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On the systematic validation of RANS-based models in OpenFOAM for atmospheric modelling applications

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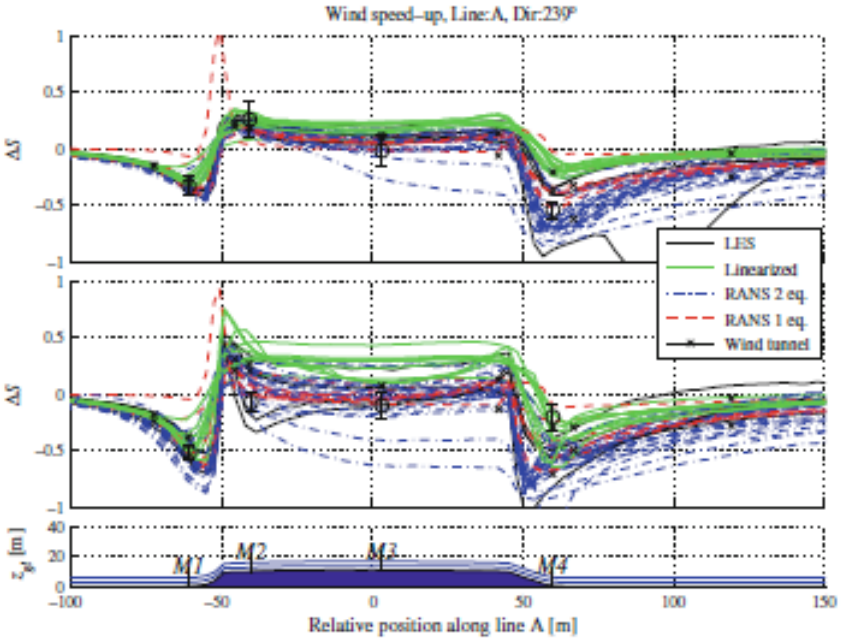
Outline:

1. Motivation
2. Numerical models and verification test cases
   a. Surface layer model
   b. Atmospheric boundary-layer model
   c. Forest modelling approaches
3. Validation test cases
4. Conclusions

1 Motivation

Motivation

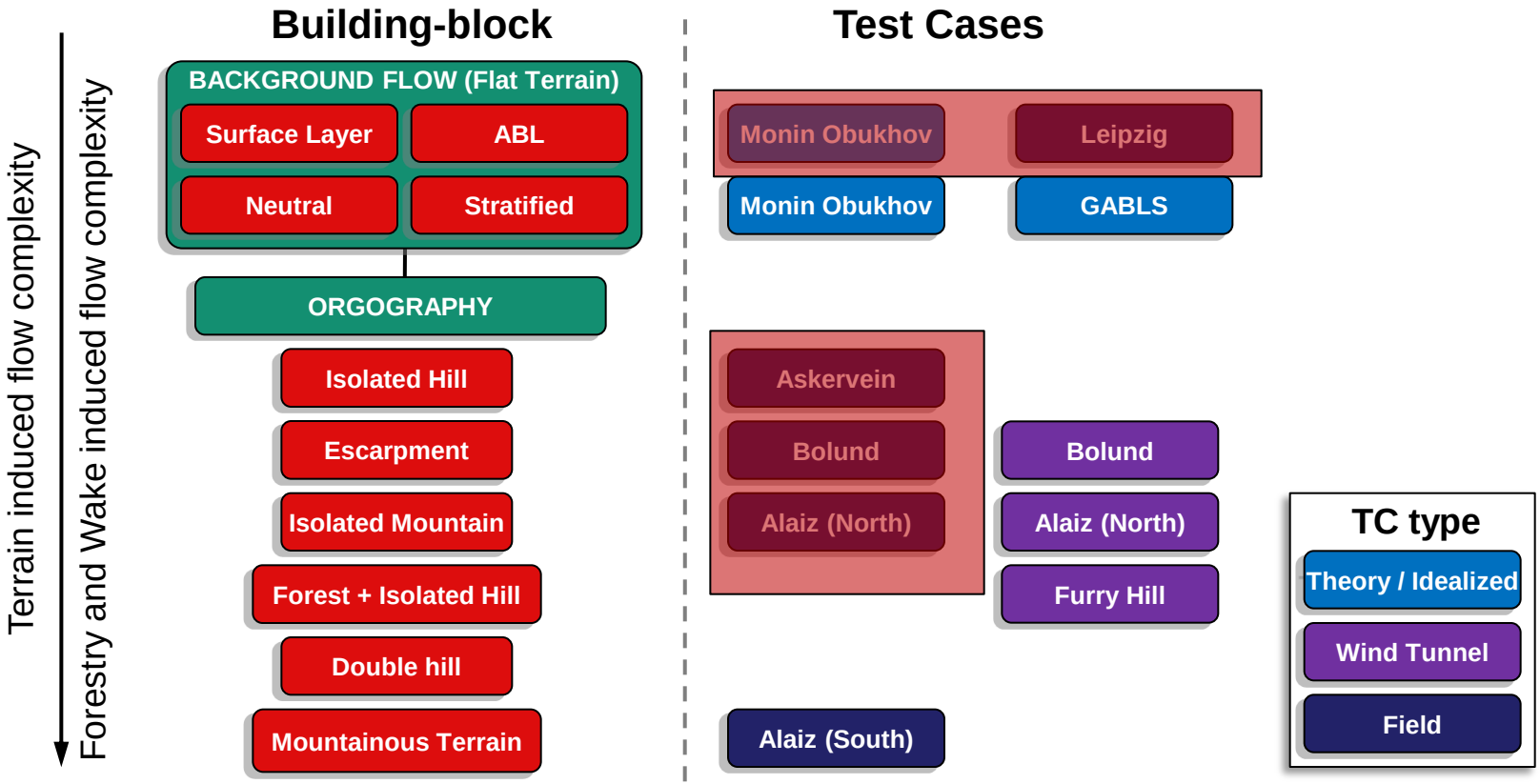
- 1.5 order RaNS model have demonstrated to provide a sufficient trade-off between accuracy and cost for wind resource assessment studies.
- Large uncertainty associated with models, approaches, users, etc



Bechmann, a. et al., 2011. The Bolund Experiment, Part II: Blind Comparison of Microscale Flow Models. Boundary-Layer Meteorology, 141(2), pp.245–271.

Building-block systematic validation approach*

- Increasing complexity as we introduce terrain-induced flow inhomogeneity



Sanz Rodrigo, J. et al., 2014. IEA-Task 31 WAKEBENCH: Towards a protocol for wind farm flow model evaluation. Part 1: Flow-over-terrain models. In The Science of Making Torque from Wind. Copenhague, Denmark.

Specific objectives

- Obtain overall metric of the accuracy for wind flow over different kind of terrains based on the validation test cases.
- Reduce the user-dependency in the simulations through an automatic procedures.
- Evaluate the differences between the Atmospheric (Apsley & Castro 1997) versus the Surface-boundary layer approach.
- Estimate the performance of two approaches to account for forestry elements in a complex terrain

Apsley, D.D. & Castro, I.P., 1997. A Limited-length-scale k-eps model for the neutral and stably-stratified atmospheric boundary layer. Boundary-Layer Meteorology, pp.75–98.

Error metric

The concept of the normalized mean absolute error is employed as a proxy to measure the overall difference between observations $\langle X_i \rangle_{obs}$ and model results $\langle X_i \rangle_{model}$,

where $\langle X_i \rangle = \{dimensionless\ metric\}$ in the i-th sensor.

$$E_X^{model} = \frac{\sum_{i=1}^{N_o} |\langle X_i \rangle_{obs} - \langle X_i \rangle_{model}|}{\overline{\langle X_i \rangle_{obs}} \cdot N_o}$$

2 Numerical models

1.1 Surface Boundary Layer
1.2 Atmospheric Boundary Layer
1.3 Forest model

Numerical model

- A RaNS-based model currently implemented OpenFOAM v2.1 for incompressible flows under neutral stratification and steady-state conditions.
- Turbulence closure is achieved using eddy-viscosity theory and the standard $k-\varepsilon$ closure scheme modified for atmospheric flows
- SIMPLE algorithm is employed to solve the pressure-velocity coupling.
- 2nd-order upwind schemes are used for the discretization of both velocity and turbulence convective terms.
- v1.0 deals with SBL flows while v2.0 is configured for ABL flows

2 Numerical models

1.1 Surface Boundary Layer
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Surface boundary layer (SBL) model

Most RaNS-based CFD models used for atmospheric wind flow modelling applications are based on the well known MOST.

Implementation in OpenFOAM needs to:

-Relations of constants in the turbulence closure equations must comply with derivation of (Richards and Hoxey 1997) to enforce MOST.

-The inlet conditions are defined as the solution to a horizontally homogeneous flow

-Consistency between fully developed SBL profiles and treatment of the ground boundary (wall functions).

OpenFOAM v2.1 current libraries for atmospheric flow

INLET

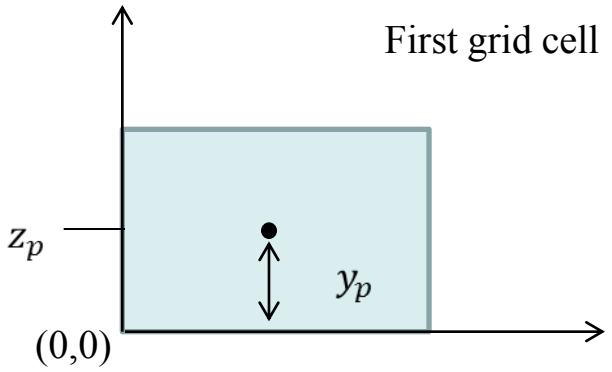
- atmBoundaryLayerInletVelocity
- atmBoundaryLayerInletEpsilon

$$u(z) = \frac{u^*}{\kappa}\ln\left(\frac{z+z0}{z0}\right)$$
$$u(z) = U_{ref}$$

$$z \leq H_{ref}$$
$$z > H_{ref}$$

$$\epsilon(z) = \frac{(u^*)^3}{\kappa(z_p+z0)}$$

$$k(z) = \frac{u^{*2}}{C_\mu^{\frac{1}{2}}}$$



Based on the assumptions of equilibrium at the wall

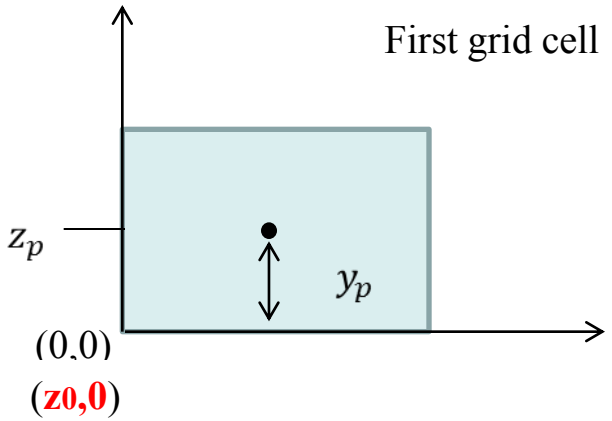
- $u_w^* = C_\mu^{1/4} k^{1/2}$
- $u_w^* = \frac{\kappa u_p}{\ln\left(\frac{z_p+z0}{z0}\right)}$

- $G_p = \nu_t \left(\frac{\partial u}{\partial z}\right)^2$

OpenFOAM v2.1 current libraries for atmospheric flow

GROUND

- nutkAtmRoughWallFunction
- epsilonWallFuntion



$$\tau_w = \frac{\kappa C_\mu^{1/4} k_p^{1/2} U_p}{\ln\left(\frac{y_p}{z_0}+1\right)}$$

- $\epsilon_p = \frac{C_\mu^{3/4} k^{3/2}}{\kappa y_p}$
- $G_k = \frac{\tau_w^2}{\kappa C_\mu^{1/4} k_p^{1/2} y_p}$

