A Global Investigation of Atmospheric Circulation Regimes Driving Wind Power Generation and its Extremes at Country and Continent Scales

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Motivation

- Wind variability and extreme wind energy events including wind droughts can pose major challenges for decarbonizing electricity grids that increasingly depend on renewables, including wind power generation.
- The conversions of available potential to horizontal kinetic energy that drives wind power are predominantly over oceanic regions remote from wind farms (Fig. 1).
- Therefore, long-range advection of horizontal kinetic energy plays an important role in wind power production.
- We systematically explore and distinguish the roles of local and remote factors in driving wind power variability at three types of scales: site-level, country-scale, continental-scale.
- We explore the impacts of large-scale kinetic energy generation and long-range advection of kinetic energy on power generation at wind farms.

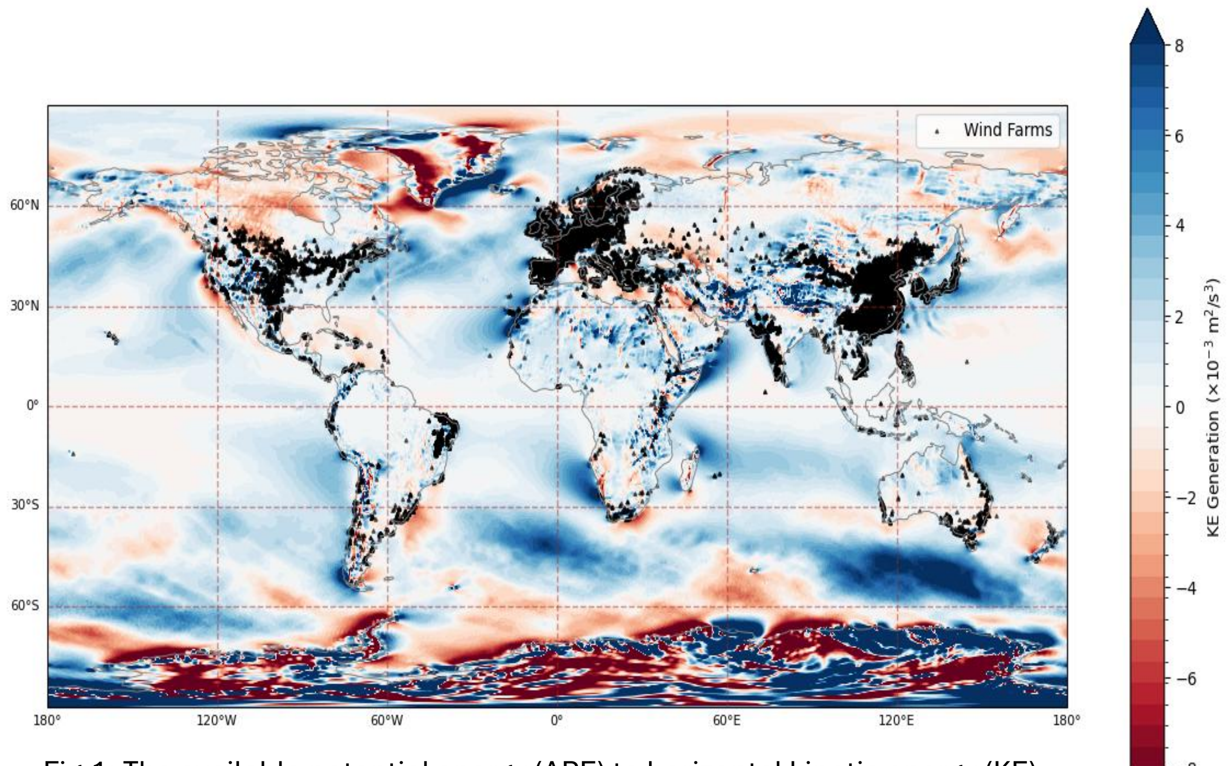


Fig.1: The available potential energy (APE) to horizontal kinetic energy (KE) conversion ("KE generation") (May – Oct, 2020) and global wind farms.

