



Supplement of

Beyond wind-induced upwelling: diverse drivers of future productivity in eastern boundary upwelling systems

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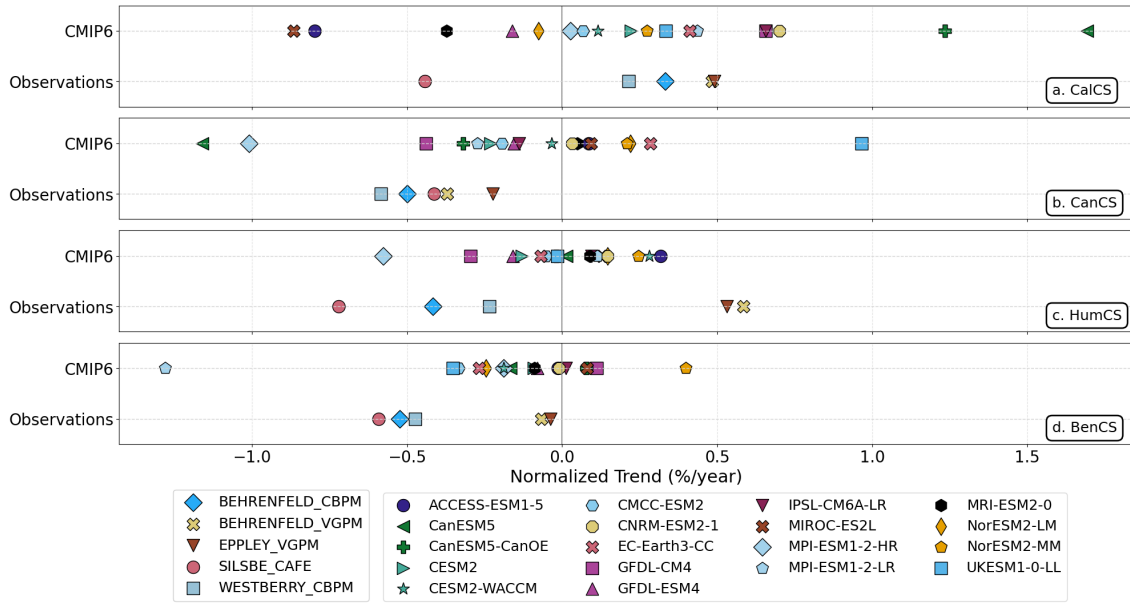


Figure S1: Evaluation of 18 CMIP6 models versus five observational data products for historical (1998–2014) NPP. Each colored marker represents the temporal and EBUS-scale spatial mean of NPP for an individual model or observational product.

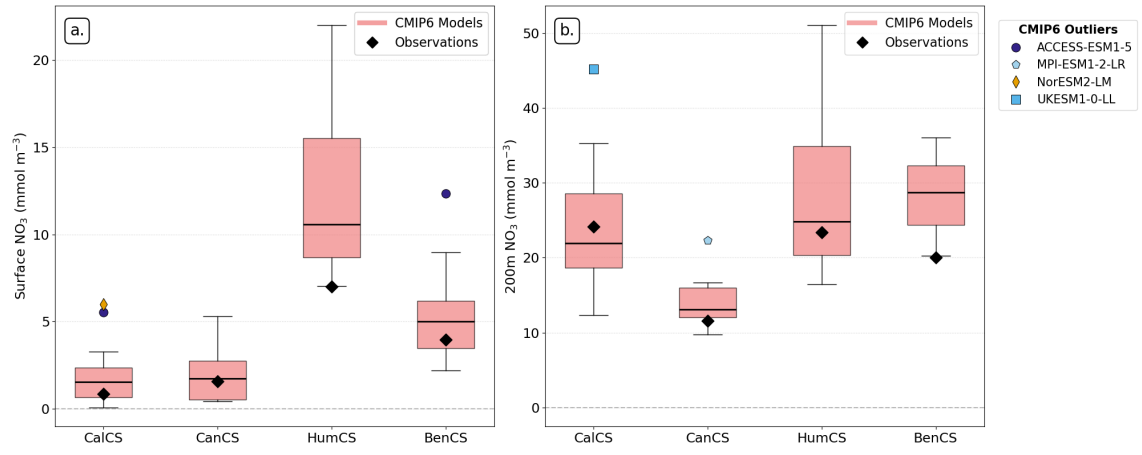


Figure S2: Box-and-whisker plots showing the distribution of climatological (1965-2022 for observations from World Ocean Atlas 2023; 1965–2014 for CMIP6 models) surface and subsurface (200 m) nitrate concentrations across EBUSs. Boxes represent the interquartile range (IQR), whiskers extend to $1.5 \times \text{IQR}$, and medians are shown as thick black lines. Observational estimates are indicated by black diamonds, colored markers show outliers in the CMIP6 ensemble.

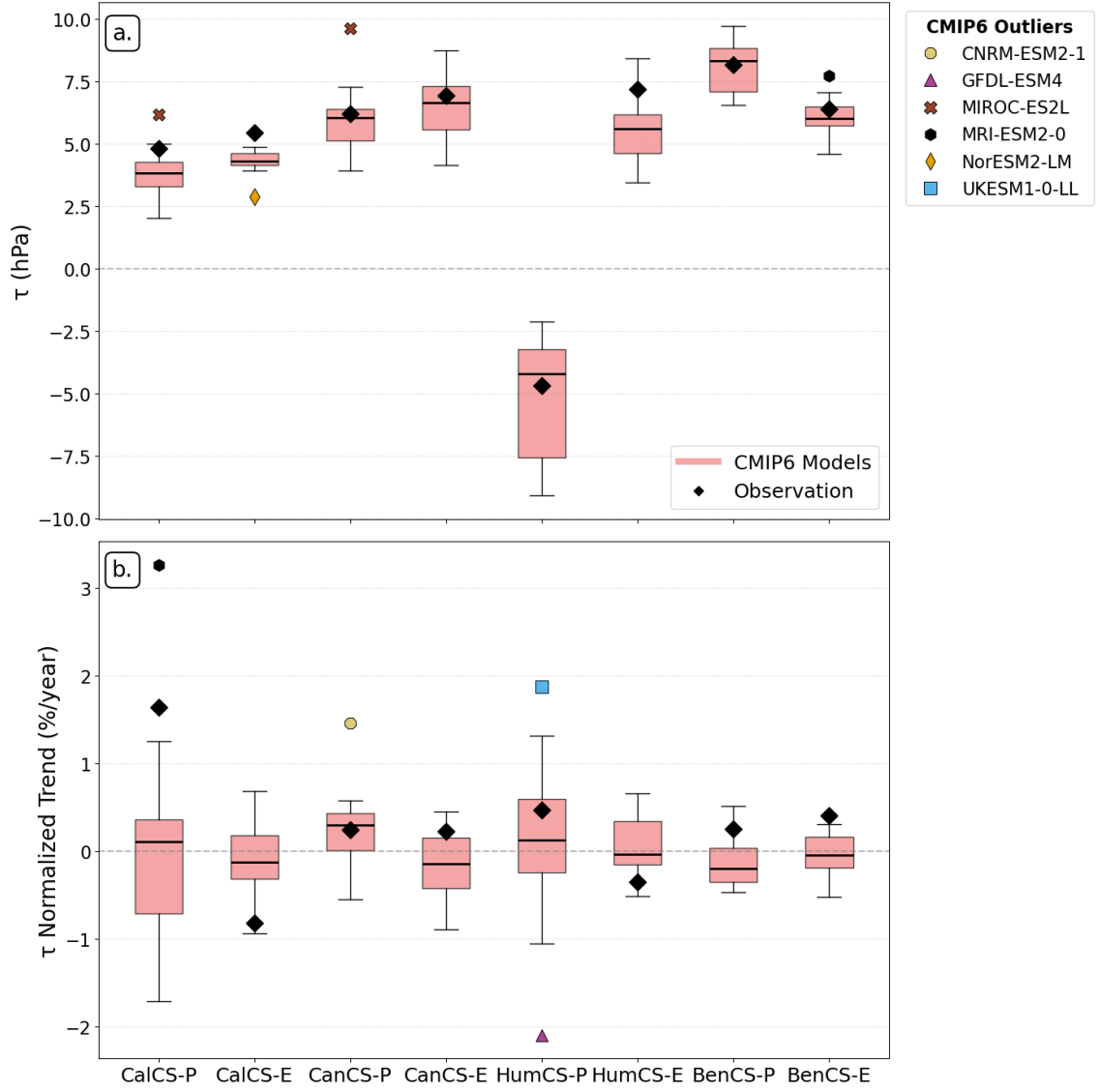


Figure S3: Box-and-whisker plots showing the distribution of historical (1998–2014) mean values (a) and trends (b) of surface equatorward wind across sub-EBUSs from ERA5 observations and CMIP6 models. Boxes represent the interquartile range (IQR), whiskers extend to $1.5 \times \text{IQR}$, and medians are shown as thick black lines. Observational estimates are indicated by black diamonds, colored markers show outliers in the CMIP6 ensemble.

