Assessment of Updraft Modeling Bias Using Computational Fluid Dynamics

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Background and Motivation

- Recent golden eagle fatality data have demonstrated the need for more detailed aerodynamics and raptor behavioral modeling around wind farms
- **Computational fluid dynamics (CFD) can be used in the investigation of typical flow fields experienced by the birds**
- Raptor presence models often rely on simple models for orographic vertical velocity (updraft/downdraft)
  - The models neglect vertical dimension and dynamic atmospheric conditions
- Objectives of this work:
  - Assess limitations of the simplified wind vector updraft model with CFD of the atmospheric boundary layer on idealized terrain geometries
  - Offer improvements to the analytical equation based on idealized cases
  - Apply our analysis to a real terrain case.

Updraft Potential

- The wind vector orographic updraft model, as defined in Brandes and Ombalski (2004), takes the following form:

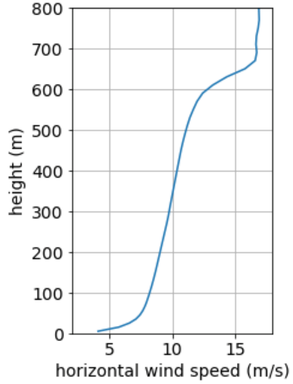
$$w_0 = V_{\text{horiz.}} \cdot \sin\theta_{\text{slope}} \cdot \cos(\alpha - \beta)$$

where α is the wind direction and β is the aspect

- Limitations:
  - It does not depend on height above ground level (AGL)
  - The mean wind speed at lower portions of the atmospheric boundary layer increases with height, thus increasing w_0
  - It fails to account for separated flow on the leeward side of hills
- Idea: Improve the analytical model by using a reference wind speed and an extra term p, which is a function of height h and slope θ_{slope}:

$$w_{0_{\text{adjusted}}} = V_{\text{ref.}} \cdot \sin\theta_{\text{slope}} \cdot \cos(\alpha - \beta) \cdot p(h, \theta_{\text{slope}})$$

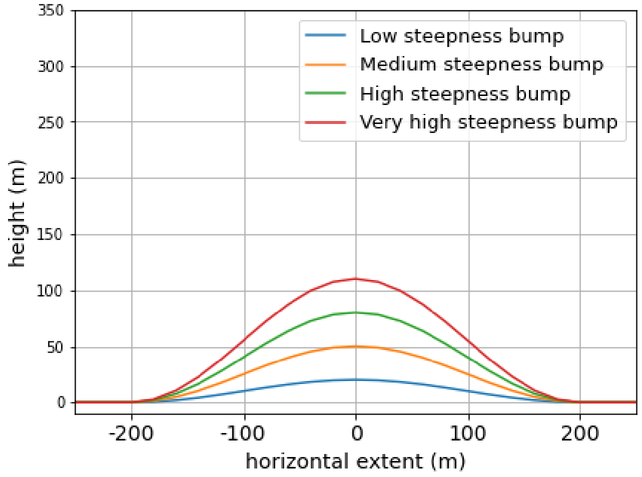
Typical idealized atmospheric boundary layer profile

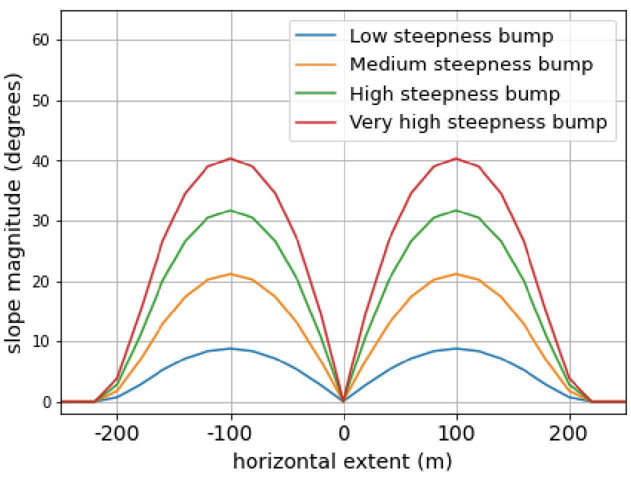


Brandes, D., & Ombalski, D.W. (2004). Modeling raptor migration pathways using a fluid-flow analogy. *Journal of Raptor Research, 38*, 195-207.