OpenFOAM v2.1 current libraries for atmospheric flow

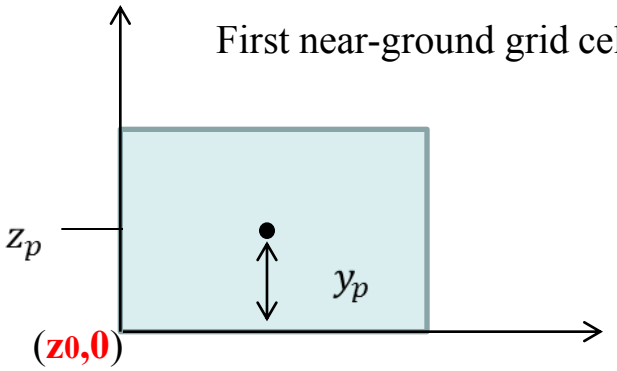
INLET

- SurfaceBoundaryLayerInletVelocity
- SurfaceBoundaryLayerInletEpsilon

$$u(z) = \frac{u^*}{\kappa} \ln\left(\frac{z+z0}{z0}\right)$$

$$\epsilon(z) = \frac{(u^*)^3}{\kappa(z_p+z0)}$$

$$k(z) = \frac{{u^*}^2}{{C_\mu}^{\frac{1}{2}}}$$



- nutAtmWallFunction
- epsilonAtmWallFuntion

- $\epsilon_p = \frac{{C_\mu}^{3/4} k^{3/2}}{\kappa(y_p+z_0)}$
- $G_k = \frac{\tau_w^2}{\kappa C_\mu^{1/4} k_p^{1/2}(y_p+z_0)}$

- z0 field that can be read by all libraries.
- Single properties dictionary

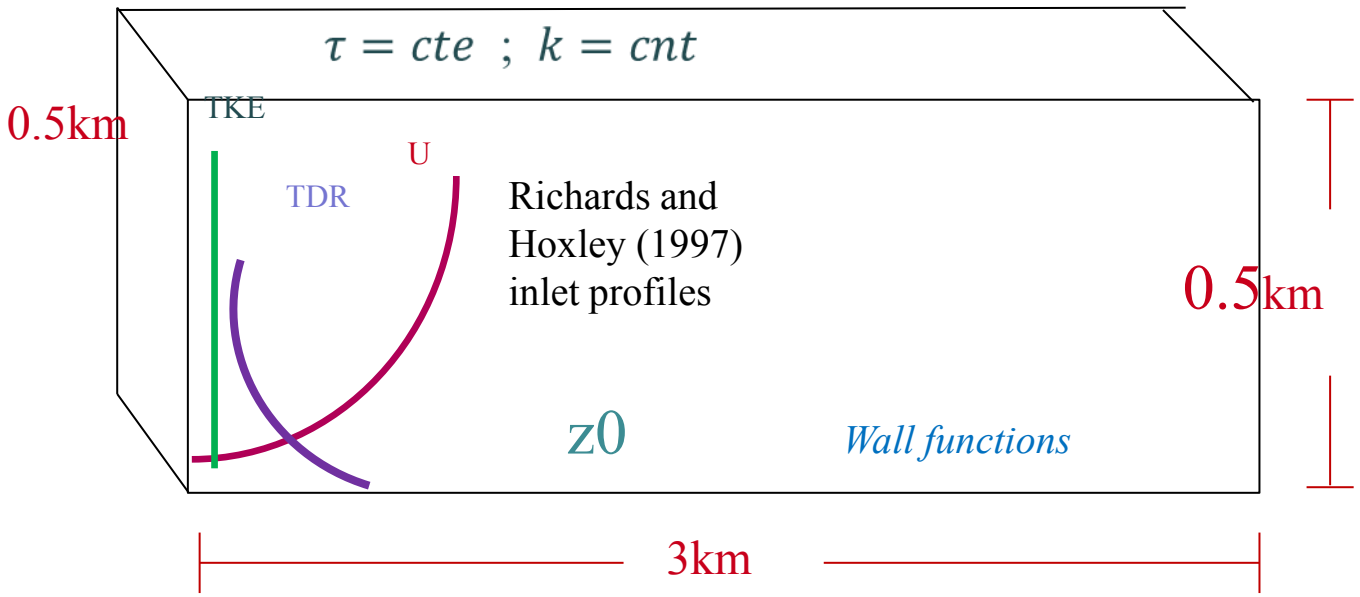
G_k is not integrated over the first cell height (Parente et al 2011)

Parente, A. et al., 2011. Improved k–ε model and wall function formulation for the RANS simulation of ABL flows. Journal of Wind Engineering and Industrial Aerodynamics, 99(4), pp.267–278.

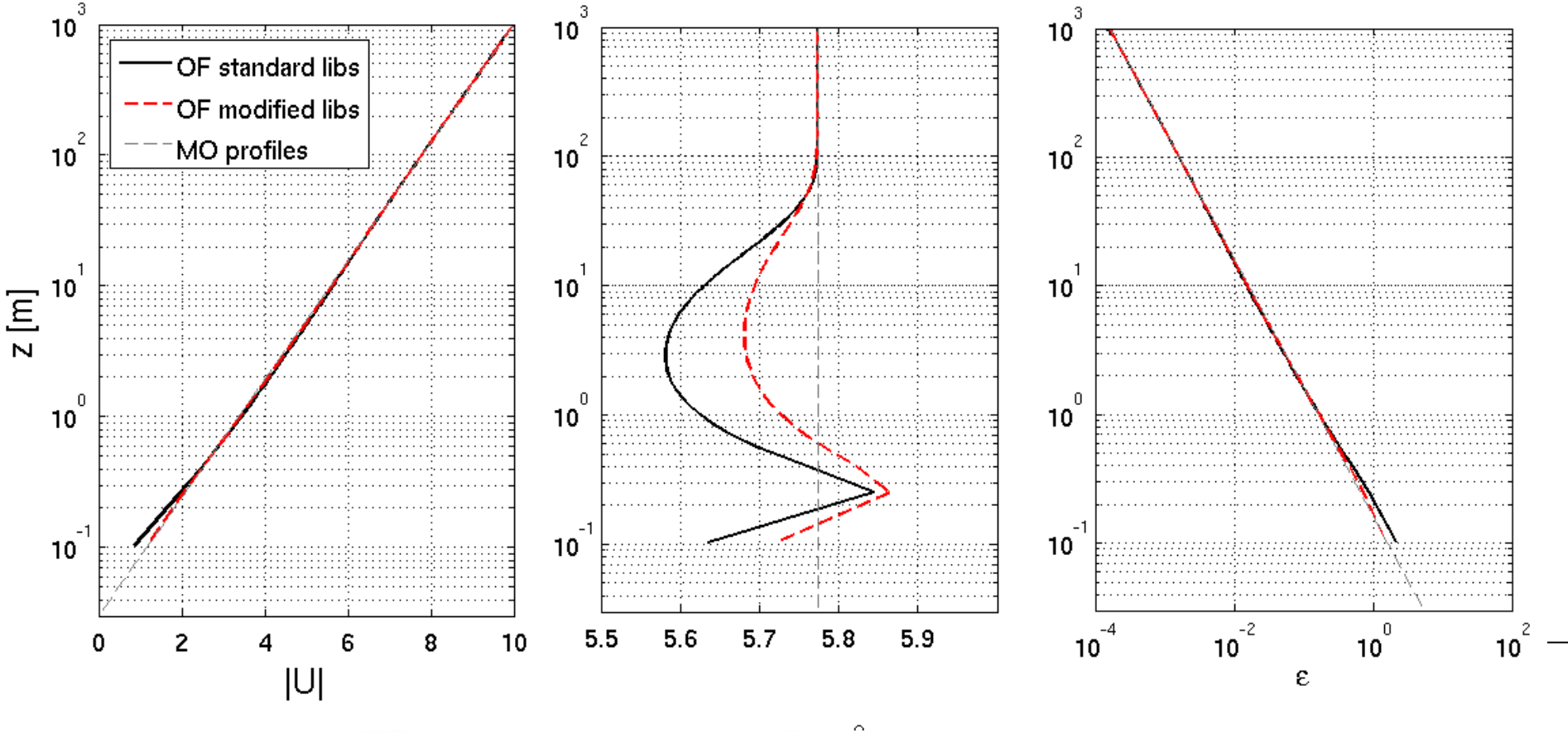
Monin-Obukhov test case for neutral conditions

$$z0 = 0.03;$$
$$\kappa = 0.43;$$
$$u^* = 0.5657;$$
$$C_\mu = 0.03;$$
$$C_{\epsilon 1} = 1.52;$$
$$C_{\epsilon 2} = 1.833;$$
$$\sigma_E = 1;$$
$$\sigma_\epsilon = 3.41;$$
$$k = 1.8478;$$
$$n_z = 36;$$
$$n_x = 12;$$
$$n_y = 32;$$

$$z_1 = 0.07;$$



Surface Boundary Layer model



Monin Obukhov test case

$z0 = 0.4;$

$\kappa = 0.4;$

$u^* = 0.8686;$

$C_\mu = 0.0256;$

$C_{\epsilon 1} = 1.13;$

$C_{\epsilon 2} = 1.9;$

$\sigma_k = 0.74;$

$\sigma_\epsilon = 1.3;$

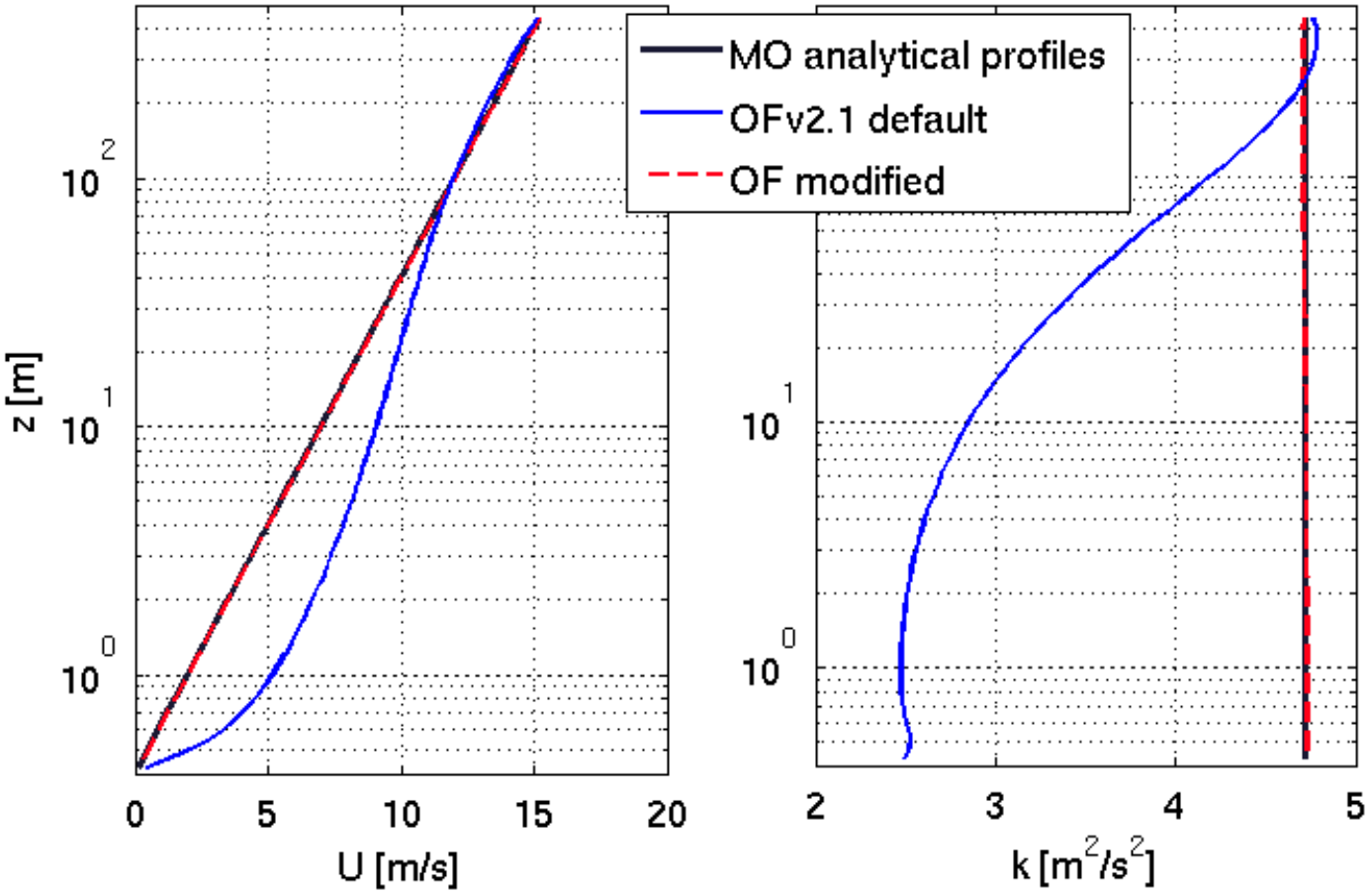
$k_{top} = 4.71;$

$n_z = 80;$

$n_x = 300;$

$n_y = 50;$

$z_1 = 0.2;$



2 Numerical models

1.1 Surface Boundary Layer

1.2 Atmospheric Boundary Layer

1.3 Forest model

Boundary Layer treatment

The Coriolis force is added $\longrightarrow$ $+ \varepsilon_{ijk}\Omega_j U_k$

$$\Omega_j{}^T = (0,0,f_c) \qquad f_c = 2\omega \sin\phi$$

Limitation of the mixing length in the ϵ equation (Apsley & Castro 1997) $\longrightarrow$ $C_{1\epsilon}{}^* = C_{1\epsilon} + (C_{2\epsilon} - C_{1\epsilon})\frac{l_m}{l_{max}}$

