Wind Flow Over Forested Hills: Mean Flow and Turbulence Characteristics

Peter Stuart

Ian Hunter

J. C. P. Lopes da Costa

José M. L. M. da Palma

What we do with CFD:

- ✓ Gain a qualitative understanding of the flow over a wind farm.
- ✓ Effectively place meteorological masts to quantify site conditions.
- ✓ Site turbines better.
- ✓ Use CFD as a complement to linear and empirical models.

What we don't do with CFD:

- ✗ Wind Resource / Energy Yield Predictions.
- ✗ Use CFD as a replacement for linear / empirical models.

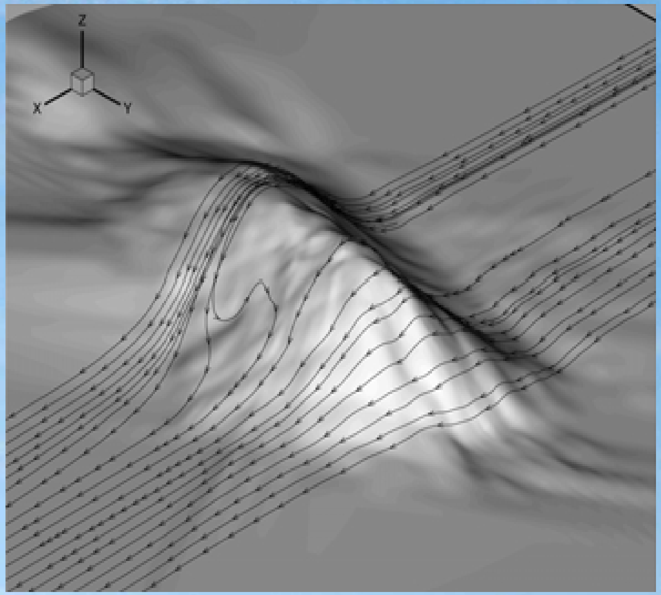
VENTOS

• CFD code specifically designed for wind energy applications at the Engineering Faculty of the University of Porto.

• Verified using the standard Askervein hill test case. Canopy Model verified using 100m measurements above a 20m forest.

• Over ten years R&D at the University of Porto.

• Used at RES for over 6 years.



Simulation of Askervein Flow using VENTOS

Simulation of the Askervein Flow. Part 1: Reynolds Averaged Navier-Stokes Equations (k-e Turbulence Model) (2003) F.A. Castro, J.M.L.M. Palma and A. Silva Lopes. Boundary Layer Meteorology 107: 501-530 (2003)

Lopes da Costa, J. C., Castro F.A., Palma J.M.L.M., Stuart P. “Computer Simulation of Atmospheric Flows over Real Forests for Wind Energy Resource Evaluation”, journal of Wind Engineering and Industrial Aerodynamics, 94 (2006) P. 603-620, 7th February 2006.

Svensson Canopy Model (Original)

The pressure and viscous forces due to the canopy result in an aerodynamic force-per-unit-volume F_i that is parameterised by:

$$F_i = -\frac{1}{2}\rho\alpha C_D \left|\overline{U}\right| U_i$$

- |U| is the local mean velocity modulus
- α (in m^2m^{-3}) is the leaf foliage area per unit of volume
- C_D is the canopy drag coefficient.

The effects of the canopy on turbulence are accounted for by additional terms S_k and S_ε in the transport equations of k and ε

$$S_k = \frac{1}{2}\rho\alpha C_D \left|\overline{U}\right|^3$$

Turbulent Production due to Canopy

$$S_\varepsilon = \frac{1}{2}\frac{\varepsilon}{k} C_{4\varepsilon}\rho\alpha C_D \left|\overline{U}\right|^3$$

Turbulent Dissipation due to Canopy

New Canopy Model

• The new canopy model is similar to the Svensson model but includes extra terms in the turbulence and dissipation equations:

$$S_k = \rho \alpha C_D \left(\beta_p \left| \overline{U} \right|^3 - \beta_d \left| \overline{U} \right| k \right)$$

Turbulent Production due to Canopy

$$S_\varepsilon = \rho \alpha C_D \left(\beta_p C_{4\varepsilon} \frac{\varepsilon}{k} \left| \overline{U} \right|^3 - C_{5\varepsilon} \beta_d \left| \overline{U} \right| \varepsilon \right)$$

Turbulent Dissipation due to Canopy

• The canopy model constants are derived by comparing CFD simulations of an idealised canopy step change with Large Eddy Simulations (LES).

