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1 Key points

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

8

9 Abstract

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

27 regional marine ecosystem model climate change projections is needed, alongside
28 observational evaluation of modelled responses.

29

30 Plain language summary

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

46

47

48 Key words

49 model intercomparison project (MIP); model ensemble; Fisheries and Marine Ecosystem Model
50 Intercomparison Project (FishMIP); Inter-Sectoral Impact Model Intercomparison Project
51 (ISIMIP); fisheries

52

53 Introduction

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

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

74 Taking a similar approach to CMIP, the Fisheries and Marine Ecosystem Model
75 Intercomparison Project (FishMIP) has developed standardized protocols to run climate change
76 impact simulations for an ensemble of global and regional marine ecosystem models (MEMs;
77 Tittensor et al. 2018; Blanchard et al. 2024). FishMIP models use outputs provided by CMIP
78 ESMs to run climate change scenarios following shared socioeconomic pathways (SSPs) and

79 representative concentration pathways (RCPs). Global FishMIP projections have been used to
80 explore changes in marine animal biomass, evaluate the level of MEM agreement, and attribute
81 sources of variability to MEMs, ESMs, SSP-RCPs, and fishing exploitation (Lotze et al. 2019).
82 FishMIP projections suggest that marine animal biomass will, on average, decline by 17% by
83 2100 under a high emissions scenario (RCP 8.5) with CMIP5 forcing data (Lotze et al. 2019)
84 and by 19% under CMIP6 (Tittensor et al. 2021). Other key findings are that with every 1 °C that
85 the planet warms, marine animal biomass is projected to decline by 5%, roughly in agreement
86 with the average of observational estimates (Free et al., 2019), and that higher trophic levels are
87 disproportionately impacted (Lotze et al. 2019; du Pontavice et al., 2021; Guibourd de Luzinai
88 et al. 2023). While not all FishMIP models represent fishing, simulations with and without fishing
89 produced similar magnitude and variability of the climate effect on marine ecosystems (Lotze et
90 al. 2019). Equivalent amounts of variability in biomass projections were contributed by ESMs
91 and MEMs, with variability increasing with higher emissions (Lotze et al. 2019). Compared to
92 CMIP5 forced MEMs, CMIP6 forced MEMs projected regional differences in the direction of
93 biomass changes, emphasizing the need to reduce uncertainty to support adaptation planning
94 (Tittensor et al. 2021). Understanding regional marine ecosystem and fisheries dynamics is
95 particularly important because many coastal communities are highly dependent on the nutrition
96 and livelihoods they derive from the ocean (e.g. FAO 2018).

97 Regional MEMs have often been developed to address fisheries, conservation, and
98 management applications. In contrast to global models, regional models do not represent the
99 entire ocean, and are generally forced by environmental variables representative of the regions
100 being simulated. This is one of several differences in model detail between global and regional
101 scale MEMs that has consequences for using global scale ESMs to force regional MEMs. One
102 particularly important issue is that ESMs produce projections of physical and biogeochemical
103 ocean properties at a coarse spatial resolution, typically on a 1 ° x 1 ° grid. A consequence of
104 this spatial resolution is that physical and biogeochemical processes that drive primary

105 productivity in coastal regions – where many nationally significant fisheries occur – are not well
106 represented (FAO 2022). For example, depths <50 m and key oceanographic processes that
107 affect primary production, such as upwelling and dispersion of coastal nutrients, are poorly
108 resolved (Stock et al. 2011; Bopp et al. 2013). This has implications for representation of
109 marginal seas, such as the Baltic Sea (Niiranen et al. 2013) and the Mediterranean Sea (Coll et
110 al. 2010), and shallow underwater plateaus such as The Grand Banks of Newfoundland
111 (Laurent et al. 2021). In Australia, discrepancies in projections from global and regional MEMs
112 for the same regions have been observed, not just in terms of the magnitude of effects but also
113 in the direction of change (Pethybridge et al. 2020). As there is a need to provide projections of
114 climate change impacts at regional scales for fisheries adaptation and mitigation planning,
115 regional MEM ensembles that allow quantification of across-model uncertainty are lacking for
116 most regions of the world (Metcalf et al. 2015). In this absence, the FishMIP global ensemble
117 has been used to fill in the gap (Blanchard et al. 2017; Cinner et al. 2022; Blanchard and
118 Novaglio 2024). Understanding how global marine ecosystem models perform at regional
119 scales is important as many resource constrained jurisdictions do not have the capacity to
120 generate their own regional specific models (Barange et al. 2014; Blanchard et al. 2017; Boyce
121 et al. 2022; Cinner et al. 2022).

122 Most global FishMIP models agree in the projected direction of change in fish production
123 for specific climate model and emissions scenarios, albeit with regional differences (Lotze et al.
124 2019; Heneghan et al. 2021; Tittensor et al. 2021). However, models at regional scales can
125 project the opposite direction of change (Barange et al. 2014; Pethybridge et al. 2020). Previous
126 FishMIP studies have analyzed variability in climate change projections of marine animal
127 biomass as a function of: ESM (Geophysical Fluid Dynamics Laboratory Earth System Model –
128 GFDL or Institute Pierre Simon Laplace Climate Model – IPSL); global MEM (ensemble of six or
129 nine; Lotze et al. 2019; Tittensor et al. 2021); and SSP-RCP scenario (four scenarios or two
130 scenarios; Lotze et al. 2019; Tittensor et al. 2021). The impact of fishing (Lotze et al. 2019) and

131 the difference between CMIP5 and CMIP6 projections have also been investigated (Tittensor et
132 al. 2021). What remains unknown is how climate change projections by FishMIP global MEMs
133 compare with regional MEMs at regional scales. In this study, we explore variability in climate
134 change projections of ocean biomass as a function of: Earth system model (ESM; GFDL vs.
135 IPSL); marine ecosystem model (MEM; ensemble of 13); marine ecosystem model spatial scale
136 (global or regional); and couple model intercomparison project generation (CMIP5 vs. CMIP6) in
137 10 regions. We evaluate the agreement in projections of global MEMs with regional MEMs at
138 regional scales.

139

140 Methods

141 *FishMIP model ensemble*

142 FishMIP provides a standardized approach to compare climate change projections
143 among MEMs of varying structure, assumptions, and spatial scale (Tittensor et al. 2018; Eddy
144 2019; Heneghan et al. 2021; Novaglio et al. 2024; Blanchard et al. 2024). MEMs differ in how
145 they are structured – whether biomass or carbon based, structured by size, trophic level,
146 species or functional group (Tittensor et al. 2018). Global MEMs are based on general
147 ecological theory and principles, are spatially resolved, and have become a major modelling
148 focus within the last decade (Table 1). Regional models generally represent more trophic
149 interactions, are fit to local ecological survey and fisheries data, may or may not be spatially
150 resolved, and have had a long history of development and refinement, originating 40 years ago
151 (Polovina 1984). Regional models generally include more feedback processes and the system
152 specific ecological idiosyncrasies that add complexity and richness to regional ecosystems
153 around the globe (Table 1).

154

155 *Global & regional MEMs*

156 We analyzed regional MEM projections for seven regions in CMIP5 and five regions in
157 CMIP6, with 10 regions represented in total (two regions with both CMIP5 and CMIP6
158 simulations; Figure 1). Regions were selected based on regional models that participated in
159 FishMIP simulation protocols (Tittensor et al. 2018; fishmip.org). Global ESMs and MEMs are
160 often not well resolved in coastal regions compared to regional models and therefore even
161 though the spatial domains used were identical, the ecosystems represented may differ (Figure
162 1; Tables 1, 2). For this reason, not all regions included in this study have all global MEM
163 simulations.

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

177

178 *FishMIP simulation protocol*

179 FishMIP simulations followed a standardized protocol that used ESM output variables as
180 MEM input variables and the same fisheries scenarios to simulate climate change (Frieler et al.

