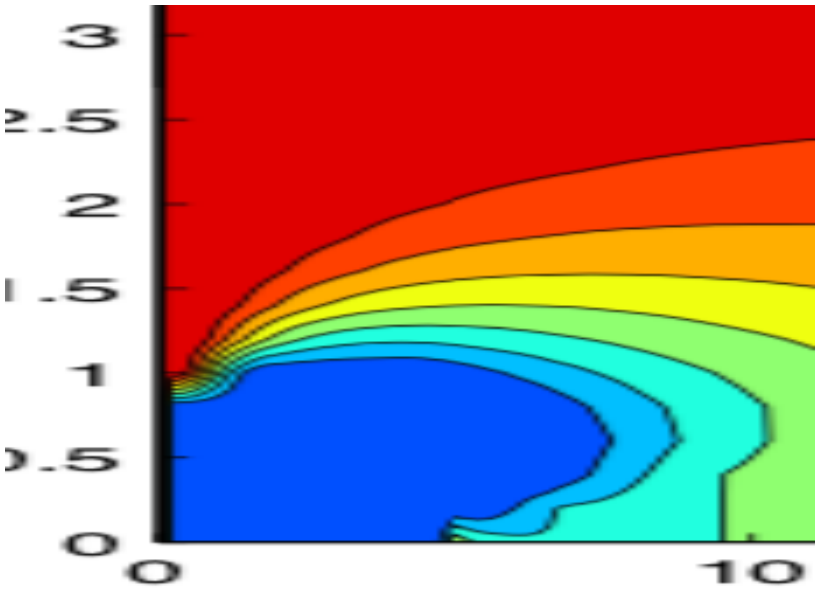
30°, $\langle \varphi \rangle \approx -9°$ (bimodal) –30°≤ φ ≤30°, $\langle \varphi \rangle \approx -1°$

height matters: for stability influence

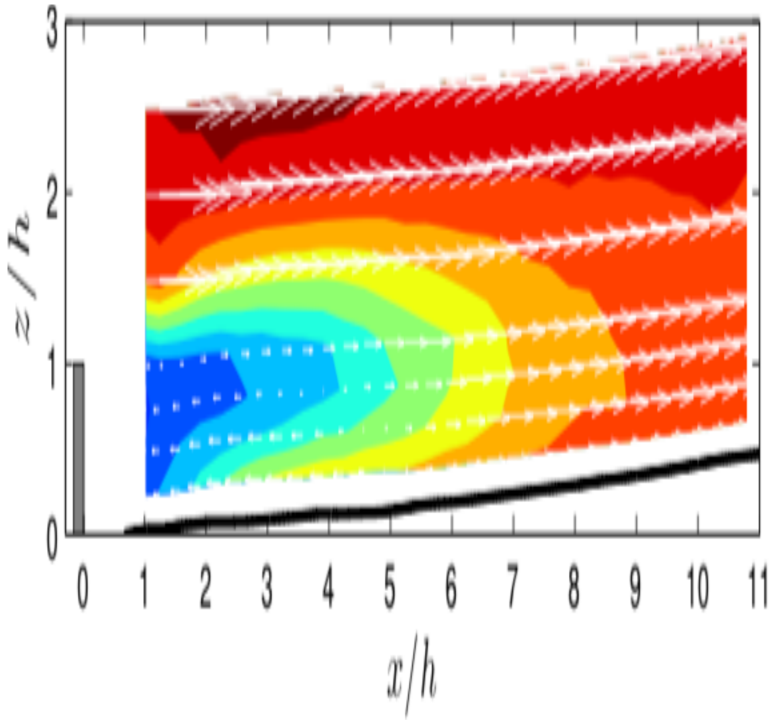
Obstacles…

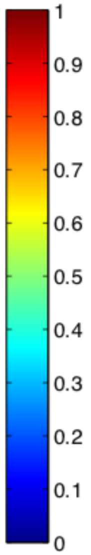
- Observation (lidar) : Risø 2014 Fence experiment
- Model (WAsP)

