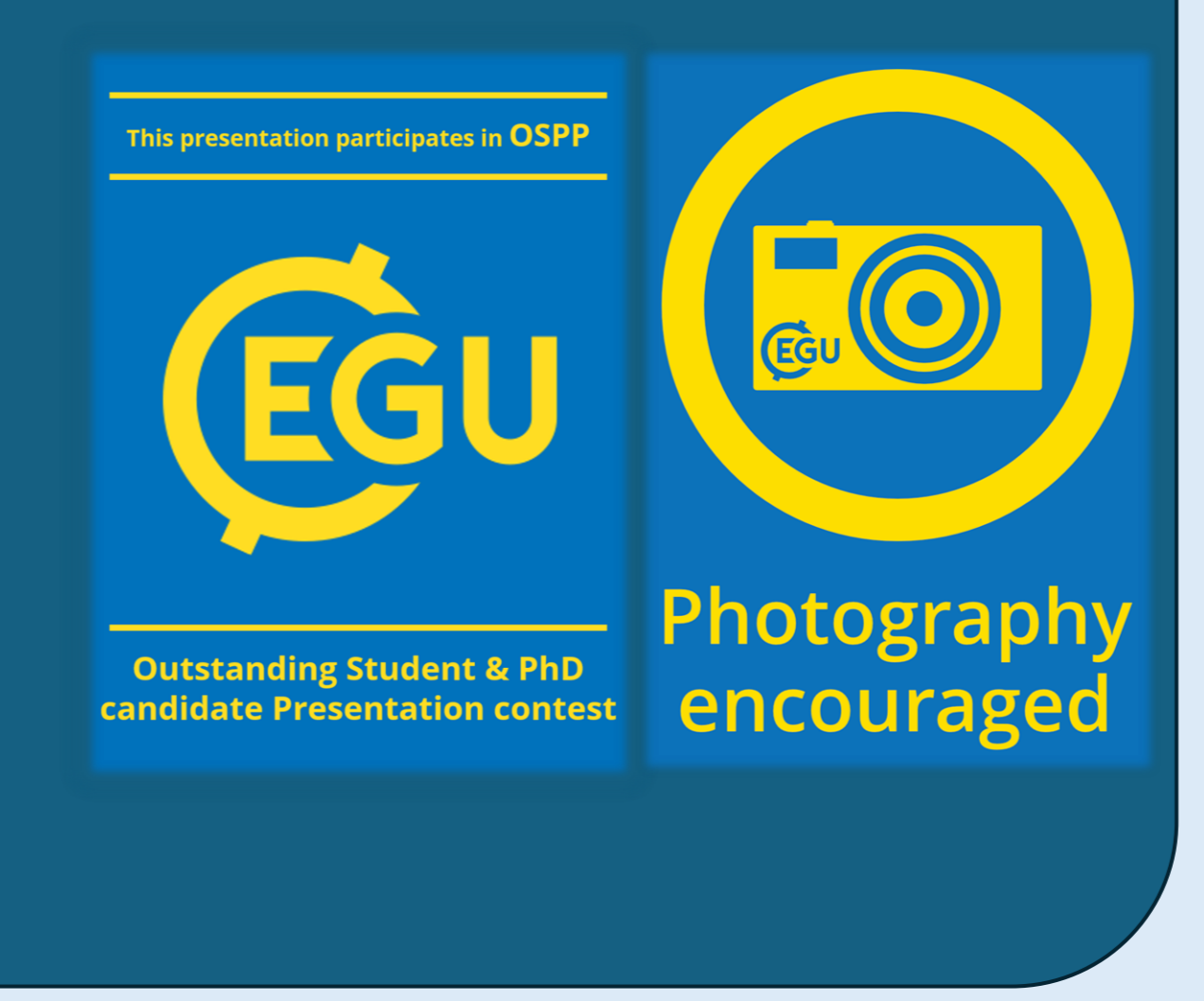


Climate change impacts on wind-solar variability and renewable energy droughts in India

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Key Points

- Wind much more uncertain across climate models than solar
- While mean changes can be modest, variability and extremes matter
- Renewable droughts longer and more frequent under climate change
- Air pollution (anthropogenic aerosols) more important than GHGs on solar

Datasets

- Hourly surface temp, surface solar radiation, and 100-m wind speeds from **ERA5 reanalysis**
- 3-hourly surface temp, surface solar radiation, and 10-m wind speeds from **14 CMIP6** GCMs, 1 ensemble member per model
- Spatial **installed capacity** data across India (from [1])

Methods

- Conversion of climate variables to wind and solar PV power **capacity factors (CFs)** using physical/empirical models, weighted by installed capacity [2]
- **Energy droughts:** periods below threshold defined by **2.5th percentile** of combined wind-solar historical generation [3]

