Improvements in wind resource assessment for the Québec market

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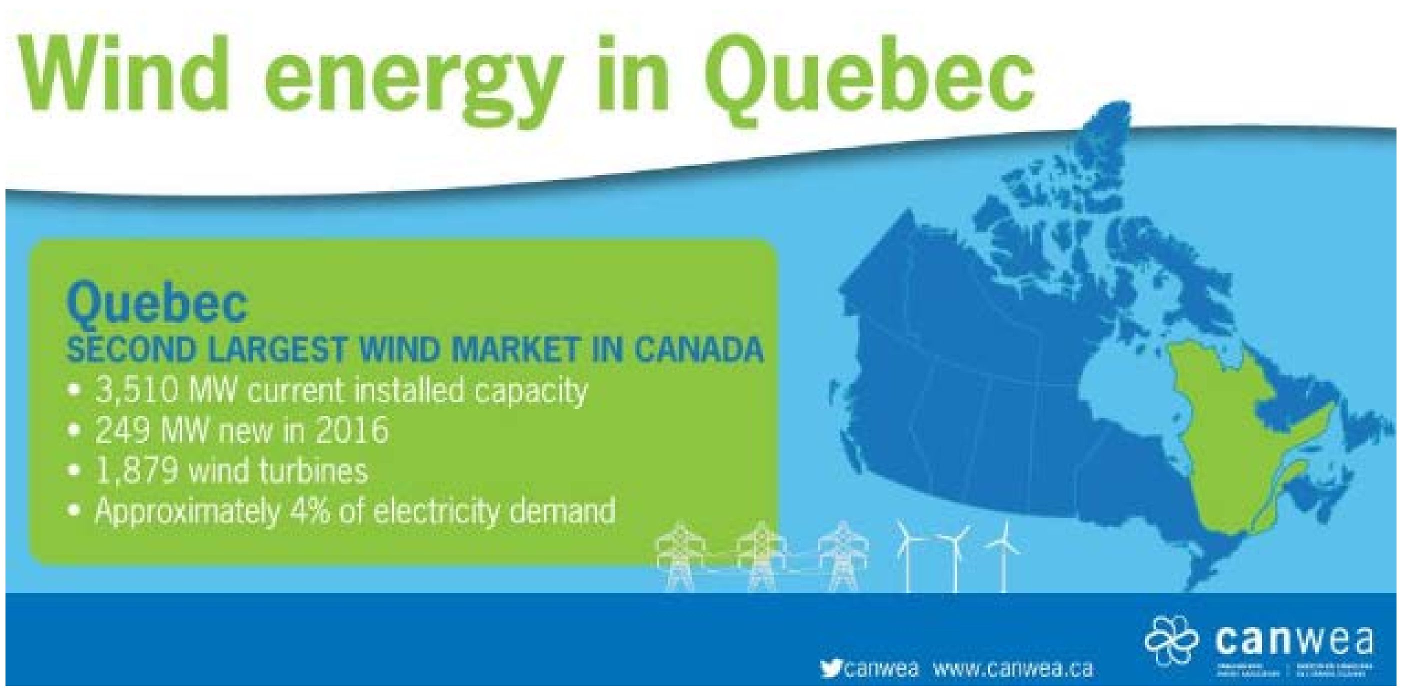
Journée de la recherche FRQNT
10 avril 2017

Wind energy installed capacity (Canada and Québec)

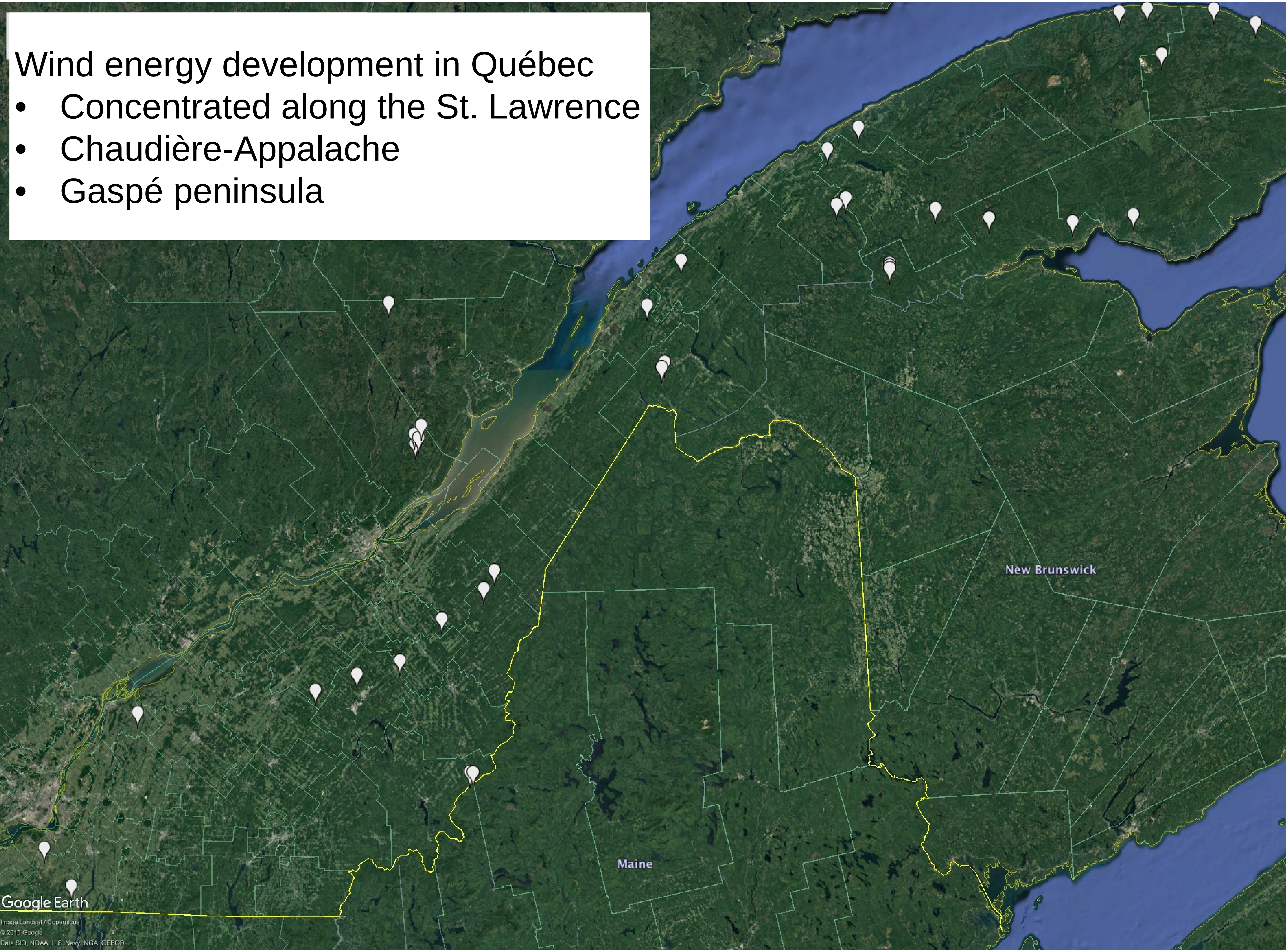
- Canada 8th in the world
- Vision to install 500 MW per year (2018-2025)



