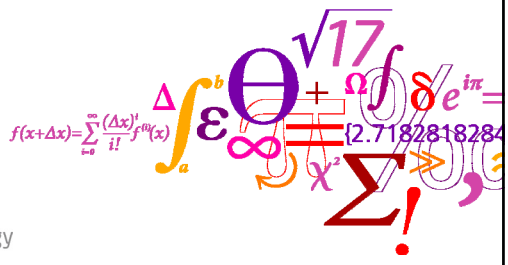
Field validation of the ΔRIX performance indicator for flow in complex terrain

Niels G. Mortensen and Ole Rathmann, Risø DTU, Denmark
Andrew Tindal and Lars Landberg, Garrad Hassan, UK



Risø DTU
National Laboratory for Sustainable Energy

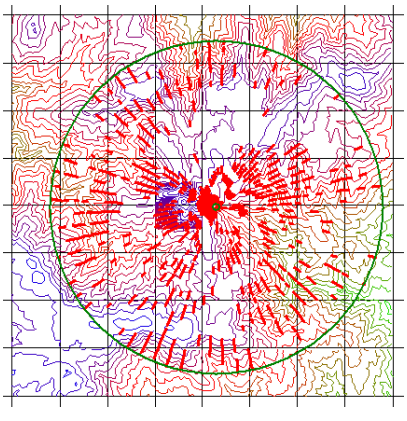
Introduction

- Motivation
- The ruggedness index (RIX)
- The performance indicator (ΔRIX)
- Previous work and results
- Methodology
- Verification at sample wind farm sites
- Conclusions
- Recommendations
  - for rugged terrain
  - and in general

Motivation

- Wind farms are installed in complex and steep terrain
  - flow separation when slopes are steeper than 30-40%
- Common engineering flow models designed for attached flow
  - WAsP and WAsP Engineering (Risø DTU): BZ model & LINCOM
  - WindFarm (ReSoft): MS Micro
- Common wind farm design software may employ WAsP calculations
  - GH WindFarmer (Garrad Hassan)
  - WindPRO (EMD International)
  - WindFarm (ReSoft)
- For any flow model applied in complex terrain, one needs to know
  - is flow separation likely to occur?
  - is situation outside the operational envelope of the flow model?
  - what are the qualitative and quantitative effects on the predictions?
  - can the effects be mitigated or corrected for?
- Analyses and results reported here based on the WAsP flow model

Ruggedness index and ΔRIX

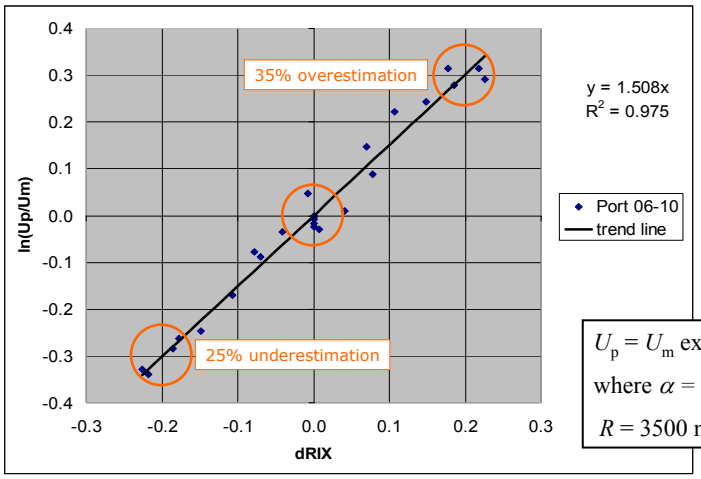


- Slopes steeper than θ_c are indicated by the thick red (radial) lines.

- **Ruggedness index, RIX**
  - fraction of terrain surface which is steeper than a critical slope θ_c
  - slopes evaluated along 72 radii
  - calculation radius ~ 3-5 km
  - critical slope θ_c ~ 0.3-0.4
  - marks onset of flow separation
  - Design operational envelope for WAsP is when RIX = 0

- **Performance indicator, ΔRIX**
  - two sites involved: MET and WTG
  - $\Delta RIX \equiv RIX_{WTG} - RIX_{MET}$
  - $\Delta RIX = 0 \Rightarrow$ reliable prediction
  - $\Delta RIX < 0 \Rightarrow$ under-prediction
  - $\Delta RIX > 0 \Rightarrow$ over-prediction

