Long-term (1-20 years) prediction of wind resources (WAsP)

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Long-term (1-20 years) prediction of wind resources (WAsP)

Lars Landberg, Niels Gylling Mortensen, Ebba Dellwik, Jake Badger, Jean-Francois Corbett, Ole Rathmann, Lisbeth Myllerup

Wind Energy Department
Risø National Laboratory

Overview

- WAsP
  - Problem
  - Solution
  - Models of WAsP
  - Complex terrain (RIX)
  - New WAsP
- Flow in and near forests
- Meso-scale modelling
The World according to WAsP

The problem
European Wind Atlas

Geostrophic winds
Thermal winds
Weibull distributions

- Fuerteventura, Canary Islands, Spain
  \( A = 7.3 \text{ mm}^{-2}, k = 2.79 \)

- Swartel, UK
  \( A = 10.4 \text{ mm}^{-2}, k = 2.06 \)

- Schiphol, The Netherlands
  \( A = 3.0 \text{ mm}^{-2}, k = 1.50 \)

- Mont de Marin, France
  \( A = 2.4 \text{ mm}^{-2}, k = 1.24 \)

Annual variation

Relative energy

Year:
- 1875
- 1900
- 1925
- 1950
- 1975

www.wasp.dk
Power production basics

The WAsP Icon
Screen lay-out

WAsP-arithmetic

WAsP = OBS + ROU + ORO
Obstacles

What is an obstacle?

After Meroney (1977)
Effects of an obstacle

Reduction of wind speed in per cent due to shelter by a two-dimensional obstacle of zero porosity. Based on the expressions given by Perera (1981)

Trees and shelter belts

Porosity
in per cent or as a fraction

Open > 50%

Dense > 35%

Very dense < 35%

Solid = 0%
Specifying obstacles in WAsP

Obstacles are specified as rectangular boxes relative to the site: by two angles and two radii, their height, depth and porosity.

Obstacle viewed in WAsP
Roughness

Equations!

\[ u(z) = \frac{u_*}{\kappa} \ln \left( \frac{z}{z_0} \right) \]

\[ G = \frac{u_*}{\kappa} \sqrt{\ln \left( \frac{u_*}{\sqrt{z_0}} \right) - A}^2 + B^2 \]
Logarithmic profile

Internal Boundary Layer (IBL)
Orography

Stream lines and turbulence over a hill

Stream lines are compressed => wind speed-up!
Askervein Hill Field Experiment

Mother of all flow-over-hill studies:
The Askervein Hill field experiment
(Benbecula Island, Outer Hebrides, Scotland)

Wind measured on masts along a line across the hill
(mast distance 100 m)

Askervein Hill velocity profile

Orography effects on wind speed profile

- Measurement
- WASP flow model
- Other flow model

Vertical profile

Horizontal profile of speed-up
Inside the BZ-flow-model of WAsP the orography is represented by a zooming polar grid.

The grid is centered around the point in focus: met-station or wind turbine site.

The resolution is highest close to the point in focus, where high resolution matters.

Effect of a steep hill

Flow Separation
Ex.#1: Steep but smooth hill

The flow behaves - to some extent - as if moving over a virtual hill with less steep sides => smaller speed-up than calculated by WAsP

Ref: N.Wood, "The onset of flow separation in neutral, turbulent flow over hills", Boundary-Layer Meteorology 76, 137-164.
Complex terrain and RIX

Outline

- Accumulation of orographic prediction errors
- WASP basics in complex terrain
  - The similarity principle
- Case study in Portugal
  - Wind speed correlations
  - Flow separation
  - RIX and ∆RIX
  - WASP prediction errors
  - RIX/∆RIX configuration
  - Vertical wind profiles
  - Improving WASP predictions in complex terrain?
Background


Accumulation of orographic prediction errors

- Application procedure
  \[ U_h + (\Delta U_2 + E_2) = U_{pe} \]

- Analysis procedure
  \[ U_{rm} - (\Delta U_1 + E_1) = U_h \]

- Combined procedure, eliminating \( U_h \)
  \[(U_{rm} - \Delta U_1 + \Delta U_2) + (E_2 - E_1) = U_{pe} \]

