Recovery Processes in Coastal Wind Farms

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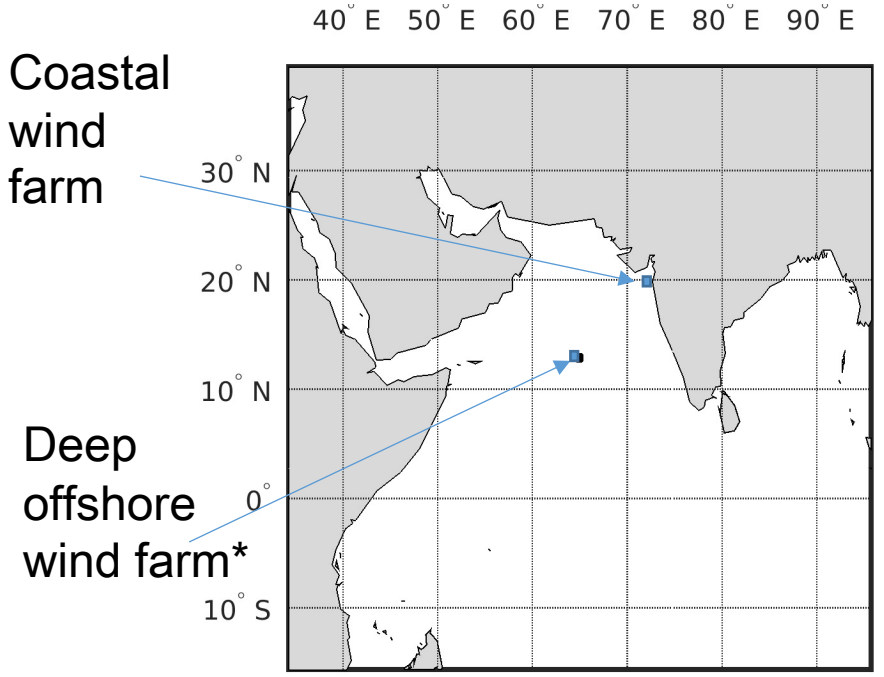
Background

- In our earlier study [Gupta and Baidya Roy, 2021], we have quantified the recovery processes for deep offshore wind farms.
- We found that that vertical turbulent transport of momentum from aloft is the main contributor to recovery except in cases with strong background winds and high inter-turbine spacing where horizontal advective momentum transport can also contribute equally.
- However, all current wind farms are near to the coast where recovery can be affected by sea breezes.

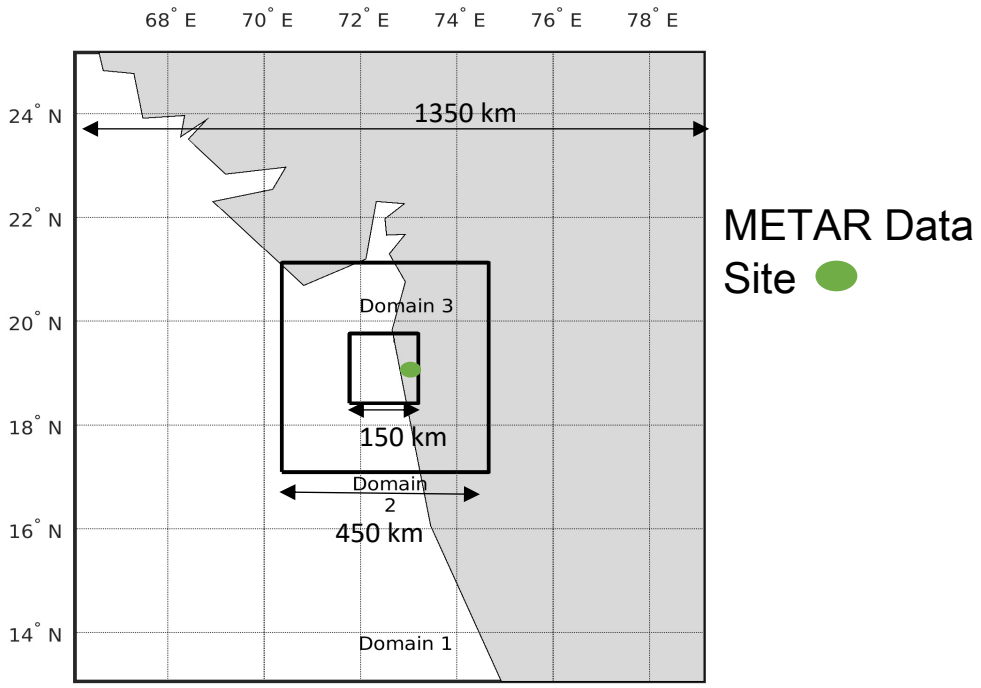


Objective

- Study recovery processes in coastal wind farms under sea-breeze conditions

Methodology

Simulations Details (For Sea Breeze Identification)

