

1 **Dynamically Downscaled Future Projections of the Northwest Atlantic Ocean**
2 **Across Low to High Emissions Scenarios**

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24 **Abstract**

25 We used a high-resolution (1/12°) Modular Ocean Model version 6 implementation for the
26 the Northwest Atlantic Ocean (MOM6-NWA12) to dynamically downscale Geophysical Fluid
27 Dynamics Laboratory Earth System Model version 4.1 (GFDL-ESM4.1) projections for the 21st
28 century. Simulations were conducted under four different Coupled Model Intercomparison
29 Project Phase 6 emission scenarios. MOM6-NWA12 accurately simulates the spatial patterns of
30 sea surface temperature, salinity, and dynamic sea surface height (SSH) during the historical
31 period. In particular, the Gulf Stream’s strength, position, recirculation, and separation from the
32 U.S. East Coast are significantly improved in MOM6-NWA12 compared to the coarse-resolution
33 GFDL-ESM4.1. Projected end-of-century warming varied strongly between scenarios, from ~
34 4 °C under prior "worst case" emissions scenarios (SSP-585), 2~3 °C under intermediate
35 scenarios (SSP-245, SSP-370) more consistent with current trajectories, to ~ 1 °C under
36 aggressive mitigation (SSP-126). Consistent with a significant weakening of the Atlantic
37 Meridional Overturning Circulation projected by GFDL-ESM4.1, MOM6-NWA12 shows a
38 substantial volume transport reduction in the Western Boundary Current (WBC) system (i.e.,
39 Yucatan Current, Florida Current, Antilles Current, and the Deep Western Boundary Current)
40 toward the late 21st century (between 23 and 38 %, varying by scenario). This projected
41 weakening of the WBC system and the associated reduction in the coastal upwelling of cold,
42 fresh subsurface waters lead to a significant increase in ocean temperature, salinity, and dynamic
43 SSH along the U.S. southeast and northeast Coasts, particularly in the South Atlantic Bight.

44

45 **1. Introduction**

46 The Northwest Atlantic Ocean (NWA), including the United States (US) East and Gulf
47 Coasts, and the Caribbean Sea, is characterized by large spatial heterogeneity in ocean conditions
48 and complex interactions between ocean circulation and biogeochemistry (e.g., Wang et al.,
49 2013; Muller-Karger et al., 2015; Wanninkhof et al., 2015; Gomez et al., 2020; 2022; Friedrichs
50 et al., 2019; Zhang et al., 2023). A myriad of living marine resources inhabit this region,
51 including the South Florida coral reefs, lobsters and shellfish, demersal fish species like
52 groupers, snappers, cod and haddock, and migratory pelagic fish species like bluefin tuna and
53 king mackerel, all of whose distribution and abundance are influenced by changes in ocean
54 temperature and circulation (e.g., Weinberg 2005; Bell et al., 2015; Karnauskas et al., 2013,
55 2015; Tanaka et al., 2020). Previous studies have shown that portions of the ocean ecosystem are
56 modulated by large scale climate variability, such as El Niño Southern Oscillation and Atlantic
57 Multidecadal Oscillation, through associated changes in ocean circulation and river runoff (e.g.,
58 Alexander and Scott, 2008; Gomez et al., 2019, 2024). Moreover, the region is undergoing
59 sustained warming, particularly along the US South and East Coasts, where the surface
60 temperature warming rate was about two or three times faster than that of the global ocean
61 average for 1970-2020 (e.g., Pershing et al., 2015; Wang et al., 2023).

62 Previous studies have also attributed regional acceleration and spatial variation of the US
63 East Coast sea level rise to ocean circulation changes, including a weakening of the Gulf Stream
64 (e.g., Ezer et al., 2013; Ezer, 2015; Goddard et al., 2015; Park and Sweet, 2015; Dong et al.,
65 2019), warming of the Gulf Stream and the entire subtropical gyre (e.g., Domingues et al., 2018;
66 Volkov et al., 2019, 2023; Steinberg et al., 2024; Huang et al., 2025), and a slowdown of the
67 Atlantic Meridional Overturning Circulation (AMOC, e.g., Levermann et al., 2005; Little et al.,
68 2017, 2019). While progress has been made in understanding ocean conditions off the US East

69 and Gulf Coasts and in the Caribbean Sea, substantial uncertainties still remain regarding future
70 changes in regional ocean circulation and their sensitivity to greenhouse gas emissions scenarios.
71 Consequently, it is essential to investigate projected changes in ocean circulation across
72 scenarios to improve our understanding of future ocean conditions and ecosystem dynamics
73 across the Northwest Atlantic.

74 Global models, such as General Circulation models (GCMs) and Earth System Models
75 (ESMs), offer valuable insights into future ocean conditions under various climate scenarios.
76 However, they are often limited in spatial resolution due to computational constraints and may
77 face significant uncertainties due to limitations in representing the fine-scale ocean circulation
78 and thermohaline structures, particularly in coastal regions. Hence, high-resolution, eddy-
79 resolving ocean models are critical for addressing these limitations, providing improved
80 representations of historical ocean circulation across multiple timescales and offering more
81 reliable future projections (e.g., Drenkard et al., 2021). To leverage the benefits of resolving
82 eddies and shelf-scale circulation while lowering the computational burden, multiple studies
83 have applied dynamic downscaling techniques to better understand and project regional impacts
84 of climate change on NWA ocean systems (e.g., Liu et al., 2012, 2015; Alexander et al., 2020;
85 Shin and Alexander, 2020; Rutherford et al., 2024).

86 By refining the outputs of GCMs/ESMs using high-resolution regional models, dynamical
87 downscaling can capture finer-scale processes and interactions that are often missed by coarse-
88 resolution models. For example, the projected weakening of the Loop Current and associated
89 reduction in warm water transport through the Yucatan Channel are poorly resolved in Coupled
90 Model Intercomparison Project Phase 5 (CMIP5) and CMIP6 global models, leading to an
91 overestimation of SST warming over the northern part of the Gulf of America (GoA; a.k.a. Gulf

92 of Mexico) and underestimation of SST warming along the West Florida shelf - an issue better
93 addressed by high-resolution downscaled models (e.g., Liu et al., 2012, 2015). Similarly,
94 systematic CMIP model biases in the Gulf Stream representation led to under-estimation of
95 warming of Northeast U.S. waters associated with future changes in the Gulf Stream path (Saba
96 et al., 2016).

97 In line with these efforts, the National Oceanic and Atmospheric Administration (NOAA)
98 Changing Ecosystems and Fisheries Initiative (CEFI) modeling team has developed a high-
99 resolution regional ocean model - the Modular Ocean Model version 6 at $1/12^\circ$ horizontal
100 resolution (~ 8 km) for the Northwest Atlantic Ocean (MOM6-NWA12; Ross et al., 2023).
101 MOM6-NWA12 is configured to capture key regional features and simulate ocean dynamics in
102 the Northwest Atlantic with high fidelity. This model provides a valuable framework for
103 studying the complex interactions between large-scale processes and local features that govern
104 both physical and biogeochemical variability in the region. MOM6-NWA12 demonstrates strong
105 performance in reproducing a broad range of observed physical and biogeochemical conditions
106 during the hindcast period (1993-2020, Ross et al., 2023). Furthermore, it exhibits skillful
107 seasonal to decadal forecast capabilities for SST anomalies (SSTAs, Koul et al., 2024; Ross et
108 al., 2024). However, while MOM6-NWA12 has shown promise for seasonal and decadal
109 predictions, its potential for multi-decadal (30~100 years) projections remains unexplored.

110 In this study, we use the high-resolution MOM6-NWA12 model to dynamically downscale
111 future projections from the Geophysical Fluid Dynamics Laboratory's Earth System Model
112 version 4.1 (GFDL-ESM4.1) for the Northwest Atlantic Ocean. With this downscaling
113 procedure, we aim to generate more accurate and regionally relevant projections of future ocean
114 conditions. Unlike prior studies, which used a single greenhouse gas emissions scenario, we

115 consider the range of potential ocean futures from projections using four different scenarios (i.e.,
116 Shared Socioeconomic Pathways; SSP-126, SSP-245, SSP-375, and SSP-585) spanning
117 aggressive mitigation to high emissions pathways beyond our current trajectory. This allows us
118 to identify the NWA responses to future climate change that are sensitive to emissions pathways
119 from those that are not, and to explore mechanisms underlying these contrasts. We also build on
120 prior work to understand regional hot-spots of ocean change and their drivers. This approach
121 enhances our understanding of regional ocean dynamics and supports the development of
122 effective mitigation and adaptation strategies in response to climate change.

123

124 **2. Model and downscaling settings**

125 2.1 MOM6-NWA12

126 MOM6-COBALT-NWA12 is a coupled ocean circulation and sea ice model which can also
127 include coupled ocean biogeochemistry (Ross et al., 2023). Here, we consider a “physics-only”
128 implementation of this system (i.e., MOM6-NWA12), which has also been applied for seasonal
129 and decadal prediction applications (Ross et al., 2024; Koul et al., 2024). The model spans the
130 Northwest Atlantic Ocean, including the Caribbean Sea, the Gulf Coast, and the U.S. East Coast
131 98°W - 36°W and 5°N - 52°N , and has 775×845 grid points (Fig. 1). The nominal horizontal
132 resolution is about $1/12^{\circ}$. The zonal distance between grid points varies with latitude, from ~ 9
133 km at the southern boundary to ~ 5 km at the northern boundary. The model has 75 vertical
134 layers using a z^* -coordinate, a depth coordinate rescaled with the free surface (Adcroft and
135 Campin, 2004). The vertical resolution is finest near the surface, where the layer thickness is 2
136 m, increasing gradually with depth to a maximum thickness of 250 m above the deepest model
137 depth of 6500 m. The model’s subgrid-scale parameterizations are adapted from the $1/4^{\circ}$ global

138 MOM6, with updates and modifications to account for the increased horizontal resolution (Ross
139 et al., 2023). MOM6-NWA12 has the option of using time steps for thermodynamics and ocean-
140 biogeochemistry longer than the baroclinic time step, which significantly reduces the running
141 time for coupled model simulations. More detailed model description, additional features, and
142 parameterization settings can be found in Ross et al. (2023).