In which ϵ is enforced to comply with Apsley & Castro 1997 as in Sogachev et al., 2012). l_{max} defined through Blackadar 1963

$$\epsilon = \max\left(\epsilon, \frac{C_\mu{}^{3/4} k^{3/2}}{l_{max}}\right)$$

$$l_{max} = 0.00027\frac{U_g}{f_c}$$

- Apsley, D.D. & Castro, I.P., 1997. A Limited-length-scale k-eps model for the neutral and stably-stratified atmospheric boundary layer. Boundary-Layer Meteorology, pp.75–98.
- Sogachev, A., Kelly, M. & Leclerc, M.Y., 2012. Consistent Two-Equation Closure Modelling for Atmospheric Research: Buoyancy and Vegetation Implementations. Boundary-Layer Meteorology, 145(2), pp.307–327.

Leipzig test case for neutral conditions

$z0 = 0.3;$

$\kappa = 0.4;$

$C_\mu = 0.0256;$

$C_{\epsilon 1} = 1.13;$

$C_{\epsilon 2} = 1.9;$

$\sigma_k = 0.74;$

$\sigma_\epsilon = 1.3;$

$f_c = 1.13\text{x}10^4$ 1/s

Ug = 17.5 m/s

$n_z = 96;$

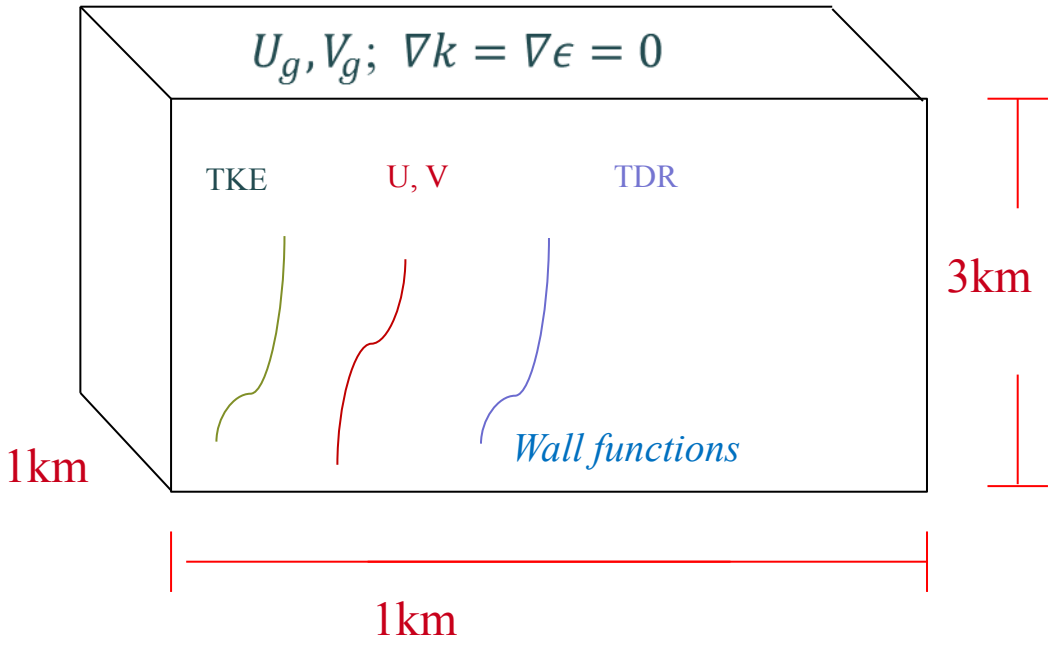
$n_x = 48;$

$n_y = 48;$

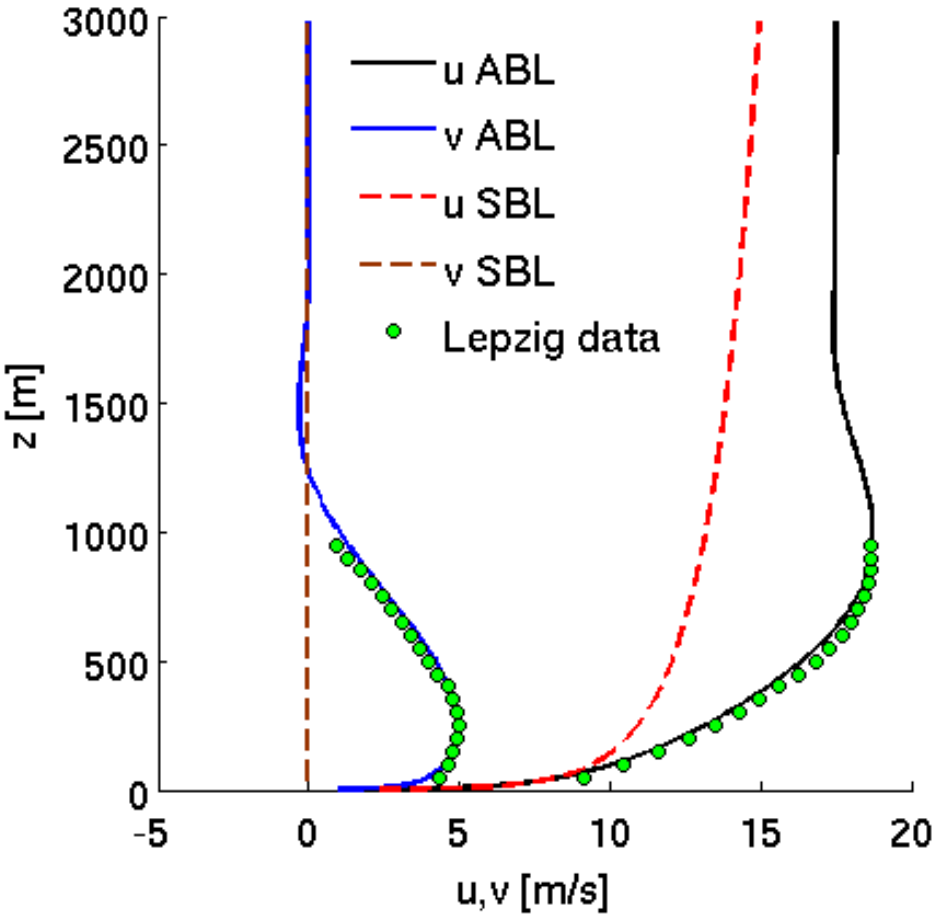
$z_1 = 0.3;$

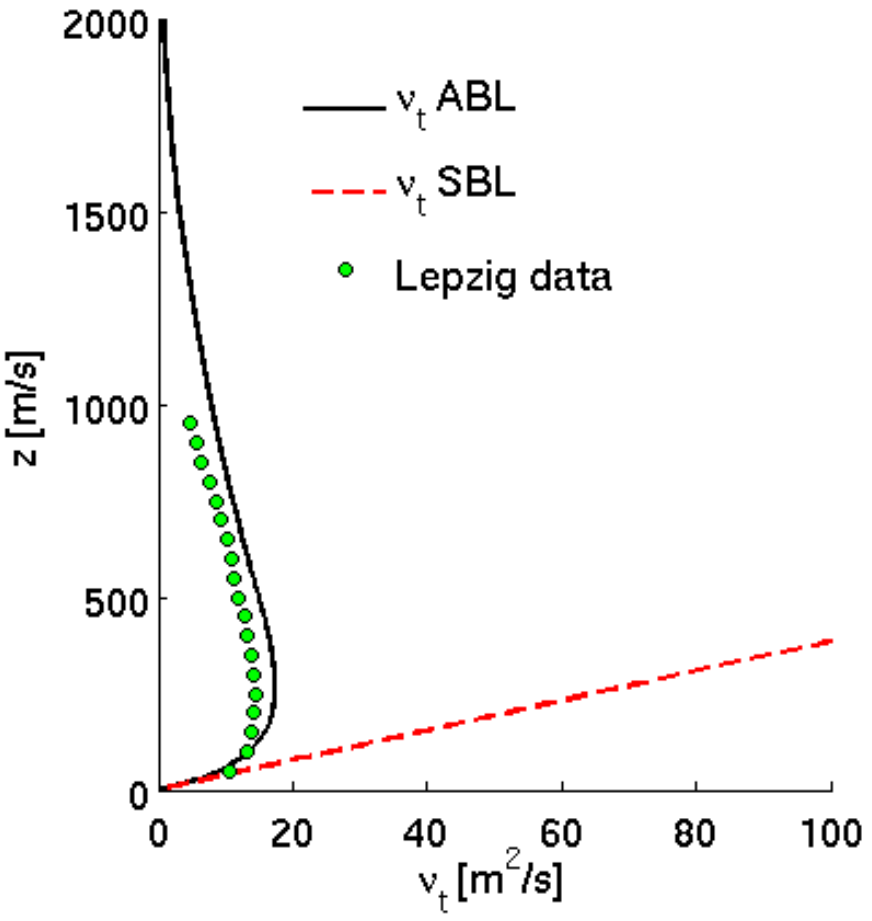
-Cyclic conditions at the sides, wall functions and symmetry conditions at the top

- Ekman profiles ($\nu_t = cnt$)



Leipzig test case





2 Numerical models

1.1 Surface Boundary Layer
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1.3 Forest model

Forest modelling

Canopy model *(Sogaachev 2009 ; Sogachev et al. 2012)*

A drag is added to momentum eqs $\longrightarrow$ $S_i = -c_d \alpha \, \bar{u}_i |u|$

Only enhanced dissipation S_d is added to dissipation rate equation

$$\frac{\partial \varepsilon}{\partial t} + \bar{u}_j \frac{\partial \varepsilon}{\partial x_j} - \frac{\partial}{\partial x_i}\left(\frac{\nu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_i}\right) = \frac{\varepsilon}{k}\left(C^*_{\varepsilon 1} P_k - C_{\varepsilon 2}\varepsilon\right) + \frac{\varepsilon}{k}\left[\left(C^*_{\varepsilon 1} - C_{\varepsilon 2}\right)\left(-S_d\right)\right]$$

$$S_d = 12 C_\mu^{1/2} c_d \alpha |u|$$

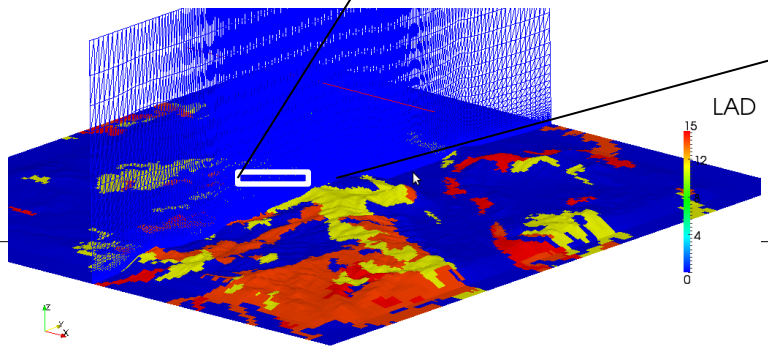
Sogachev, A., 2009. A Note on Two-Equation Closure Modelling of Canopy Flow. Boundary-Layer Meteorology, 130(3), pp.423–435.