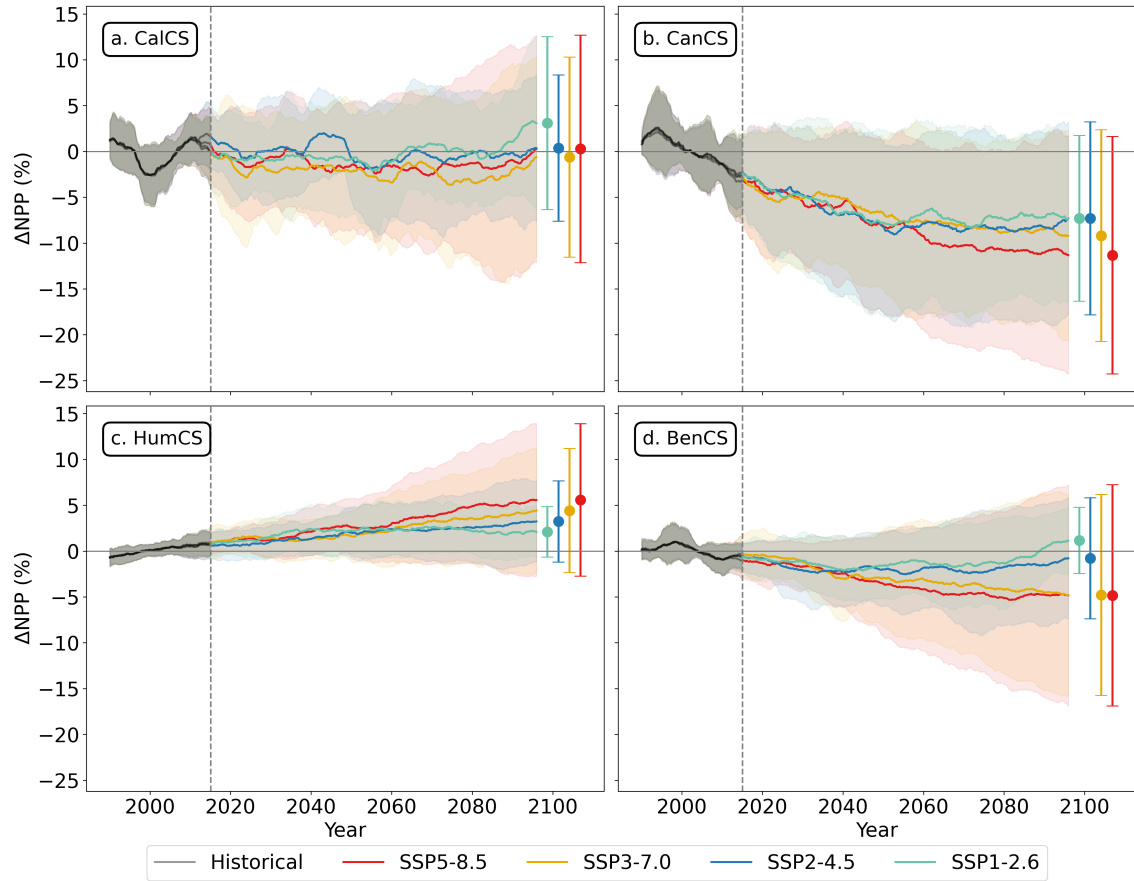


Figure S4: NPP projections using the full CMIP6 ensemble. Historical (1985-2014, grey) and projected (2015-2100, colored) relative change in NPP for different SSPs using the full CMIP6 ensemble (18 models for SSP5-8.5, 17 for SSP2-4.5, 15 for SSP3-7.0 and SSP1-2.6): ensemble means are indicated with solid lines, intermodel standard deviation with shaded regions. Colored vertical bars indicate, for each scenario, the intermodel standard deviation by the end of the century. A 10-years smoothing is applied.

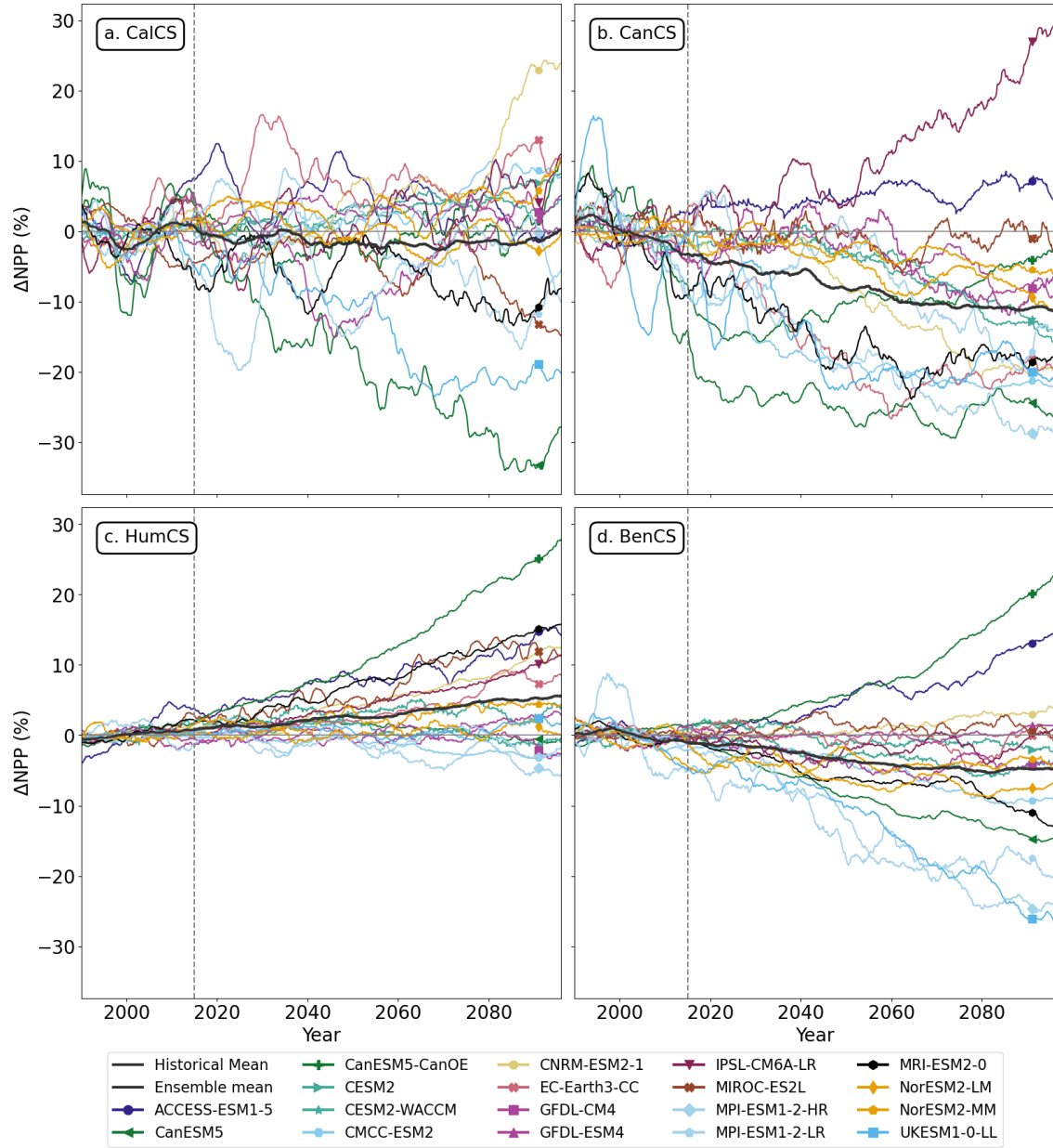


Figure S5: Historical (1985–2014) and projected (2015–2100) relative changes in NPP under SSP5-8.5 for individual models in EBUS. Ensemble means are shown as black lines. A 10-year smoothing is applied.