Historical capacity factors

- Annual cycles captured well, showing clear **complementarity**
- Greatest spread **throughout JJAS (Indian monsoon season)** especially for wind, ranging from ~0.15 to ~0.5; **huge differences** in context of total power

Future capacity factors

- General **solar improvement**, especially in north-east region, apart from SSP3-7.0 – a high aerosol scenario
- Wind changes show strong regional variability, combined with model spread, highlight profound **uncertainty in future wind resources**

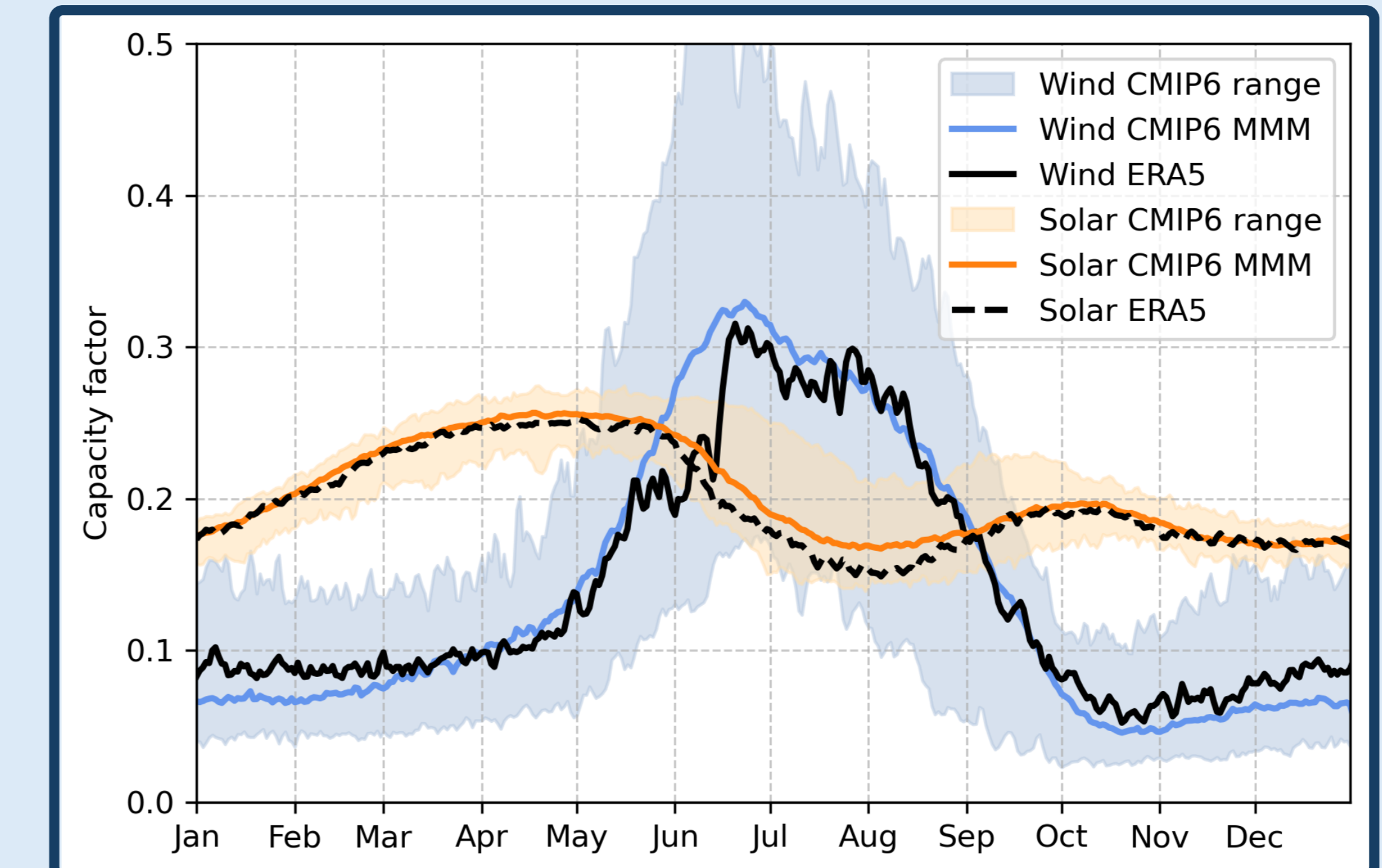


Figure 1: Multi-model mean annual cycle of wind and solar PV capacity factors over India (1979–2014). Solid lines show CMIP6 multi-model means, shaded areas indicate the full range across models, and dashed lines represent ERA5 for reference.