Methodology

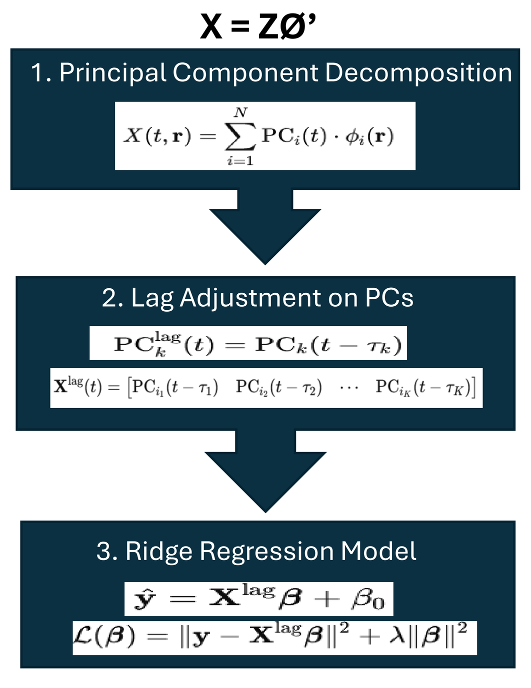


Fig.2a: PCA+ Ridge Regression Architecture.

- We apply Principal Component Analysis (PCA) to identify dominant spatiotemporal patterns in KE advection and KE generation fields. Lag-optimized PCs are used as predictors in a Ridge Regression framework to model and predict daily wind power generation. Optimal lags for each PC is selected based on univariate R^2 and significance (p-value <0.05).

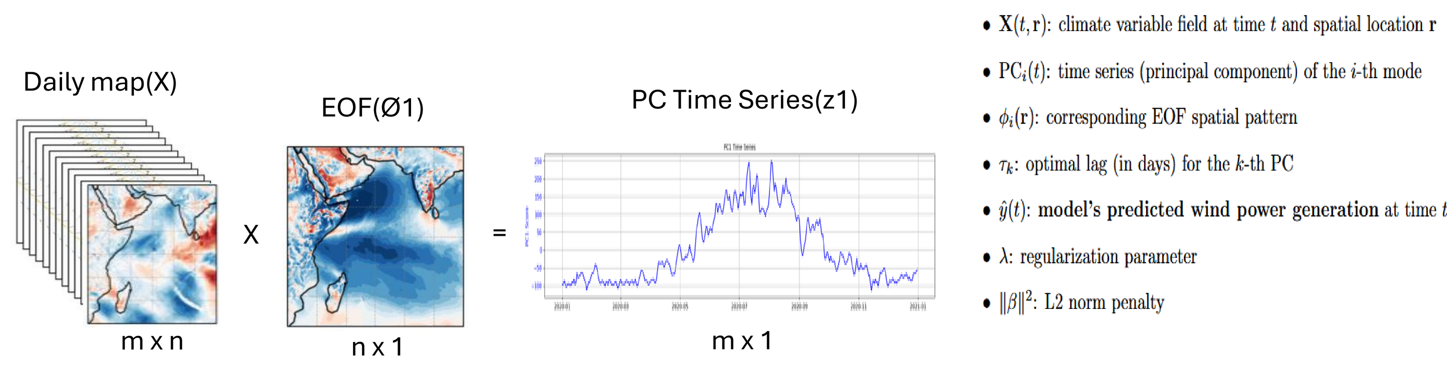


Fig.2b: Visualizing EOF spatial pattern and PC time series for KE Gen data for Indian Subcontinent . X is the data matrix and Ø1 is the eigen vector that explains largest fraction of the variability in X. z1 is the component of the linear projection of X onto the Ø1 basis vector.

