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Global and Regional Marine Ecosystem Models Reveal Key Uncertainties in Climate Change Projections

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Abstract Climate change is affecting ocean temperature, acidity, currents, and primary production, causing shifts in species distributions, marine ecosystems, and ultimately fisheries. Earth system models simulate climate change impacts on physical and biogeochemical properties of future oceans under varying emissions scenarios. Coupling these simulations with an ensemble of global marine ecosystem models has indicated broad decreases of fish biomass with warming. However, regional details of these impacts remain much more uncertain. Here, we employ CMIP5 and CMIP6 climate change impact projections using two Earth system models coupled with four regional and nine global marine ecosystem models in 10 ocean regions to evaluate model agreement at regional scales. We find that models developed at different scales can lead to stark differences in biomass projections. On average, global models projected greater biomass declines by the end of the 21st century than regional models. For both global and regional models, greater biomass declines were projected using CMIP6 than CMIP5 simulations. Global models projected biomass declines in 86% of CMIP5 simulations for ocean regions compared to 50% for regional models in the same ocean regions. In CMIP6 simulations, all global model simulations projected biomass declines in ocean regions by 2100, while regional models projected biomass declines in 67% of the ocean region simulations. Our analysis suggests that improved understanding of the causes of differences between global and regional marine ecosystem model climate change projections is needed, alongside observational evaluation of modeled responses.

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Key Points:

- Global marine ecosystem models projected greater biomass declines with climate change than regional marine ecosystem models for many regions
- For both global and regional models, greater biomass declines were projected in CMIP6 than CMIP5 and in IPSL versus GFDL simulations
- Projected impacts of climate change on marine ecosystems at regional scales are currently less certain than at global scale

Supporting Information:

Supporting Information may be found in the online version of this article.

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Plain Language Summary Climate change is affecting the world's oceans, marine ecosystems, biodiversity, and the ecosystem services that they support, including fisheries that feed millions of people worldwide. Anticipating the impacts of climate change can help society and managers to prepare for, and adapt to, changes ahead. Present understanding of climate change impacts on the world's oceans based on global models indicates a 5% loss in animal biomass with every 1°C that the planet warms. Here, we compare potential future biomass on regional scales that are most relevant for management decisions about sustainable resource use. We used regional scale ecosystem models tailored to the species and fisheries they represent. We compared climate change projections of ocean biomass changes from these regional models to corresponding areas from global models to see how well they agreed. We found key differences in climate change projections of ocean biomass between global and regional models. In some cases, both global and regional models projected biomass declines, while in others global models suggested a decline and regional models an increase. Our study highlights that we need further exploration and understanding of the differences in ocean biomass change between global and regional marine ecosystem models.

1. Introduction

Oceans play a key role in regulating global climate (IPCC, 2023). Marine ecosystems and biodiversity provide a range of ecosystem services including livelihood opportunities, food provision, coastal protection, and carbon sequestration (IPBES, 2019). However, ocean ecosystems, marine biodiversity, and the ecosystem services they provide are compromised by anthropogenic climate change impacting water temperature, hydrodynamics, geochemistry, primary productivity, and species and community dynamics (IPBES, 2019; IPCC, 2023).

The United Nations IPCC assessment reports make use of standardized climate change projections from an ensemble of Earth system models (ESMs) through the coupled model intercomparison project (CMIP; Eyring et al., 2016). ESMs provide projections of many variables important for marine life, including sea surface temperature, oxygen, hydrodynamics, sea level, primary production, low trophic level biomass, among others (IPCC, 2023). By using an ensemble of ESMs, climate change projections are not dependent on any one model, and variation among model projections can be evaluated to determine the level of confidence for a given environmental variable (IPCC, 2023). For some variables, such as acidity, ensemble model agreement is very good; while others, such as sea surface temperature and primary production show much less agreement (Bopp et al., 2013; IPCC, 2023; Kwiatkowski et al., 2020). Understanding sources of uncertainty in model projections is a key research focus for climate and marine ecosystem modelers to help build confidence in climate change and impact projections (Cheung et al., 2016; Eddy, 2019; Payne et al., 2016).

Taking a similar approach to CMIP, the Fisheries and Marine Ecosystem Model Intercomparison Project (FishMIP) has developed standardized protocols to run climate change impact simulations for an ensemble of global and regional marine ecosystem models (MEMs; Blanchard et al., 2024; Tittensor et al., 2018). FishMIP models use outputs provided by CMIP ESMs to run climate change scenarios following shared socioeconomic pathways (SSPs) and representative concentration pathways (RCPs). Global FishMIP projections have been used to explore changes in marine animal biomass, evaluate the level of MEM agreement, and attribute sources of variability to MEMs, ESMs, SSP-RCPs, and fishing exploitation (Lotze et al., 2019). FishMIP projections suggest that marine animal biomass will, on average, decline by 17% by 2100 under a high emissions scenario (RCP 8.5) with CMIP5 forcing data (Lotze et al., 2019) and by 19% under CMIP6 (Tittensor et al., 2021). Other key findings are that with every 1°C that the planet warms, marine animal biomass is projected to decline by 5%, roughly in agreement with the average of observational estimates (Free et al., 2019), and that higher trophic levels are disproportionately impacted (Guibourd de Luzinais et al., 2023; Lotze et al., 2019; du Pontavice et al., 2021). While not all FishMIP models represent fishing, simulations with and without fishing produced similar magnitude and variability of the climate effect on marine ecosystems (Lotze et al., 2019). Equivalent amounts of variability in biomass projections were contributed by ESMs and MEMs, with variability increasing with higher emissions (Lotze et al., 2019). Compared to CMIP5 forced MEMs, CMIP6 forced MEMs projected regional differences in the direction of biomass changes, emphasizing the need to reduce uncertainty to support adaptation planning (Tittensor et al., 2021). Understanding regional marine ecosystem and fisheries dynamics is particularly important because many coastal communities are highly dependent on the nutrition and livelihoods they derive from the ocean (e.g., FAO, 2024).

Regional MEMs have often been developed to address fisheries, conservation, and management applications. In contrast to global models, regional models do not represent the entire ocean, and are generally forced by environmental variables representative of the regions being simulated. This is one of several differences in model detail between global and regional scale MEMs that has consequences for using global scale ESMs to force regional MEMs. One particularly important issue is that ESMs produce projections of physical and biogeochemical ocean properties at a coarse spatial resolution, typically on a 1° × 1° grid. A consequence of this spatial resolution is that physical and biogeochemical processes that drive primary productivity in coastal regions—where many nationally significant fisheries occur—are not well represented (FAO, 2024). For example, depths <50 m and key oceanographic processes that affect primary production, such as upwelling and dispersion of coastal nutrients, are poorly resolved (Bopp et al., 2013; Stock et al., 2011). This has implications for representation of marginal seas, such as the Baltic Sea (Niiranen et al., 2013) and the Mediterranean Sea (Coll et al., 2010), and shallow underwater plateaus such as The Grand Banks of Newfoundland (Laurent et al., 2021). In Australia, discrepancies in projections from global and regional MEMs for the same regions have been observed, not just in terms of the magnitude of effects but also in the direction of change (Pethybridge et al., 2020). As there is a need to provide projections of climate change impacts at regional scales for fisheries adaptation and mitigation planning, regional MEM ensembles that allow quantification of across-model uncertainty are lacking for most regions of the world (Metcalfe et al., 2015). In this absence, the FishMIP global ensemble has been used to fill in the gap (Blanchard et al., 2017; Blanchard & Novaglio, 2024; Cinner et al., 2022). Understanding how global marine ecosystem models perform at regional scales is important as many resource constrained jurisdictions do not have the capacity to generate their own regional specific models (Barange et al., 2014; Blanchard et al., 2017; Boyce et al., 2020; Cinner et al., 2022).

Most global FishMIP models agree in the projected direction of change in fish production for specific climate model and emissions scenarios, albeit with regional differences (Heneghan et al., 2021; Lotze et al., 2019; Tittensor et al., 2021). However, models at regional scales can project the opposite direction of change (Barange et al., 2014; Pethybridge et al., 2020). Previous FishMIP studies have analyzed variability in climate change projections of marine animal biomass as a function of: ESM (Geophysical Fluid Dynamics Laboratory Earth System Model—GFDL or Institute Pierre Simon Laplace Climate Model—IPSL); global MEM (ensemble of six or nine; Lotze et al., 2019; Tittensor et al., 2021); and SSP-RCP scenario (four scenarios or two scenarios; Lotze et al., 2019; Tittensor et al., 2021). The impact of fishing (Lotze et al., 2019) and the difference between CMIP5 and CMIP6 projections have also been investigated (Tittensor et al., 2021). What remains unknown is how climate change projections by FishMIP global MEMs compare with regional MEMs at regional scales. In this study, we explore variability in climate change projections of ocean biomass as a function of: Earth system model (ESM; GFDL vs. IPSL); marine ecosystem model (MEM; ensemble of 13); marine ecosystem model spatial scale (global or regional); and couple model intercomparison project generation (CMIP5 vs. CMIP6) in 10 regions. We evaluate the agreement in projections of global MEMs with regional MEMs at regional scales and explore causes of disagreement.

2. Methods

2.1. FishMIP Model Ensemble

FishMIP provides a standardized approach to compare climate change projections among MEMs of varying structure, assumptions, and spatial scale (Blanchard et al., 2024; Eddy, 2019; Heneghan et al., 2021; Novaglio et al., 2024; Tittensor et al., 2018). MEMs differ in how they are structured—whether biomass or carbon based, structured by size, trophic level, species or functional group (Tittensor et al., 2018). Global MEMs are based on general ecological theory and principles, are spatially resolved, and have become a major modeling focus within the last decade (Table 1). Regional models generally represent more trophic interactions, are fit to local ecological survey and fisheries data, may or may not be spatially resolved, and have had a long history of development and refinement, originating 40 years ago (Polovina, 1984). Regional models generally include more feedback processes and the system specific ecological idiosyncrasies that add complexity and richness to regional ecosystems around the globe (Table 1).