Forest modelling

$\alpha(z)$ =Leaf Area Density

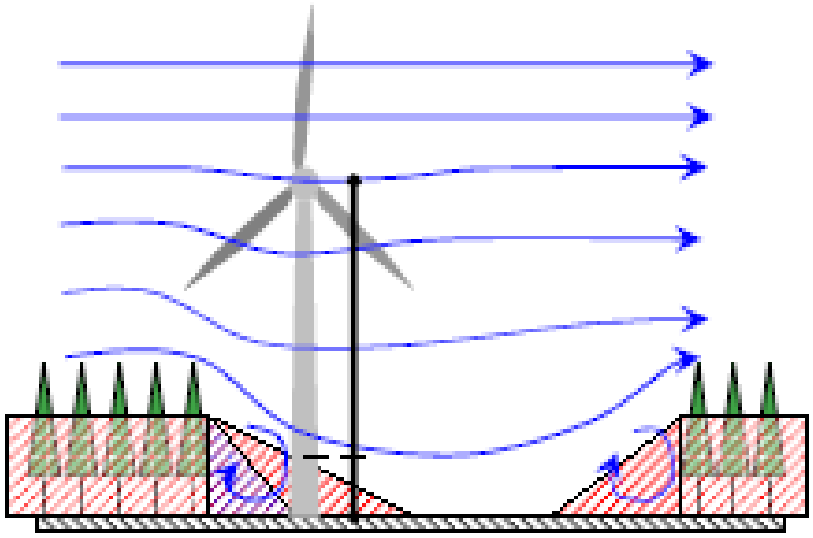
c_d =drag coefficient

h average forest height which is used as the upper limit whose cells below are affected by the additional source/sink terms.



Forest modelling

The large roughness length and zero-plane displacement approach.



Madsen & Corre 2010 – VindKraftNet meeting

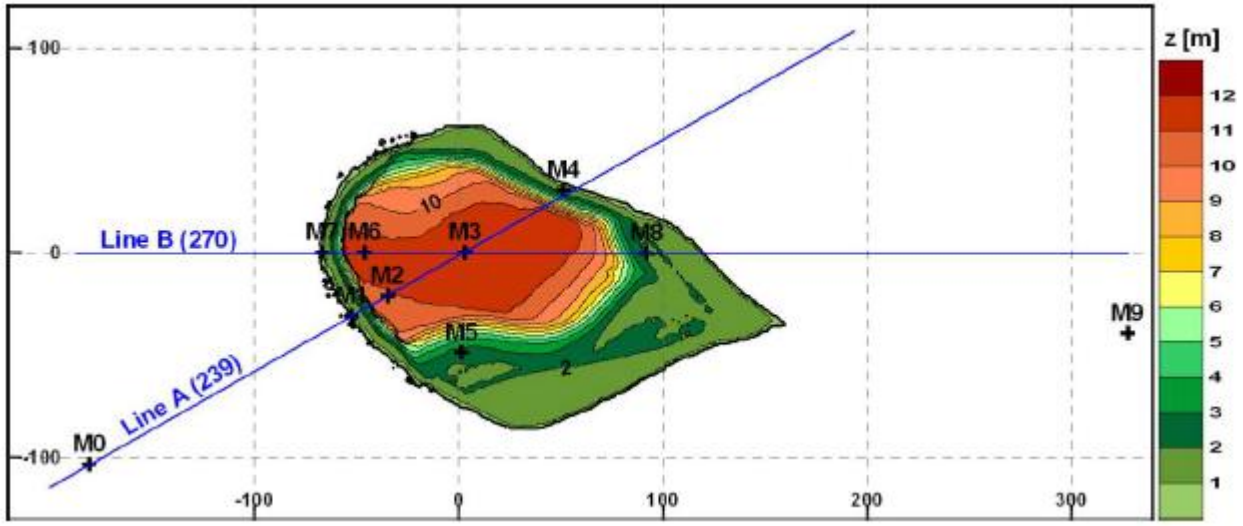
3 Validation test cases

3.1 Bolund

3.2 Askervein

3.3 Alaiz

Bolund test case. Mesh comparisons



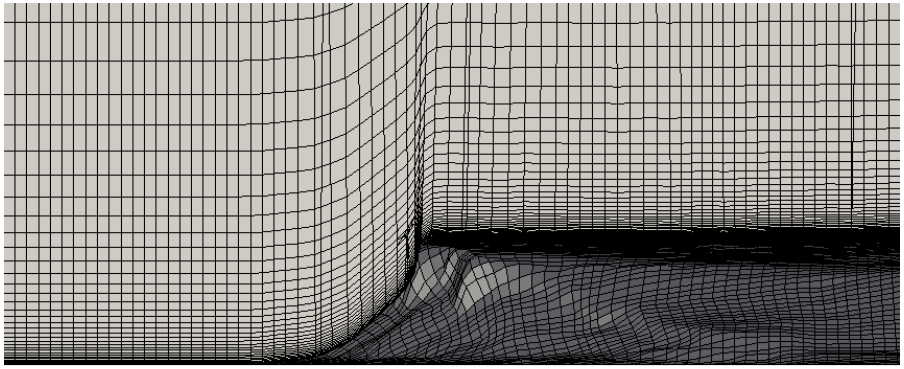
$$\kappa = 0.4;$$
$$C_\mu = 0.0297;$$
$$C_{\epsilon 1} = 1.138;$$
$$C_{\epsilon 2} = 1.92;$$
$$\sigma_k = 1.0;$$
$$\sigma_\epsilon = 1.3;$$

$$n_z = 40;$$
$$d_x = 0.3;$$
$$d_y = 0.3;$$
$$z_1 = 0.025;$$

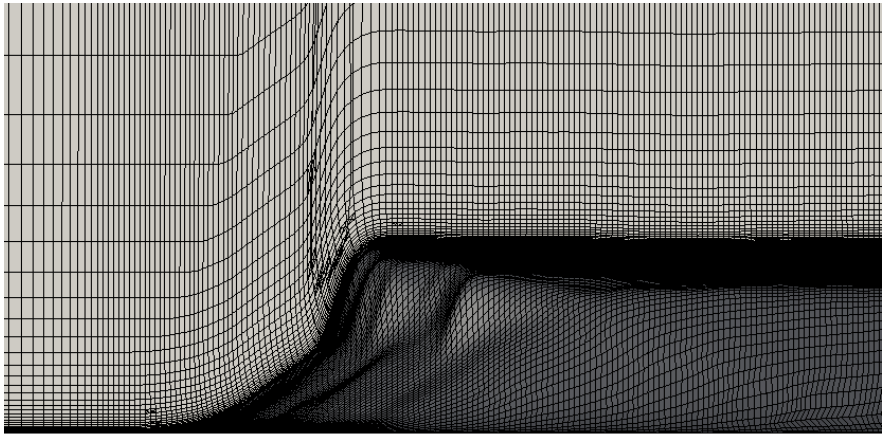
$$u^*_0 = 0.4 \text{ m/s}$$
$$\frac{k_0}{{u^*_0}^2} = 5.8$$

Bechmann, A. et al., 2009. The Bolund Experiment : Overview and Background, Roskilde,Denmark.