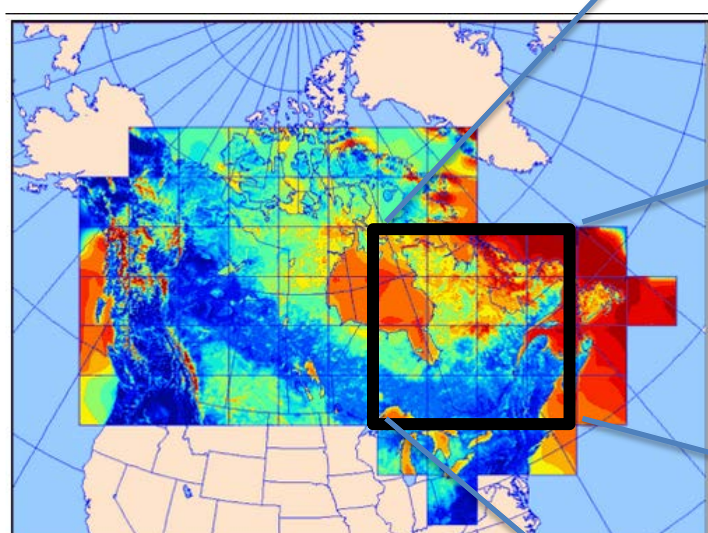
Source: http://canwea.ca/

Wind energy development in Québec

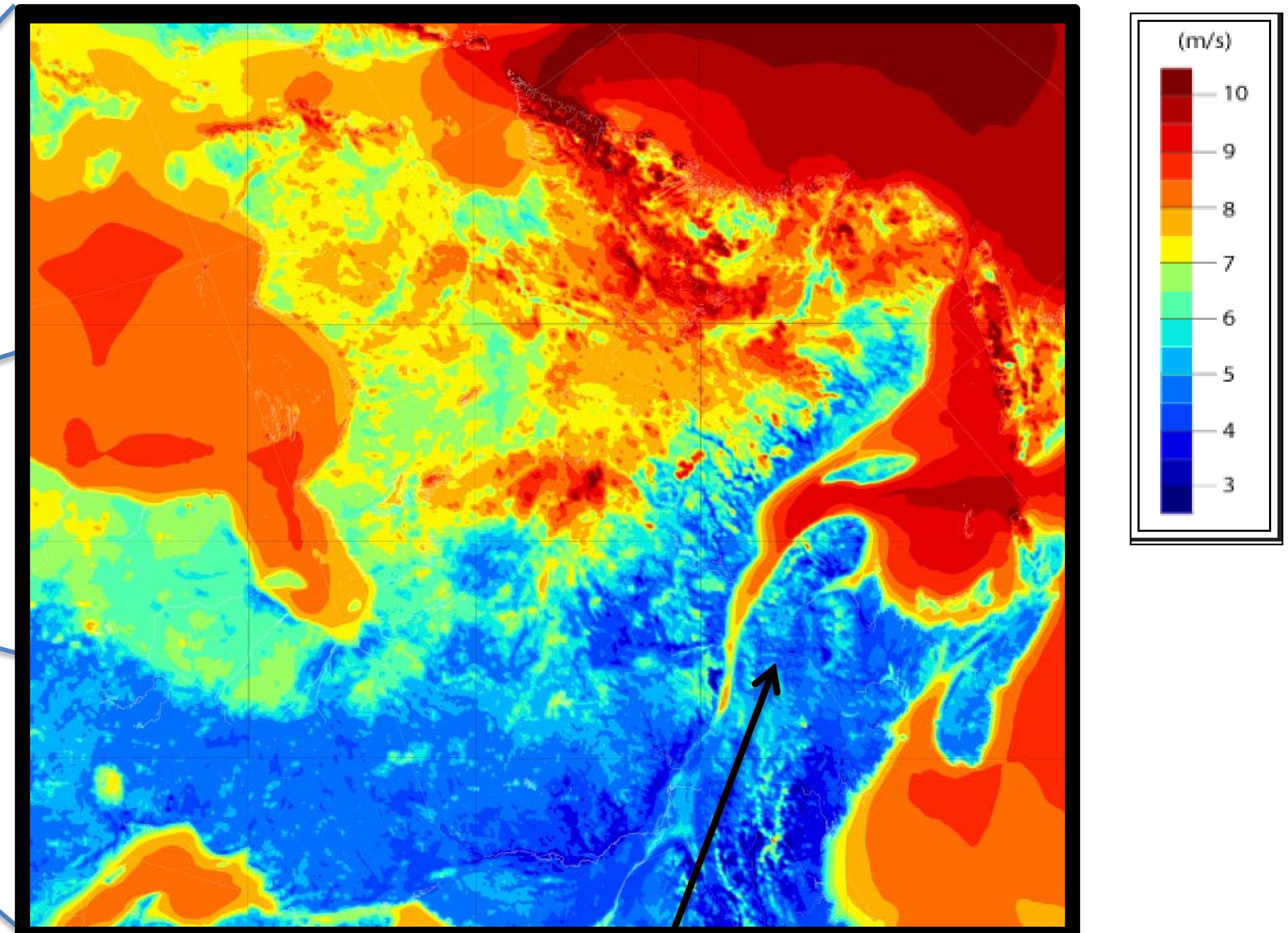
- Concentrated along the St. Lawrence
- Chaudière-Appalache
- Gaspé peninsula



The wind resource in Québec



Source: http://www.windatlas.ca/maps-en.php



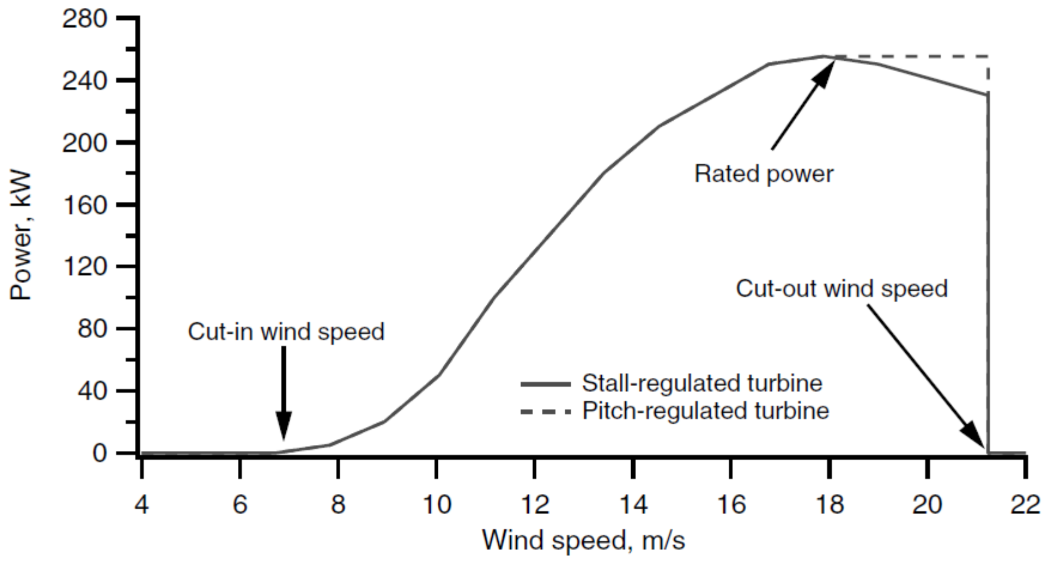
Low wind speeds and complex topography (varied terrain + forests)

Wind farm planning and production forecasting

The power generation cannot be exactly forecasted due to the intermittent nature of the wind[1].

The forecasting of energy yield is obtained by integrating two terms:

1. the turbine power curve
2. the wind resource[2]



1 Lange, M. & Focken, U. (2006). Physical approach to short-term wind power prediction.
2 Ayotte, K. W. (2008). Computational modelling for wind energy assessment. Journal of wind engineering and industrial aerodynamics, 96(10), 1571–1590.