obs.: more neutral $\langle z/L\rangle \simeq 0.021$



φ =0°





–30°≤ φ ≤30°, $\langle\varphi\rangle \approx -1^\circ$

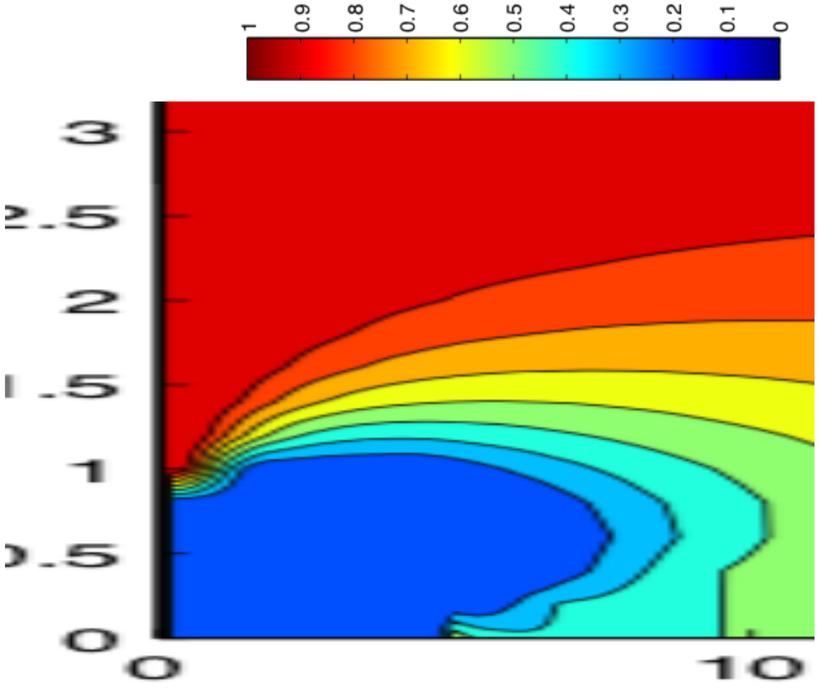
[same color scale: speedups from 0 to 1]

Obstacles…

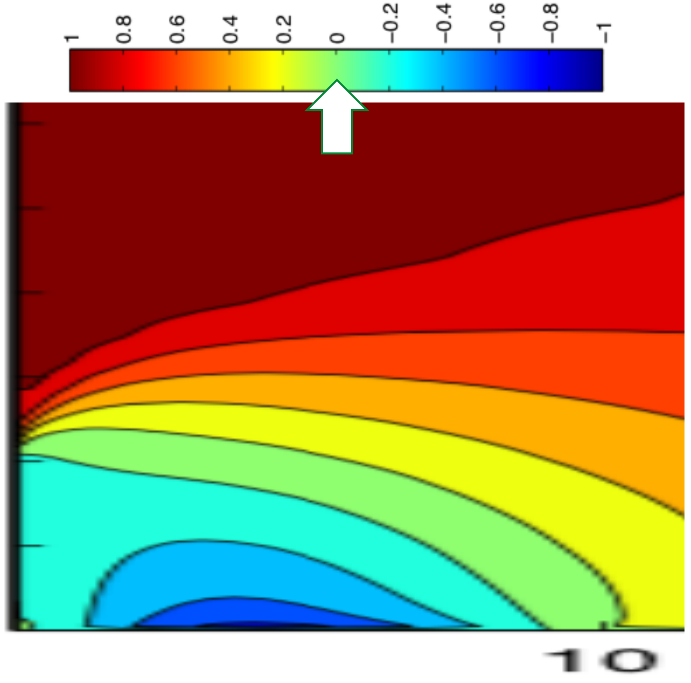
- Model vs. lidar observations: Risø Fence (2014)

[Peña *et al.* DTU E-0092 (2015), IEA Task 27]