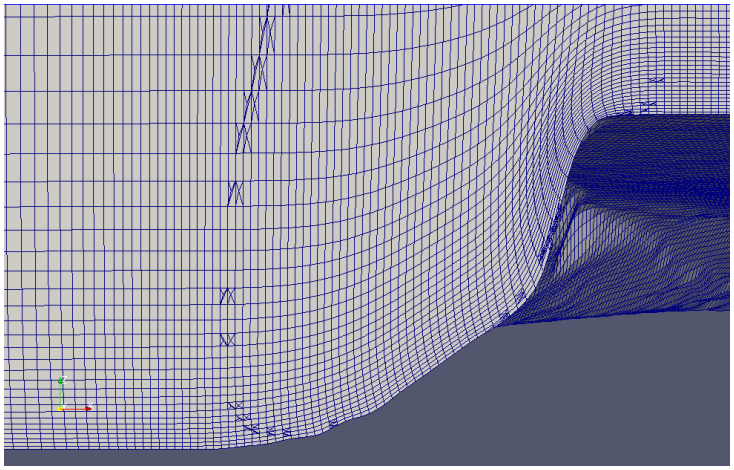
Bolund test case. Mesh comparisons



ICEM mesh



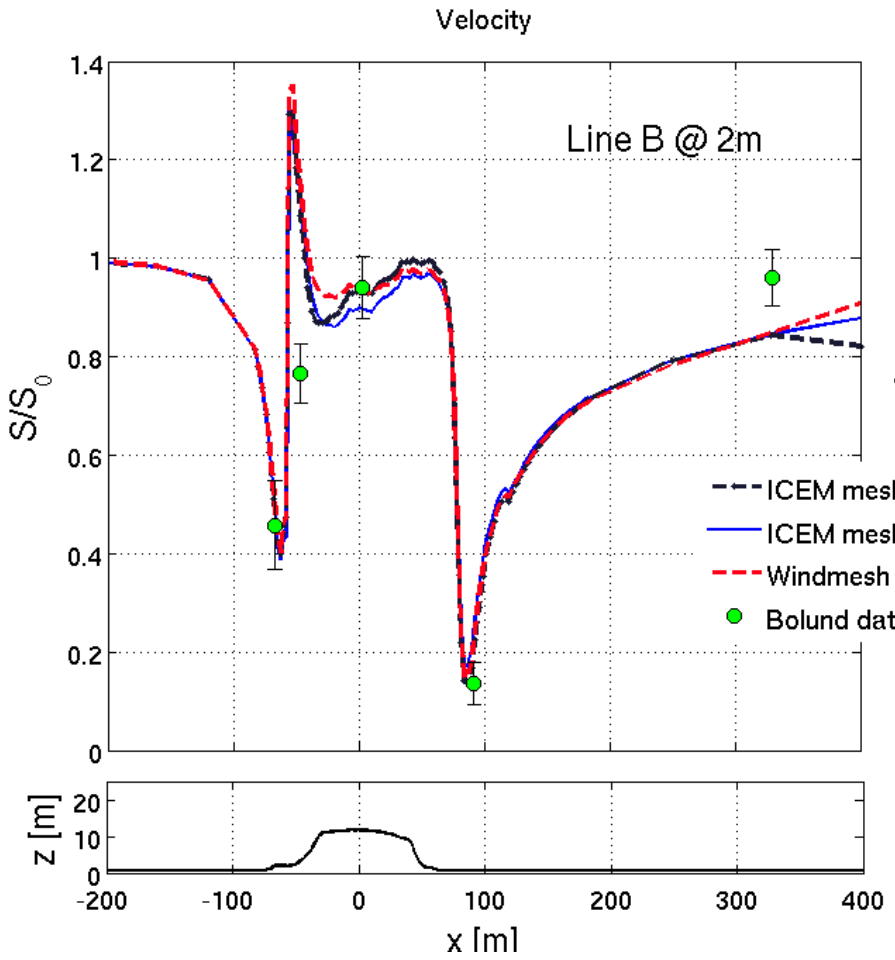
Windmesh*

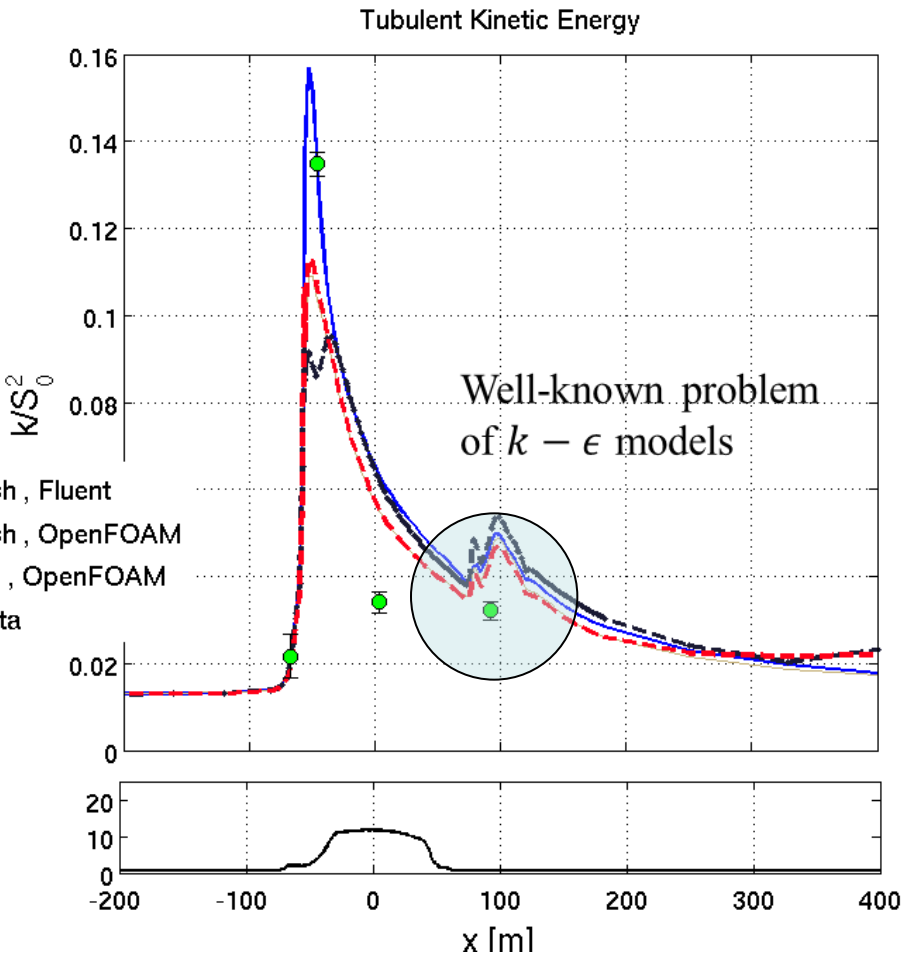


Windmesh with distribution of vertical nodes improved

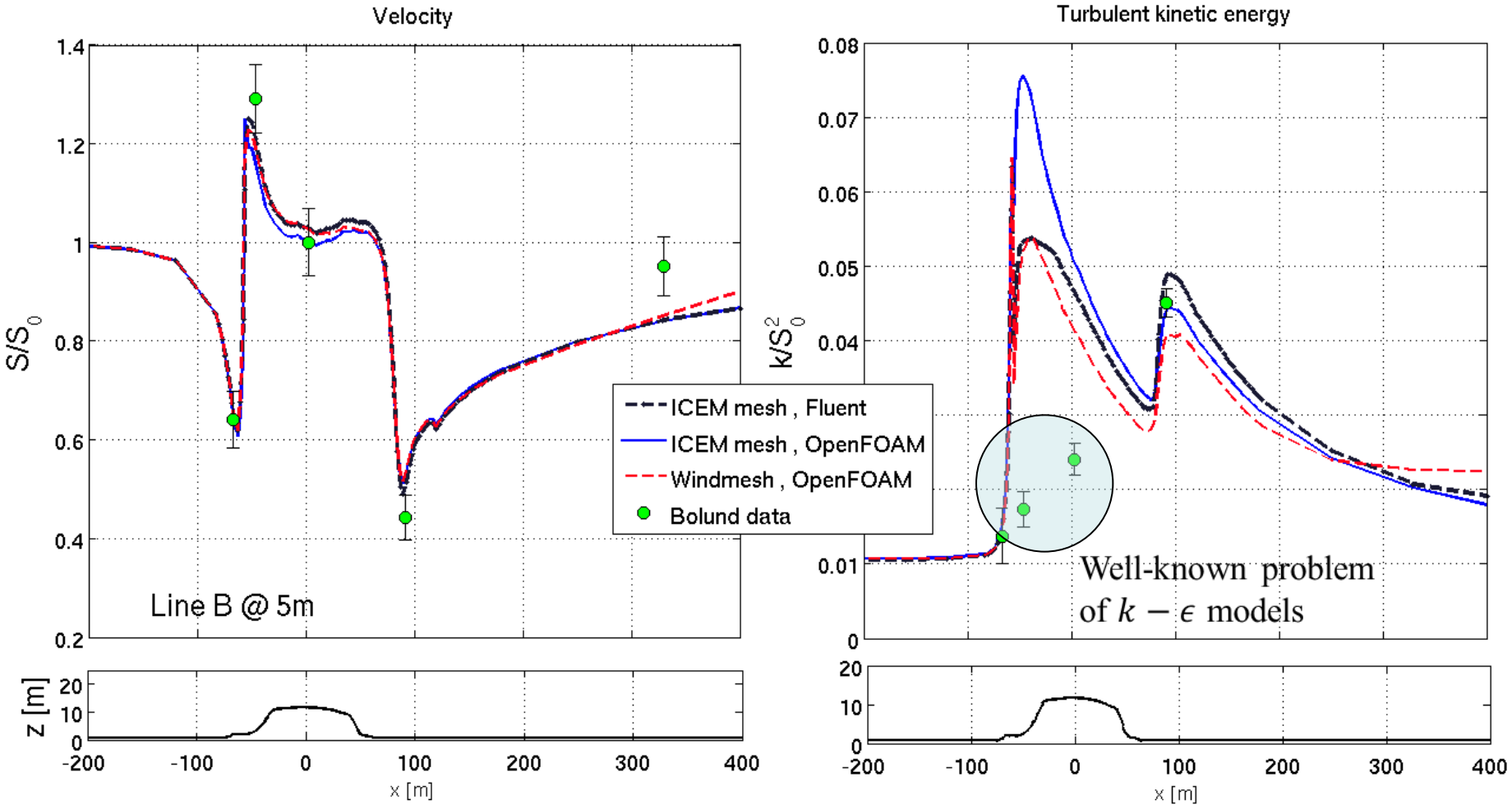
- *Avila M., Folch A., Houzeaux G., Eguzkitza B., Prieto L., Cabezon D. 2013 A Parallel CFD Model for Wind Farms. Int. Conf. on Comp. Science. Barcelona

Bolund test case. Mesh and solver comparisons





Bolund test case. Mesh and solver comparisons



Bolund test case. Mesh and solver comparisons

	Velocity LineB 2m	*Velocity LineB 5m*	*k LineB 2m*	*k LineB 5m*
ICEM mesh , Fluent	13	5.9	43	62.7
ICEM mesh, OpenFOAM	14	6.6	21	87
Windmesh, OpenFOAM	14.4	6.7	29	57

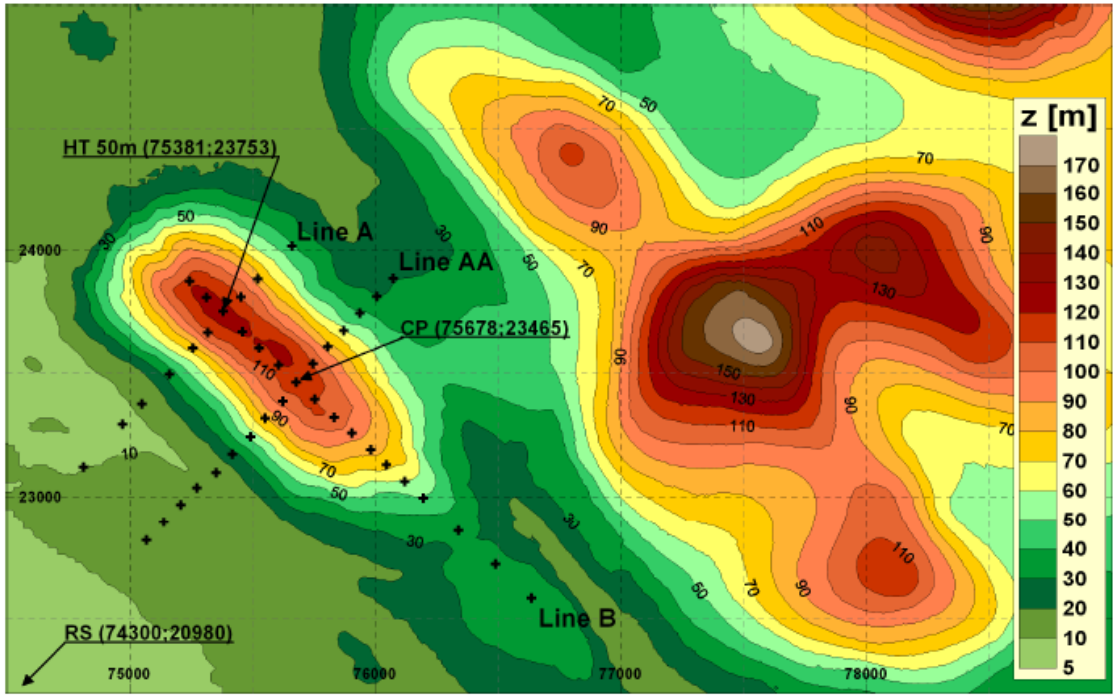
3 Validation test cases

3.1 Bolund

3.2 Askervein

3.3 Alaiz

Askervein test case



1. A coarse 25m was used.
2. Problems with roughness file

Taylor, P. and Teunissen, H., "The Askervein Hill project: Overview and background data", Boundary-Layer Meteorology, 1987, 39, 15-39

Askervein test case

-Rotated 210º mesh

-A “precursor” 1D simulation provides the inflow conditions in the ABL case.

-Symmetry conditions used at the top

-No-gradient used at the sides

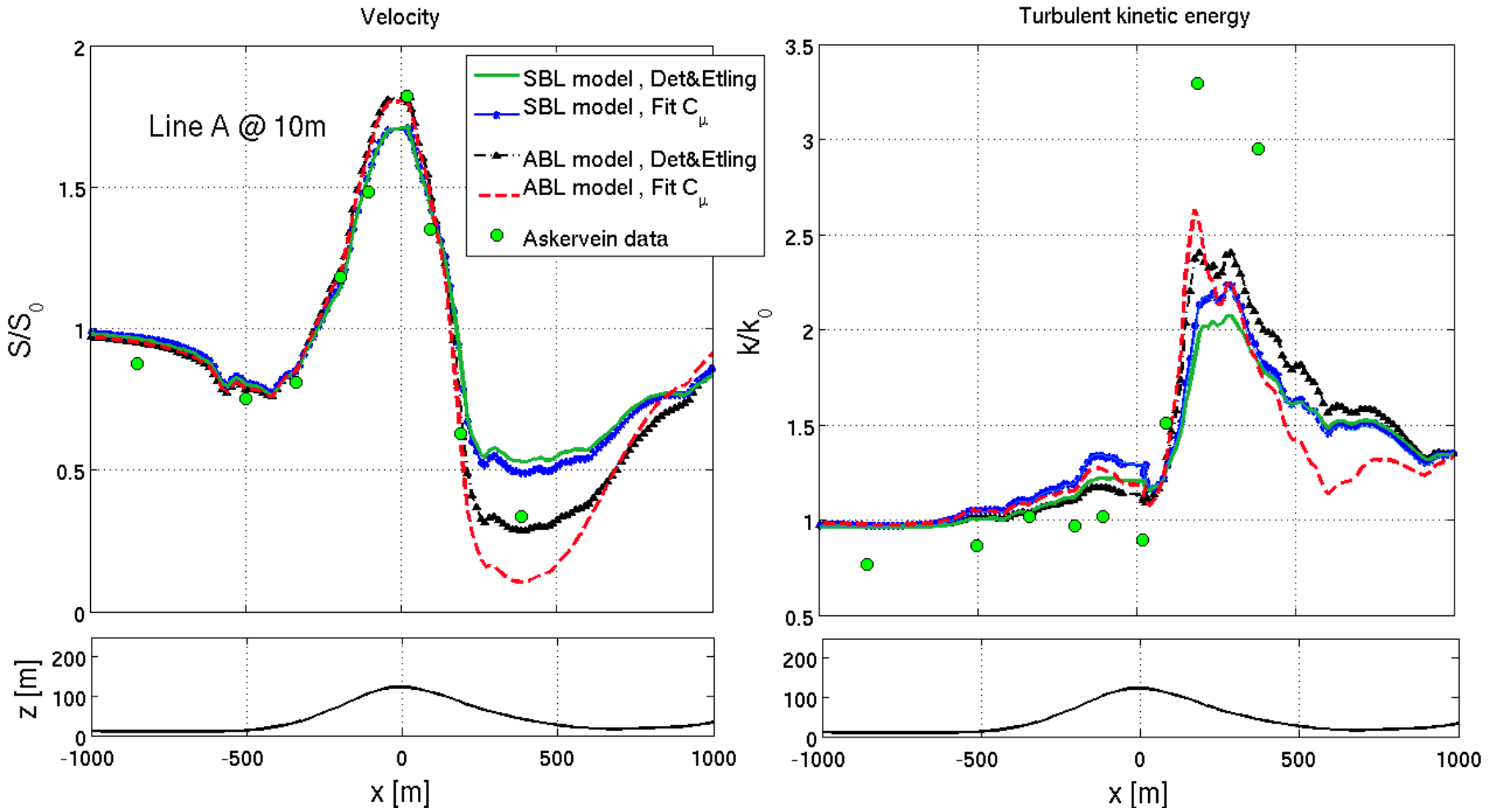
-Based on RS mast, u^* is obtained from a fit to the log profile $(u_{RS}{}^*)$