Wind resource assessment

Commonly, campaign of ~1 year wind measurements extracted from a few anemometers.

To have the wind map of the whole site requires **the spatial extrapolation of a non-linear field**.

- A combination of microscale modelling and statistical tools is often the most reliable method
- However, the process is far from exact

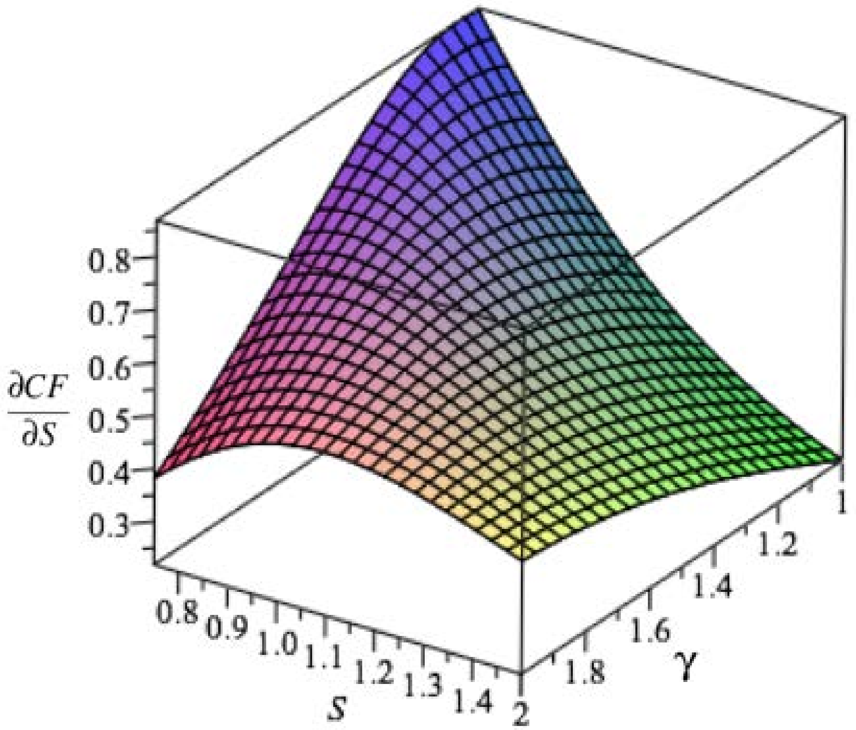
The effect of uncertainty

To attract investment in the wind energy sector, financial risk needs to be minimized.

There is a direct link between prediction accuracy and financial risk. **Uncertainty in energy prediction can be decreased with better modelling**.

The Quebec context is *unique*:

- Uncertainty is inversely proportional to wind speed (model accuracy more important for low wind speed sites)
- But complex terrain (with forest) is hardest to accurately model!



The promise of computational fluid dynamics

Model	Linearized (WAsP, MS-Micro, *etc*)	**RANS**	LES
Assumption to resolve convection	Linearized flow model	**Time-averaged flow and mean flow turbulence properties**	Mean flow plus large eddies
Maturity for wind energy purposes	Routinely used	**Sometimes used**	Rarely used
Computational resources	Economical	**Modest**	Very costly
Reliability	Good results for simple to moderately complex terrain	**More appropriate for very complex sites but treatment of turbulence limits accuracy**	Many fewer theoretical limitations, but difficult to realize

Biggest challenges

Terrain

- Especially sharp features that may cause flow separation/recirculation

Forest cover

- Acts as a momentum sink and source of turbulence

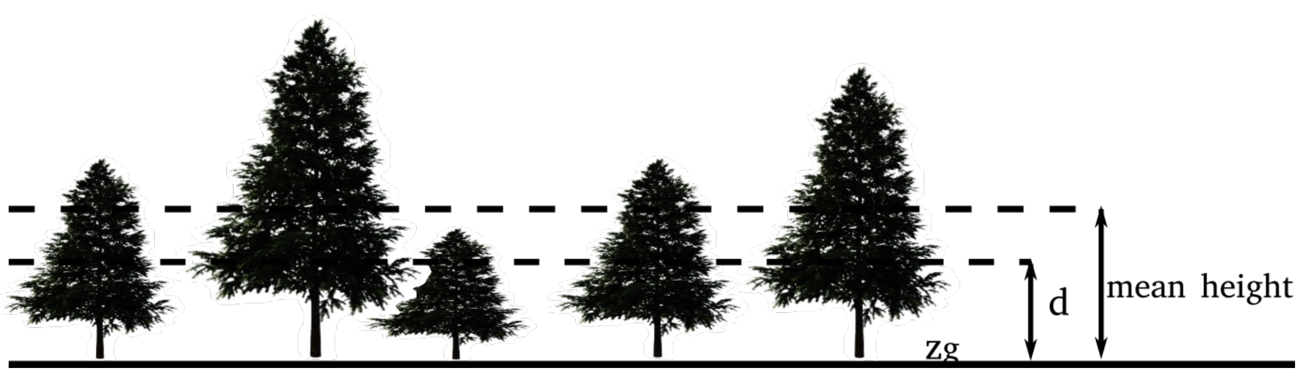
Thermal effects

- Increases/decreases turbulence depending on stratification

Forest modelling

Displacement height (DH) model
Assumption of a solid volume of leaves, therefore a logarithmic wind speed profile will start at its edge[5].

Promising results[6,7] but does not consider the aerodynamic drag due to the particular foliage.



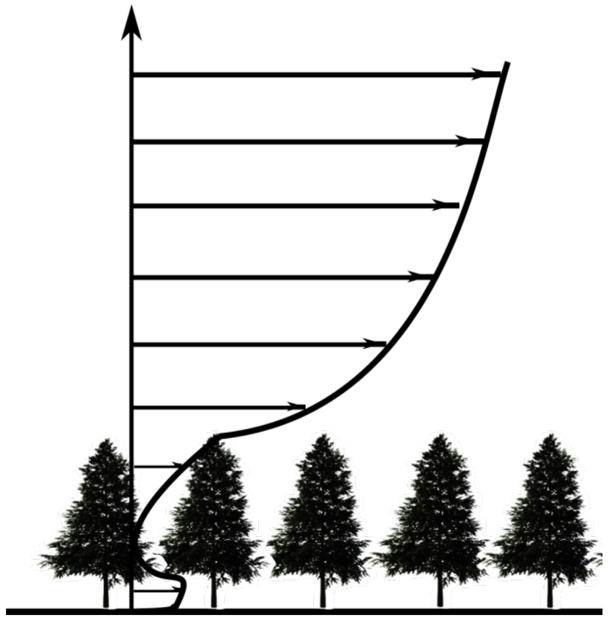
5 Stull, R. B. (1988). An Introduction to Boundary Layer Meteorology.
6 Raupach, M. R. (1994). Simplified expressions for vegetation roughness length and zero-plane displacement as functions of canopy height and area index. Boundary-layer meteorology, 71(1-2), 211–216.
7 Verhoef, A., McNaughton, K. G. & Jacobs, A. F. G. (1997). A parameterization of momentum roughness length and displacement height for a wide range of canopy densities. Hydrology and earth system sciences, 1(1), 81–91.

Forest modelling

Canopy model

It aims to represent the drag effect of the forest per unit volume in the governing equations (as source terms)

Originally developed by Svensson[8], it has been implemented in several computational codes[9]. Important research subject at ETS under direction of Prof. Christian Masson[10,11,12,13].