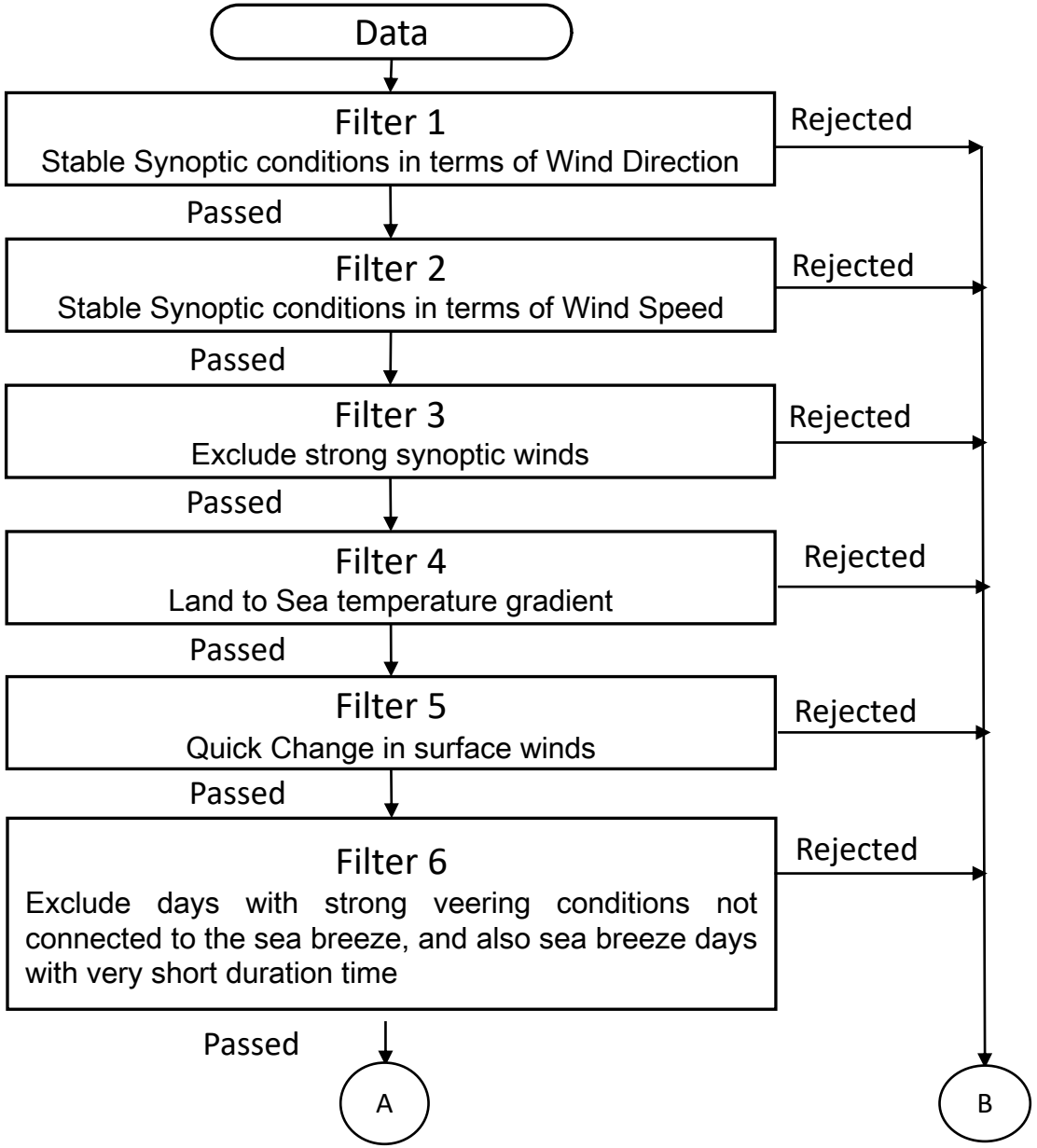


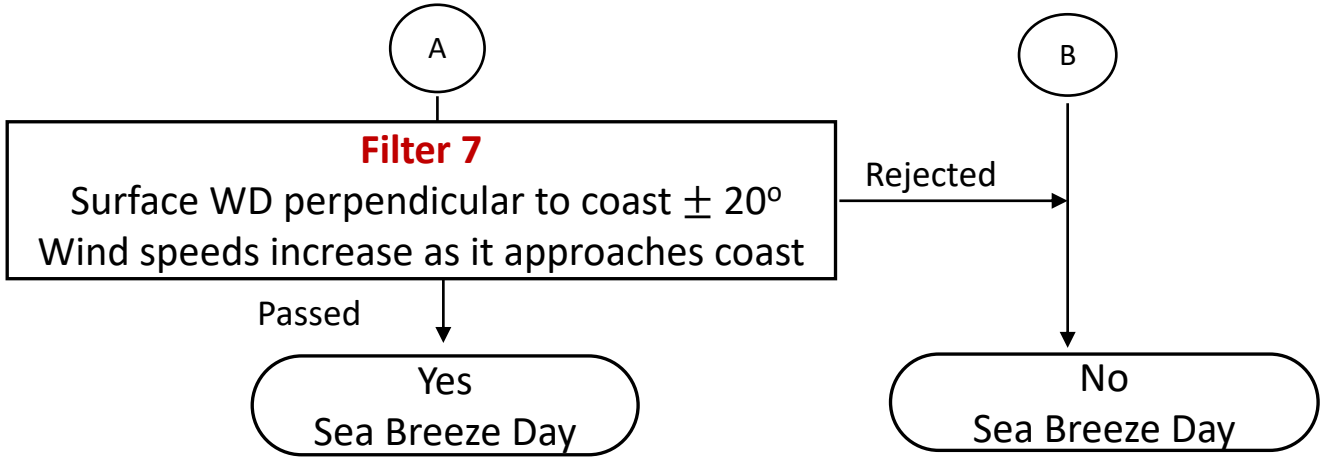
Simulation Domain

WRF Domain		
Domain No.	Spacing (km)	No. of grid points
1	1 km	150X150
2	3 km	150X150
3	9 km	150X150

- The study area is the Arabian sea coastline that is one of the two regions with the highest wind power potential in India.
- The study period is April-May of 2018 and 2019.
- We used the Borne's method (Borne et al., 1998) to identify the sea breeze days.
- The input data for Borne's method is the wind field simulated by the Weather Research and Forecast (WRF) Model. The simulation domain is shown in the figure. The WRF model physics configuration is given in Gupta and Baidya Roy (2021)
- 5 days were identified as sea breeze days after using modified Borne's method.