Table 1
Global and Regional FishMIP Models With Key Characteristics

Model	Spatial scale	Class	CMIP5	CMIP6	Key forcing variables used	Taxonomic scope	Reference
APECOSM (Apex predators ECOSystem model)	Global	Composite (size- and trait-based; functional group structure)	X	X	Carbon concentrations (small phytoplankton, large phytoplankton, small zooplankton, large zooplankton), particulate organic matter (small and large), zonal and meridional currents, turbulent mixing, temperature, water density, dissolved oxygen concentration, light irradiance. All fields 3D and monthly	Sized-based communities (epipelagic, migratory, mesopelagic, bathypelagic) and focus species	Maury (2010)
Atlantis	Regional	Composite (hybrid)	X	X	NPP, SST, pH currents, dissolved oxygen concentration, salinity	All trophic levels and taxonomic groups can be represented using a mix of biomass pools and age structured populations	Fulton et al. (2011)
BOATS (Bioeconomic Marine Trophic Size-spectrum)	Global	Size-based	X	X	Mean temperature 0–75 m, NPP	All commercially fished species, both finfish and invertebrates	Carozza et al. (2016)
DBEM (Dynamic Bioclimate Envelope Model)	Global	Species distribution model	X	X	Surface and bottom O2, pH, salinity and temperature. Ice cover, current velocity, NPP, NPP pico and NPP diat. All variables on a yearly basis	956 species of exploited fishes and invertebrates	Cheung et al. (2010)
DBPM (Dynamic Benthic Pelagic Model)	Global	Composite (size- and trait-based)	X	X	Surface and bottom temperature, phytoplankton carbon groups	All benthic and pelagic marine animals weighing between 1 mg and 1 tonne	Blanchard et al. (2012)
EcoOcean	Global	Composite (trophodynamic and species distribution model)	X	X	SST, seafloor temperature, column average temperature, phytoplankton carbon groups	Includes 51 functional groups representing the whole spectrum of marine organisms from bacteria to whales, and integrates explicit information for 3,400 species of vertebrates, invertebrates and primary producers	Christensen et al. (2015) and Coll et al. (2020)
Ecopath with Ecosim	Regional	Trophodynamic (if Ecospace included also composite with species distribution model included)	X	X	NPP, bottom O2, SST	All trophic levels and taxonomic groups can be represented, including age structured groups	Christensen and Walters (2004) and Christensen et al. (2014)
EcoTroph	Global	Trophic-level based		X	NPP, SST, integrated mesozooplankton carbon	Implicitly all groups, including pelagic and demersal fishes and invertebrates	Gascuel et al. (2011) and du Pontavice et al. (2021)

Table 1
Continued

Model	Spatial scale	Class	CMIP5	CMIP6	Key forcing variables used	Taxonomic scope	Reference
FEISTY	Global	Composite		X	Seafloor temperature, seafloor detritus flux, mean temperature 0–100 m, integrated mesozooplankton carbon 0–100 m	Small pelagic fish, large pelagic fish, demersal fish, benthic invertebrates	Petrik et al. (2019)
Macroecological	Global	Size-based	X	X	NPP, SST	Implicitly all marine organisms from 1 g to 1 tonne	Jennings and Collingridge (2015)
mizer	Regional	Size-based		X	Vertically integrated, size-fractionated phytoplankton and zooplankton carbon, ocean temperature	Single plankton community, species-specific fish	Scott et al. (2014)
OSMOSE	Regional	Composite (size- and trait-based)	X		SST, SSS, NPP, phytoplankton and zooplankton concentration	Fish and invert species and functional groups	Shin and Cury (2004) and Travers et al. (2009)
ZooMSS	Global	Composite (size- and trait-based; functional group structure)	X	X	Chlorophyll-a, SST	Flagellates, cilliates, omnivorous copepods, carnivorous copepods, larvaceans, salps, chaetognaths, euphausiids, jellyfish, fish	Heneghan et al. (2020)

Note. CMIP5 and CMIP6 indicate which models participated in each simulation round. Adapted from Tittensor et al., 2021; Tittensor et al., 2018.

2.2. Global & Regional MEMs

We analyzed regional MEM projections for seven regions in CMIP5 and five regions in CMIP6, with 10 regions represented in total (two regions with both CMIP5 and CMIP6 simulations; Figure 1). Regions were selected based on regional models that participated in FishMIP simulation protocols (Tittensor et al., 2018; fishmip.org). Global ESMs and MEMs are often not well resolved in coastal regions compared to regional models and therefore even though the spatial domains used were identical, the ecosystems represented may differ (Figure 1; Tables 1 and 2). For this reason, not all regions included in this study have all global MEM simulations.

An important difference between global and regional model development is that regional models are often forced with one or more time series of: fishing mortality or effort by species or fishery, oceanographic flows that capture current patterns, net primary productivity (NPP), temperature, salinity, pH, nutrient and other inflow from coastal sources, and are fit to independent, historical observational data such as fisheries catch data and/or biomass survey data for individual species (Table 1). These observational data sets are often not available at the global scale, which limits the calibration process for global MEMs. As ESM hindcasts do not always match observations at regional scales, all regional MEMs employed bias correction using the delta method to maintain calibration (Schoeman et al., 2023; Table 2) or statistical or dynamical downscaling of ESM outputs (Coll et al., 2024; Oliveros-Ramos et al., 2023). This introduced variation in how global and regional models performed climate change simulations, affecting the magnitude of projected biomass. For this reason, we report relative changes in biomass.

2.3. FishMIP Simulation Protocol

FishMIP simulations followed a standardized protocol that used ESM output variables as MEM input variables and the same fisheries scenarios to simulate climate change (Blanchard et al., 2024; Frieler et al., 2017, 2024; Tittensor et al., 2018; Figure S1 in Supporting Information S1; Tables 1 and 2). FishMIP simulations were designed to align with the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) 2 and 3b protocols corresponding to CMIP5 and CMIP6 simulation rounds, respectively (Frieler et al., 2017, 2024). In both protocols, MEM

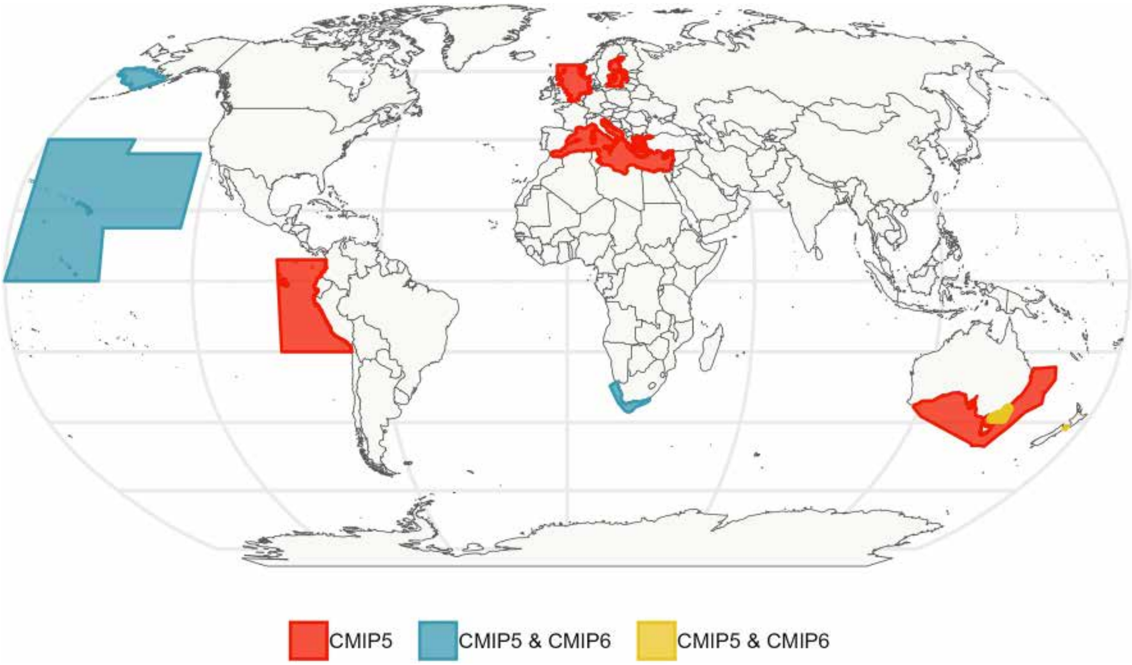

Figure 1. Location of FishMIP regional model domains that completed CMIP5, CMIP6, and both CMIP5 & CMIP6 simulations. From left to right, regions are: Hawaii, Eastern Bering Sea, Humboldt Current, North Sea, Mediterranean Sea, Baltic Sea, Southern Benguela, Southeast Australia, East Bass Strait, and Cook Strait.

simulations were run from 1950 to 2100 using climate and oceanographic conditions from two ESMs (GFDL-ESM2M for CMIP5 and GFDL−ESM4 for CMIP6, collectively referred to as GFDL; and IPSL-CM5A-LR for CMIP5 and IPSL−CM6A−LR for CMIP6, collectively referred to as IPSL), under four emissions scenarios (RCP2.6/SSP1-2.6, RCP4.5/SSP2-4.5, RCP6.0/SSP4-6.0, RCP8.5/SSP5-8.5; Blanchard et al., 2024; Frieler et al., 2024; Tittensor et al., 2018).