8 Svensson, U. & Haggkvist, K. (1990). Two-equation turbulence model for canopy flows. Journal of wind engineering and industrial aerodynamics, 35(1), 201–211.
9 Lopes da Costa, J. C., Castro, F. a., Palma, J. M. L. M. & Stuart, P. (2006). Computer simulation of atmospheric flows over real forests for wind energy resource evaluation.
10 Dalpé, B. & Masson, C. (2008). Numerical study of fully developed turbulent flow within and above a dense forest. Wind energy, 11(5), 503–515.
11 Dalpé, B. & Masson, C. (2009). Numerical simulation of wind flow near a forest edge . Wind Engineering & Industrial Aerodynamics 97(5), pp.228-241.
12 Jeannotte, Eric (2013). Estimation of lidar bias over complex terrain using numerical tools. M.Ing thesis, École de Technologie Supérieure.
13 Ben Younes, Hajer (2016). Simulation de la couche limite atmosphérique sur un couvert forestier en terrain avec orographie. PhD thesis, École de Technologie Supérieure.

Mathematical model

Steady incompressible RANS eqns at large *Re*

Conservation of mass

$$\frac{\partial U_j}{\partial x_j} = 0$$

Conservation of momentum

$$\frac{\partial (U_i U_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_j \partial x_j} - \frac{\partial \overline{u_i' u_j'}}{\partial x_j} + S_{Ui}$$

Transport of turbulent kinetic energy

$$\frac{\partial (k U_i)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \varepsilon + S_k$$

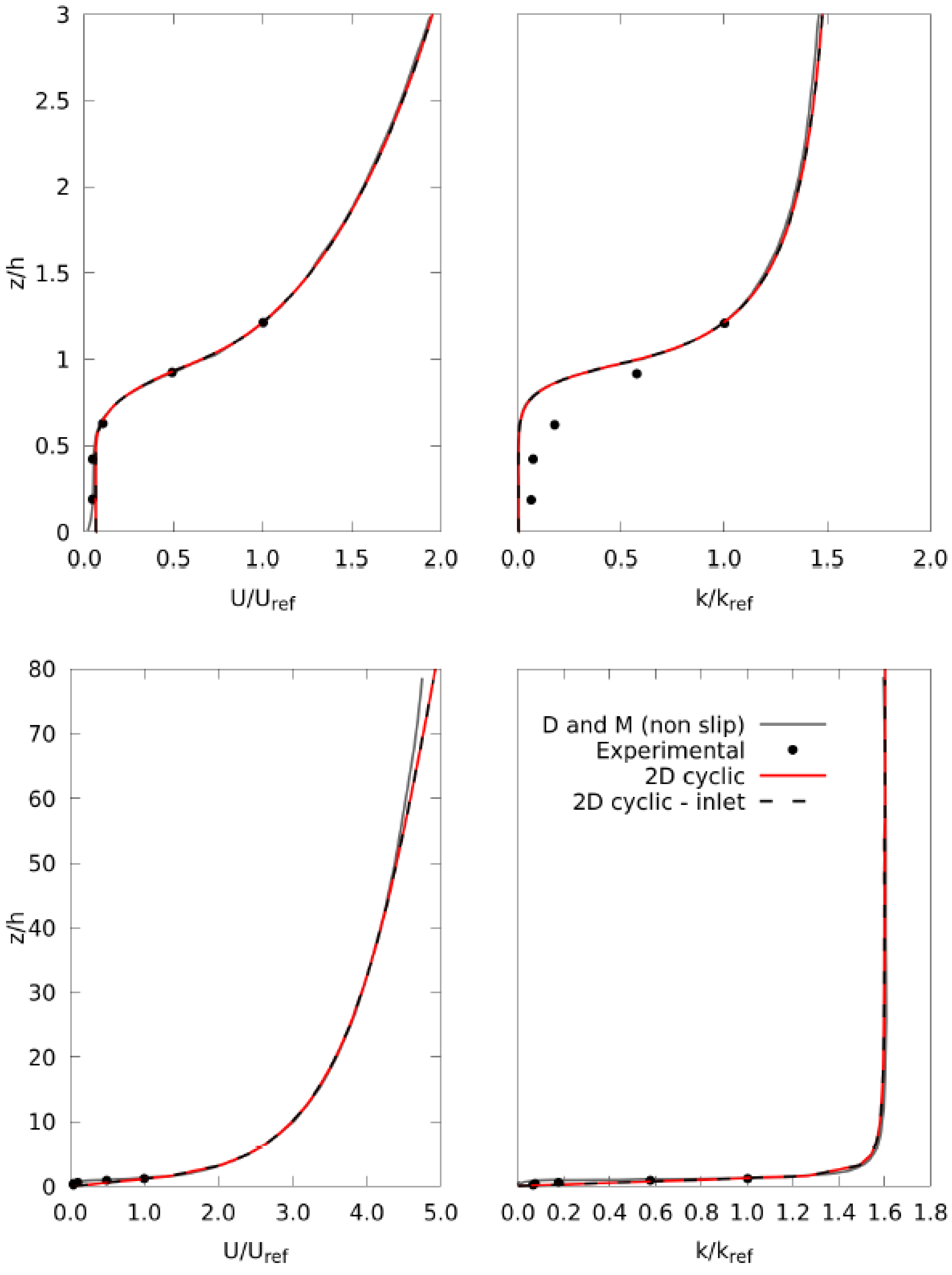
Transport of turbulent dissipation rate

$$\frac{\partial (\varepsilon U_i)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\nu + \frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{\varepsilon 1}\frac{\varepsilon}{k}G_k - C_{\varepsilon 2}\frac{\varepsilon^2}{k} + S_\varepsilon$$

Validation of canopy model

Black spruce modelling

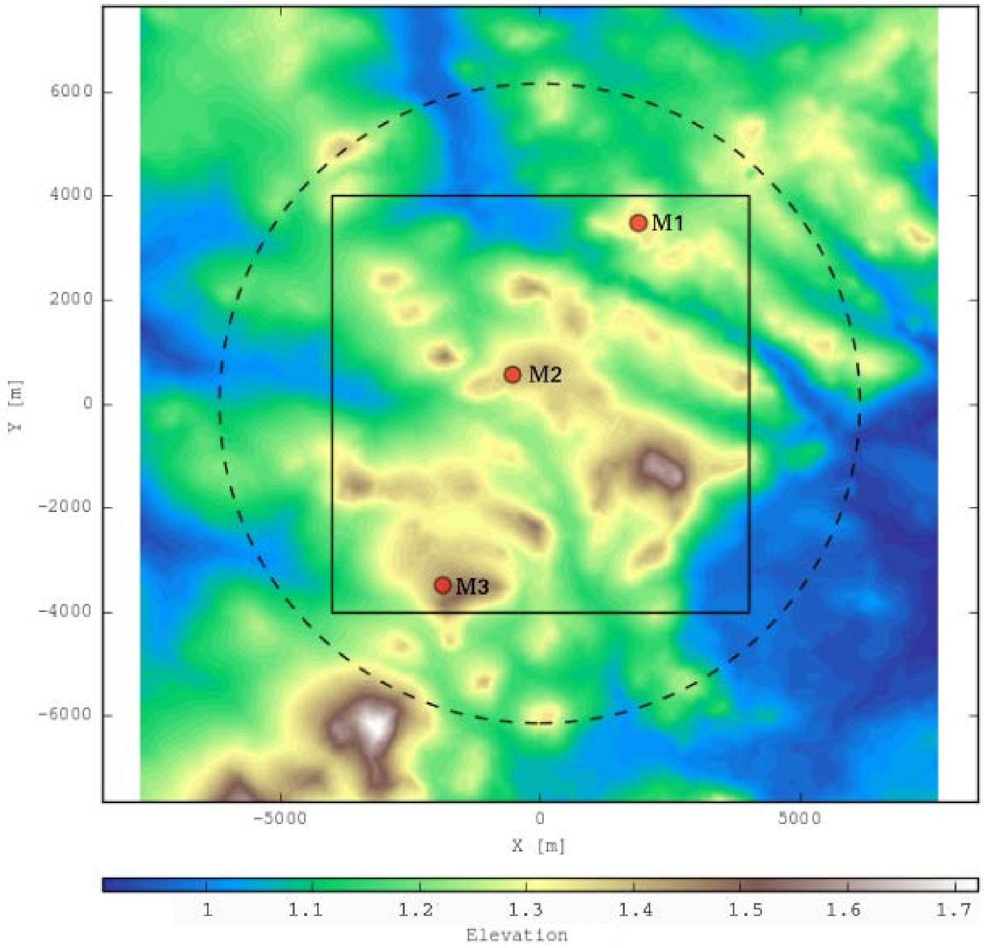
Good results in comparison with work of Dalpé and Masson[10].