- The correct estimation is then made up of
  \[U_{pm} = U_{rm} - \Delta U_1 + \Delta U_2 \quad \text{(perfect prediction)}\]
  \[U_{pe} = U_{pm} + (E_2 - E_1) \quad \text{(prediction error!)}\]
The similarity principle

The predictor and the predicted site should be as similar as possible

- Topographical setting
  - Ruggedness index (RIX)
  - Elevation and exposure
  - Distance to significant roughness changes (coastline)
  - Background roughness lengths
- Climatic conditions
  - Same regional wind climate (synoptic and meso-scale)
  - General forcing effects
  - Atmospheric stability

This means that the basic input data should also be similar

- WAsP map
  - Map size
  - Contour interval
  - Accuracy and detail
  - Roughness classification
  - ...
Cross-correlation of wind speeds

The flow behaves – to some extent – as if moving over a virtual hill with less steep slopes than the actual hill =>
actual speed-up is smaller than calculated by WAsP

Complex terrain analysis

- **Ruggedness index, RIX**
  - fraction of terrain surface which is steeper than a critical slope \( \theta \)
  - Calculation radius \( \sim 3.5 \text{ km} \)
  - Critical slope \( \theta_c \sim 0.3-0.4 \)
  - Onset of flow separation
  - Performance envelope for WAsP is when RIX = 0

- **Performance indicator, \( \Delta \)RIX**
  - \( \Delta \)RIX = RIXWTG – RIXMET
  - \( \Delta \)RIX < 0 ⇒ under-prediction
  - \( \Delta \)RIX > 0 ⇒ over-prediction

Prediction error vs. RIX difference

“This performance indicator provides encouraging results…”
The Ruggedness Index – revisited

- Reanalyses of the Portuguese data set
  - Larger, more detailed and accurate maps (SRTM)
  - Improved RIX calculation (WAsP or ME)
  - More calculation radii: 72 rather than 12
  - RIX configuration corresponds to WAsP BZ-model grid
  - Both the prediction errors and ∆RIX change

- Data analysis and presentation
  - Asymmetry in plot of speed error vs. ∆RIX
    - speed error was defined as \( \frac{U_p}{U_m} - 1 \)
    - not obvious which trend line(s) to fit…
  - Substitute \( \log\left( \frac{U_p}{U_m} \right) \) for \( \left( \frac{U_p}{U_m} - 1 \right) \)
  - Easier to fit a trend line…?

Maps for RIX calculation and test

- Hand-digitised map
  - 8 by 8 km²
  - 50- and 10-m cont.

- SRTM-derived map
  - 20 km diameter
  - 50-, 10- and 5-m height contours
Wind speed error vs. ΔRIX

\[ y = 1.508x \]
\[ R^2 = 0.975 \]

\[ U_p = U_m \exp(\alpha \Delta RIX) \]
where \( \alpha = 1.5 \)
\[ R = 3500 \text{ m} \text{ and } \theta_c = 0.3 \]
Things to test...

- Wind speed prediction error is (almost) fixed...
  - Number of sectors
  - Modelling parameters
- RIX configuration can be varied easily
  - Original configuration somewhat arbitrary
  - Different calculation radii (3, 3.5, 4, and 5 km)
  - Calculation radius that provides max. RIX?
  - Different critical slopes (0.30, 0.35, 0.40, 0.45)
  - Matrix of $R^2$ (coefficient of determination) for different set-up’s
- Weighting RIX with wind rose frequencies

Influence of radius and critical slope

<table>
<thead>
<tr>
<th>Radius $R$ [m]</th>
<th>Critical slope $\theta_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.30</td>
</tr>
<tr>
<td>3000</td>
<td>0.960</td>
</tr>
<tr>
<td>3500</td>
<td>0.972</td>
</tr>
<tr>
<td>4000</td>
<td>0.971</td>
</tr>
<tr>
<td>5000</td>
<td>0.969</td>
</tr>
</tbody>
</table>

$R^2$ for different values of the calculation radius and critical slope.
Recalculation – best fit values

\[ y = 2.406x \]
\[ R^2 = 0.984 \]