Prediction error vs. ΔRIX (EWEC 2006)



$$U_p = U_m \exp(\alpha \Delta \mathrm{RIX})$$

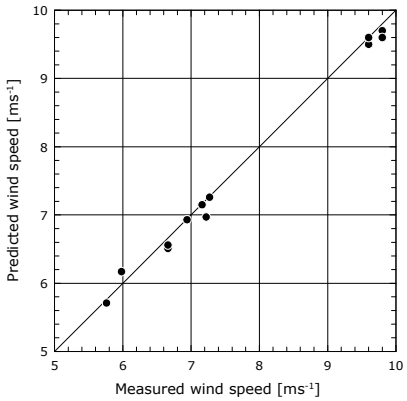
where $\alpha = 1.5$

$R = 3500$ m and $\theta_c = 0.3$

Methodology

- Comparisons of measured and/or predicted wind speeds
  - plot prediction error versus ΔRIX for met. masts
  - find site-specific fitting constant (α)
  - calculate corrected predictions
  - plot original and ΔRIX-corrected data
  - mean bias and mean absolute error (MAPE)
- Eight wind farm sites with 30 meteorological masts
  - Italy, Morocco, N Europe, Spain, Portugal
  - anemometer levels from 10 to 60 m a.g.l.
  - |ΔRIX| > 0; varies from 0-23%
  - all sites more or less outside operational envelope of model
- Prerequisites
  - sites selected so other effects are of minor importance: meso-scale effects, complicated land-use, forest effects, thermal effects, etc.
  - high-quality wind and topographical inputs

Case 1: Predictions when |ΔRIX| = 0



Profile predictions only!

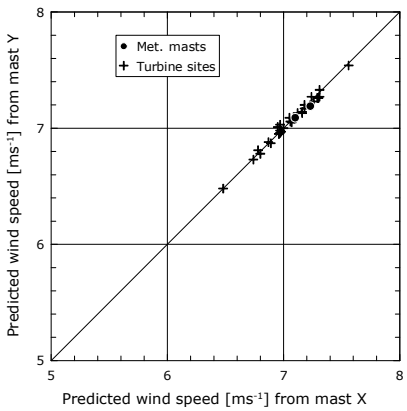
- Three wind farm sites
- Five different met. masts
- Levels 10/40, 30/60, 10/20/30/40

- Mast 1 (30/60), RIX = 6%
- Mast 2 (30/60), RIX = 9%
- Mast 3 (10/40), RIX = 15%
- Mast 4 (10/40), RIX = 26%
- Mast 5 (10-40), RIX = 16%

- **ΔRIX = 0%**
- MAPE = 1.3%

- Difficult comparison!
  - roughness lengths
  - stability effects
  - flow distortion

Case 2: Predictions when |ΔRIX| is small



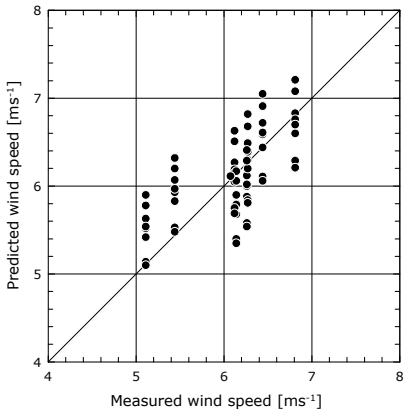
- Wind farm site with 28 turbine sites
- Two 60-m met. masts, 2 km apart
- Predictions for 60 m a.g.l.
- Location: Iberian Peninsula

- Mast X RIX = 6%
- Mast Y RIX = 9%
- Turbine sites RIX = 4% to 13%

- **ΔRIX masts = ±3%**
  - ΔRIX_X = -2% to 7%
  - ΔRIX_Y = -5% to 4%

- Standard WAsP calculation
  - $Y = 1.00 \cdot X$
  - MAPE = 0.3%

Case 3: Predictions when |ΔRIX| is small



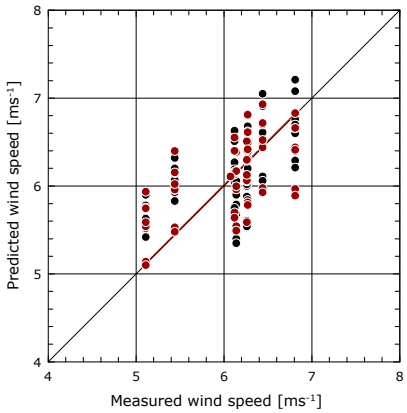
- Eight 30-50 m masts, up to 8 km apart
- Predictions for 30-50 m a.g.l.
- Location: Italy

- Mast 1, RIX = 2%
- Mast 2, RIX = 1%
- Mast 3, RIX = 1%
- Mast 4, RIX = 1%
- Mast 5, RIX = 1%
- Mast 6, RIX = 0%
- Mast 7, RIX = 1%
- Mast 8, RIX = 1%