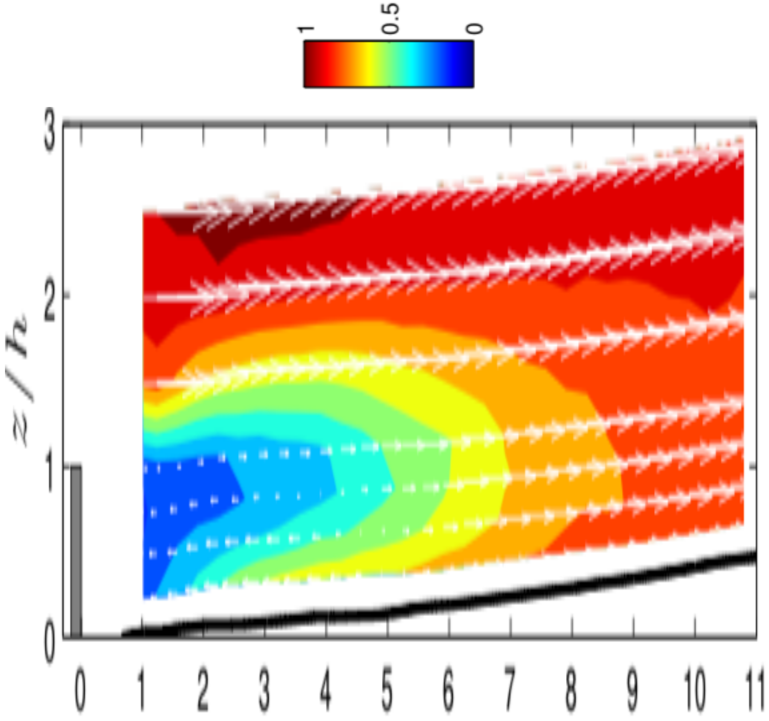
WAsP



RANS



obs.: ($\langle z/L \rangle \simeq 0.021$)



$\varphi = 0°$

$-30° \leq \varphi \leq 30°$, $\langle \varphi \rangle \approx -1°$

note different color scales: RANS has re-circulation!

Resource vs. site “assessment” in DW

- $\{I_u, \alpha\}$ due to surfaces → big effect on SWT performance
  - fatigue/lifetime also affected
  - usually single turbine (except μ-turbines)
  - rarely measured
  - obstacle models designed for mean speed/up
    - » not I_u, α
  - Missing Power curves in representative conditions
  - RANS has difficulty predicting *both* I_u and U in the ABL [Atmospheric Boundary Layer]

- Resource/site considerations ‘*mixed together*’ compared to conventional/MW wind
  - cost versus production
  - guidelines

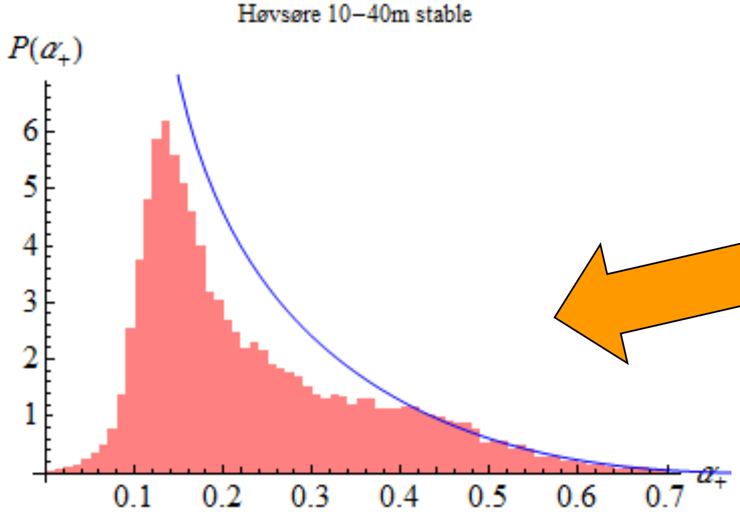
- We do have some guidance for simple terrain…

simple-terrain basis : statistical "help"

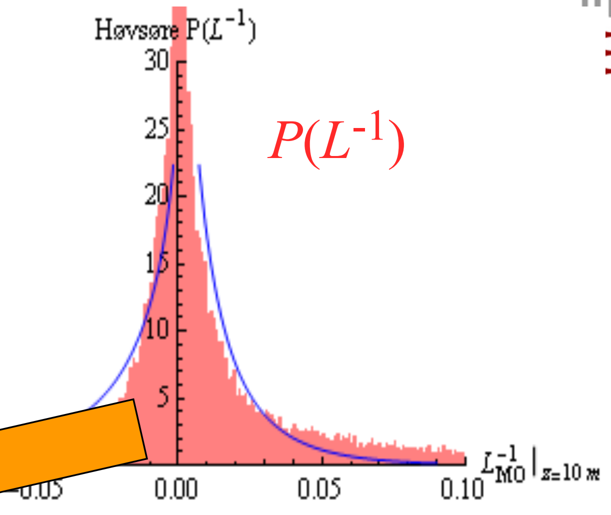
- example of shear exponent from stability