Diaz Wind Power Station, Namibia (Site – Scale)

Year: 2020

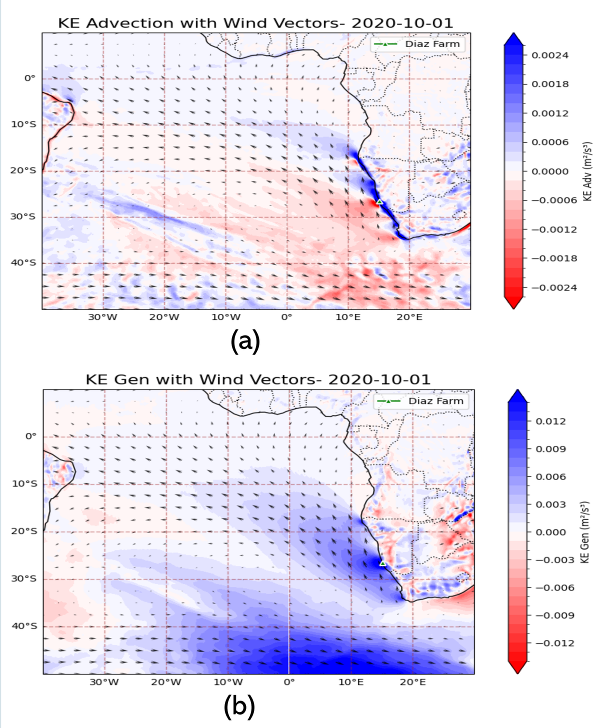


Fig.3a: KE Adv (a) and KE Gen (b) for Highest Power Generation month at Diaz Farm (Oct, 2020).

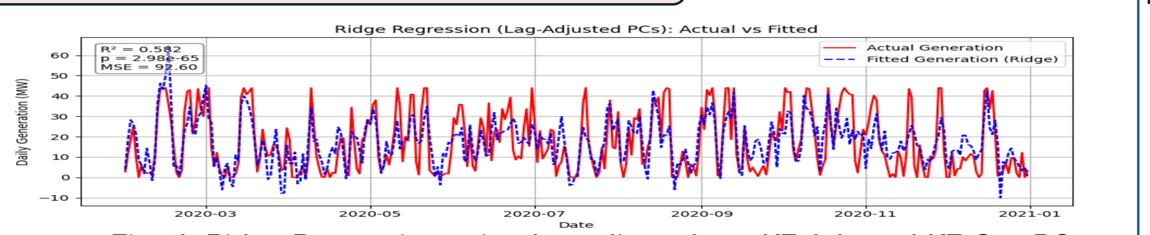


Fig.3b Ridge Regression using lag-adjusted top KE Adv and KE Gen PCs.

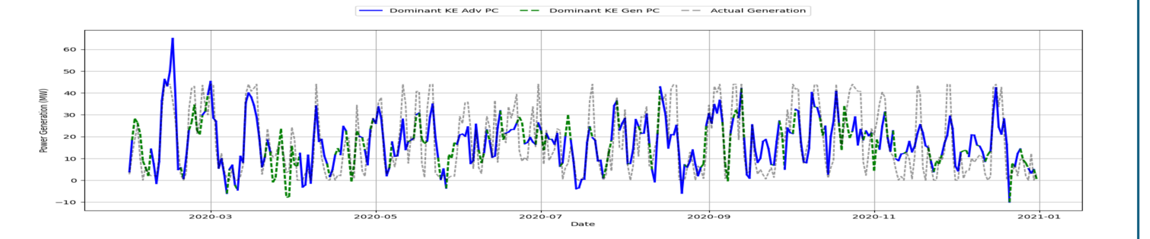


Fig.3c Visualizing dominant KE Adv and KE Gen Modes in fitted generation.

