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

Landberg, L.; Mortensen, N.G.; Dellwik, E.; Badger, J.; Corbett, J.-F.; Rathmann, O.; Myllerup, L.

Published in:
Introduction to wind technology

Publication date:
2006

Document Version
Peer reviewed version

Citation (APA):
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
Thermal winds
Weibull distributions

- Fuerteventura, Canary Islands, Spain
  $A = 7.2 \text{ m/s}^2$, $\alpha = 1.79$

- Sweedel, UK
  $A = 15.4 \text{ m/s}^2$, $\alpha = 2.96$

- Schiphol, The Netherlands
  $A = 5.0 \text{ m/s}^2$, $\alpha = 1.20$

- Mot de Meran, France
  $A = 2.4 \text{ m/s}^2$, $\alpha = 1.24$

Annual variation

- Relative energy

- Year: 1875 to 1975

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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!

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

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

Vertical profile

Horizontal profile 
of speed-up

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BZ-model: Zooming Polar Grid

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
  \[ U_A + (\Delta U_2 + E_2) = U_{pe} \]

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

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

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

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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
  - ...

Case study in northern Portugal
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 $\theta_c$
  - Calculation radius $\sim 3.5$ km
  - Critical slope $\theta_c \sim 0.3-0.4$
  - Onset of flow separation
  - Performance envelope for WAsP is when $RIX = 0$

• **Performance indicator, $\Delta RIX$**
  - $\Delta RIX = RIX_{WTG} - RIX_{MET}$
  - $\Delta RIX < 0 \Rightarrow$ under-prediction
  - $\Delta RIX > 0 \Rightarrow$ 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 \( \Delta \text{RIX} \) change

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

Maps for RIX calculation and test

- Hand-digitised map
  - 8 by 8 km\(^2\)
  - 50- and 10-m cont.

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

$\ln(U_p/U_m)$ vs. $\Delta$RIX

$U_p = U_m \exp(\alpha \Delta RIX)$
where $\alpha = 1.5$

$R = 3500$ m 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

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

\[ U_p = U_m \exp(\alpha \Delta RIX) \]
where \( \alpha = 2.4 \)
\( R = 3500 \text{ m} \) and \( \theta_c = 0.4 \)

Recalculation – weighted w. wind rose

\[ y = 2.370x \]
\[ R^2 = 0.977 \]

\[ U_p = U_m \exp(\alpha \Delta RIX) \]
where \( \alpha = 2.4 \)
\( R = 3500 \text{ m} \) and \( \theta_c = 0.4 \)
Weighted with wind rose
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>$P_e/P_m$</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>
</tr>
<tr>
<td>40</td>
<td>9.6</td>
<td>2565</td>
<td>9.6</td>
<td>2565</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Vertical profile is predicted well because of the similarity in RIX:

$$\Delta RIX = RIX_{WTG} - RIX_{MET} = 0$$

Improvement of AEP predictions

<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></td>
<td>77%</td>
<td>85%</td>
<td>96%</td>
<td>90%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(11%)</td>
<td>(53%)</td>
<td>(72%)</td>
<td>(89%)</td>
</tr>
<tr>
<td>Port 07</td>
<td></td>
<td></td>
<td>96%</td>
<td>89%</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(70%)</td>
<td>(75%)</td>
<td>(103%)</td>
</tr>
<tr>
<td>Port 08</td>
<td>80%</td>
<td>91%</td>
<td></td>
<td>6%</td>
<td>86%</td>
</tr>
<tr>
<td></td>
<td>(23%)</td>
<td>(39%)</td>
<td></td>
<td>(1%)</td>
<td>(23%)</td>
</tr>
<tr>
<td>Port 09</td>
<td>89%</td>
<td>95%</td>
<td>-68%</td>
<td></td>
<td>3%</td>
</tr>
<tr>
<td></td>
<td>(38%)</td>
<td>(47%)</td>
<td>(5%)</td>
<td></td>
<td>(0%)</td>
</tr>
<tr>
<td>Port 10</td>
<td>97%</td>
<td>81%</td>
<td>82%</td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(42%)</td>
<td>(46%)</td>
<td>(13%)</td>
<td>(0%)</td>
<td></td>
</tr>
</tbody>
</table>
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 ΔRIX
  – Concepts supported by new data and procedures
• Relation between WASP prediction error and ΔRIX
  – Linear relation between log(U_p/U_m) and ΔRIX
  – Relation not very sensitive to calculation radius R, critical slope θ_c, or prediction height h
  – ΔRIX weighted with the wind rose does not improve the relation between log(U_p/U_m) and ΔRIX

