VORTEX

# On the benefit of a multivariate description of wind for a better long-term extrapolation

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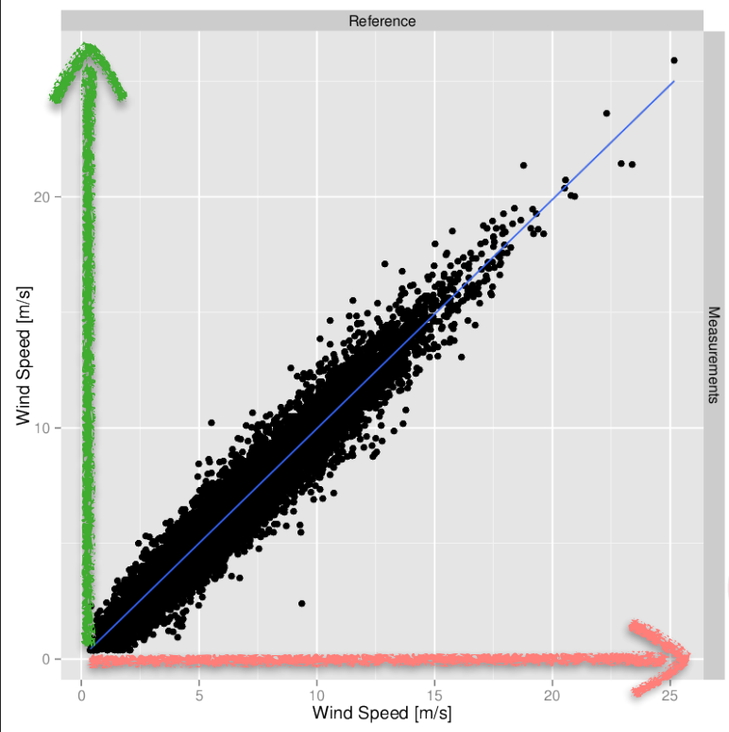
# Outline

- MCPs/LTCs
- MCPs shortcomings: illustrative problems of the industry
- Remodeling: description
- Remodeling success: illustrative cases
- Validation results
- Users feedback
- Summary

**MCPs:** Long-term correction method based on a (linear) regression analysis of a wind reference SERIES with on-site measurements.




SERIES

## MEASURE

on-site measures

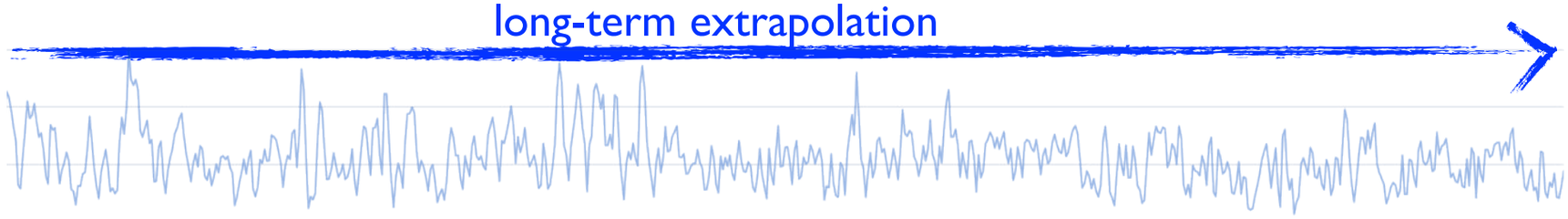
## CORRELATE

long-term reference data (NWP, stations)