For this analysis, we used no-fishing simulations as most global models do not represent fishing and did not run fishing simulations. We focussed on the RCP8.5/SSP5-8.5 high emissions scenario as the impacts of emission scenario have been previously explored for CMIP5 and CMIP6 (Lotze et al., 2019; Tittensor et al., 2021). While considering a broader set of scenarios would be ideal, it was not possible in this instance as only the RCP8.5/SSP5-8.5 had been run by all models. Extending to another scenario was unfortunately not feasible due to computational intensity and capacity as FishMIP and ISIMIP are largely volunteer contributions unlike CMIP. The high emissions scenario samples a large range of global warming, and as many impacts scale approximately with global warming, impacts under a low scenario may be similar to, just smaller than, a high scenario. For example, if 2.0°C is reached earlier in RCP8.5 than in RCP4.5, RCP8.5 might still give a fair estimate of the impacts of 2.0°C, irrespective of when it is reached. However, the rates of change between these scenarios need to be considered, as they can lead to different ecosystem consequences. FishMIP models simulated climate change scenarios by incorporating relevant outputs from ESMs as MEM forcing variables, such as temperature, primary productivity, phytoplankton biomass, zooplankton biomass, acidity, oxygen concentration, and water velocities (Tables 1 and 2; Figures 2 and 3).

2.4. Model Comparisons

We used regional model spatial domains to subset global model simulation output for corresponding grid cells, such that the geographical domains were identical (https://github.com/Fish-MIP/Regional_v_Global). Following previous FishMIP studies (Lotze et al., 2019; Tittensor et al., 2021), for each combination of CMIP, ESM, MEM, and region, we calculated the percent change in total consumer biomass (all consumers of trophic level >1, vertebrates and invertebrates) for 2090–2099 relative to 1990–1999. To evaluate model agreement among global and regional scale models in each region, we calculated the proportion that the regional model time series projection fell within the range of the global model ensemble, the root mean squared error (RMSE), and Spearman correlation.

Table 2
Regions and Regional Marine Ecosystem Models (MEMs) Investigated in This Study With Key Characteristics

Region	Model	Domain area (km^2)	Spatial resolution	Forcing variables for regional models	Bias correction method applied	Reference
Baltic Sea	Ecopath with Ecosim	240,000	No	intpp, tos, bottom O2	Delta	Niiranen et al. (2013)
Cook Strait, New Zealand	Ecopath with Ecosim	54	No	intpp	Delta	Eddy et al. (2014)
East Bass Strait, Australia	Ecopath with Ecosim	30,623	No	intpp	Delta	Bulman et al. (2006)
Eastern Bering Sea	mizer	493,506	No	phydiat-vint; phydiaz-vint; phypico-vint; zmeso-vint; zmicro-vint; tos	Delta	Reum et al. (2024)
Hawaii	therMizer	19,694,991	No	phydiat-vint; phydiaz-vint; phypico-vint; zmeso-vint; zmicro-vint; tos	Delta	Woodworth-Jefcoats et al. (2019)
Humboldt Current	OSMOSE	4,949,170	Yes	intpp, phydiat, zmeso-vint, zmicro-vint, tos	Statistical downscaling	Oliveros-Ramos et al. (2017)
Mediterranean Sea	Ecopath with Ecosim	2,500,000	Yes	intpp; thethao		Piroddi et al. (2017)
North Sea	Ecopath with Ecosim	570,000	No	intpp	Delta	Mackinson and Daskalov (2007)
Southeast Australia	Atlantis	3,000,000	Yes	thetao, O2, intpp		Fulton et al. (2018)
Southern Benguela	Atlantis; Ecopath with Ecosim	220,000	Yes; no	intpp; thetao	Delta	Ortega-Cisneros et al. (2017) Shannon et al. (2020)

Note. Forcing variables are: intpp, net primary organic carbon production by all types of phytoplankton; thethao, sea water potential temperature; phydiat, concentration of diatoms expressed as carbon in sea water; phydiaz, concentration of diazotrophs expressed as carbon in sea water; phypico-vint, mole concentration of picophytoplankton expressed as carbon in sea water; zmeso-vint, concentration of mesozooplankton expressed as carbon in sea water; zmicro-vint, concentration of microzooplankton expressed as carbon in sea water, tos, sea surface temperature.

2.5. Drivers of Biomass Change

To explore relationships between ESM environmental forcing variables and MEM total consumer biomass, for each region, model, and year combination, we calculated change in SST and NPP (relative to 1990–1999) to compare with the corresponding change in total consumer biomass (relative to 1990–1999). For each model, we calculated the amount of variation in delta total consumer biomass that was explained by delta NPP or delta SST.

3. Results

3.1. Climate Forcing Variable Projections

3.1.1. Sea Surface Temperature

For both CMIP5 and CMIP6 simulation rounds, SST was projected to increase in all regions (Figures 2 and 3). For CMIP5, GFDL projections were warmer in three regions, while there was overlap in four regions (Figure 2). GFDL projections were higher in 2100 in three regions, while IPSL projections were higher in four regions (Figure 2; Table 3). Interannual variability was similar for GFDL and IPSL projections, with exceptions for greater variability in the GFDL projection for the Humboldt Current and IPSL projections for the Cook Strait and East Bass Strait (Figure 2). The magnitude of SST increase from 1950 to 2100 was greater in IPSL projections in all seven regions (Figure 2). For CMIP6, GFDL projections were warmer in three regions, an IPSL projection was warmer in one region, with overlap between a GFDL and IPSL projection in one region (Figure 3). GFDL projections were higher in 2100 in three regions, while IPSL projections were higher in two (Figure 3; Table 3). Interannual variability was similar for GFDL and IPSL projections except in the East Bass

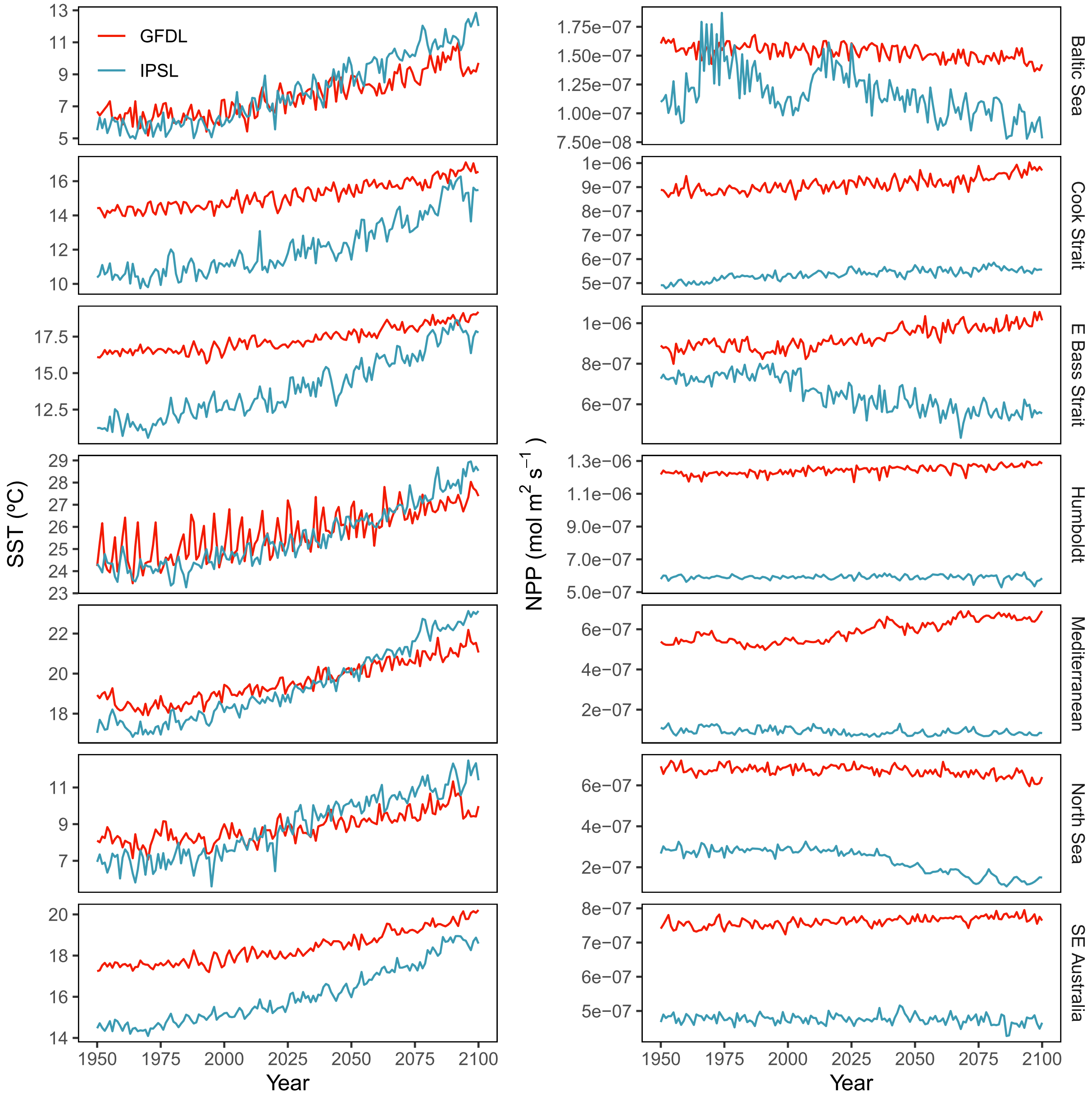

Figure 2. CMIP5 Earth system model SST and NPP forcing variables for GFDL (red) and IPSL (blue) by region for the RCP 8.5 scenario.

Strait, where the GFDL projection showed greater variability (Figure 3). The magnitude of SST increase from 1950 to 2100 was greater for a GFDL projection in one region, IPSL projections in two regions, and similar in two regions (Figure 3).