Numerical Study

- Use terrain and atmospheric turbulence-resolving flow simulation
  - Use simple sine-based bumps of varying steepness
  - Vary the angle between aspect and wind direction
- Analyze time-averaged winds at different heights above ground.



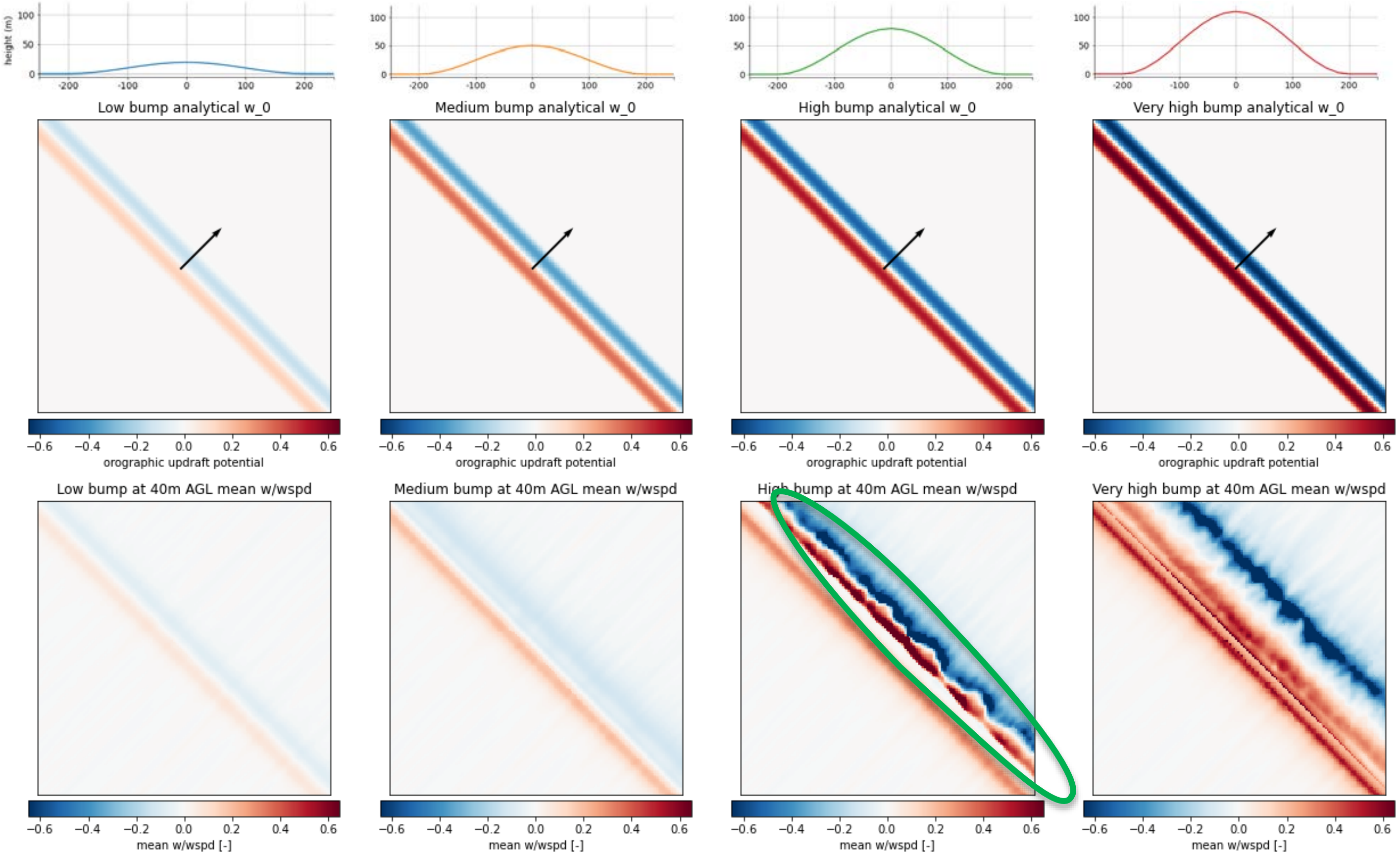


Results – Aligned Flow