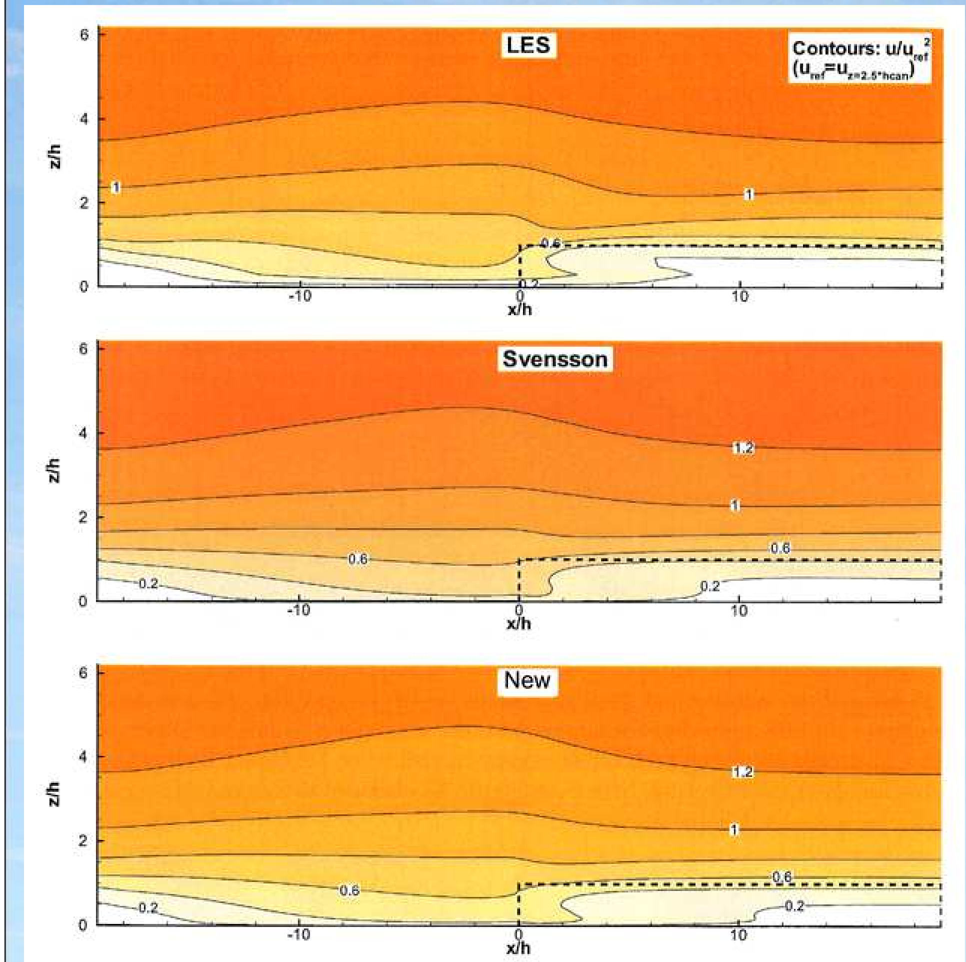
Model	β_p	B_d	$C_{\varepsilon 4}$	$C_{\varepsilon 5}$
Svensson	1.0	0.0	1.95	0.0
Lopes da Costa (New Model)	0.17	3.37	0.9	0.9

Lopes da Costa, J. C. P., “Atmospheric Flow Over Forested and Non-Forested Complex Terrain”, PhD Thesis University of Porto, July 2007.

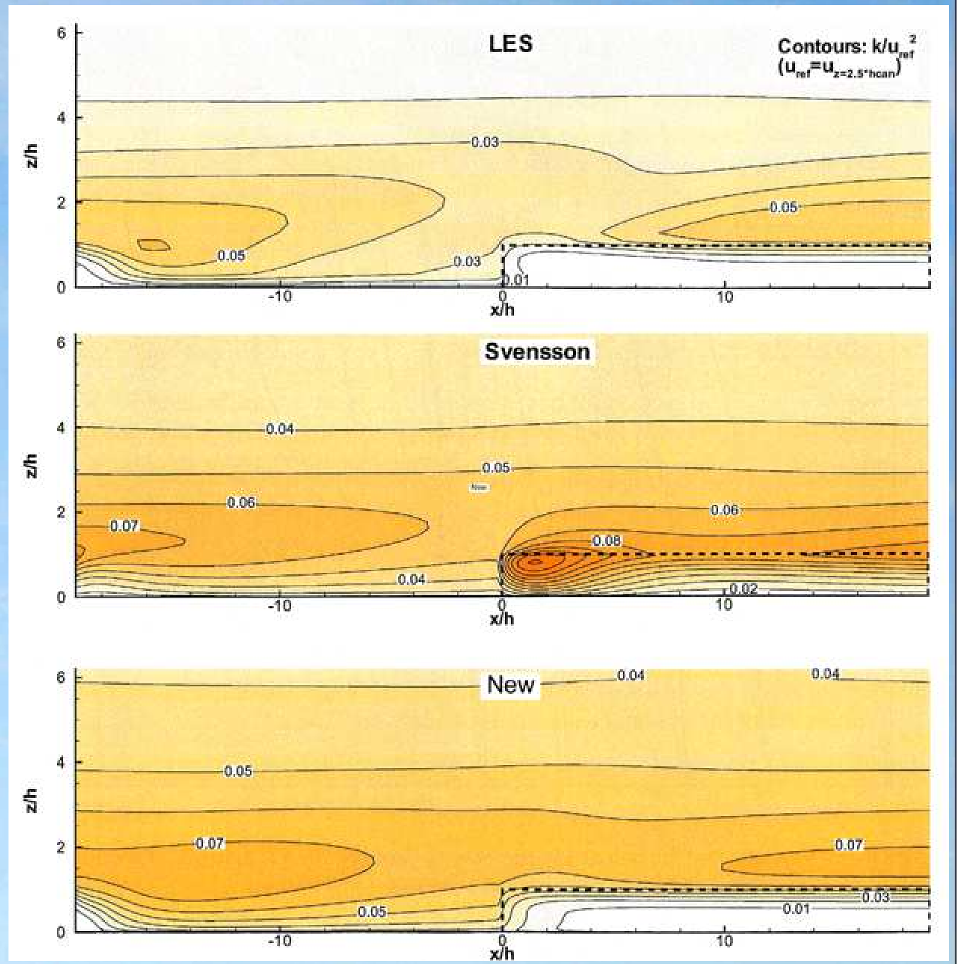
wind flow prediction

RANS / CFD vs. Large Eddy Simulation (LES)