3.1.2. Net Primary Productivity

For both CMIP5 and CMIP6 projections, there was variability in direction of NPP change by 2100 (Figures 2 and 3). For CMIP5, GFDL NPP projections were higher in six regions, with one region showing overlap (Figure 2). GFDL projections were higher in 2100 in all regions (Figure 2; Table 3). There were similar amounts of interannual variability for GFDL and IPSL projections, except in the Baltic Sea and East Bass Strait, where IPSL projections were more variable (Figure 2). IPSL projections indicated greater NPP declines from 1950 to 2100 in four of seven regions, while in the other three regions there were no strong trends (Figure 2). For CMIP6, GFDL projections of NPP were greater than IPSL projections in all five regions (Figure 3). There was similar interannual variability for GFDL and IPSL projections, except in the

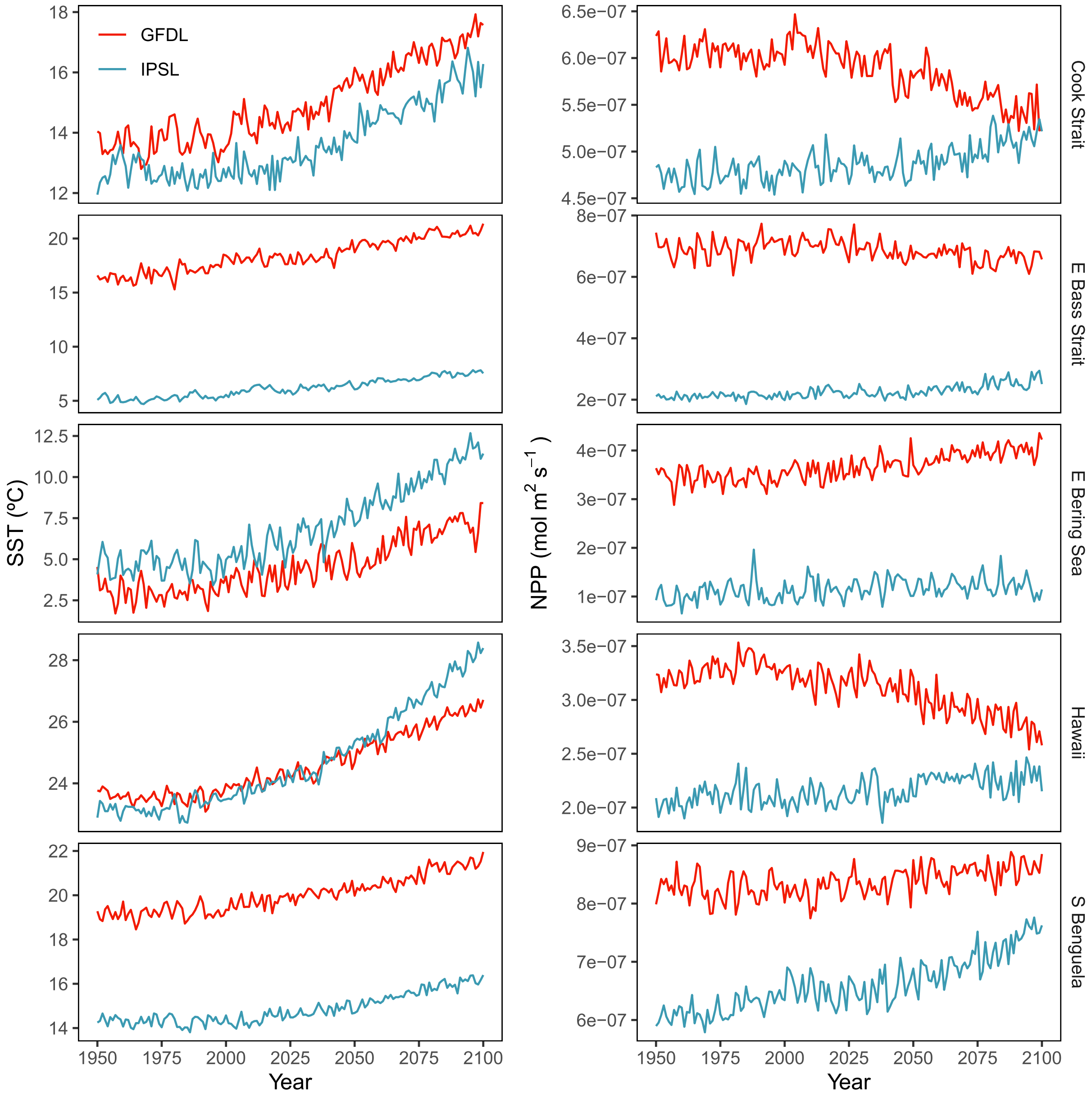

Figure 3. CMIP6 Earth system model SST and NPP forcing variables for GFDL (red) and IPSL (blue) by region for the SSP5-8.5 scenario.

East Bass Strait where the GFDL projection showed greater variability (Figure 3). The magnitude of change in NPP was variable, with GFDL projected decreases and IPSL increases in Cook Strait, East Bass Strait, and Hawaii regions (Figure 3). Both GFDL and IPSL projections indicated increases in NPP for the Southern Benguela and Eastern Bering Sea, with greater increase in the IPSL projection for the Southern Benguela and greater increase in the GFDL projection for the Eastern Bering Sea (Figure 3).

3.2. Global & Regional Model Ensemble Projections

On average, global models projected greater biomass declines than regional models. For CMIP5 simulations, the average biomass decline at the end of the century was 6% for regional models compared to 18% for global models (Figure 4, S2 in Supporting Information S1; Table 4). For CMIP6 simulations, on average regional models projected a decline of 18% at the end of the century, while global models projected a decline of 27% (Figure 5, S3 in Supporting Information S1, Table 4).

Table 3
Summary of Results for Forcing Variables

	CMIP5				CMIP6			
	SST		NPP		SST		NPP	
Region	GFDL	IPSL	GFDL	IPSL	GFDL	IPSL	GFDL	IPSL
Baltic Sea	53.7	100.3	−6.7	−17.1				
Cook Strait, New Zealand	14.8	41.9	8.5	5.1	26.9	26.3	−9.5	9.0
East Bass Strait, Australia	14.4	39.6	17.8	−25.2	18.1	43.4	−8.7	23.2
East Bering Sea					135.1	164.4	18.8	23.9
Hawaii					11.9	19.4	−16.9	11.0
Humboldt Current	9.0	15.5	4.4	−1.2				
Mediterranean Sea	13.8	26.0	23.8	−19.1				
North Sea	24.4	64.1	−6.4	−52.9				
Southeast Australia	12.8	24.2	3.5	−2.0				
Southern Benguela					11.3	12.6	3.5	18.9
Average	20.4	44.5	6.4	−16.1	40.7	53.2	−2.5	17.2

Note. Mean percent sea surface temperature (SST) and net primary productivity (NPP) change from 2090–2099 relative to 1990–1999 for GFDL and IPSL Earth system models in CMIP5 and CMIP6.

Global model ensemble projections often produced a decline in biomass at the end of the century. For CMIP5, only 14% of the global ensemble projections showed increases (n = 2/14; biomass increases for GFDL simulations in East Bass Strait and Mediterranean Sea; Table 4; Figures 2, 4, and 7). In contrast, regional models projected biomass increases at the end of the century in 50% of CMIP5 simulations (n = 7/14, for 7 regions and 2 ESMs; Table 4; Figures 2, 4, and 6). For CMIP6 simulations, global model ensemble projections always projected biomass declines at the end of the century (n = 12), while regional models projected biomass increases in 33% of simulations (n = 4/12; IPSL simulations for Cook Strait and East Bass Strait; GFDL and IPSL simulations for Southern Benguela EwE; Table 4; Figures 3, 5, and 7). However, it should be noted that some global models in some regions projected the opposite direction of change as the global model ensemble (Figures 6 and 7).

For some regions, biomass projections from regional models showed different trends than projections from the global ensemble (Figures 4 and 5). This was observed in both GFDL and IPSL simulations and in both CMIP5 and CMIP6 simulation rounds (Figures 4 and 5). In the CMIP5 simulation round, disagreement in direction of biomass change was observed in the Cook Strait and Southeast Australia for both GFDL and IPSL simulations (Figure 4) and the East Bass Strait for GFDL simulations (Figure 4; Table 4). In the CMIP6 simulation round, differences in projected direction of change were observed in the Cook Strait and the East Bass Strait for IPSL simulations and the Southern Benguela EwE model for both GFDL and IPSL simulations (Figure 7; Table 4). In the Eastern Bering Sea and Hawaii, for both GFDL and IPSL simulations and in the East Bass Strait for GFDL simulations, biomass trends were very different in terms of magnitude of change and variability, with the regional models projecting greater biomass declines in the Eastern Bering Sea, while the opposite response was observed in Hawaii and East Bass Strait (Figure 5).