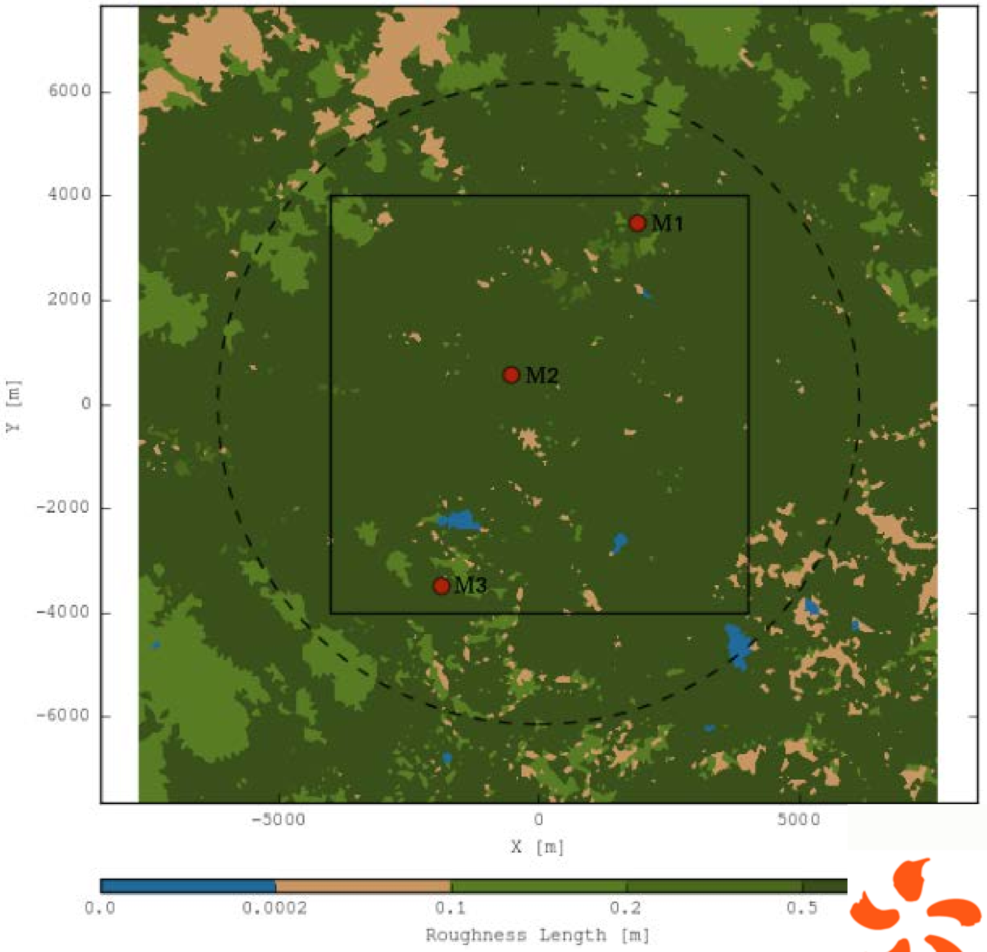


10 Dalpé, B. & Masson, C. (2008). Numerical study of fully developed turbulent flow within and above a dense forest. Wind energy, 11(5), 503–515.

Real case

Two years of wind measurements at a potential wind farm in Québec were carried out by **EDF-EN** and were used for validation purposes.

