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Incorporating Spatial Uncertainty Modeling into Wind Plant Development, Design, and Assessment

Michael C. Brower, PhD
President & Chief Technical Officer

Jose Vidal, MSc
Consulting Services Europe & Latin America Manager

Santi Vila Moreno, MSc
Lead Engineer

Nicholas M. Robinson
Director of Openwind

Introduction

- Wind energy analysts have made great strides understanding the uncertainty of energy production estimates
- But current methods lack a rigorous model of the spatial variation of the uncertainty across a project site
- This gap can increase project costs and risks due to
  - Inefficient deployment of measurement assets
  - Poorly designed turbine layouts
  - Incorrect uncertainty estimates
- Spatial uncertainty models can help answer such questions as
  - Where should I place my towers to minimize energy uncertainty?
  - By how much can I reduce the uncertainty if I add more towers?
  - What is an optimal turbine layout to maximize P99, not just P50?

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Why does uncertainty vary across a site?

- Influence of terrain, land-water boundaries, and other conditions:
  - Requires an understanding of wind flow modeling uncertainty (hard)
- Uncertainties associated with different masts and measurement systems
  - Requires a general model of uncertainty (harder)

We'll start by focusing on

wind flow modeling uncertainty

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Two common ways of thinking about wind flow modeling uncertainty

It is constant with position…

…or depends on distance to nearest mast

Neither is realistic! How do we know?

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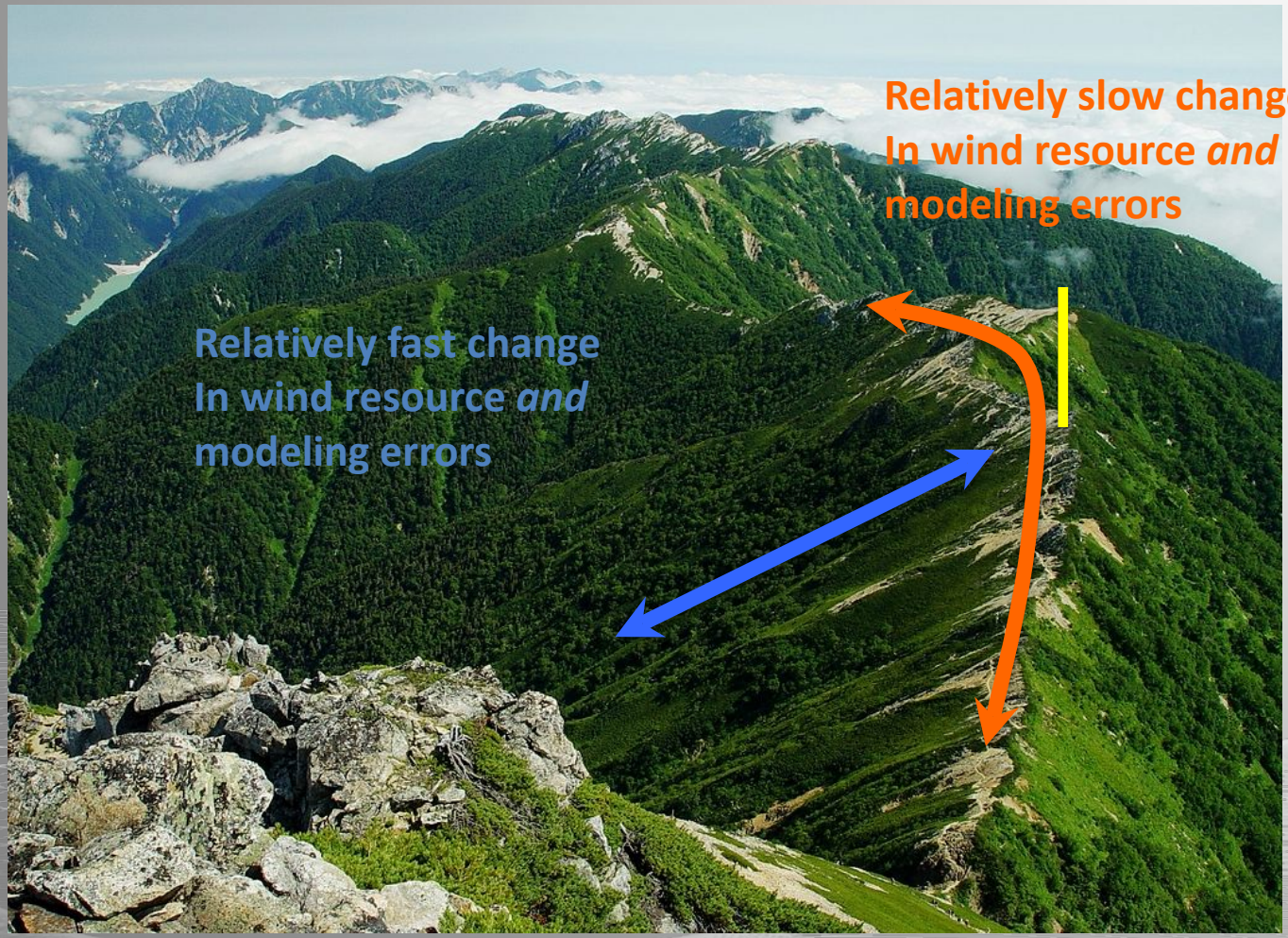
Thought Experiment: Steep Ridge