143

144 2.2 GFDL-ESM4.1

145 NOAA GFDL's Earth System Model version 4.1 (GFDL-ESM4.1, Dunne et al. 2020)
146 provides the boundary conditions for the MOM6-NWA12 simulations. We carried out four sets
147 of MOM6-NWA12 simulations downscaling GFDL-ESM4.1 simulations under SSP-126, SSP-
148 245, SSP-375, and SSP-585 scenarios (O'Neill et al, 2016). GFDL-ESM4.1 is built on a basis of
149 GFDL's AM4.0 atmospheric model, which has 49 hybrid vertical layers and approximately $1^\circ \times$
150 1° horizontal resolution (Zhao et al., 2018a, 2018b), using the Finite Volume version 3 (FV3;
151 Lin, 2004) dynamical core with advanced parameterizations of moist convection, clouds,
152 radiation, topographical drag, and several other physical processes from its previous version. The
153 land model in GFDL-ESM4.1 is GFDL's Land Model version 4.1 (LM4.1; Shevliakova et al.,
154 2024), which improved radiative properties for vegetation, soil, and snow, and updated
155 hydrology in LM4.0. The ocean model component of GFDL-ESM4.1 uses MOM6 (Adcroft et
156 al., 2019), configured with a nominal resolution of $1/2^\circ$ horizontally and 75 vertical hybrid z^* -
157 coordinate layers within the Arbitrary-Lagrangian-Eulerian algorithm (Adcroft & Hallberg,
158 2006), and the GFDL's Sea Ice Simulator (SIS2; Adcroft et al., 2019). More detailed model
159 description, additional features, and parameterization settings of GFDL-ESM4.1 can be found in
160 Dunne et al. (2020). It is noted that the equilibrium climate sensitivity (ECS) of GFDL-ESM4 is

161 approximately 2.6 K, which is at the lower end of the sensitivity range for CMIP6 models
162 (Dunne et al., 2020; Meehl et al., 2020; Sentman et al., 2026).

163

164 2.3 Reanalysis datasets

165 The global reanalysis datasets used to force the retrospective ocean simulation of Ross et al.
166 (2023) are also used here for bias corrections of ocean lateral boundary conditions, surface
167 forcings, and river discharge for the historical and future projections derived from GFDL-
168 ESM4.1 (Table 1). We use the high-resolution ($1/12^\circ$) Global Ocean Physics Reanalysis
169 (GLORYS12; Lellouche et al., 2021) to derive monthly ocean temperature, zonal and meridional
170 speeds of ocean current, salinity, and sea surface height (SSH) for 1993-2020 period. We also
171 use 3-hourly European Centre for Medium-Range Weather Forecast (ECMWF) Reanalysis
172 version 5 (ERA5) atmospheric reanalysis datasets to derive near-surface zonal and meridional
173 winds, near-surface air temperature, specific humidity, precipitation, and downwelling short- and
174 long-wave radiative fluxes (Hersbach et al., 2020).

175 For river discharge, we use the gridded daily Global Flood Awareness System (GloFAS)
176 version 3.1 reanalysis (Alfieri et al., 2020). Although global river discharge driven by climate
177 change exhibits a clear positive trend, the projected changes in river discharge in our regional
178 model domain (i.e., the southern and eastern US seaboards) are insignificant and uncertain
179 during the first half of the 21st century (Muller et al., 2024). Therefore, we did not consider
180 future changes in runoff in this single-model downscaling and instead applied the daily mean
181 climatology (1993–2020) of GloFAS river runoff data for the entire simulation period (1950–
182 2100). As a result, the potential effects of regional runoff change on nearshore salinity and sea
183 level are not addressed in this study.

184

185 **Table 1.** Reanalysis products and associated variables used for the bias correction and validation

186 in this study.

Reanalysis product	Variables	Frequency
ERA5	2 m temperature	3 hourly
	2 m specific humidity	3 hourly
	10 m zonal wind	3 hourly
	10 m meridional wind	3 hourly
	Sea level pressure	Daily
	Liquid precipitation rate	Daily
	Snowfall rate	Daily
	Downward shortwave radiative flux	Daily
	Downward longwave radiative flux	Daily
GLORYS12	Sea water potential temperature	Monthly
	Sea water salinity	Monthly
	Sea water zonal velocity	Monthly

	Sea water meridional velocity	Monthly
	Sea surface height	Monthly
GloFAS	River runoff rate	Daily

187

188 2.4 Mean bias correction

189 To reduce systematic biases in the GFDL-ESM4 outputs, we applied a climatological mean
 190 bias correction to the lateral ocean boundary conditions (BCs) and surface atmospheric forcing
 191 fields using the GLORYS12 and ERA5 reanalysis datasets as follows:

$$192 \text{ Bias-corrected variables} = \text{GFDL-ESM4} + \text{Delta}$$

$$193 \text{ Delta} = \langle \text{Reanalysis} \rangle - \langle \text{GFDL-ESM4} \rangle$$

194 where the GFDL-ESM4 refers to the raw outputs from the GFDL-ESM4 simulations.

195 $\langle \text{Reanalysis} \rangle$ and $\langle \text{GFDL-ESM4} \rangle$ are the long-term averaged annual cycles from the reanalysis
 196 and GFDL-ESM4 simulations for the 1993-2020 period, respectively. For the GFDL-ESM4
 197 simulations, we merged the data from its historical simulation (1993-2014) with the data from
 198 the future period in each of the four SSP scenarios (2015-2020). The long-term (1993-2020)
 199 means for each month of the year determine the mean annual cycle of the ocean variables, while
 200 the long-term means for each 3-hourly frequency of the year determine the mean annual cycle of
 201 the atmospheric variables. The mean bias correction terms, Delta, were then added to the GFDL-
 202 ESM4 outputs for the entire simulation period (1950-2100) to correct the mean biases. This bias
 203 correction method ensures that mean states of MOM6-NWA12 during the historical period
 204 (1993-2020) are comparable to those in the reanalysis datasets and in Ross et al., (2023).

205 It is noted that our “Delta method” shares similarities with approaches from previous studies
206 (Liu et al., 2012; 2015; Alexander et al., 2020; Shin and Alexander, 2020; Pozo-Buil et al.,
207 2021), which replace model climatology with reanalysis climatology to reduce mean biases.
208 However, our method fundamentally differs in its treatment of high-frequency atmospheric
209 forcing. While those previous studies utilized high-frequency atmospheric forcing (i.e., daily
210 time scales) from historical reanalysis datasets for future projections — thereby assuming that
211 high-frequency forcing remains unchanged in the future — we retained the model-generated
212 high-frequency atmospheric variability (e.g., 3-hourly and daily). We took this approach to
213 ensure more consistent climate projections, recognizing that weather and climate are
214 interdependent. Indeed, not only does weather depend strongly on low-frequency variability
215 (e.g., weather conditions during the different phases of ENSO are substantially different), but
216 also weather statistics can substantially change under future climate conditions (e.g., Cheng et
217 al., 2012; Jeong and Sushama, 2019).

218 A second notable difference between the methodology herein and past Northwest Atlantic
219 downscaling studies is the replacement of limited “time slice” experiments with a continuous
220 integration over the historical and future periods. The continuous integration approach requires
221 more computational investment (time slices were generally compared across 10-30 year intervals
222 while continuous integrations required 150 years), but it allows for a more complete analysis of
223 the emergence of significant differences between scenarios and historical conditions, and
224 between the scenarios themselves (e.g., Drenkard et al., 2021).

225 Finally, for sea level, we note that both GFDL-ESM4.1 and MOM6-NWA12 utilize the
226 Boussinesq approximation, which conserves ocean volume. The dynamic sea level in both
227 models can respond to local density changes driven by local warming and freshening (e.g.,

228 Steinberg et al., 2024). However, these models cannot simulate global mean sea-level (GMSL)
229 rise caused by thermosteric expansion or added mass from ice melt (e.g., Greatbatch, 1994;
230 Griffies and Greatbatch, 2012; Griffies et al., 2014). Furthermore, to prevent potential drifts in
231 the basin-integrated water volume associated with the lateral open boundary conditions, we
232 explicitly constrain the basin-averaged SSH anomaly to be zero throughout all MOM6-NWA12
233 simulations. Consequently, the SSH changes derived from MOM6-NWA12 strictly represent the
234 dynamic redistribution of water mass driven by regional ocean circulation and local steric
235 adjustments.

236

237 **3. Results**

238 3.1. Model validation for the historical period

239 To evaluate the performance of GFDL-ESM4.1 and MOM6-NWA12 in the historical period,
240 we first compared model-derived climatologies of SST, sea surface salinity (SSS), and surface
241 current speed against the GLORYS12-derived climatological patterns (Fig. 2 and Supplementary
242 Fig. S1). The GFDL-ESM4.1 outputs show considerable biases in the SST and SSS mean
243 patterns. Specifically, the SST has a warm bias $>3^{\circ}\text{C}$ in the Mid-Atlantic Bight (MAB), and a
244 cold bias $>2^{\circ}\text{C}$ in magnitude along the North Atlantic Current path compared to the data-
245 assimilative GLORYS12 product (Fig. 2d). GFDL-ESM4.1 SSS is saltier than the GLORYS SSS
246 over the entire domain (Fig. 2e), especially in the MAB and along the US Gulf Coast, where the
247 bias reaches values >3 PSU. These biases are greatly reduced in the MOM6-NWA12. For
248 example, the SST biases in the MAB and along the Gulf Stream are $\sim 1^{\circ}\text{C}$ or lower (Fig. 2g).
249 The SSS shows a small negative bias, except over the Gulf of Maine, where SSS is
250 overestimated by about 0.7 PSU (Fig. 2h).

251 The bias patterns for surface ocean velocity reveal that ESM4.1's Loop Current is more
252 diffusive and extended more northward compared to that in GLORYS12 (Fig. 2f and
253 Supplementary Fig. S1c). This appears to be due to the coarse horizontal resolution of GFDL-
254 ESM4.1 ($\sim 0.5^\circ$), which is not fine enough to resolve the Loop Current dynamics (e.g., Liu et al.,
255 2012; 2015). In addition, ESM4.1's Gulf Stream along the South Atlantic Bight (SAB) is weaker
256 and slightly shifted away from the US East Coast compared to that in GLORYS12
257 (Supplementary Fig. S2). In contrast, MOM6-NWA12 shows much improvement of both the
258 Loop Current and Gulf Stream System (Fig. 2i and Supplementary Fig. S1f). For instance, the
259 Florida Current (beginning of the Gulf Stream System) in MOM6-NWA12 flows closer to the
260 coastline compared to that in GFDL-ESM4.1 with speeds exceeding 1 m s^{-1} , a pattern similar to
261 GLORYS12 (Fig. 2f and Fig. 2i).

262 After the separation of the Gulf Stream from the US East Coast, the sluggish flow in GFDL-
263 ESM4.1 is shifted northward compared to GLORYS12, both at its separation point and as it
264 travels eastward across the North Atlantic (Fig. 2f). In contrast, the faster Gulf Stream in
265 MOM6-NWA12 (Fig. 2i) is shifted southward at its separation from the coast before regaining
266 consistency with the data-assimilative GLORYS12 path to the east. This is more clearly shown
267 in Supplementary Fig. S2, which shows the position of the Gulf Stream core as a 15°C isotherm
268 at 200m (e.g., Sanchez-Franks and Zhang, 2015; Hameed et al., 2018; Seidov et al., 2019; Ross
269 et al., 2023). A northward shift in the Gulf Stream position is typical in low-resolution ocean
270 models and has been attributed to misrepresentation of nonlinear vorticity boundary dynamics.
271 While it is not clear why the Gulf Stream in MOM6-NWA12 is shifted southward, previous
272 studies have indicated that the separation of the Gulf Stream in an eddy-resolving model is very

273 sensitive to the choices made for subgrid scale parameterizations (e.g., Chassignet and Marshall,
274 2008).