Calibrated $C_\mu{}^{RS} = \left(\frac{{u_{RS}}^{*2}}{k_{RS}}\right)^2$

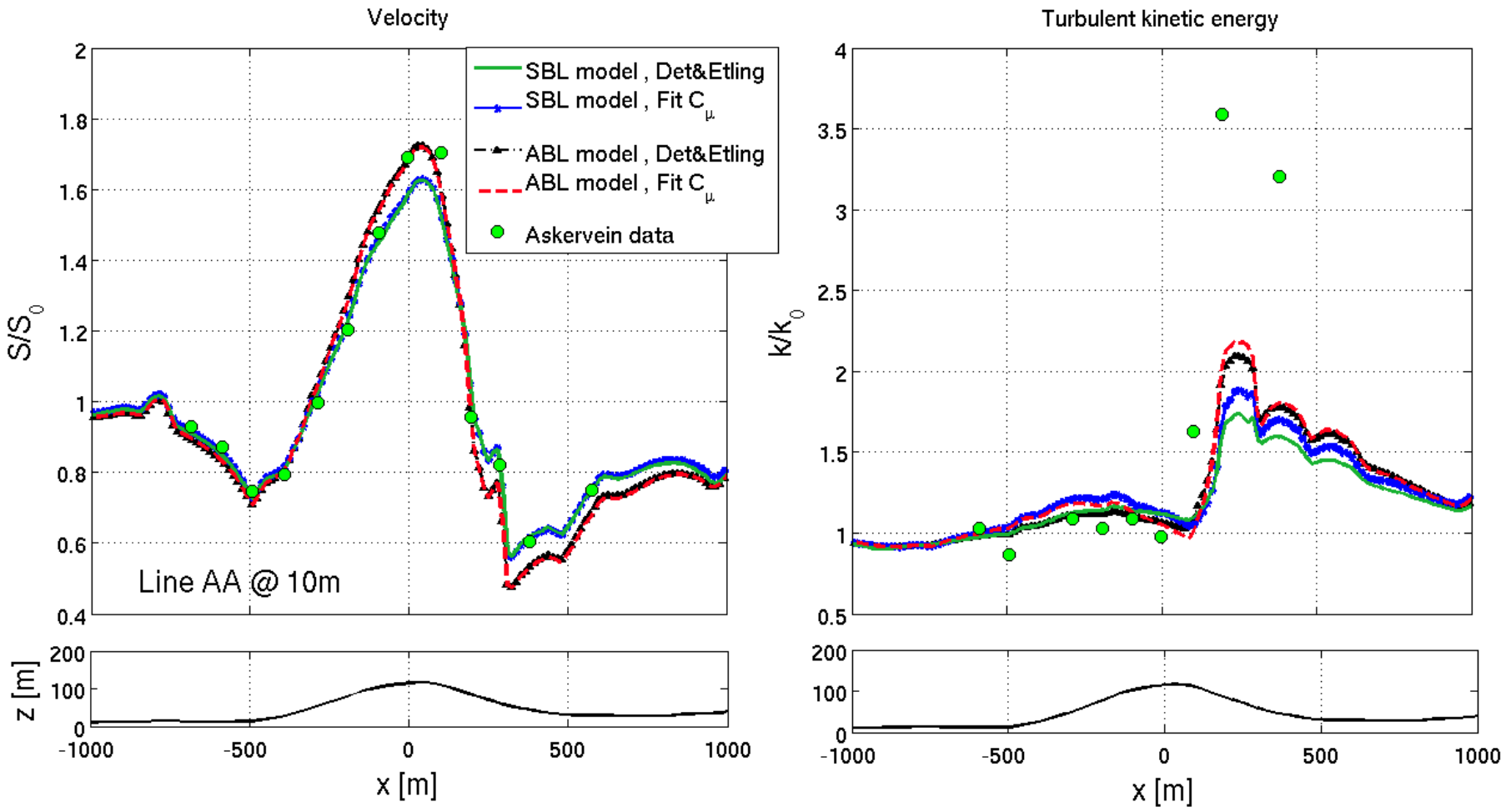
$$C_{\epsilon 1} = C_{\epsilon 2} - \frac{\kappa^2}{\sqrt{C_\mu{}^{RS}}\sigma_\epsilon}$$

Detering & Etling 1985

Askervein test case Line A



Askervein test case – Line AA



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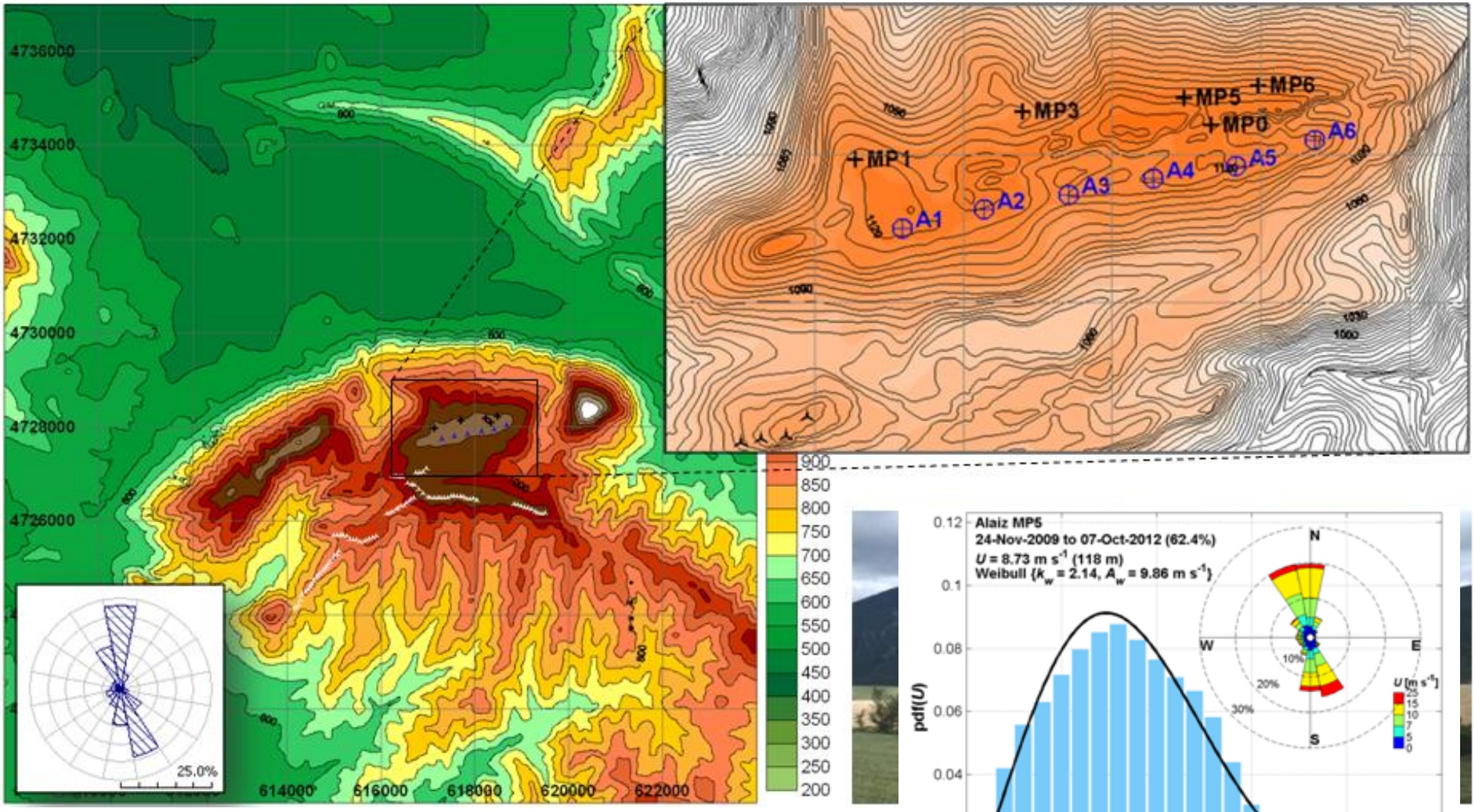
Askervein test case

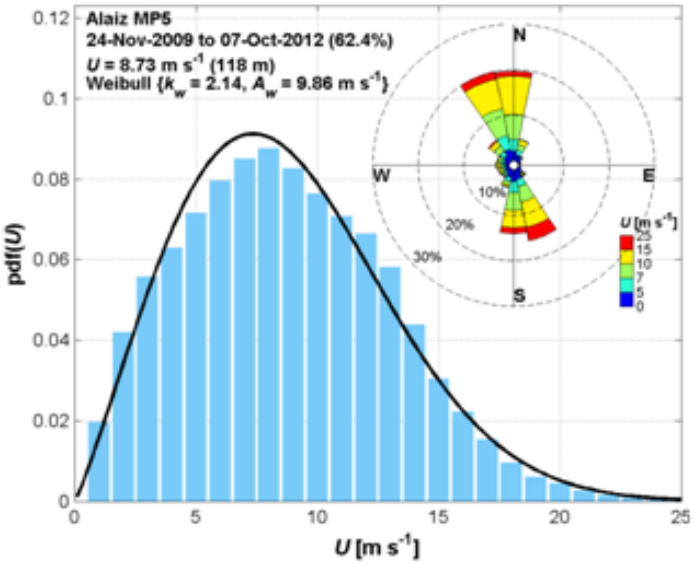
	S/S_0		k/k_0	k/k_0
	Line A	Line AA	Line A	Line AA
SBL D&E	9.5	4.1	28.2	32.2
SBL tuned C_μ	9.1	3.9	29.4	32.8
ABL D&E	6.3	4.96	21.8	27.7
ABL tuned C_μ	7.9	4.98	24.1	28.5

4 Validation test cases

3.1 Bolund
3.2 Askervein
3.3 Alaiz

Alaiz Site: topography





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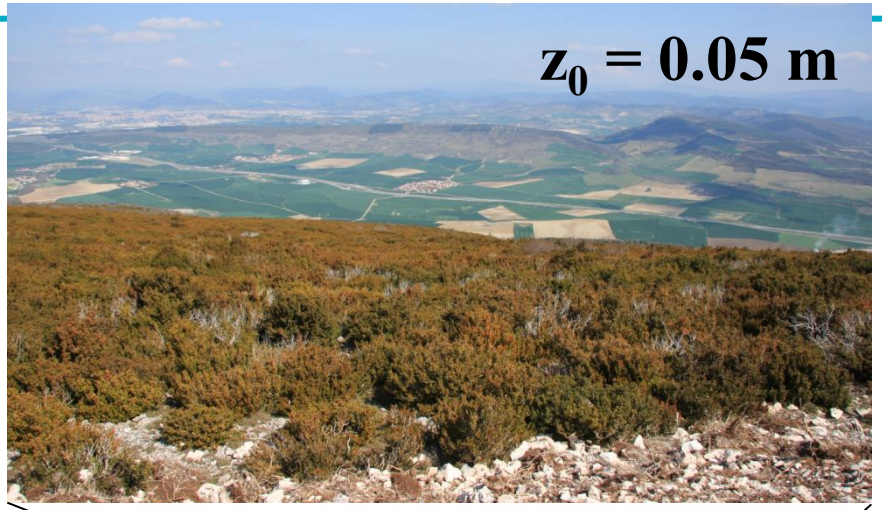
The roughness and forest map