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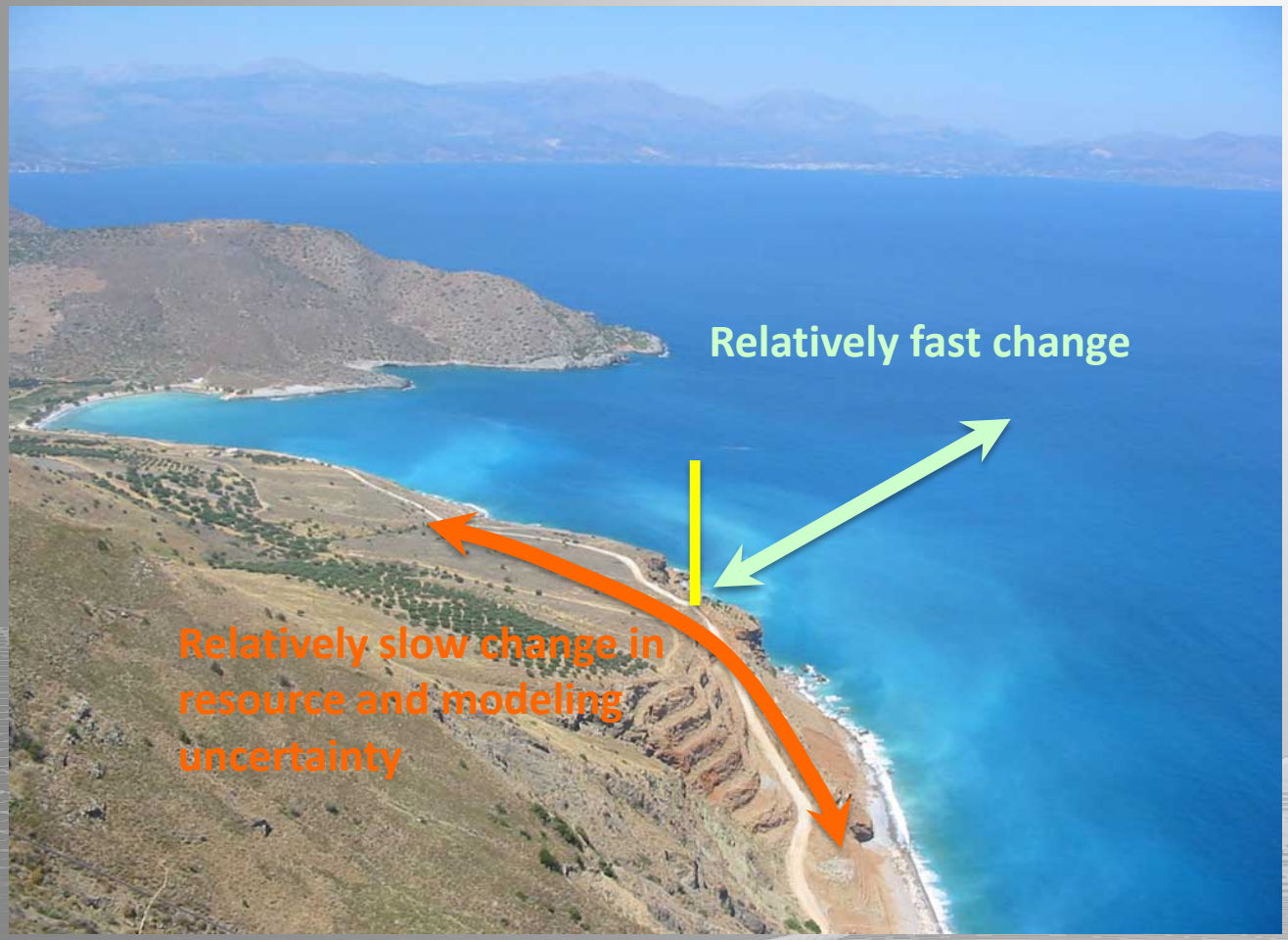
Thought Experiment: Coastline



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So what does modeling uncertainty depend on, if not strictly on distance?