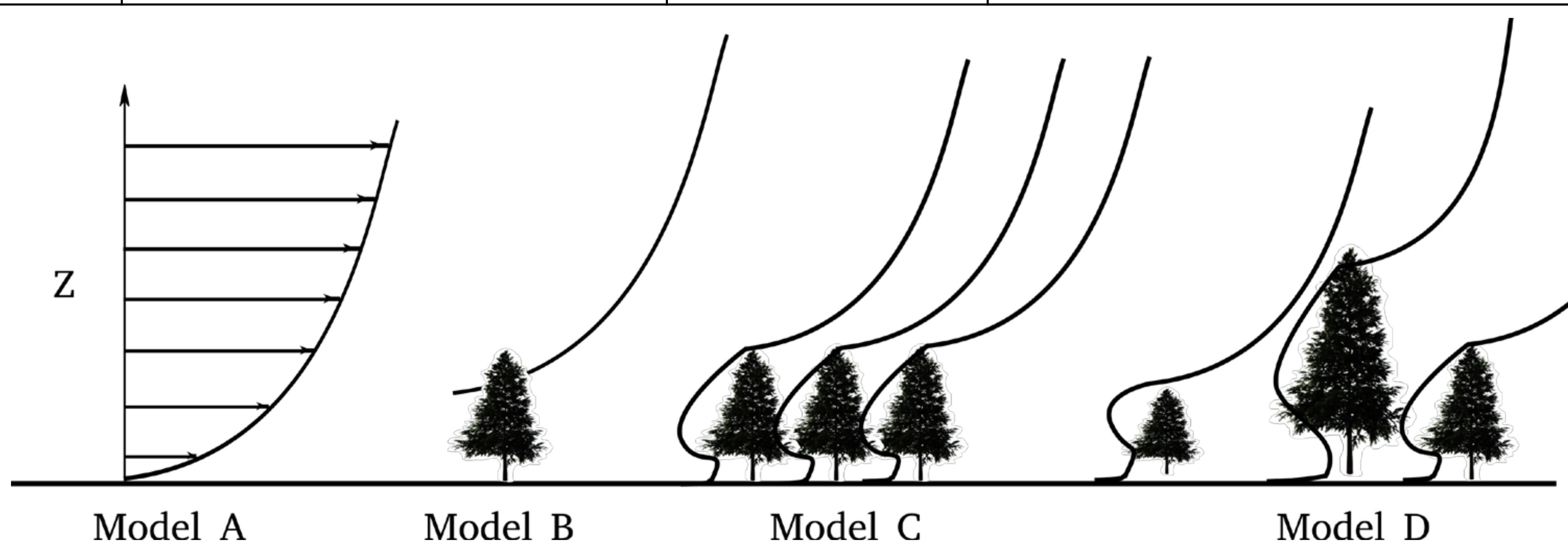




edf energies nouvelles

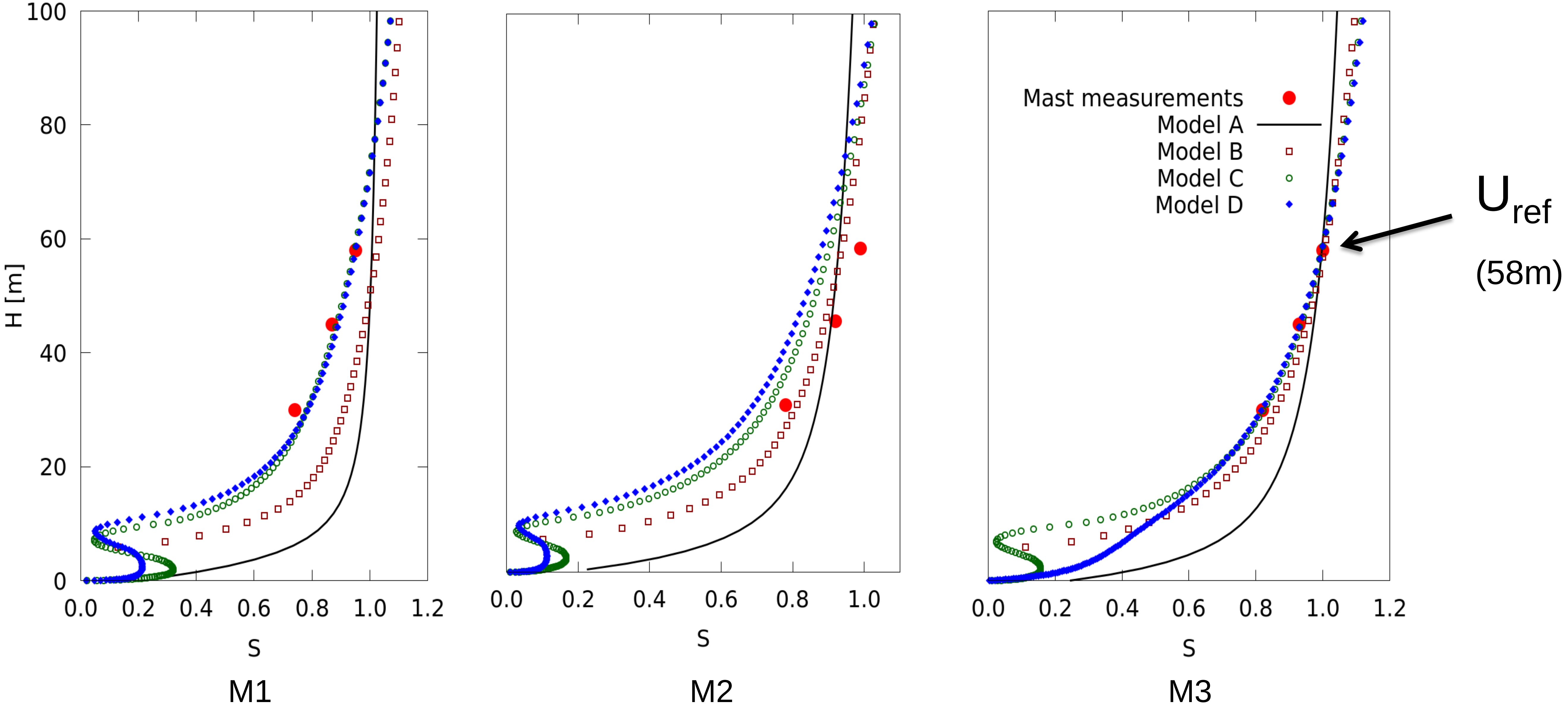
Real case

Case	Model	Turbulence closure	Logarithmic wind profile trough
A	Terrain only	Standard	No obstacles
B	Displacement height (DH)		No obstacles and terrain elevation
C	Canopy	Modified	Uniform forest distribution
D			Real forest map distribution



RANS results for forest model

Speed-up factor $S = \frac{U}{U_{ref}}$



To be submitted for publication in ***American Society of Mechanical Engineers***

The influence of temperature

- Thermal effects also play a role in wind resource assessment as they directly affect turbulence production
- A stable atmosphere will dampen turbulent eddies and reduce momentum exchange -> High wind shear, low TI
- An unstable atmosphere will enhance turbulence eddies and increase momentum exchange -> Low wind shear, high TI
- Particularly true for offshore sites

Mathematical model

Steady incompressible RANS eqns at large *Re*

Conservation of mass

$$\nabla \cdot \mathbf{U} = 0$$

Conservation of momentum

$$\mathbf{U} \cdot \nabla U_i = -\frac{\partial p}{\partial x_i} + \nabla \tau - \alpha \Delta \Theta \mathbf{g}$$

Transport equation for potential temperature

$$\mathbf{U} \cdot \nabla \Theta = \nabla \cdot (\Gamma_\mathrm{T} \nabla \Theta)$$

Transport of turbulent kinetic energy

$$\nabla \cdot k\mathbf{U} = \nabla \cdot \left(\frac{\nu_\mathrm{T}}{\sigma_k} \nabla k \right) + \Pi_k - \varepsilon$$

Transport of turbulent dissipation rate

$$\nabla \cdot \varepsilon \mathbf{U} = \nabla \cdot \left(\frac{\nu_\mathrm{T}}{\sigma_\varepsilon} \nabla \varepsilon \right) + P_\varepsilon - C_{\varepsilon 2} \frac{\varepsilon^2}{k}$$

Governing equations

Source term adjustment in dissipation equation

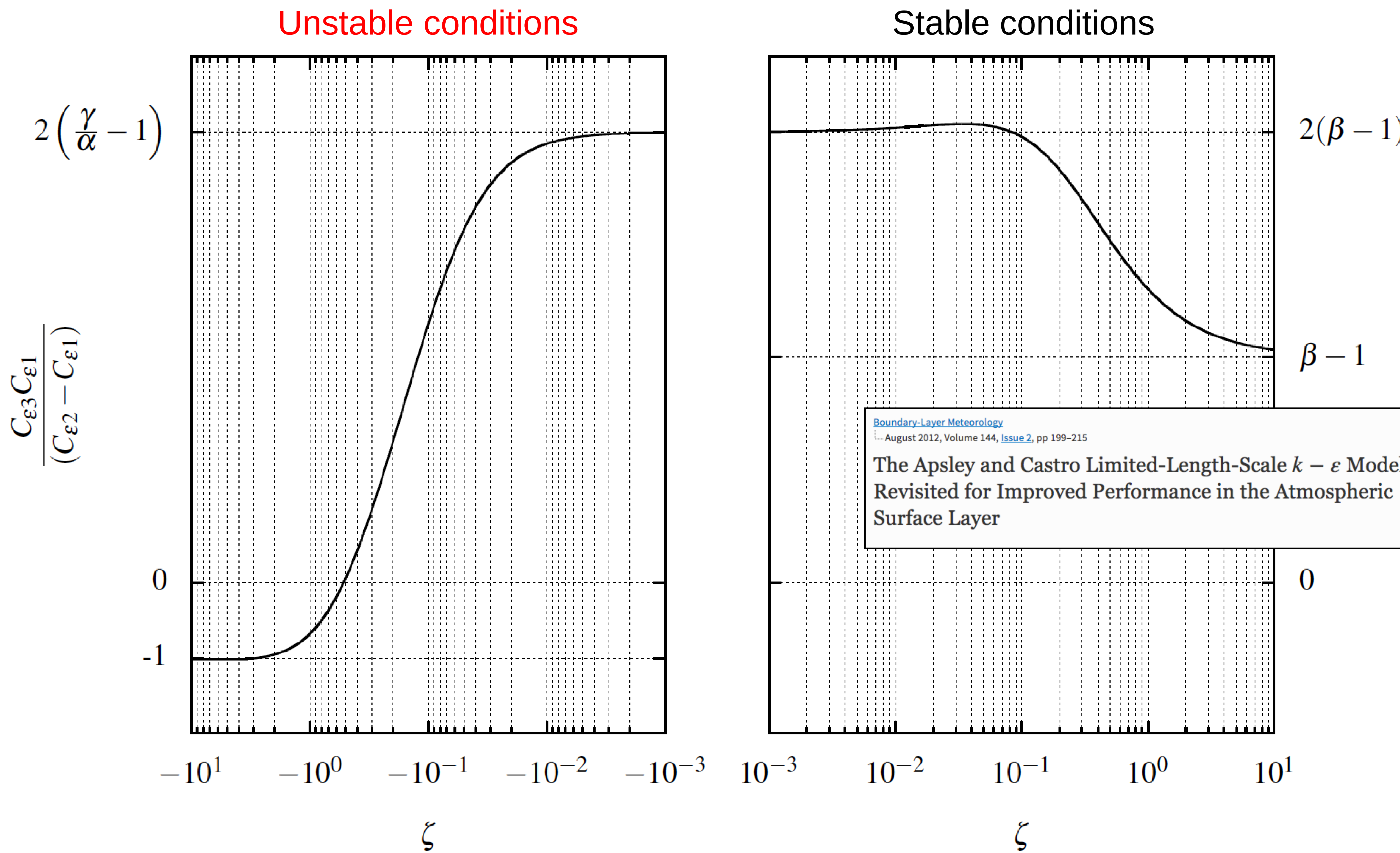
$$P_\varepsilon = C_{\varepsilon 1}\left(1 + C_{\varepsilon 3} R'_f\right)\frac{\Pi_k \varepsilon}{k}$$