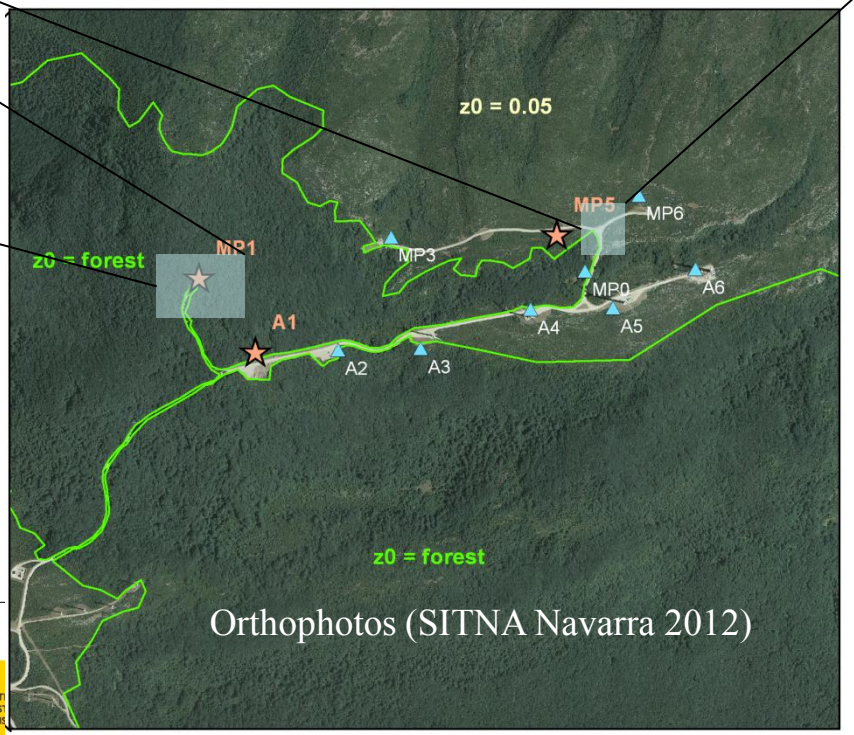
Fagus Sylvatica

$z_0 = 0.4$ m

Asner et al. 2003; Breda et al 2003 and Meier 208

$z_0 = 0.4$ m
LAI = ~6 → LAD=0.4
Cd = 0.2
H=15m





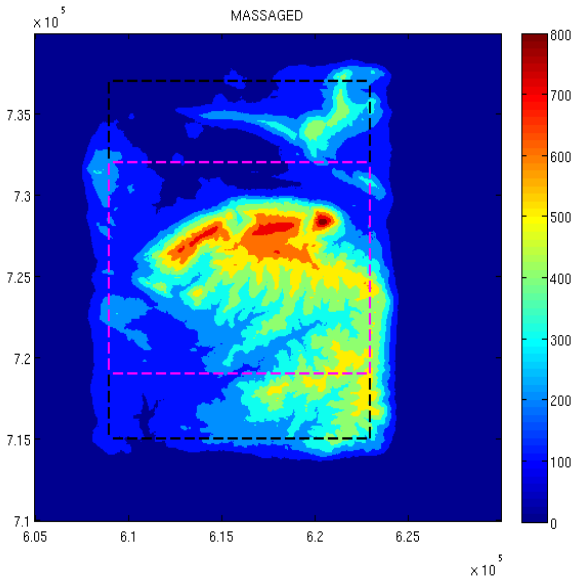
Orthophotos (SITNA Navarra 2012)

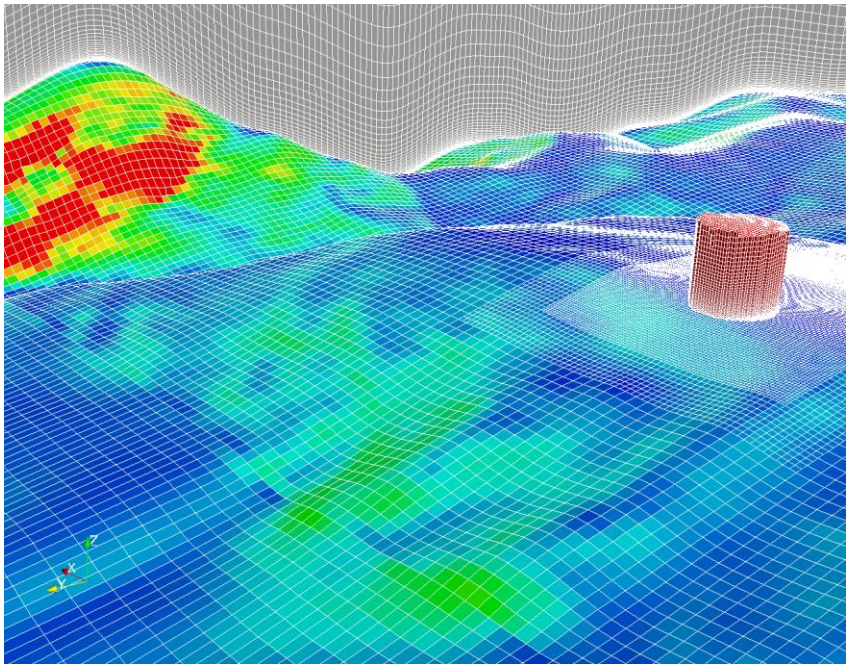
Stability classifcation

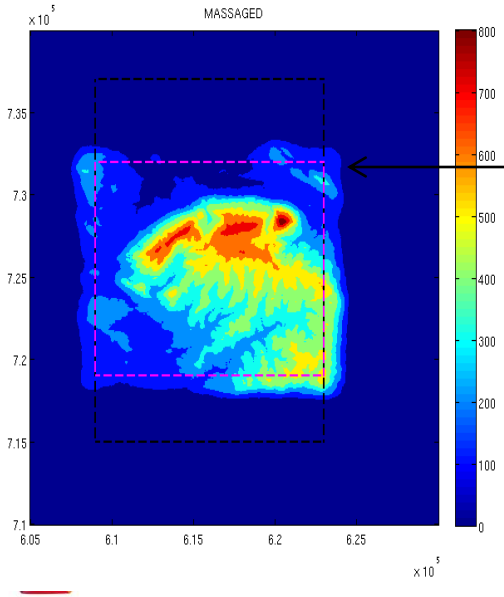
	D d [m]	*D RIX*$_N$ [%]	*D RIX*$_S$ [%]	*U* levels [m]	*WD* levels [m]	*T/RH* levels [m]
MP1	1125	2.1	-3.3	40, 78, 90, 102, 118	78, 90, 102, 118	81, 97, 113
MP3	544	-2.6	-0.9	40, 78, 90, 102, 118	78, 90, 102, 118	81, 97, 113
MP5	0	0.0	0.0	40, 78, 90, 102, 118	78, 90, 102, 118	2[1], 38[1], 81, 97, 113
MP0	129	0.7	0.8	40, 78, 90, 102, 118	78, 102, 118	81, 97, 113
MP6	253	0.7	1.3	40, 78, 90, 102, 118	78, 90, 102, 118	81, 97, 113
A1	1043	-1.0	-3.8	78, 90, 102, 118	78, 90, 102, 118	81, 97, 113
A2	771	-1.3	-1.3	40, 78, 90, 102, 118	40, 78, 90, 102, 118	81, 97, 113
A3	506	-2.0	-0.9	78, 90, 102, 118	78, 90, 102, 118	81, 97, 113
A4	290	1.5	-0.1	40, 78, 90, 102, 118	78, 90, 102, 118	81, 97, 113
A5	288	1.0	0.6	40, 78, 90, 102, 118	78, 90, 102, 118	81, 97, 113
A6	462	0.9	0.6	78, 90, 102, 118	78, 90, 102, 118	81, 97, 113

[1] operational since 18/01/2011

Domain dimensions







2km “massaged“ region

$$0.5 \mp \frac{\cos(F_1 + M_1 + x_{lim1} - x(F1))\,\pi}{xM_1} * \frac{1}{2}$$

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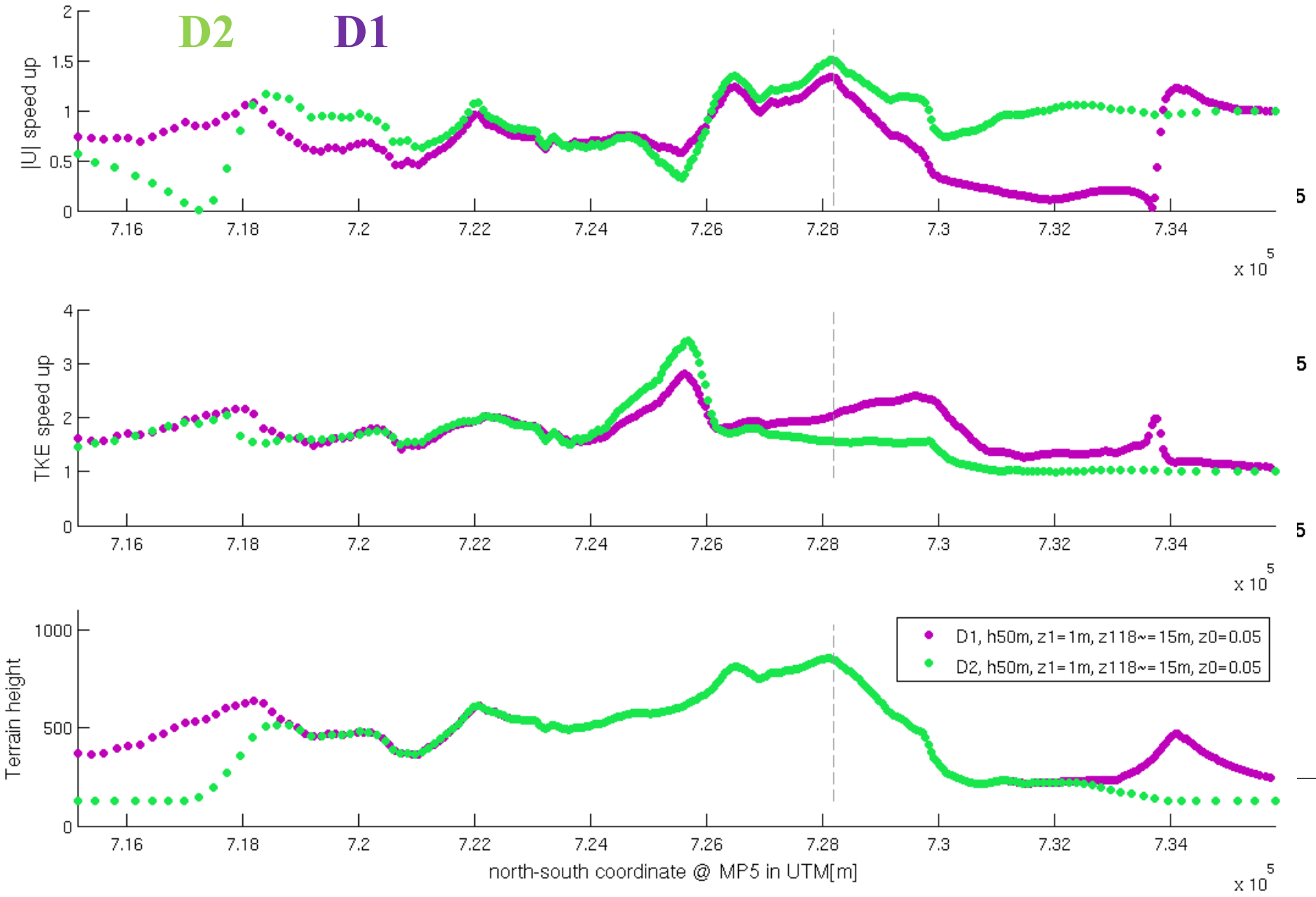
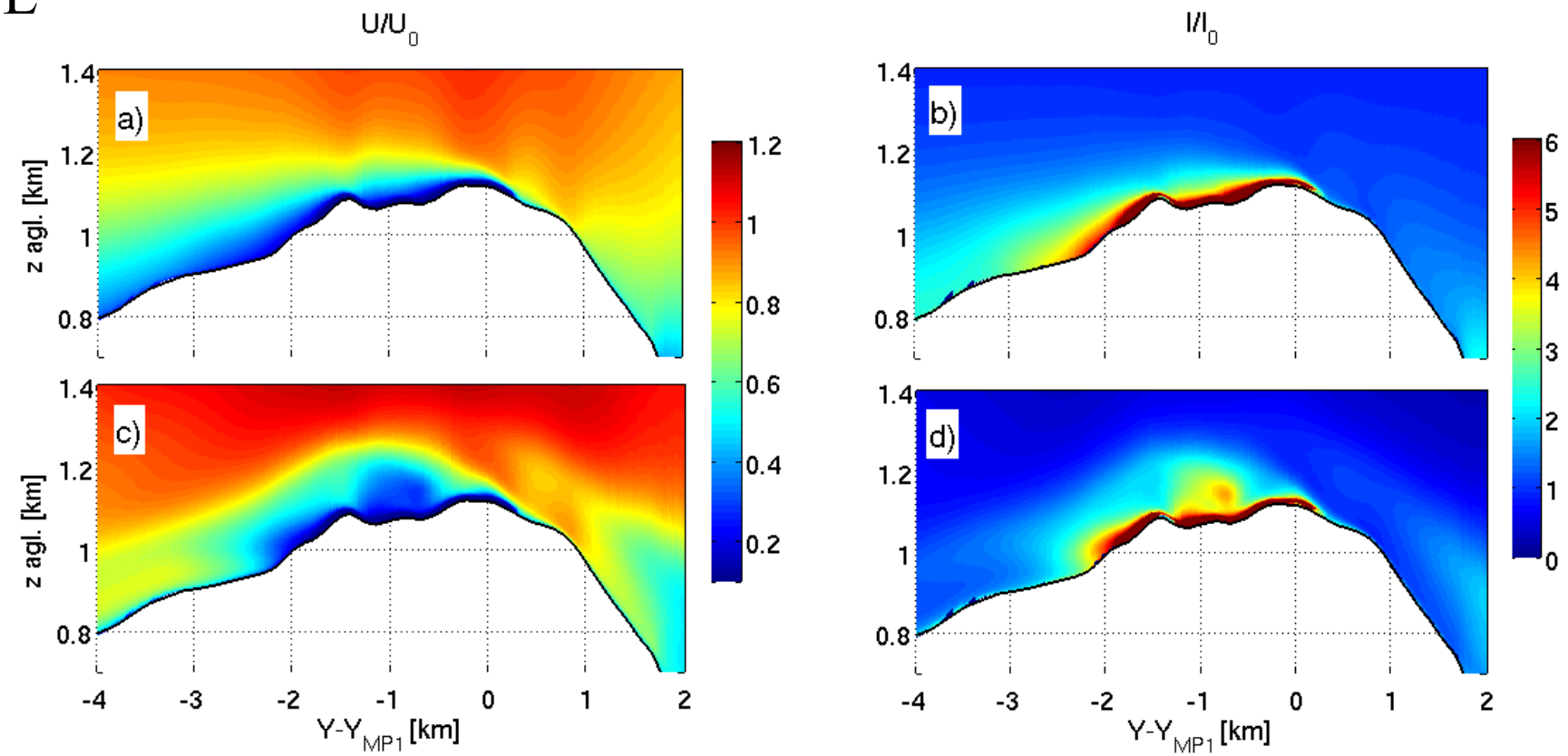
Domain dimensions – MP5 comparison @118m