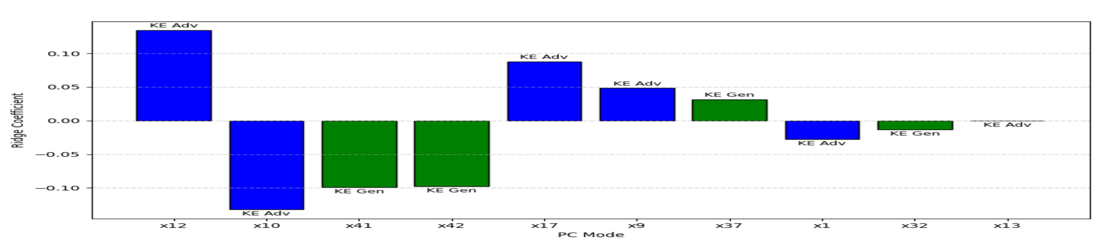


Fig.3d Top 10 statistically significant KE Adv (Blue) and KE Gen (Green) modes according to their contribution (descending order).

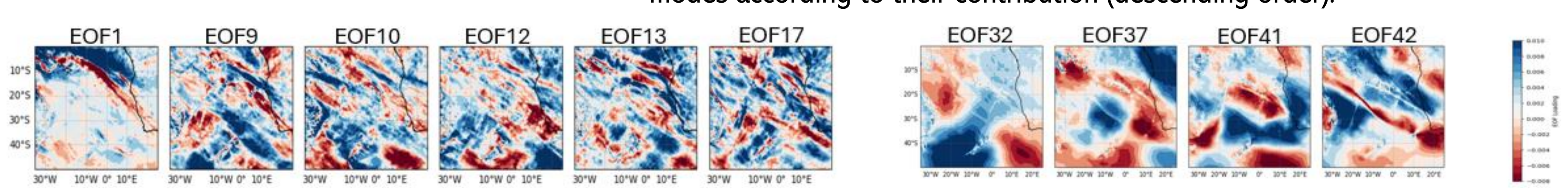


Fig.3e Visualizing EOFs for top 10 most statistically significant modes, on left KE Adv, on right KE Gen modes.

- Top 30 lag-adjusted PCs for KE Adv (X1-X30) and KE Gen (X31-X60) are required to obtain the best result. (R^2=0.58).
- Avg Optimal lag for most significant modes = 10.89 days.
- There is strong contribution from KE Adv modes (X12,X10,X17 & X9) and some less dominant KE Gen modes e.g. X41, X42 & X37.
- Most of the peaks of power generation are driven by KE Adv.

India (Country – Scale)

Year: 2009, Indian Summer Monsoon, May-Oct (Drought Year)

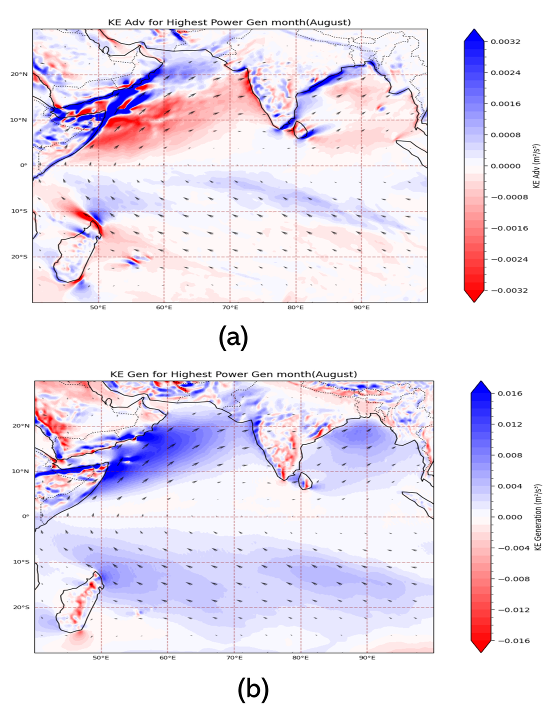


Fig.4a KE Adv (a) and KE Gen (b) for Highest Power Generation month in India (Aug, 2009).