275 Consistent with the surface current speed and position of the Gulf Stream, GFDL-ESM4.1
276 displays a large negative bias in the dynamic sea surface height (SSH), immediately south of the
277 Gulf Stream core and its extension to the North Atlantic Current. Connected with this, the
278 recirculation gyre south of the Gulf Stream (35°N- 73°W), known as the Worthington Gyre
279 (Worthington, 1976), is almost completely absent in GFDL-ESM4.1 (Fig. 3b and d). On the
280 other hand, the spatial pattern of the dynamic SSH in MOM6-NWA12 exhibits improved
281 agreement with that in GLORYS12 (Fig. 3c and e), reproducing a Worthington Gyre albeit
282 weaker than GLORYS12. Given that the Worthington Gyre is a long-term mean rectification of
283 the Gulf Stream rings and instability waves not resolved at coarse resolution, it is not surprising
284 that the recirculation gyre is better represented in MOM6-NWA12 while it is nearly absent in
285 GFDL-ESM4.1.

286 Lastly, we evaluated the volume transports of Northwestern Atlantic boundary current
287 systems across four zonal transects for the Yucatan Current, Florida Current, Antilles Current,
288 and the Deep Western Boundary Current (DWBC), which are key components of AMOC
289 (McCarthy et al., 2015), as shown in Fig. 4. The zonal transection lines for the four current
290 systems are shown in Fig. 1 (red solid lines). The Antilles Current transport was obtained by
291 integrating the meridional flow over the upper 500 m across 26.5°N and 77.5°W-75°W.
292 Similarly, the DWBC transport was obtained by integrating the meridional velocity between
293 1,000m and 5,000m across 26.5°N and 77.5°W-75°W. GFDL-ESM4.1 simulates a Yucatan
294 Current transport of 43.9 ± 2.87 Sv, which is about 62% larger than in-situ observation of $27.5 \pm$
295 2.6 Sv (Athié et al., 2020, Fig. 4a). In contrast, MOM6-NWA12 simulates a transport of $24.2 \pm$

296 1.7 Sv, which agrees much better with the observed transport. However, the Florida Current
297 (80°W-77.5°W) transport simulated by MOM6-NWA12 (24.3 ± 1.6 Sv) underestimates the
298 observation (32.5 ± 3.2 Sv in Volkov et al., 2024), whereas the Florida Current transport
299 simulated by GFDL-ESM4 (34.4 ± 2.5 Sv) is comparable to the observation. This occurs despite
300 far more realistic surface current speeds in MOM6-NWA12 (i.e., Fig. 2f and i) because the
301 ESM4.1 Florida Current is far more diffuse and extends to greater depth. Additional sensitivity
302 simulations indicate that the Florida Current transport in MOM6-NWA12 is quite sensitive to the
303 eddy viscosity (not shown). By increasing the model diffusivities in MOM6-NWA12, the
304 simulated Florida Current transport also increased closer to the observed value. However, this
305 occurred at the expense of other model features, such as the latitude of Gulf Stream separation
306 from the coast, becoming less realistic. Therefore, the momentum and density diffusivities for
307 MOM6-NWA12 are unchanged from those used in Ross et al. (2023).

308 As shown in Fig. 4c and d, the simulated transports for both the Antilles Current (12.3 ± 4.1
309 Sv) and the DWBC (-20.8 ± 8.8 Sv) in the GFDL-ESM4.1 show substantial disagreement with
310 observations (4.7 ± 5.2 Sv for the Antilles Current, Meinen et al., 2019; and -31.2 ± 5.5 Sv for
311 the DWBC, Zantopp et al., 2017). MOM6-NWA12, in contrast, better reproduced both the
312 Antilles Current (3.4 ± 5.6 Sv) and the DWBC (-35.2 ± 9.5 Sv). The large biases in GFDL-
313 ESM4.1 appear to be linked to the overly diffusive and broad Antilles Current and DWBC
314 (Supplementary Fig. S3).

315 Overall, the high-resolution MOM6-NWA12 configuration generally shows large
316 improvement in simulating regional ocean circulation and mean conditions compared to the low-
317 resolution GFDL-ESM4.1. Some deficiencies, however, still exist. Potential impacts of these

318 deficiencies on projected changes, and pathways for future model improvement, will be
319 discussed in Section 4.

320

321 3.2. Future projections

322 3.2.1. SST and SSS

323 We first examine the projected spatial changes in SST and SSS derived from the MOM6-
324 NWA12, comparing the historical period (HIST: 1993–2020) with the late 21st century (L21C:
325 2073–2100) across four SSP scenarios (SSP-126, SSP-245, SSP-370, and SSP-585). MOM6-
326 NWA12 shows that SST changes in the future exhibit basin-wide warming with discernable end-
327 of-century differences (Fig. 5a-e). The domain-averaged SST warming is lowest in the SSP-126
328 (0.52 °C) simulation and intensifies progressively in SSP-245 (1.21 °C), SSP-370 (1.86 °C) and
329 SSP-585 (2.23 °C) simulations. The SST increase is particularly large in the MAB, the Gulf of
330 Maine, and around the Georges Bank. Temperatures are projected to warm by 4°C in some areas
331 in the SSP-585 scenario (Fig. 5e). Warming in these regions around the MAB and the Gulf of
332 Maine (35°N–42°N, 75°W–60°W) is reduced to ~3°C, ~2°C and ~1°C in SSP-370, SSP-245 and
333 SSP-126, respectively (Fig. 5b-d). Mean warming over the next 30 years (2025-2055), is
334 expected to ~1-2°C with less separation between scenarios (Supplementary Fig. S4).

335 Similar to the SST change, the amplitude of the SSS change is sensitive to the SSP scenarios
336 (Fig. 5f-j). The increase in domain-averaged SSS is more pronounced in the higher emission
337 scenarios (0.13 PSU for SSP-126, 0.22 PSU for SSP-245, 0.41 PSU for SSP-370, and 0.46 PSU
338 for SSP-585). While SSS tends to increase in the subtropical part of the domain, the largest
339 projected SSS increase is along the SAB, the continental slope off the MAB and the West

340 Florida Shelf where the future change intensifies progressively under the high-emission
341 scenarios.

342 The large increases in SST and SSS on the West Florida Shelf and the SAB appear to be
343 linked to ~~a reduction in shelf break upwelling due to~~ the projected weakening of the Loop
344 Current and Gulf Stream (Fig. 6). Additionally, the weakening of the Gulf Stream leads to a
345 northward shift after its separation from the US East Coast in the late 21st century in all four SSP
346 scenarios (Fig. 6, Section 3.2.2), consistent with previous studies (e.g., Saba et al., 2016; Caesar
347 et al., 2018; Bellomo et al., 2021). It appears that the SST increase along the edge of the MAB is
348 linked to the northward shift of the Gulf Stream and the implied warm water intrusion to the
349 Slope Sea (Saba et al., 2016). Warming via this mechanism is fortified by commensurate mean
350 reductions of the advection of cold high-latitude waters from the Labrador Sea as described
351 further in the Discussion section. Interestingly, a narrow region of minimal surface warming is
352 evident immediately south of the historical Gulf Stream path around 35 °N, 60°W (Fig. 6e). A
353 similar, but smaller area of minimum surface warming is also evident in the northern GoA,
354 which is largely consistent with previous studies (Liu et al., 2012, 2015). These regions of
355 minimal SST warming appear to be linked to the reduced Gulf Stream or the reduced Loop
356 Current, implying a reduction in ocean heat convergence to these regions (Figs. 6e and ~~6j~~6i).

357 While GFDL-ESM4.1 shows the SSP scenario sensitivity for the amplitude of the future SST
358 and SSS changes, the pronounced SST warming identified by MOM6-NWA12 in the Mid-
359 Atlantic Bight (MAB) and Gulf of Maine regions is ~~almost completely absent~~much reduced in
360 GFDL-ESM4.1 (Fig. 7). This is consistent with the absence of a future northward shift in the
361 Gulf Stream in the coarse resolution GFDL-ESM4.1 (Fig. 8) and prior findings of Saba et al.,
362 (2015).

363 In summary, MOM6-NWA12 projections of SST, SSS, and surface current speed indicate
364 that under all four future scenarios, the Northwestern Atlantic basin becomes significantly
365 warmer, and saltier especially along the US East Coast and the West Florida shelf regions, and
366 the Gulf Stream becomes considerably weaker and shifts northward. The magnitude of projected
367 end-of-century changes, however, varies considerably across scenarios. Most notably, the
368 severity of the impacts projected by the prior worst-case scenario in CMIP5 (i.e., SSP-585) are
369 progressively mitigated by lower emissions scenarios. Differences between scenarios, however,
370 are far smaller in the first half of the century.

371

372 3.2.2. WBC transports

373 As shown in Figs. 6, the entire WBC system, including the North Brazil Current, Caribbean
374 Current, Yucatan Current, Loop Current, Florida Current, and the Gulf Stream, weakens, at least
375 at the surface, consistent with previous future projection studies (e.g., Liu et al., 2012, 2015;
376 Saba et al, 2016; Alexander et al., 2020; Shin and Alexander, 2020; Beadling et al., 2018;
377 Roberts et al., 2019). The regions of minimal SST warming appear to be linked to the reduced
378 Gulf Stream or the reduced Loop Current, implying a reduction in ocean heat convergence to
379 these regions (Figs. 6e and 6f). To further explore volume transport by the WBCs system, we
380 examine the temporal changes in the volume transport in the Florida Current, Yucatan Current,
381 Antilles Current, and the Deep Western Boundary Current (DWBC), as shown in Fig. 9.

382 The Florida Current exhibits a gradual decline throughout the 21st century across all SSP
383 scenarios. The largest decrease in the late 21st century is shown in the SSP-585 scenario (Fig.
384 9a), from 24.2 ± 1.7 Sv in the historical period to 15.2 ± 3.5 Sv in the late 21st century (37.2 %
385 decline) while the smallest decrease in the late 21st century is shown in the SSP-126 scenario

386 (24.3% decline). The intermediate cases more consistent with current CO₂ trajectories also
387 exhibit smaller shifts than the prior worst case. The Yucatan Current shows similar rates of
388 decrease and scenario sensitivity. Under SSP-585, the Yucatan Current transport decreased from
389 21.0 ± 2.1 Sv in the historical period to 13.2 ± 3.1 Sv in the late 21st century (37.1 % decline,
390 Fig. 9b) but end-of-century declines are partially mitigated at intermediate and low emissions
391 cases. The mean transport by the Antilles Current is significantly reduced from 3.4 ± 5.6 Sv in
392 the historical period to -0.72 ± 4.5 Sv in the late 21st century, under SSP-585, with relatively
393 weak variation across scenarios. This suggests that the Antilles Current may disappear (nearly
394 zero mean transport) after around 2080 (Fig. 9c). This weakening (and the reversal) of the
395 Antilles Current, which is consistent with a previous modeling study (Cai et al., 2024), may play
396 a key role in the subtropical gyre recirculation and the upper-ocean stratification in the SAB. Fig.
397 9d shows that volume transport of the Deep Western Boundary Current (DWBC), which is a
398 vital return flow component of the AMOC from the high latitudes, exhibits the strongest
399 response to anthropogenic warming. Particularly under the SSP-585 scenario, the DWBC
400 transport declines from -35.2 ± 9.5 Sv in the historical period to -20.2 ± 16.0 Sv in the late 21st
401 century (42.7 % decline), reflecting a substantial slowdown in the AMOC under SSP-585 (Fig.
402 10). This slowdown is once again mitigated in part by intermediate and low emissions scenarios.