181 2017; Tittensor et al. 2018; Frieler et al. 2024; Blanchard et al. 2024; Figure S1; Tables 1, 2).
182 FishMIP simulations were designed to align with the Inter-Sectoral Impact Model
183 Intercomparison Project (ISIMIP) 2b and 3b protocols corresponding to CMIP5 and CMIP6
184 simulation rounds, respectively (Frieler et al. 2018; Frieler et al. 2024). In both protocols, MEM
185 simulations were run from 1950 – 2100 using climate and oceanographic conditions from two
186 ESMs (GFDL-ESM2M for CMIP5 and GFDL-ESM4 for CMIP6, collectively referred to as GFDL;
187 and IPSL-CM5A-LR for CMIP5 and IPSL-CM6A-LR for CMIP6, collectively referred to as
188 IPSL), under four emissions scenarios (RCP2.6/SSP1-2.6, RCP4.5/SSP2-4.5, RCP6.0/SSP4-
189 6.0, RCP8.5/SSP5-8.5; Tittensor et al. 2018; Frieler et al. 2024; Blanchard et al. 2024).

190 For this analysis, we used no-fishing simulations as most global models do not represent
191 fishing and did not run fishing simulations. We focussed on the RCP8.5/SSP5-8.5 high
192 emissions scenario as the impacts of emission scenario have been previously explored for
193 CMIP5 and CMIP6 (Lotze et al. 2019; Tittensor et al. 2021). While considering a broader set of
194 scenarios would be ideal, it was not possible in this instance as only the RCP8.5/SSP5-8.5 had
195 been run by all models. Extending to another scenario was unfortunately not feasible due to
196 computational intensity and capacity as FishMIP and ISIMIP are largely volunteer contributions
197 unlike CMIP. The high emissions scenario samples a large range of global warming, and as
198 many impacts scale approximately with global warming, impacts under a low scenario may be
199 similar to, just smaller than, a high scenario. For example, if 2.0 °C is reached earlier in RCP8.5
200 than in RCP4.5, RCP8.5 might still give a fair estimate of the impacts of 2.0 °C, irrespective of
201 when it is reached. However, the rates of change between these scenarios need to be

202 considered, as they can lead to different ecosystem consequences. FishMIP models simulated
203 climate change scenarios by incorporating relevant outputs from ESMs as MEM forcing
204 variables, such as temperature, primary productivity, phytoplankton biomass, zooplankton
205 biomass, acidity, oxygen concentration, and water velocities (Tables 1, 2; Figures 2, 3).

206

207 *Model comparisons*

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

217

218 *Drivers of biomass change*

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

224

225 3. Results

226 3.1 – Climate forcing variable projections

227 3.1.1 – Sea surface temperature

228 For both CMIP5 and CMIP6 simulation rounds, SST was projected to increase in all
229 regions (Figures 2, 3). For CMIP5, GFDL projections were warmer in three regions, while there
230 was overlap in four regions (Figure 2). GFDL projections were higher in 2100 in three regions,
231 while IPSL projections were higher in four regions (Figure 2; Table 3). Interannual variability was
232 similar for GFDL and IPSL projections, with exceptions for greater variability in the GFDL
233 projection for the Humboldt Current and IPSL projections for the Cook Strait and East Bass
234 Strait (Figure 2). The magnitude of SST increase from 1950 – 2100 was greater in IPSL
235 projections in all seven regions (Figure 2). For CMIP6, GFDL projections were warmer in three
236 regions, an IPSL projection was warmer in one region, with overlap between a GFDL and IPSL
237 projection in one region (Figure 3). GFDL projections were higher in 2100 in three regions, while
238 IPSL projections were higher in two (Figure 3; Table 3). Interannual variability was similar for
239 GFDL and IPSL projections except in the East Bass Strait, where the GFDL projection showed
240 greater variability (Figure 3). The magnitude of SST increase from 1950 – 2100 was greater for
241 a GFDL projection in one region, IPSL projections in two regions, and similar in two regions
242 (Figure 3).

243

244 3.1.2. – Net primary productivity

245 For both CMIP5 and CMIP6 projections, there was variability in direction of NPP change
246 by 2100 (Figures 2, 3). For CMIP5, GFDL NPP projections were higher in six regions, with one
247 region showing overlap (Figure 2). GFDL projections were higher in 2100 in all regions (Figure
248 2; Table 3). There were similar amounts of interannual variability for GFDL and IPSL
249 projections, except in the Baltic Sea and East Bass Strait, where IPSL projections were more
250 variable (Figure 2). IPSL projections indicated greater NPP declines from 1950-2100 in four of
251 seven regions, while in the other three regions there were no strong trends (Figure 2). For
252 CMIP6, GFDL projections of NPP were greater than IPSL projections in all five regions (Figure
253 3). There was similar interannual variability for GFDL and IPSL projections, except in the East

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

260

261 *3.2 – Global & regional model ensemble projections*

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

267 Global model ensemble projections often produced a decline in biomass at the end of
268 the century. For CMIP5, only 14% of the global ensemble projections showed increases ($n =$
269 $2/14$; biomass increases for GFDL simulations in East Bass Strait and Mediterranean Sea;
270 Table 4; Figures 2, 4, 7). In contrast, regional models projected biomass increases at the end of
271 the century in 50% of CMIP5 simulations ($n = 7/14$, for 7 regions and 2 ESMs; Table 4; Figures
272 2, 4, 6). For CMIP6 simulations, global model ensemble projections always projected biomass
273 declines at the end of the century ($n=12$), while regional models projected biomass increases in
274 33% of simulations ($n = 4/12$; IPSL simulations for Cook Strait and East Bass Strait; GFDL and
275 IPSL simulations for Southern Benguela EwE; Table 4; Figures 3, 5, 7). However, it should be
276 noted that some global models in some regions projected the opposite direction of change as
277 the global model ensemble (Figures 6, 7).

278 For some regions, biomass projections from regional models showed different trends
279 than projections from the global ensemble (Figures 4, 5). This was observed in both GFDL and

280 IPSL simulations and in both CMIP5 and CMIP6 simulation rounds (Figures 4, 5). In the CMIP5
281 simulation round, disagreement in direction of biomass change was observed in the Cook Strait
282 and Southeast Australia for both GFDL and IPSL simulations (Figure 4) and the East Bass Strait
283 for GFDL simulations (Figure 4; Table 4). In the CMIP6 simulation round, differences in
284 projected direction of change were observed in the Cook Strait and the East Bass Strait for IPSL
285 simulations and the Southern Benguela EwE model for both GFDL and IPSL simulations (Figure
286 7; Table 4). In the Eastern Bering Sea and Hawaii, for both GFDL and IPSL simulations and in
287 the East Bass Strait for GFDL simulations, biomass trends were very different in terms of
288 magnitude of change and variability, with the regional models projecting greater biomass
289 declines in the Eastern Bering Sea, while the opposite response was observed in Hawaii and
290 East Bass Strait (Figure 5).

291 Regional model biomass change projections were within the range of the global model
292 ensemble on average for 43% of the time series in CMIP5 and 36% of the time series in CMIP6
293 (Figures 4, 5; Table S1). In the CMIP5 simulation round, less than half of the regional model
294 time series was within the global model ensemble range for: Baltic Sea – IPSL, Cook Strait –
295 GFDL and IPSL, East Bass Strait – IPSL, Humboldt Current – GFDL and IPSL, Mediterranean
296 Sea – GFDL, North Sea – GFDL, and SE Australia – both GFDL and IPSL (Figures 4, 6; Table
297 S1). In the CMIP6 simulation round, regions where the regional model was within the range of
298 the global ensemble for less than half of the time series were: Cook Strait – IPSL, East Bass
299 Strait – GFDL and IPSL; East Bering Sea – GFDL and IPSL; Hawaii – GFDL and IPSL; and
300 Southern Benguela Atlantis for GFDL and IPSL and Southern Benguela EwE for GFDL
301 (Figures 5, 7; Table S1). On average, for CMIP5, this was 42.7% for GFDL and 44.1% for IPSL
302 for an overall average of 43.4% (Table S1). For CMIP6, this was 38% for GFDL, 34% for IPSL
303 for an overall average of 36% (Table S1).

304

305 *3.3 – CMIP simulation round variability*

306 For both global and regional models, greater average projected biomass changes at the
307 end of the 21st century relative to 1990-1999 were observed in CMIP6 than in CMIP5 (23% vs.
308 12%, respectively; Figures 4, 5; Table 4). While the regions represented by both regional and
309 global models differed in CMIP5 and CMIP6 simulation rounds, the two regions that participated
310 in both rounds – Cook Strait and East Bass Strait – both showed greater average biomass
311 declines in CMIP6 (Cook Strait: CMIP5 10% increase vs. CMIP6 28% decrease; East Bass
312 Strait: CMIP5 3% decrease vs. CMIP6 12% decrease; Figures 4, 5; Table 4).