- Our hypothesis: the uncertainty is proportional to the *predicted difference* in the wind resource between two points
- Interpretation #1: the more “work” a model has to do, the larger the likely error
- Interpretation #2: the uncertainty is proportional to the “resource distance”

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We propose two parameters to measure resource similarity between points

RMS Speed Deviation:

$$SD = \left[\sum_{i=1}^{ND} f_i^{(R)} \left(\frac{v_i^{(T)}}{v_i^{(R)}} - 1 \right)^2 \right]^{1/2}$$

RMS Direction Deviation:

$$DD = \left[\sum_{i=1}^{ND} \left(f_i^{(T)} - f_i^{(R)} \right)^2 \right]^{1/2}$$

Where:

- T: Target (WTG)
- R: Reference (mast)
- ND: number of dirs
- f: frequency
- v: wind speed

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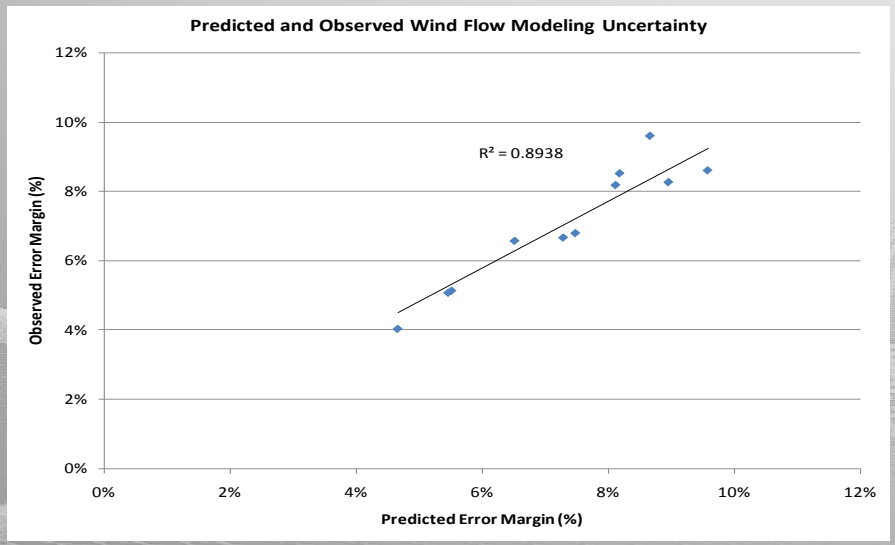
Derived Wind Flow Model Uncertainty

$$WFMU = E\left[1 - B\frac{A}{DD + A} - D\frac{C}{SD + C}\right]$$

Where A, B, C, D, E are fitted constants.

- Assumes the wind flow model captures main sources of variation of wind resource (you need a good model!)
- Implemented in AWST openWind software

Predicted vs. Observed Standard Errors



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What can we do with this?

- Obtain a rigorous estimate of wind flow modeling uncertainty for energy production estimates
- Efficiently deploy resource monitoring assets to obtain highest accuracy vs. investment
- Objectively identify gaps and pick locations for new masts to reduce uncertainty in the energy production
- Optimally blend estimates from different masts (beyond distance-squared weighting)
- Guide layout design to maximize P90 or P99 production, not necessarily P50

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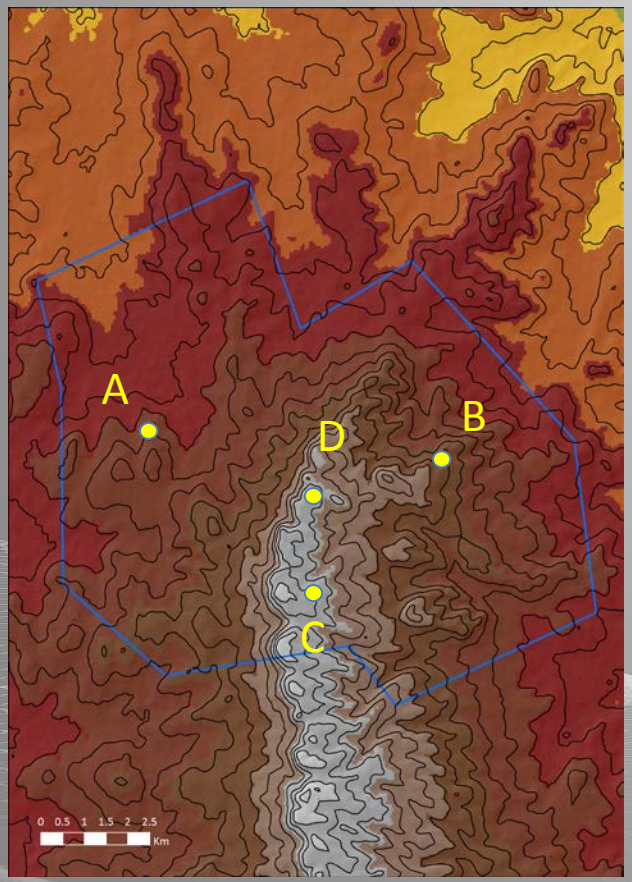
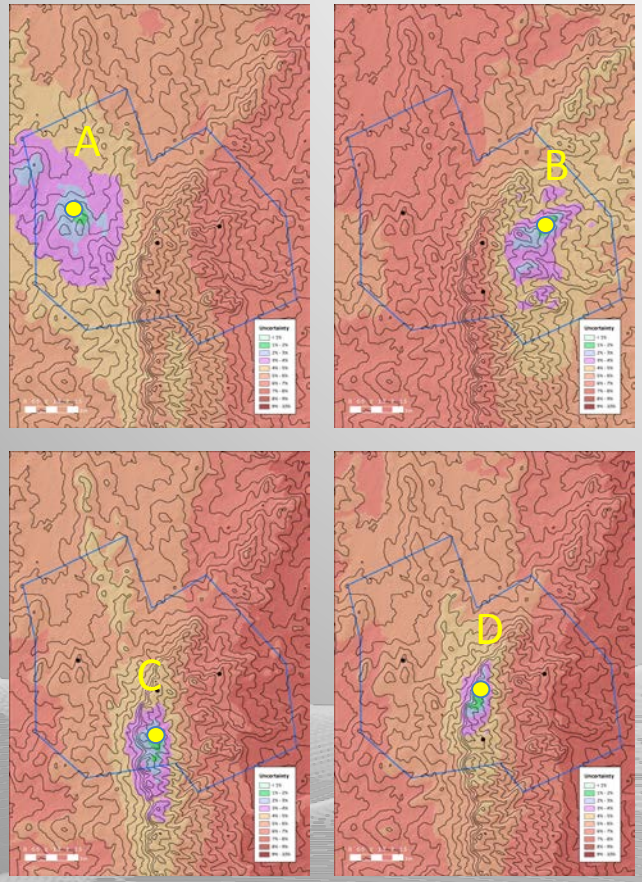
Example #1: Single-Tower Uncertainty Maps