Wind Speed

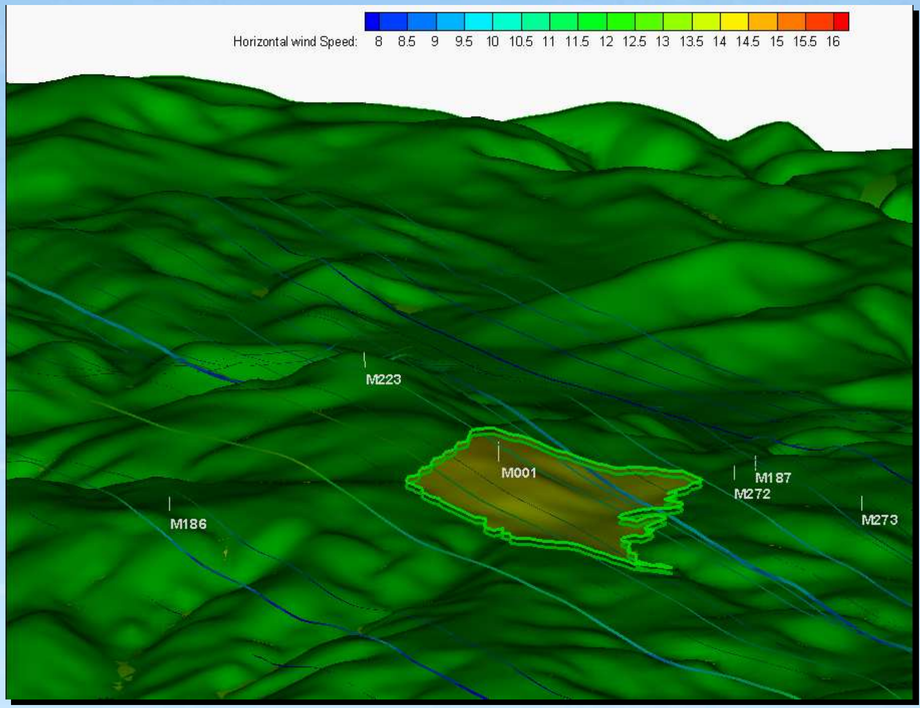


Turbulence



Real Test Site

- European site with complex orography and extensive forest cover.
- Tree height ~ 15m.
- 6 meteorological masts used for validation.

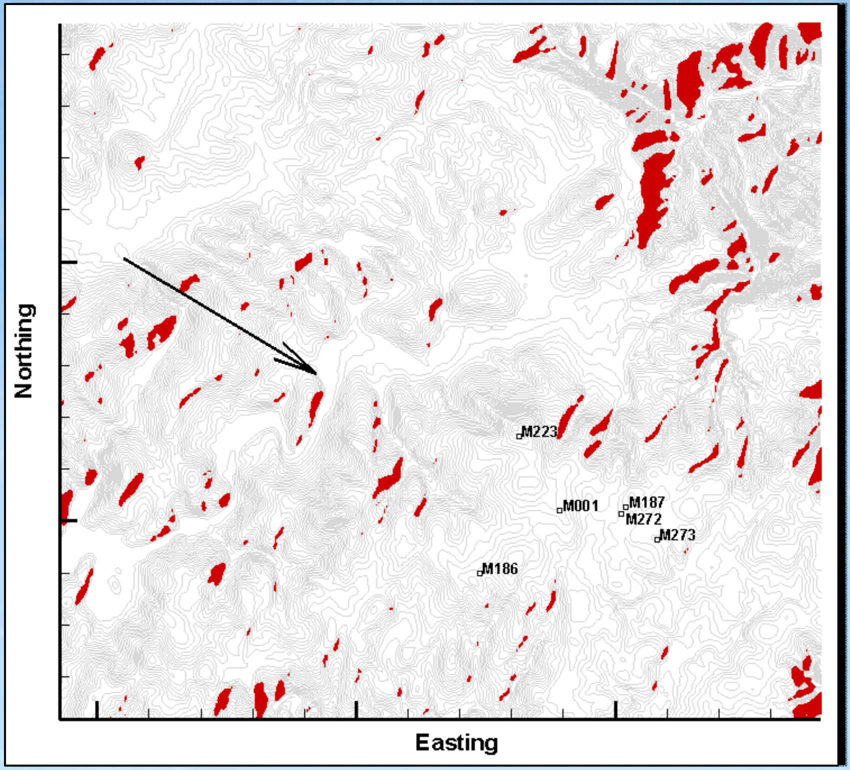


Mast	Anemometer Height, Upper / Lower (m)
M001	40 / 30
M186	68 / 40
M187	68 / 40
M223	68 / 40
M272	68 / 40
M273	68 / 40