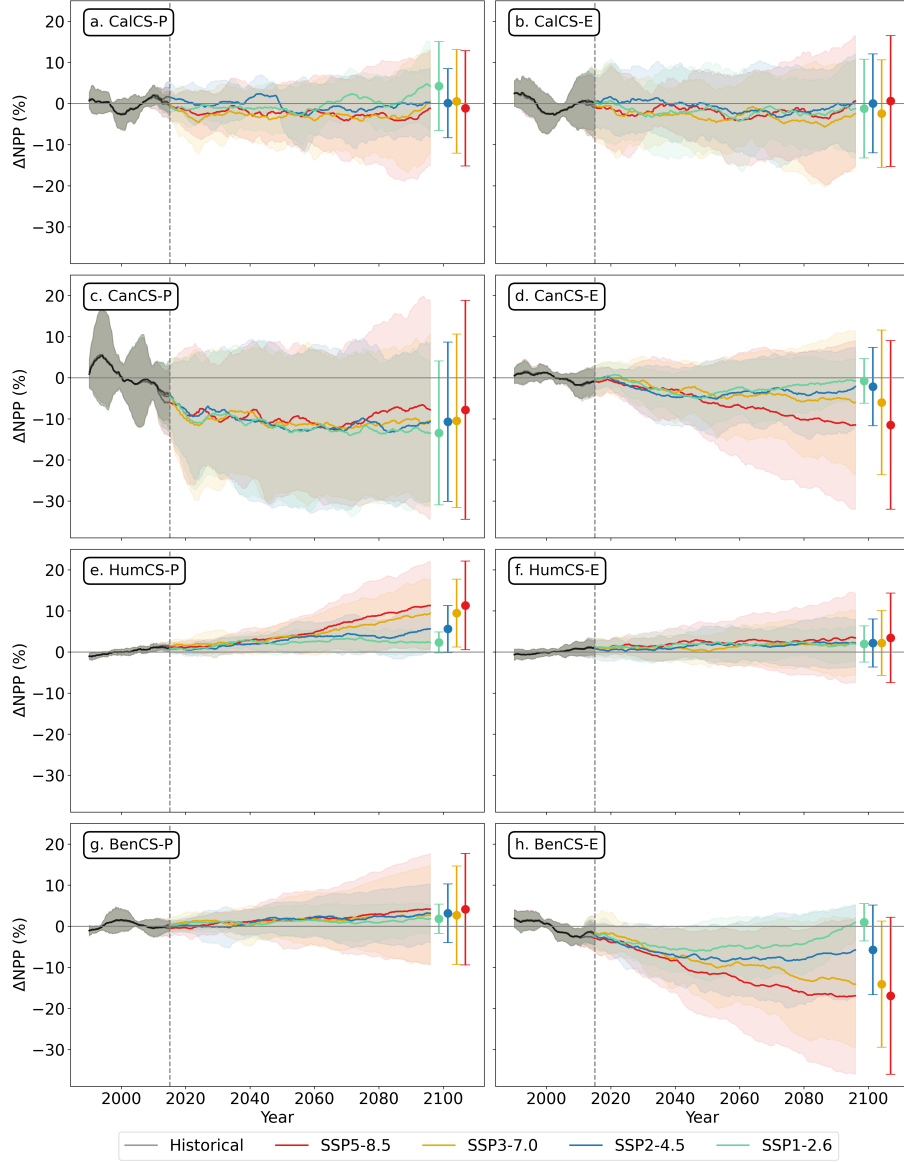


Figure S6: NPP projections in the sub-EBUS. Historical (1985-2014, grey) and projected (2015-2100, colored) relative change in NPP for different SSPs using the selected models from CMIP6 ensemble: ensemble means are indicated with solid lines, intermodel standard deviation with shaded regions. Colored vertical bars indicate, for each scenario, the intermodel standard deviation by the end of the century. A 10-year smoothing is applied.

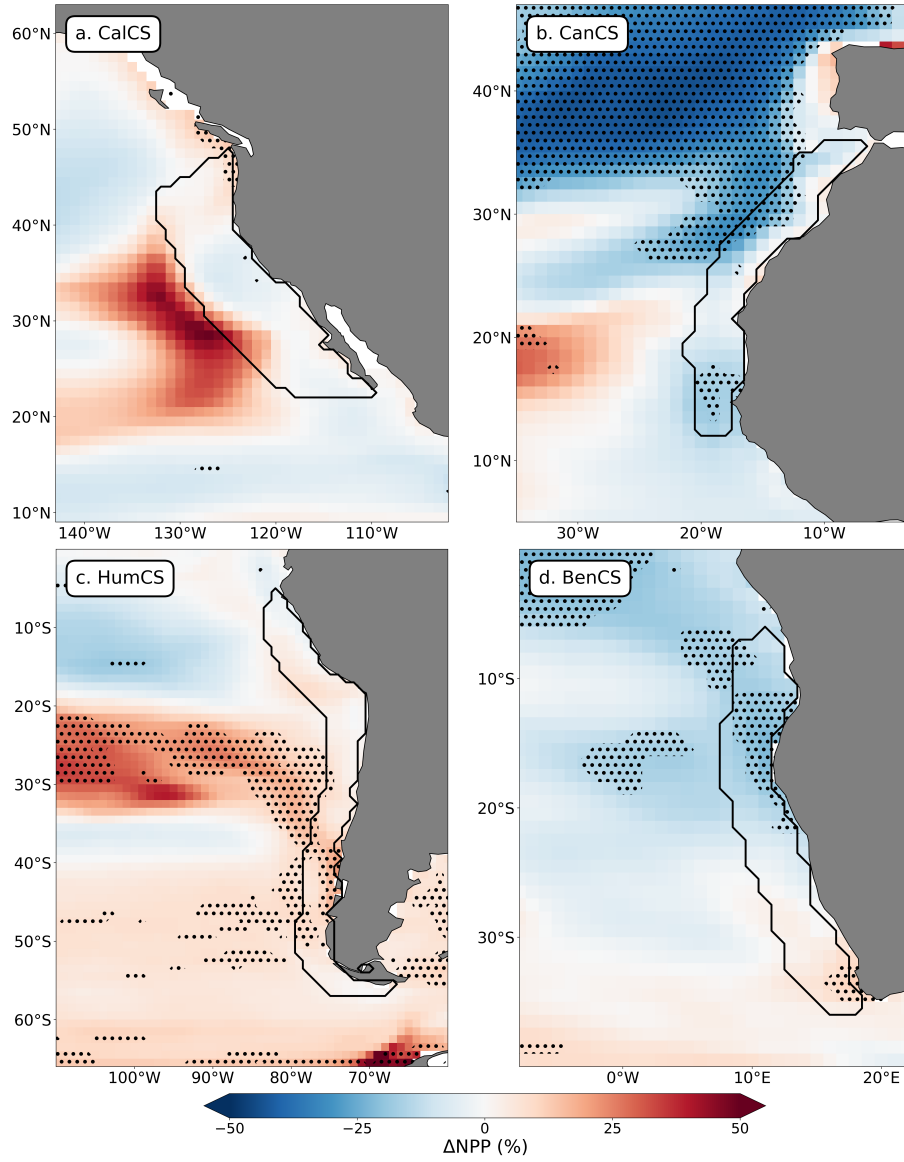


Figure S7: NPP anomalies in the full CMIP6 ensemble are comparable to projections from the selected ensemble. Ensemble mean (18 models) NPP anomalies (2071–2100 relative to 1985–2014) under SSP5-8.5 in the four eastern boundary upwelling systems. Stippling highlights areas of high model agreement.