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 ΔRIX
  – 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] = \( R(WA_sP) \)

<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>
</tr>
<tr>
<td></td>
<td>+12%</td>
<td>+73%</td>
<td>+84%</td>
<td>+104%</td>
<td></td>
</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>
</tr>
<tr>
<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>
</tr>
<tr>
<td></td>
<td>-42%</td>
<td>-50%</td>
<td>-7%</td>
<td>+16%</td>
<td></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>
</tr>
<tr>
<td></td>
<td>-44%</td>
<td>-56%</td>
<td>-16%</td>
<td>-8%</td>
<td></td>
</tr>
</tbody>
</table>

### AEP [GWh] = \( R(WA_sP, \Delta RIX) \)

<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>
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</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>
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<td></td>
<td>-3%</td>
<td>+10%</td>
<td>-3%</td>
<td>+9%</td>
<td></td>
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<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>
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<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>
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<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>
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<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 WA²P 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 ($\sim 10^9$ km)
  - Horizontally: $\sim 20$ km
  - Terrain-following grid
Example grid

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

New flow model for complex terrain

START

- RANS equations
- Limited length-scale k-ε turb model
- General curvilinear coordinates

Linearisation: Perturbation expansion

Zero-order equations horizontally homogeneous

Finite difference vertically

Zero-order solution (horizontally homogeneous)

First-order equations

- Momentum transport
- Continuity
- Turbulent kinetic energy
- Dissipation of TKE

MSFD: Horizontal Fourier transformation

Finite difference vertically

Discretised first-order equations

- Momentum transport w/o pressure
- Pressure Poisson
- Pressure correction on velocity

Complete solution

Fractional step method: ensures P-V coupling

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

Problem with BC

Speed-up

Vertical velocity

Zero-order solution

First-order solution

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Final solution

- 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 1?

\[ z \rightarrow z - d \]

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How is a forest different?

\[ z (\text{m}) \]

inflection point

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How is a forest different?

The roughness sublayer effect

Displacement height => Forest edge effects

Problem areas
How is a forest different?

- 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

\[ 0.5m < z_{0,\text{forest}} < 2.5m \]
\[ 0.01m < z_{0,\text{agric}} < 0.15m \]
\[ 10^{-3} m < z_{0,\text{sea}} < 10^{-2} m \]
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

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How is forest flow parameterised?


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

- \( \lambda \): Roughness length
- \( b \): 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

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

How far away from the forest is the forest influence of no consequence?

\[
\frac{h_c}{z_{02}} = 0.09 \left( \frac{x}{z_{02}} \right)^{0.77}
\]

(Dellwik and Jensen, 2000, WAsP)
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
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
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*

higher roughness + orographic speed-up

low roughness ~30km

higher roughness
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

### Domain mean absolute error on 50 m wind speed

<table>
<thead>
<tr>
<th>Domain</th>
<th>Eastern Egypt</th>
<th>Western Egypt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9.7 %</td>
<td>12.9 %</td>
</tr>
<tr>
<td>North-eastern coast</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Western Egypt)</td>
<td>5.5 %</td>
<td>13.6 %</td>
</tr>
<tr>
<td>Western Desert</td>
<td>4.5 %</td>
<td>4.6 %</td>
</tr>
<tr>
<td>(W and E Egypt)</td>
<td>9.7 %</td>
<td>6.2 %</td>
</tr>
<tr>
<td>Gulf of Suez</td>
<td></td>
<td>7.5 %</td>
</tr>
<tr>
<td>(Eastern Egypt)</td>
<td>6.4 %</td>
<td></td>
</tr>
<tr>
<td>Red Sea</td>
<td></td>
<td>5.9 %</td>
</tr>
<tr>
<td>(Eastern Egypt)</td>
<td></td>
<td>6.8 %</td>
</tr>
</tbody>
</table>
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