Terrain



Uncertainty maps per mast



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Details, details

- Combining wind flow modeling and other uncertainties from different measurements *in an optimal way* is not easy
- What weight to give the predicted resource from each mast?
- The solution must consider the degree of correlation (covariance) among errors from different masts, including wind flow and other errors
- The Openwind uncertainty model contains a general solution to this problem

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Combining Different Masts

Blended estimate:

$$e = \sum w_i e_i$$

Blended variance:

$$\sigma^2 = \sum_i w_i^2 \sigma_i^2 + \sum_i \sum_{j<>i} w_i w_j r_{ij} \sigma_i \sigma_j$$

Derivative:

$$\frac{\partial \sigma^2}{\partial w_k} = \sum \frac{\partial w_i^2}{\partial w_k} \sigma_i^2 + \sum_i \sum_{j<>i} \frac{\partial w_i w_j}{\partial w_k} r_{ij} \sigma_i \sigma_j = 0$$

Independent terms

Covariant terms

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Determining the covariances

- We developed a pragmatic model based on “resource distance”
- If two masts are much closer to each other in resource space than they are to a point, they are assumed to be correlated
- Conversely, if two masts are much farther apart in resource space than either is to the point, they are assumed to be uncorrelated

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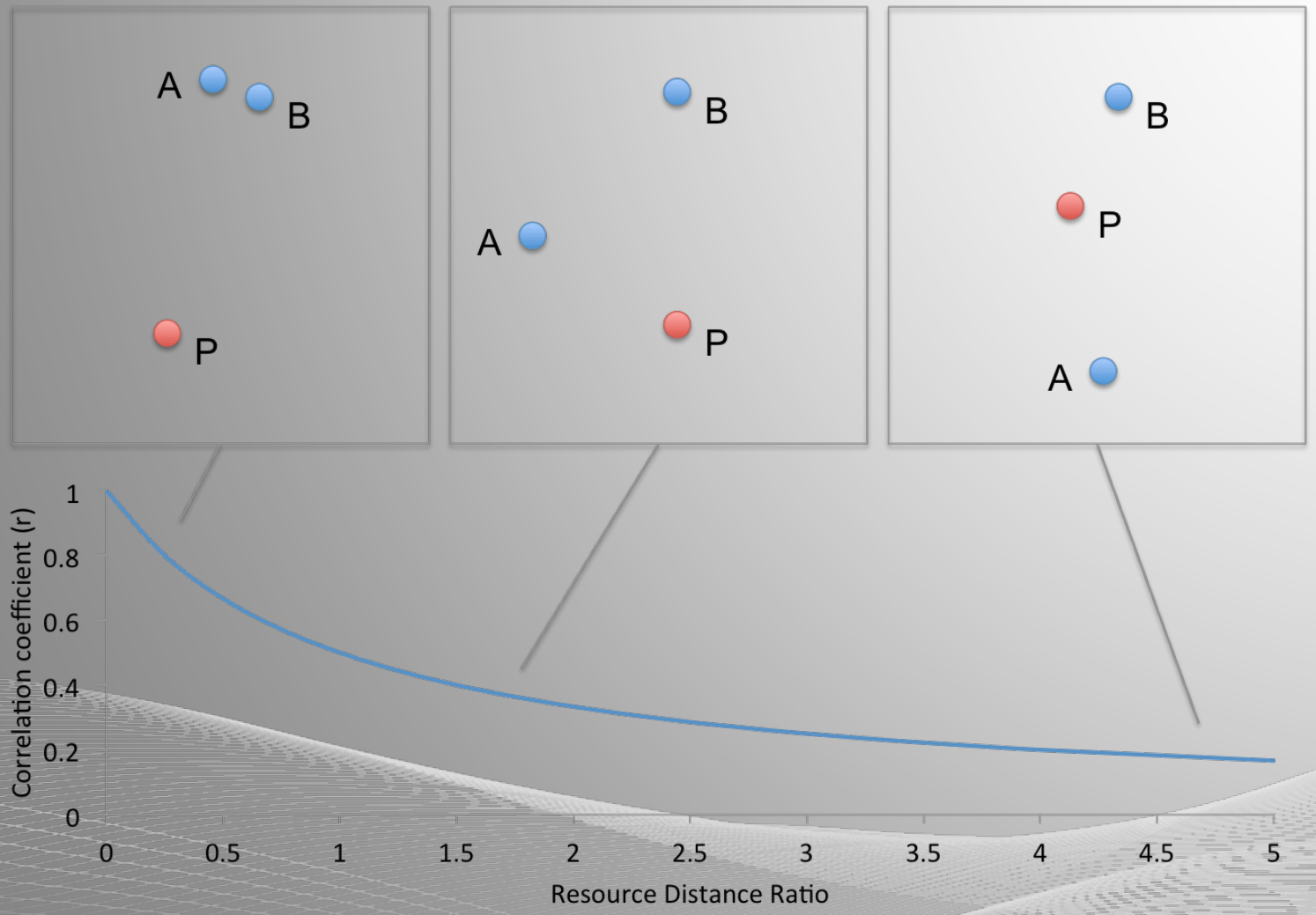