Regional model biomass change projections were within the range of the global model ensemble on average for 43% of the time series in CMIP5 and 36% of the time series in CMIP6 (Figures 4 and 5; Table S1 in Supporting Information S1). In the CMIP5 simulation round, less than half of the regional model time series was within the global model ensemble range for: Baltic Sea—IPSL, Cook Strait—GFDL and IPSL, East Bass Strait—IPSL, Humboldt Current—GFDL and IPSL, Mediterranean Sea—GFDL, North Sea—GFDL, and SE Australia—both GFDL and IPSL (Figures 4 and 6; Table S1 in Supporting Information S1). In the CMIP6 simulation round, regions where the regional model was within the range of the global ensemble for less than half of the time series were: Cook Strait—IPSL, East Bass Strait—GFDL and IPSL; East Bering Sea—GFDL and IPSL; Hawaii—GFDL and IPSL; and Southern Benguela Atlantis for GFDL and IPSL and Southern Benguela EwE for GFDL (Figures 5 and 7; Table S1 in Supporting Information S1). On average, for CMIP5, this was 42.7%

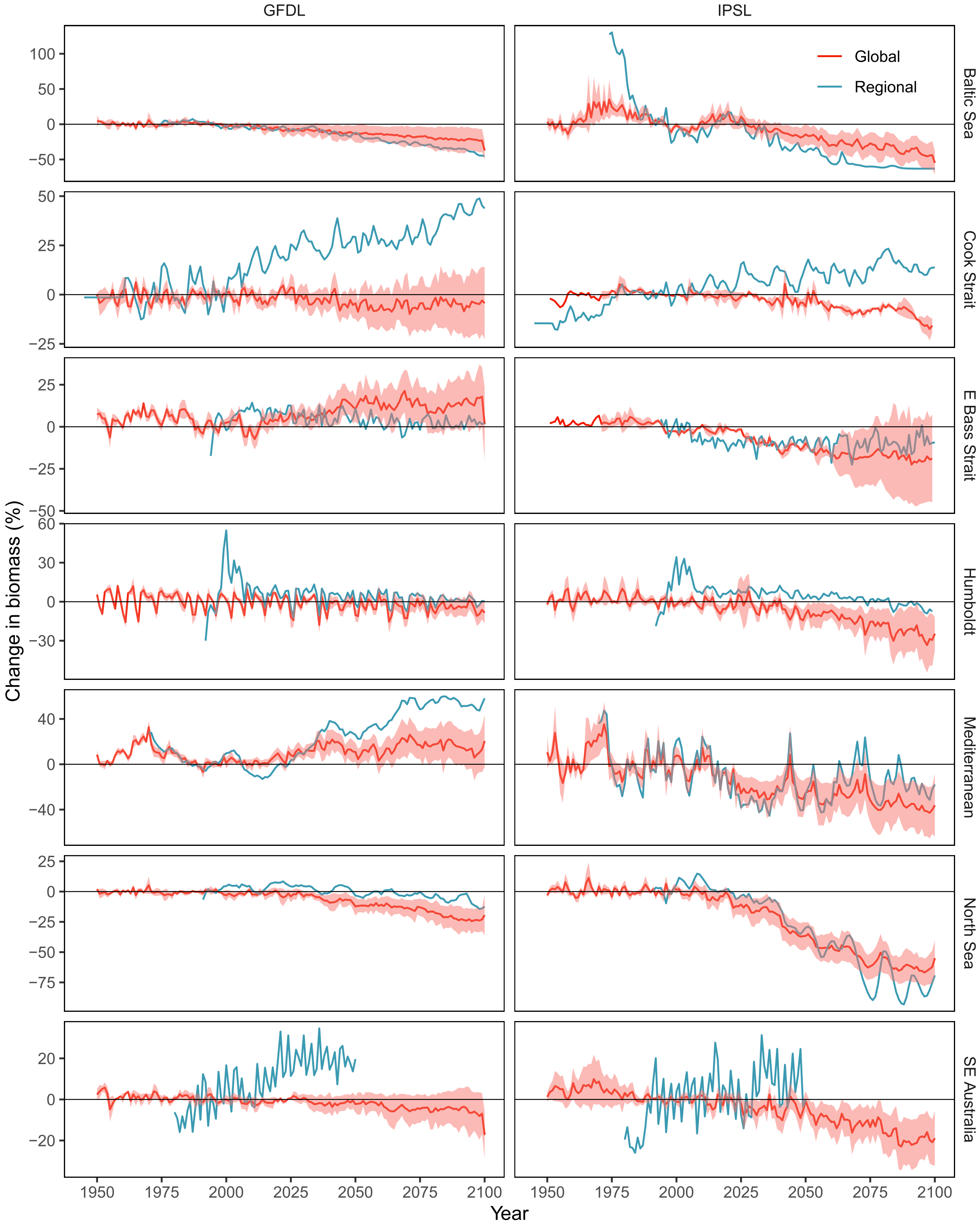

Figure 4. CMIP5 simulations for global (red) and regional (blue) models showing percent change in total consumer biomass relative to 1990–1999 for GFDL and IPSL under no-fishing scenarios and RCP 8.5. Shaded areas indicate standard deviation for the global model ensemble. There is one regional model for each region. Note that the regional model in SE Australia only ran simulations until 2050.

Table 4
Summary of Results for Marine Ecosystem Model Climate Change Projections

	CMIP5				CMIP6			
	GFDL		IPSL		GFDL		IPSL	
Region	Regional	Global	Regional	Global	Regional	Global	Regional	Global
Baltic Sea	−38.9	−22.3	−63.0	−40.3				
Cook Strait, New Zealand	44.4	−5.0	12.3	−13.3	−60.0	−49.6	23.5	−25.9
East Bass Strait, Australia	2.3	15.3	−8.0	−19.8	−2.9	−31.8	15.0	−27.7
East Bering Sea					−68.3	−9.4	−74.0	−35.3
Hawaii					−2.3	−36.7	−2.8	−28.7
Humboldt Current	0.8	−4.7	−4.2	−25.5				
Mediterranean Sea	51.3	12.1	−21.4	−38.8				
North Sea	−7.7	−23.5	−78.0	−63.8				
Southeast Australia	18.3	−4.1	6.4	−13.2				
Southern Benguela Atlantis					−21.0	−12.3	−49.1	−12.4
Southern Benguela EwE					1.1	−12.3	19.7	−12.4
Average	10.1	−4.6	−22.3	−30.7	−25.6	−28.0	−11.3	−26.0

Note. Mean percent total consumer biomass change from 2090–2099 relative to 1990–1999 for regional and global models forced by GFDL and IPSL Earth system models in CMIP5 and CMIP6. Note that SE Australia regional Atlantis model only ran simulations until 2050 and results for SE Australia are shown for 2040–2049 relative to 1990–1999.

for GFDL and 44.1% for IPSL for an overall average of 43.4% (Table S1 in Supporting Information S1). For CMIP6, this was 38% for GFDL, 34% for IPSL for an overall average of 36% (Table S1 in Supporting Information S1).

3.3. CMIP Simulation Round Variability

For both global and regional models, greater average projected biomass changes at the end of the 21st century relative to 1990–1999 were observed in CMIP6 than in CMIP5 (23% vs. 12%, respectively; Figures 4 and 5; Table 4). While the regions represented by both regional and global models differed in CMIP5 and CMIP6 simulation rounds, the two regions that participated in both rounds—Cook Strait and East Bass Strait—both showed greater average biomass declines in CMIP6 (Cook Strait: CMIP5 10% increase vs. CMIP6 28% decrease; East Bass Strait: CMIP5 3% decrease vs. CMIP6 12% decrease; Figures 4 and 5; Table 4).

3.4. ESM Variability

On average, IPSL simulations produced greater biomass declines than GFDL simulations (Figures 4–7, S4, S5 in Supporting Information S1; Table 4). In the CMIP5 simulation round, regional model GFDL runs produced an average biomass increase of 10%, compared to a 22% decline for IPSL simulations (Figures 4 and 6, S4 in Supporting Information S1; Table 4). For global models in the CMIP5 simulation round, GFDL runs produced an average biomass decline of 5% while IPSL runs produced an average biomass decline of 31% (Table 4). For the CMIP6 simulation round, GFDL simulations produced greater biomass declines than IPSL, although IPSL showed larger variability over time (Figures 5 and 7, S5 in Supporting Information S1; Table 4). For regional models, GFDL simulations produced an average biomass decline of 26%, with 11% for IPSL (Table 4). For global models, GFDL simulations produced an average biomass decline of 28% while IPSL simulations produced an average decline of 26% (Table 4).

Agreement between global and regional models was similar for GFDL and IPSL runs in the CMIP5 simulation round (average RMSE of 14.9 vs. 15.0, respectively; Table S2 in Supporting Information S1). For the CMIP6 simulation round, global and regional model agreement was better for GFDL simulations than IPSL (average RMSE of 18.3 vs. 24.5, respectively; Table S2 in Supporting Information S1).