403 As was the case for SST, SSS and current speed, the rate of weakening was not very sensitive
404 to the emission scenarios before the 2070s. Similarly, the time series of volume transports in the
405 WBCs system shows a similar rate of decline across all four SSP scenarios until approximately
406 2070 (Fig. 9). The insensitivity of Northwestern Atlantic WBCs to emission scenarios before
407 2070s is consistent with the AMOC decline in GFDL-ESM4.1, given that the WBCs are key
408 contributors to the AMOC which is the major contributor to the modulation of the Atlantic

409 ~~WBCs system~~ (Fig. 10). Previous studies (e.g., Weijer et al., 2020; Baker et al., 2023) found that
410 the rate of AMOC weakening derived from most CMIP6 models shows limited sensitivity to
411 emission scenarios prior to around 2070, consistent with GFDL-ESM4.1. It is important to note
412 that the greenhouse gas forcings for the CMIP6 SSP scenarios begin to diverge after the
413 historical period (~2014), with separation in their radiative forcing pathways emerging by the
414 mid-21st century. The results that WBC volume transports and AMOC remain relatively
415 insensitive to these diverging emissions scenarios for several decades provides critical evidence
416 for a delayed ocean response to greenhouse gas forcing.

417

418 3.2.3. Dynamic SSH

419 We next explore dynamic SSH and its projected changes under four SSP scenarios (Fig. 11).
420 Substantial changes in both the amplitude and spatial pattern of dynamic SSH are projected in
421 the Northwestern Atlantic. In particular, dynamic SSH increases greatly along the West Florida
422 Shelf (WFS), SAB, MAB, and Georges Bank, and decreases immediately south of the Gulf
423 Stream (after its separation from the US East Coast) under all four SSP scenarios (Fig. 11).
424 Given that these changes are largely confined to the region of WBCs and the southern
425 recirculation (or Worthington) gyre south of the Gulf Stream, the dynamic SSH changes appear
426 to be directly linked to the substantial weakening of the WBC system (e.g., the Loop Current, the
427 Florida Current, and the Gulf Stream) and the implied relaxation of the thermocline slope (i.e., a
428 redistribution of mass) across the WBCs. The projected increases in dynamic SSH along the
429 WFS, SAB, MAB, and the Georges Bank appear to be largely driven by the AMOC weakening
430 (e.g., Yin et al., 2009; Little et al., 2017; Weijer et al., 2020). [Note that the dynamic SSH](#)

431 [changes in these regions can be also modulated by the future change in the wind-driven gyre](#)
432 [circulation, which is not explicitly isolated and evaluated in this study.](#)

433 Consistent with MOM6-NWA12, GFDL-ESM4.1 shows an increase in dynamic SSH near
434 the U.S. East Coast and decreases south of the Gulf Stream (after its separation from the US East
435 Coast) in the late 21st century (Fig. 12). An interesting point to note is that MOM6-NWA12
436 projects a stronger SSH increase in the SAB than in the MAB while GFDL-ESM4.1 projects a
437 stronger SSH increase [over the MABnorth-of-Cape-Hatteras](#) than in the [SABsouth](#). Consistent
438 with this result, Li et al. (2022) show that the projected SSH derived from a high-resolution
439 Community Earth System Model (CESM) increases more in the SAB than in the MAB, while
440 that derived from a low-resolution CESM increases more in the MAB than in the SAB.

441 To further explore the future increases in dynamic SSH along the US South and East Coasts,
442 we examine the projected dynamic SSH changes over the continental shelf (i.e., depths < 200m)
443 for five sub-regions, namely the Northern GoA, WFS, SAB, MAB, and Gulf of Maine, as shown
444 in Fig. 13. The future increase in dynamic SSH is relatively modest in the Northern GoA and
445 WFS, ranging between 5 and 7 cm during the mid- and late-21st century (2041-2100). These
446 increases occur mainly during the mid-21st century (2041-2060), after which there is no
447 significant increase in the dynamic SSH in these shelf regions. Another important feature is that
448 the dynamic SSH increases in the GoA and WFS (Figs. 13a-b) are not sensitive to the emission
449 scenarios considered. Given that the dynamic SSH increase in these regions is mainly driven by
450 the projected weakening of the AMOC and the associated Loop Current, this result appears to be
451 consistent with the insensitivity in the rate of AMOC's future weakening to the emission
452 scenarios prior to 2070 (Fig. 10).

453 In contrast to the Northern GoA and WFS, the projected dynamic SSH changes in the US
454 East Coast shelf regions (i.e., SAB, MAB, and Gulf of Maine) are significantly larger, ranging
455 between 10 and 20 cm in the late-21st century. Additionally, unlike the US GoA shelf regions
456 (i.e., Northern GoA and WFS), the increase in dynamic SSH in these regions continues beyond
457 the mid-21st century to the late-21st century, implying that the weakening of the AMOC and the
458 associated WBCs have much tighter control over these regions. A systematic tendency toward
459 greater dynamic SSH changes in higher emissions scenarios also begins to emerge after 2070,
460 though there is still significant variation around this trend (e.g., SSP-370 has a lower local
461 dynamic sea level change than SSP245 despite having higher emissions), presumably due to
462 internal climate variability.

463 Among the five sub-regions considered, the dynamic SSH change in the SAB is subject to
464 the largest increase. The dynamic SSH in the SAB is projected to increase dramatically after
465 around 2040, reaching close to 20 cm in the late 21st century compared to that in the historical
466 period. This suggests that the SAB is the most sensitive to the projected slowdown of the AMOC
467 and the WBCs in MOM6-NWA12. Specifically, as shown in Fig. 14, a strong negative
468 correlation exists between the Florida Current transport and the SAB dynamic SSH (e.g., Ezer,
469 2019; Ezer and Atkinson, 2014) indicating that a -1 Sv reduction in the Florida Current transport
470 corresponds to about 1.7 cm of dynamic SSH increase in the SAB. This indicates that the SAB is
471 the future dynamic SSH rise hotspot, potentially posing an increasing flooding risk in the coastal
472 communities. This appears to be partly due to close proximity of the SAB to the WBC (i.e.,
473 Florida Current in this case). In the other subregions, the shelf area is too far away from the
474 WBC (Northern GoA), too wide (WFS), or mediated by the slope water (MAB and Gulf of
475 Maine).

476 To better understand the relationship between the SAB dynamic SSH increase and the Gulf
477 Stream weakening, we show the vertical profile of ocean temperature and salinity across 26.5°N
478 during the historical period and their projected changes under the four SSP scenarios (Fig. 15).
479 Fig. 15 clearly illustrates a substantial warming and an increase in salinity, mainly along the
480 continental slope and shelf. A distinct decrease in density (i.e., lighter water) emerges on the
481 western side of the Florida Current around 200 m depth (Supplementary Fig. S5). This localized
482 density reduction reflects a relaxation, or flattening, of the upward-tilted isopycnals along the
483 Florida coast. Consequently, this flattening of the isopycnals weakens the cross-stream
484 horizontal density gradient, thereby reducing northward volume transport in the Florida Straits.
485 Due to reduced bottom Ekman transport and a relaxation, or a flattening, of the upward-tilted
486 isopycnals associated with a weakened Gulf Stream, upwelling decreases along the continental
487 slope and shelf, limiting the supply of cold and relatively fresh subsurface water from underneath
488 the Gulf Stream. This indicates that the warm and salty Gulf Stream water penetrates deeper into
489 the continental slope and shelf region due to the weakening of the Gulf Stream. This [baroclinic](#)
490 mass redistribution ~~between~~ from the open ocean ~~to~~ and the coastal region is also directly
491 responsible for the large projected increase in dynamic SSH across the SAB, which is consistent
492 with the historical analysis of Steinberg et al. (2024). These future changes in ocean conditions
493 near the coastline are also projected in West Florida. The reduction of the Loop Current leads to
494 an increase in dynamic SSH across West Florida and a significant reduction in the upwelling of
495 cold and relatively fresh subsurface water. This, in turn, results in warm, salty Loop Current
496 water penetrating deeper into the WFS (Fig. 16).

497 In the MAB (30°N–41°N, 76°W–67°W), the weakening and shoreward shift of the Gulf
498 Stream in the late 21st century drives an increase in ocean temperature and salinity along the

499 continental slope and shelf (Fig. 17). The maximum SSH anomaly is observed near the core
500 location of the shifted Gulf Stream. Specifically, projected SSH increases on the coastal side of
501 the current while decreasing on the open-ocean side. This differential change results in a reduced
502 cross-stream SSH gradient (slope), consistent with the geostrophic weakening of the flow.

503 Finally, we emphasize that the dynamical SSH changes driven by changes in ocean currents
504 change described in this study would occur in addition to the GMSL rise associated with ocean
505 warming and glacial and ice-sheet melt. As described in the methods, MOM6-NWA12 can
506 respond to local density changes driven by local warming and freshening (e.g., Steinberg et al.,
507 2024), even though GMSL rise is not directly reflected in the model simulation due to the
508 Boussinesq approximation. Therefore, to explore the total coastal SSH change (i.e., dynamic
509 SSH changes plus GMSL rise) in the late 21st century, the dynamic SSH changes derived from
510 MOM6-NWA12 are combined with the projected GMSL change. According to the IPCC AR6
511 report (IPCC, 2021), the projected GMSL rise by the late 21st century relative to the historical
512 period is 0.38 m for SSP-126, 0.47 m for SSP-245, 0.56 m for SSP-370, and 0.64 m for SSP-585,
513 respectively. Specifically, in the SAB under the SSP-585 scenario, the dynamic sea level
514 increase by the late 21st century (~0.2 m) accounts for nearly 25% of the total sea level increase.
515 This highlights that the SAB could experience extreme and compounding (e.g., high tides and
516 storm surges) coastal flooding risks in the future.