313

314 *3.4 – ESM variability*

315 On average, IPSL simulations produced greater biomass declines than GFDL
316 simulations (Figures 4-7, S4, S5; Table 4). In the CMIP5 simulation round, regional model GFDL
317 runs produced an average biomass increase of 10%, compared to a 22% decline for IPSL
318 simulations (Figures 4, 6, S4; Table 4). For global models in the CMIP5 simulation round, GFDL
319 runs produced an average biomass decline of 5% while IPSL runs produced an average
320 biomass decline of 31% (Table 4). For the CMIP6 simulation round, GFDL simulations produced
321 greater biomass declines than IPSL, although IPSL showed larger variability over time (Figures
322 5, 7, S5; Table 4). For regional models, GFDL simulations produced an average biomass
323 decline of 26%, with 11% for IPSL (Table 4). For global models, GFDL simulations produced an
324 average biomass decline of 28% while IPSL simulations produced an average decline of 26%
325 (Table 4).

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

330

331 *3.5 – Temperature and net primary productivity relationships with total consumer biomass*

332 All MEMs showed a negative relationship between change in SST and change in total
333 consumer biomass, however the slopes of the linear regressions differed among models (Figure
334 8; Table S3). The greatest slopes were observed for mizer and Macroecological (-11.7 and -
335 11.5, respectively) and the smallest slope was observed for Ecopath with Ecosim (EwE; -3.2).
336 The amount of variation in delta total consumer biomass that was explained by delta SST was
337 greatest for DBPM ($R^2 = 0.66$), while the smallest was observed for EwE ($R^2 = 0.03$). Most
338 MEMs had a positive relationship between change in NPP and total consumer biomass, except
339 for Atlantis and mizer, both of which are regional models (Figure 9, Table S3). The model that
340 had the greatest positive slope was EwE ($2.3E+08$), while the greatest negative slope was
341 observed for mizer ($-4.3E+08$; Figure 9, Table S3). The highest amount of variation in delta total
342 consumer biomass that was explained by delta NPP was observed for EwE ($R^2 = 0.41$), while
343 the lowest value was observed for OSMOSE ($R^2 = 0.04$; Figure 9).

344

345 Discussion

346 Our results indicate that climate change projections by global and regional marine
347 ecosystem models covering the same location often differ in magnitude and sometimes
348 direction of biomass change. On average, global models projected greater biomass declines
349 than regional models, CMIP6 simulations projected greater biomass declines than CMIP5
350 simulations, and IPSL simulations projected greater biomass declines than GFDL simulations.
351 Overall, regional model projections were within the range of global model ensembles for less
352 than half of the time series.

353 Mismatches between global and regional models can be attributed to several factors.
354 The first is how ecology and the multifaceted effects of climate drivers interact and are
355 represented in each MEM. Global MEMs have been mostly developed for climate impact
356 studies and tend to include more climate forcing variables compared with the regional models
357 considered in this study (Table 1). For example, the divergent trends for Cook Strait and East

358 Bass Strait compared to global MEMs may reflect the fact that these two models were forced
359 with primary production changes only, and do not include temperature effects on bioenergetics
360 (Table 2). The latter can lead to more marked declines in biomass (Carozza, 2019, Heneghan et
361 al. 2021) and we observed variable relationships between delta total consumer biomass and
362 delta SST and NPP (Figures 8,9). On the other hand, including more regional species-specific
363 detail in temperature responses (as in the Hawaii therMizer model), can dampen or lead to
364 antagonistic effects as they propagate from individual physiological to community levels. An
365 analysis of global FishMIP MEMs showed that incorporating temperature effects led to biomass
366 changes of -35% to 3% while simulating climate change through low trophic level effects
367 (primary production; phytoplankton and/or zooplankton biomass or production) produced
368 biomass changes of -17% to 15% (Heneghan et al. 2021).

369 The ecological complexity of global and regional MEMs also differs, as regional models
370 often include more food web interactions and functional diversity than global models (Tables 1,
371 2). Using the same underlying regional size-based modelling framework and only temperature
372 altered, fish community responses were not generalizable among regions and were dependent
373 on the species or functional group position in the food web and food web structure (Reum et al.
374 2024). Compared to general trait-based food web model configurations, more detailed regional
375 food web structures led to damped effects of warming (Reum et al. 2024). This could explain
376 why global FishMIP MEMs overestimated the observed impacts in an analysis that used the
377 2003 European heat wave as a case study and compared global FishMIP MEM hindcasts of
378 ocean biomass to observations (Schewe et al. 2019). In a comparison of global and regional
379 MEMs in SE Australia, it was not the climate drivers but the representation of the ecology that
380 proved critical in explaining variation in model projections (Pethybridge et al. 2020; Fulton
381 2021). The regional Atlantis modelling framework, as applied in SE Australia, includes all the
382 same climate drivers as the global models but produced divergent results with global MEMs.
383 Differences between the Atlantis projections and those from global MEMs had many causes –

384 from variable representation of species or spatial sub-domains of the model (Pethybridge et al.
385 2020; Fulton 2021). However, one common dynamic leading to divergence between this
386 regional MEM and the overlapping global MEMs was due to ecologically mediated interactions.
387 The trophic resolution of Atlantis included more detail and more feedback pathways than in the
388 global MEMs. This meant that situations arose where decreased predation or competition acting
389 on a structurally important species for the food web outweighed direct climate effects on that
390 species (Pethybridge et al. 2020; Fulton 2021). In other instances, movement and
391 ontogenetically mediated processes and connectivity were important (Pethybridge et al. 2020;
392 Fulton 2021).

393 It has also been noted that among three commonly used regional MEM platforms -
394 Atlantis, EwE, and OSMOSE – there is system specificity in the degree of convergence and
395 divergence in projections (Smith et al. 2011). For example, running the same maximum
396 sustainable yield (MSY) fisheries simulations in each of these modelling frameworks in four
397 regional ecosystems (Benguela, Humboldt, and California Current systems and Southeast
398 Australia) showed clear variability in projected ecosystem responses (Smith et al. 2011).
399 However, in other instances various combinations of Atlantis, OSMOSE and Ecopath with
400 Ecosim models have projected similar general patterns of change to fishing (Travers et al.,
401 2010; Forrest et al. 2015; Smith et al. 2015; Ortega-Cisneros et al. 2018), where aggregated
402 properties showed more consistency across models than species level variables (Ortega et al.
403 2018). The specific degree of model responsiveness to perturbation is also typically system
404 specific, though in general terms the Atlantis modelling framework is less sensitive to ecosystem
405 perturbations, especially environmentally driven events, than Ecopath with Ecosim and
406 OSMOSE (Fulton and Smith 2004; Smith et al. 2011). Model sensitivity is an important
407 consideration when using models to guide policy advice, such as that provided by the IPCC at
408 the global scale, but also for interpreting models and providing strategic fisheries management

409 guidance as provided by the FAO at national, regional, and local scales (Blanchard and
410 Novaglio 2024).

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

429 Comparisons of CMIP5 ESM projections to regional observations of environmental
430 variables have concluded that coarsely resolved ESMs failed to accurately capture complex
431 patterns of circulation and elemental fluxes on the shelves along ocean margins of the
432 northwest Atlantic shelf (Laurent et al. 2021). ESMs underestimated observed chlorophyll and
433 nitrate, while a regional ocean modelling system (ROMS) biogeochemical model with higher
434 spatial resolution reproduced observed trends better (Laurent et al. 2021). Similar mismatches

435 between model projections and observed values were observed in regions we investigated,
436 such as for the Humboldt Current, where ESM projections of NPP were half the magnitude
437 compared to observed values – which was bias-corrected through statistical downscaling
438 (Lange et al. 2019; Oliveros-Ramos et al. 2024). Global and regional model mismatches have
439 also been observed in comparisons of hydrological models, where global models not calibrated
440 to regional observations failed to reproduce regional trends, with the recommendation that
441 regional models were more appropriate for regional water management (Gosling et al. 2016;
442 Hattermann et al. 2017).