Modified Borne's Method (Sea Breeze Identification)

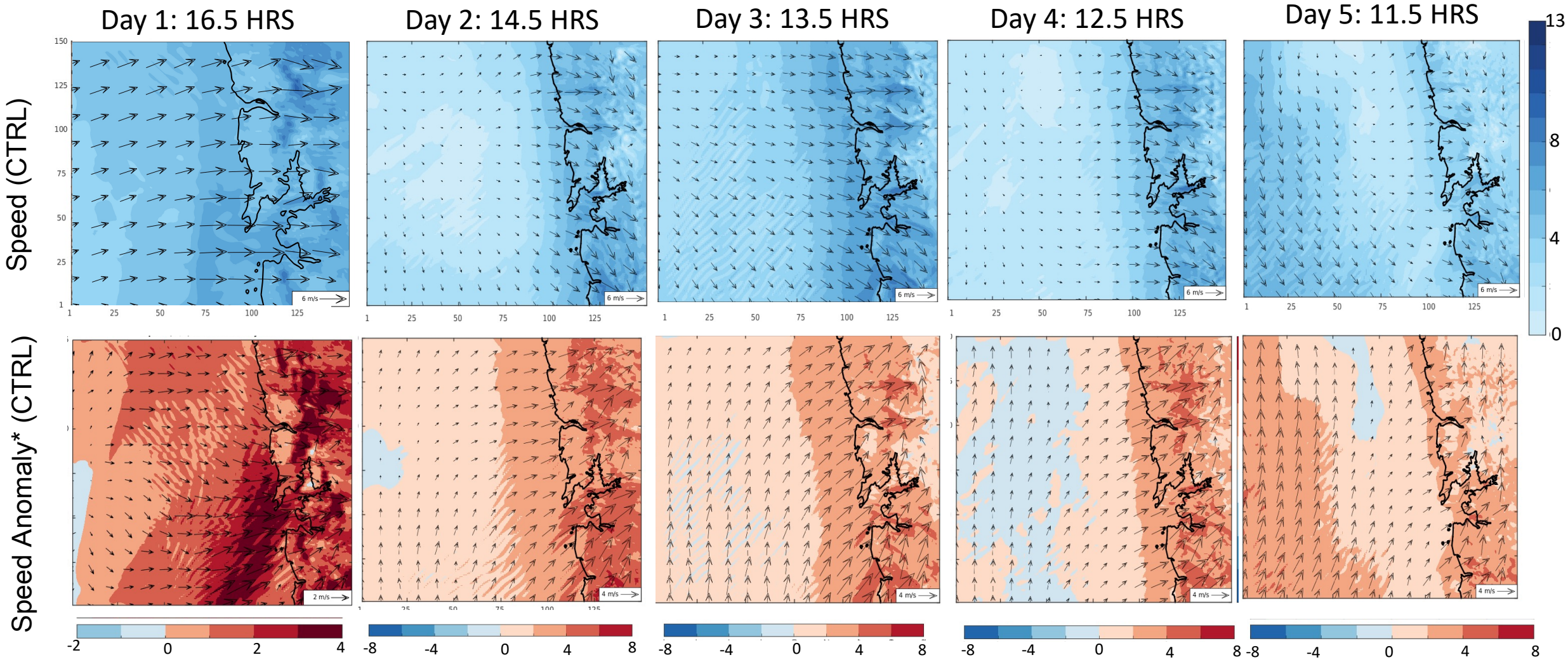




- **I/P Data:** 4 months (April, May 2018 and 2019) of WRF simulations
- **Filter 1-6: Same as that of Borne's Method**
- **Filter 7:** Visual Inspection - Remove the background winds to inspect mesoscale winds (Speed anomalies)
- **O/P:** 5 days were identified as sea breeze days after using modified Borne's method- Day 1: May 4, 2018; Day 2: April 7, 2019; Day 3: April 8, 2019; Day 4: April 9, 2019 and Day 5: April 21, 2019