- Bumps at 40 m AGL: flow separation

Analytical

CFD

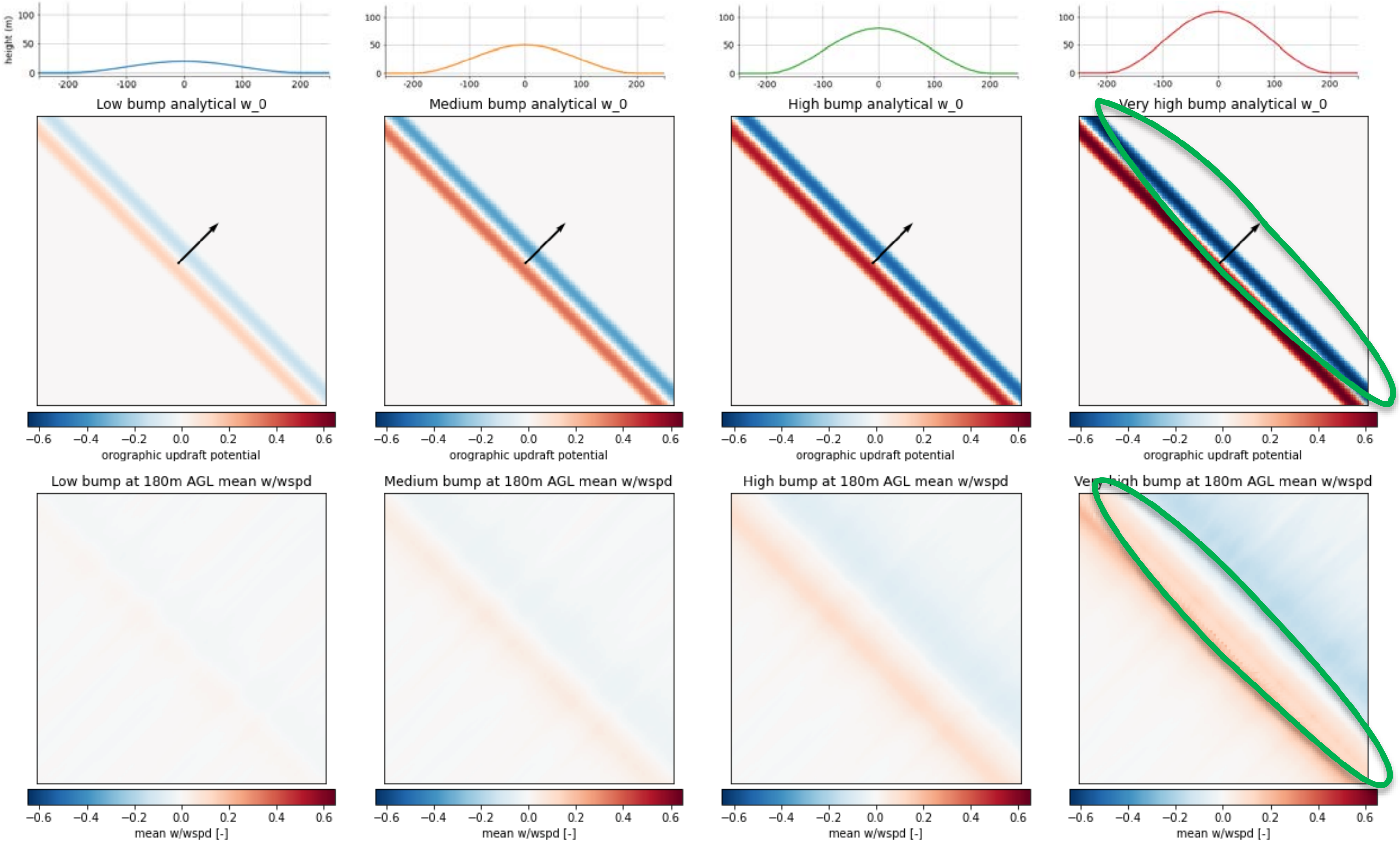


Results – Aligned Flow

- Bumps at 180 m AGL: updraft in the leeward side

Analytical

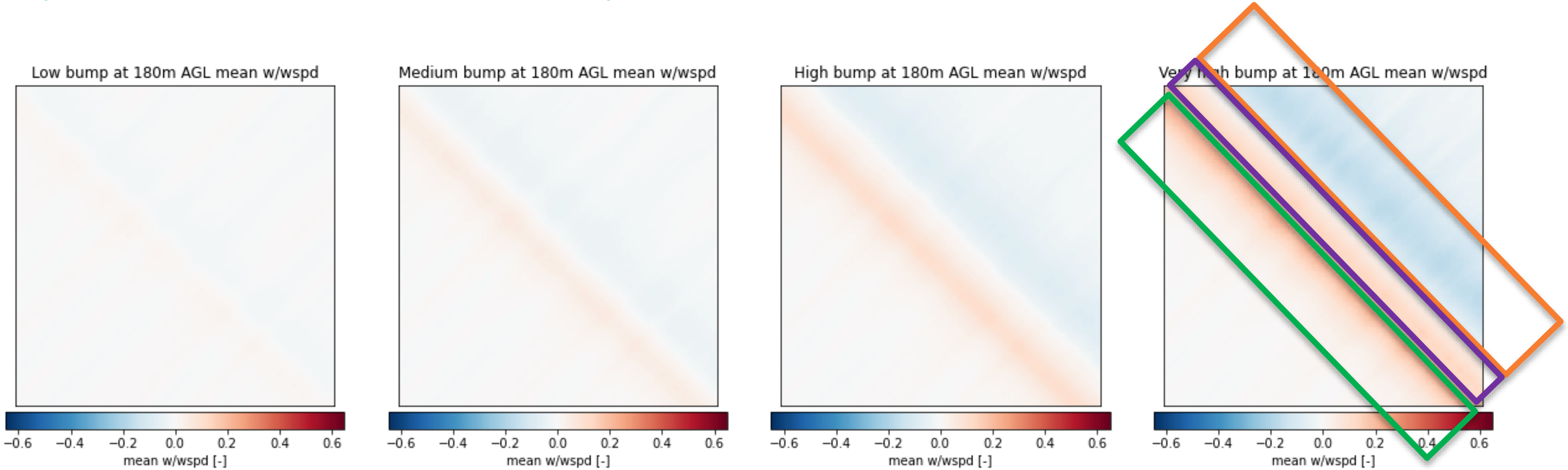
CFD



Results

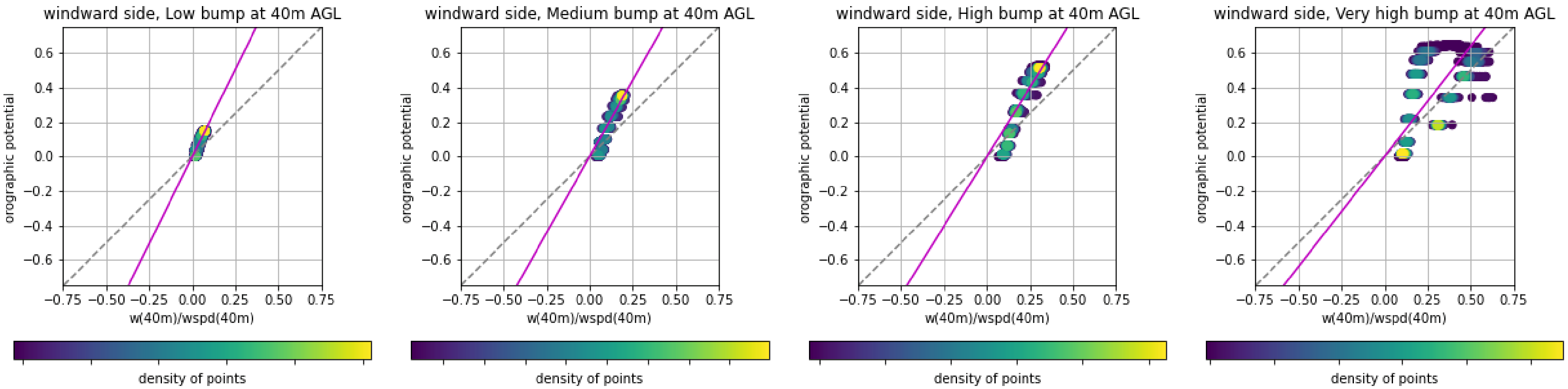
- The updrafts w are not symmetrical, as suggested by the analytical equation
  - Split the analytical equation into leeward and windward sides
- On the **leeward side**, due to recirculation and an adverse pressure gradient, **updrafts are present,** and **downdrafts are delayed**
- Updrafts also extend further upstream on the windward side.