443 Model calibration is a key source of variation among global and regional models. Fitting
444 models to time series of fisheries and biomass surveys has been a focus of many regional
445 models since their inception (Bentley et al., 2024) but is only just beginning for global models.
446 Regional models often use fisheries catch and fisheries independent survey data in the region
447 (Maureaud et al. 2021; Maureaud et al. 2024). Global models are often limited by observational
448 data for calibration, as only exclusive economic zone (EEZ) or large marine ecosystem (LME)
449 scale catch data are available. Data at these scales have many uncertainties, including how
450 fishing effort is spatially allocated and representativeness of total system removals (Watson
451 2017; Rousseau et al. 2019; Rousseau et al. 2024).

452 As ESM accuracy improves and computing power increases, the spatial resolution of
453 ESMs will increase and processes within coastal and shelf regions will be better resolved and
454 more consistent with regional oceanographic models. ESM runs undertaken at a 0.25 ° grid
455 scale do a better job of representing coastal and shelf features, such as fine scale eddies,
456 currents, and upwelling. Such changes in resolution can vastly improve the representation of
457 ecologically relevant features, such as production hotspots, both in global but also regional
458 modelling initiatives (Matear et al. 2013). As global scale ESMs and MEMs at both global and
459 regional scales continue to evolve, a central goal of FishMIP is to understand sources of
460 variation to build confidence in projections of climate change impacts on marine ecosystems at

461 regional scales and to provide guidance about which scales different models can be applied for
462 adaptation and mitigation planning. We note that the test undertaken here, comparing
463 projections at the end of the 21st century looks at the end point not the transition pathways, and
464 that we may be missing divergence that has real meaning at temporal scales meaningful for
465 decision makers.

466 A key source of uncertainty that has not yet been explored with global and regional
467 MEMs within FishMIP is socioeconomics. Market, management, and policy responses could be
468 more important than climate change for the future of fish populations (Cheung et al. 2021,
469 2024). To date, FishMIP has focussed on the climate change impact and treated the
470 socioeconomic impact simply by holding fishing levels constant at 2005 or 2015 levels or with a
471 no-fishing scenario. The SSPs were not specifically developed for marine systems and are not
472 directly applicable to socioeconomic factors for ocean systems. To address this important
473 consideration, FishMIP has established a Scenarios Working Group to develop ocean system
474 pathways (OSPs) of future fishing effort and ocean usage, based on the SSP scenarios, with
475 the intention that they be used in combination with RCP emissions scenarios in future FishMIP
476 simulation rounds (Maury et al. in revision).

477 The value of model ensembles lies in building confidence in model projections through
478 the exploration of multiple models. When the exact processes and structures to represent
479 observations are unknown, comparison of varying model formulations provides a hypothesis
480 testing approach. If models agree in projections, there is greater confidence that key processes
481 and structures have been represented. Conversely, large variation in model projections points to
482 missing knowledge. The global and regional models explored here employ different approaches
483 to represent marine ecosystems due to imperfect knowledge. Our study highlights areas for
484 future exploration but cautions that there is high uncertainty about how ecology and eco-
485 evolutionary processes will unfold in rapidly changing marine environments. Of high importance
486 are additional physical processes that function at scales not represented by the resolution of the

487 ESMs but are implicit in regional models that have been bias corrected. Our comparison of
488 global and regional MEMs highlights that there are key uncertainties for climate change
489 projections of biomass change at regional scales. While management and conservation
490 organizations require this information for adaptation and mitigation planning, it should be
491 recognized that projections at these scales remain uncertain in many regions. FishMIP has
492 plans to continue to address these uncertainties at regional scales to build confidence in
493 projections of climate change impacts on marine ecosystems worldwide (Ortega-Cisneros et al.
494 In revision; Murphy et al. In revision).

495

496

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513
514 Open Research

515 The R scripts used to execute the analyses in the paper can be found at <https://github.com/Fish->
516 [MIP/Regional_v_Global](https://github.com/Fish-MIP/Regional_v_Global). The simulations used for the study are available at ISIMIP data
517 repository (<https://data.isimip.org/>) under the tree 'ISIMIP2a/OutputData/marine-
518 fishery_regional' and 'ISIMIP3a/OutputData/marine-fishery_regional', for instructions to get
519 access see <https://www.isimip.org/gettingstarted/data-access/>.

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Table 1. Global and regional FishMIP models with key characteristics. CMIP5 and CMIP6 indicate which models participated in each simulation round. Adapted from Tittensor et al. 2021 and Tittensor et al. 2018.

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	Sized-based communities (epipelagic, migratory, mesopelagic, bathypelagic) and focus species	Maury (2010)

					concentration, light irradiance. All fields 3D and monthly		
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 commercial ly 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. 2011
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	Christensen et al. 2015; Coll et al., 2020

Ecopath with Ecosim	Regional	Trophodynamic (if Ecospace included also composite with species distribution model included)	X	X	NPP, bottom O ₂ , SST	from bacteria to whales, and integrates explicit information for 3 400 species of vertebrates, invertebrates and primary producers All trophic levels and taxonomic groups can be represented, including age structured groups	Christensen and Walters 2004; 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	Gascue, 2005; du Pontavice et al., 2021
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 gram to 1 tonne	Jennings and Collingridge (2015)
mizer	Regional	Size-based		X	Vertically integrated, size-fractionated phytoplankton and	Single plankton community, species-specific fish and	Scott et al. 2014

OSMOSE	Regional	Composite (size- and trait-based)	X		zooplankton carbon, ocean temperature	Fish and invert species and functional groups	Shin and Cury 2004, Travers et al. 2009
ZooMSS	Global	Composite (size- and trait-based; functional group structure)	X	X	SST, SSS, NPP, phytoplankton and zooplankton concentration	Flagellates, ciliates, omnivorous copepods, carnivorous copepods, larvaceans, salps, chaetognaths, euphausiids, jellyfish, fish	Heneghan et al. 2020

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Table 2. Regions and regional marine ecosystem models (MEMs) investigated in this study with key characteristics. 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.

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 O ₂	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. 2020

Central North Pacific	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
SE Australia	Atlantis	3 000 000	Yes	thetao, O2, intpp		Fulton et al. 2014
Southern Benguela	Atlantis; Ecopath with Ecosim	220 000	Yes; no	intpp; thetao	Delta	Ortega Cisneros et al. 2017 Shannon et al. 2020

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Table 3. Summary of results. 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.

Region	CMIP5				CMIP6			
	SST		NPP		SST		NPP	
	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				
SE 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

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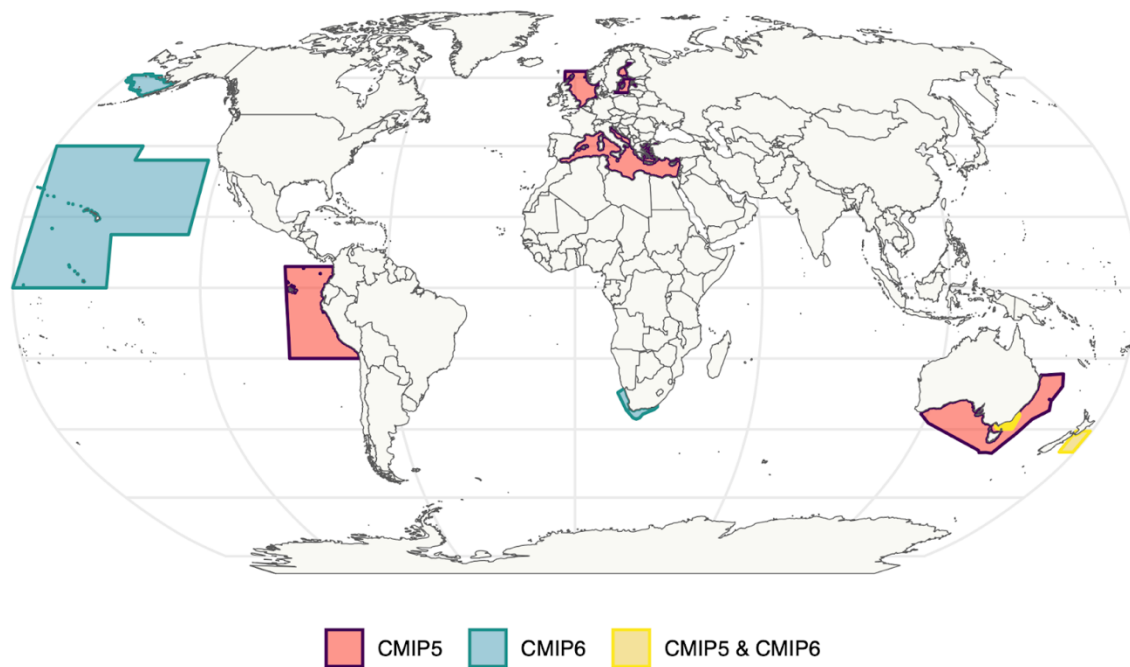
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Table 4. Summary of results. Mean percent total consumer biomass change from 2090-2099 relative to 1990-1999 for regional and global models forced by GFDL and IPSL Earth system models in CMIP5 and CMIP6. Note that SE Australia regional Atlantis model only ran simulations until 2050 and results for SE Australia are shown for 2040-2049 relative to 1990-1999.