Recalculation – weighted w. wind rose

\[ y = 2.370x \]
\[ R^2 = 0.977 \]
Vertical profile in complex terrain

Tetouan in northern Morocco, RIX = 16%

<table>
<thead>
<tr>
<th>z [m]</th>
<th>\langle U_m \rangle [m/s]</th>
<th>\langle P_m \rangle [MWh]</th>
<th>\langle U_e \rangle [m/s]</th>
<th>\langle P_e \rangle [MWh]</th>
<th>\frac{P_e}{P_m}</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>9.8</td>
<td>2643</td>
<td>9.7</td>
<td>2532</td>
<td>0.97</td>
</tr>
<tr>
<td>20</td>
<td>9.6</td>
<td>2518</td>
<td>9.5</td>
<td>2504</td>
<td>0.99</td>
</tr>
<tr>
<td>30</td>
<td>9.8</td>
<td>2616</td>
<td>9.6</td>
<td>2529</td>
<td>0.97</td>
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<tr>
<td>40</td>
<td>9.6</td>
<td>2565</td>
<td>9.6</td>
<td>2565</td>
<td>1.00 (predictor)</td>
</tr>
</tbody>
</table>

Vertical profile is predicted well because of the similarity in RIX:
\[ \Delta RIX = RIX_{WTG} - RIX_{MET} = 0 \]
Conclusions

• The similarity principle
  – WASP analysis and application errors tend to cancel out
  – The SP is the most important guiding principle for WASP use
  – WASP inputs (maps) should also be similar, of course
• Ruggedness index RIX and performance indicator $\Delta$RIX
  – Concepts supported by new data and procedures
• Relation between WASP prediction error and $\Delta$RIX
  – Linear relation between $\log(U_p/U_m)$ and $\Delta$RIX
  – Relation not very sensitive to calculation radius $R$, critical slope $\theta_c$, or prediction height $h$
  – $\Delta$RIX weighted with the wind rose does not improve the relation between $\log(U_p/U_m)$ and $\Delta$RIX

Conclusions (cont’d)

• Extension of WASP procedures outside operational envelope
  – Requires two or more (non-similar) met. stations
  – Linear relation between $\ln(P_p/P_m)$ and $\Delta$RIX
  – Case study AEP predictions improve significantly
  – Linear fit before extended procedure:
    • $AEP_p = -0.11 AEP_M + 2.42$
    • $R^2 = 0.01$
  – Linear fit after extended procedure:
    • $AEP_p = 1.01 AEP_M$
    • $R^2 = 0.92$
• Procedure can be applied with (2...n) met. stations
• Procedure should be tested with other data sets...
### AEP [GWh] = \( R(\text{WAsP}) \)

<table>
<thead>
<tr>
<th>Predictor/predicted</th>
<th>Port 06</th>
<th>Port 07</th>
<th>Port 08</th>
<th>Port 09</th>
<th>Port 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port 06</td>
<td>1.398</td>
<td>1.197</td>
<td>2.271</td>
<td>2.444</td>
<td>2.771</td>
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<tr>
<td></td>
<td>-14%</td>
<td>+62%</td>
<td>+75%</td>
<td>+98%</td>
<td></td>
</tr>
<tr>
<td>Port 07</td>
<td>1.877</td>
<td>1.670</td>
<td>2.882</td>
<td>3.078</td>
<td>3.402</td>
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<tr>
<td></td>
<td>+12%</td>
<td>+73%</td>
<td>+84%</td>
<td>+104%</td>
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</tr>
<tr>
<td>Port 08</td>
<td>1.818</td>
<td>1.467</td>
<td>2.552</td>
<td>2.810</td>
<td>3.229</td>
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<td></td>
<td>-29%</td>
<td>-43%</td>
<td>+10%</td>
<td>+27%</td>
<td></td>
</tr>
<tr>
<td>Port 09</td>
<td>1.434</td>
<td>1.245</td>
<td>2.290</td>
<td>2.475</td>
<td>2.882</td>
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<tr>
<td></td>
<td>-42%</td>
<td>-50%</td>
<td>-7%</td>
<td>+16%</td>
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<tr>
<td>Port 10</td>
<td>1.427</td>
<td>1.113</td>
<td>2.145</td>
<td>2.351</td>
<td>2.546</td>
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<td></td>
<td>-44%</td>
<td>-56%</td>
<td>-16%</td>
<td>-8%</td>
<td></td>
</tr>
</tbody>
</table>