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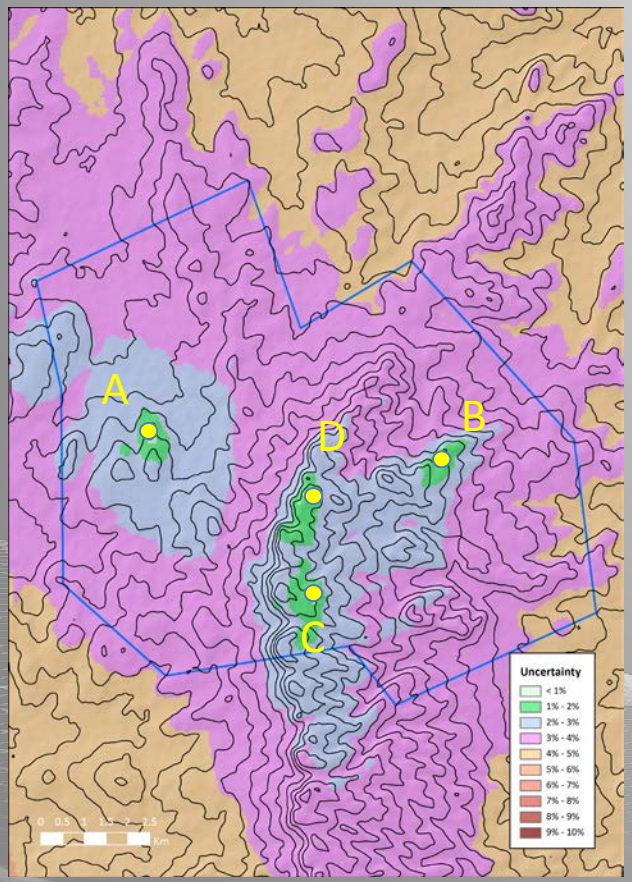
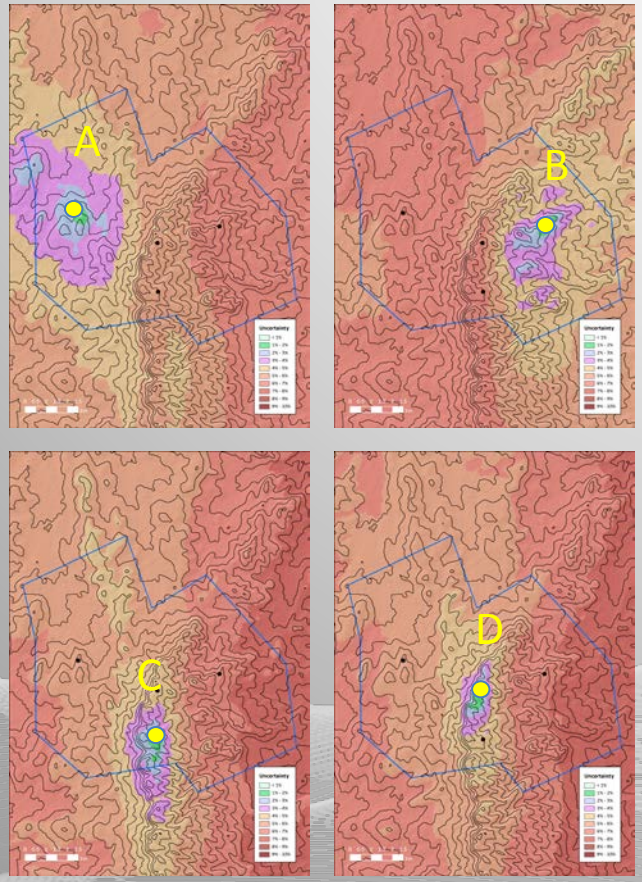
Finally! Blended Uncertainty Maps