- Many authors have proposed corrections to the production term to account for stability effects

- We seek a closure which exactly agrees with similarity theory, *e.g.*

$$U(z) = \frac{u^*}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) - \Psi_M(\alpha, \beta, \gamma, L, z)\right]$$

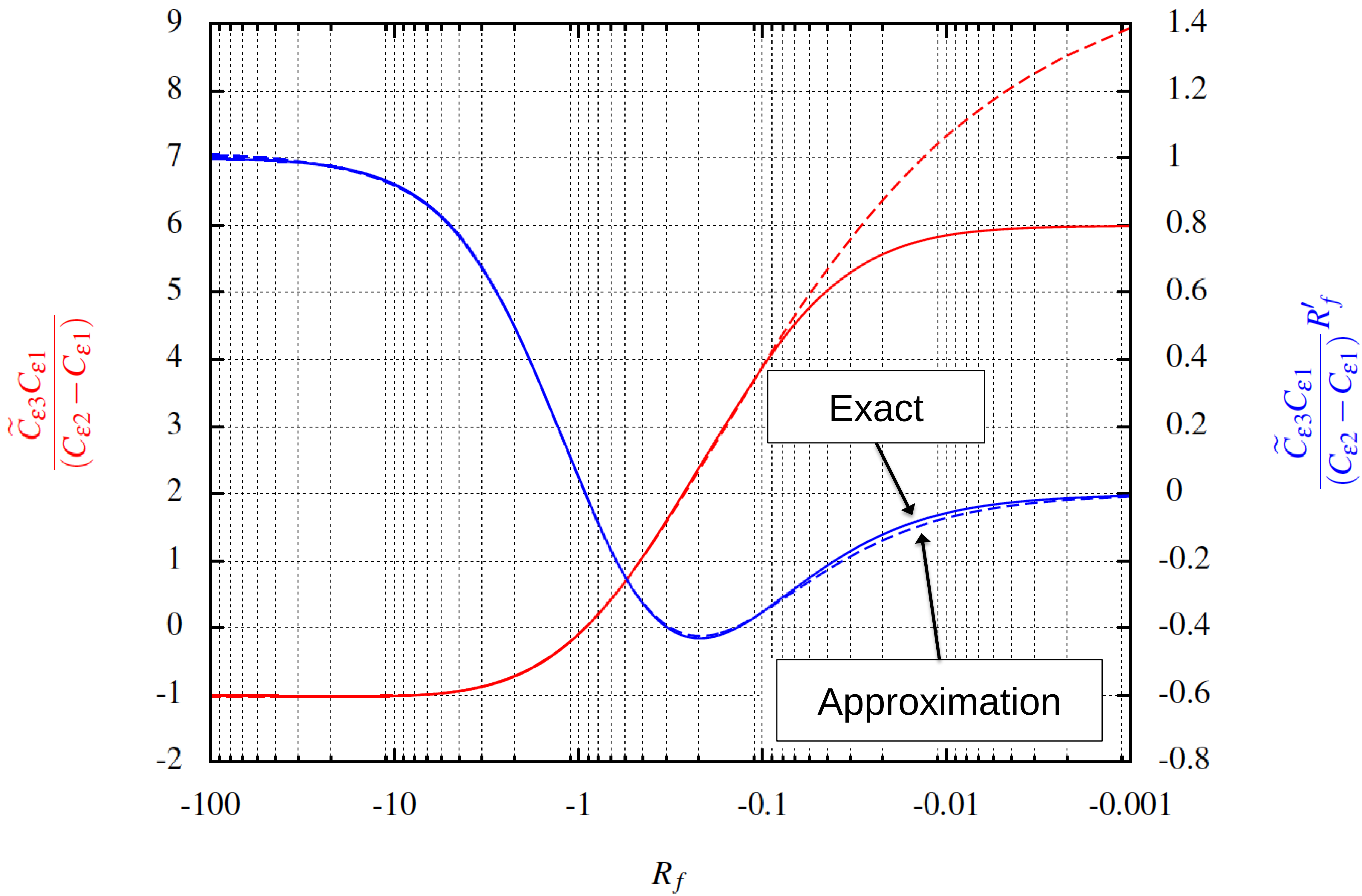
Analytical solution

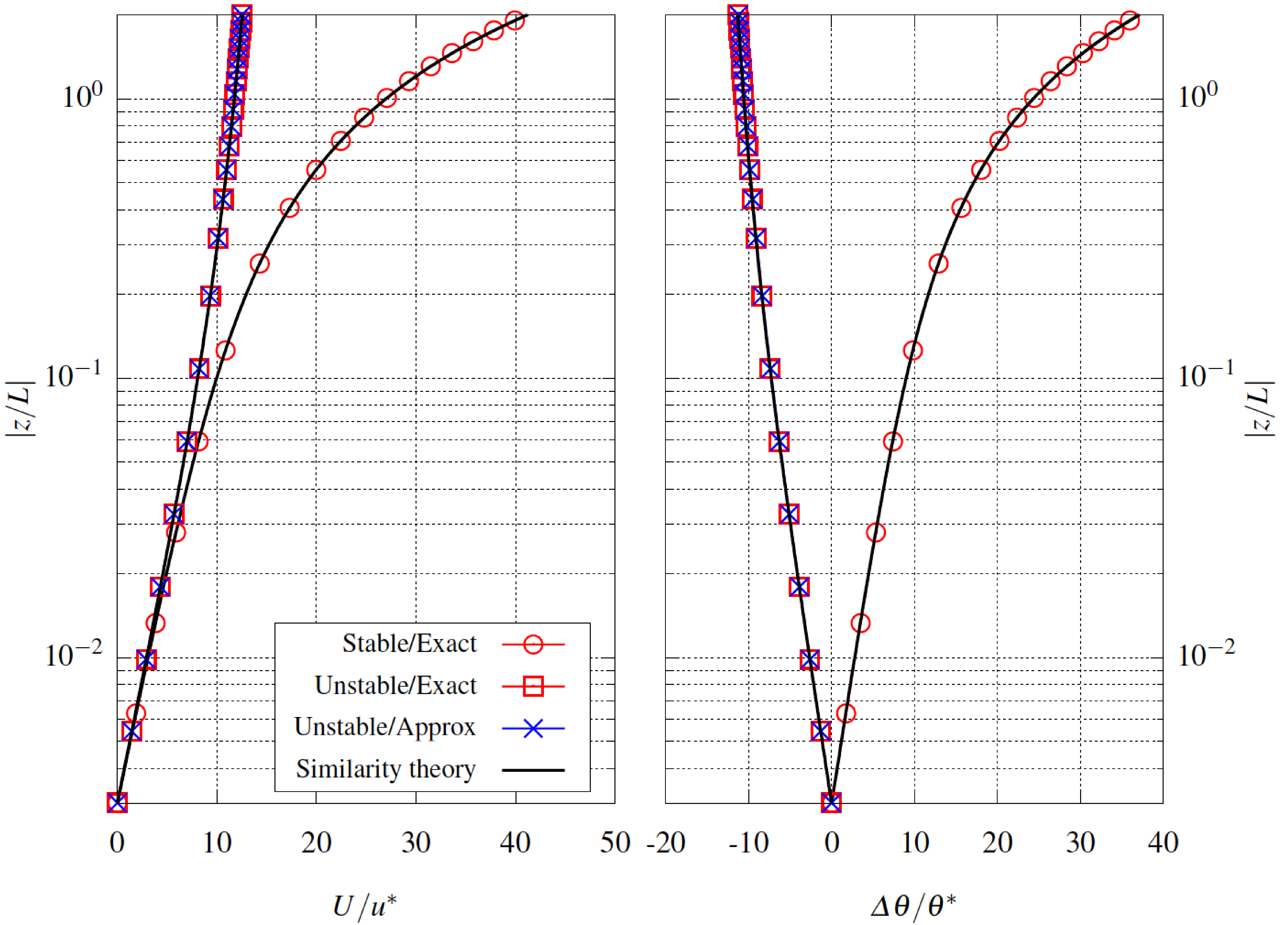


Boundary-Layer Meteorology
August 2012, Volume 144, Issue 2, pp 199–215

The Apsley and Castro Limited-Length-Scale $k-\varepsilon$ Model Revisited for Improved Performance in the Atmospheric Surface Layer

Local approximation





10^0
10^{-1}
10^{-2}
$|z/L|$
0
10
20
30
40
50
-20
-10
U/u^*
$\Delta\theta/\theta^*$
Stable/Exact
Unstable/Exact
Unstable/Approx
Similarity theory

Ongoing research

