Best practices for quantifying, interpreting, and utilizing Atmospheric Stability measurements using standard wind resource assessment sensors and CFD simulations

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Objectives

- Review state-of-the-art methods for measuring, modeling, and classifying atmospheric stability
- Identify improved atmospheric stability metrics from existing wind resource assessment sensors
- Recommend best practices for accounting for stability effects in numerical models

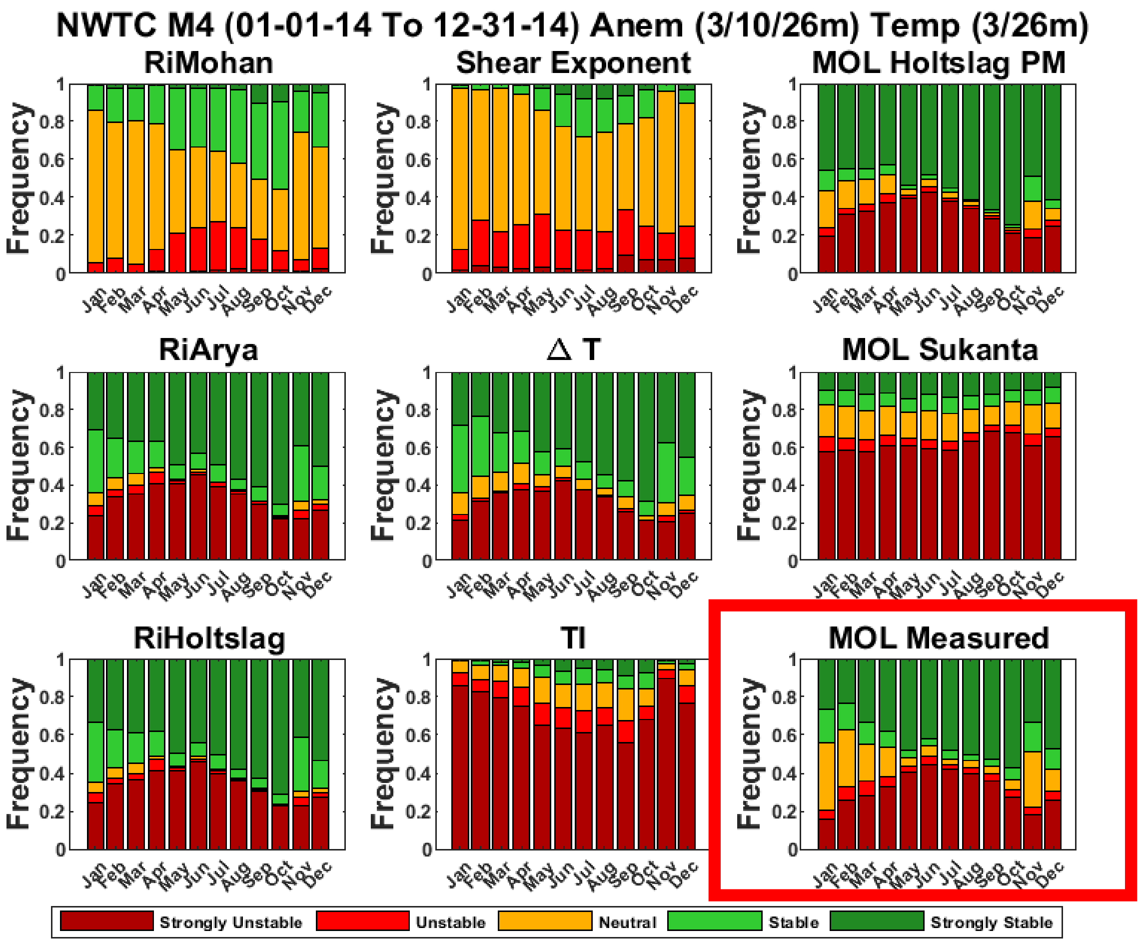
Field Test Sites

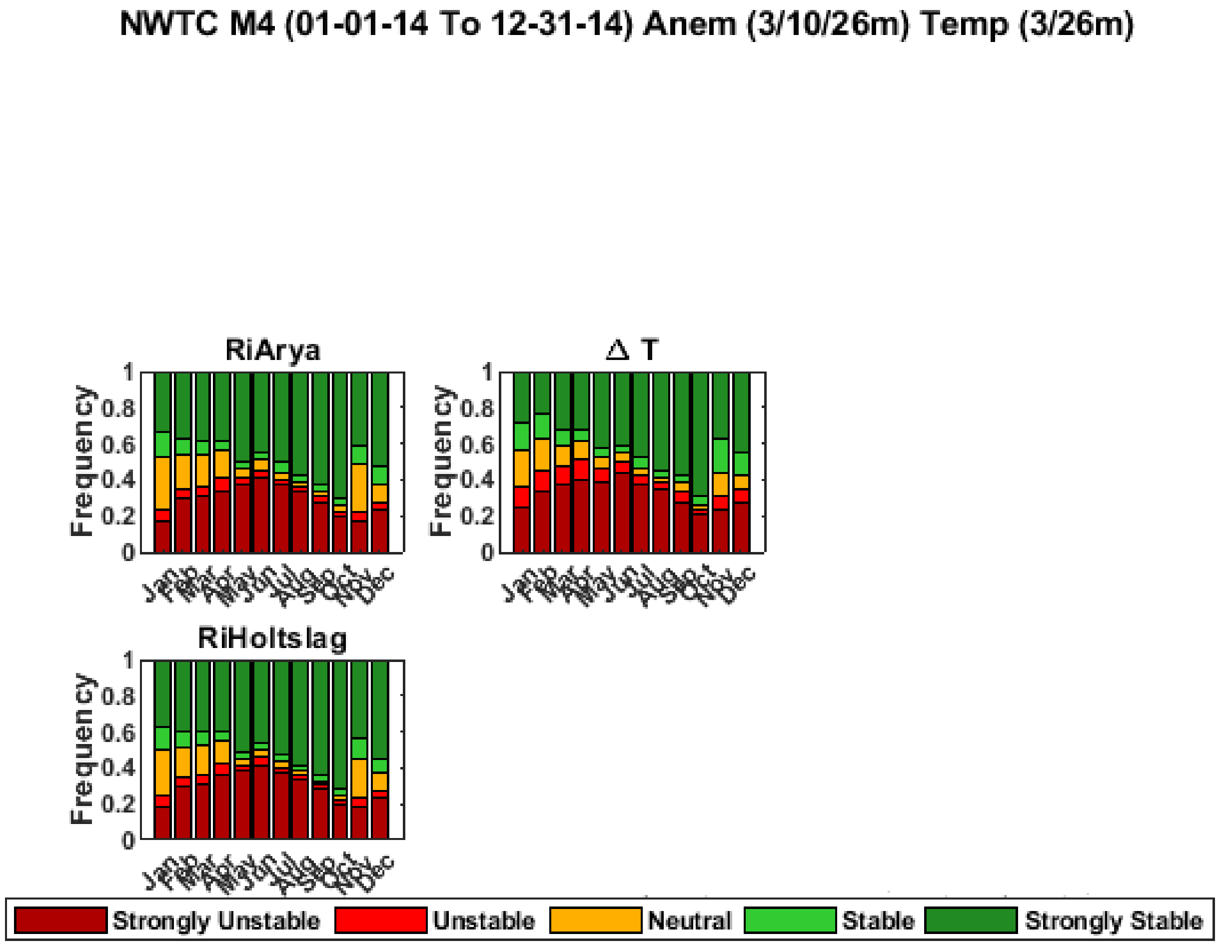
Field Test Sites	Location	Terrain	Meteorology	Number of Met Masts (Height)	Wind Speed Sensors	Temperature Sensors
NWTC	Colorado US	Flat	Thermally driven flow	2 (135m)	ATI Sonic, Thies FCA, Met One 5-6 levels	Met One
Site 2	Northern Europe	Medium complexity, Forested	Cold winter climate, stable conditions	6 (100m & 120m)	Thies FCA (50m/60m, 75m/80m and 100m/120 m) WindCube LiDAR	NRG 110S at 10m/15m and 100m/120m
Site 3	South Africa	Complex	Thermally driven flow	3 (80m)	Thies FCA at 40m/60m/80m	NRG 110S at 5m/80m on 2 masts
Site 4	Northern Europe	Medium complexity, Forested	Cold winter climate, stable conditions	1 (80m) 3 (100m) 1 (120m)	Thies FCA at 50m/60m, 75m/80m, and 100m	5m/98m on 1 mast
Site 5	North America	Medium complexity	Thermally driven flow	(6) 60m	Thies FCA at 20m/40m/60m	Thies 3m/58m on 2 masts