SSP1-2.6

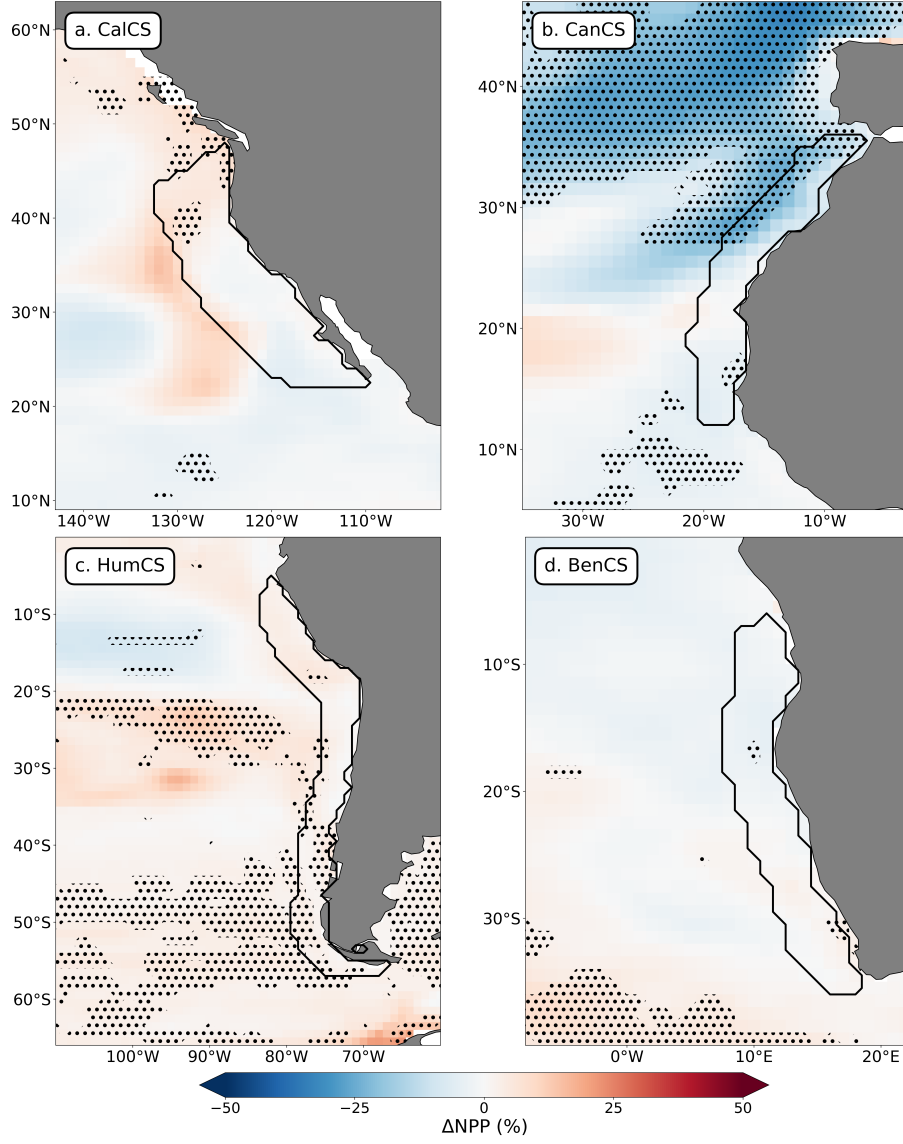


Figure S8: Consistent directions of NPP changes across SSPs. Ensemble mean NPP anomalies (2071–2100 relative to 1985–2014) under SSP1-2.6 (15 models) in the four eastern boundary upwelling systems. Stippling highlights areas of high model agreement.

SSP2-4.5

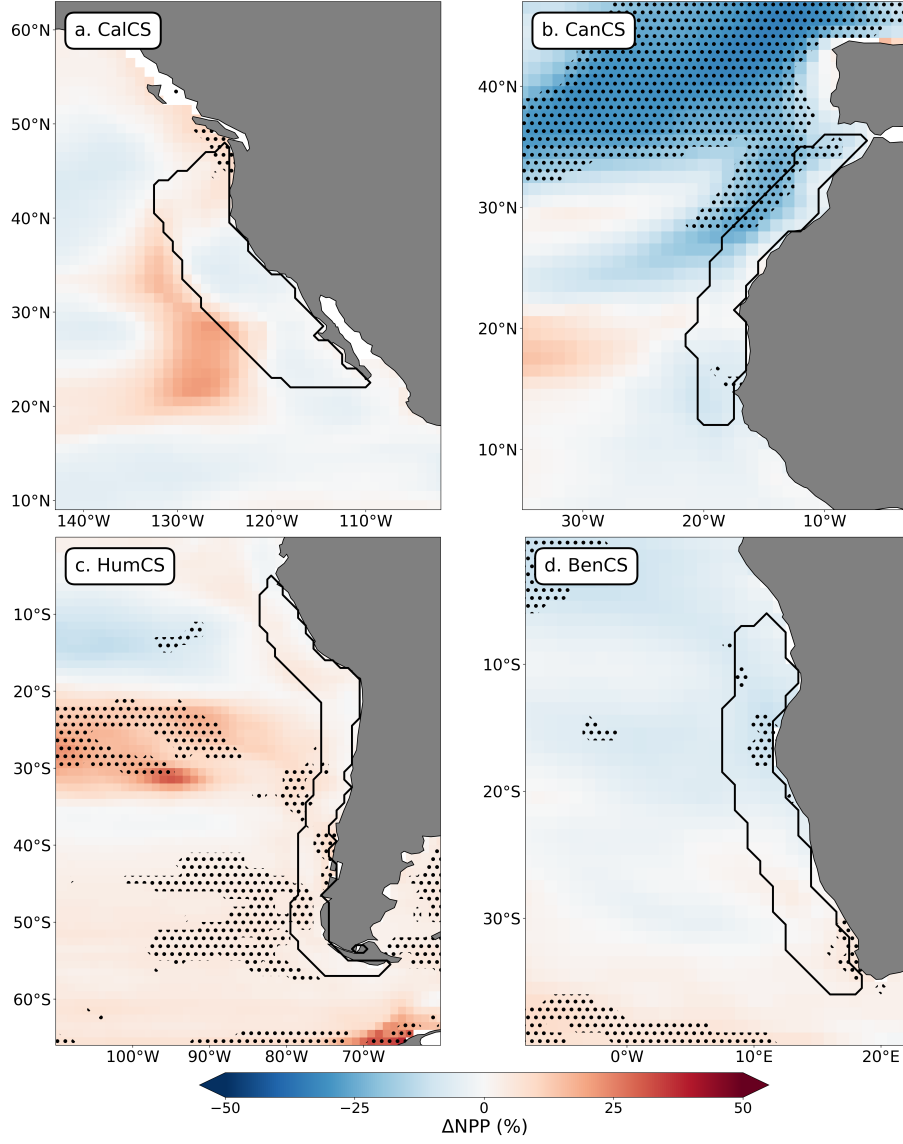


Figure S9: Consistent directions of NPP changes across SSPs. Ensemble mean NPP anomalies (2071–2100 relative to 1985–2014) under SSP2-4.5 (17 models) in the four eastern boundary upwelling systems. Stippling highlights areas of high model agreement.

SSP3-7.0

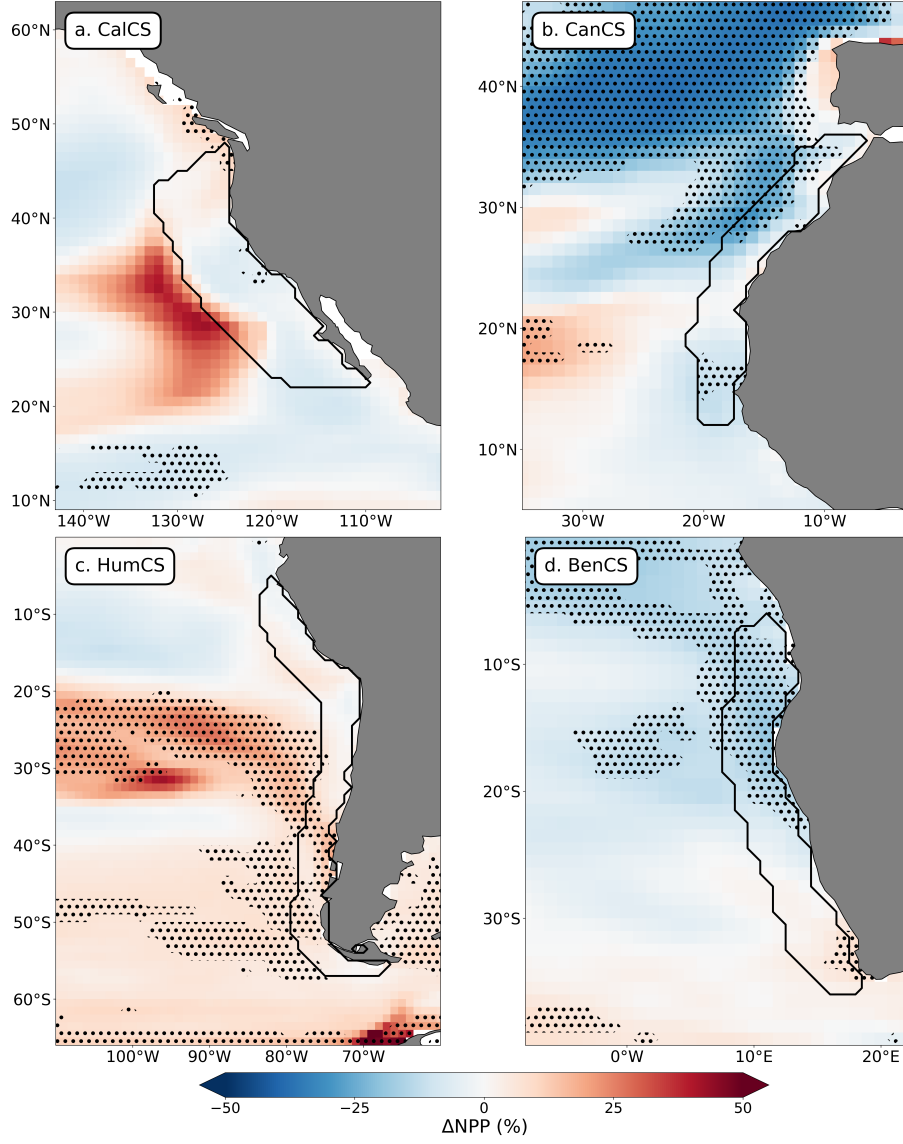


Figure S10: Consistent directions of NPP changes across SSPs. Ensemble mean NPP anomalies (2071–2100 relative to 1985–2014) under SSP3-7.0 (15 models) in the four eastern boundary upwelling systems. Stippling highlights areas of high model agreement.