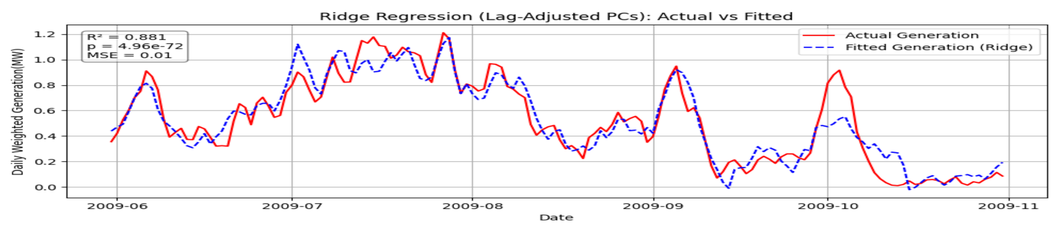
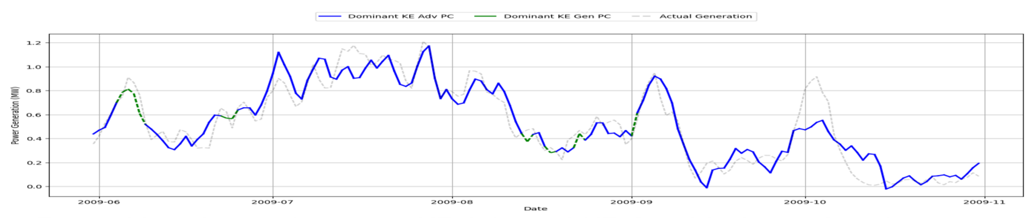


Fig.4b Ridge Regression using lag-adjusted top KE Adv and KE Gen PCs.



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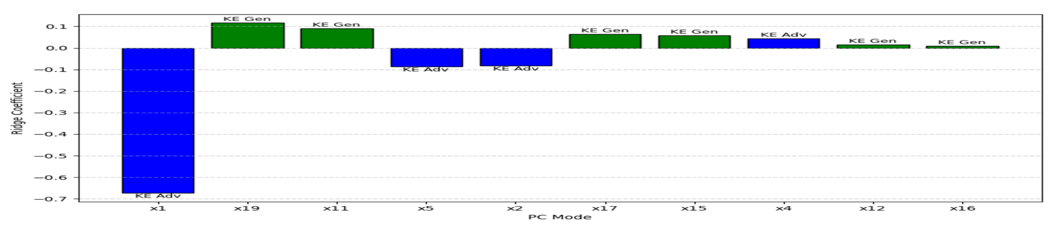


Fig.4d Top 10 statistically significant KE Adv (Blue) and KE Gen (Green) modes according to their contribution (descending order).

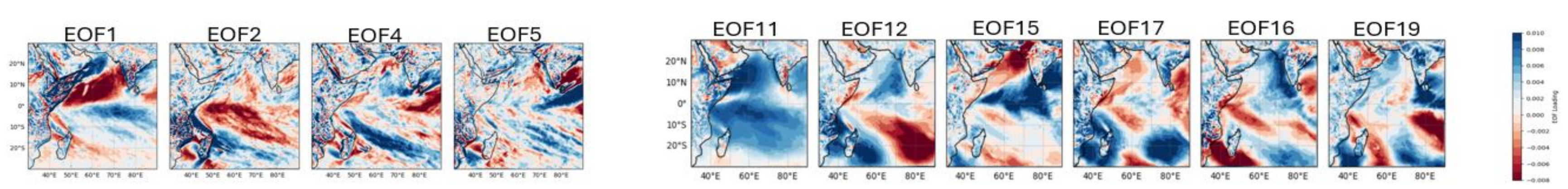


Fig.4e Visualizing EOFs for top10 most statistically significant modes, on left KE Adv, on right KE Gen.