What about the combined effects of complex topography + forested regions + thermal stratification?

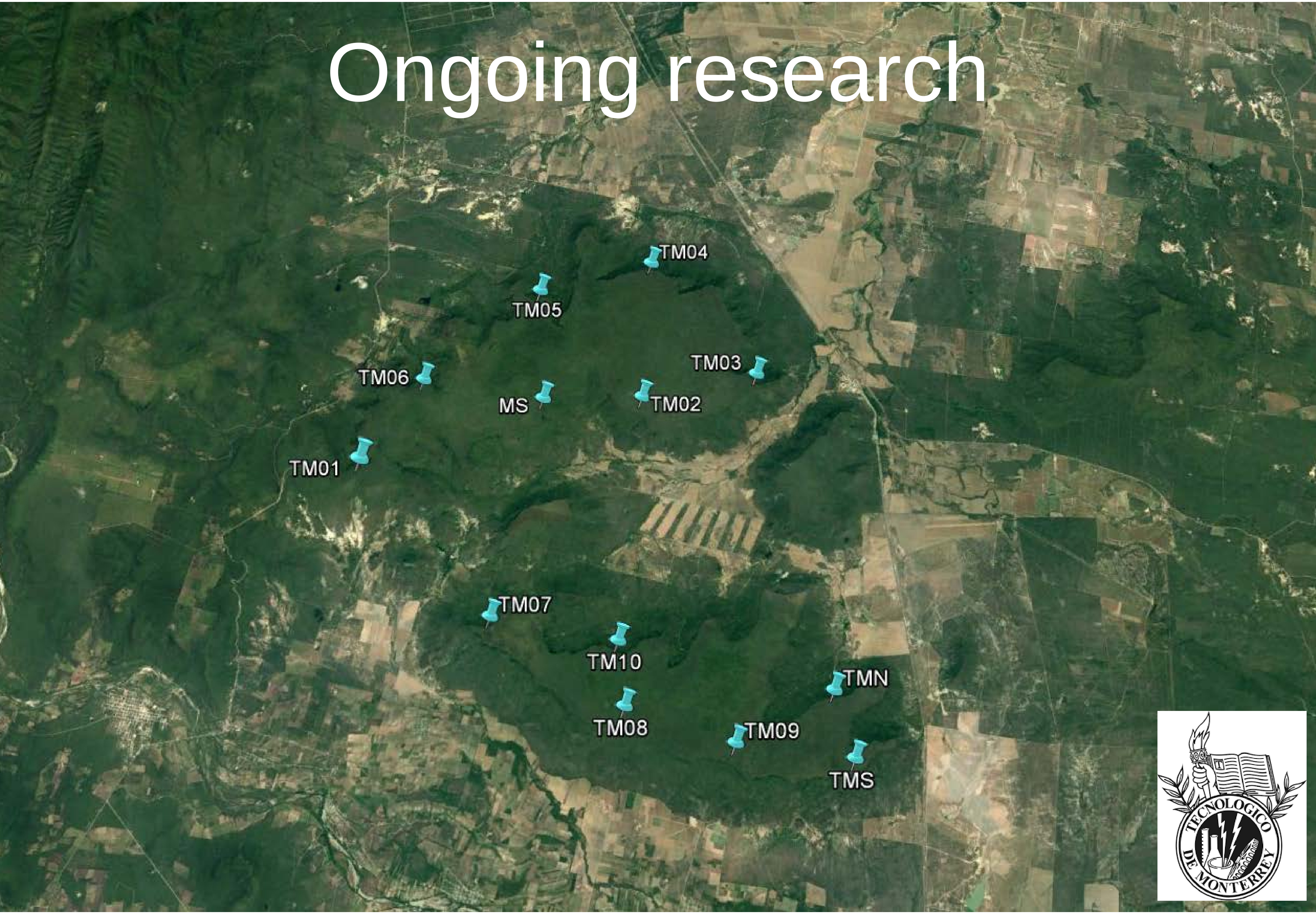
- This is a very active area of research

New collaboration with Tecnológico de Monterrey and Prof. Oliver Probst.

- Two years measurements of wind flow and temperature at several towers (80m) located at the upstream and downstream side of a mesa structure.

Novel dataset where forest and thermal effects may both play an important role

Ongoing research



ÉTS
Le génie pour l'industrie

NEAT
Research Laboratory on the Nordic Environment Aerodynamics of Wind Turbines

Thank you

Instituto de Innovación y Transferencia de Tecnología

EDF energies nouvelles

DAWSON COLLEGE

CONACYT

Tecnológico de Monterrey

Fonds de recherche sur la nature et les technologies
Québec