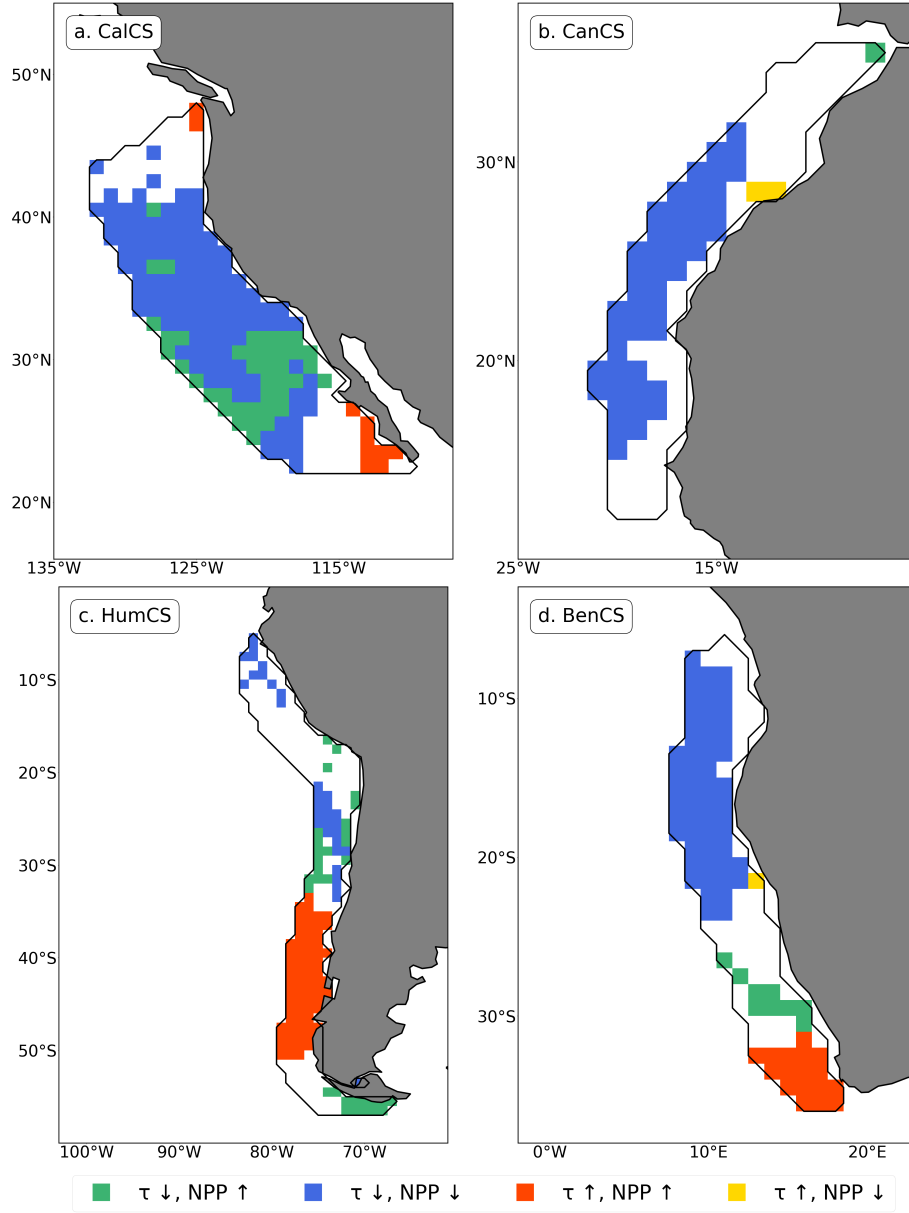


Figure S11: Summertime relationships between projected anomalies in τ_v and NPP are similar to yearly relationships. Signs of twenty-first century co-localized anomalies in summer τ_v and summer NPP under SSP5-8.5 (2071-2100). Grid cells are colored if there is $\geq 50\%$ model agreement.

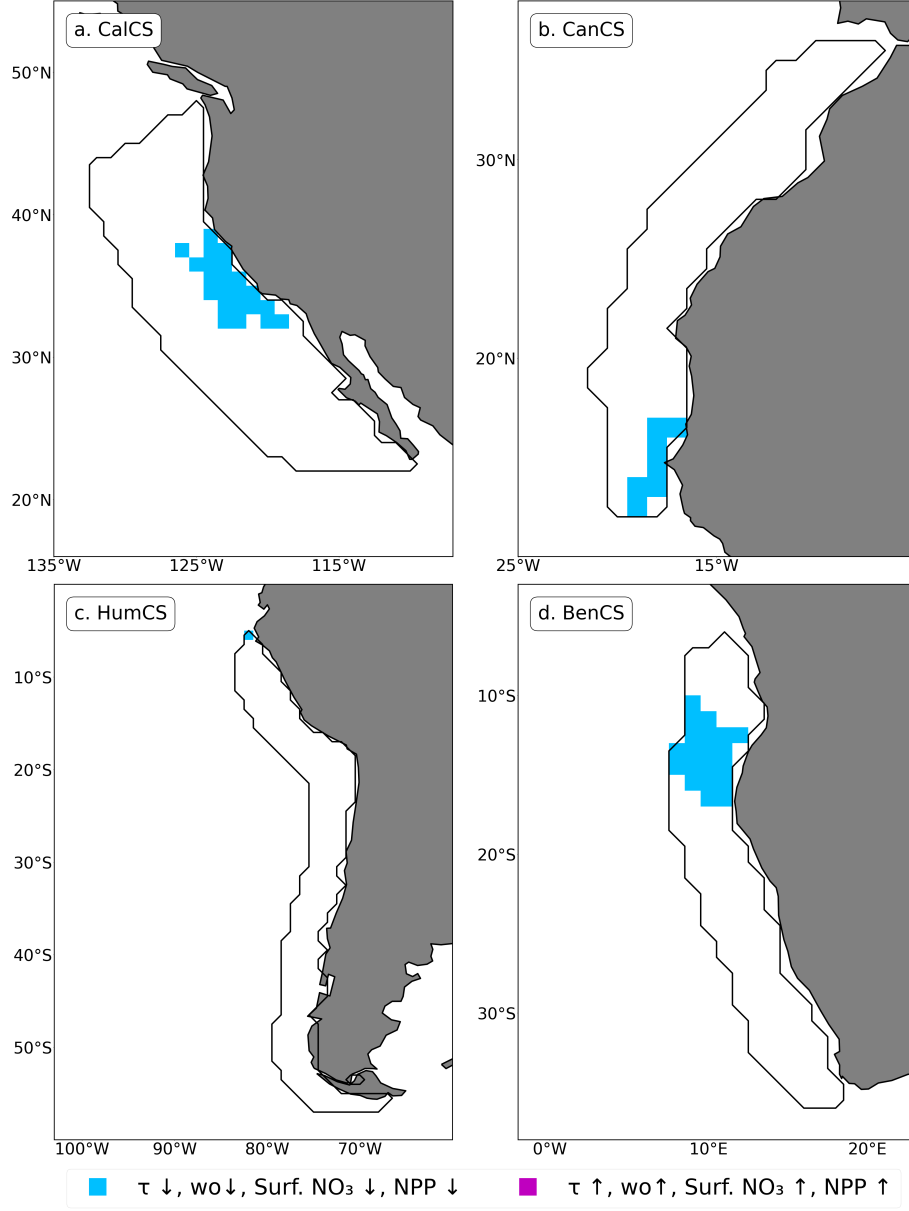


Figure S12: Consistent decreases of τ_v , w_{o60} , surface NO_3 , and NPP only in the equatorward portions of CanCS and BenCS and in a localized spot of CalCS. Signs of twenty-first century co-localized anomalies among key variables under SSP5-8.5 (2071–2100). Grid cells are colored if there is $\geq 50\%$ model agreement on the relationship between anomalies of τ_v , w_{o60} , surface NO_3 , and NPP combined.