## PREDICT

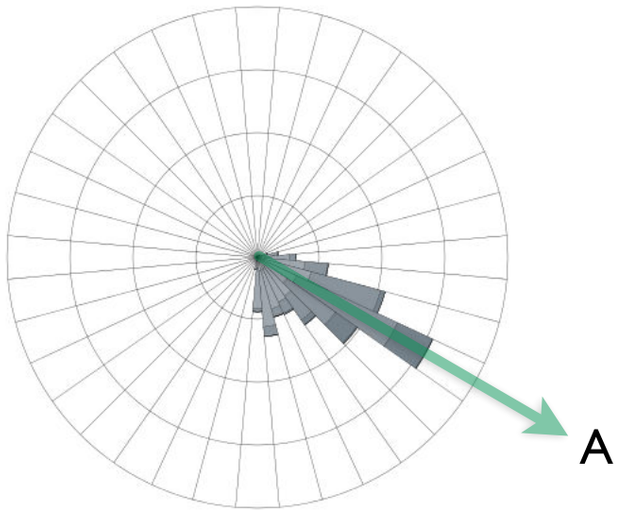
$$y_i = \beta_1 x_{i1} + \cdots$$

long-term extrapolation



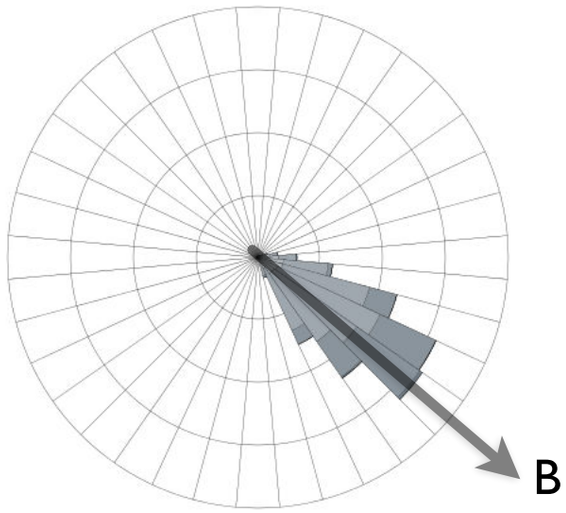
# Industry Problem 1: Wind-Rose

**MEASURES**



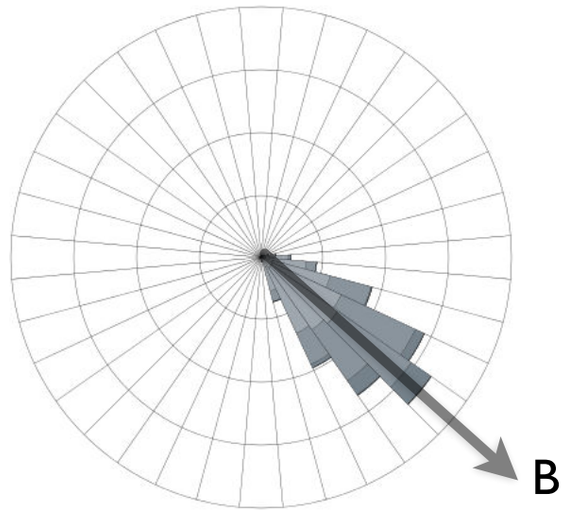

**Wind-Rose - Site Data**
**(5 years)**

**SERIES**




**Wind-Rose - Vortex Series**
**(same period)**

**INDUSTRY - MCP**

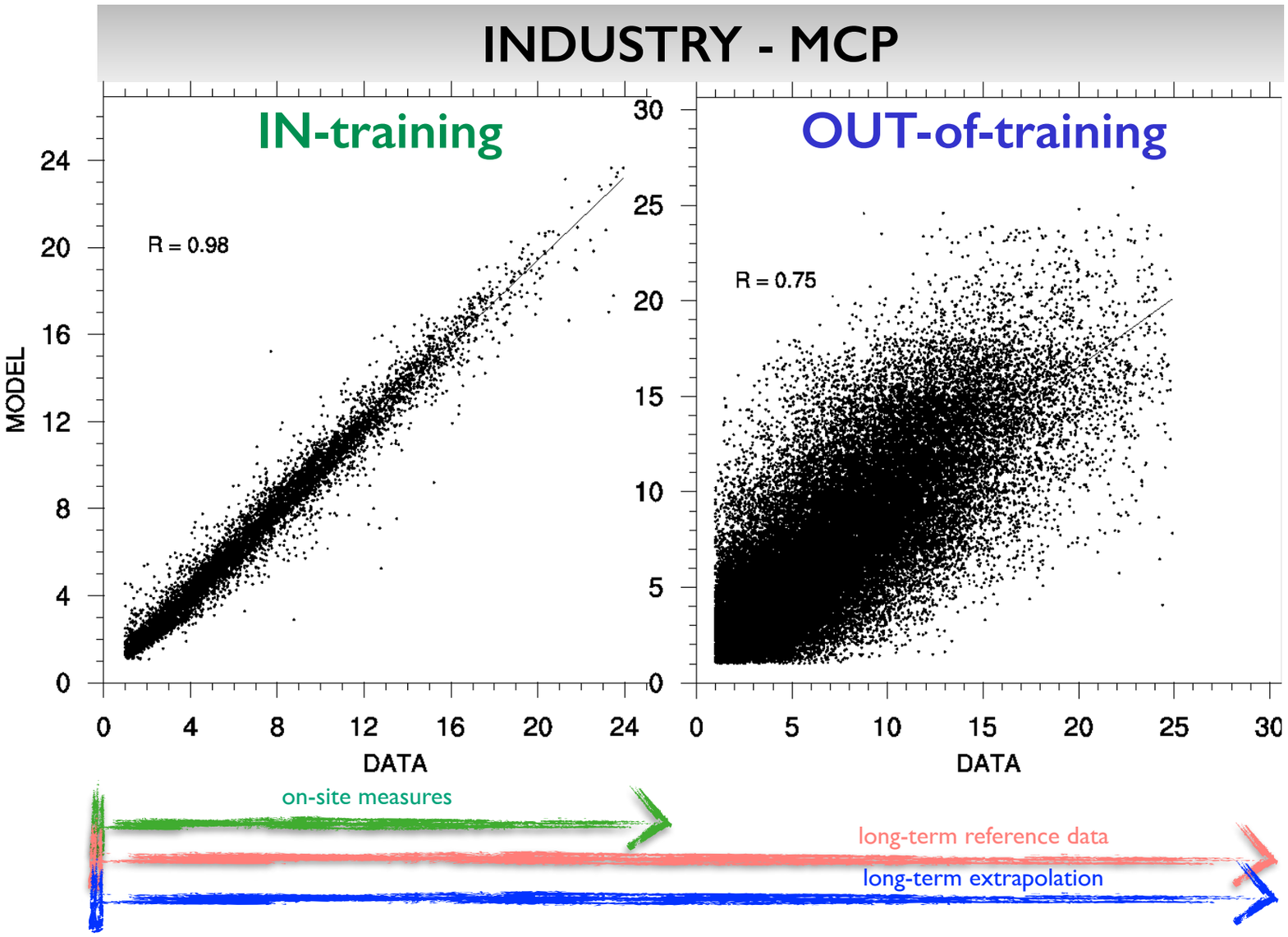



**Wind-Rose - MCP**
**(same period)**

MCP does not properly correct the Wind-Rose

| Direction | $R^2$ | RMSE |
|---|---|---|
| MCP | 0,58 | 20,9 |
| SERIES | 0,58 | 22,0 |