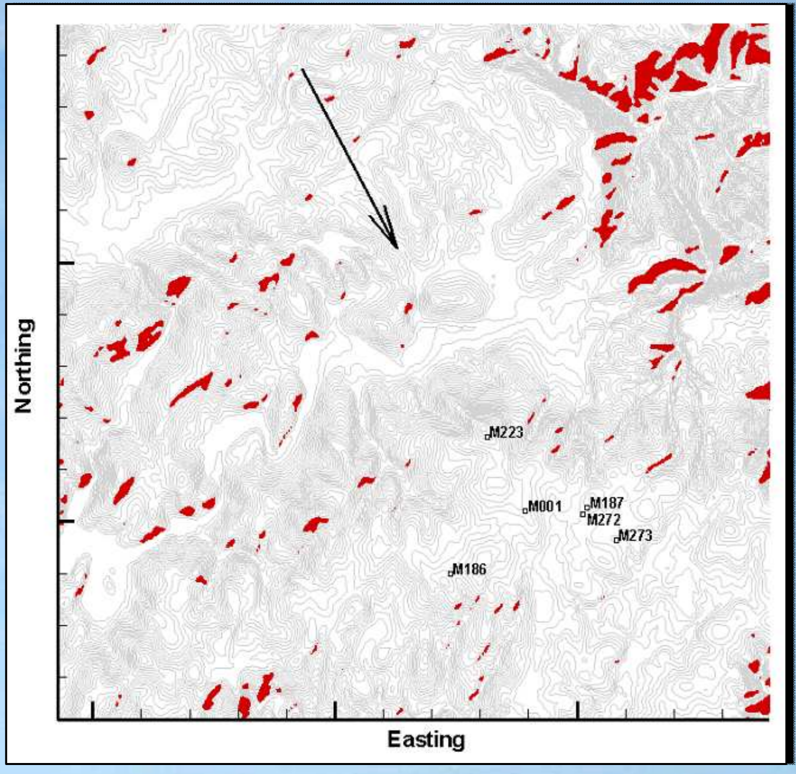
wind flow prediction

Critical Slopes

Adverse slopes which exceed the two dimensional threshold for flow separation (17°) are indicated in red.



Critical slopes for direction of 300°

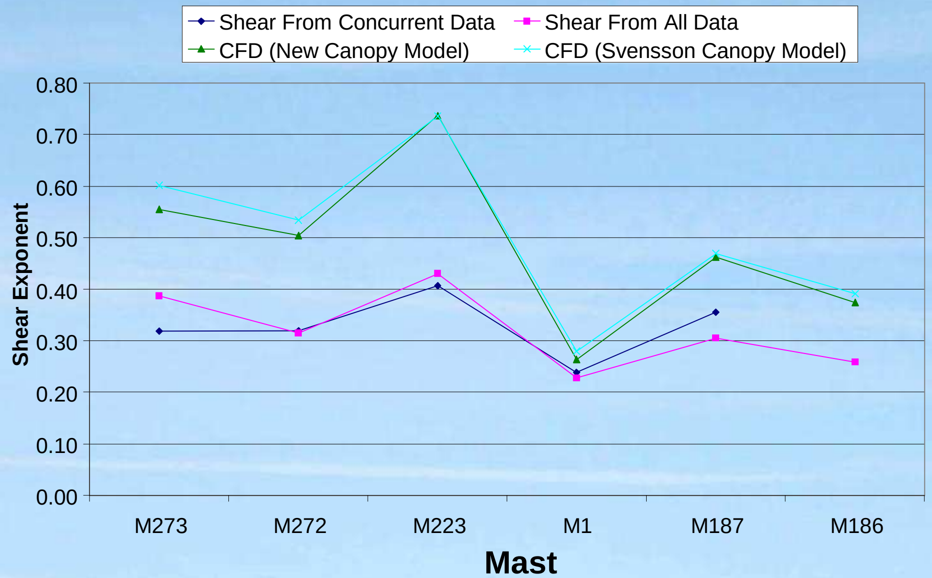


Critical slopes for direction of 330°

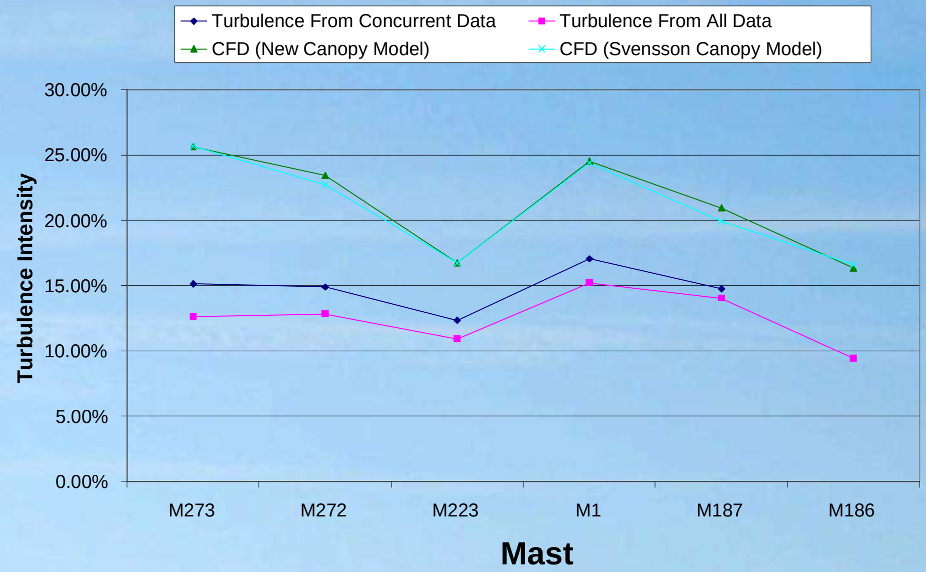
Kaimal, J.C., Finnigan, J.J., “Atmospheric Boundary Layer Flows: Their Structure and Measurement”, Oxford University Press 1994.

