

Climate-Change Impacts on Offshore Wind Energy Potential across India's EEZ

A bias-corrected multi-model climate assessment with machine-learning refinement

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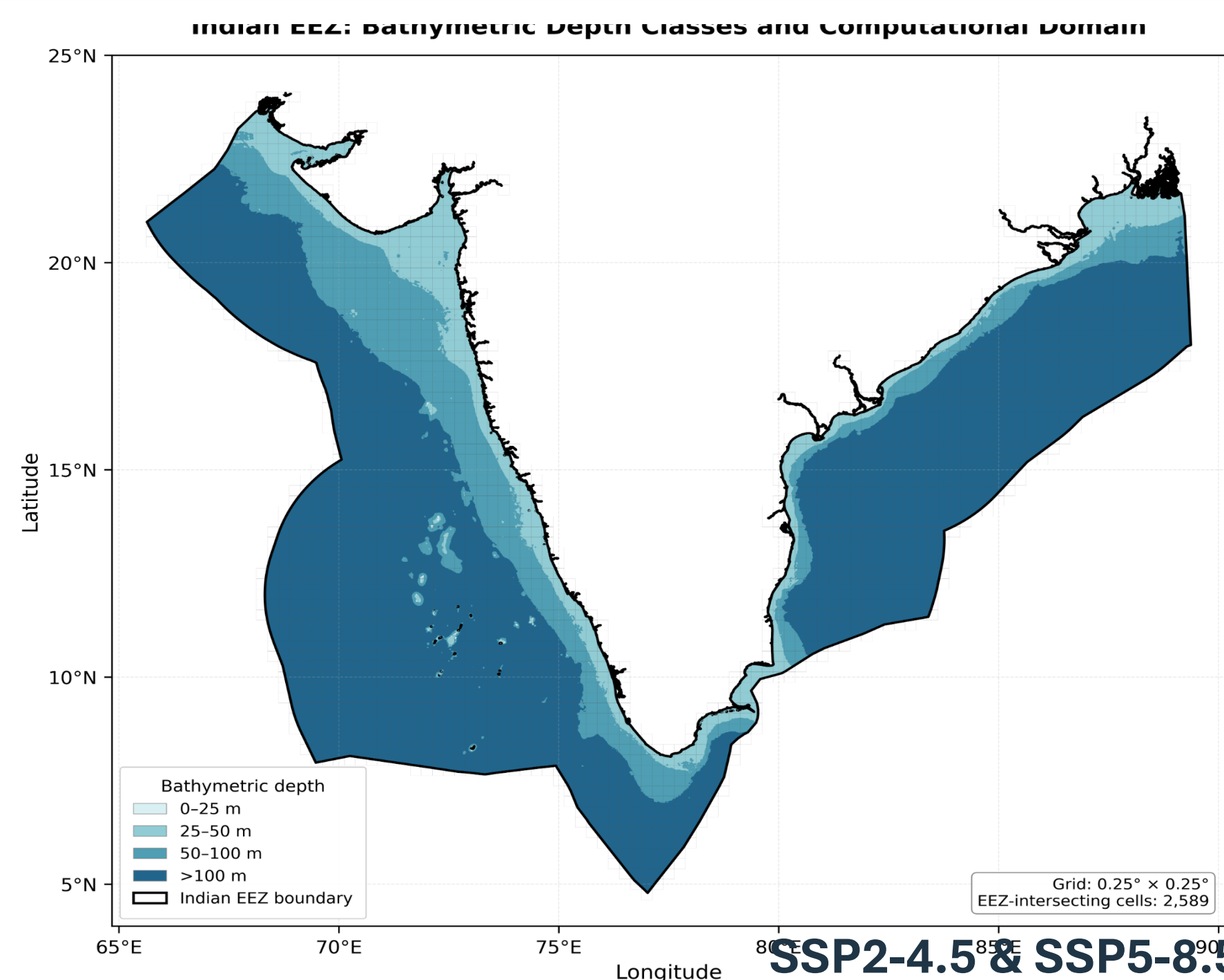
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ABSTRACT