- $P(\alpha)$ is wide…
  – predictable

Stability and shear



ASL (10-40m)



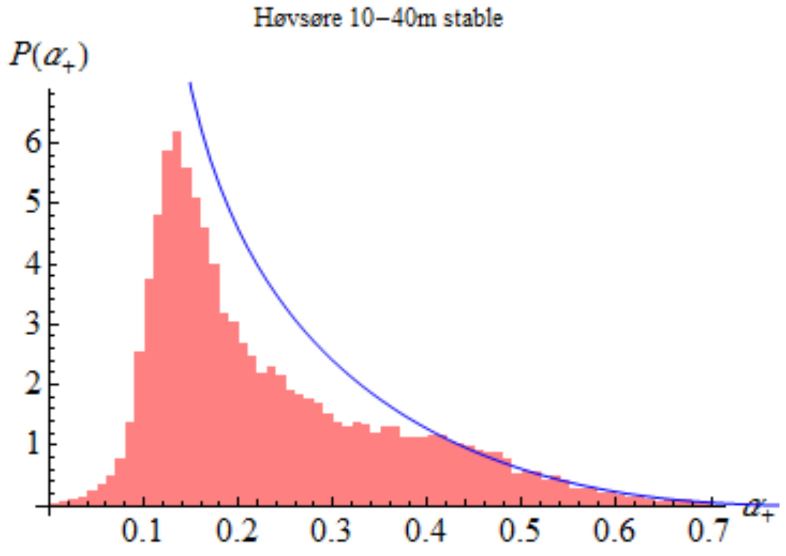
(Kelly et al., 2014)

$$P_+(\alpha_+) \approx P_+(L_+^{-1}) \frac{1+5zL_+^{-1}}{\alpha_+ 5z\,|1-\alpha_+|}$$

- Can map stability to shear in ASL

shear near ground…

- SWT "see" bigger α than multi-MW turbines
- old theory adaptable
  - (stability)
- obstacles disrupt



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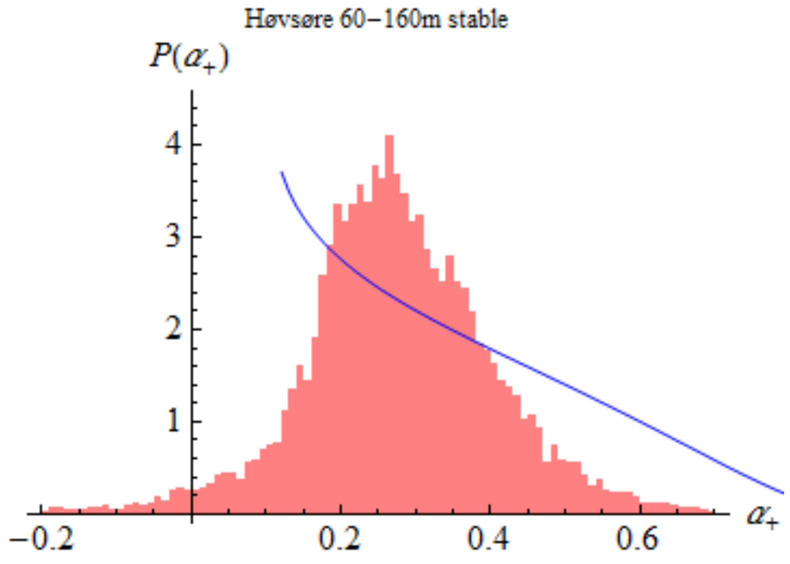


above ASL (60-160m)

- Can map stability to shear in ASL; **NOT** at current hub heights ☹ ...