Initial CFD Estimates

- Tree Height = 15m
- Canopy Drag Coefficient C_D = 0.25
- Canopy Density α = 0.2



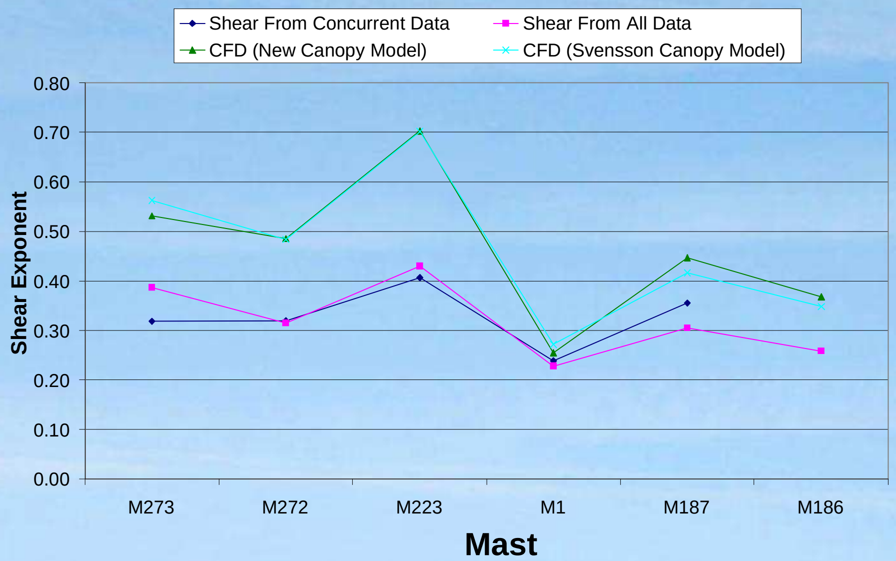
Predicted and measured shear exponents for 330° direction.



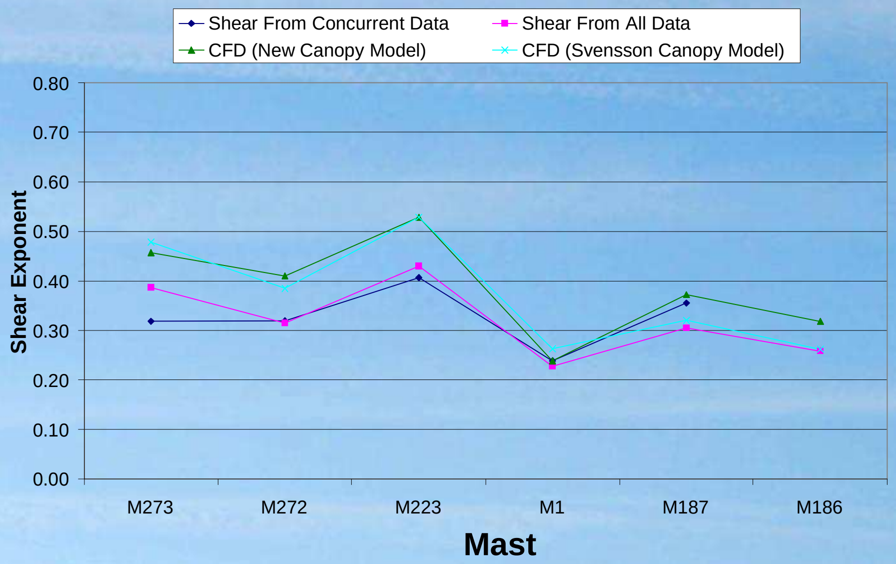
Predicted and measured turbulence intensity for 330° direction.