Blended Uncertainty Map



Uncertainty maps per mast



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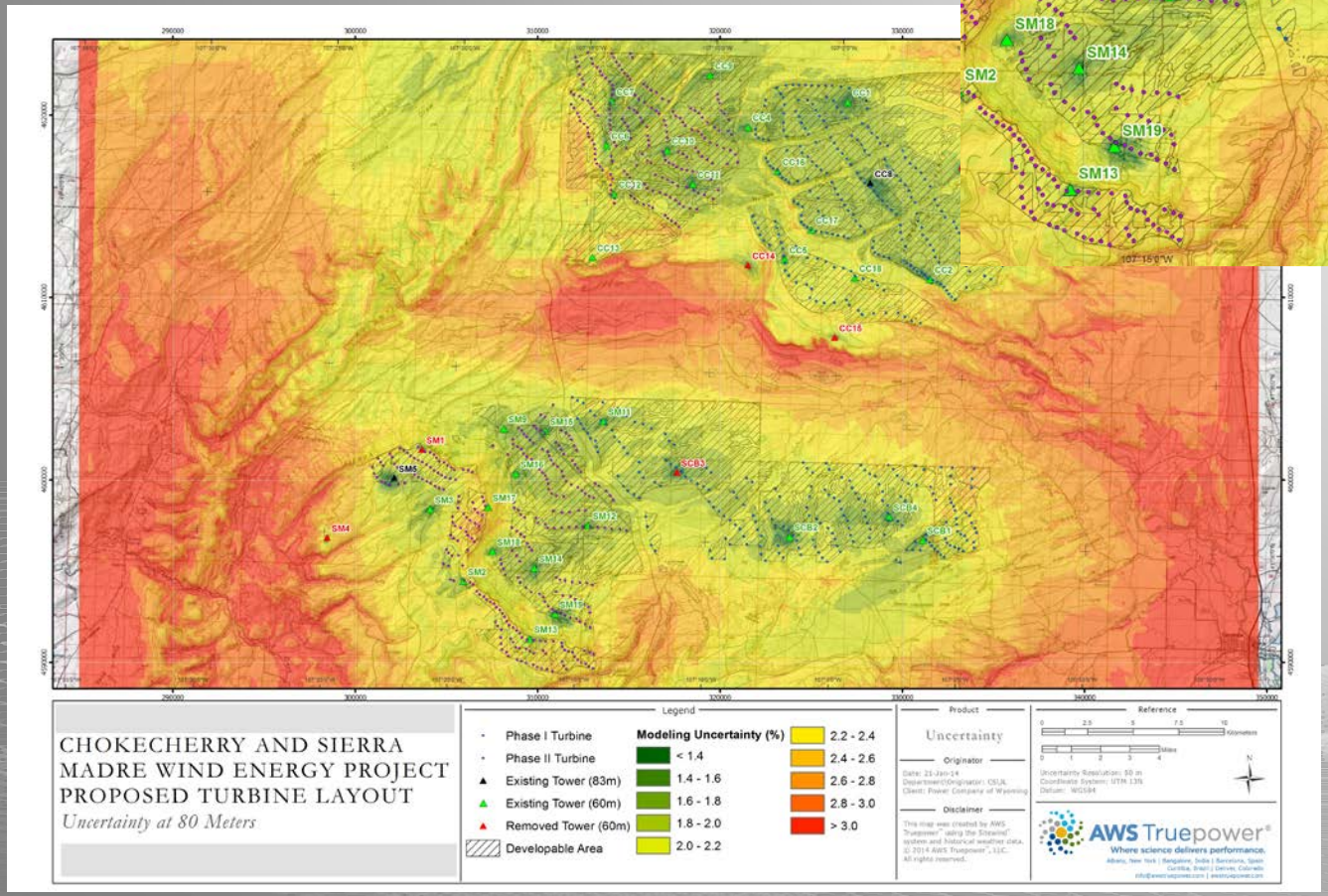
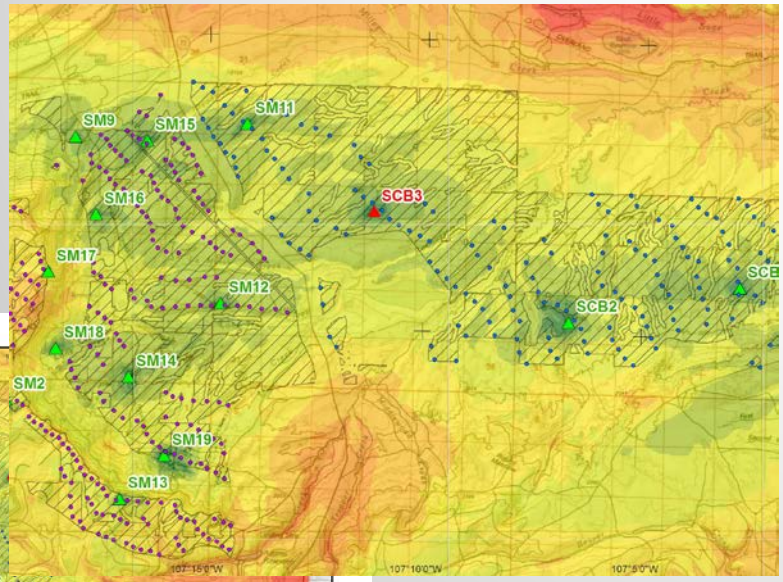
Applicable to very large projects with many masts …