WS: Wind Speed, WD: Wind Direction

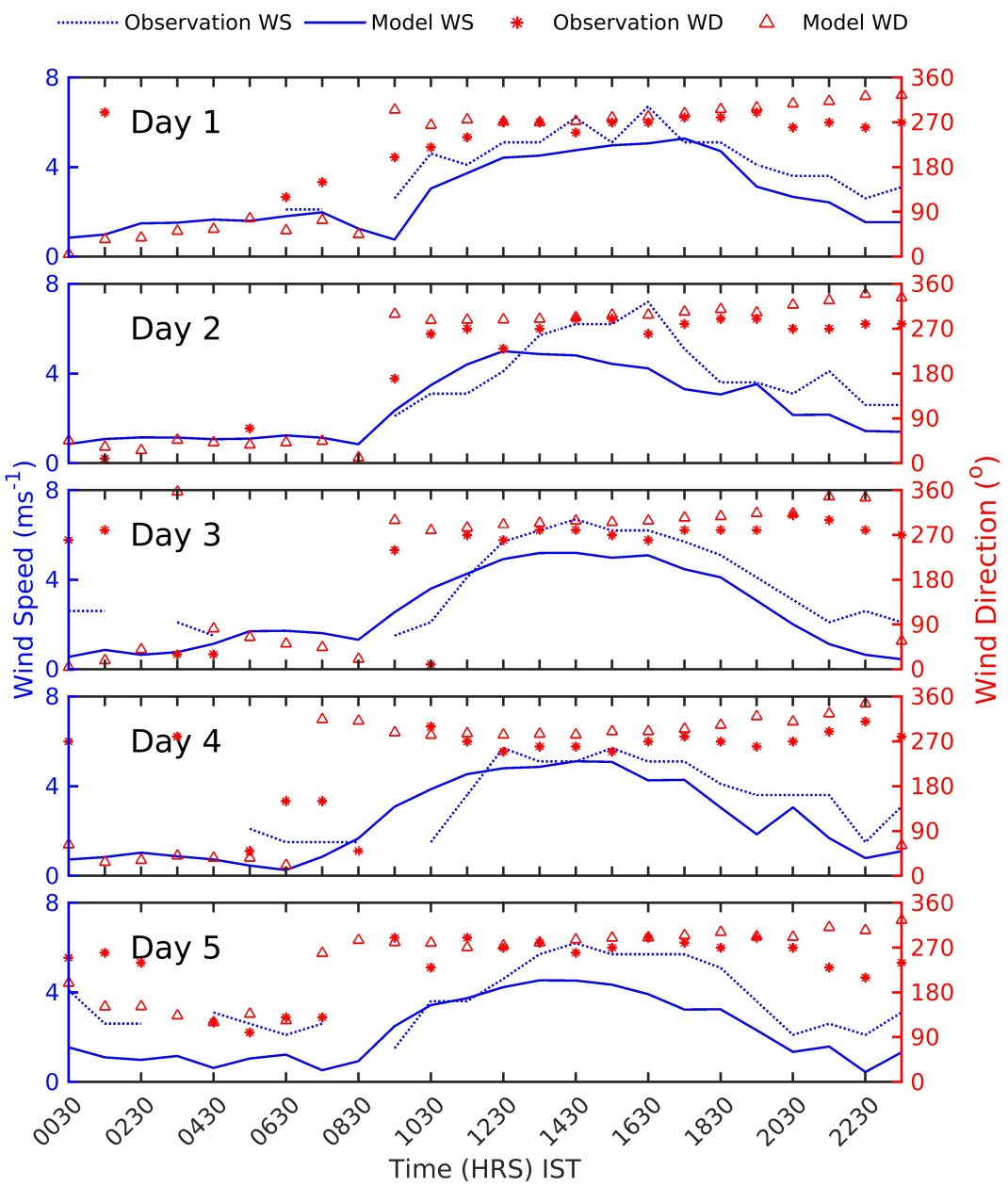
Modified Borne's Method: Filter 7



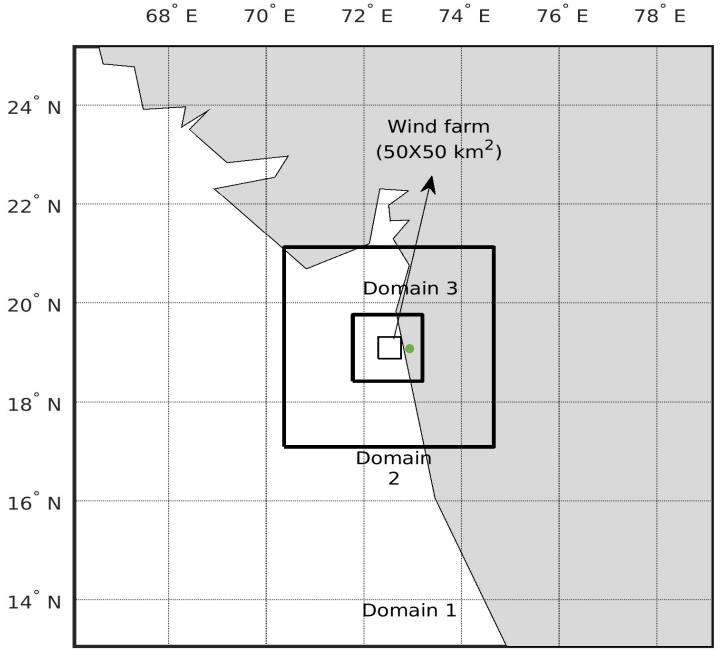
- For all the sea-breeze days, increase in wind speed as the wind approaches land can be seen at the time around noon till late afternoon