CFD



Results

- We can separate the windward and leeward sides and compare CFD to the model
  - For example, for the windward side at 40 m AGL:



- A linear curve-fit relationship going through (0,0) can be established (pink slopes) for all heights and conditions investigated.

Results

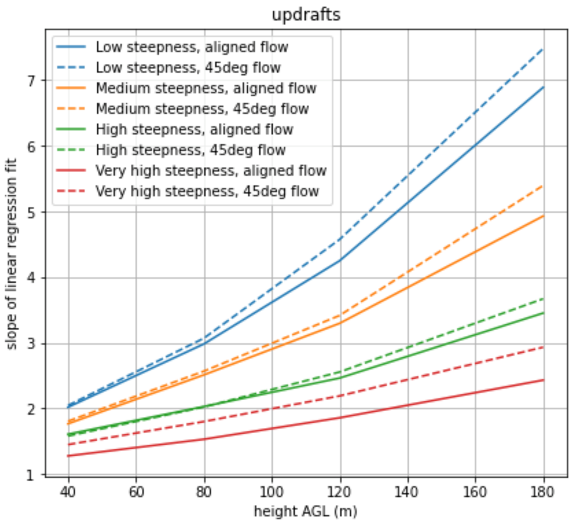
- We can obtain the slope for each combination of steepness, flow alignment, and height
  - Curves vary parabolically with height, and exponentially with cosine of slope

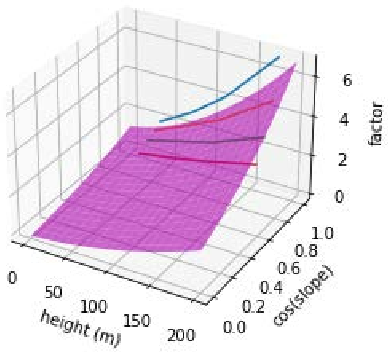
- Therefore, we can surface-fit these curves in the three-dimensional plane with a function of form

$$p(h,\theta) = \left[(ah^2 + bh + c)\cdot\left(d^{-\cos\theta + e}\right) + f\right]^{-1}$$

which results in the following constants:

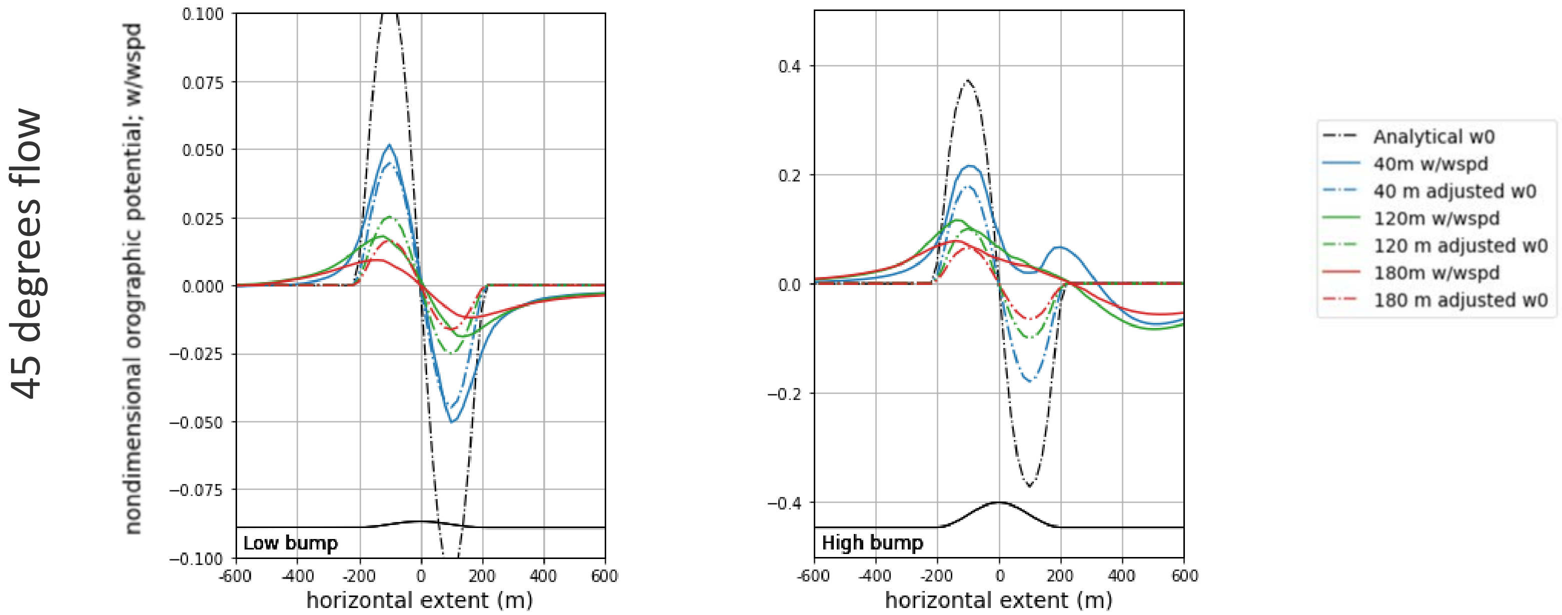
$$a = 4\times10^{-5},\ b = 0.0028,\ c = 0.8,$$
$$d = 0.35,\ e = 0.095,\ f = -0.09$$