# Industry Problem 2: IN & OUT-of-training sensitivity

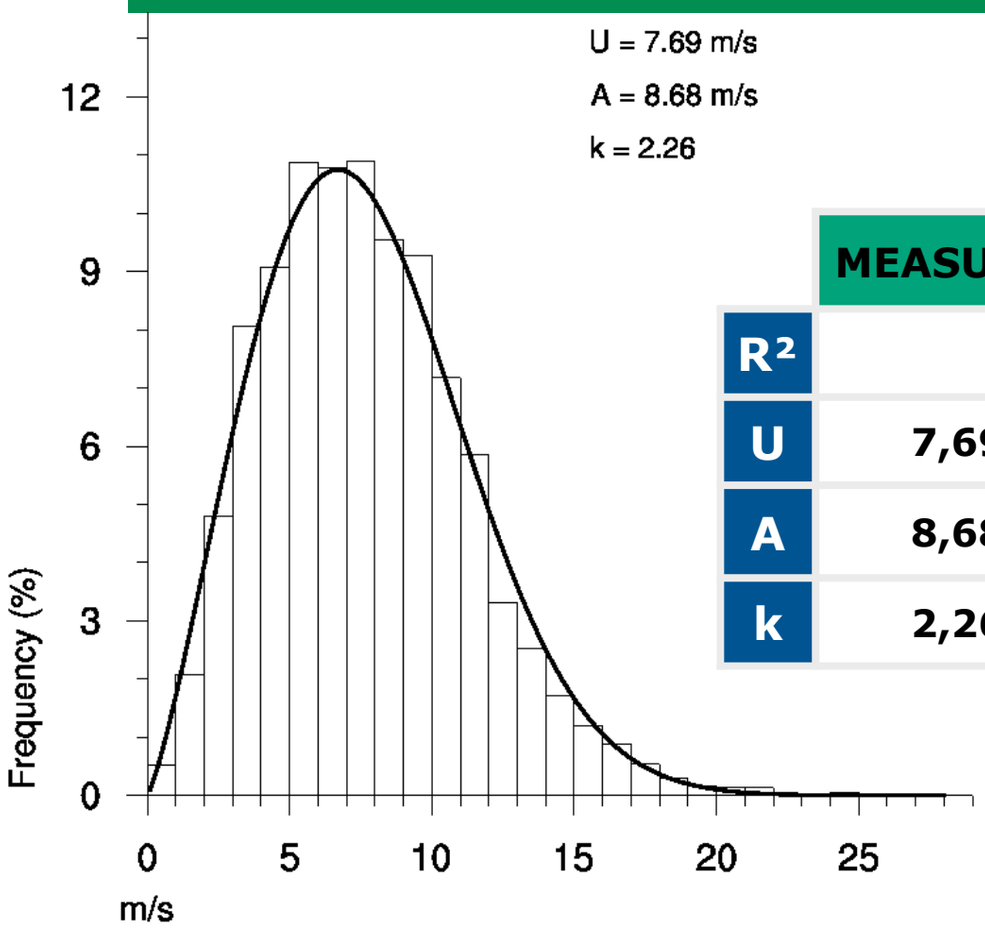



| R^2 | IN | OUT |
|---|---|---|
| MCP | 0,96 | 0,56 |
| SERIES | 0,71 | 0,71 |

MCP performance degrades considerably from the IN to the OUT-of-training sample.

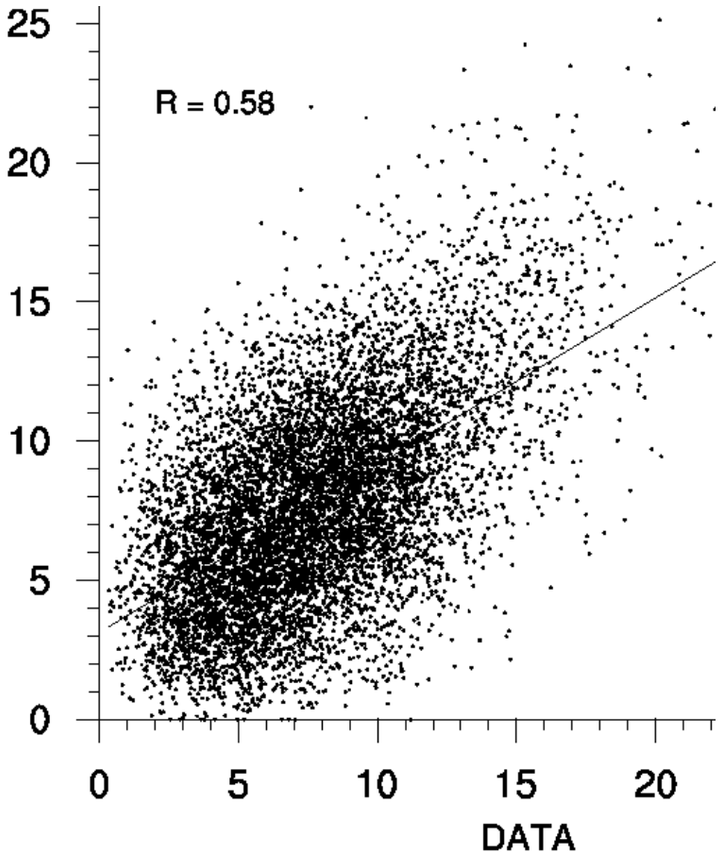
# Industry Problem 3: Metric degradation

## MEASURES




| | MEASURES | SERIES | MCP |
|---|---|---|---|
| $R^2$ | | 0,54 | 0,34 |
| U | 7,69 | 6,26 (18,6%) | 7,75 (0,78%) |
| A | 8,68 | 6,93 (20,2%) | 8,73 (0,58%) |
| k | 2,26 | 2,59 (14,6%) | 2,18 (3,54%) |

## INDUSTRY - MCP



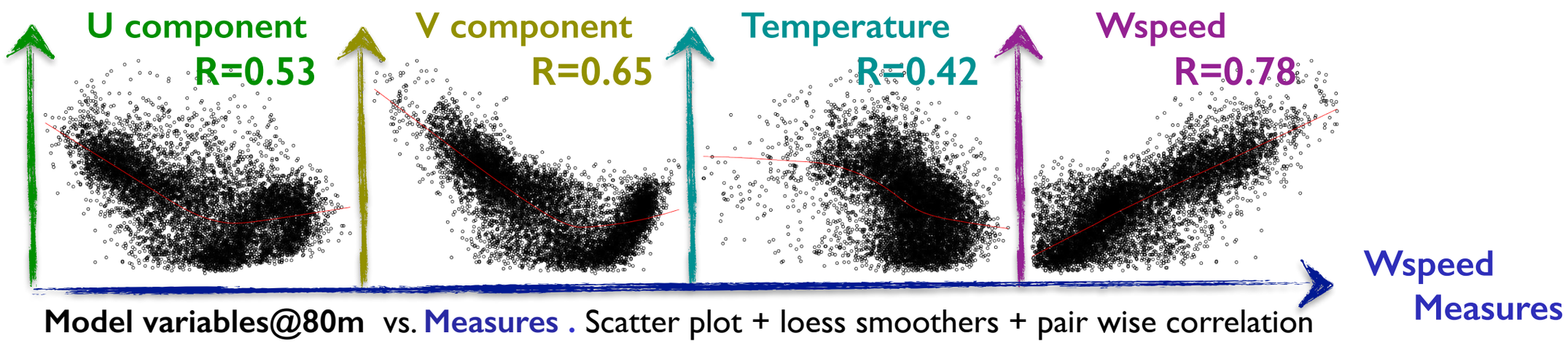

MCP produce a exceptional good fit for some metrics while significantly degrades others.