Region	CMIP5				CMIP6			
	GFDL		IPSL		GFDL		IPSL	
	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				
SE 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

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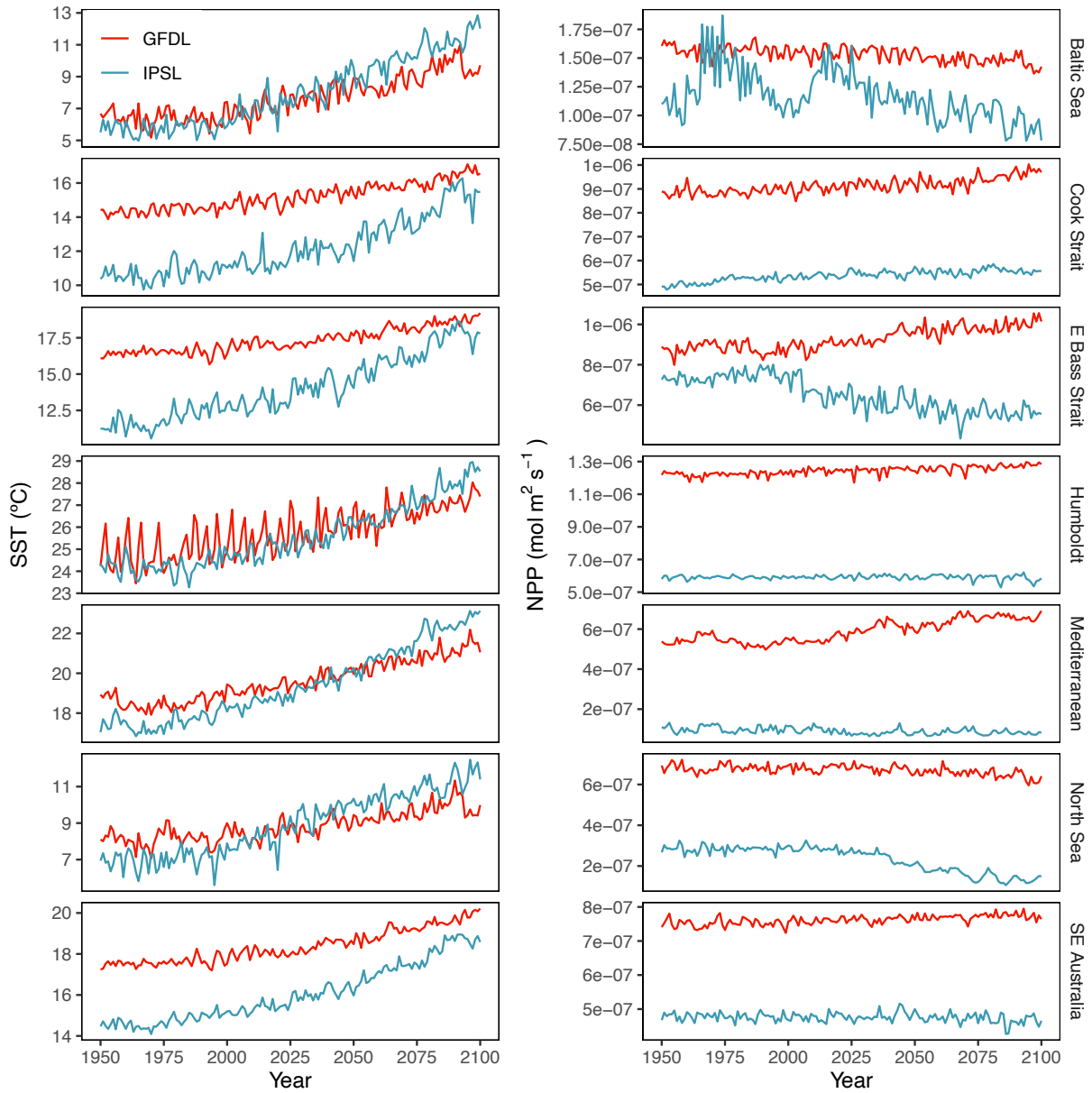
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1056 Figure 1. Location of FishMIP regional model domains that completed CMIP5, CMIP6, and both
1057 CMIP5 & CMIP6 simulations. From left to right, regions are: Central North Pacific, Eastern
1058 Bering Sea, Humboldt Current, North Sea, Mediterranean Sea, Baltic Sea, Southern Benguela,
1059 South East Australia, East Bass Strait, and Cook Strait.

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1069 Figure 2. CMIP5 Earth system model SST and NPP forcing variables for GFDL (red) and IPSL
 1070 (blue) by region for the RCP 8.5 scenario.

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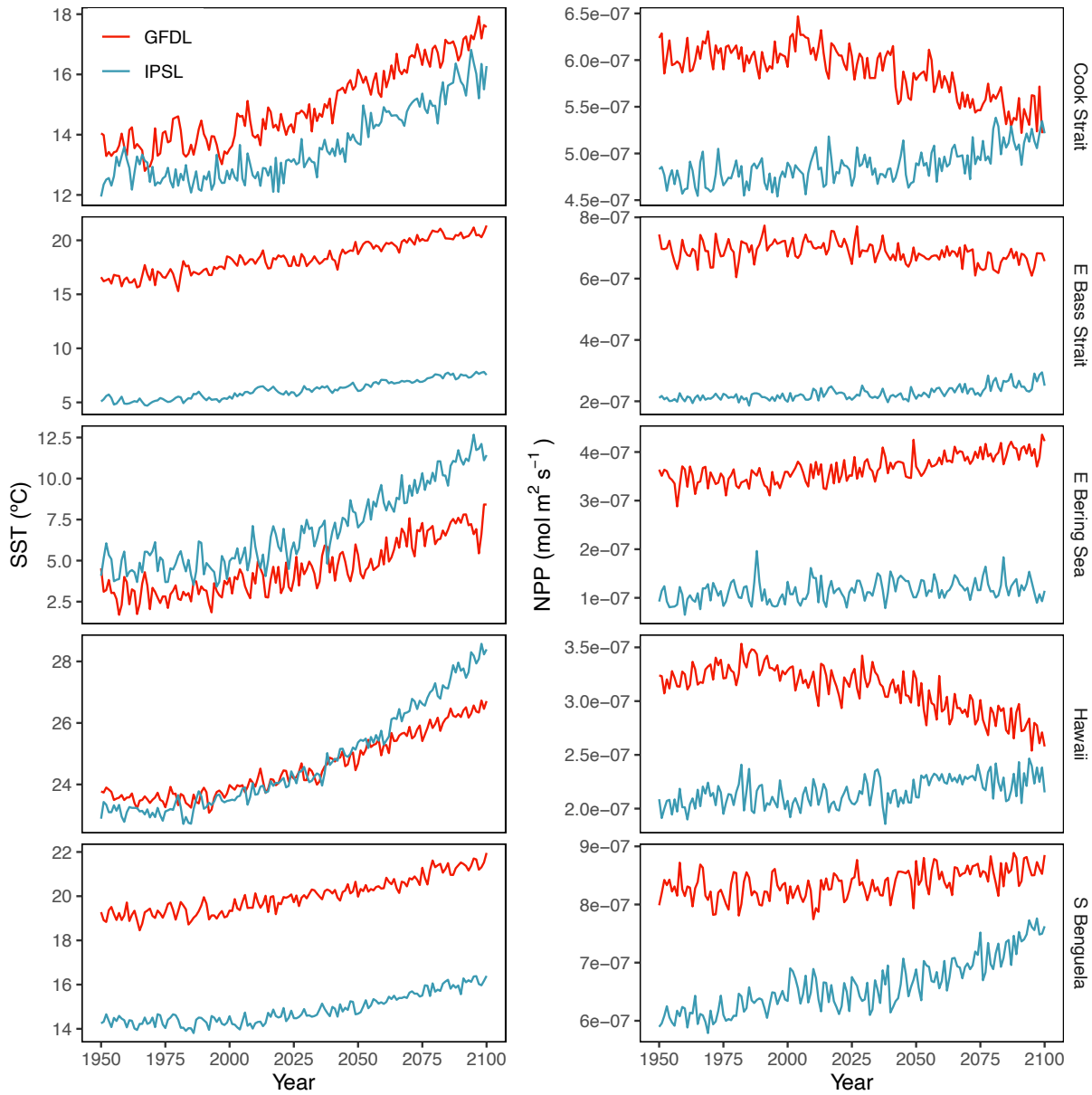
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1079 Figure 3. CMIP6 Earth system model SST and NPP forcing variables for GFDL (red) and IPSL
1080 (blue) by region for the SSP5-8.5 scenario.