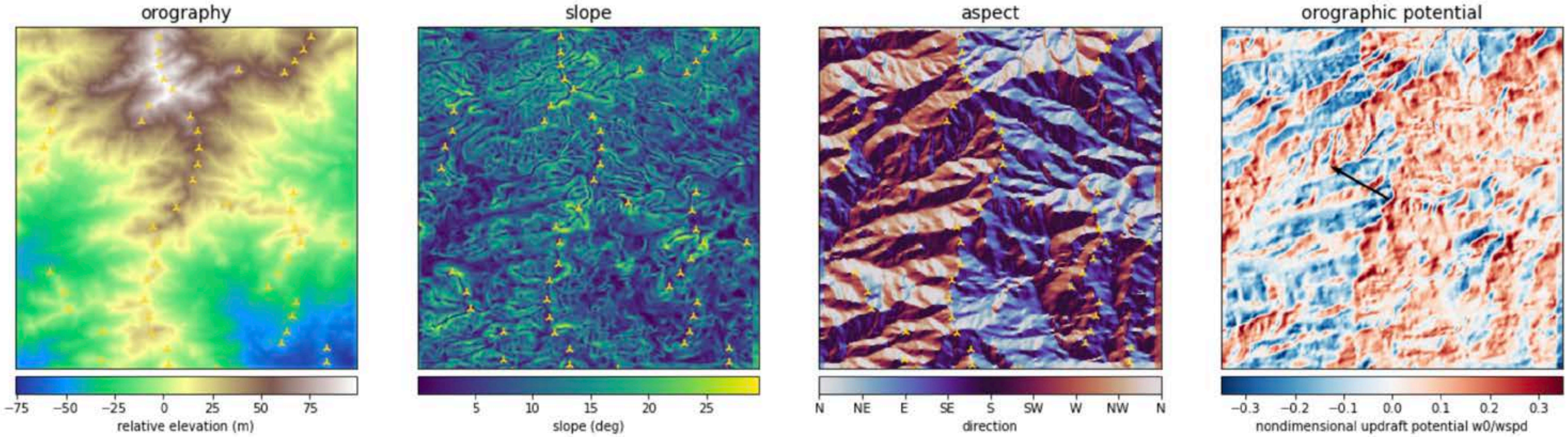
Cross Sections

- Average vertical velocity in the cross section
  - Showing oblique flow; results are similar under aligned flow
- **Updraft present on the leeward side of steep hills**
- **Updraft extends upstream the geometry on the windward side.**



Applications to a Real Case

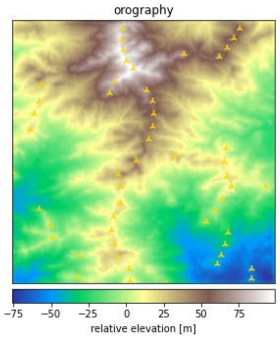
- Real complex terrain case
  - Top of the World (TOTW) wind farm, located in Wyoming.