# Remodeling: yet another MCP/LTC?

| | |
|---|---|
| YES | • The principe is the same: fit campaign measurements with reference data to extrapolate the long-term wind resource. |
| NO | • It employs a variety of modeled variables at different levels/heights **(multivariate approach)**, not just wind reference series<br>• It is **not linear**<br>• The long-term correction **keeps the representativeness of the series in all its attributes** (correlation, frequency distribution, Rose,...)<br>• **Reduces out-of-training degradation**<br>• ... Thus, it **does not preclude the use of traditional MCPs** as second layer (if needed) |

# Multivariate approach

A multivariate analysis allows to identify (and fit) **regime dependent winds** (i.e. associated to a particular climate pattern or weather situation).

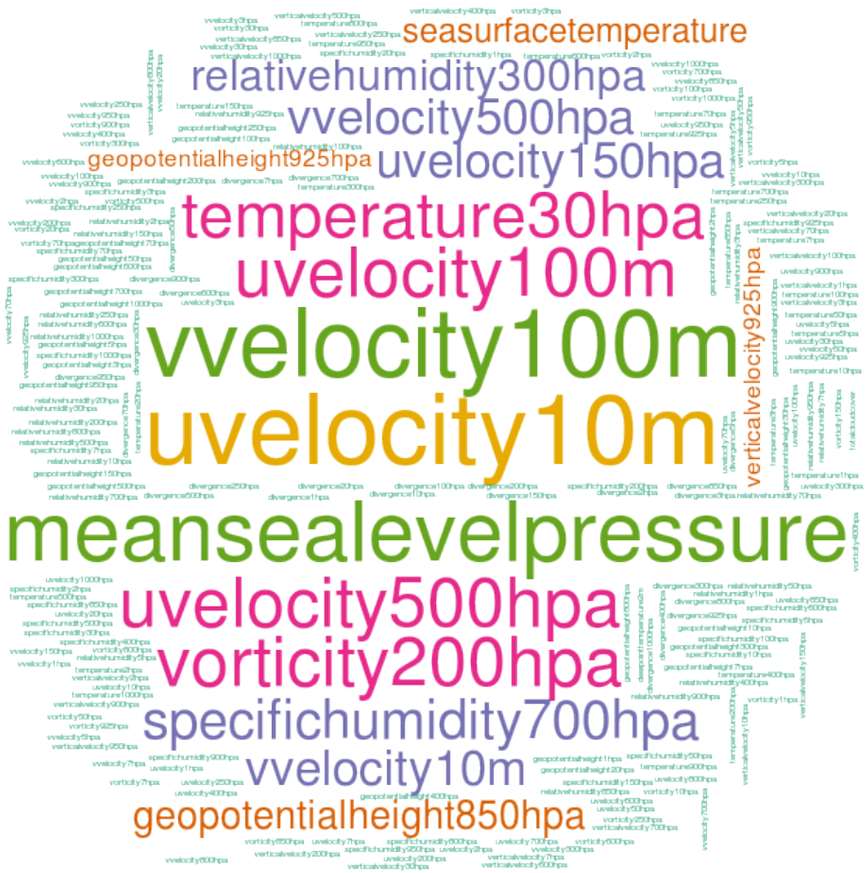



**Model variables@80m** vs. **Measures .** Scatter plot + loess smoothers + pair wise correlation

The highly dynamic and non-linear fashion in which the atmospheric variables are linked suggests the **need for a more sophisticated statistical tools for MCPs/ LTCs** than current linear approaches based solely on wind.

# Remodeling: Data reduction

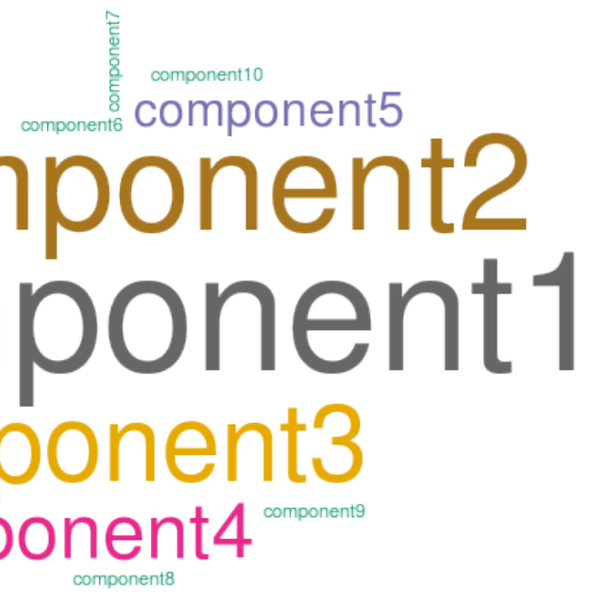
## NWP output




Linear transformation

$$f(a_1\mathbf{x}_1 + \cdots + a_m\mathbf{x}_m) = a_1 f(\mathbf{x}_1) + \cdots + a_m f(\mathbf{x}_m).$$