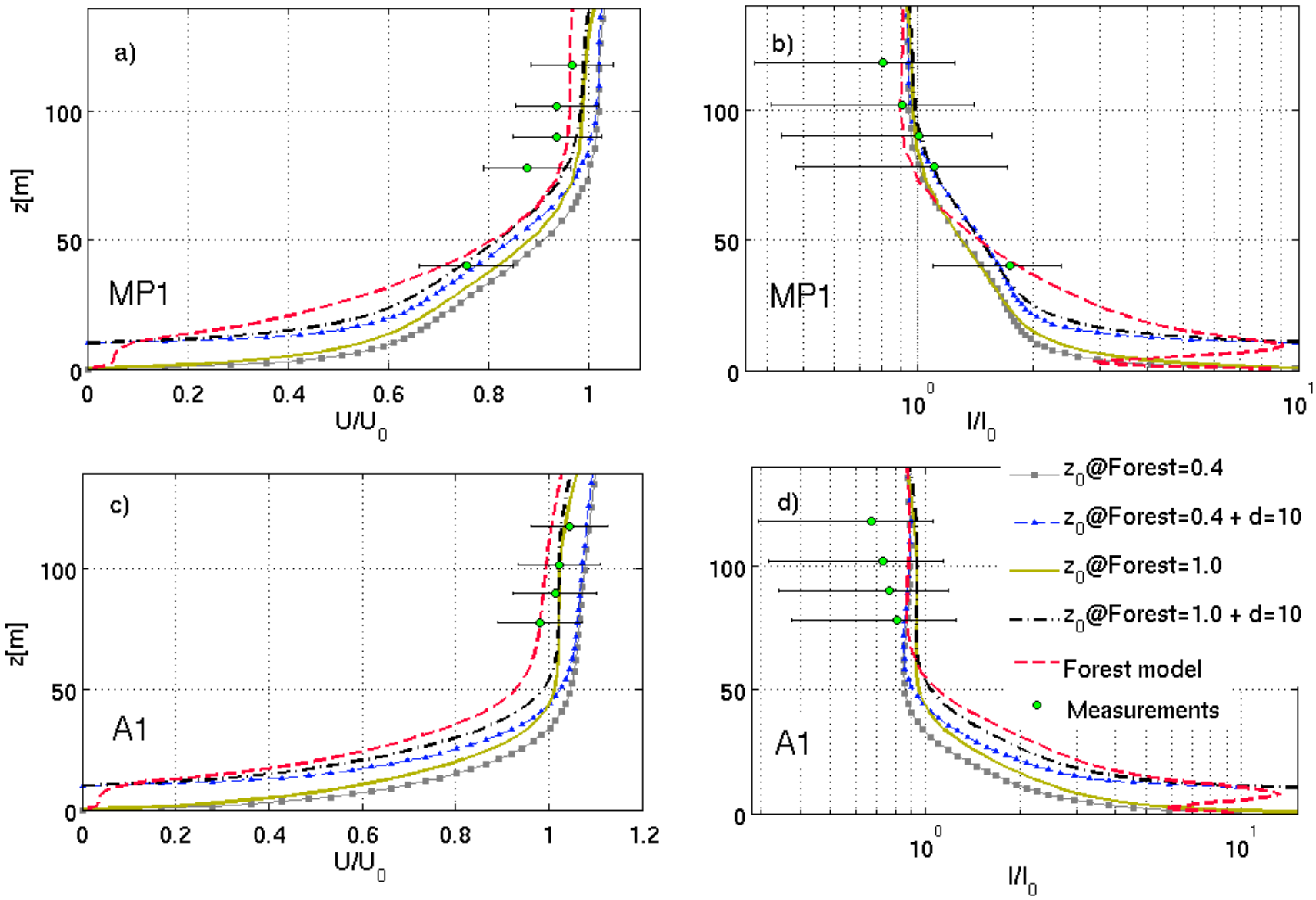


SBL

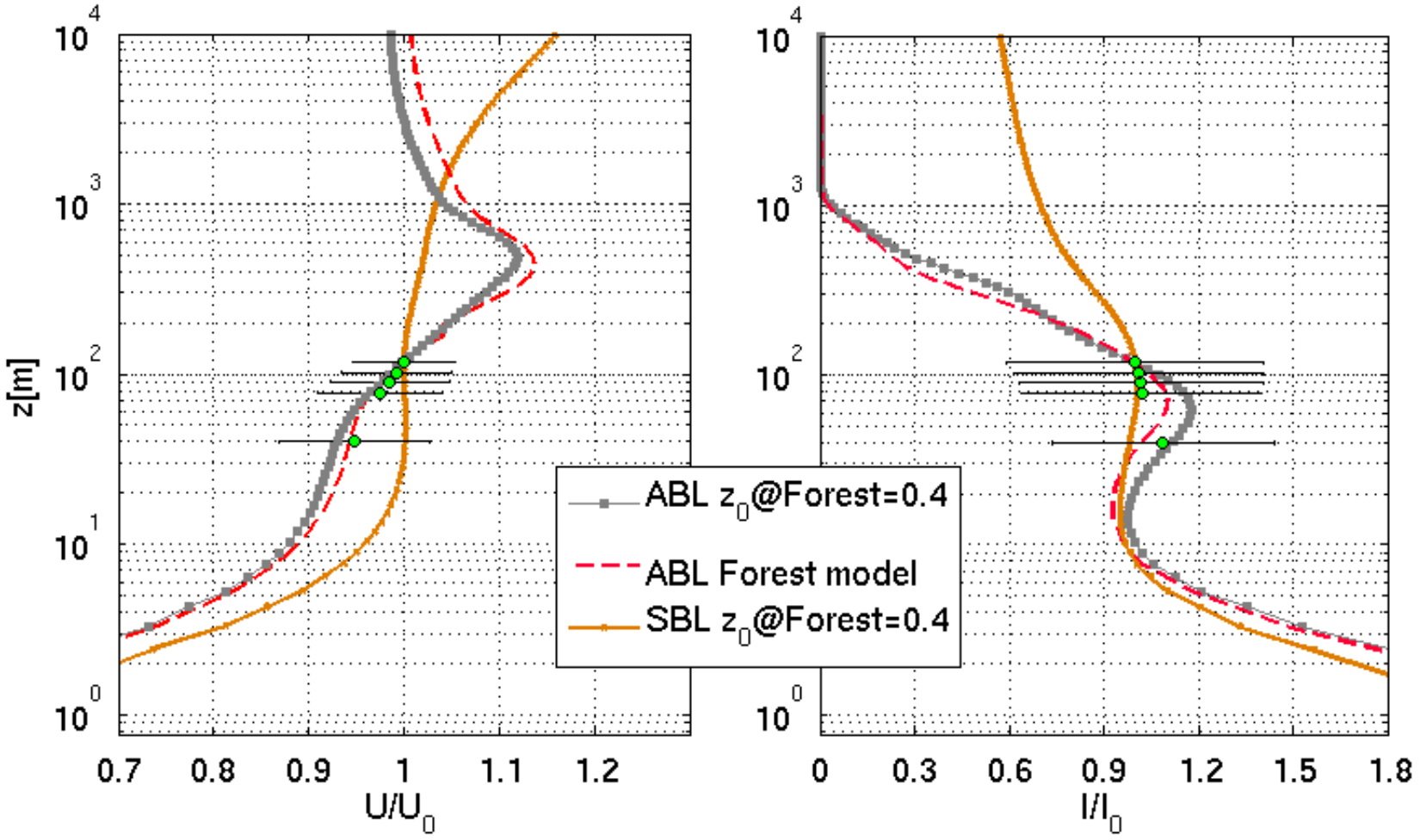


ABL

Profiles of velocity and turbulence intensity at MP1 and A1



Differences at MP1



Results

	MP5		MP1		A1			
	U/U_0	I/I_0	U/U_0	I/I_0	U/U_0	I/I_0	R_U	R_I
$z_0 = 0.4\mathbf{m}$	0.86	5.99	9.59	10.25	5.9	19.1	**7.6**	**14.8**
$z_0 = 0.4\mathrm{m} + d = 10\mathbf{m}$	-	-	7.16	5.72	5.41	18.14	**6.2**	**12.1**
$z_0 = 1.0\mathrm{m}$	-	-	6.35	10.47	1.47	25.56	**3.8**	**18.2**
$z_0 = 1.0\mathrm{m} + d = 10$	-	-	4.39	6.73	1.63	25.86	**2.9**	**16.6**
Forest model	0.51	4.66	3.70	7.62	2.1	18.45	**2.8**	**13.2**

Normalized mean absolute errors (in %) at the three masts.

4 Conclusions, discussion and further work

Conclusions and discussions

- A systematic evaluation of models through a block system is useful to separately associate model deficiencies or uncertainties to specific physical/numerical processes.

- It allows a more objective measure of improvements or models benchmarking purposes.

Discussions

- Idealized test cases are helpful to validate boundary-layer theories, however in complex terrain universal ABL parameterizations developed in horizontally homogeneous conditions are not always suitable.
- Turbulence models and wall functions not suitable for detached flow (flow separation, recirculation areas, etc)
- Domain dimensions and inlet boundary conditions difficult to determine.
- Grid sensitivity can be important and direction dependent
- Wake modeling integration with complex terrain is a mess

Further work

ABL models impose a limit on the turbulence length scale which should improve wind speed predictions outside the surface layer, but the consequences of such an approach for the near-ground flow over complex terrain, especially in areas of recirculation, require further investigation

Neutral is only a transitional state between unstable and stable… in general we rely that unstable and stable cases compensate each other.

Implementation of full ABL formulation from Sogachev et al. 2012 and Koblitz et al. 2013.

Aknowledgemnets

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Thank you

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