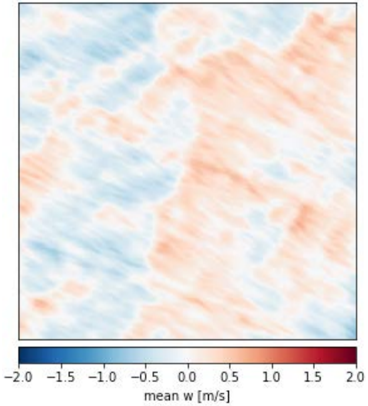
5-km-by-5-km region shown: yellow marks denote wind turbine locations; black arrow is mean wind direction

Applications to TOTW

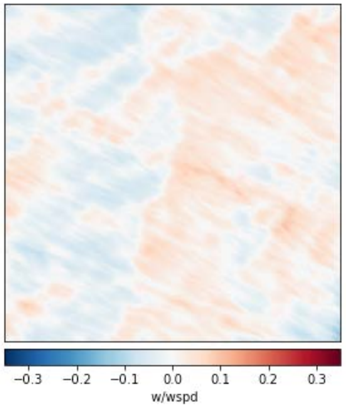
80 m AGL, conditions on
May 20, 2018 12 p.m.



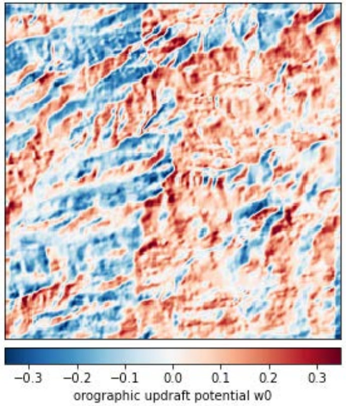
1-hour mean w



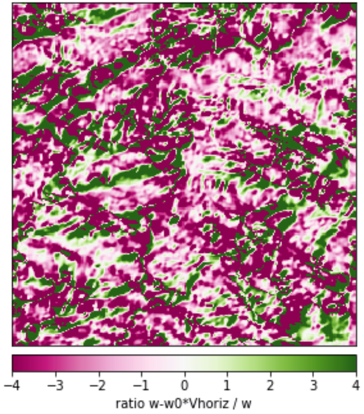
$\frac{w}{V_{\mathrm{horiz}}}$



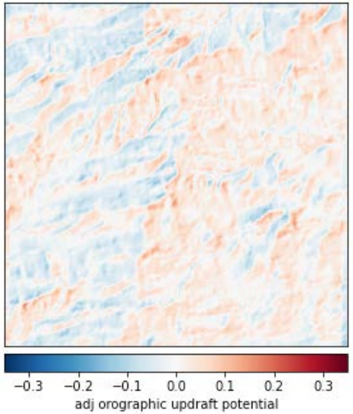
normalized w_0



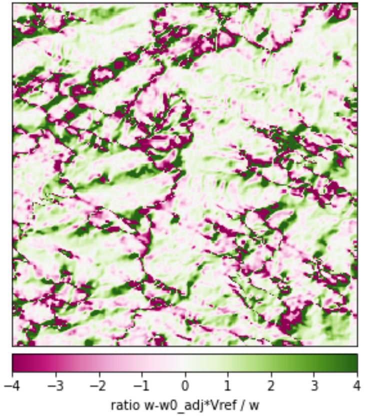
$$\frac{w(80m) - w_0 \cdot V_{\mathrm{horiz.}}(80m)}{w(80m)}$$