Offshore wind development requires reliable estimates of present and future wind resources, particularly under changing climatic conditions. This study investigates climate-driven changes in offshore wind energy potential across India's Exclusive Economic Zone (EEZ) using ERA5 reanalysis (1990–2014) and ten CMIP6 global climate models. A three-tier correction framework is implemented, comprising Weibull-based Quantile Delta Mapping (T0), seasonal residual adjustment (T1), and Quantile Random Forest-based residual refinement with temporal treatment (T2). Model performance is assessed using an independent test period (2010–2014), alongside temporal and distributional diagnostics. The hybrid T2 framework reduces the mean root mean square error (RMSE) from 2.662 m s⁻¹ (T0) and 2.576 m s⁻¹ (T1) to 2.510 m s⁻¹, while improving the Perkins Skill Score from 0.881 to 0.906. Substantial improvements are observed in temporal characteristics, with lag-1 dependence error decreasing from 0.112 to 0.031 and ramp Kolmogorov–Smirnov statistics decreasing from 0.179 to 0.058 relative to T1. These improvements occur across all ten models for temporal persistence and ramp behaviour, although RMSE and MAE improvements are observed in eight models. The hybrid framework largely preserves the projected ensemble-mean climate-change signal. Future projections under SSP2-4.5 and SSP5-8.5 indicate EEZ-averaged wind-speed reductions of approximately 0.066–0.092 m s⁻¹ (1.21–1.68%) across near- (2026–2050), mid- (2051–2075), and far-future (2076–2099) periods. Spatial projections reveal contrasting regional responses, with declining wind speeds across much of the Arabian Sea and southern EEZ and localized increases in parts of the Bay of Bengal. These findings demonstrate the value of combining statistical bias correction with machine-learning refinement to improve offshore wind projections and support climate-informed assessment of future wind energy resources.