- Top 10 lag-adjusted PCs for KE Adv (X1-X10) and KE Gen (X11-X20) were needed to get the best result. (R^2=0.88).
- Avg Optimal lag for most significant modes = 11.6 days.
- There is strong contribution from KE Adv modes (X1,X5 & X2) and some KE Gen modes e.g. X19, X11 & X17.
- Most of the peaks of power generation are driven by KE Adv as top KE Adv mode X1 has substantial contribution during Indian Summer Monsoon.

Europe (Continent – Scale)

Year: 2021 (Drought Year)

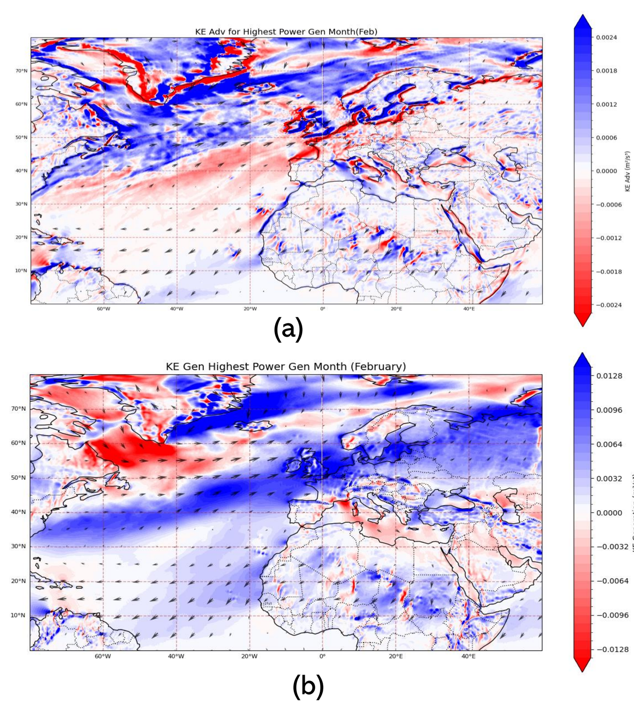


Fig.5a KE Adv (a) and KE Gen (b) for Highest Power Generation month in Europe (Feb, 2021).

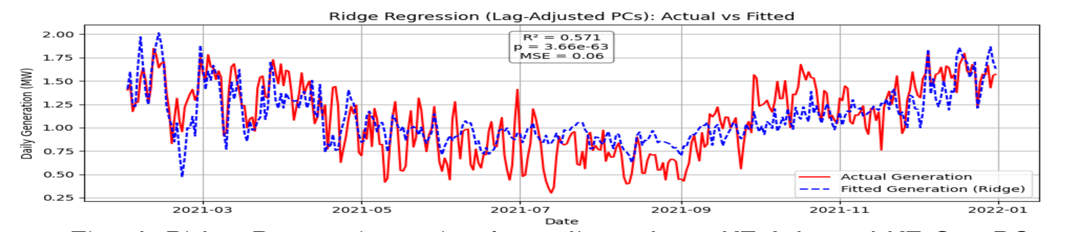
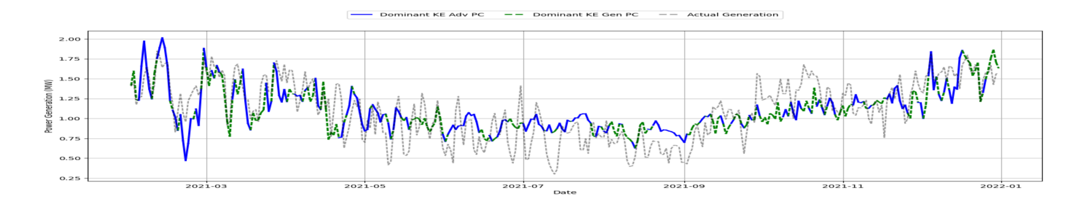


Fig.5b Ridge Regression using lag-adjusted top KE Adv and KE Gen PCs.