### AEP [GWh] = \( R(\text{WAsP}, \Delta RIX) \)

<table>
<thead>
<tr>
<th>Predictor/predicted</th>
<th>Port 06</th>
<th>Port 07</th>
<th>Port 08</th>
<th>Port 09</th>
<th>Port 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port 06</td>
<td>1.398</td>
<td>1.352</td>
<td>1.532</td>
<td>1.355</td>
<td>1.531</td>
</tr>
<tr>
<td></td>
<td>-3%</td>
<td>+10%</td>
<td>-3%</td>
<td>+9%</td>
<td></td>
</tr>
<tr>
<td>Port 07</td>
<td>1.661</td>
<td>1.670</td>
<td>1.720</td>
<td>1.510</td>
<td>1.663</td>
</tr>
<tr>
<td></td>
<td>-1%</td>
<td>+3%</td>
<td>-10%</td>
<td>-0%</td>
<td></td>
</tr>
<tr>
<td>Port 08</td>
<td>2.695</td>
<td>2.458</td>
<td>2.552</td>
<td>2.310</td>
<td>2.644</td>
</tr>
<tr>
<td></td>
<td>+6%</td>
<td>-4%</td>
<td>-10%</td>
<td>+4%</td>
<td></td>
</tr>
<tr>
<td>Port 09</td>
<td>2.587</td>
<td>2.538</td>
<td>2.786</td>
<td>2.475</td>
<td>2.872</td>
</tr>
<tr>
<td></td>
<td>+5%</td>
<td>+3%</td>
<td>+13%</td>
<td>+16%</td>
<td></td>
</tr>
<tr>
<td>Port 10</td>
<td>2.584</td>
<td>2.277</td>
<td>2.619</td>
<td>2.360</td>
<td>2.546</td>
</tr>
<tr>
<td></td>
<td>+1%</td>
<td>-11%</td>
<td>+3%</td>
<td>-7%</td>
<td></td>
</tr>
</tbody>
</table>
The New WAsP flow model

Objective

- Micro-scale flow model better able to handle “steep” slopes
  - current WAsP performs poorly over steep slopes (>30%)
- To replace/complement the current WAsP orography and roughness models
- Yet not too heavy computationally
Ressource prediction

- Location of turbines ≠ location of met. Masts
- Different surroundings → different wind climates:
  - Obstacles, orography, roughness

The WAsP approach

Wind climate that would be observed on a flat surface

problem
Requirements

The new flow model must be:

- **Quick:**
  - A few hours on a PC for a predicted wind climate
- **Easy to use:**
  - Needs only limited user intervention
  - User expertise on numerical methods not required
  - Minimal number of user-input parameters
- **Stable**
  - Convergence takes place without extensive fine-tuning

Description of the model

- **Governing equations**
  - RANS equations including Coriolis term, continuity
  - Turbulence closure: variant of $k$-$\varepsilon$ model
  - Formulated in
    - General curvilinear coordinates
    - Strong conservation form
- **Calculation domain**
  - Vertically: entire boundary layer (~10° km)
  - Horizontally: ~ 20 km
  - Terrain-following grid
Example grid

- Horizontally periodic
- Flow driven by geostrophic wind at top
- Lower BC
  - law-of-the-wall
  - no-slip when testing...

New flow model for complex terrain

START
- RANS equations
- limited length-scale $k$-$\epsilon$ turb model
  - General curvilinear coordinates
  - Linearisation: *Perturbation* expansion
  - Zero-order equations
    - horizontally homogeneous
    - Finite difference vertically
  - Zero-order solution
    - (horizontally homogeneous)

First-order equations
- Fractional step method: ensures P-V coupling
- Discretised first-order equations
  - Momentum transport
  - Continuity
  - Turbulent kinetic energy
  - Dissipation of TKE

MSFD:
- Horizontal Fourier transformation
- Finite difference vertically

Complete solution

FINISH
Results: flat terrain

- Comparison of turbulence models:

Results – non-flat terrain

- First-order turbulence equations are not ready yet
- Still debugging first-order momentum solver