Atmospheric Stability and its Metrics

Method	*Formula*	*Criteria*: Strongly Unstable	Unstable	Neutral	Stable	Strongly Stable
Delta-T	$\frac{dT}{dZ} = \frac{\Delta T}{\Delta Z} \times 100$	-∞ to -1.5	-1.5 to -0.5	-0.5 to 0.4	0.4 to 1.4	1.4 to ∞
Shear Exponent	$\alpha = \frac{\ln\left(\frac{v_u}{v_l}\right)}{\ln\left(\frac{h_u}{h_l}\right)}$	-∞ to -0.14	-0.14 to 0.1	0.1 to 0.17	0.17 to 0.25	0.25 to ∞
Turbulence Intensity	$TI = \frac{\sigma}{\overline{U}}$	∞ to 18%	18% to 15%	15% to 12%	12% to 8%	8% to 0
Richardson Number (Ri_g)	$Ri_g = \frac{g\Delta\overline{\theta_v}(\Delta z_{anem})^2}{\Delta z_{temp}\overline{\theta_v}(\Delta\bar{u})^2}$	-∞ to -0.07	-0.07 to -0.01	-0.01 to 0.04	0.04 to 0.08	0.08 to ∞
Monin-Obukhov Length (MOL)	$L = \frac{-\overline{\theta_v}u_*^3}{kg\left(\overline{w\theta_v'}\right)} = \frac{\overline{\theta_v}u_*^2}{kg\theta_*}$	0 to -213	-213 to -417	-417 to 417	417 to 189	189 to 0

Atmospheric Stability Metrics



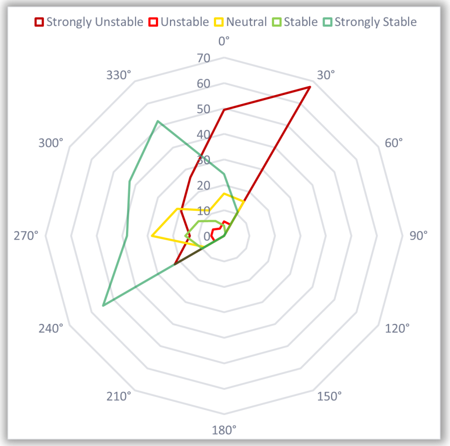


Using Published Criteria

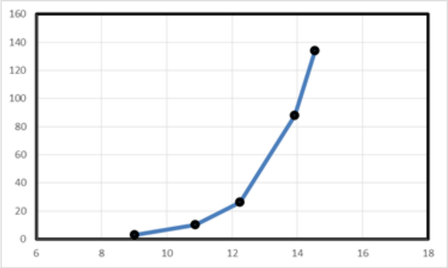
Using K-Means Clustering Criteria

CFD Numerical Modeling with Stability

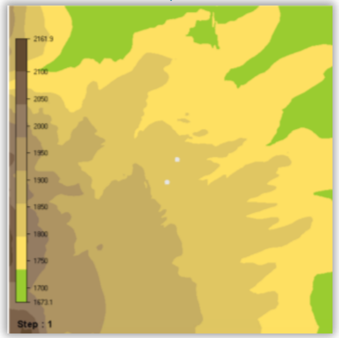
1. Select tower met mast least influenced by terrain
2. Generate VORTEX SERIES (wind speed and rate direction, MOL, Ri)
3. Verify VORTEX data represents well the wind rose by direction and stability class