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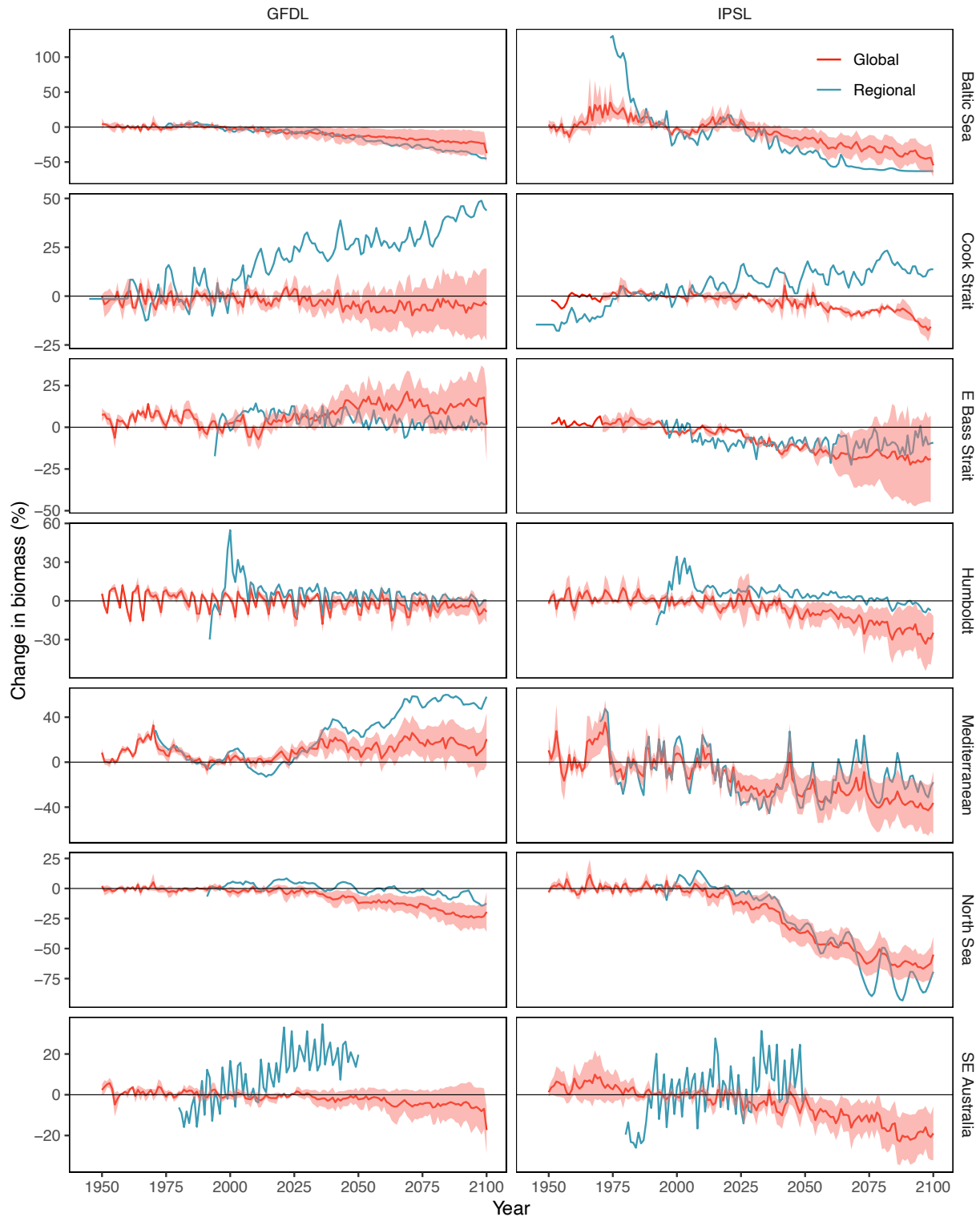
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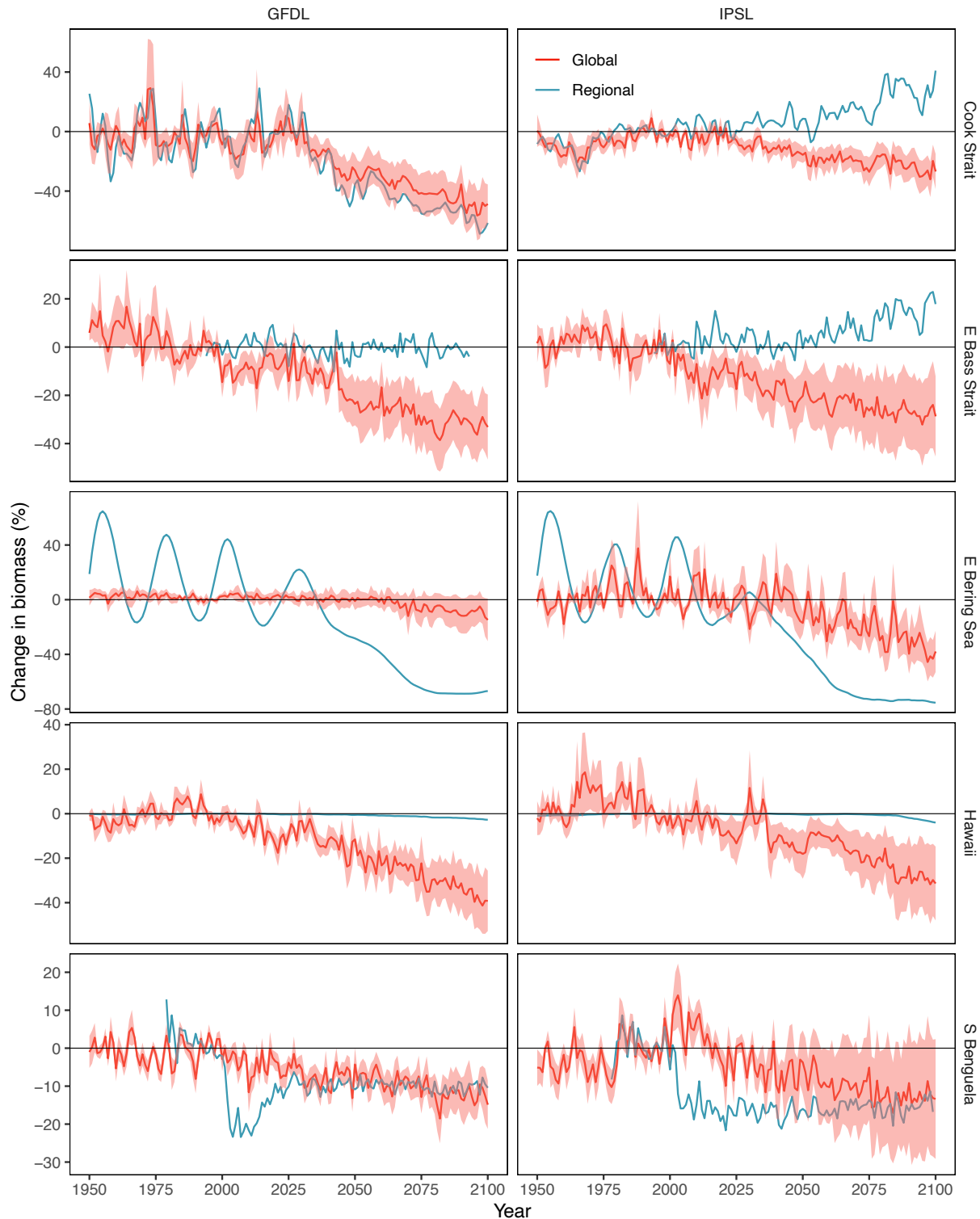
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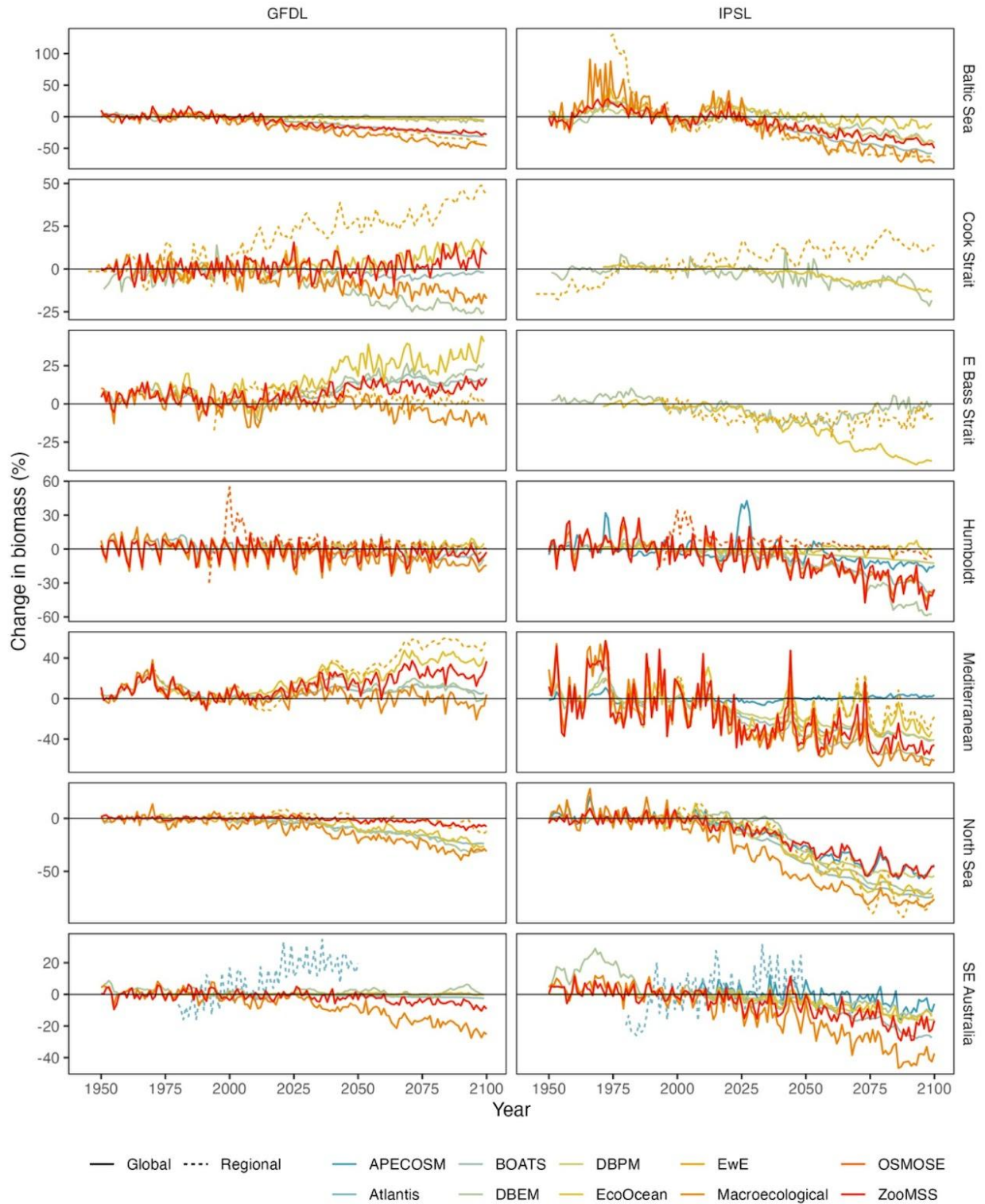
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Figure 4. CMIP5 simulations for global (red) and regional (blue) models showing percent change in total consumer biomass relative to 1990-1999 for GFDL and IPSL under no-fishing scenarios and RCP 8.5. Shaded areas indicate standard deviation for the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



