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

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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 $\Delta RIX$

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

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

- Slopes steeper than $\theta_c$ are indicated by the thick red (radial) lines.
Methodology

- Comparisons of measured and/or predicted wind speeds
  - plot prediction error versus $\Delta RIX$ for met. masts
  - find site-specific fitting constant ($\alpha$)
  - calculate corrected predictions
  - plot original and $\Delta RIX$-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.
  - $|\Delta RIX| > 0$; 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 $|\Delta RIX| = 0$

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), $RIX = 16\%$
- $\Delta RIX = 0\%$
- $MAPE = 1.3\%$
- Difficult comparison!
  - roughness lengths
  - stability effects
  - flow distortion

Case 2: Predictions when $|\Delta RIX|$ 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 $13\%$
- $\Delta RIX$ masts $= \pm 3\%$
  - $\Delta RIX_X = -2\%$ to $7\%$
  - $\Delta RIX_Y = -5\%$ to $4\%$
- Standard WASP calculation
  - $Y = 1.00 \cdot X$
  - $MAPE = 0.3\%$
Case 3: Predictions when $|\Delta RIX|$ 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%

$\Delta RIX$ masts = ±2%

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

<table>
<thead>
<tr>
<th>Measured wind speed [ms$^{-1}$]</th>
<th>Predicted wind speed [ms$^{-1}$]</th>
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$\Delta RIX$-corrections applied
- $Y = 1.00 \cdot X$
- MAPE = 5.7%
Case 4: Predictions when $|\Delta RIX|$ 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, $RIX = 5\%$

- $\Delta RIX_{masts} = \pm 6\%$
- Standard WASP calculation
  - $Y = 1.00 \cdot X$
  - MAPE = 2.6\% (SD = 2.1\%)

Measured wind speed [ms$^{-1}$]

Predicted wind speed [ms$^{-1}$]
Case 5: Predictions when $|\Delta RIX|$ 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 $24\%$

- $\Delta RIX$ masts $= \pm 11\%$
  - $\Delta RIX_x = 0\%$ to $9\%$
  - $\Delta RIX_y = -11\%$ to $-2\%$

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

- $\Delta RIX$-corrections applied
  - $Y = 1.00 \cdot X$
  - MAPE = 1.3\%
Case 6: Predictions when $|\Delta \text{RIX}|$ 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%

$\Delta \text{RIX masts} = \pm 23\%$

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

$\Delta \text{RIX-corrections applied}$
  - $Y = 1.00 \cdot X$
  - MAPE = 1.7%
Conclusions

- WASP flow model generally works well for $|\Delta \text{RIX}| < 5\%$
  - no improvement by applying $\Delta \text{RIX}$-procedure
  - large bias and scatter related to large distances and low wind speeds
  (mesoscale effects? thermal effects?)
- WASP standard predictions significantly biased for $|\Delta \text{RIX}| > 10\%$
  - magnitude and sign of bias explained by simple arguments
  - significant improvements by applying $\Delta \text{RIX}$-procedure
  - scatter increases only slightly with increasing $\Delta \text{RIX}$
- $\Delta \text{RIX}$ correction procedure based on wind speed
  - works well for relatively ‘uncomplicated’ sites with steep slopes
  - $\ln(U_p/U_m)$ versus $\Delta \text{RIX}$ 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($100 \times h$, 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 $\Delta \text{RIX}$ analyses required
- Use similarity principle if and when applying $\Delta \text{RIX}$ 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!