Optimisation of Canopy Parameters…

Predicted and measured shear exponents for 330° direction



2nd Iteration: α → 0.13

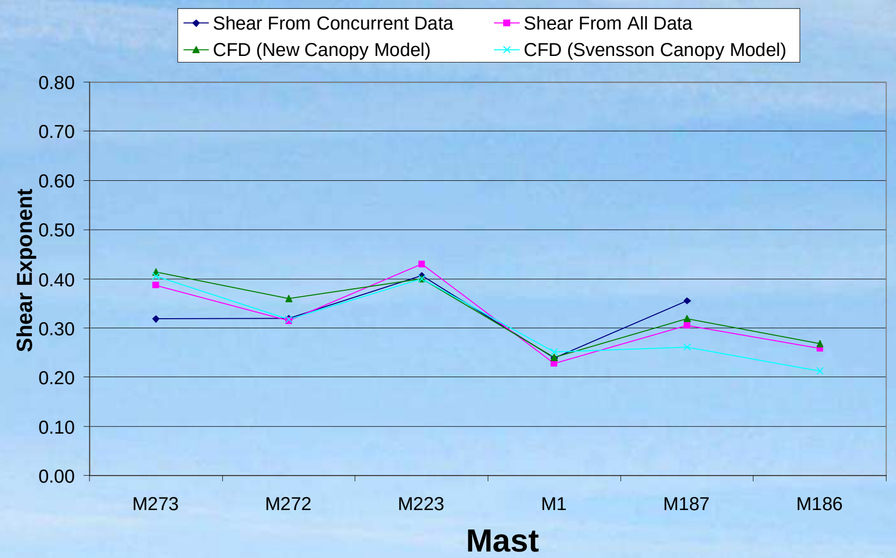


3rd Iteration: α → 0.05

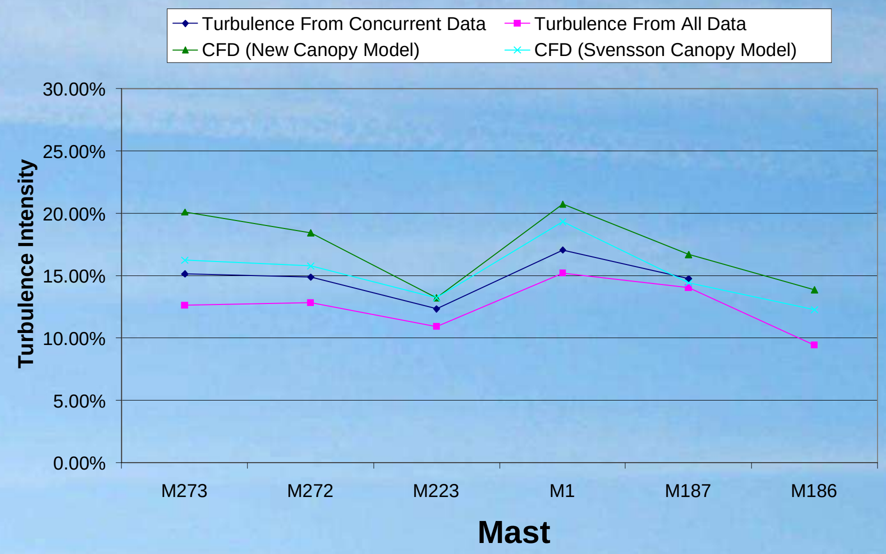
- Reducing the canopy density improves agreement, but even with α = 0.05 the predicted shear exponents are still too high.

Optimised Estimates (330° direction)

Further improvement gained by using an effective tree height of ¾ the actual height.



Predicted and measured shear exponents for 330° direction.



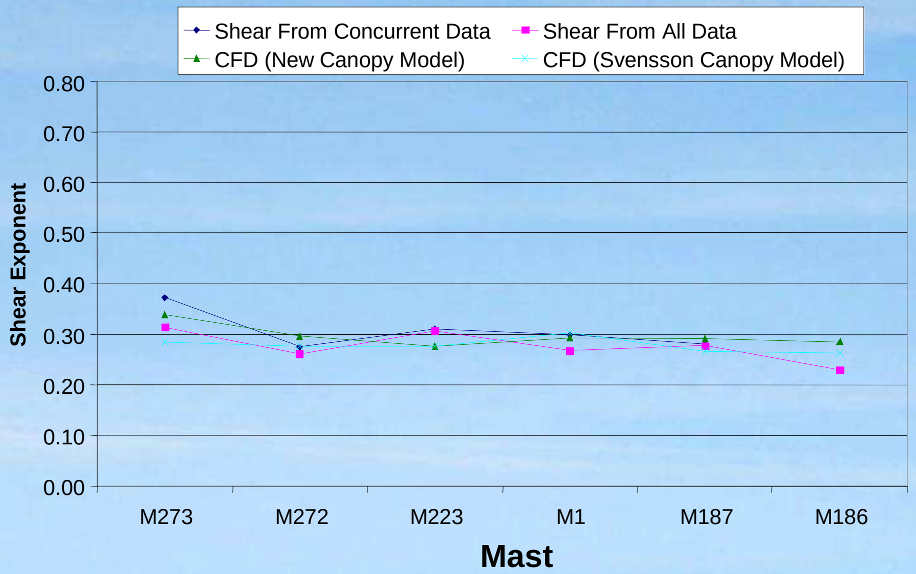
Predicted and measured turbulence intensity for 330° direction.

Final canopy parameters:

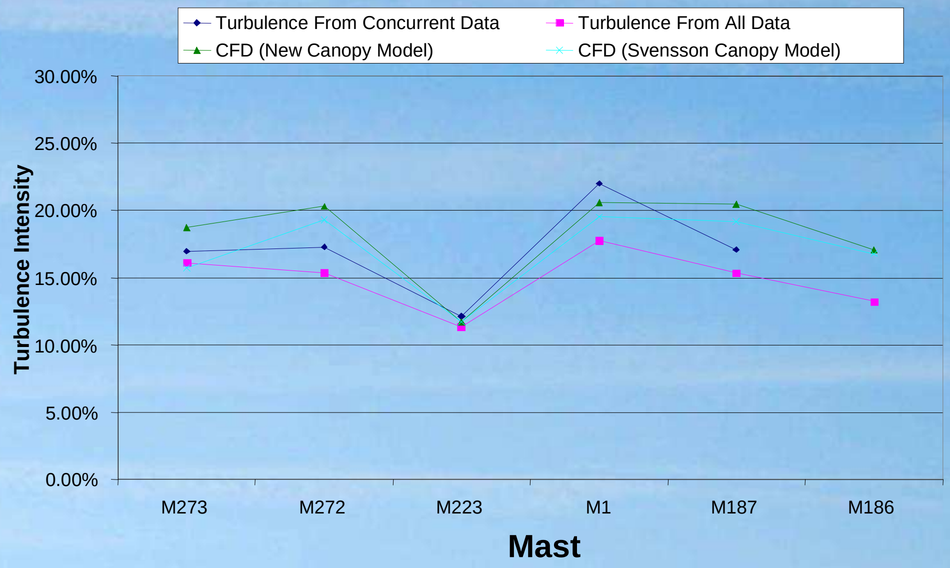
- Tree Height = 11.25m
- Canopy Density C_D = 0.25
- Canopy Density α = 0.05

Optimised Estimates (300° direction)

Optimised parameters derived from 330° direction applied to 300° direction.