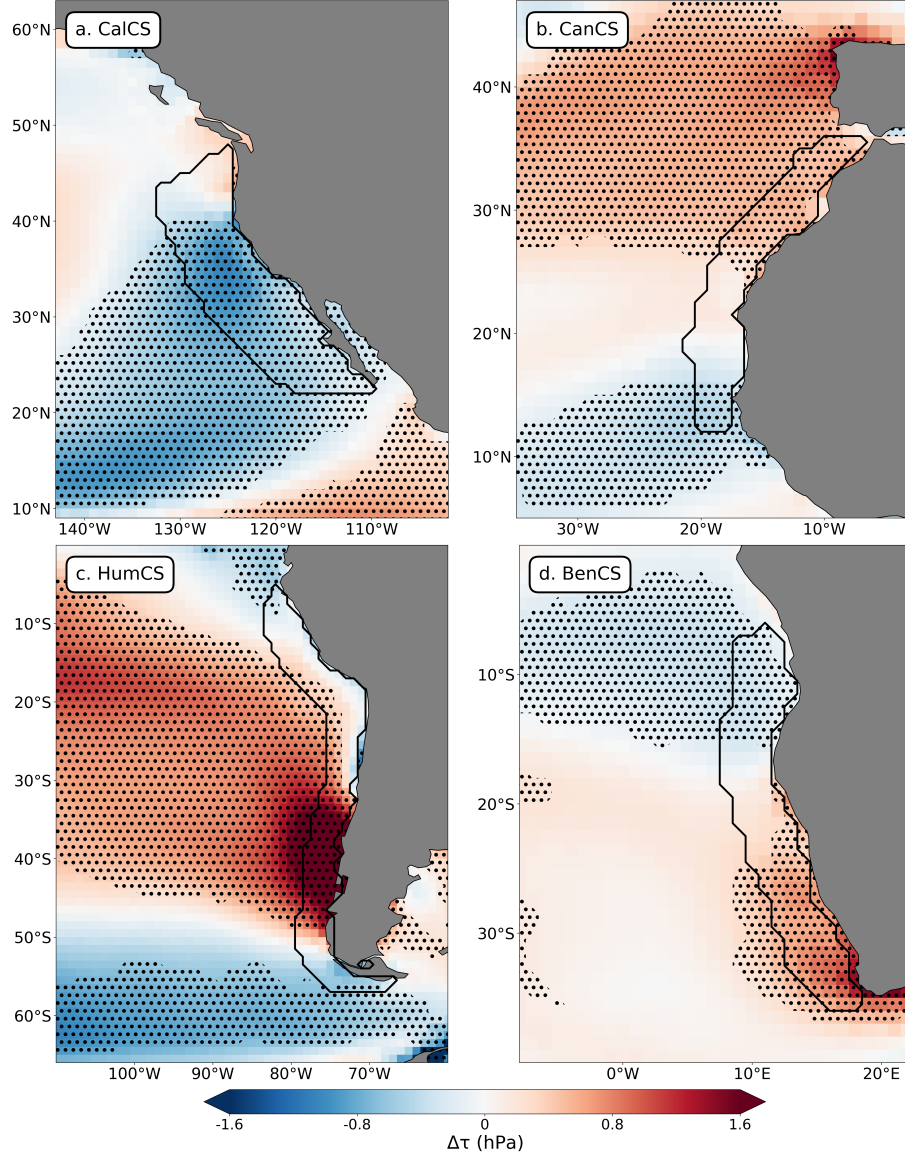


Figure S13: Meridional gradient of τ_v anomalies, strengthening poleward and weakening equatorward. Ensemble mean (13 models) τ_v anomalies (2071–2100 relative to 1985–2014) under SSP5-8.5 in the four eastern boundary upwelling systems. Stippling highlights areas of high model agreement.

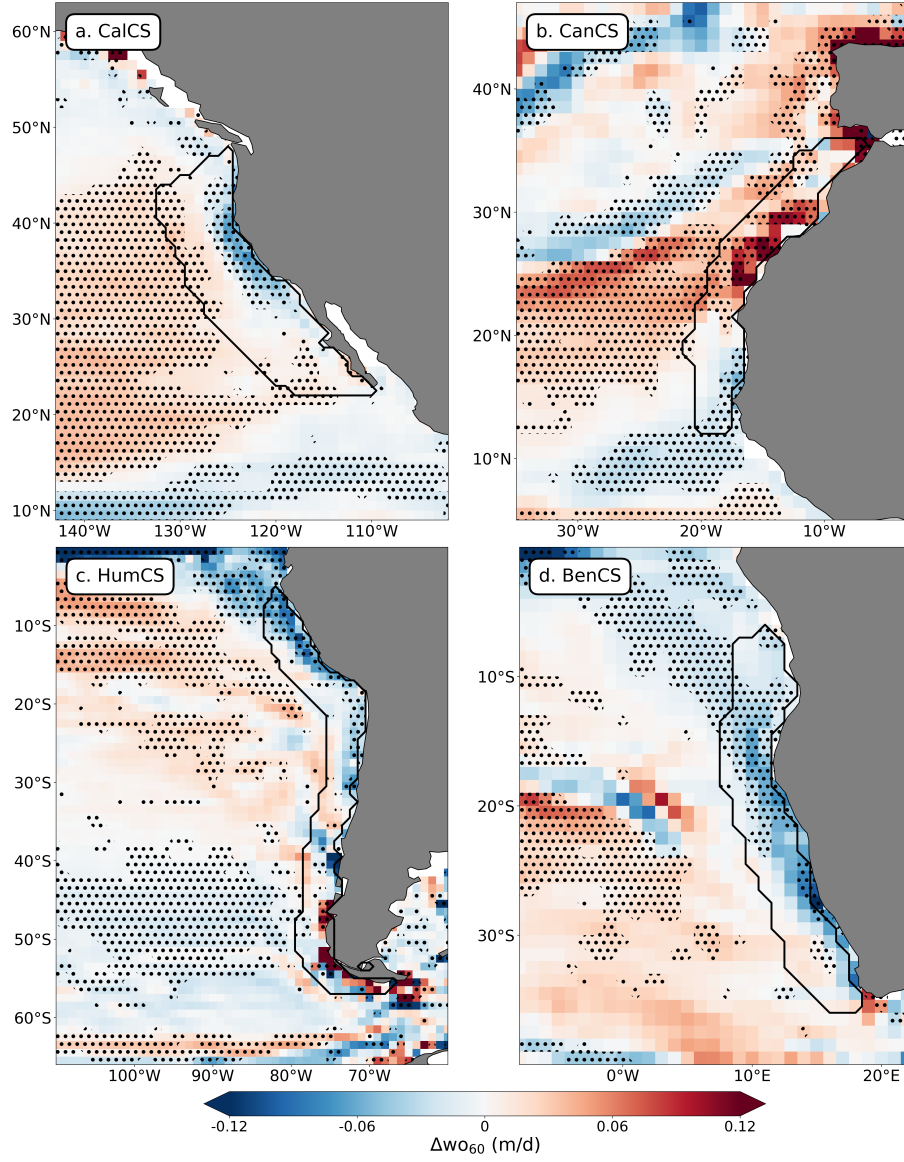


Figure S14: Projected changes in upward sea water velocity at 60 m. Ensemble mean (10 models) w_{o60} anomalies (2071–2100 relative to 1985–2014) under SSP5-8.5 in the four eastern boundary upwelling systems. Stippling highlights areas of high model agreement.