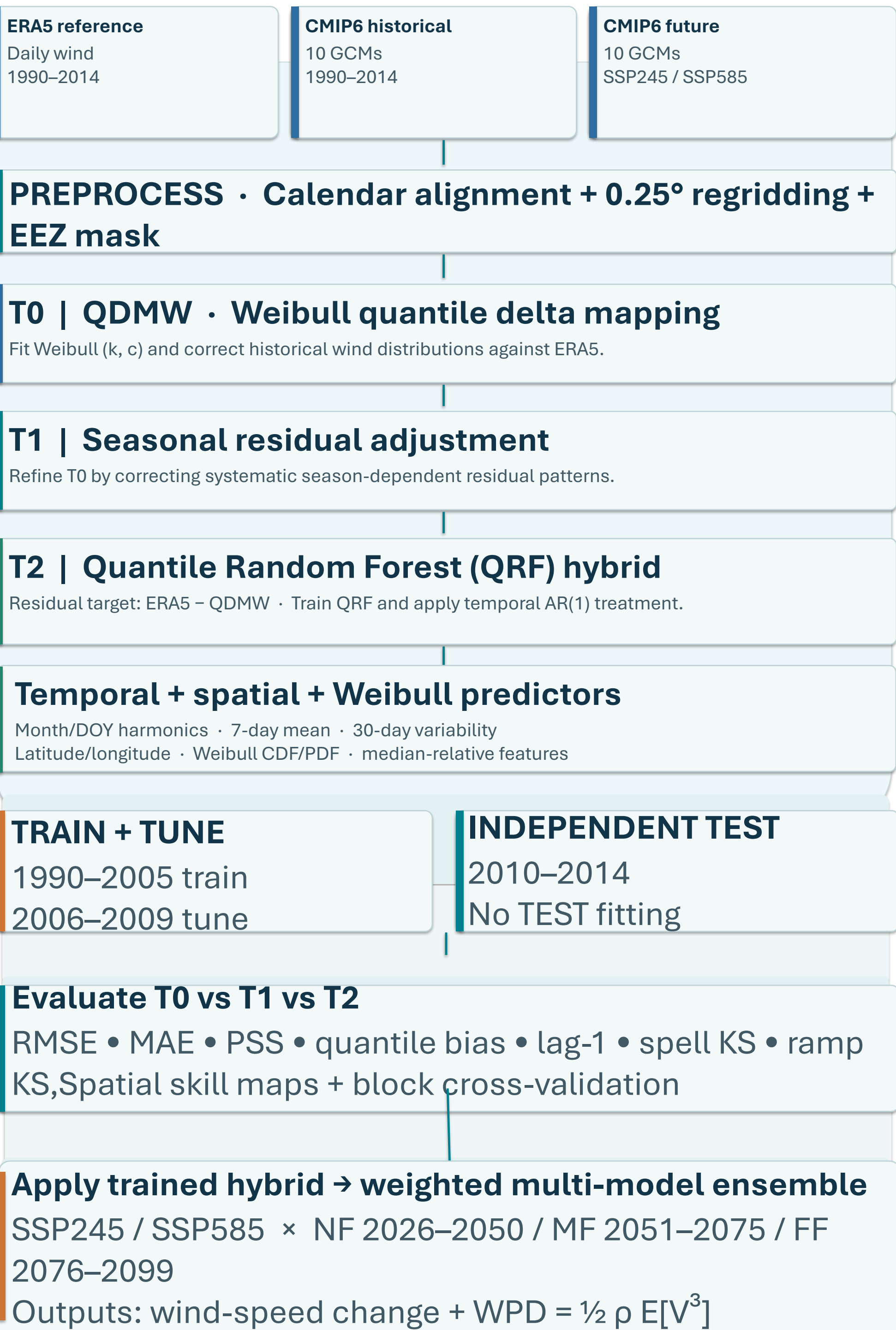
STUDY AREA & DATA



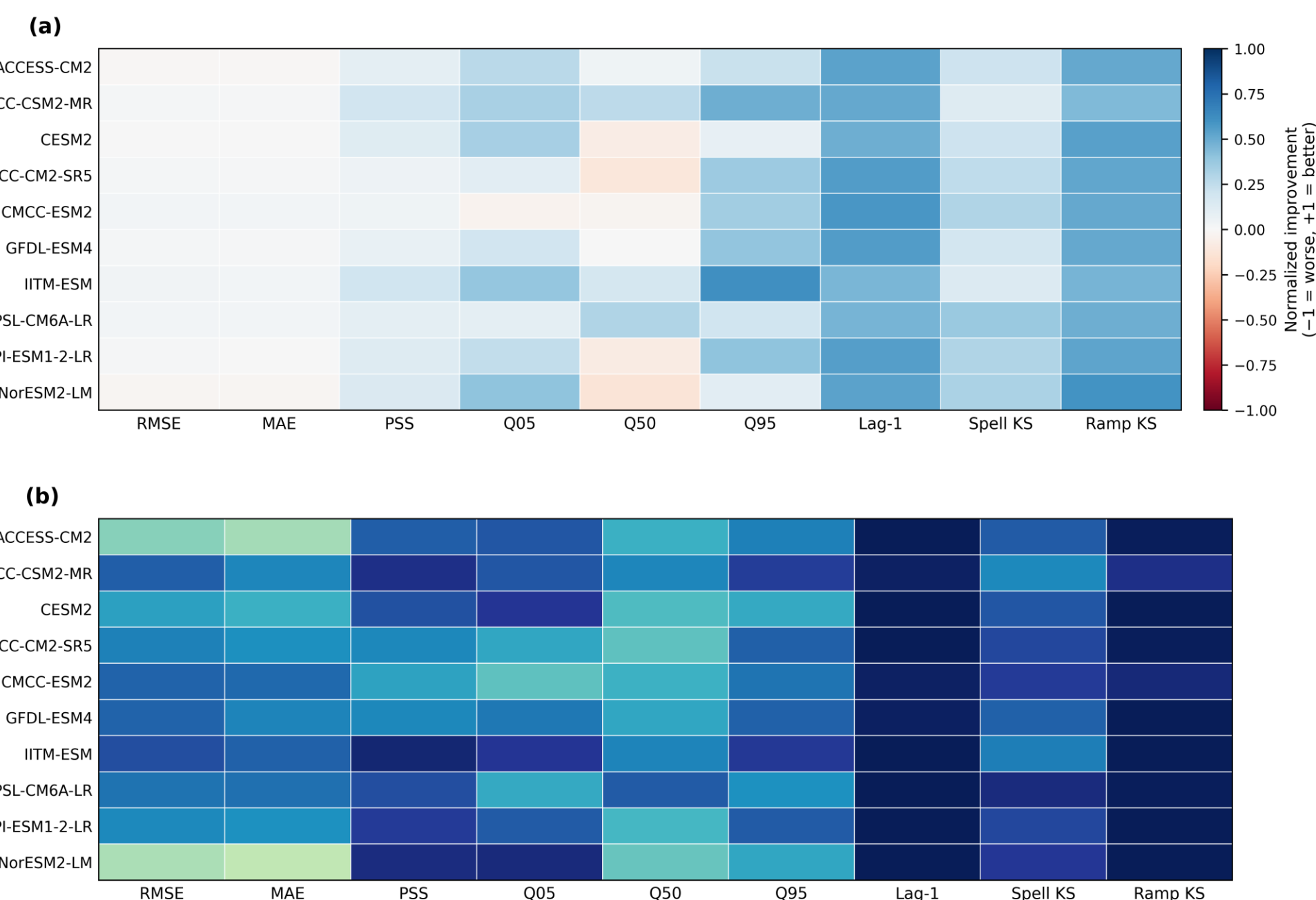
10 CMIP6 GCMs at 0.25° grid
ERA5 reference((1990–2014)
:0.25° grid
Historical : 1990–2014