Predicted and measured shear exponents for 300° direction.



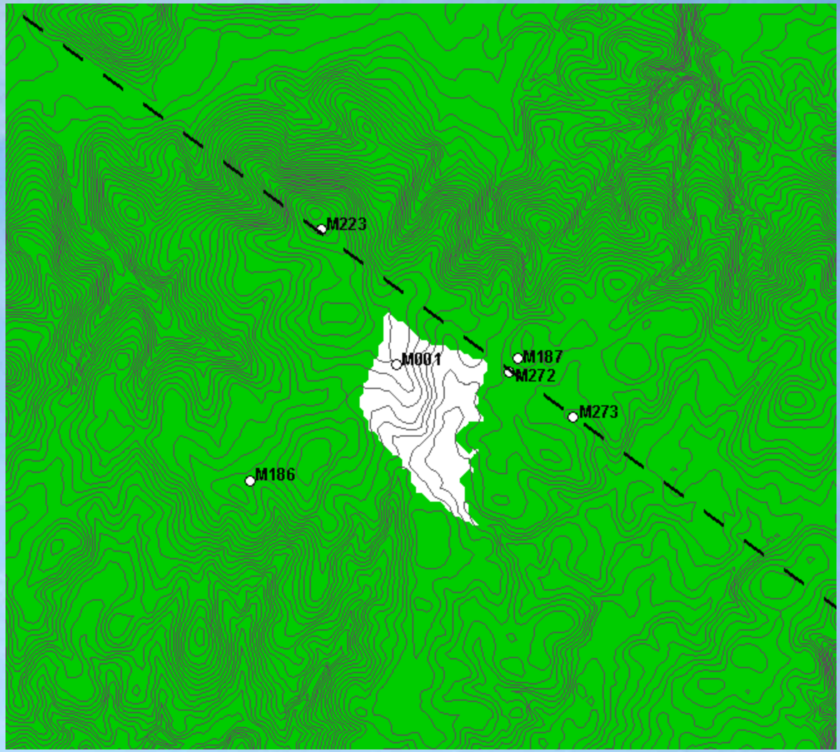
Predicted and measured turbulence intensity for 300° direction.

Profiles

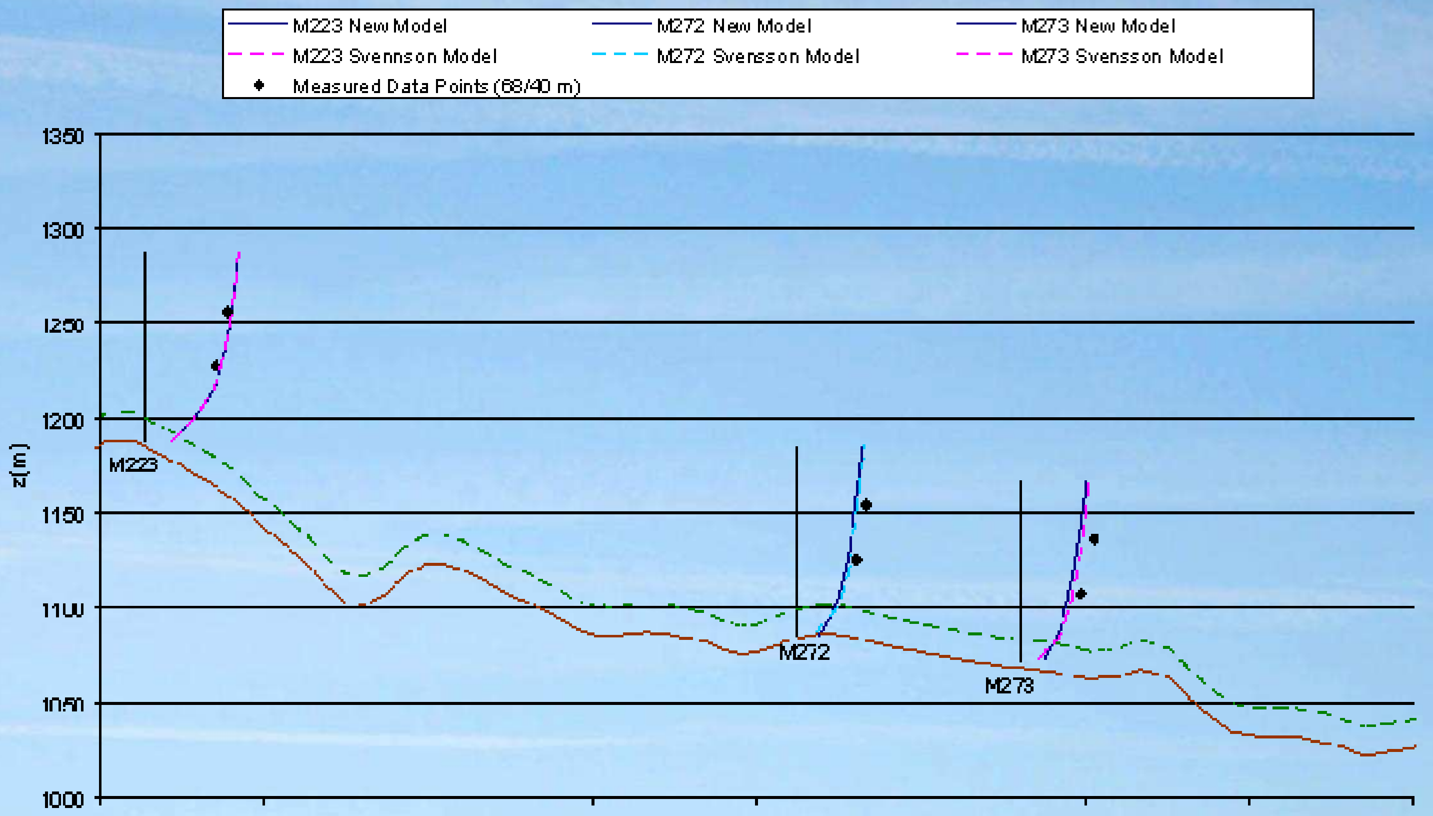
• A line along a direction of 306° passes neatly through three of the masts; M223, M272 and M273.