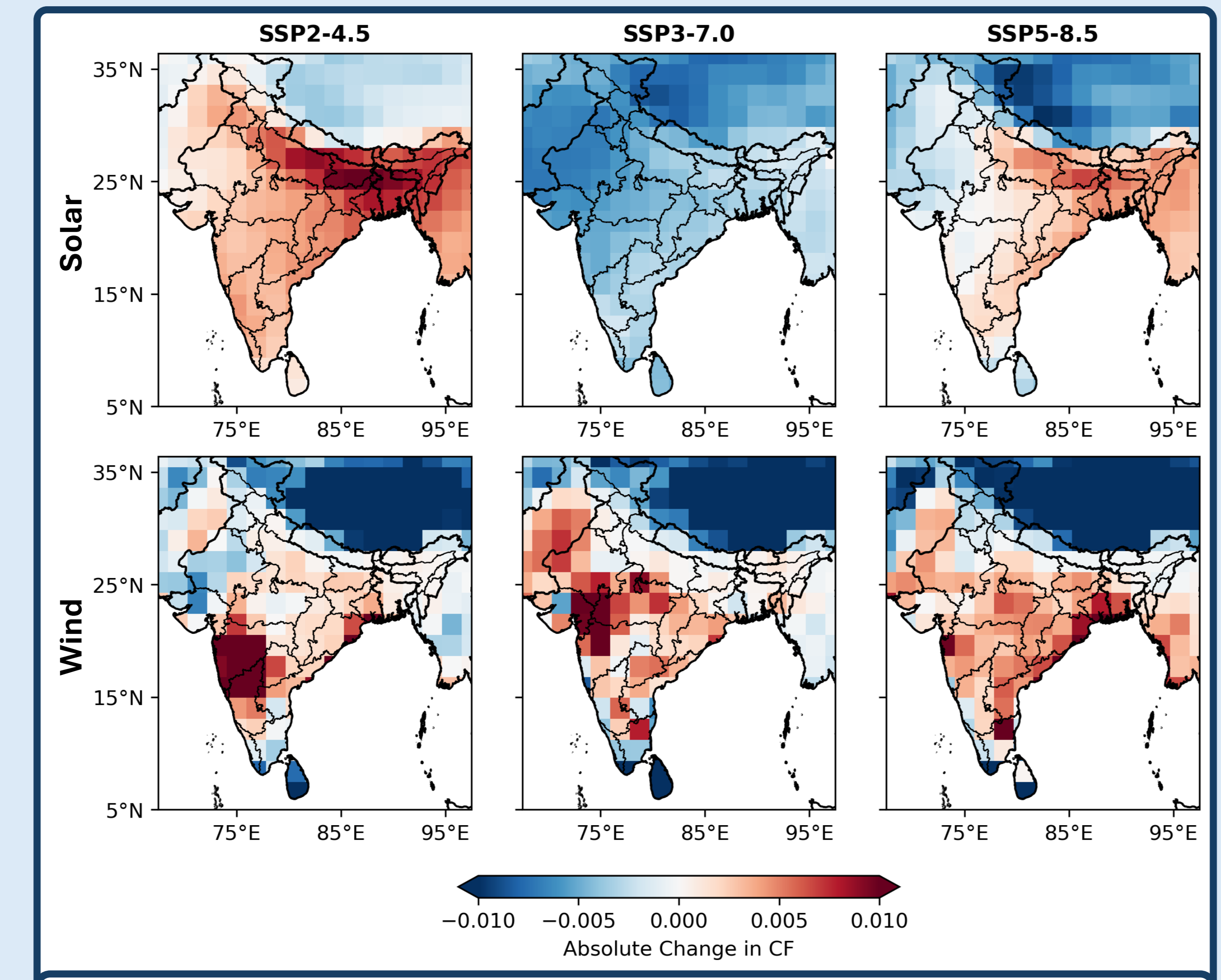


Figure 2: Multi-model mean projected spatial changes in solar and wind power capacity factor, 2075–2095 compared to present-day baseline for three future scenarios.