(Kelly et al., 2014)

turbulence and wind ... assessment

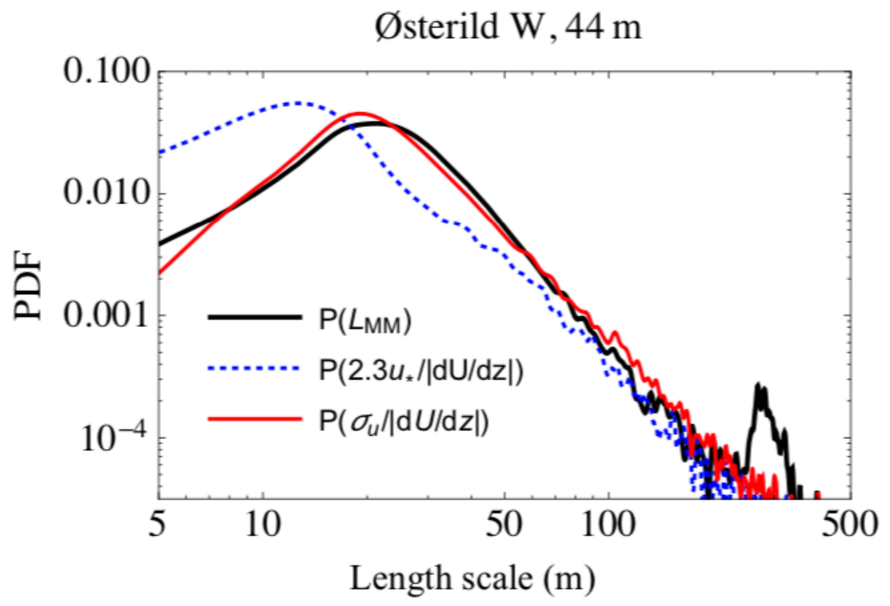
- Not “resource assessment” per se, but for SWT’s siting is somewhat mixed with WRA
  - turbulence affects power curve
  - turbulence → lifetime changes → total yield differs

- Length scales affected by obstacles, terrain, etc.
  - relation with local shear and σ_u

- use wind-atlases if measurements inadequate
  - need local terrain/obstacle description

- leverage [model] uncertainties (?)
  - speedup due to obstacles/surfaces
  - power-curve (σ_u, α basis)

- **reporting is crucial**...



(Kelly, 2018)

Terrain / obstacles…

High-Re flow around bluff bodies isn't easy, even for CFD…

- In the ABL: multi-scale interaction
  - engineering scaling (similitude) fails: stability vs. $z_{0,\mathrm{eff}}$ …
- High-Reynolds number flow
- recirculation; difficult PDF of velocity:
  - not uni-modal, sensitive to position, terrain (obstacle) geometry, inflow angle

- Belcher *et al* (1993): $F \sim \rho u_*^2 (h^2/L)(U_1/U_2)^4$ for terrain-drag
- low-order models preferable *in practice*
  - universal metrics useful (see e.g. Pope); reduce input parameter space
  - (allowable) uncertainty should be considered
    - requirements of end-user dictate this…

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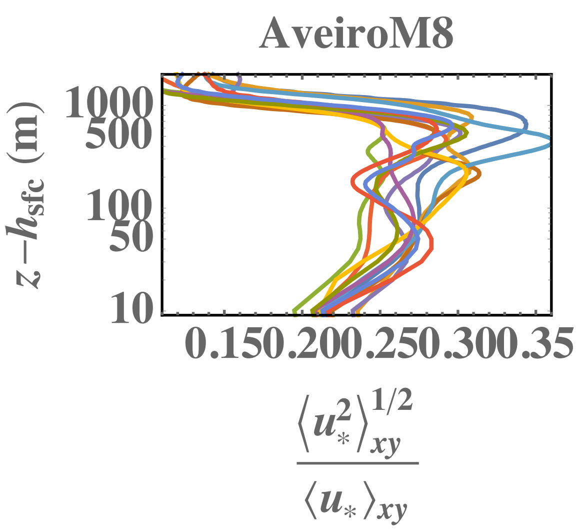
(Kelly & Cavar, 2021)