• Vertical profiles of wind speed and turbulence intensity were extracted at these locations from a CFD simulation and compared with measurements.

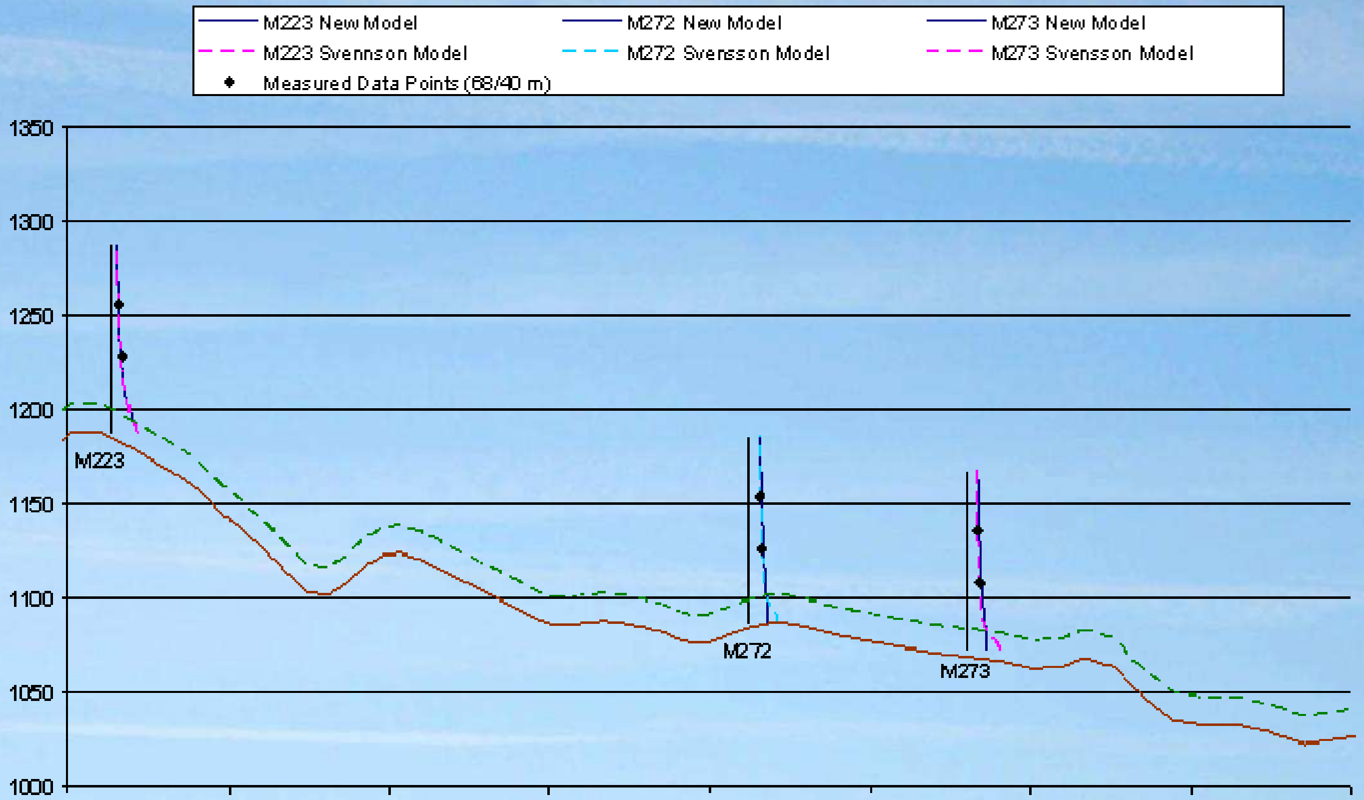
• The measured data points were derived from concurrent data in the range 285°- 315°.



Wind Speed Profiles



Turbulence Intensity Profiles



Conclusions & Further Work

- The new *Ventos* canopy model has been tuned using LES to give more realistic predictions of turbulence intensity. The old and new models give very different results at elevations below ~3 tree heights.

- At elevations above ~3 tree heights the difference between the models is less profound. Analysis of real site data does not indicate that either the Svensson or the new model is consistently more accurate at higher elevations.

- Tuning the canopy density (α) improves the accuracy of the predicted shear exponents and turbulence intensities.

- It may be useful to assign an effective tree height of around ¾ the actual tree height. This may be a useful parameterisation of the vertical variation of canopy density.

- In the future investigate using a vertically variable leaf area density, in order to more realistically model canopy drag at the top of the forest.

VENTOS™

http://paginas.fe.up.pt/ventos/

RES

http://www.res-group.com