<table>
<thead>
<tr>
<th>BWEA Tree Workshop Glasgow 2003</th>
<th>Wind Industry 2011</th>
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<tbody>
<tr>
<td>• Limited industry knowledge and some bad early experiences.</td>
<td>• Substantial cumulative experience of wind energy in forests.</td>
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<tr>
<td>• <strong>Linear/Empirical</strong> (several approaches):</td>
<td>• <strong>Linear/Empirical</strong></td>
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<td>• Modified Mast / Hub Height</td>
<td>• Early approaches refined → workable engineering solutions.</td>
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<tr>
<td>• Augmented Terrain</td>
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<tr>
<td>• Very large roughness</td>
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<td>• <strong>CFD</strong></td>
<td>• <strong>CFD</strong></td>
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<tr>
<td>• Parameterization of forests using high roughness</td>
<td>• Use of canopy models well established → very useful tools.</td>
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<tr>
<td>• Early canopy model using commercial software.</td>
<td>• ...work to improve canopy models still ongoing.</td>
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<tr>
<td>• Early rules of thumb for clearance from trees.</td>
<td>• Established rules of thumb for clearance from trees.</td>
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</table>
The Challenges of Forested Complex Terrain - Some Observations

Masts A & B are in simple non forested terrain

Masts C & D are in complex forested terrain

However masts A,B,C & D are all on the same wind farm site!
Predicting the Breakdown of Linear Flow Models in Forested Complex Terrain
• Calculate flow over idealised hills using both CFD and linear models for incrementally increasing slopes and tree heights.

MS3DJH / RES Roughness

• Establish guidelines for where linear models fail by comparing to CFD.

• Use simple geometrical considerations to assess likely impact on real sites.

• Confirm predicted effects using CFD.
Critical angle for recirculation reduced by \(~ \frac{1}{4}^\circ\) per metre of tree height.
Critical angle for linear model break down reduced by $\sim 1/2^\circ$ per metre of tree height.
Tuning Canopy Parameters
The drag due to the canopy is taken into account via an additional term entering the momentum equation:

\[ F_i = -\frac{1}{2} \rho \alpha C_D \overline{U} \overline{U} U_i \]

\( \alpha \) (in m²m⁻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 source terms \( S_k \) and \( S_\varepsilon \) in the transport equations of \( k \) and \( \varepsilon \)

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

\[ S_\varepsilon = \rho \alpha C_D \left( \beta_p C_{4\varepsilon} \frac{\varepsilon}{k} \overline{U}^3 - C_{5\varepsilon} \beta_d \overline{U} \varepsilon \right) \]
Original parameters: $H = 15\text{m}$, $C_D = 0.25$ and $\alpha = 0.2$

Predicted and measured shear exponents for $330^\circ$ direction.
Final parameters: $H = 11.25\text{m}$, $C_D = 0.25$, $\alpha = 0.05$

Predicted and measured shear exponents for $330^\circ$ direction.
• Tree height (h) most important parameter, but $\alpha$ does have some effect.

• Canopy Density ($\alpha$) and Canopy Drag Coefficient ($C_D$) always appear together in canopy model equations so tuning $\alpha$ amounts to tuning both $\alpha$ and $C_D$.

• In practice a constant value of $\alpha$ is normally applied across a whole site, while a variable tree height will be used where this information is available.

• Worthwhile to perform a sensitivity analysis of both tree height and canopy density to assess uncertainty in results due to these parameters.
Future challenges: Modelling Non-Neutral Canopy Flow
Comparison of Measurements and CFD on Predominantly Stable Site

Comparison of CFD and measured turbulence & shear on predominantly stable site (Northern Sweden)

Turbulence is over predicted by neutral stability model.

Shear is under predicted by neutral stability model.

This type of disagreement is very common, and near systematic in certain regions.
Modelling Non-Neutral Canopy Flow: Coupling of Mesoscale and Microscale

Mesoscale Domain

Mesoscale boundary conditions imposed on microscale model e.g. Inlet profiles (free stream stability), surface fluxes (surface stability) etc.

Stability measurements used to ‘audit’ boundary conditions supplied by mesoscale model?

CFD Domain
Measured Diurnal Surface Stability (Close to Neutral)

High Wind Speed and Low Solar Insolation Period

Richie Cotton & Simon Feeney
Measured Diurnal Surface Stability (Far from Neutral)

Low Wind Speed and High Solar Insolation Period

*Richie Cotton & Simon Feeney*
Future challenges: Modelling Non-Neutral Canopy Flow

- How does non-neutral atmospheric stability change canopy flows e.g. Internal Boundary Layer:

\[
\frac{h}{x} \left[ \ln\left(\frac{h}{z_0}\right) - 1 \right] = B \kappa
\]

Empirical IBL growth formula (mechanical only no buoyancy)

Expected reduced IBL growth rate in stable conditions.

The effect of the canopy can vanish in stable conditions.
• The capability of the wind industry to deal with forested complex terrain has increased substantially in recent years, but much more work is needed.

• Trees and complex terrain can cause very different site conditions to occur within the same wind farm e.g. 8% change in turbulence intensity.

• Tree height has a strong impact on the critical slope at which linear models breakdown.

• Tuning of canopy parameters help improve agreement between observations and CFD model predictions.

• Stability can often play a key role in why models and measurements don’t agree. Work is needed to improve the representation of stability in CFD models. High quality stability measurements are needed to inform these developments.
CFD Transient Simulation with Complex Ridge Upwind

Alex Clerc
Additional Slide: Tuning Canopy Parameters.
• European site with complex orography and extensive forest cover (H ~ 15m).
• 6 meteorological masts used for validation.
Optimized parameters derived from $330^\circ$ direction applied to $300^\circ$ direction.

Tuning Canopy Parameters: Example site

Predicted and measured shear exponents for $300^\circ$ direction.
Additional Slide: Stability Measurements
Measuring Stability: GRADIENT METHODS vs. FLUX METHODS

GRADIENT METHODS

• Measure temperature at two or more levels and assume linear relationship between the points

• Issues:

  1. Accuracy
  2. Cost / Complexity
  3. Calibration requirements due to small vertical distances

FLUX METHODS

• Measure heat energy passing through a plane “directly”

• Issues:

  1. Need high frequency 3D wind speed measurements to resolve eddies
  2. Need high frequency temperature measurements
  3. Site must have a near-zero vertical wind (limited applicability in complex terrain).

Both can be measured using a single high frequency sonic

Richie Cotton & Simon Feeney
Measured Frequency of Stability Classes

Neutral = \(-0.01 < \frac{z}{L} < 0.01\)

Richie Cotton & Simon Feeney
Additional Slide: Predicting the Breakdown of Linear Flow Models in Forested Complex Terrain.
• Establish critical angle considering tree height (20m).