- Results presented are for "laminar" flow
  - i.e. a uniform eddy viscosity is provided artificially
  - lower boundary condition: no-slip

- In direction perpendicular to the screen:
  - Grid is uniform, no driving
  - 2D problem solved in 3D
Streamwise velocity

Zero-order solution  First-order solution

Vertical velocity

Zero-order solution  First-order solution
Final solution

Streamwise velocity

Vertical velocity

• Lean, mean, and, well… “room for improvement” in the accuracy department
• 512 (L) x 64 (H) x 4 (W) grid : calculation takes a few minutes

Work ahead

• Debugging and testing of the first-order momentum solver
  – Newly-discovered error in the upper/lower boundary conditions of the Poisson and projection equations
  – Re-writing terms of the first equation to include previously neglected geometry terms
  – And more...
• Debugging and testing of the turbulence closure
• Test cases, calculations, fine-tuning and analysis
Forest and wind turbines

.... is generally a bad combination...

Outline

• How is a forest different?
• Forest model parameters
• Turbine/mast close to forest
• Turbine/mast not so close to forest
How is a forest different?

\[ z \rightarrow z - d \]

inflection point
How is a forest different?

The roughness sublayer effect

Displacement height => Forest edge effects

Problem areas

www.wasp.dk
How is a forest different?

How is a forest different, summary?

- Introduction of displacement height – porous surface in tree crown level
  1. Roughness sublayer
  2. Flow effects at forest edge

- Forests are aerodynamically much rougher than for example the sea surface
Roughness and zero displacement height

Depends on
1. The mean height of the roughness elements (trees)
2. The density of the forest

The roughness sub-layer effect
Forest edge effects

- dense
- sparse

Forest density 1

How is it parameterised?
Raupach (1992):
\[
\lambda = \frac{bh}{D^2} = bh\left(\frac{n}{S}\right)
\]

\[
\lambda \approx \frac{LAI}{2}
\]

leaf area index
Forest density 2

Displacement height

Roughness length

Height and wind in roughness sublayer

Forest edge effect

How is forest flow parameterised?


\[ \lambda = \frac{bh}{D^2} \]

- \( b \): Tree breadth
- \( h \): Tree height
- \( D \): Distance between trees
What is close?

Close \( x < 20d \)
Not so close \( x > 20d \)

Forest edge effect should be included

Orographic effects of forest edge, mean wind
Turbulent effects of forest edge

\[ \frac{\sigma_u}{u} \]

- high up
- close to forest

Wind turbine not so close to a forest, \( x > 20d \)

\[ u \]

- Internal boundary layers
- \( h_{\text{rough}} \)
- \( h_{\text{smooth}} \)
IBL structure

\[ \frac{h_i}{z_{02}} = 0.09 \left( \frac{x}{z_{02}} \right)^{0.77} \]  
(Dellwik and Jensen, 2000, WAsP)

Wind turbine not so close to a forest, \( x > 20d \)

*How far away from the forest is the forest influence of no consequence?*
Scary story – low turbine in small clearing

- high roughness, no effect of clearing
- orographic effect leads to a reduction in wind
- edge effects may cause a very turbulent environment

New project: *Wind Profiles and Forest*

Masts for turbulence and mean wind speed measurements
Use in WAsP

• Estimate $\lambda$
• Calculate $z_0$
• Calculate $d$
• Input $z_0$ in WAsP map
  – effect of high roughness taken into account
  – effect of IBL growth taken into account
• Subtract $d$ from all heights (mast and turbine)

• Turbines in forest do not necessarily “see” a forest.
• Turbines outside a forest are likely to be influenced by the forest if the forest is not very far away (take care at edge!)
The logarithmic profile

KAMM/WAsP Methodology - meso-scale modelling
Numerical Wind Atlas Methodology

- useful when long-term measurement data unavailable
- uses the principle of statistical dynamical downscaling

**large-scale meteorological conditions**

**small-scale meteorological conditions**

Need:
- tool to calculate how atmospheric flow modified by terrain
  - mesoscale model
- information about large-scale meteorological conditions
- information about terrain
  - surface elevation (orography)
  - surface roughness

www.wasp.dk
KAMM – Mesoscale model

Karlsruhe Atmospheric Mesoscale Model
non-hydrostatic, regular horizontal grid, stretched vertical coordinate (terrain following)

Large-scale meteorological conditions

- NCEP/NCAR reanalysis data provides large-scale, long-term atmospheric forcing.
  - 2.5 x 2.5 degree resolution
  - 4 times daily
  - 1948 to present

Calculate profiles of
- geostrophic wind
- potential temperature
at 0, 1500, 3000, 5500 m (1965-1998)
Terrain description

Orography
• United States Geological Survey (USGS), GTOPO30 data – approx. 1km resolution.