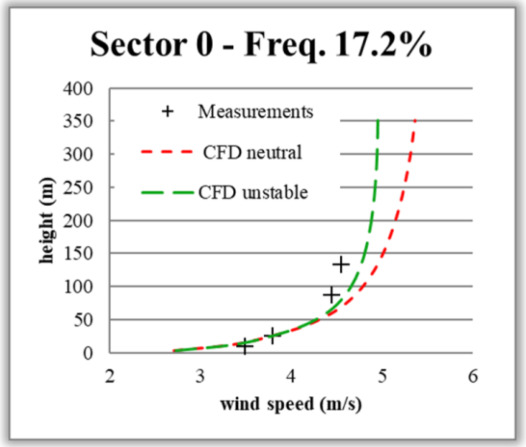
4. Run CFD with neutral stability



5. Impose stability profile



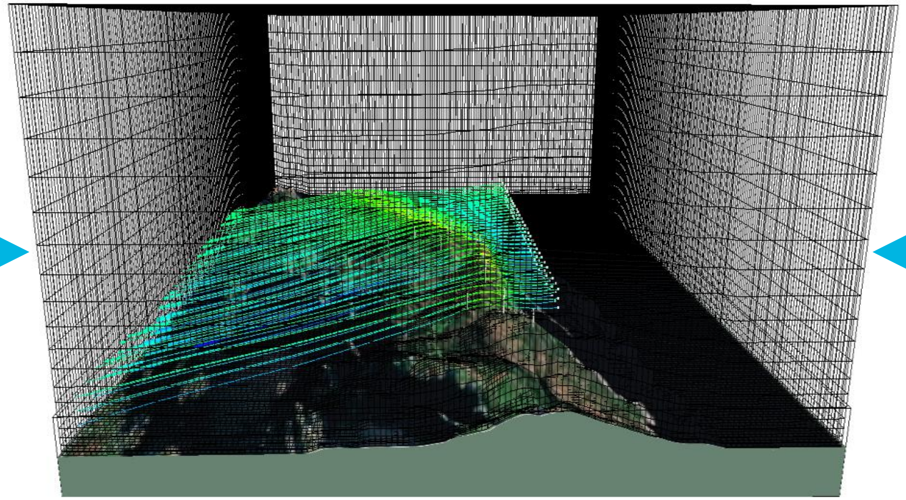
6. Run CFD with stability
7. Verify

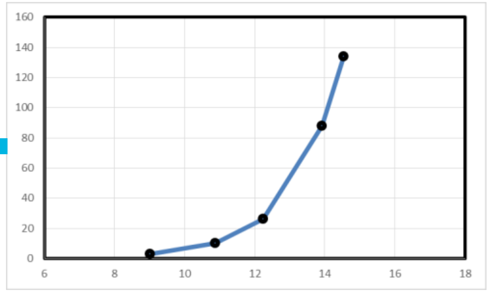


CFD Numerical Modeling with Stability

- CFD modeling applies neutral profiles
- Propose adding stable or unstable profiles when …