517 **4. Summary and Discussion**

518 This study describes and evaluates the dynamically downscaled physics-only MOM6-
519 NWA12 simulations of GFDL-ESM4, and then explores future changes of the Northwest
520 Atlantic Ocean under four CMIP6 emission scenarios (SSP-126, SSP-245, SSP-370, and SSP-
521 585). Validation of model outputs against direct ocean observational and reanalysis data shows

522 that the biases in GFDL-ESM4 are significantly reduced in MOM6-NWA12, particularly in the
523 spatial SST and SSS patterns, as well as the Gulf Stream’s path and volume transport. For
524 instance, while GFDL-ESM4 exhibits pronounced warm and high salinity biases along the US
525 East Coast and a northward shift of the Gulf Stream, MOM6-NWA12 simulates improved
526 representation of these key features, including a better alignment of the Gulf Stream path with
527 observations. Furthermore, MOM6-NWA12 captures the spatial pattern of SSH much more
528 accurately, as well as the WBCs (i.e., Florida Current, Yucatan Current, Antilles Current, and
529 DWBC).

530 The projections derived from MOM6-NWA12 show significant changes in SST, SSS and the
531 WBCs under the four SSP scenarios considered. The magnitude of end-of-century changes is
532 strongly scenario-dependent: pronounced SST warming in the MAB and Gulf of Maine,
533 exceeding 4°C in some areas, emerges as a distinct feature of the prior “worst-case” high-
534 emission scenarios (SSP-585), partial mitigation is apparent in intermediate trajectories more
535 consistent with current CO2 trajectories (SSP-370, SSP-245), and this signal remains modest
536 under low-emission scenarios (SSP-126). The amplified warming and salinification along the US
537 South and East Coasts appears to be linked to a weakening of the Loop Current and Gulf Stream
538 (e.g., Liu et al., 2012, 2015; Saba et al., 2016) alongside a shoreward and northward shift of the
539 Gulf Stream following its separation from the coast (e.g., Yin et al., 2009; Saba et al., 2016;
540 Bellomo et al., 2021; Li et al., 2022). In addition, as discussed in New et al. (2021), the MAB
541 and the Gulf of Maine are also strongly influenced by the Labrador Current and the Labrador
542 Slope Water (LSLW). The Slope Current in MOM6-NWA12 shows a large bias in its position
543 and the strength along the MAB. More specifically, it is much weaker compared to that in
544 GLORYS12, and is replaced by northward flow in the upper 400m or so ([Supplementary Fig.](#)

545 [6Fig. 18](#)). Another core of southward flow appears immediately shoreward of the Gulf Stream in
546 MOM6-NWA12. Since it is positioned away from the continental slope (near 73°W), it is
547 referred to as the northern recirculation flow of the Gulf Stream. In the future scenarios, both the
548 northern recirculation flow and the Slope Current (below 600m) drastically weaken. The Gulf
549 Stream also weakens and its core shifts shoreward. In the SSP370 and SSP585 scenarios, the
550 Gulf Stream core is positioned along the continental slope. Thus, both the northern recirculation
551 flow and the Slope Current (below 600m or so) completely disappear in those high emission
552 scenarios. Therefore, despite a large bias in the location and strength of the Slope Current in
553 MOM6-~~NWS12~~[NWA12](#), we can still conclude that the future warming and salting in the
554 MAB, shown in Fig. 17, are the result of a compounding effect -- a weakening and shoreward
555 shift of the Gulf Stream combined with reduced advection of cold, fresh Labrador Sea waters.

556 A consistent feature across all projections is the significant deceleration of the surface speed
557 and volume transport of the four WBCs (i.e., Yucatan Current, Florida Current, Antilles Current
558 and DWBC), which aligns well with the significant weakening of the AMOC. Reductions in the
559 meridional transports of the four WBCs remain insensitive to emission scenarios until the 2070s,
560 after which they diverge significantly (ranging from ~23% in SSP-126 to ~38% in SSP-585
561 scenarios).

562 The projections also suggest that the slowdown of the WBCs leads to an increase in dynamic
563 SSH along the US South and East Coasts, which is largest in the SAB. The increased dynamic
564 SSH in these regions is directly related to the weakening of the WBCs and the associated
565 redistribution of the mass across the WBCs (Minobe et al., 2017). As such, a strong negative
566 correlation exists between the Florida Current transport and the dynamic SSH in the SAB, for
567 example. Further analysis shown in Fig. 15 indicates that the weakening of the Florida Current

568 accompanies a substantial reduction of upwelling of cold and fresh subsurface water to the
569 continental slope and shelf region. The associated decrease in nutrient supply, implied by the
570 reduced upwelling, has important implications for the marine ecosystems and productivity in the
571 SAB, as the Gulf Stream-induced upwelling represents the main source of nutrients to the SAB
572 outer and mid shelf (e.g., Lee et al., 1991; Gomez et al., 2026).

573 While this study has mostly focused on describing the future mean changes across scenarios,
574 there are several areas that require further investigation, such as the changes in the seasonal
575 circulation patterns and their impact on the anomalous ocean conditions. This could be relevant,
576 for example, in the MAB where seasonal changes in wind stress drives the annual sea level
577 height variability (e.g., Yang and Chen, 2025). It could also be relevant for the SAB where the
578 seasonal wind stress changes impact coastal temperature and cross-shore interchanges through
579 upwelling (e.g., Castelao et al., 2011; Yuan et al., 2017). Therefore, further study is needed to
580 explore future changes in the seasonality of WBCs, and their impacts.

581 Lastly, building on these results derived from physics-only simulations, we plan to couple the
582 physical ocean model with the Carbon, Ocean Biogeochemistry and Lower Trophics (COBALT,
583 Stock et al., 2020, 2025) model to explore future changes in ocean ecosystems in the Northwest
584 Atlantic. Additionally, we will expand the scenario-focused ensemble presented here to include
585 multiple GCMs to fully assess the potential range of the future changes in the Northwest
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587

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598

599 **Code availability**

600 The source code for each component of the MOM6-NWA12 model has been archived by
601 Ross et al. (2023) and the GitHub repositories are located at [https://github.com/NOAA-](https://github.com/NOAA-GFDL/CEFI-regional-MOM6)
602 [GFDL/CEFI-regional-MOM6](https://github.com/NOAA-GFDL/CEFI-regional-MOM6). All codes for analyses were performed using the Grid Analysis
603 and Display System (GrADS), which is publicly available from the Center for Ocean-Land-
604 Atmosphere Studies at <http://cola.gmu.edu/grads> and NCL, which is publicly available from the
605 NCAR Command Language (NCL) at <https://www.ncl.ucar.edu/>. The GrADS, NCL, and Fortran
606 codes used to perform the analyses can be accessed upon request to D. K.

607

608 **Data availability**

609 The model outputs derived from the MOM6-NWA12 future projections under four SSP
610 scenarios will be available at CEFI portal soon (https://psl.noaa.gov/cefi_portal/). GLORYS12
611 reanalysis dataset is available at <https://data.marine.copernicus.eu/product/>. ERA5 reanalysis
612 dataset is available at <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels>.

613 GFDL-ESM4 outputs are freely available at the CMIP6 archive

614 (<https://aims2.llnl.gov/search/cmip6/>).

615

616 **Author Contribution**

617 D Kim, AC Ross, SI Shin and SK Lee contributed source code for the downscaling system for
618 the regional MOM6. D Kim, SI Shin and SK Lee contributed to preparation of model input files.
619 D Kim, FA Gomez and SK Lee contributed to evaluation and interpretation of the model results.
620 D Kim and SK Lee prepared the initial draft of the manuscript. All coauthors participated in
621 discussions during various stages of the model development and evaluation and read and
622 approved the final version of the manuscript.

623

624 **Competing interests**

625 Dr. Charles A. Stock (one of co-authors) serves as editor for the special issue to which this paper
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627

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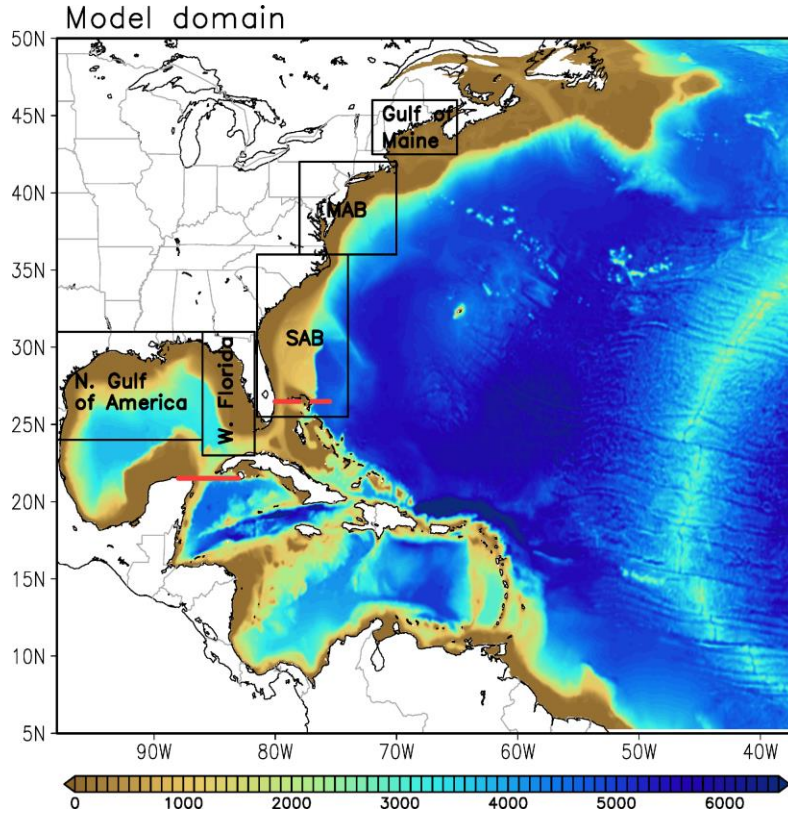
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989 Figure list

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991

992 **Fig. 1.** MOM6-NWA12 model domain and bathymetry (m). The black boxes indicate the
993 location of the Northern Gulf of America, West Florida, South Atlantic Bight (SAB), and middle
994 Atlantic Bight (MAB), and Gulf of Maine for exploring sea-level rise. The red solid lines are the
995 locations of four major Northwestern Atlantic boundary current systems (Yucatan Current,
996 Florida Current, Antilles Current (0~500 m), and Deep Western Boundary Current (1,000-
997 4,000m).