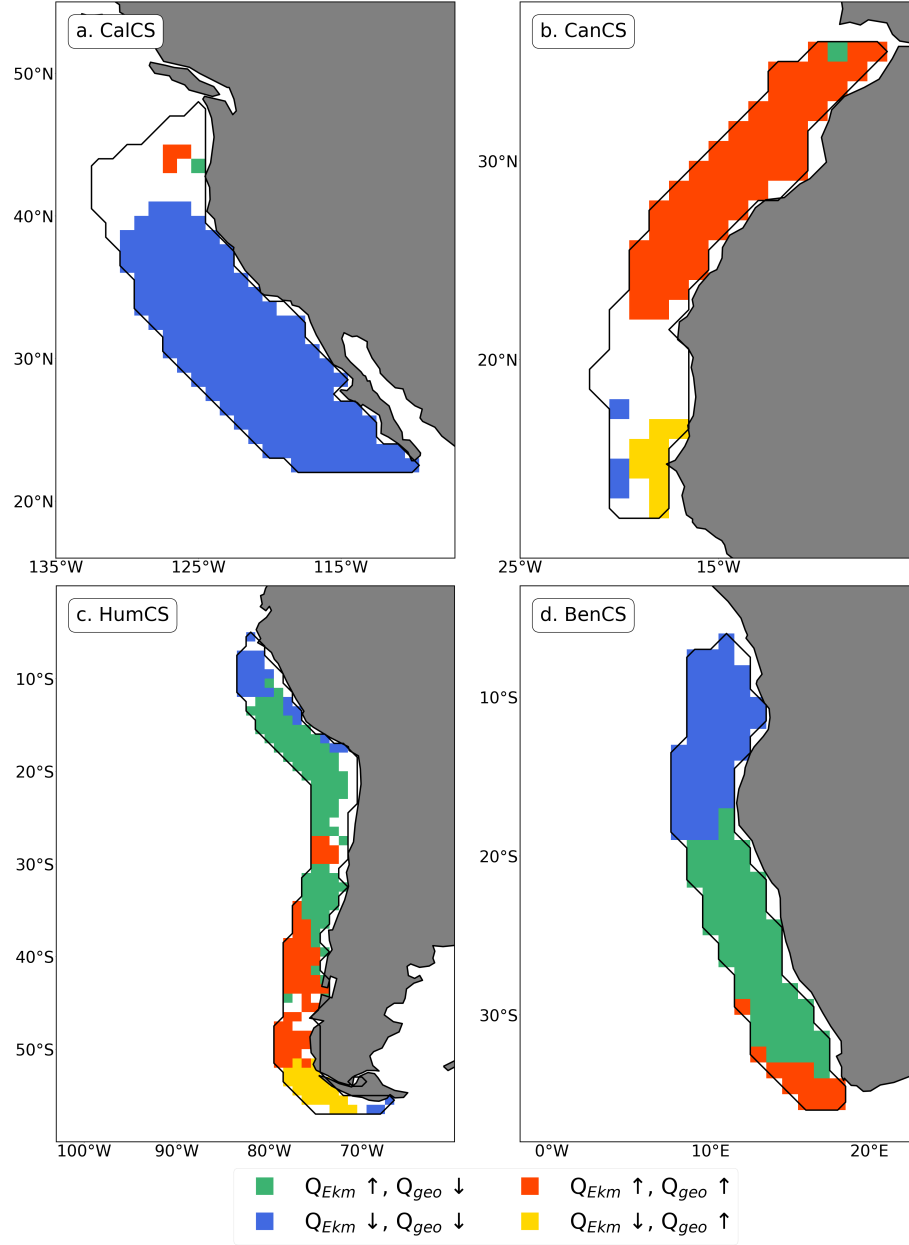


Figure S15: Ekman and geostrophic transport changes are reinforcing each other in some regions, offsetting in others. Signs of twenty-first century colocalized anomalies in Ekman and geostrophic transport under SSP5-8.5 (2071-2100). Grid cells are colored if there is $\geq 50\%$ model agreement.

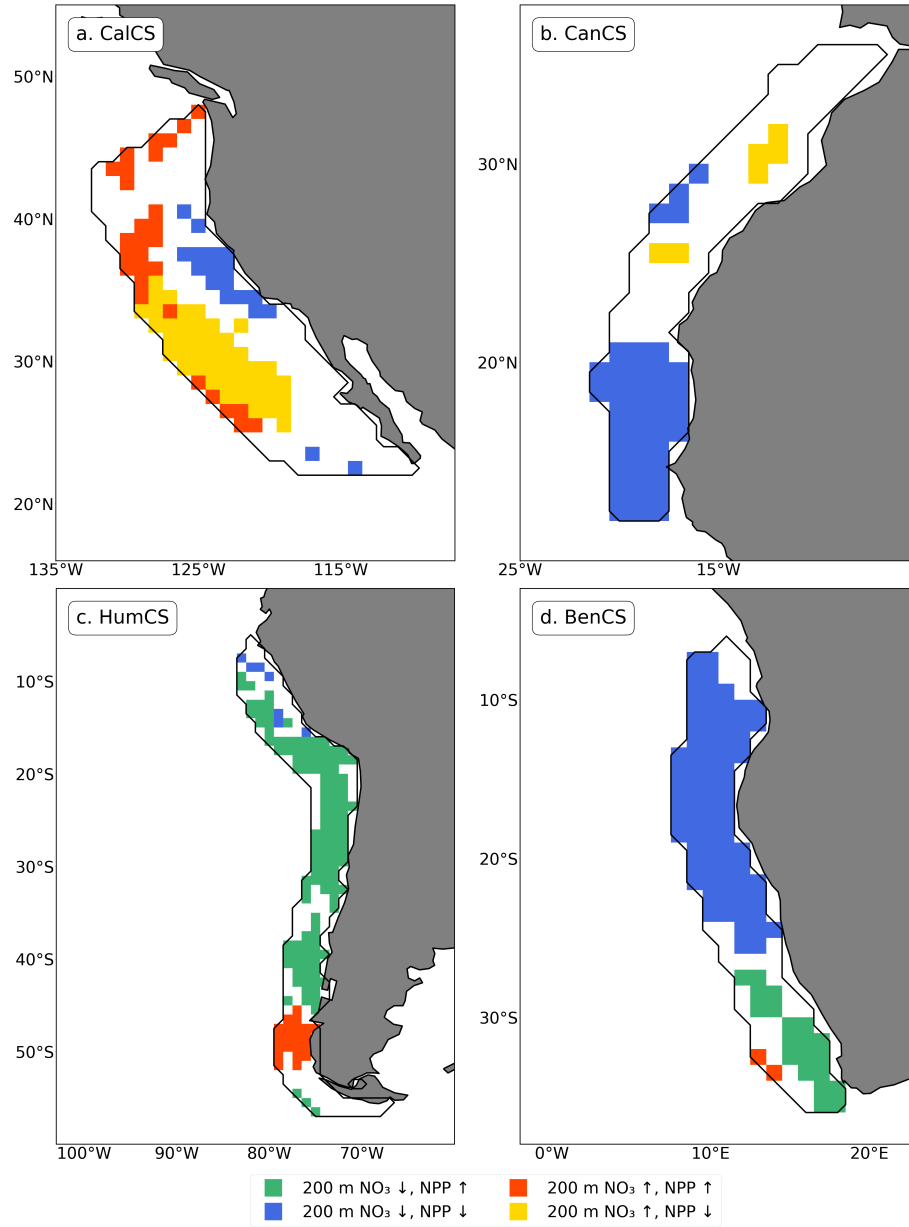


Figure S16: NPP and 200 m NO_3 change accordingly only in the equatorward areas of CanCS and BenCS and in the coastal spot between 30° N–40° N of CalCS. Signs of twenty-first century co-localized anomalies in NO_3 and NPP under SSP5-8.5 (2071-2100). Grid cells are colored if there is $\geq 50\%$ model agreement.