10x10km, 1.7 million cells, model height 3000 m, 1 hour runtime

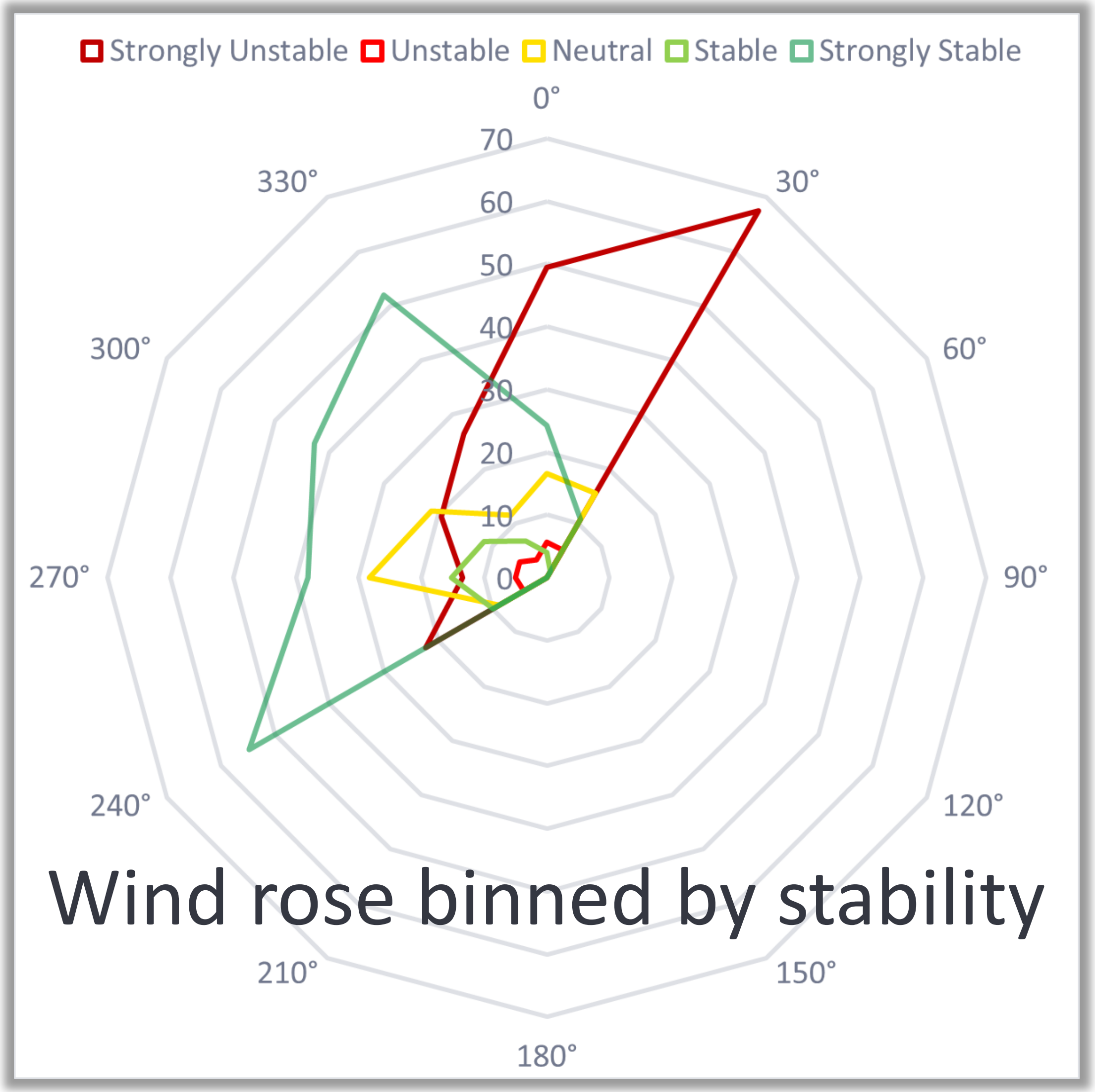




Neutral, stable, or unstable wind and temperature profiles

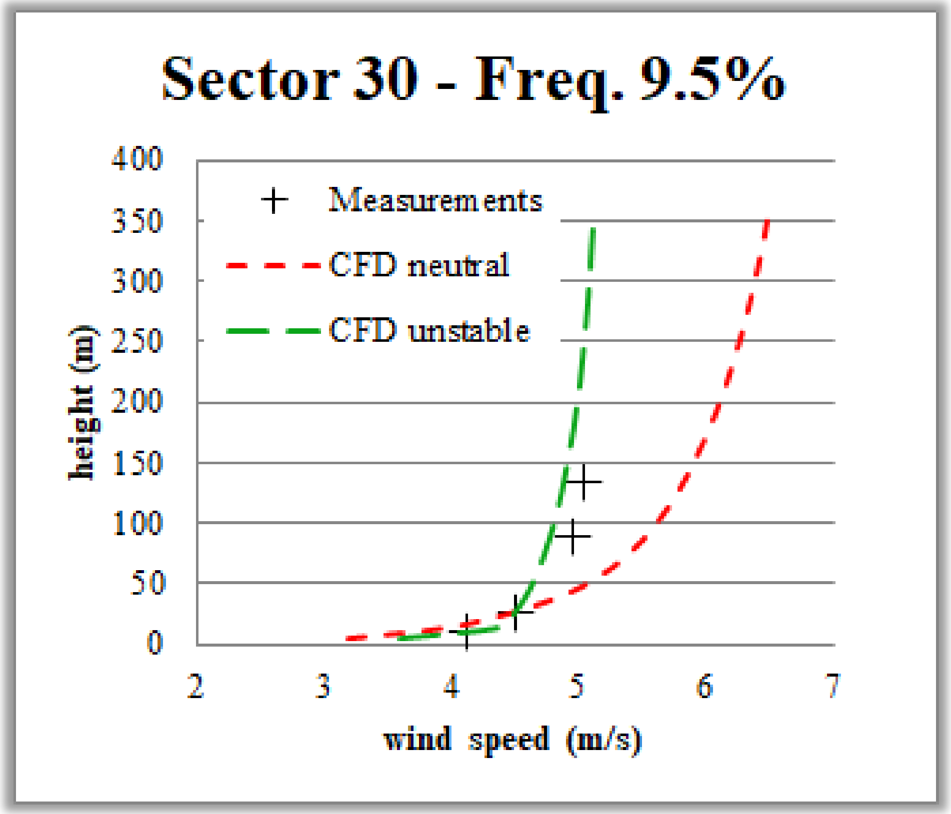
CFD Numerical Modeling with Stability

- Apply stable/unstable boundary conditions when imbalance observed
- Stability from sensors and VORTEX SERIES data