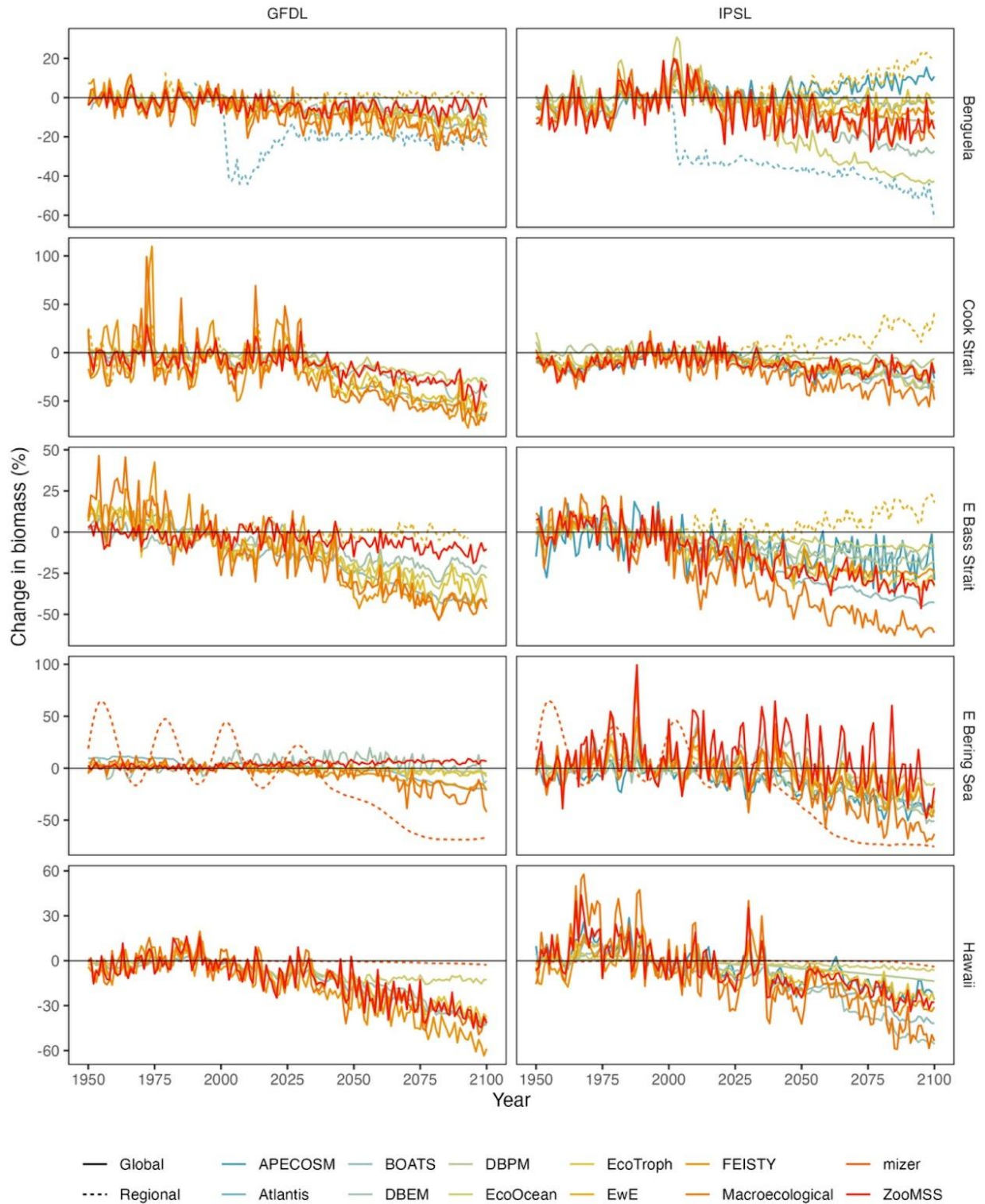
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Figure 5. CMIP6 simulations for global and regional models showing percent change in total consumer biomass relative to 1990-1999 for GFDL and IPSL under no-fishing scenarios and SSP5-8.5. Shaded areas indicate standard deviation for the global model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