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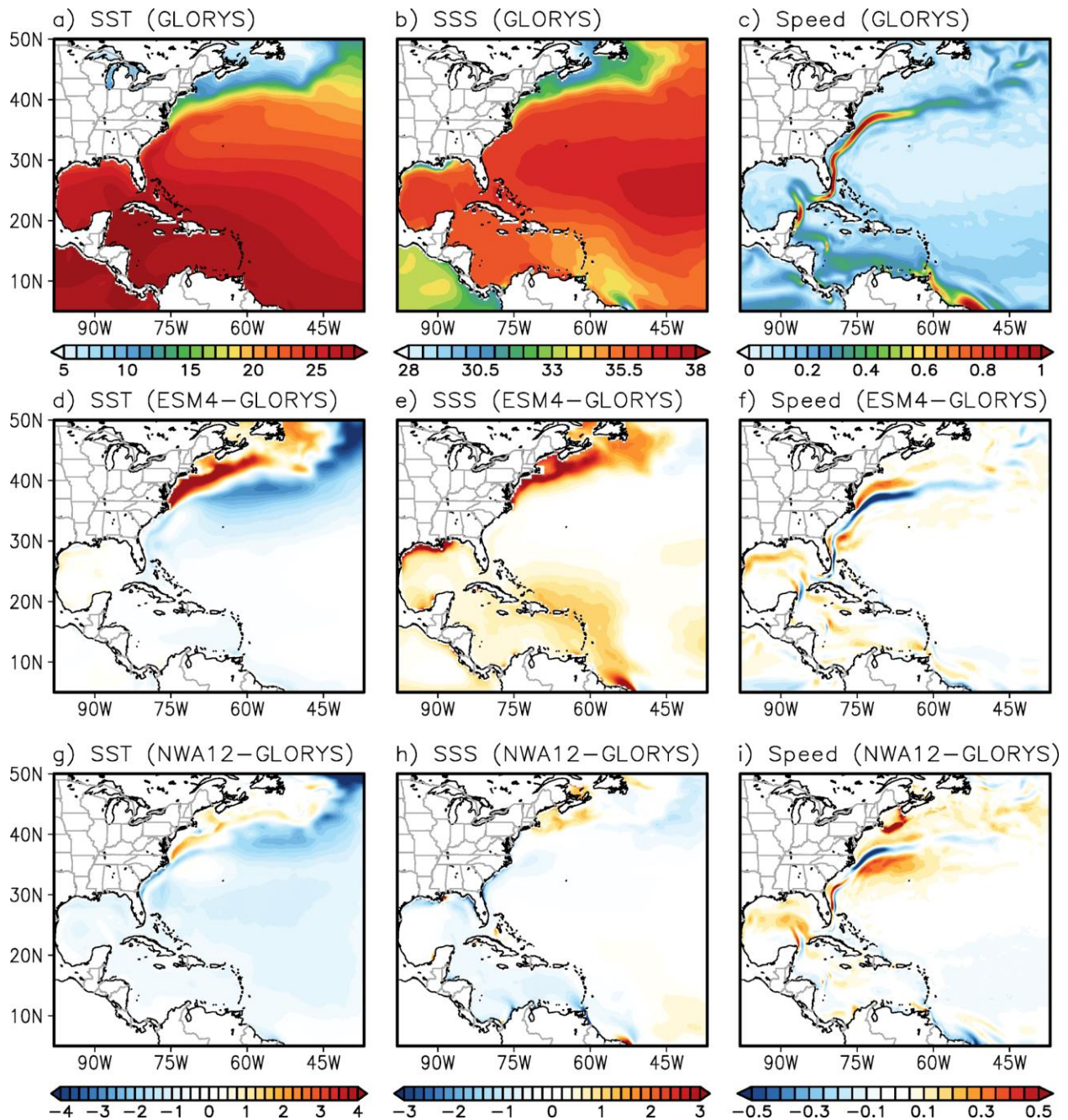
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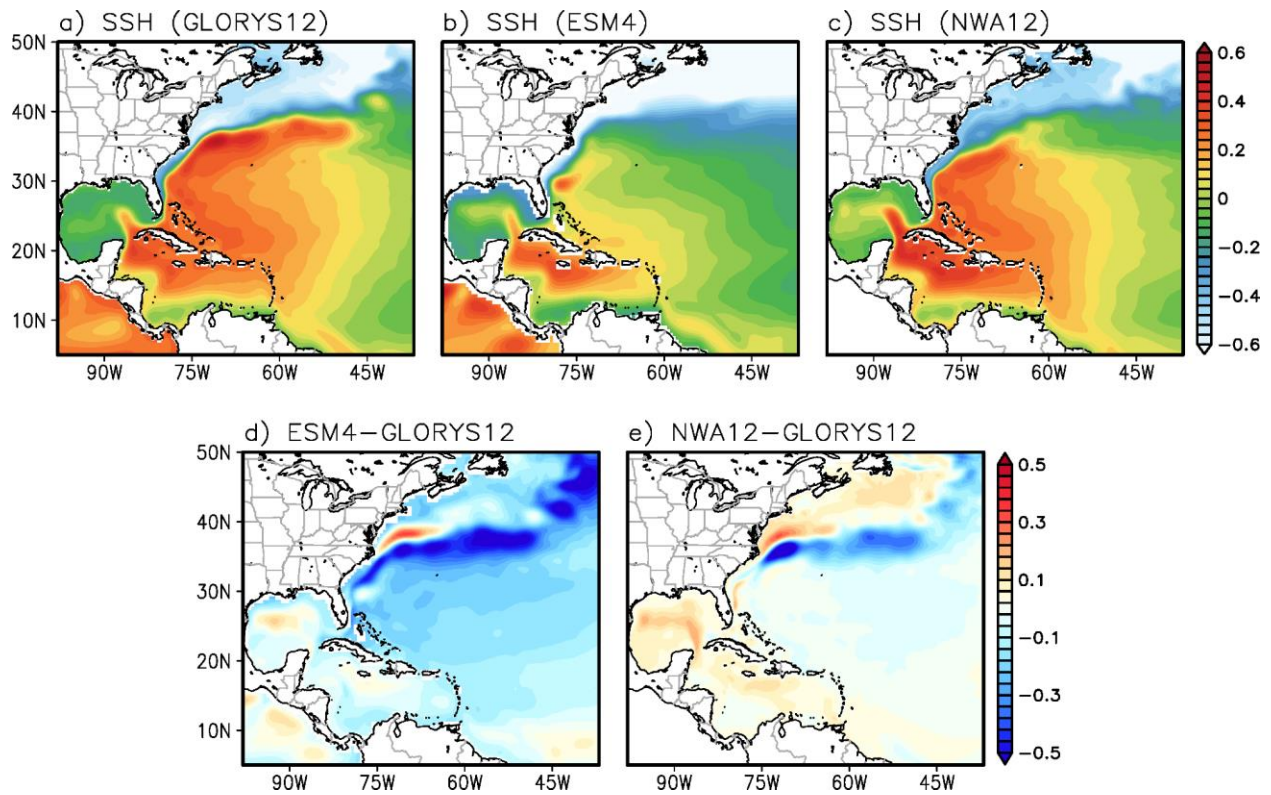
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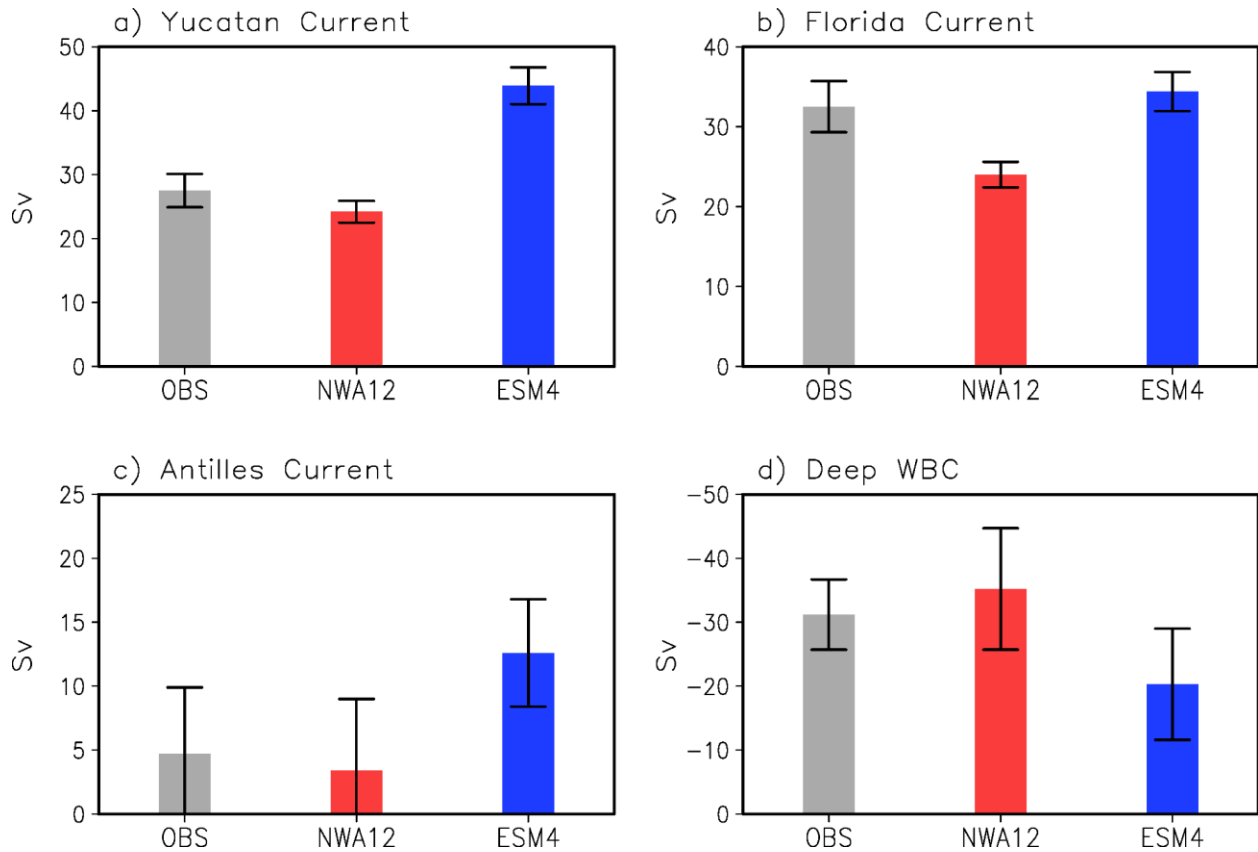
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 1013 **Fig. 2.** Spatial patterns of the historical (1993–2020) mean (a) sea surface temperature (SST, °C),
 1014 (b) sea surface salinity (SSS, psu), and (c) surface current speed (m s^{-1}) in GLORYS12. (d)–(f)
 1015 show the GFDL-ESM4 biases for SST, SSS, and surface current speed. (g)–(i) are the same as
 1016 (d)–(f), but for MOM6-NWA12.

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Fig. 3. Spatial pattern of the historical (1993-2020) mean sea surface height (SSH, m) in (a) GLORYS12, (b) GFDL-ESM4.1 and (c) MOM6-NWA12. (d) The difference between GFDL-ESM4.1 and GLORYS12. (e) difference between MOM6-NWA12 and GLORYS12.