**Background winds removed*

Model Validation with METAR Data

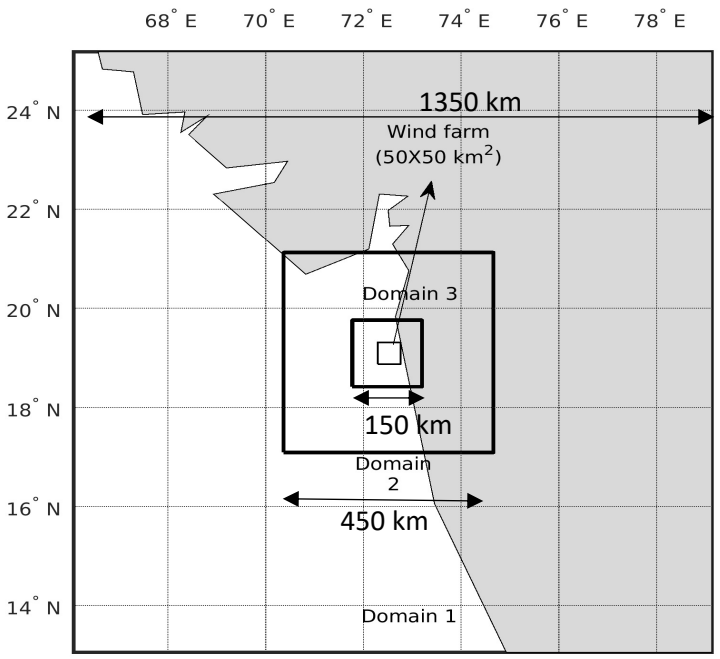


METAR Data Site (Observation)



- Model-10m wind speed and wind direction follows the same trend as of METAR data.
- Quick change in wind direction and speed at hub-height level over the wind farm can be seen for all the cases

Simulations Details (For Recovery in Coastal Wind Farms)



WRF Simulation Domain

Simulation details	CTRL	WF		
		Case I	Case II	Case III
Day 1	• May 3-5, 2018 • No wind turbine	• May 3-5, 2018 • 10,000 wind turbine, 3 MW each	• May 3-5, 2018 • 2500 wind turbines, 3MW each	• May 3-5, 2018 • 625 wind turbines, 3MW each
Day 2	• April 6-8, 2019 • No wind turbine	• April 6-8, 2019 • 10,000 wind turbine, 3 MW each	• April 6-8, 2019 • 2500 wind turbines, 3MW each	• April 6-8, 2019 • 625 wind turbines, 3MW each
Day 3	• April 7-9, , 2019 • No wind turbine	• April 7-9, , 2019 • 10,000 wind turbine, 3 MW each	• April 7-9, , 2019 • 2500 wind turbines, 3MW each	• April 7-9, , 2019 • 625 wind turbines, 3MW each
Day 4	• April 8-10, 2019 • No wind turbine	• April 8-10, 2019 • 10,000 wind turbine, 3 MW each	• April 8-10, 2019 • 2500 wind turbines, 3MW each	• April 8-10, 2019 • 625 wind turbines, 3MW each
Day 5	• April 20-22, 2019 • No wind turbine	• April 20-22, 2019 • 10,000 wind turbine, 3 MW each	• April 20-22, 2019 • 2500 wind turbines, 3MW each	• April 20-22, 2019 • 625 wind turbines, 3MW each

- WRF Version 4.2.1, with horizontal TKE advection “ON”
- 15 simulations (WF case) for 5 sea breeze days and with 3 MW turbines placed three inter-turbine spacings (Case I: d=0.5 km, Case II: 1km and Case III: 2 km) solved using Fitch et al. (2012) parameterization
- 5 CTRL case simulations for the identified sea-breeze days
- 1 day spin-up time removed from the analysis
- Hypothetical coastal wind farm simulated 1 km offset from the coast
- Initial and boundary conditions from NCEP FNL data (1ºX1º)

WRF Domain		
Domain No.	Spacing (km)	No. of grid points
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Recovery

Energy extracted by the windfarm is partially recovered by the convergence of higher momentum air from aloft and lateral ends*.

$$\text{Vertical Recovery} = \left[-\left(\frac{\partial u'w'}{\partial z} \right)\hat{i} - \left(\frac{\partial v'w'}{\partial z} \right)\hat{j} \right]_{WF} - \left[-\left(\frac{\partial u'w'}{\partial z} \right)\hat{i} - \left(\frac{\partial v'w'}{\partial z} \right)\hat{j} \right]_{CTRL}$$

$$\text{Horizontal Recovery} = \left[\left(-u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} \right)\hat{i} + \left(-u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} \right)\hat{j} \right]_{WF} - \left[\left(-u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} \right)\hat{i} + \left(-u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} \right)\hat{j} \right]_{CTRL}$$

$$\left(-u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} \right)\Bigg|_{(i,j)} = -u(i,j)\frac{u(i+1,j) - u(i-1,j)}{2\Delta x} - v(i,j)\frac{v(i,j+1) - v(i,j-1)}{2\Delta y}$$