Surface roughness
• USGS Global Land Cover Classification – approx. 1km resolution.
• Land use → surface roughness (via look-up table)

Statistical-dynamical downscaling

• We could run KAMM using 30 years of 4 times daily data as large-scale forcing conditions
  30*365*4 = 43800 integrations
  A lot of work! ...and also repetition.

• Instead we select around 100 representative conditions, called wind classes profiles.

  • Statistical-dynamical downscaling
The WAsP part in KAMM/WAsP

Example:
simulated wind
wind corrected to standard conditions

flat terrain with homogeneous roughness

low roughness
higher roughness + orographic speed-up

higher roughness

~30km
Egypt – case study

Egypt calculation domains

Large domains
- 7.5 km resolution
- generalized wind class profiles

Smaller domains
- 5 km resolution
- location specific wind class profiles
Eastern Egypt: orography & roughness

Wind class rose
- each x indicates a different forcing of the mesoscale model
- frequency of occurrence of each wind varies within domain
Eastern Egypt: example wind class

Mean simulated wind speed at 50 m a.g.l.

Weighting of each wind class varies within domain.

Remember: resolution is 7.5 km
Eastern Egypt: wind atlas map

Mean generalized wind speed at 50 m a.g.l. above flat terrain with 0.0002 m surface roughness

- channelling
- orographic barriers

Egypt: wind resource map

Combine East and West Egypt domains
Egypt: wind atlas map

Combine East and West Egypt domains

Other domains
KAMM / WAsP Numerical Wind Atlas

- many maps can be produced, i.e.
  - wind speed and wind speed at different heights
  - Weibull A and k parameters at different heights

- output can also be used in WAsP
  - WAsP .lib files can be generated
  - for any location within domain

KAMM / WAsP Numerical Wind Atlas

El-Hekma

WAsP display of generalized wind atlas
Verification

Scatter plot for Western Desert

Wind speed at 25, 50, 100, 200 m above flat surface, 0.03 m roughness

<table>
<thead>
<tr>
<th>Domain</th>
<th>mean absolute error on 50 m wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern Egypt</td>
<td>9.7 %</td>
</tr>
<tr>
<td>Western Egypt</td>
<td>12.9 %</td>
</tr>
<tr>
<td>North-eastern coast</td>
<td>5.5 %</td>
</tr>
<tr>
<td>Western Desert</td>
<td>4.5 % / 4.6 %</td>
</tr>
<tr>
<td>Gulf of Suez</td>
<td>7.5 %</td>
</tr>
<tr>
<td>Red Sea</td>
<td>5.9 %</td>
</tr>
</tbody>
</table>

(All values rounded to one decimal place)
Conclusions

The KAMM / WAsP method has been used to create numerical wind atlases for Egypt.

- 2 large domains cover all of Egypt
  - 7.5 km resolution
- 4 smaller domains cover specific regions of interest in more detail
  - 5 km resolution
  - location specific wind profiles

- Colour maps produced are just a graphical “slice” of the data generated by the method.
- .lib files are also generated
- WAsP can then be used to determine local effects
  - orographic speed up
  - roughness change
- Verification shows error to be around 5-10 % on wind speed.
Summary

- Wind Atlas Methodology: industry-standard (rou, oro, obs)
- Complex terrain: RIX, new WAsP
- Forest (λ)
- KAMM/WAsP (Egypt case)

Web-sites

- www.risoe.dk
- www.wasp.dk
- www.windatlas.dk
- www.prediktor.dk
- www.waspengineering.dk
- www.cleverfarm.com
- www.mesoscale.dk
- www.windpower.org