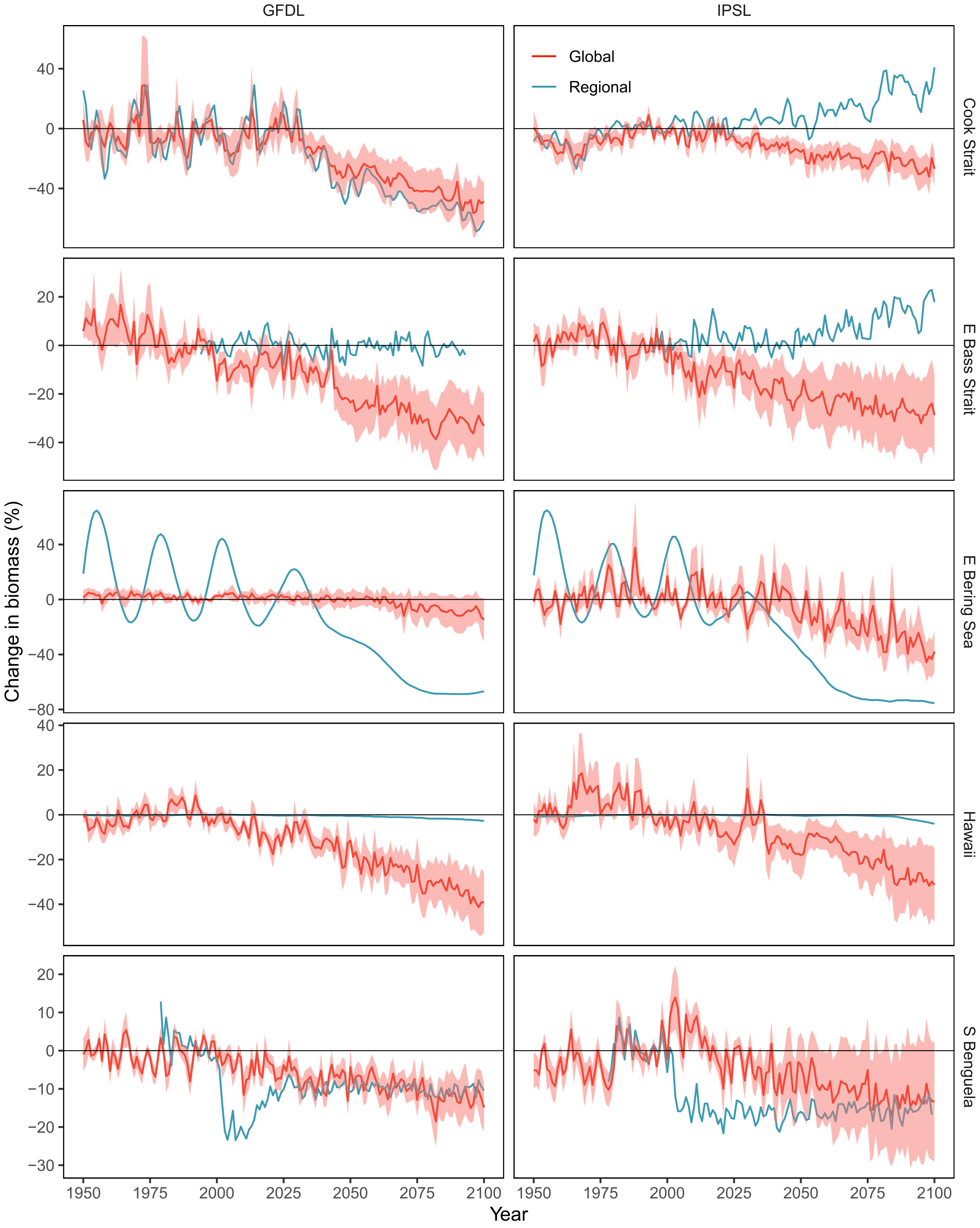

Figure 5. CMIP6 simulations for global and regional models showing percent change in total consumer biomass relative to 1990–1999 for GFDL and IPSL under no-fishing scenarios and SSP5-8.5. Shaded areas indicate standard deviation for the global model ensemble. The Southern Benguela region has two regional models; the mean of the two models is shown. Other regions have one regional model.

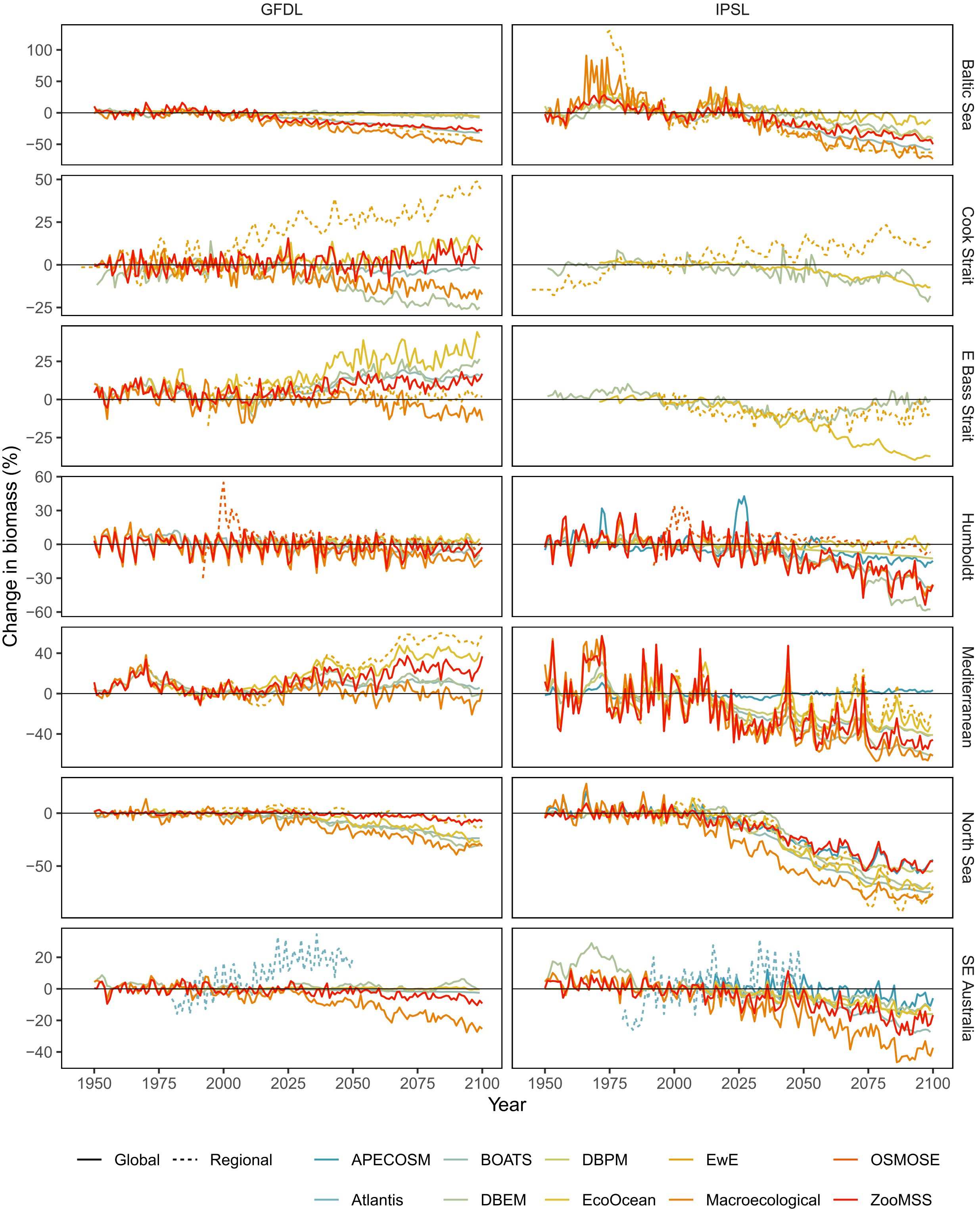

Figure 6. CMIP5 simulations for global and regional models showing percent change in total consumer biomass relative to 1990–1999 for GFDL and IPSL under no-fishing scenarios and RCP8.5. Note that the regional model in SE Australia only ran simulations until 2050.

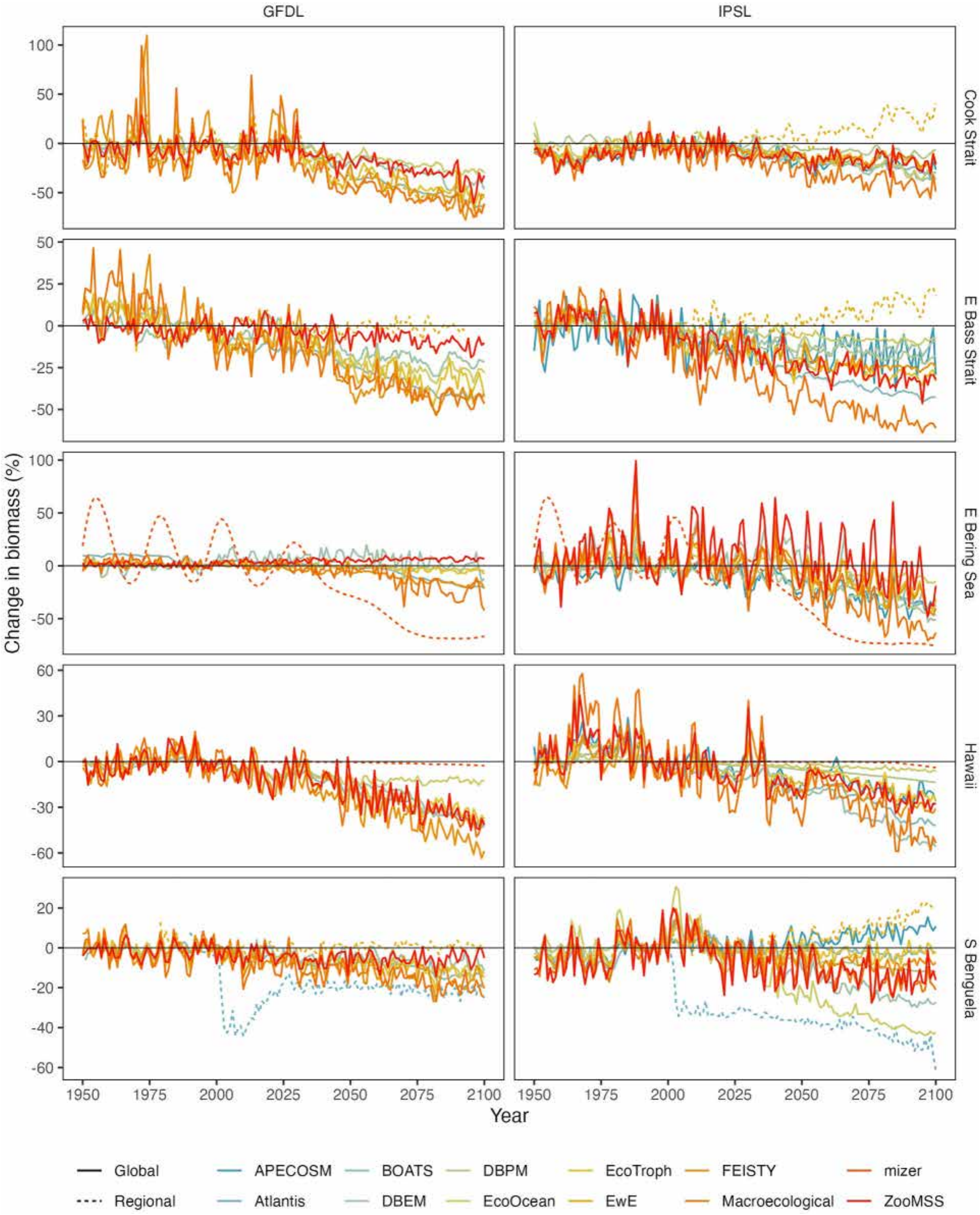

Figure 7. CMIP6 simulations for global and regional models showing percent change in total consumer biomass relative to 1990–1999 for GFDL and IPSL under no-fishing scenarios and SSP5-8.5.