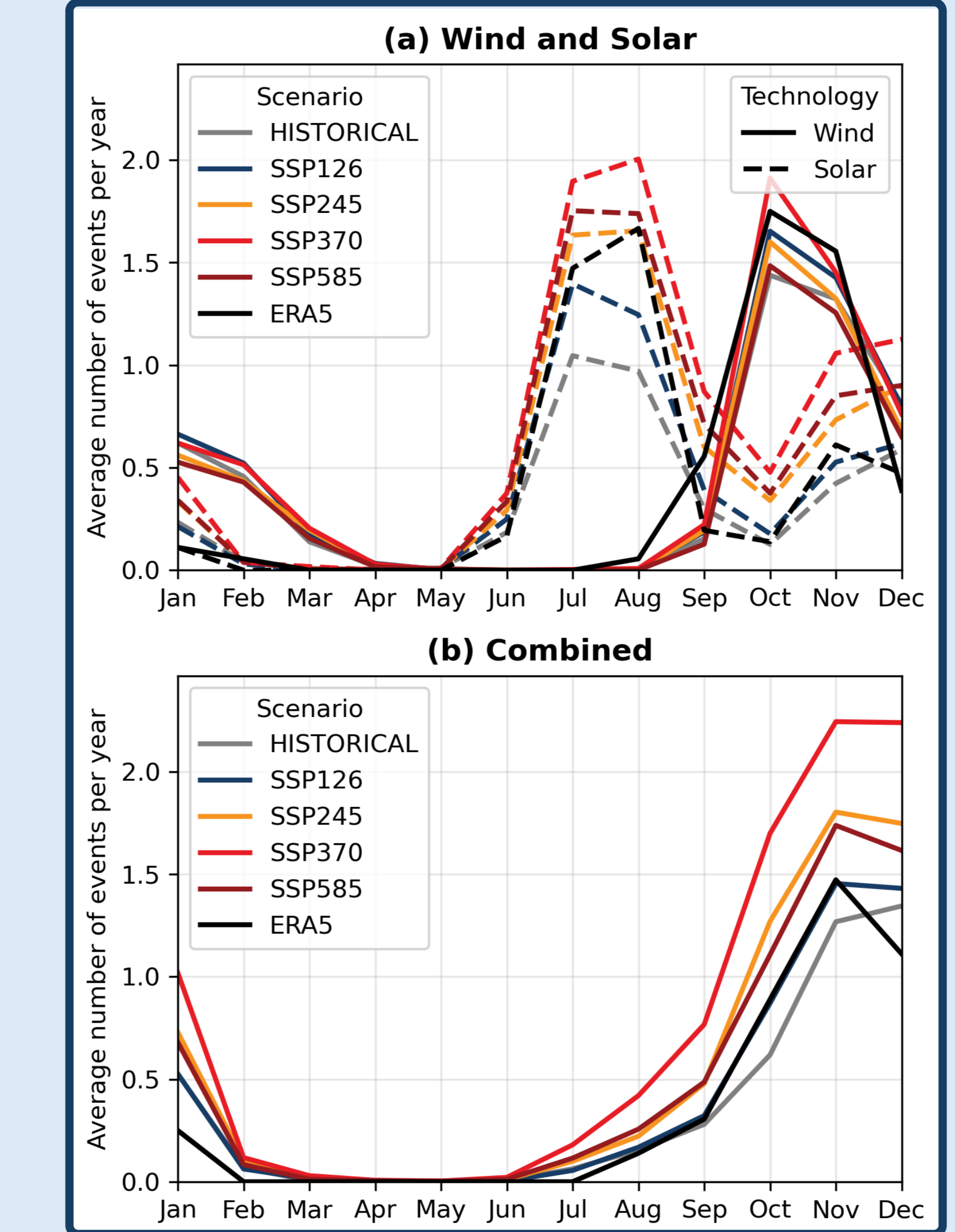


Figure 3: Annual cycles of renewable energy droughts over India for 1979–2024, (a) solar-only and wind-only droughts (b) combined wind-solar, shown for the CMIP6 multi-model means across historical and future SSP projections, and ERA5 for reference

Renewable droughts

- Solar droughts peak during **monsoon**, wind droughts **post-monsoon**; potential mutual compensation with improved storage and transmission
- Annual cycles **largely match ERA5**, but seem to **undershoot** peak wind droughts post-monsoon
- Seasonality preserved but **magnitude intensifying** under climate change
- Least compensation occurs **Nov-Dec**, when **system stress** exposure is highest
- Individual models find renewable droughts **increasing** in both **frequency and duration** under climate change

Also ask me about...

- How the climate data is converted to electricity generation
- Why wind is harder to model and predict than solar
- The role of the Indian monsoon and other meteorological drivers
- How this work feeds into power system modelling

References

[1] Hunt, K. M. R., & Bloomfield, H. C. (2024). Quantifying renewable energy potential and realized capacity in India: Opportunities and challenges. *Meteorological Applications*, 31(3), e2196. <https://doi.org/10.1002/met.2196>
 [2] Bloomfield H. C., Brayshaw D. J., Charlton-Perez A. J. (2020). Characterizing the winter meteorological drivers of the European electricity system using targeted circulation types. *Meteorol Appl.* 2020;27:e1858. <https://doi.org/10.1002/met.1858>
 [3] Dijkstra, I., Bloomfield, H. C., and Hunt, K. M. R. (2025). Identifying weather patterns responsible for renewable energy droughts over India. *Adv. Geosci.*, 65, 127–140, <https://doi.org/10.5194/adgeo-65-127-2025>

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