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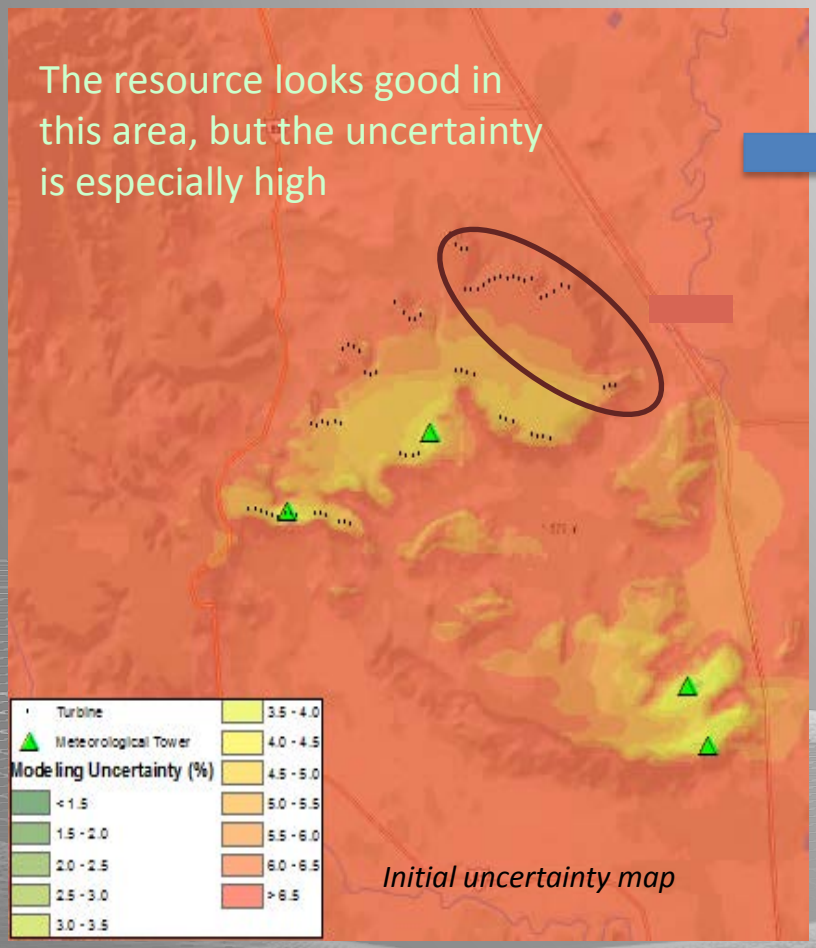
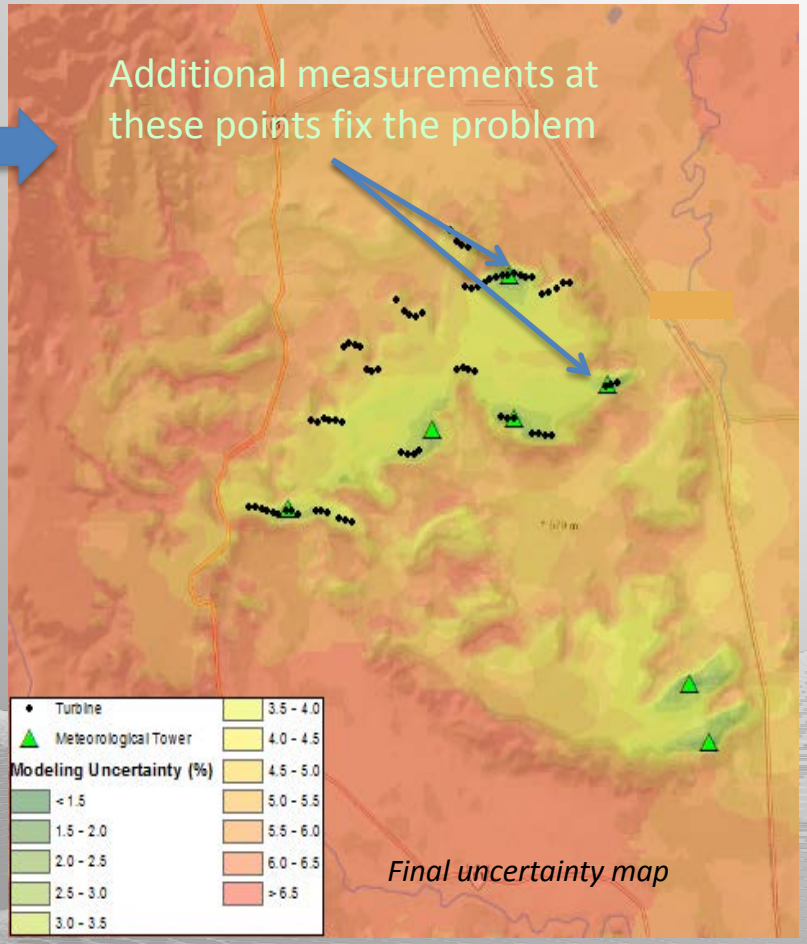
Support cost-effective monitoring campaign design…