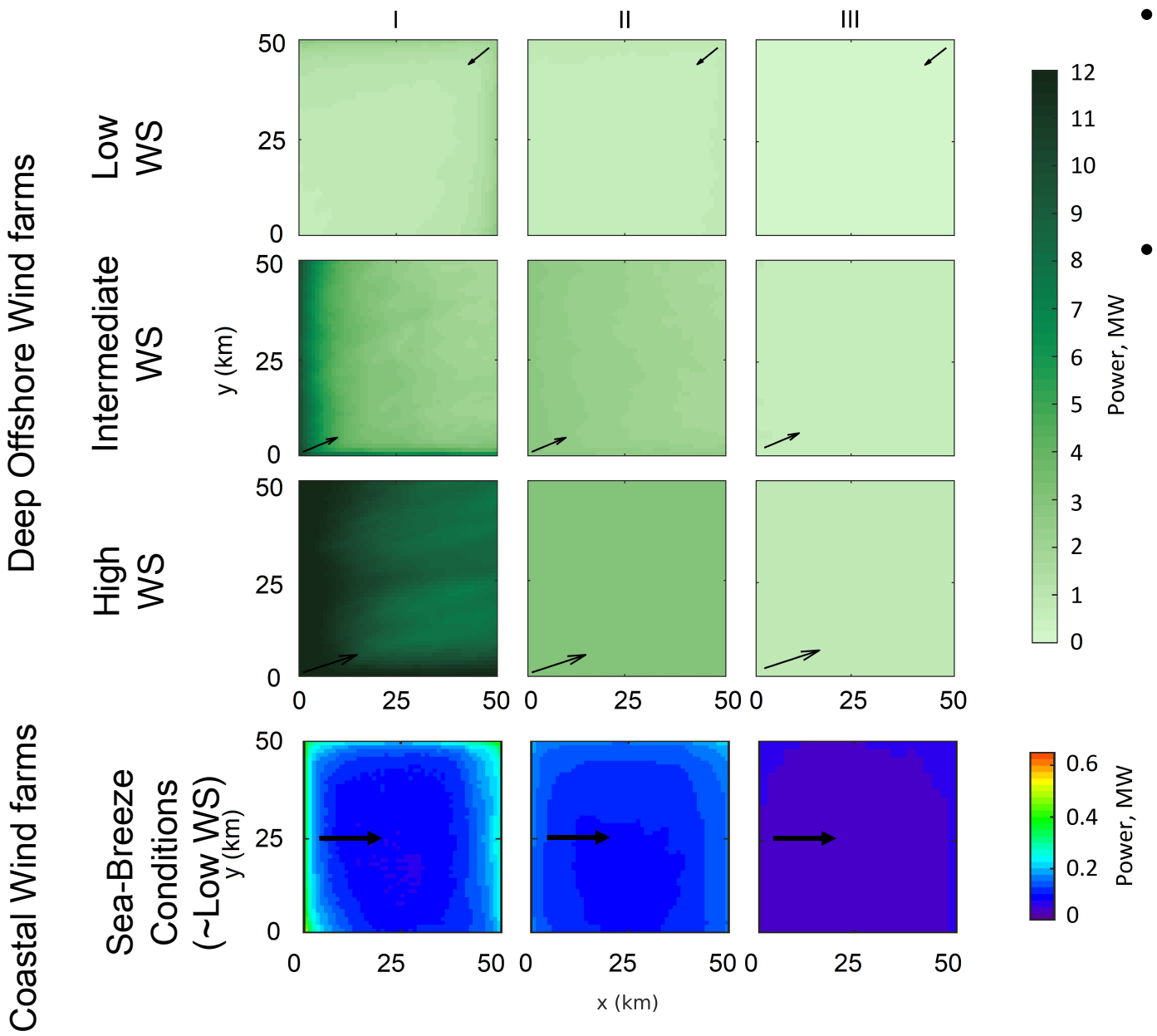
The momentum loss rate (ms^{-2}) is calculated as per Fitch et al. (2012):

$$\left.\frac{\partial |V|}{\partial t}\right|_{(k,i,j)} = -\frac{\frac{1}{2} N_t(i,j) C_T \left\{ |V(k,i,j)| \right\} |V(k,i,j)|^2 A(k,i,j)}{z(k+1,i,j) - z(k,i,j)}$$