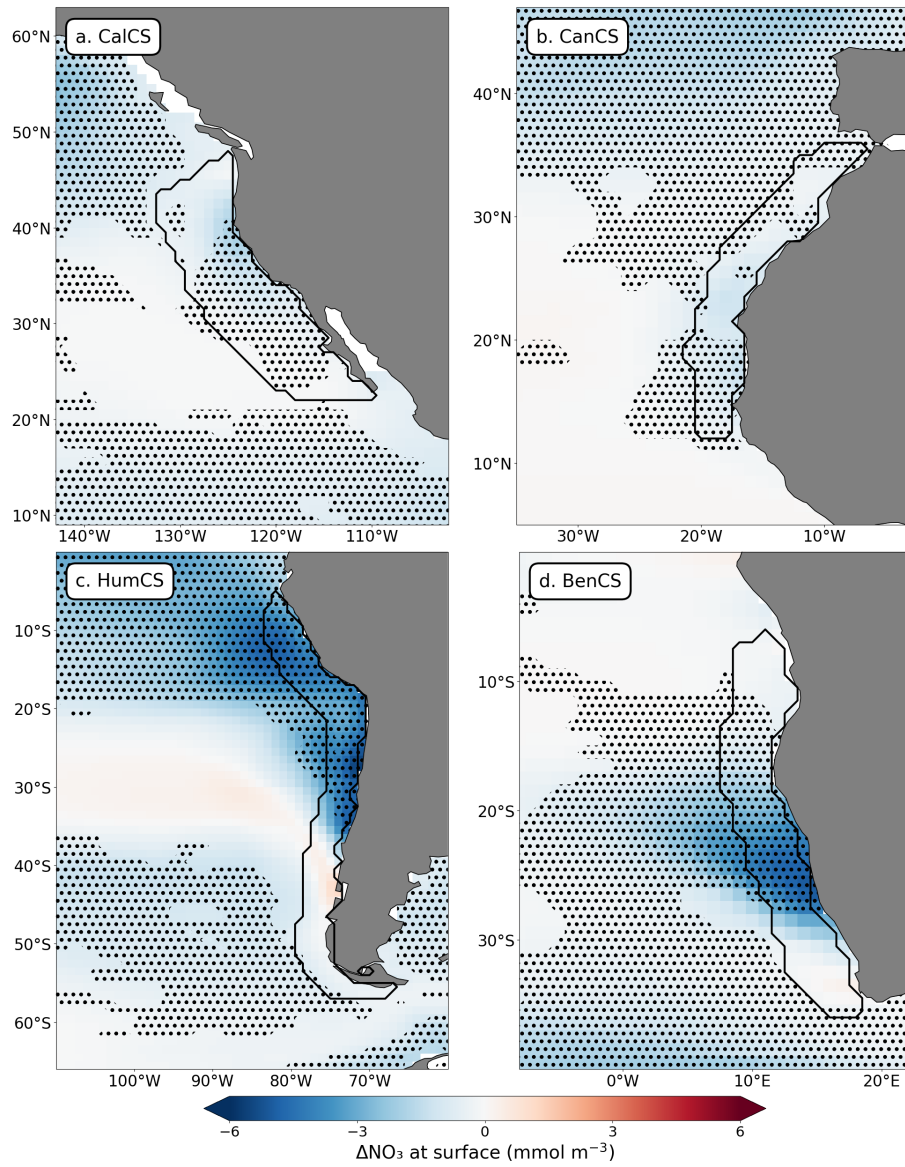


Figure S17: Ensemble mean (13 models) anomalies (2071–2100 relative to 1985–2014) of NO_3 concentrations at surface under SSP5-8.5 in the four eastern boundary upwelling systems. Stippling highlights areas of high model agreement.

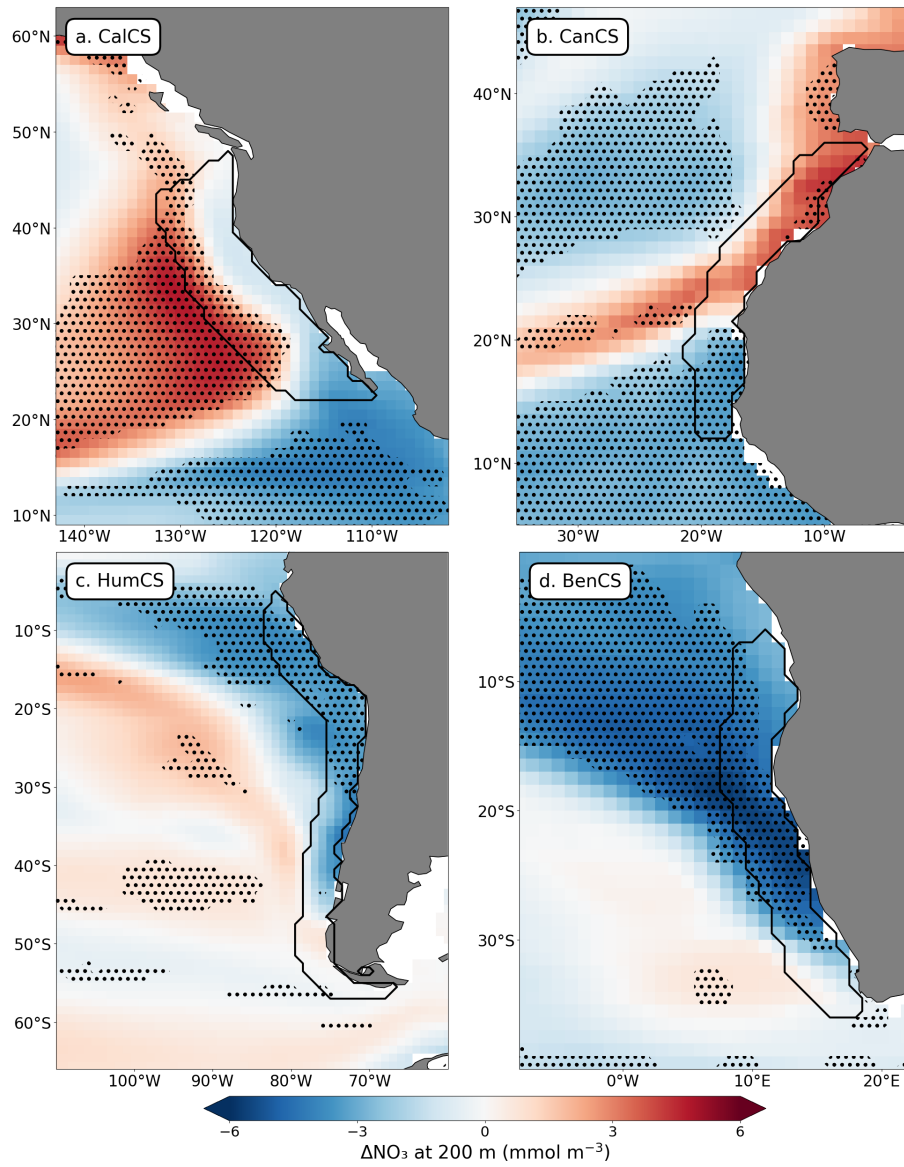


Figure S18: Ensemble mean (13 models) anomalies (2071–2100 relative to 1985–2014) of NO_3 concentrations at 200 m depth under SSP5-8.5 in the four eastern boundary upwelling systems. Stippling highlights areas of high model agreement.

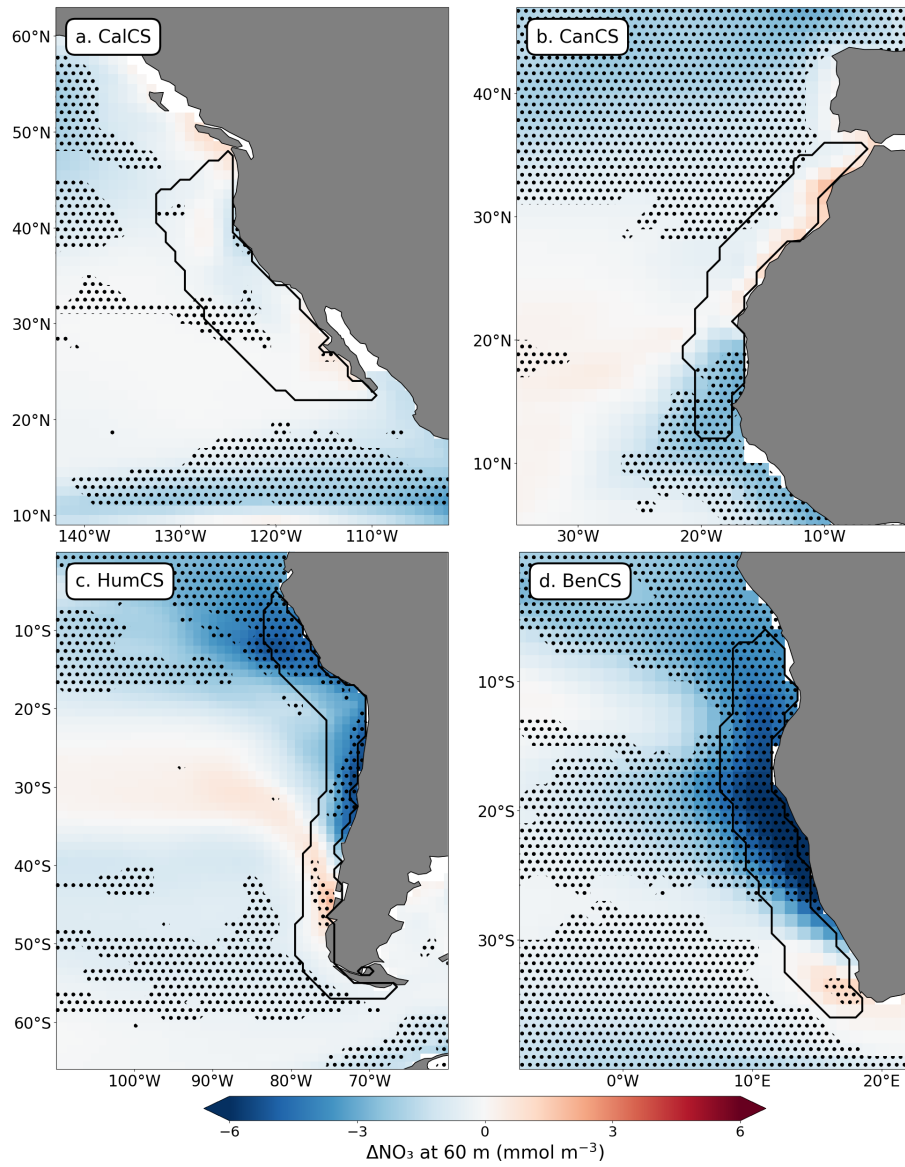


Figure S19: Ensemble mean (13 models) anomalies (2071–2100 relative to 1985–2014) of NO_3 concentrations at 60 m depth under SSP5-8.5 in the four eastern boundary upwelling systems. Stippling highlights areas of high model agreement.