RANS 17x17km cplx



extra slides

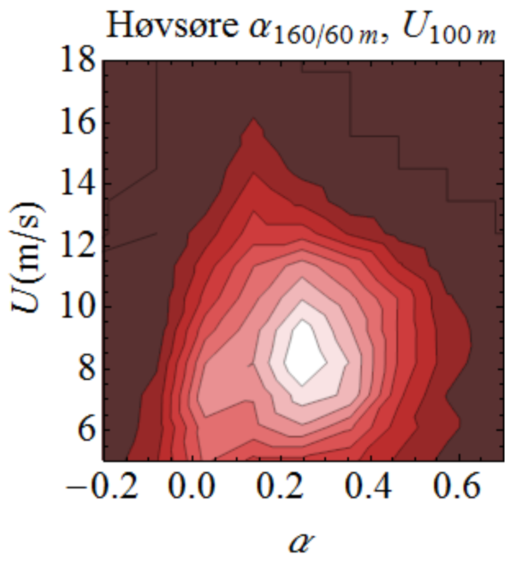
“Simple” example (?!?): uncertainty for WAsP-Online

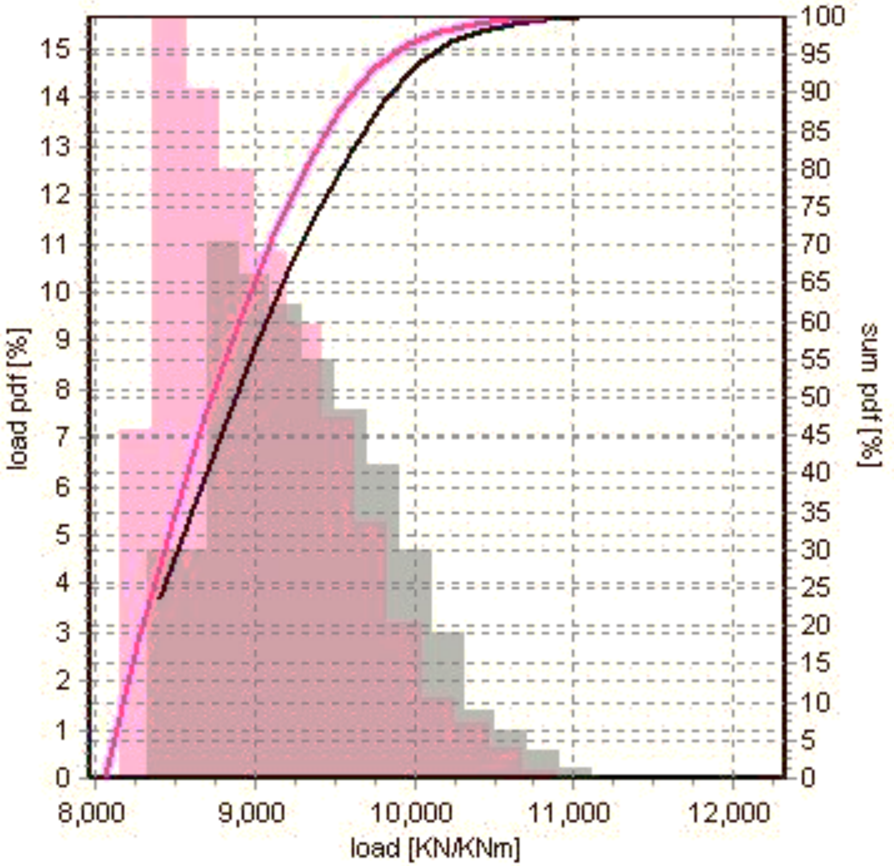
- “Observation” / input
  - CREYAP shows <5% in wind speed for measurements
  - Global wind atlas data: >40km resolution, via upper-air *dp/dx*
    - meso models give >5% error in wind speed
    - CREYAP gave error ~5% for horiz.extrapolations <20km
  - Obstacle inputs/representation:
    - probability of missing; mis-characterization metric
  - Power curve ~~(e.g. due to turbulence)~~
  - Map input: roughness/terrain
- Flow modelling
  - complex terrain issues (Troen *et al*.: 10-40% for d>10km)
  - roughness: local vs. global (<5%)
  - obstacles!

Example 5…Monte Carlo methods

HAWC2, NREL 5MW ref. (black/grey)

Flapwise Blade root 1Hz equiv. moments (14-16 m/s bin)





from Kelly *et al* (2014),
Journal of Physics: Conference Series **524**(1): 012076