## Reduced variables (Components)

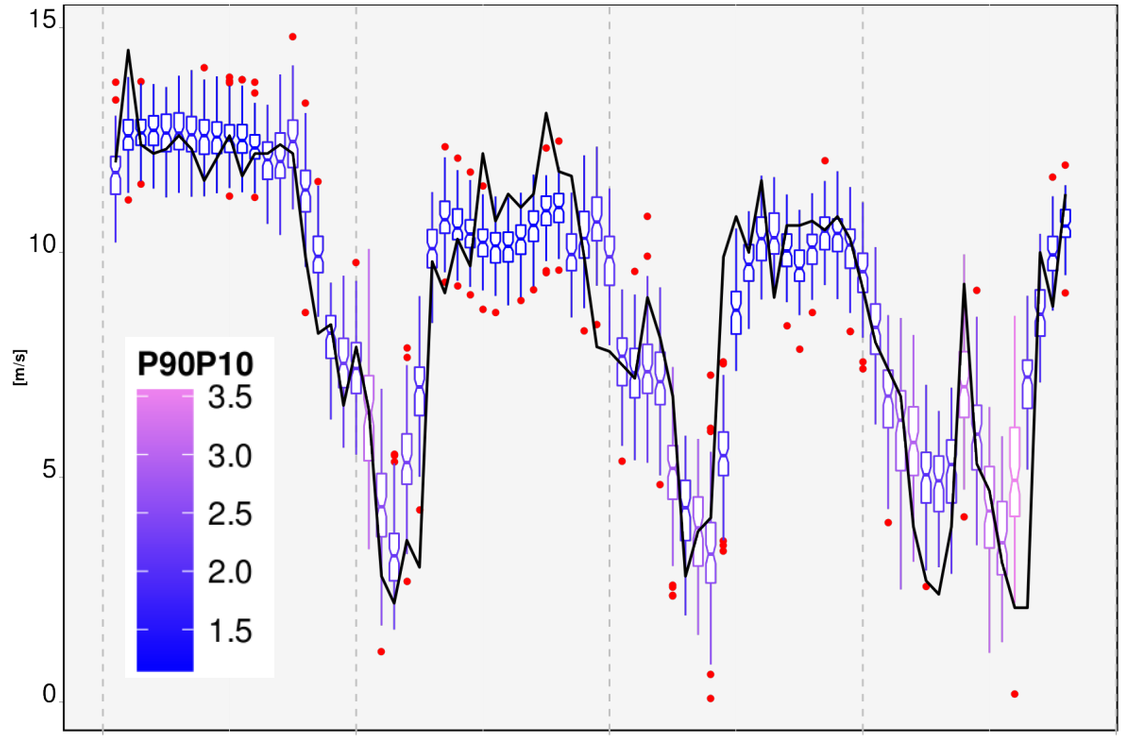


# Remodeling: non-linear ensemble

Linear models can account for non-linear trends/relationships if the non-linear nature of the data is known...The non-linearity of wind is unknown *a priori* and it is site and weather regime dependent. **The alternative: inherently non-linear models.**

Remodeling follows an **ENSEMBLE approach of non-linear models:**

- Palliate inherent drawbacks of single non-linear models (local solutions, over-fit, instabilities, etc.)
- Stable solutions
- Characterize uncertainty