SSP2-4.5 & SSP5-8.5:
Near Future : 2026–2050
Mid Future : 2051–2075
Far future : 2076–2100

METHODOLOGY

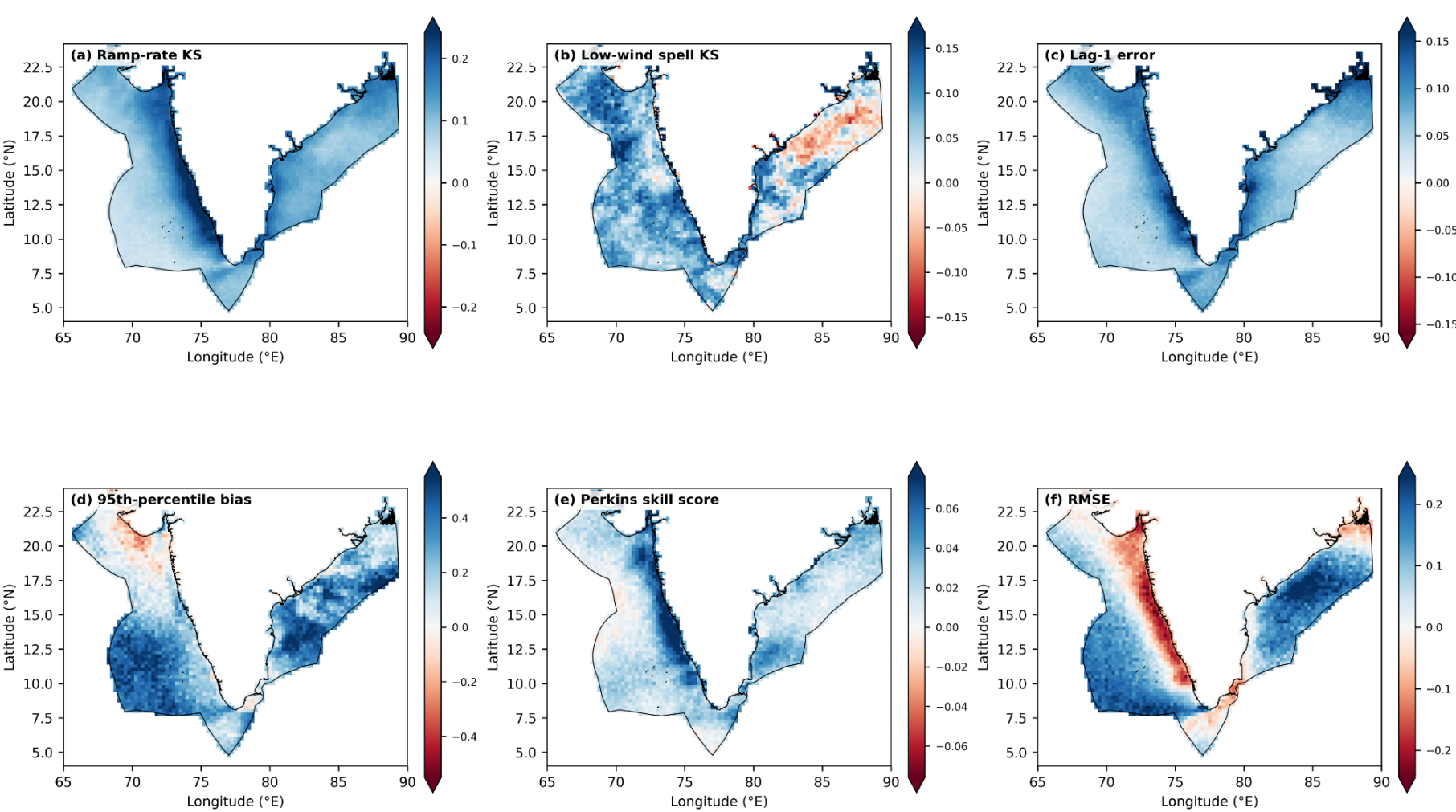


MODEL PERFORMANCE



Mean RMSE decreases from 2.662 to 2.510 m s⁻¹, a reduction of 0.152 m s⁻¹ (5.7%) relative to T0. PSS increases from 0.881 to 0.906, a gain of 0.025. Relative to T1, lag-1 dependence error decreases from 0.112 to 0.031 (72.3%), while ramp KS decreases from 0.179 to 0.058 (67.6%). Temporal persistence and ramp behaviour improve across all 10 models, while RMSE and MAE improve in 8 models.

SPATIAL VALIDATION



The displayed maps indicate reductions in ramp KS of approximately 0.10–0.20 and in lag-1 error of approximately 0.05–0.15 in areas with strong improvement. RMSE decreases by approximately 0.10–0.20 m s⁻¹ in parts of the southwestern EEZ and Bay of Bengal, but increases by approximately 0.10–0.20 m s⁻¹ along sections of the west coast.

BENCHMARK SUMMARY

A measurable gain beyond QDMW

RMSE

2.662 → 2.510

m s⁻¹ (T0 → T2)