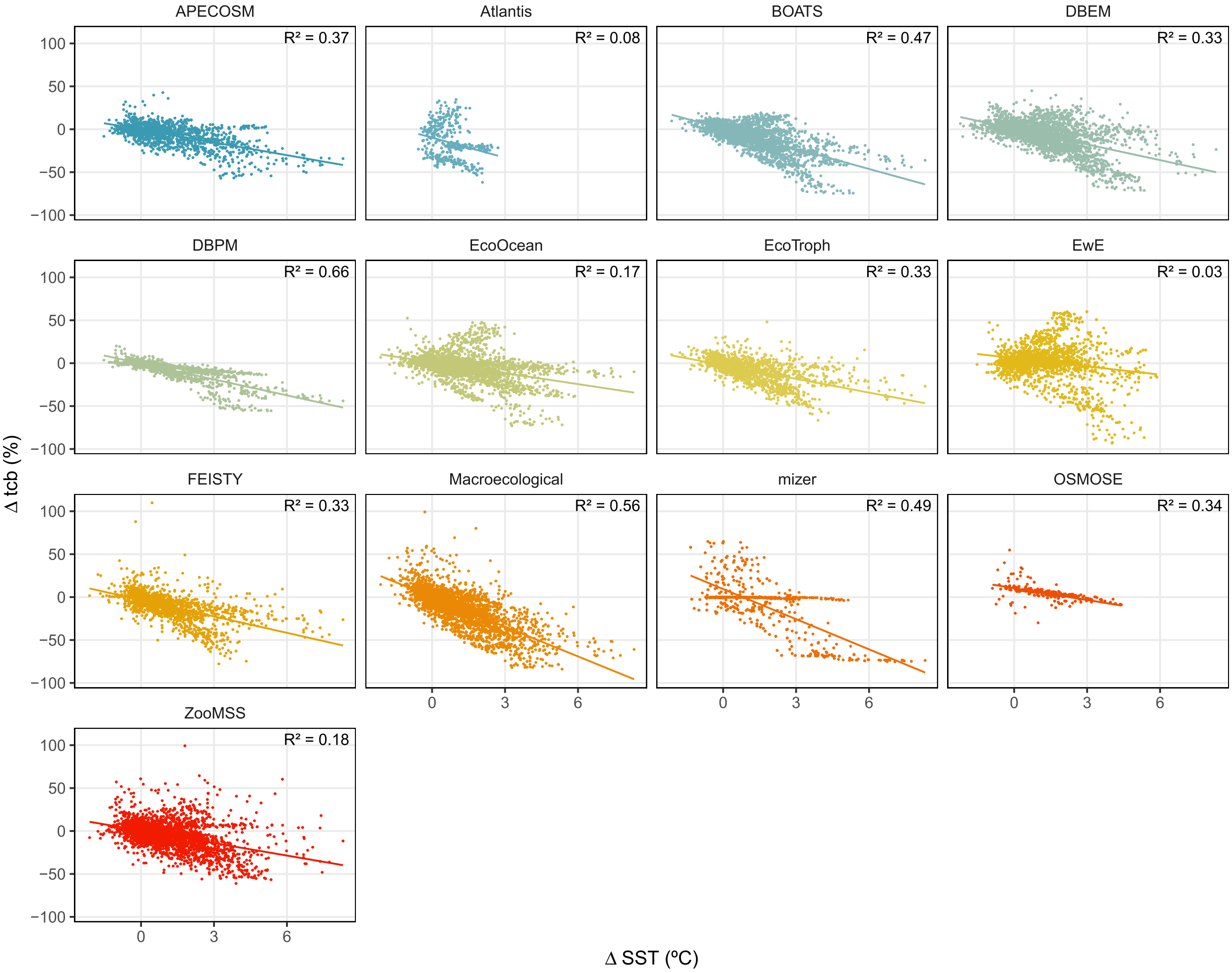

Figure 8. Relationship between change in total consumer biomass (Δ tcb) and change in sea surface temperature (Δ SST) by marine ecosystem model. Each point represents 1 year from a model simulation.

3.5. Temperature and Net Primary Productivity Relationships With Total Consumer Biomass

All MEMs showed a negative relationship between change in SST and change in total consumer biomass, however the slopes of the linear regressions differed among models (Figure 8; Table S3 in Supporting Information S1). The greatest slopes were observed for mizer and Macroecological (−11.7 and −11.5, respectively) and the smallest slope was observed for Ecopath with Ecosim (EwE; −3.2). The amount of variation in delta total consumer biomass that was explained by delta SST was greatest for DBPM ($R^2 = 0.66$), while the smallest was observed for EwE ($R^2 = 0.03$). Most MEMs had a positive relationship between change in NPP and total consumer biomass, except for Atlantis and mizer, both of which are regional models (Figure 9, Table S3 in Supporting Information S1). The model that had the greatest positive slope was EwE (2.3E+08), while the greatest negative slope was observed for mizer (−4.3E+08; Figure 9, Table S3 in Supporting Information S1). The highest amount of variation in delta total consumer biomass that was explained by delta NPP was observed for EwE ($R^2 = 0.41$), while the lowest value was observed for OSMOSE ($R^2 = 0.04$; Figure 9).

4. Discussion

Our results indicate that climate change projections by global and regional marine ecosystem models covering the same location often differ in magnitude and sometimes direction of biomass change. On average, global models projected greater biomass declines than regional models, CMIP6 simulations projected greater biomass declines than CMIP5 simulations, and IPSL simulations projected greater biomass declines than GFDL

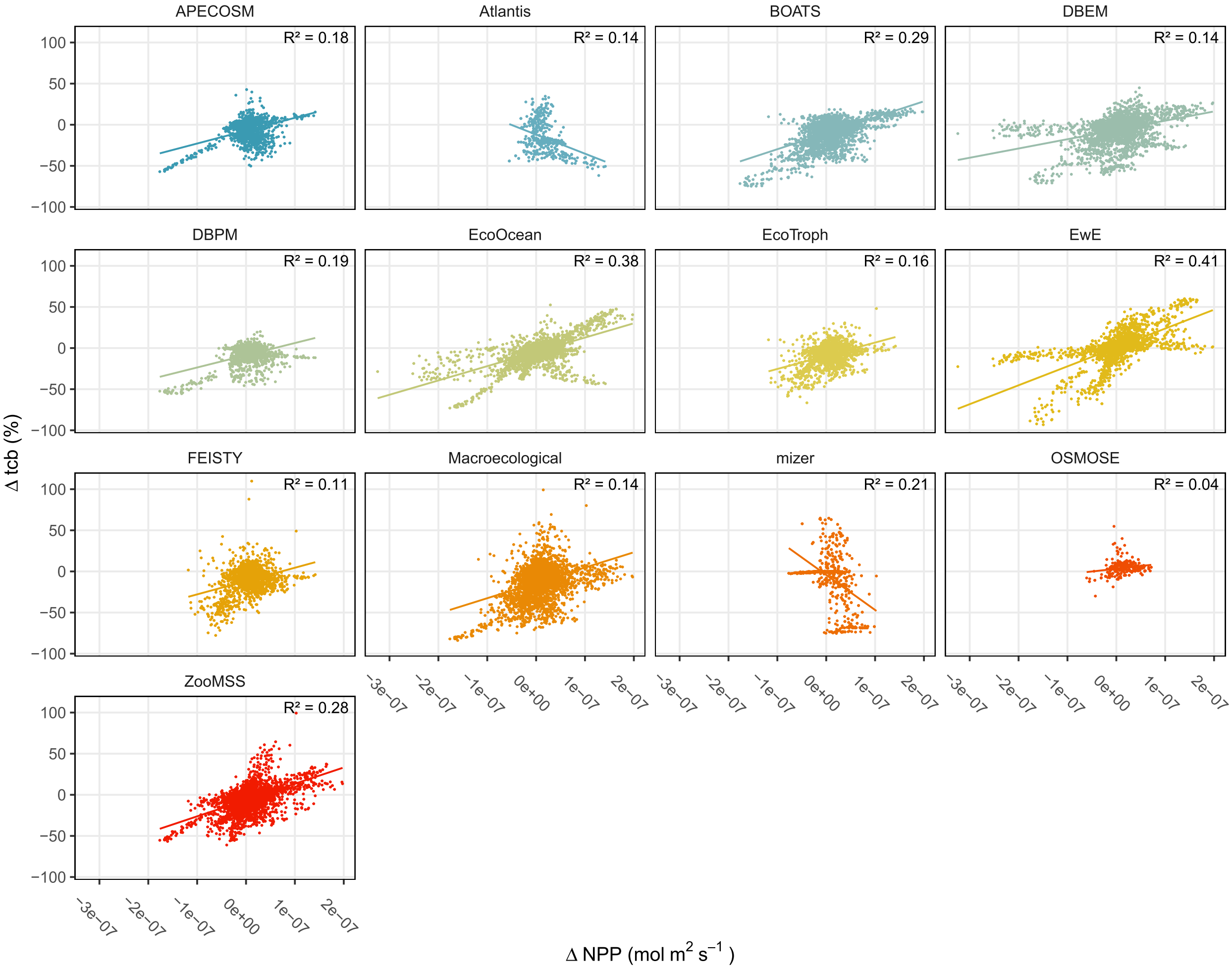

Figure 9. Relationship between change in total consumer biomass (Δ tcb) and change in net primary productivity (Δ NPP) by marine ecosystem model. Each point represents 1 year from a model simulation.

simulations. Overall, regional model projections were within the range of global model ensembles for less than half of the time series.