**BoxPlot**: non-linear models

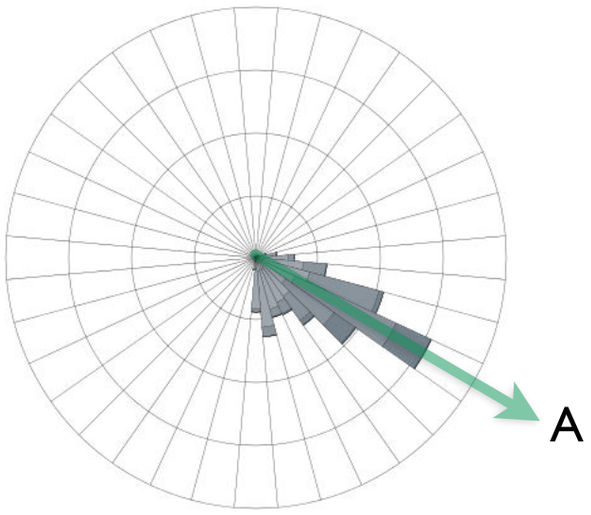
**Outliers**: in red

**Color scale**: P90-P10 band width

**Measures**: black solid line

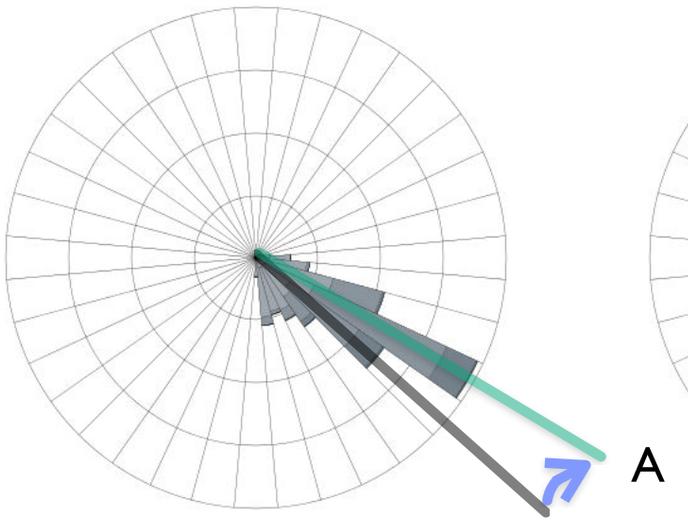
# Remodeling Success 1: Wind-Rose

**MEASURES**



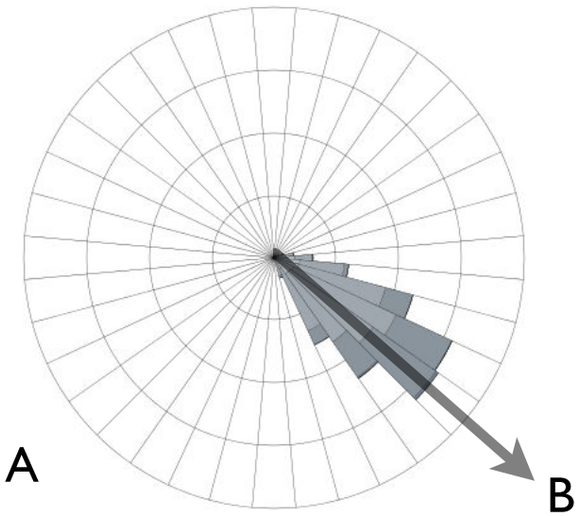

**Wind-Rose - Site Data (5 years)**

**REMODELING**



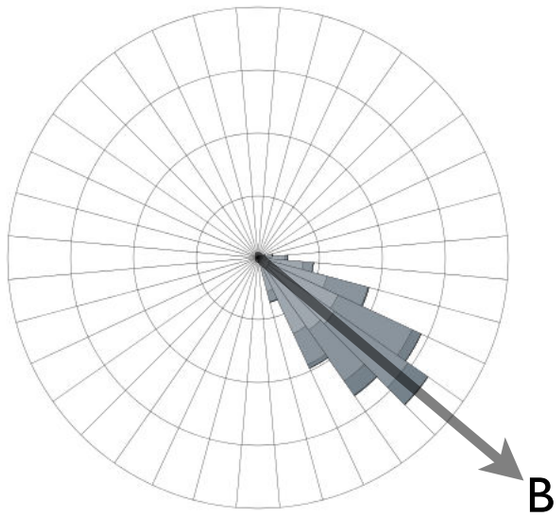

**Wind-Rose - Remodeling (same period)**

**SERIES**




**Wind-Rose - Vortex (same period)**

**INDUSTRY - MCP**

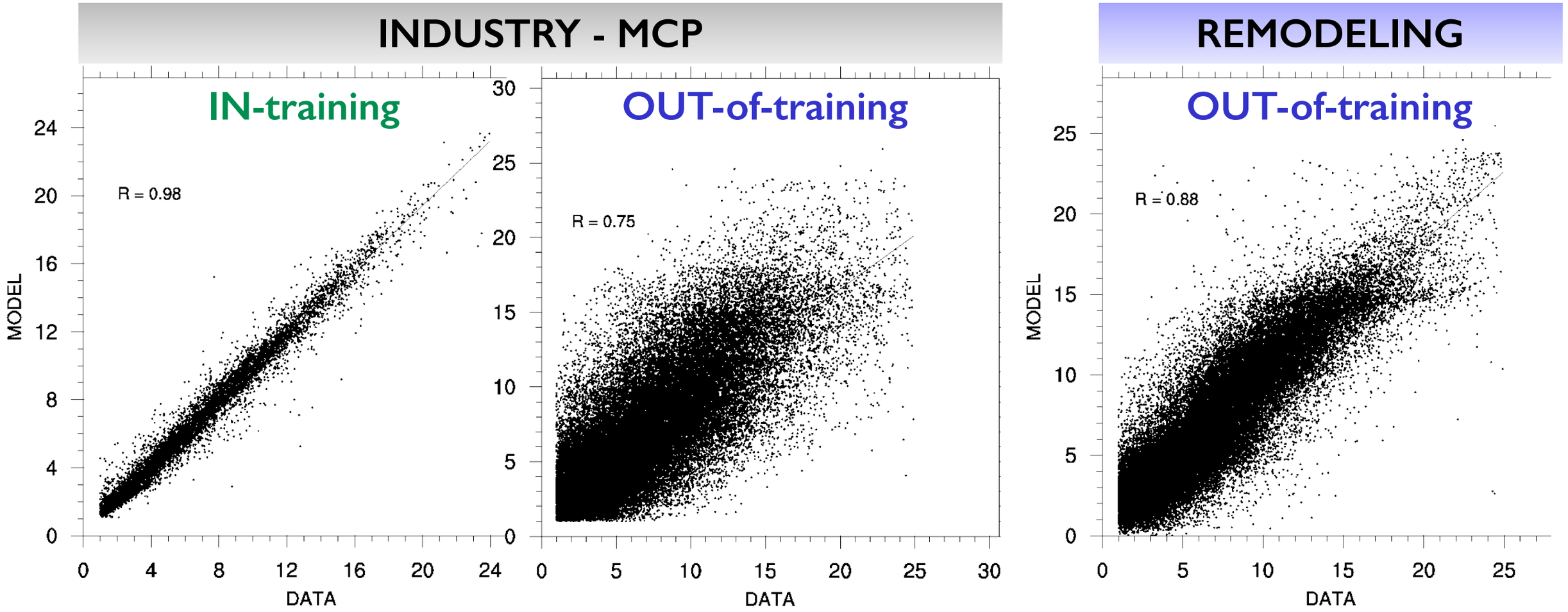



**Wind-Rose - MCP (same period)**

Remodeling corrects the Wind-Rose: increases the correlation and decreases de RMSE/Bias

| Direction | $R^2$ | RMSE |
|---|---|---|
| REMODELING | 0,64 | 19,5 |
| MCP | 0,58 | 20,9 |
| SERIES | 0,58 | 22,0 |