PSS

0.881 → 0.906

distributional similarity

Lag-1 error

0.112 → 0.031

T1 → T2

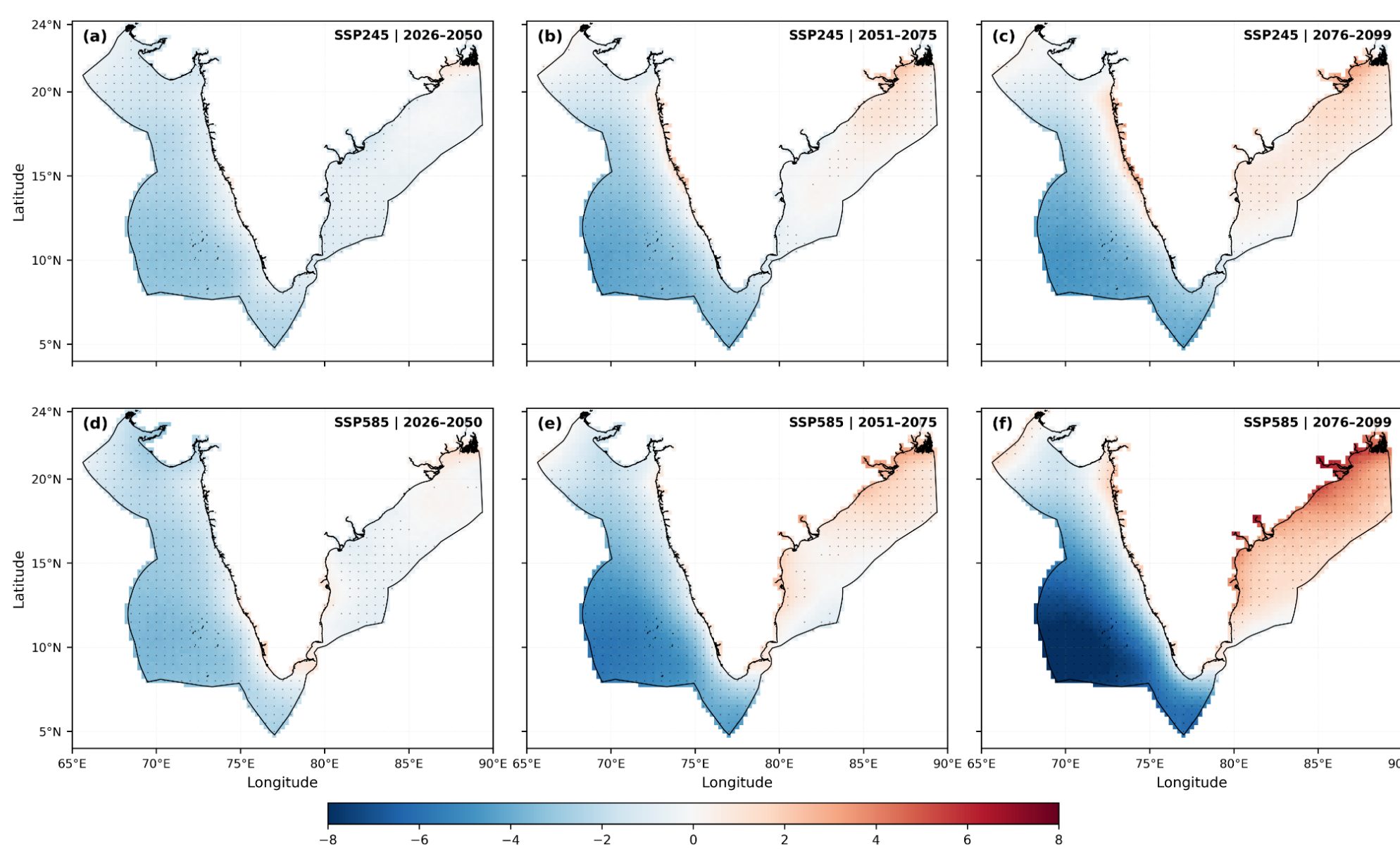
Ramp KS

0.179 → 0.058

T1 → T2

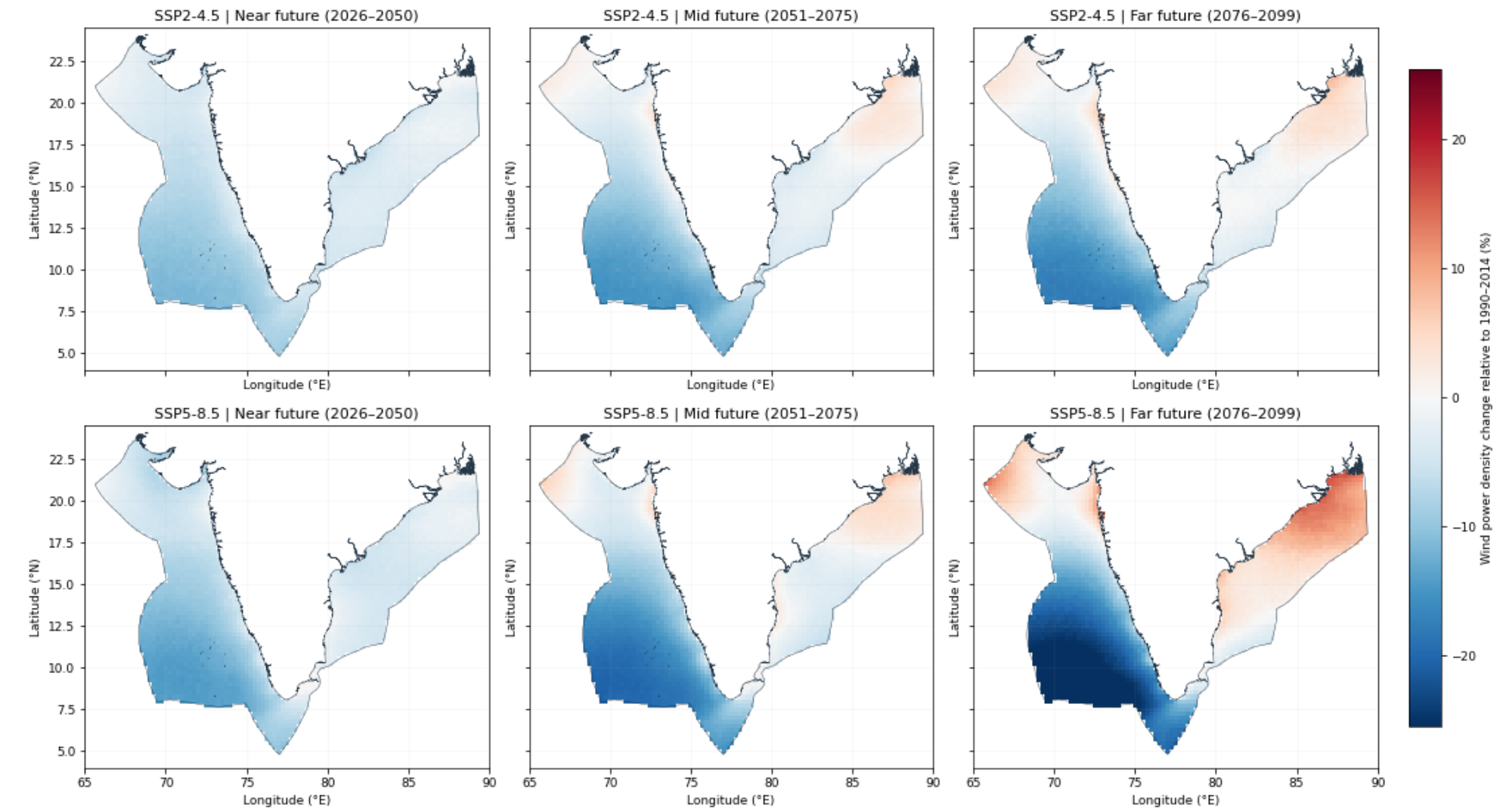
Across all ten models, temporal metrics show the clearest benefits; not every cell or metric improves.

FUTURE CLIMATE RESPONSE



Across SSP2-4.5 and SSP5-8.5, projected EEZ-mean wind speed decreases by 0.066–0.092 m s⁻¹ (1.21–1.68%) across the assessed future periods. The displayed maps show local reductions approaching 6–8% in the southwestern and southern EEZ under far-future SSP5-8.5, alongside increases of approximately 4–6% in parts of the northern Bay of Bengal.

WIND POWER DENSITY



The displayed maps indicate wind power density reductions of approximately 20–25% in parts of the southwestern and southern EEZ under far-future SSP5-8.5. Parts of the northern Bay of Bengal show increases of approximately 10–20%. These local energy changes are larger than the corresponding mean wind-speed changes because wind power density depends on the cube of wind speed.

CONCLUSION

Improved temporal realism

T2 reduces mean RMSE from 2.662 to 2.510 m s⁻¹ and increases PSS from 0.881 to 0.906 relative to T0. Temporal persistence and ramp behaviour improve across all ten models.

Future responses vary across the EEZ

EEZ-mean wind speed decreases by about 1.21–1.68%. Regional maps reveal larger declines in the Arabian Sea and southern EEZ, alongside localized increases in the Bay of Bengal.

Implications for offshore wind planning

Assess future resource stability alongside current wind potential. Detailed site selection also requires hub-height winds, turbine performance, bathymetry and environmental constraints.