* Please see Gupta and Baidya Roy (2021) for further details

Results

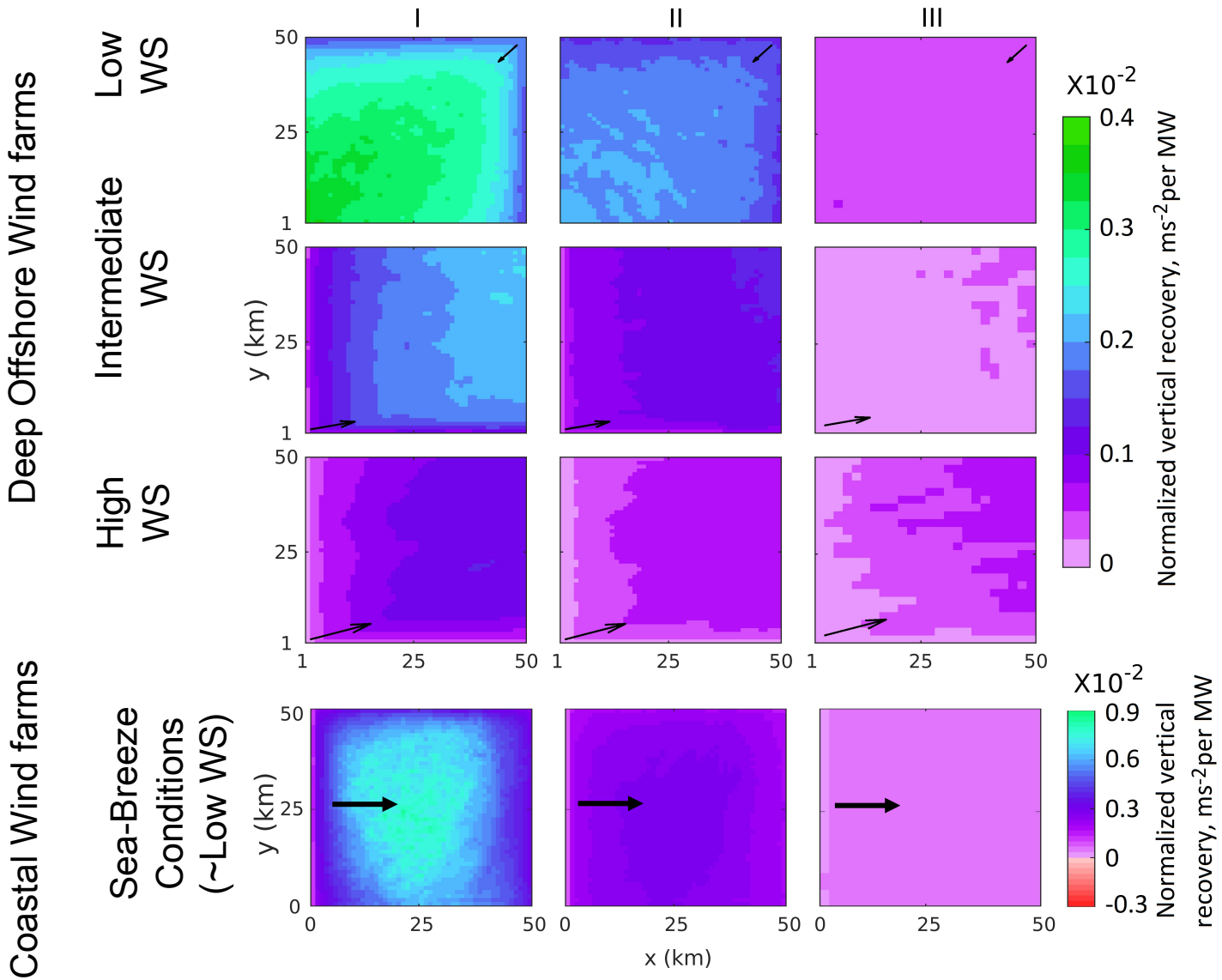
Power Generation



- In deep offshore wind farms, the power produced decreases monotonically from the upwind edge to the downwind edge of the wind farm.
- In coastal wind farms under sea breeze conditions, the power production is high at the upwind edge, and thereafter it decreases, because of wake effects. However, the power production again increases towards the downwind edge of the wind farm because of the increase in wind speed as the winds approach land.

WS: Wind Speed
I: Inter-turbine distance -0.5 km
II: Inter-turbine distance -1 km
III: Inter-turbine distance -2 km

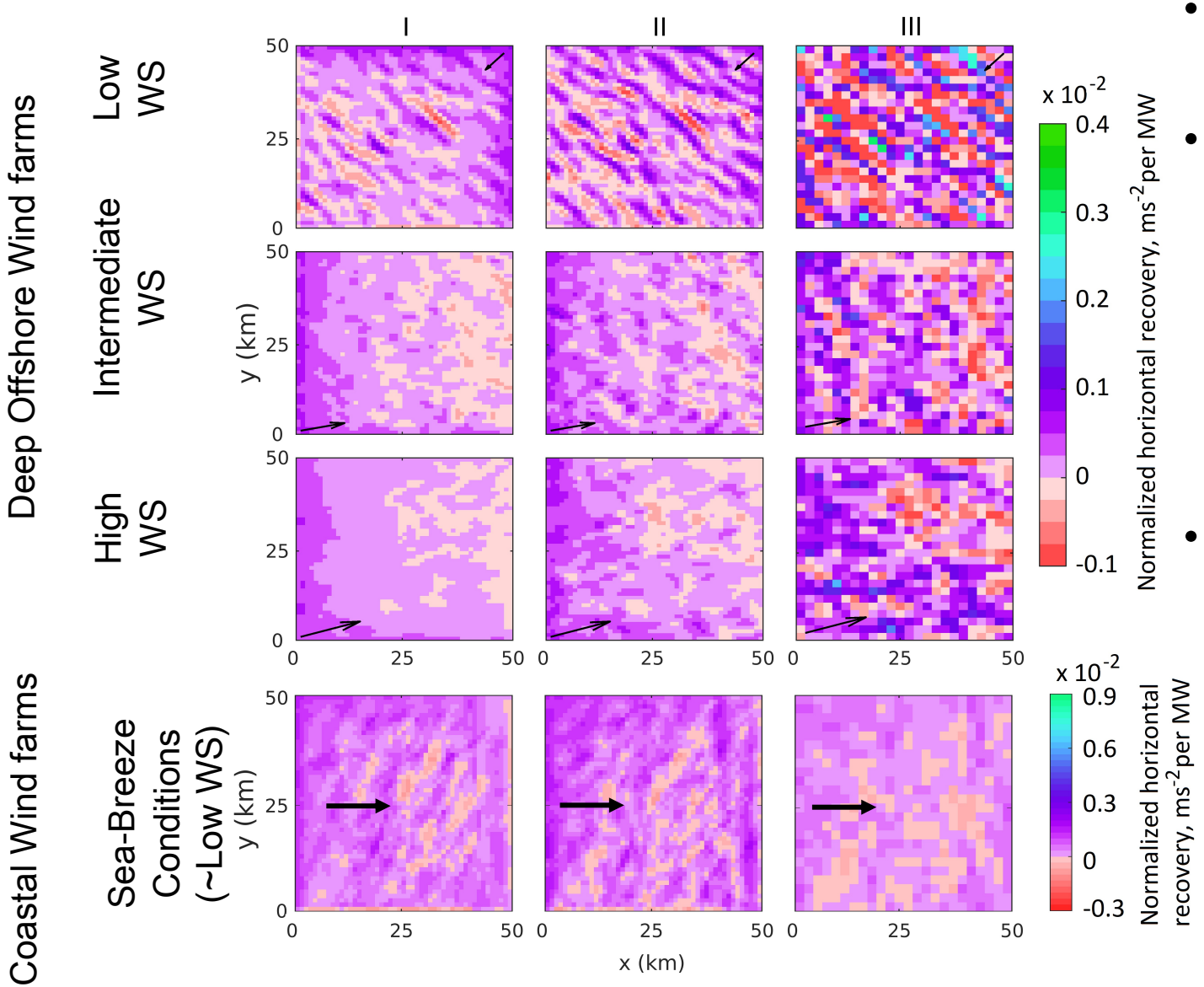
Normalized Vertical Recovery (Quantitative)