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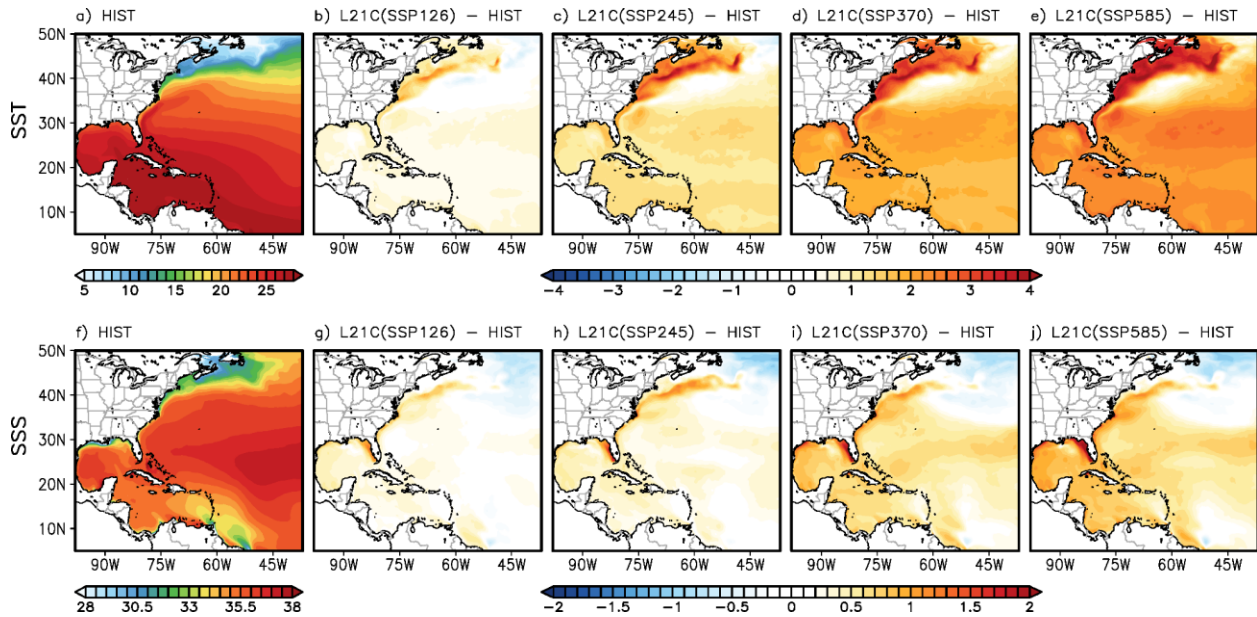
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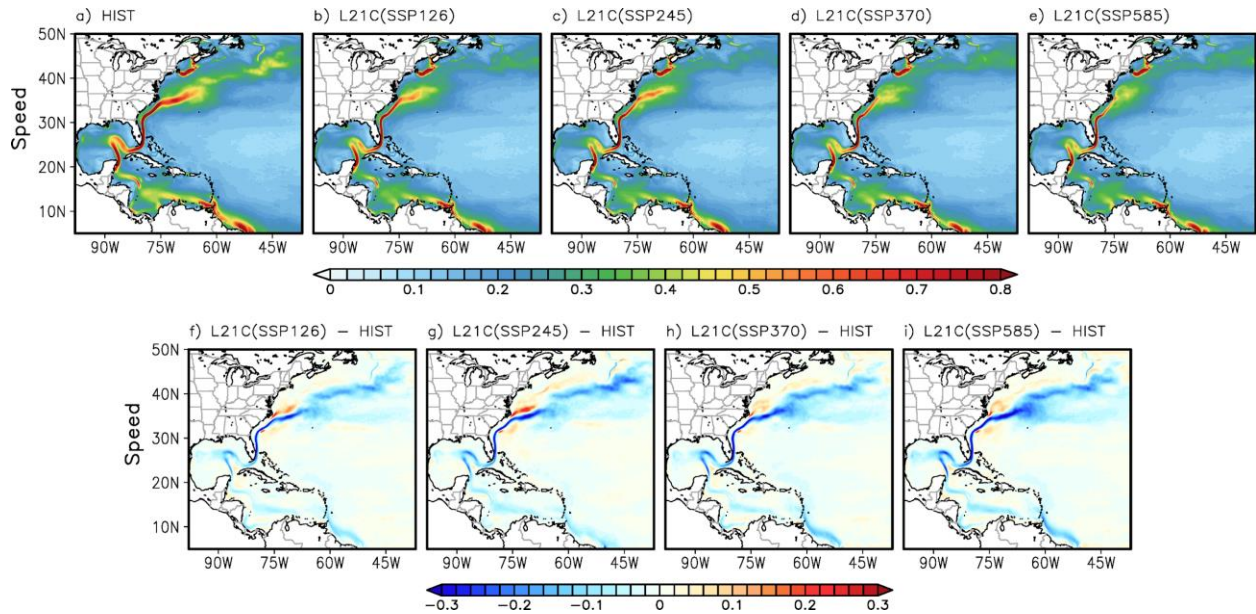
Fig. 4. The historical mean (1993-2020) of (a) the Yucatan Channel, (b) Florida Current, (c) Antilles Current, and (d) Deep Western Boundary Current transport derived from observational records (gray bars), MOM6-NWA12 (red bars) and GFDL-ESM4 (blue bars). Note that the observational transport records of the Florida Current, Yucatan Current, Antilles Current, and Deep Western Boundary Current (DWBC) are from Volkov et al. (2024), Athié et al. (2020), Meinen et al. (2019) and Zantopp et al. (2017), respectively.



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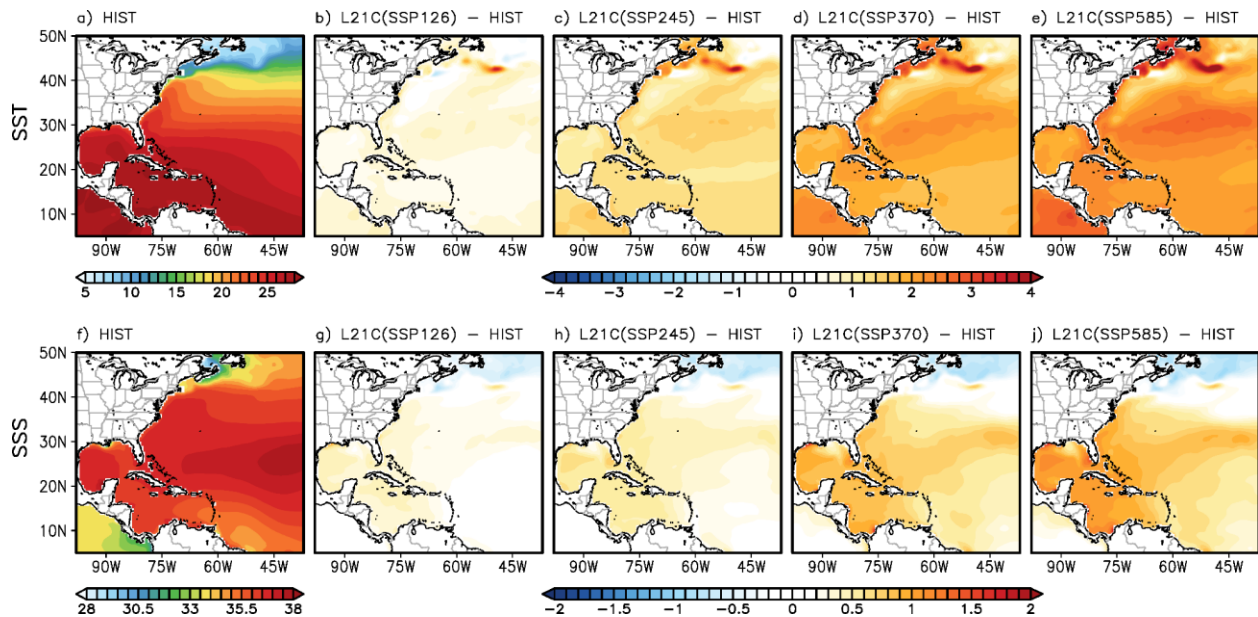
Fig. 5. (a) Spatial patterns of sea surface temperature (SST, °C) derived from MOM6-NWA12 during (a) historical period (1993-2020). The differences in SST between the future (2073-2100) and historical periods in the (b) SSP-126, (c) SSP-245, (d) SSP-370 and (e) SSP-585 simulations. (f)-(j) are the same (a)-(e) but for sea surface salinity (SSS, psu).

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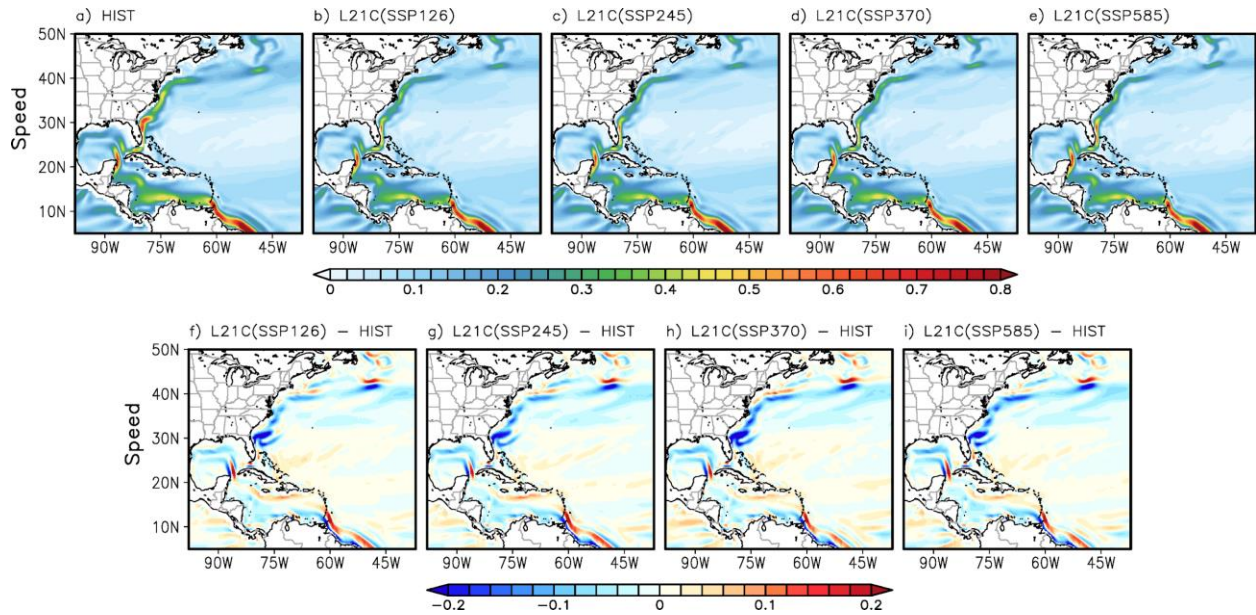
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Fig. 6. Spatial surface current speed (m s^{-1}) patterns derived from MOM6-NWA12 during (a) the historical (1993-2020) period and future (2073-2100) period in (b) SSP-126, (c) SSP-245, (d) SSP-370 and (e) SSP585 simulations. The difference in surface current speed between the future and historical periods in (f) SSP-126, (g) SSP-245, (h) SSP-370 and (i) SSP585 simulations, respectively.