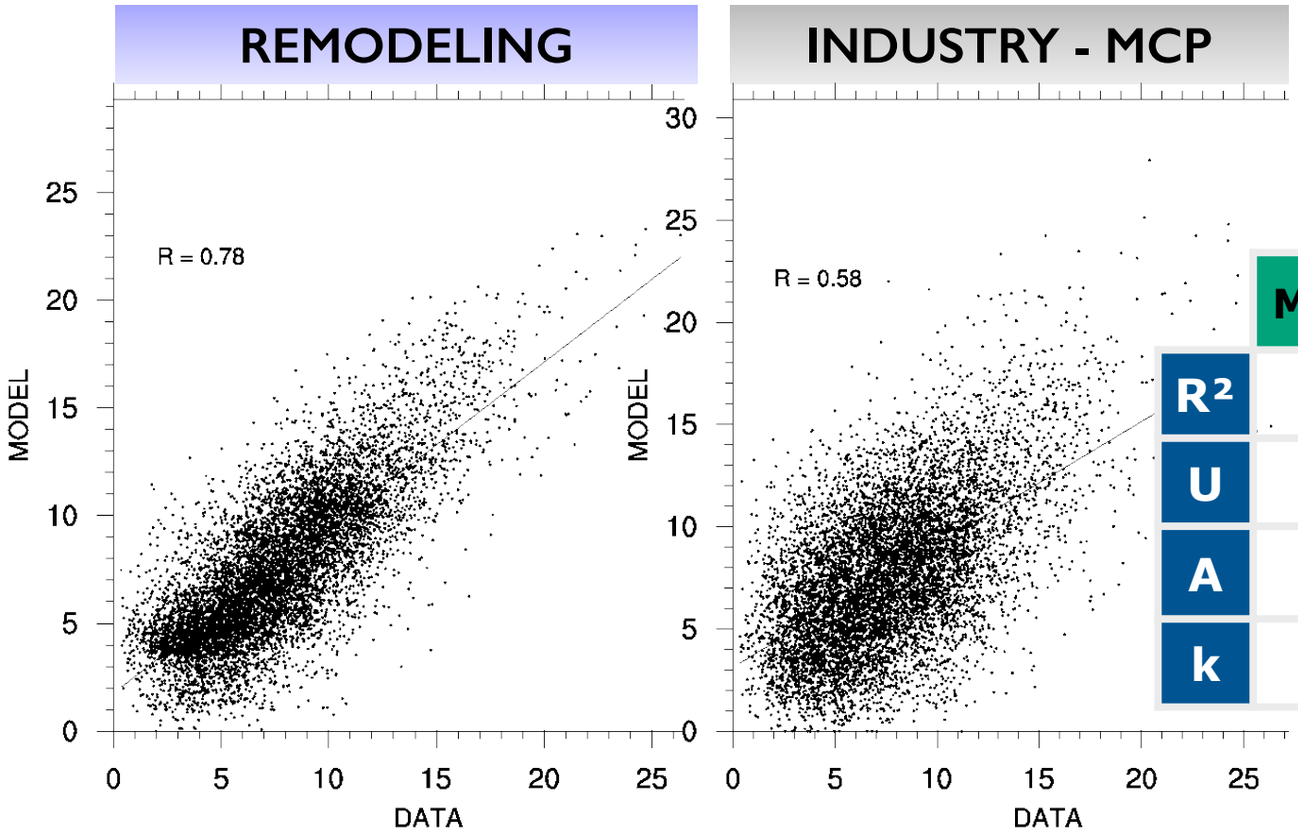
# Remodeling Success 2: IN & OUT-of-training




Remodeling consistently extrapolates the lessons learned in the period coincident with measures, to the rest of the SERIES. The sensitivity/dependence of results to the training period is reduced.

| R | IN | OUT |
|---|---|---|
| REMODELING | 0,81 | 0,77 |
| MCP | 0,96 | 0,56 |
| SERIES | 0,71 | 0,71 |

# Remodeling Success 3: Metric degradation

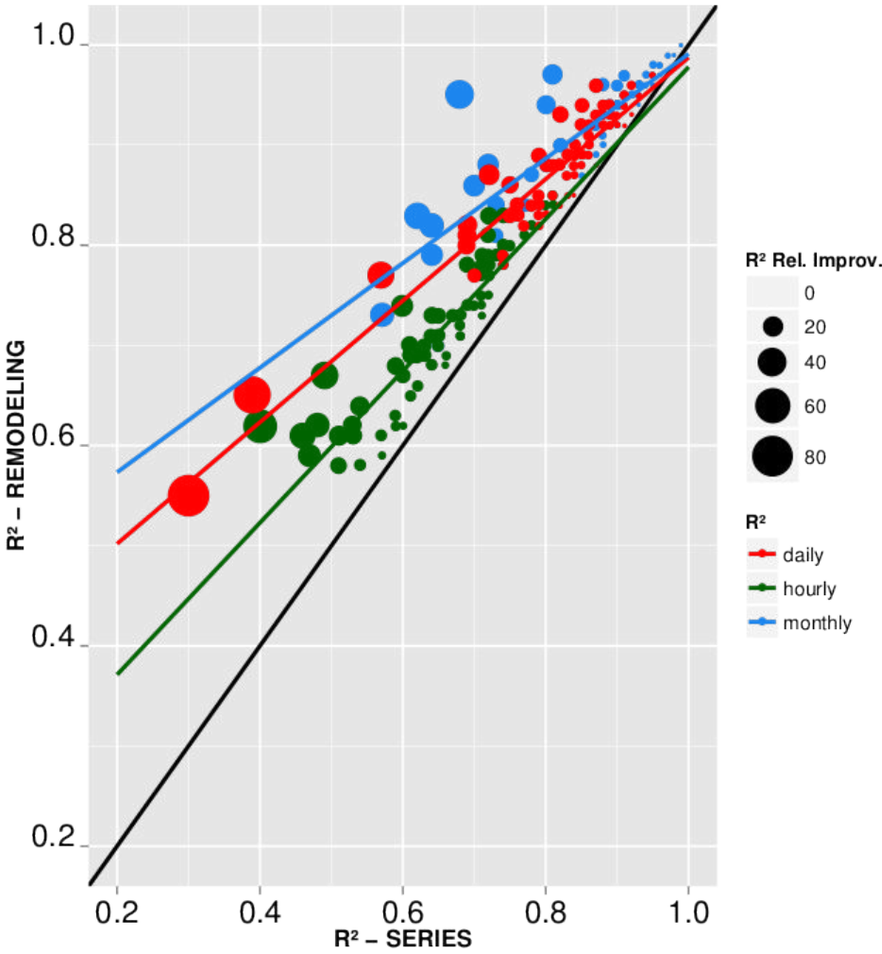



| MEASURES | REMODELING | MCP | SERIES |
|---|---|---|---|
| $R^2$ | 0,61 | 0,34 | 0,54 |
| U | 7,69 | 7,68 (0,13%) | 7,75 (0,78%) | 6,26 (18,6%) |
| A | 8,68 | 8,67 (0,11%) | 8,73 (0,58%) | 6,93 (20,2%) |
| k | 2,26 | 2,29 (1,33%) | 2,18 (3,54%) | 2,59 (14,6%) |

Remodeling does not degrades the attributes of the SERIES in order to improve a particular metric, it improves overall all the attributes.