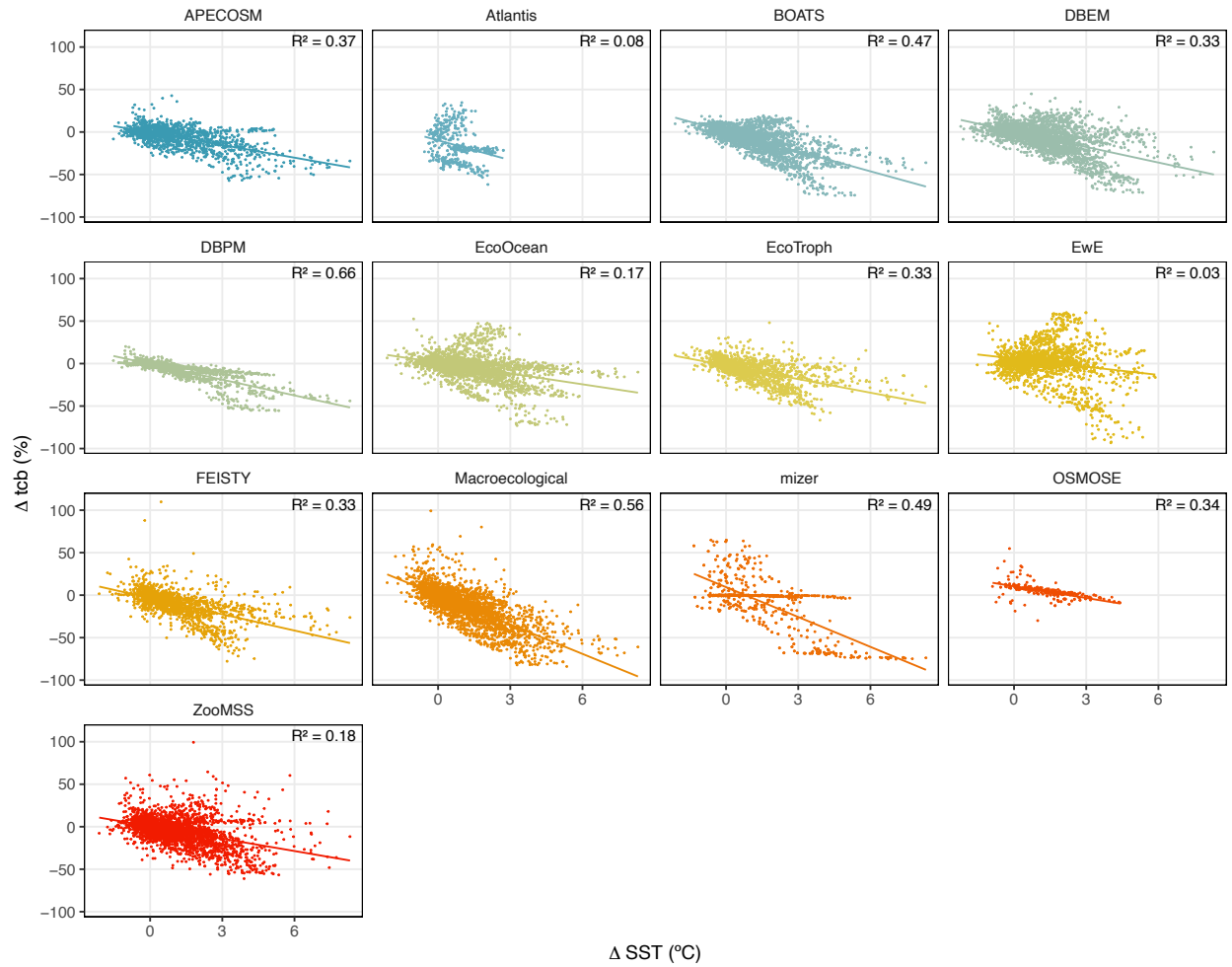
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Figure 6. CMIP5 simulations for global and regional models showing percent change in total consumer biomass relative to 1990-1999 for GFDL and IPSL under no-fishing scenarios and RCP8.5. Note that the regional model in SE Australia only ran simulations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



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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 RCP8.5.



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1112 Figure 8. Relationship between change in total consumer biomass (delta tcb) and change in sea
 1113 surface temperature (delta SST) by model.

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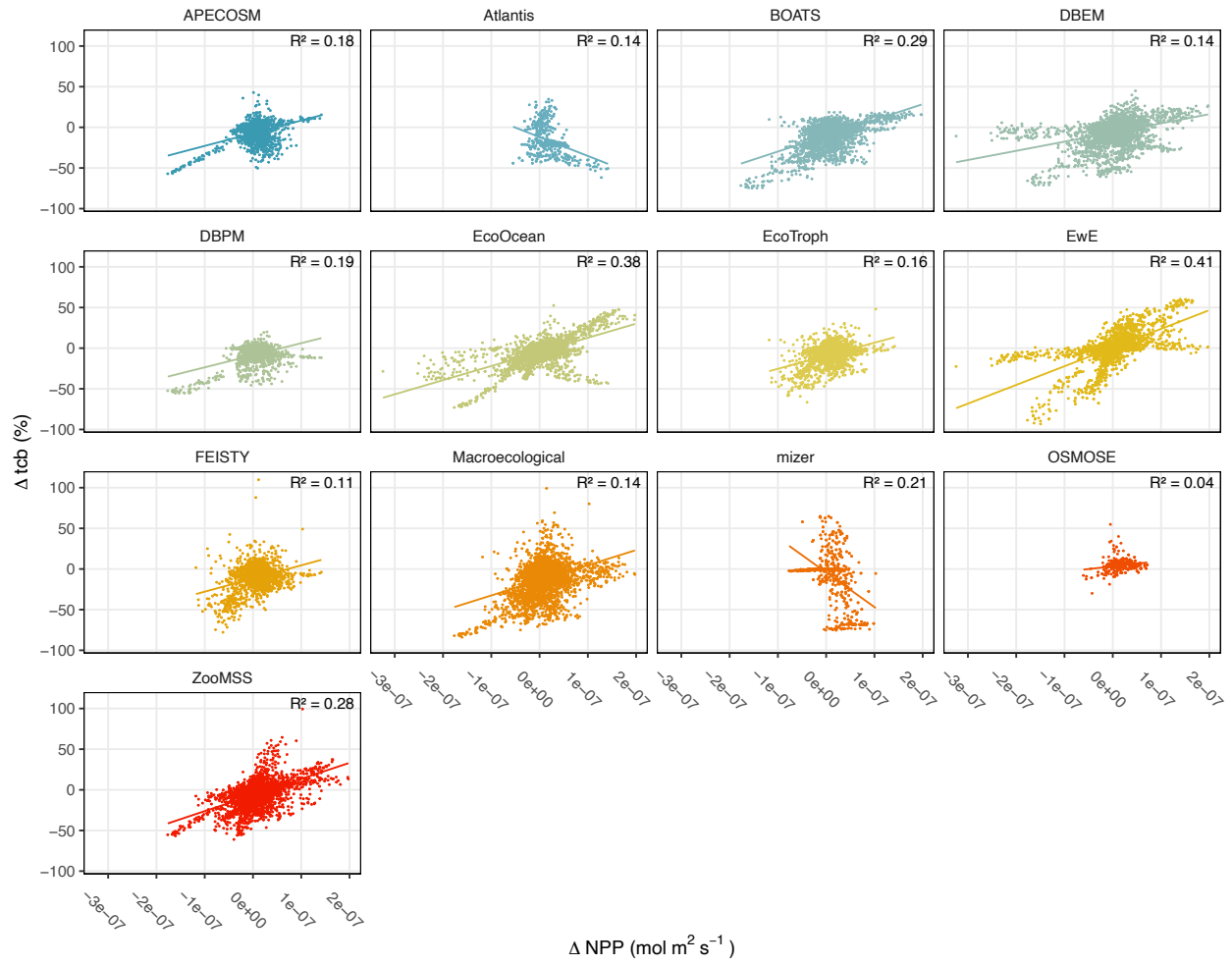
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1123 Figure 9. Relationship between change in total consumer biomass (delta tcb) and change in net
 1124 primary productivity (delta NPP) by model.

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