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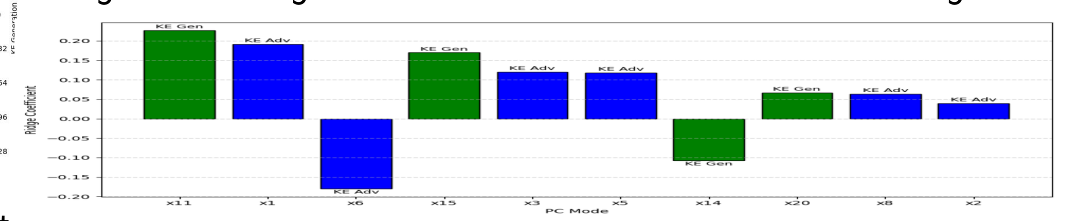

Fig.5d Top 10 statistically significant KE Adv (Blue) and KE Gen (Green) modes according to their contribution (descending order).

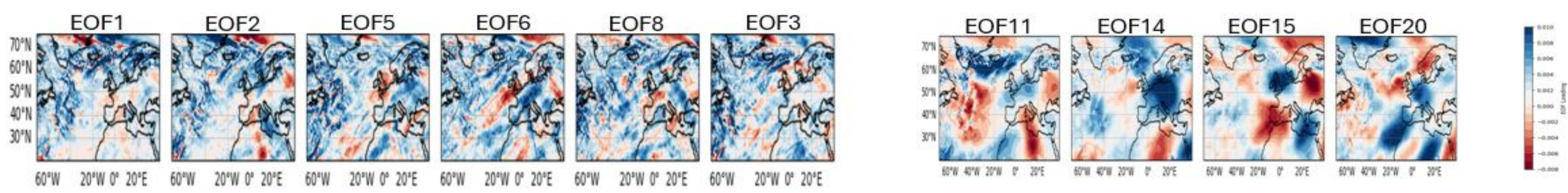

Fig.5e Visualizing EOFs for top 10 most statistically significant modes, on left KE Adv, on right KE Gen modes.

- Top 10 lag-adjusted PCs for KE Adv (X1-X10) and KE Gen (X11-X20) were needed to get the best result. (R^2=0.57).
- Avg Optimal lag for most significant modes = 12.3 days.
- There is strong contribution from KE Adv modes (X1,X6,X3 & X5) and some of the leading KE Gen modes e.g. X11, X15 & X14.
- Most of the peaks of power generation are driven by KE Adv, while some of the leading KE Gen modes contribute to peaks in between.

Results

- Lag-adjusted modes of the most significant Principal Components (PCs) of both KE generation and KE advection, when used together as predictors, yield the best results for forecasting power generation across different scales during wind drought years.
- It highlights the underlying lag effect of 10 - 12 days between major hotspots of KE generation and KE advection out of remote ocean regions and the resulting power generation at the chosen continental farms, consistently across spatial scales.
- Generation and long range advection of KE are both important for understanding wind power, but the relative roles vary with region, scale, and time.
- The number of dimensions needed to model power generation varies across scales. At country and continental scales, the relationship appears low-dimensional, with around 10 modes each for KE generation & KE advection. However at site scale, a higher number of modes around 30 each are required to account for power generation.

Conclusion and Future Work

- We find that KE generation as well as advection are vital for predicting daily wind power production variations across spatial scales.
- Site specific analysis require more PCs to explain the variation compared to the country scale or continent scale analysis.
- Going forward, to increase the robustness of the findings, we plan to extend the study temporally as well as spatially.

Questions Addressed

- What background conditions over open oceanic regions facilitate long-range advection of wind energy?
- How critical are KE generation and long-range advection for wind power variability?
- Is wind power generation sufficiently low-dimensional in the context of large scale advection of wind energy?

References

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3. Antonini, E.G.A., Virgüez, E., Ashfaq, S. *et al.* Identification of reliable locations for wind power generation through a global analysis of wind droughts. *Commun Earth Environ* **5**, 103](2024). https://doi.org/10.1038/s43247-024-01260-7