- **ΔRIX masts = ±2%**

- Standard WAsP calculation
  - $Y = 1.00 \cdot X$
  - MAPE = 5.7%

Case 3: Predictions when |ΔRIX| is small



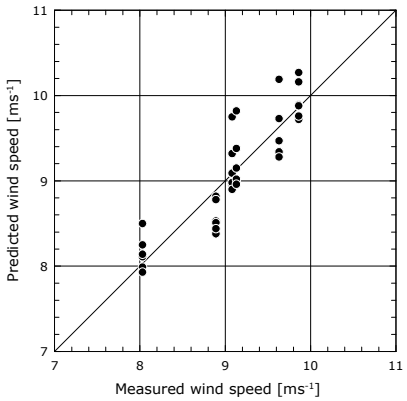
- Eight 30-50 m masts, up to 8 km apart
- Predictions for 30-50 m a.g.l.
- Location: Italy

- Mast 1, RIX = 2%
- Mast 2, RIX = 1%
- Mast 3, RIX = 1%
- Mast 4, RIX = 1%
- Mast 5, RIX = 1%
- Mast 6, RIX = 0%
- Mast 7, RIX = 1%
- Mast 8, RIX = 1%

- **ΔRIX masts = ±2%**

- ΔRIX-corrections applied
  - $Y = 1.00 \cdot X$
  - MAPE = 5.7%

Case 4: Predictions when |ΔRIX| is small



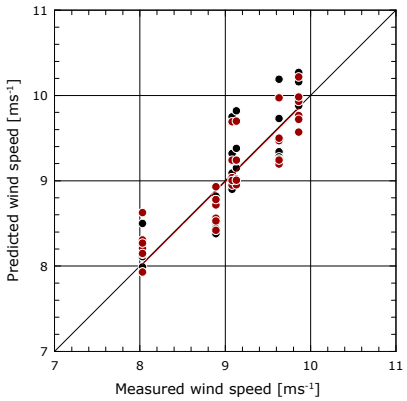
- Six 50-m met. masts, up to 5 km apart
- Predictions for 50 m a.g.l.
- Location: N Europe

- Mast 1, RIX = 11%
- Mast 2, RIX = 7%
- Mast 3, RIX = 8%
- Mast 4, RIX = 9%
- Mast 5, RIX = 5%
- Mast 6, RIX = 5%

- **ΔRIX masts = ±6%**

- Standard WAsP calculation
  - $Y = 1.00 \cdot X$
  - MAPE = 2.6% (SD = 2.1%)

Case 4: Predictions when |ΔRIX| is small



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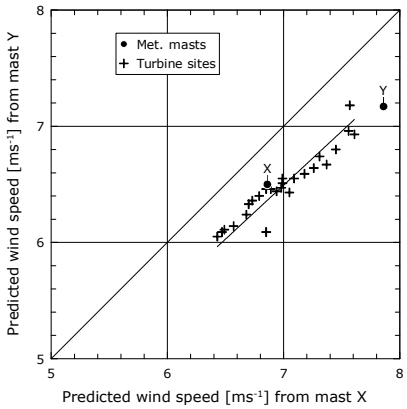
- Mast 1, RIX = 11%
- Mast 2, RIX = 7%
- Mast 3, RIX = 8%
- Mast 4, RIX = 9%
- Mast 5, RIX = 5%
- Mast 6, RIX = 5%

- **ΔRIX masts = ±6%**

- ΔRIX-corrections applied
  - $Y = 1.00 \cdot X$
  - MAPE = 2.5% (SD = 1.8%)

Case 5: Predictions when |ΔRIX| is large



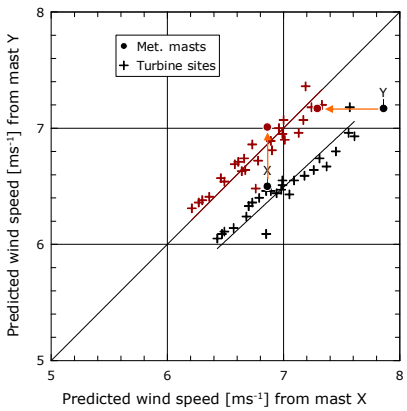
- Wind farm site with 25 turbine sites
- Two 40-m met. masts, 2.5 km apart
- Predictions for 40 m a.g.l.
- Location: Iberian Peninsula