Initial uncertainty map



Final uncertainty map

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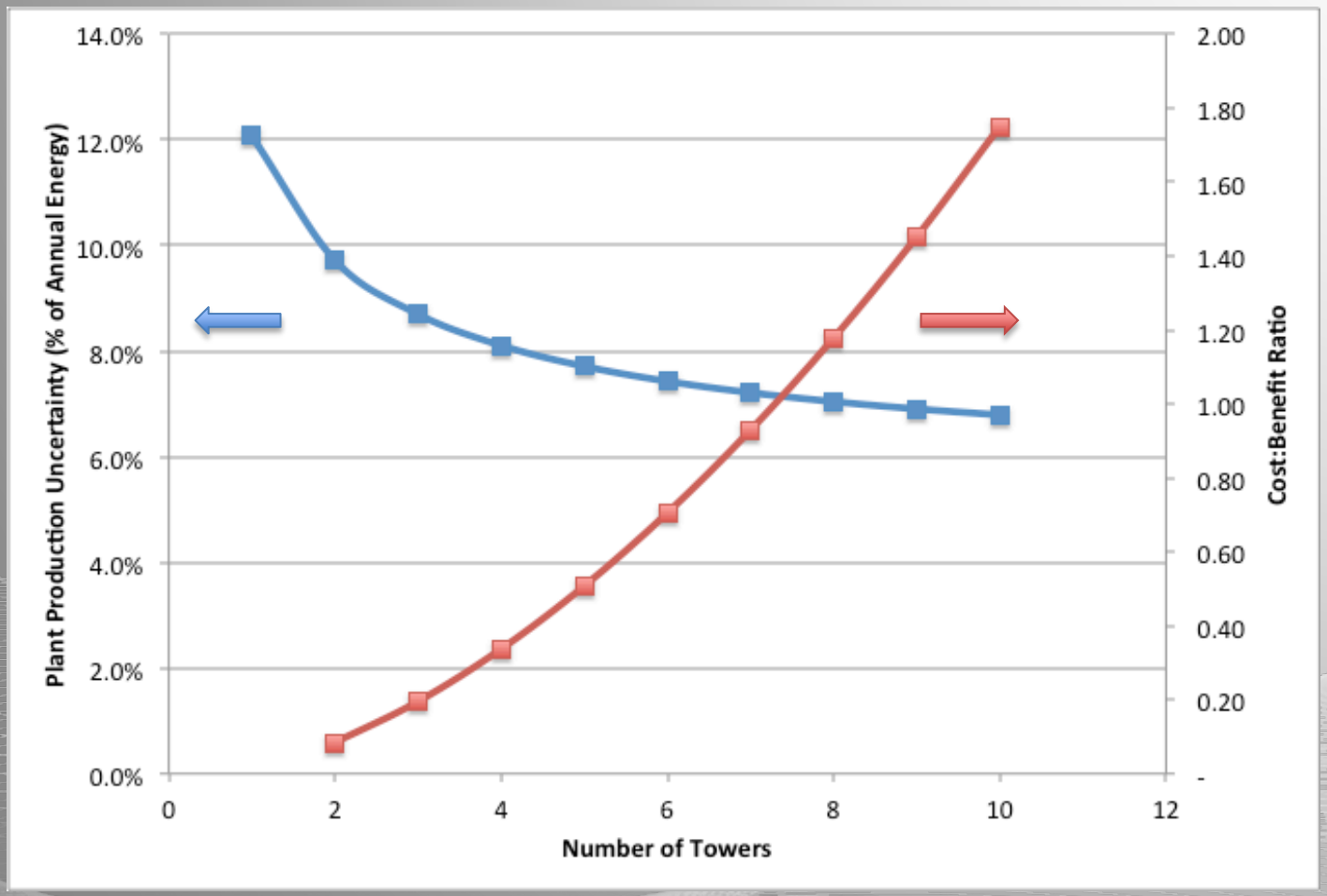
…with quantitative conclusions



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Summary

- Spatial uncertainty modeling can be a useful tool in designing wind resource assessment programs and optimizing plant layouts to reduce project risk
- If done correctly, it implements quantitatively what we know intuitively: that uncertainty varies in complicated ways depending on terrain, wind conditions, and the wind flow model used
- It is a key piece of developing a comprehensive uncertainty model for wind plants
- Using tools like Openwind, resource assessment can go beyond merely estimating the expected production to take an active part in managing project risk and cost

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