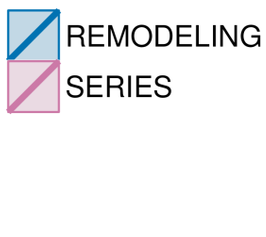
# Validation at +100 sites worldwide

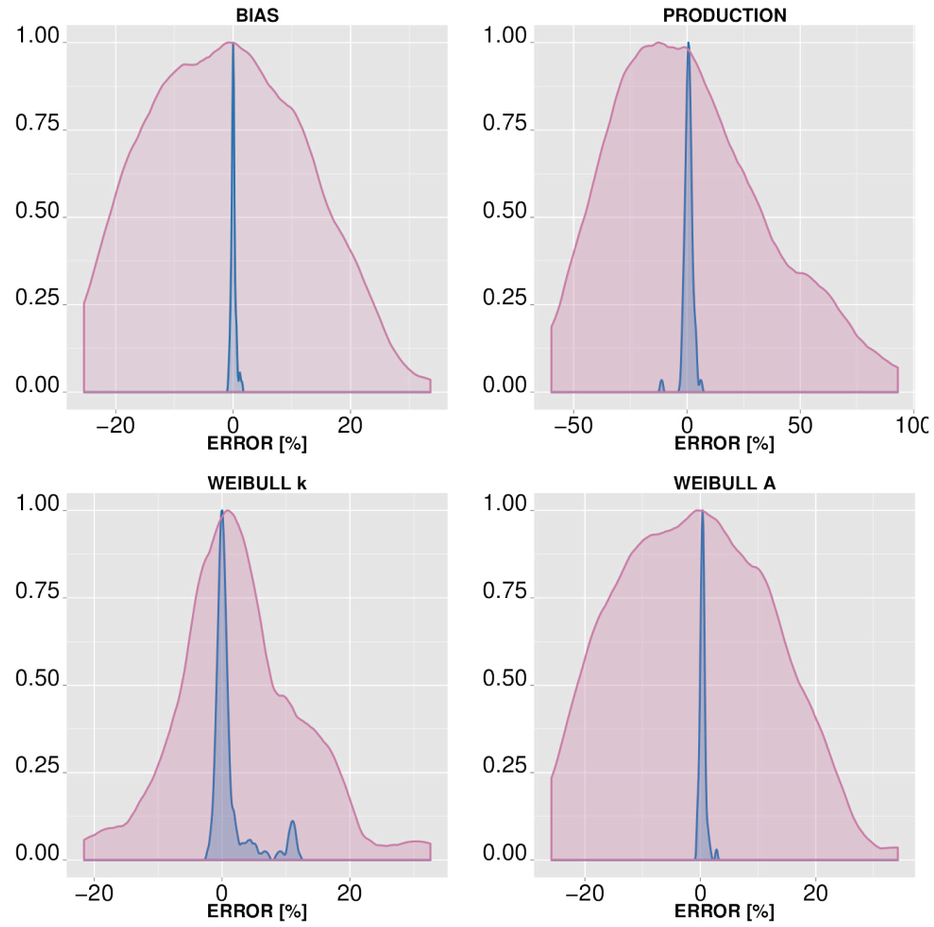
# Validation at +100 sites worldwide










| IMPROVEMENTS | R² (hourly) | R² (daily) | R² (monthly) | R² dir (hourly) | RMSE | BIAS | PROD | k | A |
|---|---|---|---|---|---|---|---|---|---|
| Events | 100% | 100% | 100% | 95% | 100% | 100% | 97% | 82% | 97% |
| Average Val. | 0,06 | 0,06 | 0,05 | 0,12 | 0,4m/s | 10,6% | 26,3% | 7,4% | 10,6% |
| Std. Deviation | 0,04 | 0,05 | 0,06 | 0,10 | 0,3m/s | 7,20% | 19,1% | 6,8% | 7,1% |

# Users feedback

| | POSITIVE FEEDBACK … | POINTS TO BE IMPROVED … |
|---|---|---|
| acciona | "Remodeling provides good potential to improve long-term estimates". | |
| ALSTOM * | "Remodeling combines very good results and low effort into an astonishing effective standardized procedure". | "In complex terrain there is a significant improvement in some parameters while in others the original series reproduces better the data". |
| barlovento recursos naturales | "Remodeled series significantly improves the original series in simple terrain sites". | The results for the wind direction are satisfactory overall, although there is still room for improvement. |
| e·on Renewables | "Remodeling improves in a high percentage of cases the $R^2$ respect to the Vortex Series and other Industry MCPs". | Although the Weibull fit is good, the wind histogram for the remodeled series should be improved. |
| IBERDROLA RENEWABLES ** | | |
| SOWITEC | "Remodeling provides good results for the Wind Bias/RMSE and the Weibull parameters". | |

(*) Check Poster Id. 088: "*Benefits of multiscale modelling to reduce long term wind resource uncertainty: the Gouda case*"
(**) in the process of testing the re-modeling

# Summary

Full colored petal identifies the **BEST** average performance of that metric.

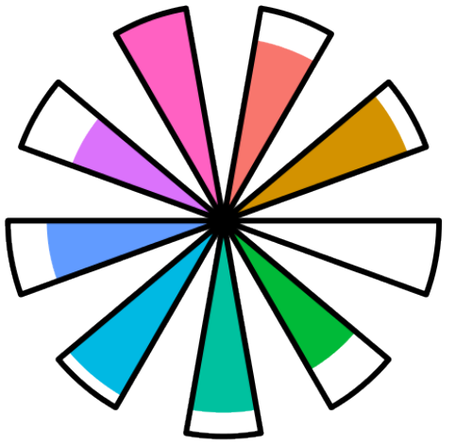
Statistical sample includes sites worldwide with different terrain complexities.

**OUT-of-training:** 4 yrs
**IN-training:** 1 yr

**SERIES**

**MCP-A-LINEAR**

**MCP-B-LINEAR**




**MCP-A-MATRIX**

**MCP-B-MATRIX**

**REMODELING**