Mismatches between global and regional models can be attributed to several factors. The first is how ecology and the multifaceted effects of climate drivers interact and are represented in each MEM. Global MEMs have been mostly developed for climate impact studies and tend to include more climate forcing variables compared with the regional models considered in this study (Table 1). For example, the divergent trends for Cook Strait and East Bass Strait compared to global MEMs may reflect the fact that these two models were forced with primary production changes only, and do not include temperature effects on bioenergetics (Table 2). The latter can lead to more marked declines in biomass (Carozza et al., 2019; Heneghan et al., 2021) and we observed variable relationships between delta total consumer biomass and delta SST and NPP (Figures 8 and 9). On the other hand, including more regional species-specific detail in temperature responses (as in the Hawaii therMizer model), can dampen or lead to antagonistic effects as they propagate from individual physiological to community levels. An analysis of global FishMIP MEMs showed that incorporating temperature effects led to biomass changes of −35%–+3% while simulating climate change through low trophic level effects (primary production; phytoplankton and/or zooplankton biomass or production) produced biomass changes of −17%–+15% (Heneghan et al., 2021).

The ecological complexity of global and regional MEMs also differs, as regional models often include more food web interactions and functional diversity than global models (Tables 1 and 2). Using the same underlying regional size-based modeling framework and only temperature altered, fish community responses were not generalizable among regions and were dependent on the species or functional group position in the food web and food web structure (Reum et al., 2024). Compared to general trait-based food web model configurations, more detailed regional food web structures led to damped effects of warming (Reum et al., 2024). This could explain why global FishMIP MEMs overestimated the observed impacts in an analysis that used the 2003 European heat wave as a case study and compared global FishMIP MEM hindcasts of ocean biomass to observations (Schewe et al., 2019). In a comparison of global and regional MEMs in SE Australia, it was not the climate drivers but the representation of the ecology that proved critical in explaining variation in model projections (Fulton, 2021; Pethybridge et al., 2020). The regional Atlantis modeling framework, as applied in SE Australia, includes all the same climate drivers as the global models but produced divergent results with global MEMs. Differences between the Atlantis projections and those from global MEMs had many causes – from variable representation of species or spatial sub-domains of the model (Fulton, 2021; Pethybridge et al., 2020). However, one common dynamic leading to divergence between this regional MEM and the overlapping global MEMs was due to ecologically mediated interactions. The trophic resolution of Atlantis included more detail and more feedback pathways than in the global MEMs. This meant that situations arose where decreased predation or competition acting on a structurally important species for the food web outweighed direct climate effects on that species (Fulton, 2021; Pethybridge et al., 2020). In other instances, movement and ontogenetically mediated processes and connectivity were important (Fulton, 2021; Pethybridge et al., 2020).

It has also been noted that among three commonly used regional MEM platforms—Atlantis, EwE, and OSMOSE—there is system specificity in the degree of convergence and divergence in projections (Smith et al., 2011). For example, running the same maximum sustainable yield fisheries simulations in each of these modeling frameworks in four regional ecosystems (Benguela, Humboldt, California Current, and Southeast Australia) showed clear variability in projected ecosystem responses (Smith et al., 2011). However, in other instances, various combinations of Atlantis, OSMOSE, and Ecopath with Ecosim models have projected similar general patterns of change to fishing (Forrest et al., 2015; Ortega-Cisneros et al., 2018; Smith et al., 2015; Travers et al., 2010), where aggregated properties showed more consistency across models than species level variables (Ortega-Cisneros et al., 2018). The specific degree of model responsiveness to perturbation is also typically system specific, though in general terms the Atlantis modeling framework is less sensitive to ecosystem perturbations, especially environmentally driven events, than Ecopath with Ecosim and OSMOSE (Fulton & Smith, 2004; Smith et al., 2011). Model sensitivity is an important consideration when using models to guide policy advice, such as that provided by the IPCC at the global scale, but also for interpreting models and providing strategic fisheries management guidance as provided by the FAO at national, regional, and local scales (Blanchard & Novaglio, 2024).

An additional factor contributing to global and regional model mismatches is the coarse resolution of coastal regions in global ESMs and MEMs. Global models often poorly represent waters <50 m depth, and at the 1° grid size scale (~100 km by 100 km at the equator) fail to capture fine-scale coastal and shelf processes such as eddies and upwelling—important for nutrient supply, and production of phytoplankton, zooplankton, higher trophic levels, and fisheries (Laurent et al., 2021; Pozo Buil et al., 2021). Two approaches to increase resolution are: statistical downscaling to a higher resolution grid—which will be influenced by the ESM that it was downscaled from (Lange, 2019; Oliveros-Ramos et al., 2023); or by dynamical downscaling with a regional biogeochemical model or a regional ocean modeling system (ROMS; Laurent et al., 2021; Pozo Buil et al., 2021). Regional MEMs have faced challenges incorporating highly resolved spatial data as drivers of change. Some regional MEMs have been developed without explicit spatial resolution; instead using implicit representation to structure food webs by depth or other influencing process. There is also a tradeoff between downscaled models having higher spatial resolution but poorer estimates of uncertainty because their boundary conditions are often driven by only one ESM, and commonly few emission scenarios are included (Pozo Buil et al., 2021). Regional models can also be limited by an inaccurate representation of boundary conditions, such as the import and export of water and biomass to the model domain (across both land/riverine and oceanic boundaries).

Comparisons of CMIP5 ESM projections to regional observations of environmental variables have concluded that coarsely resolved ESMs failed to accurately capture complex patterns of circulation and elemental fluxes on the shelves along ocean margins of the northwest Atlantic shelf (Laurent et al., 2021). ESMs underestimated observed chlorophyll and nitrate, while a ROMS biogeochemical model with higher spatial resolution reproduced observed trends better (Laurent et al., 2021). Similar mismatches between model projections and observed values were observed in regions we investigated, such as for the Humboldt Current, where ESM projections of NPP were half the magnitude compared to observed values—which was bias-corrected through statistical downscaling (Lange, 2019; Oliveros-Ramos et al., 2024). Global and regional model mismatches have also been observed in comparisons of hydrological models, where global models not calibrated to regional observations failed to reproduce regional trends, with the recommendation that regional models were more appropriate for regional water management (Gosling et al., 2016; Hattermann et al., 2017).

Model calibration is a key source of variation among global and regional models. Fitting models to time series of fisheries and biomass surveys has been a focus of many regional models since their inception (Bentley et al., 2024) but is only just beginning for global models. Regional models often use fisheries catch and fisheries independent survey data in the region (Maureaud et al., 2021, 2024). Global models are often limited by observational data for calibration, as only exclusive economic zone or large marine ecosystem scale catch data are available. Data at these scales have many uncertainties, including how fishing effort is spatially allocated and representativeness of total system removals (Rousseau et al., 2019, 2024; Watson, 2017).

As ESM accuracy improves and computing power increases, the spatial resolution of ESMs will increase and processes within coastal and shelf regions will be better resolved and more consistent with regional oceanographic models. ESM runs undertaken at a 0.25° grid scale do a better job of representing coastal and shelf features, such as fine scale eddies, currents, and upwelling. Such changes in resolution can vastly improve the representation of ecologically relevant features, such as production hotspots, both in global but also regional modeling initiatives (Matear et al., 2013). As global scale ESMs and MEMs at both global and regional scales continue to evolve, a central goal of FishMIP is to understand sources of variation to build confidence in projections of climate change impacts on marine ecosystems at regional scales and to provide guidance about which scales different models can be applied for adaptation and mitigation planning. We note that the test undertaken here, comparing projections at the end of the 21st century looks at the end point not the transition pathways, and that we may be missing divergence that has real meaning at temporal scales meaningful for decision makers.

A key source of uncertainty that has not yet been explored with global and regional MEMs within FishMIP is socioeconomics. Market, management, and policy responses could be more important than climate change for the future of fish populations (Cheung et al., 2021, 2024). To date, FishMIP has focussed on the climate change impact and treated the socioeconomic impact simply by holding fishing levels constant at 2005 or 2015 levels or with a no-fishing scenario. The SSPs were not specifically developed for marine systems and are not directly applicable to socioeconomic factors for ocean systems. To address this important consideration, FishMIP has established a Scenarios Working Group to develop ocean system pathways of future fishing effort and ocean usage, based on the SSP scenarios, with the intention that they be used in combination with RCP emissions scenarios in future FishMIP simulation rounds (Maury et al., 2024).

The value of model ensembles lies in building confidence in model projections through the exploration of multiple models. When the exact processes and structures to represent observations are unknown, comparison of varying model formulations provides a hypothesis testing approach. If models agree in projections, there is greater confidence that key processes and structures have been represented. Conversely, large variation in model projections points to missing knowledge. The global and regional models explored here employ different approaches to represent marine ecosystems due to imperfect knowledge. Our study highlights areas for future exploration but cautions that there is high uncertainty about how ecology and eco-evolutionary processes will unfold in rapidly changing marine environments. Of high importance are additional physical processes that function at scales not represented by the resolution of the ESMs but are implicit in regional models that have been bias corrected. Our comparison of global and regional MEMs highlights that there are key uncertainties for climate change projections of biomass change at regional scales. While management and conservation organizations require this information for adaptation and mitigation planning, it should be recognized that projections at these scales remain uncertain in many regions. FishMIP plans to continue to address these uncertainties at regional scales to build confidence in projections of climate change impacts on marine ecosystems worldwide (Ortega-Cisneros et al., 2025; Murphy et al., 2024).

Data Availability Statement

The R scripts used to execute the analyses in the paper can be found at https://github.com/Fish-MIP/Regional_v_Global. The simulations used for the study (Eddy et al., 2023, 2024; Tittensor et al., 2023) are available at ISIMIP data repository (https://data.isimip.org/) under the tree "ISIMIP2a/OutputData/marine-fishery_regional" and "ISIMIP3a/OutputData/marine-fishery_regional," for instructions to get access see https://www.isimip.org/gettingstarted/data-access/.

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