- Mast X RIX = 15%
- Mast Y RIX = 26%
- Turbine sites RIX = 15% to 24%

- **ΔRIX masts = ±11%**
  - ΔRIX_X = 0% to 9%
  - ΔRIX_Y = -11% to -2%

- Standard WAsP calculation
  - $Y = 0.93 \cdot X$
  - MAPE = 7.5%

Case 5: Predictions when |ΔRIX| is large



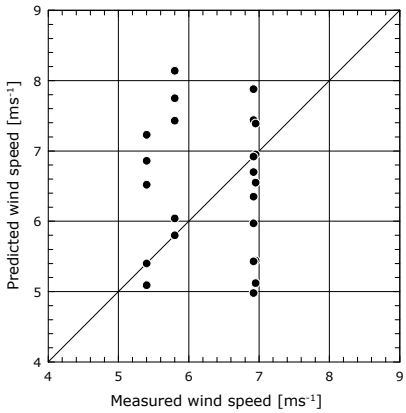
- Wind farm site with 25 turbine sites
- Two 40-m met. masts, 2.5 km apart
- Predictions for 40 m a.g.l.
- Location: Iberian Peninsula

- Mast X RIX = 15%
- Mast Y RIX = 26%
- Turbine sites RIX = 15% to 24%

- **ΔRIX masts = ±11%**
  - ΔRIX_X = 0% to 9%
  - ΔRIX_Y = -11% to -2%

- ΔRIX-corrections applied
  - $Y = 1.00 \cdot X$
  - MAPE = 1.3%

Case 6: Predictions when |ΔRIX| is very large



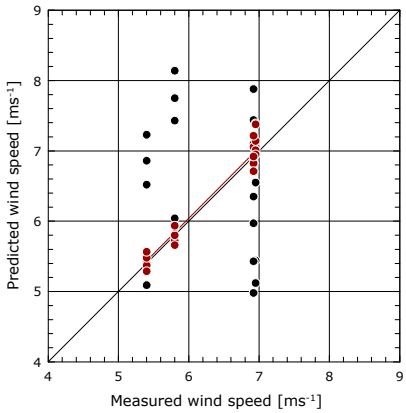
- Five 10-m met. masts, 2-15 km apart
- Predictions for 10 m a.g.l.
- Location: Northern Portugal

- Mast 06, RIX = 28%
- Mast 07, RIX = 33%
- Mast 08, RIX = 18%
- Mast 09, RIX = 10%
- Mast 10, RIX = 11%

- **ΔRIX masts = ±23%**

- Standard WAsP calculation
  - $Y = 1.00 \cdot X$
  - MAPE = 14.9%

Case 6: Predictions when |ΔRIX| is very large



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- Mast 08, RIX = 18%
- Mast 09, RIX = 10%
- Mast 10, RIX = 11%

- **ΔRIX masts = ±23%**

- ΔRIX-corrections applied
  - $Y = 1.00 \cdot X$
  - MAPE = 1.7%

Conclusions

- WAsP flow model generally works well for |ΔRIX| < 5%
  - no improvement by applying ΔRIX-procedure
  - large bias and scatter related to large distances and low wind speeds (mesoscale effects? thermal effects?)
- WAsP standard predictions significantly biased for |ΔRIX| > 10%
  - magnitude and sign of bias explained by simple arguments
  - significant improvements by applying ΔRIX-procedure
  - scatter increases only slightly with increasing ΔRIX
- ΔRIX correction procedure based on wind speed
  - works well for relatively 'uncomplicated' sites with steep slopes
  - $\ln(U_p/U_m)$ versus ΔRIX fit is linear and goes through (0, 0)
  - fitting constant site-specific (0.7-1.5 for default parameters)
  - procedure easy to implement in WAsP
- Prediction of actual AEP for operating wind farm improved by 70%
  - from overestimation of 13% to 3% on AEP

Best practices in rugged terrain

Measurement programme [bankable]

- Two or more masts required
  - sited according to similarity principle (including forestry)
  - cover range of RIX over site
  - distances not greater than 1 km
  - supported by remote LT mast

Topographical inputs

- Minimum size of map
  - Elevation: 10 km from any site
  - Land-use: max(100×h, 10 km)
- Detail and accuracy of map
  - wind farm site: 2-m contours
  - nearby terrain: 10-m contours
  - further away: 10-50 m contours
  - SRTM data may be used, but must be quality-controlled and detailed

WAsP modelling

- RIX and ΔRIX analyses required
- Use similarity principle if and when applying ΔRIX correction procedure
- Standard heights in wind atlas
  - change one level to hub height
  - never change 10-m level!
- Standard roughnesses in wind atlas
  - other classes may be added or roughness lengths changed
  - never change z_0 = 0 m class!
- Heat flux parameters
  - may be adapted to site

Future

- Evidently, 'best practices' is not a long-term substitute for further research and improved models, such as CFD!