- For deep offshore wind farms with lower inter-turbine spacing (Case I and II), irrespective of the wind speed, the vertical recovery is weak at the upwind edge of the wind farm in the direction of wind flow.
- However, for coastal wind farms under sea-breeze conditions, for Case I and II, the vertical recovery is lower at both upwind and downwind edges.

WS: Wind Speed
I: Inter-turbine distance -0.5 km
II: Inter-turbine distance -1 km
III: Inter-turbine distance -2 km

Normalized Horizontal Recovery (Quantitative)



- The spatial patterns of vertical and horizontal recovery are complimentary.
- For deep offshore wind farms, vertical recovery is stronger in the interiors while horizontal recovery is stronger at the upwind edges. However, in coastal wind farms, the horizontal recovery occurs at both upwind and downwind edge of wind farm.
- In sparsely packed wind farms, horizontal recovery occurs inside the wind farms as alternating bands normal to the direction of the flow for both deep offshore and coastal wind farms.

WS: Wind Speed
I: Inter-turbine distance -0.5 km
II: Inter-turbine distance -1 km
III: Inter-turbine distance -2 km

Comparative Role of Horizontal & Vertical Recovery (Qualitative)

Table: Momentum loss rate (x 10^{-3}), ms^{-2}, vertical recovery (x 10^{-3}), ms^{-2}, and horizontal recovery (x 10^{-3}), ms^{-2} averaged over the wind farm and the simulation period. The numbers in the parenthesis give the percentage recovery with respect to the corresponding total recovery.

Cases	I			II			III		
	Mom. Loss Rate	Vert. Rec.	Hor. Rec.	Mom. Loss Rate	Vert. Rec.	Hor. Rec.	Mom. Loss Rate	Vert. Rec.	Hor. Rec.
Coastal WF Under Sea Breeze	-1.212	0.651 (91.9%)	0.057 (8.1%)	-0.534	0.277 (82.0%)	0.061 (18.0%)	-0.165	0.083 (72.2%)	0.032 (27.8%)
Deep Ocean WF ~Low WS	-3.93	2.78 (91.4%)	0.26 (8.6%)	-1.62	1.15 (85.2%)	0.20 (14.8%)	-0.47	0.32 (88.9%)	0.04 (11.1%)

For coastal wind farms under sea-breeze conditions, the vertical recovery plays the dominant role. However, the relative contribution of horizontal recovery increases compared to deep offshore wind farms. This result is more pronounced in Case II and III.

WS: Wind Speed
I: Inter-turbine distance -0.5 km
II: Inter-turbine distance -1 km
III: Inter-turbine distance -2 km

Conclusions

Conclusions

- Spatial patterns of power generation shows an interesting pattern under sea breeze conditions. Unlike deep offshore wind farm where the power produced monotonically decreases from the upwind edge of the wind farm till the downwind edge of the wind farm, the power production increases again towards the down wind edge because of sea breeze formation.

- For coastal wind farms under sea-breeze conditions, the vertical recovery plays the dominant role like deep offshore wind farms. However, the relative contribution of horizontal recovery increases compared to deep offshore wind farms. This result is more pronounced for larger inter-turbine distances.

- Spatial patterns of vertical and horizontal are complementary to each other. However, for coastal wind farm under sea breeze conditions, the horizontal recovery also occurs on downwind edge of the wind farm along with the upwind edge. This is because of increase in wind speeds at the sea- breeze approaches land.

References

References

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- Fitch, A. C., Olson, J. B., Lundquist, J. K., Dudhia, J., Gupta, A. K., Michalakes, J., and Barstad, I.: Local and mesoscale impacts of wind farms as parameterized in a mesoscale NWP model, Mon. Weather Rev., 140, 3017–3038, https://doi.org/10.1175/MWR-D-11-00352.1, 2012.
- Gupta, T. and Baidya Roy, S.: Recovery Processes in a Large Offshore Wind Farm, Wind Energ. Sci. Discuss. [preprint], https://doi.org/10.5194/wes-2021-7, in review, 2021.