normalized $w_{0_{\mathrm{adjusted}}}$

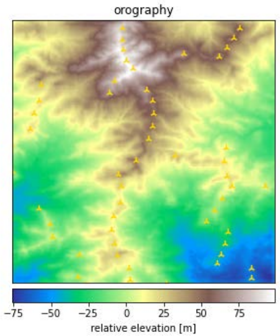


$$\frac{w(80m) - w_{0_{\mathrm{adjusted}}} \cdot V_{\mathrm{ref.}}}{w(80m)}$$

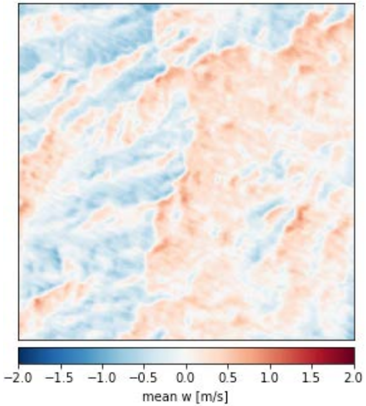


Applications to TOTW

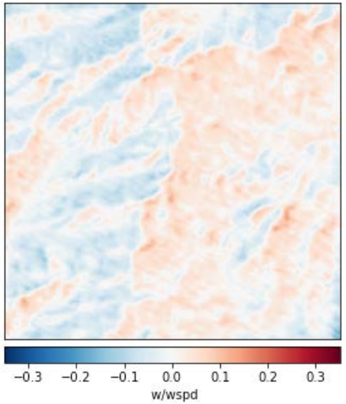
30 m AGL, conditions on
May 20, 2018 12 p.m.



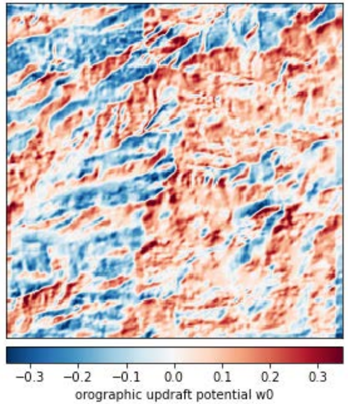
1-hour mean w



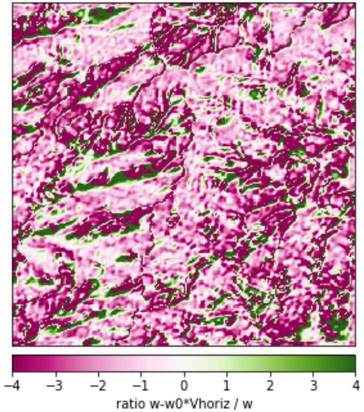
$$\frac{w}{V_{\text{horiz}}}$$



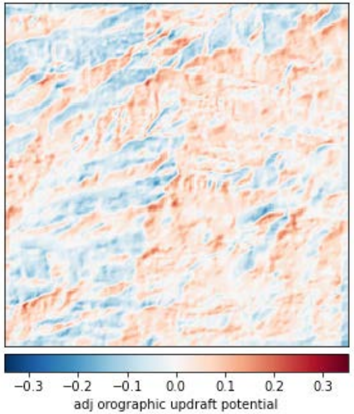
normalized w_0



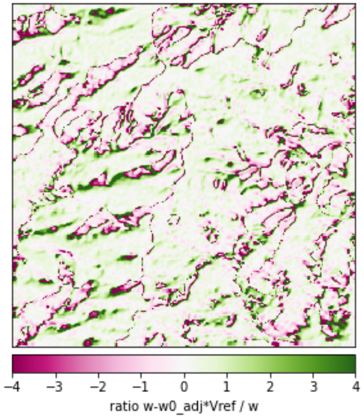
$$\frac{w(30m) - w_0 \cdot V_{\text{horiz.}}(30m)}{w(30m)}$$



normalized $w_{0_{\text{adjusted}}}$



$$\frac{w(30m) - w_{0_{\text{adjusted}}} \cdot V_{\text{ref.}}}{w(30m)}$$



Conclusions and Outlook

- The adjusted equation for orographic updraft potential better captures the magnitude of the average vertical velocity, accounting for the height
- CFD solutions are consistent with field observations of raptor behavior: positive updraft is also present in the leeward side

  – Next Steps:
    - Additional terms can be included to account for updrafts present upstream of a hill as well as for leeward-side updrafts
    - Apply adjusted $w_{0_{\mathrm{adjusted}}}$ model to (i) different terrain geometries, and (ii) a raptor simulation code.

Thank you

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