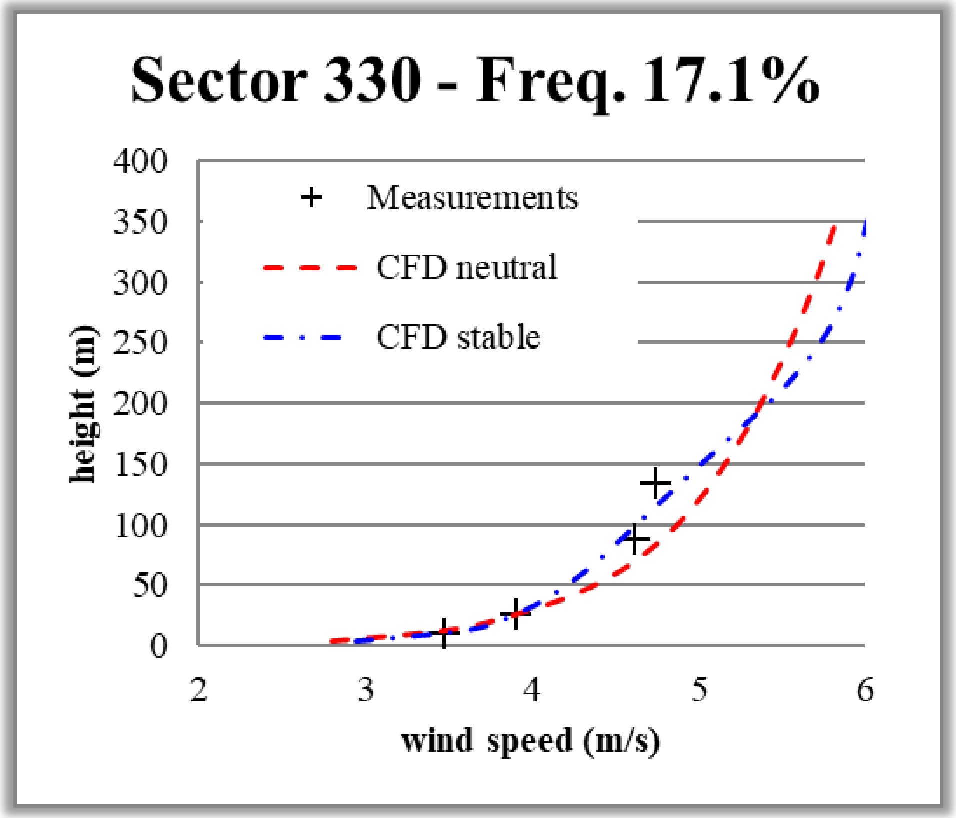


CFD Numerical Modeling at NWTC

Model with unstable conditions



Model with stable conditions



CFD results improve when accounting for atmospheric stability

Summary of CFD Modeling Results

Field Test Sites	Location	Terrain	Meteorology	CFD Simulations Incorporating Atmospheric Stability
NWTC	Colorado US	Flat	Thermally driven flow	Improvement in Results
Site 2	Northern Europe	Medium complexity, Forested	Cold winter climate, stable conditions	Improvement in Results
Site 3	South Africa	Complex	Thermally driven flow	Improvement in Results
Site 4	Northern Europe	Medium complexity, Forested	Cold winter climate, stable conditions	N/A • Balanced wind rose • Good neutral-stability CFD results
Site 5	North America	Medium complexity	Thermally driven flow	N/A • Balanced wind rose • Good neutral-stability CFD results

Conclusions

- Accurate atmospheric stability prediction can be made using Richardson number (Arya and Holtslag), ΔT, and the MOL (Holtslag)
- Accurate stability measurements requires 2 levels of wind speed and temperature sensors in the surface layer; 10-minute statistics sufficient
- Unsupervised machine learning successfully automated stability criteria
- Developed a method for incorporating measured and modelled stability into CFD models
  - Resulted in improved model predictions at 3 sites

NRG Systems windsim e·on VORTEX

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