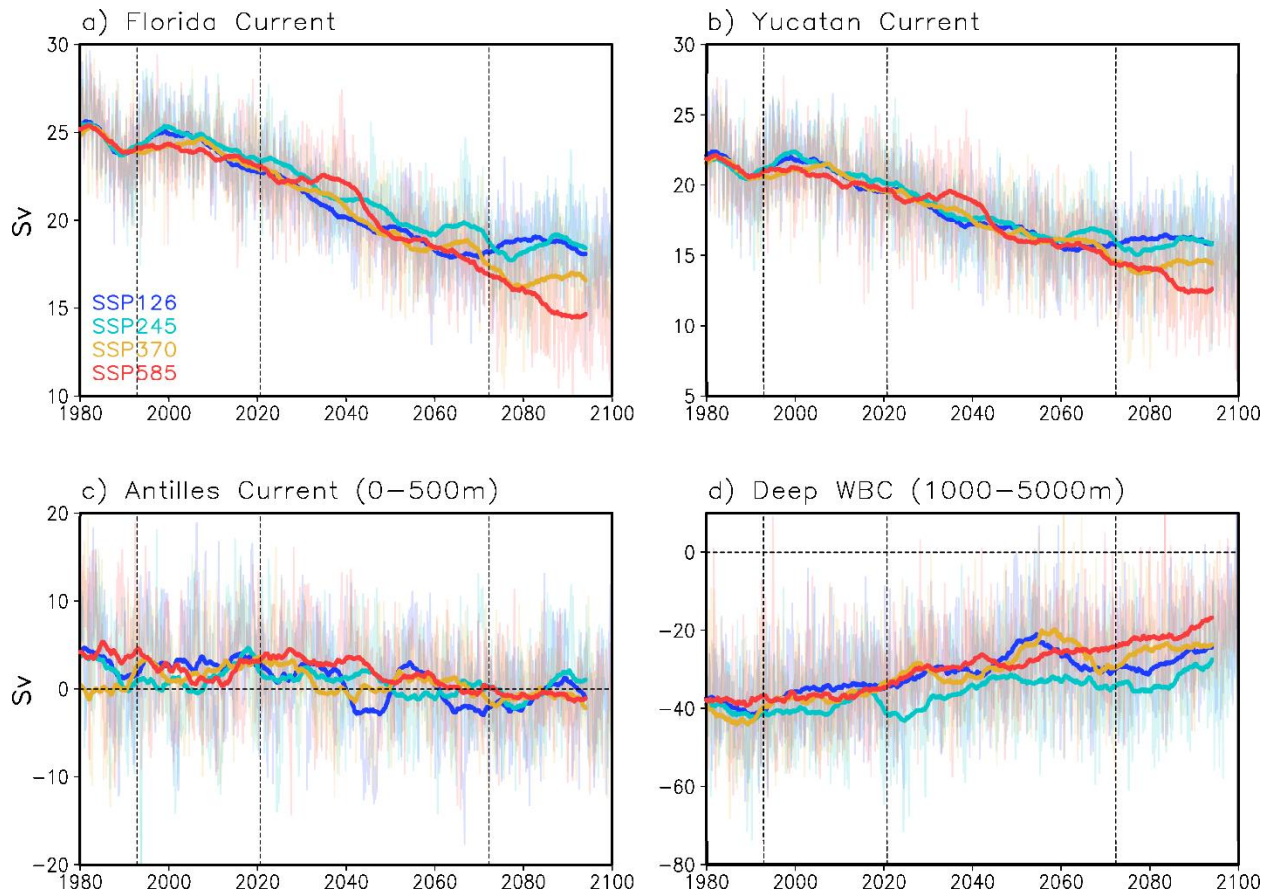
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 1078 **Fig. 7.** (a) Spatial patterns of sea surface temperature (SST) derived from GFDL-ESM4.1 during
 1079 the historical period (1993-2020). (b)-(e) are the differences in SST between the future (2073-
 1080 2100) and historical (1993-2020) periods in the SSP-126, SSP-245, SSP-370, and SSP-585
 1081 simulations, respectively. (f) and (j) are the same (a) and (e) but for the sea surface salinity
 1082 (SSS).

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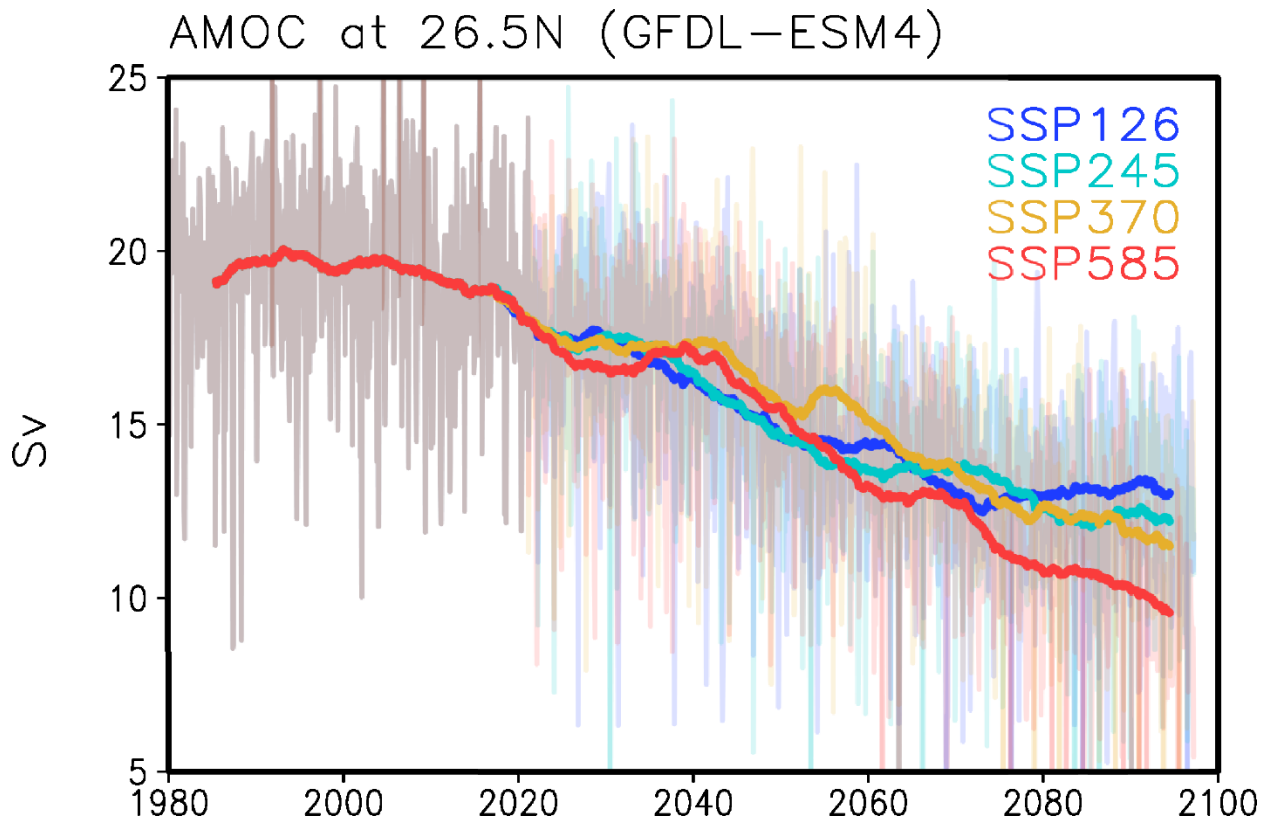
Fig. 8. Spatial surface current speed patterns derived from GFDL-ESM4.1 during (a) the historical (1993-2020) period, and future (2073-2100) period in the (b) SSP-126, (c) SSP-245, (d) SSP-370, and (e) SSP-585 simulations. The difference in surface current speed between the future and historical periods in (f) SSP-126, (g) SSP-245, (h) SSP-370, and (i) SSP-585 simulations, respectively.



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 1095 **Fig. 9.** Time series of (a) the Florida Current transport, (b) transport across the Yucatan Channel,
 1096 (c) Antilles Current transport and (d) Deep Western Boundary Current transport in MOM6-
 1097 NWA12. The cyan, green, orange, and red lines are the SSP-126, SSP-245, SSP-370 and SSP-
 1098 585 simulations, respectively. The bold lines indicate 11-year running means. The dotted lines
 1099 indicate the historical and future periods. The vertical dotted lines indicate the historical and
 1100 future averaging periods.

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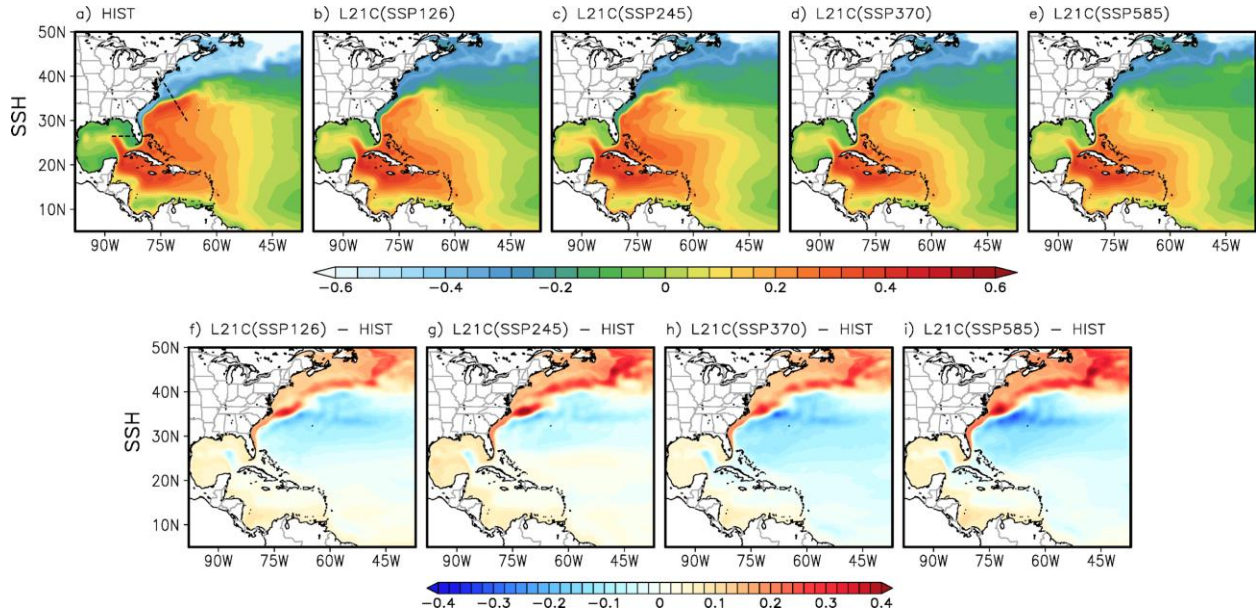


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1118 **Fig. 10.** Time series of AMOC in GFDL-ESM4.1. The blue, green, orange, and red lines are the
1119 SSP-126, SSP-245, SSP-370 and SSP-585 simulations, respectively.

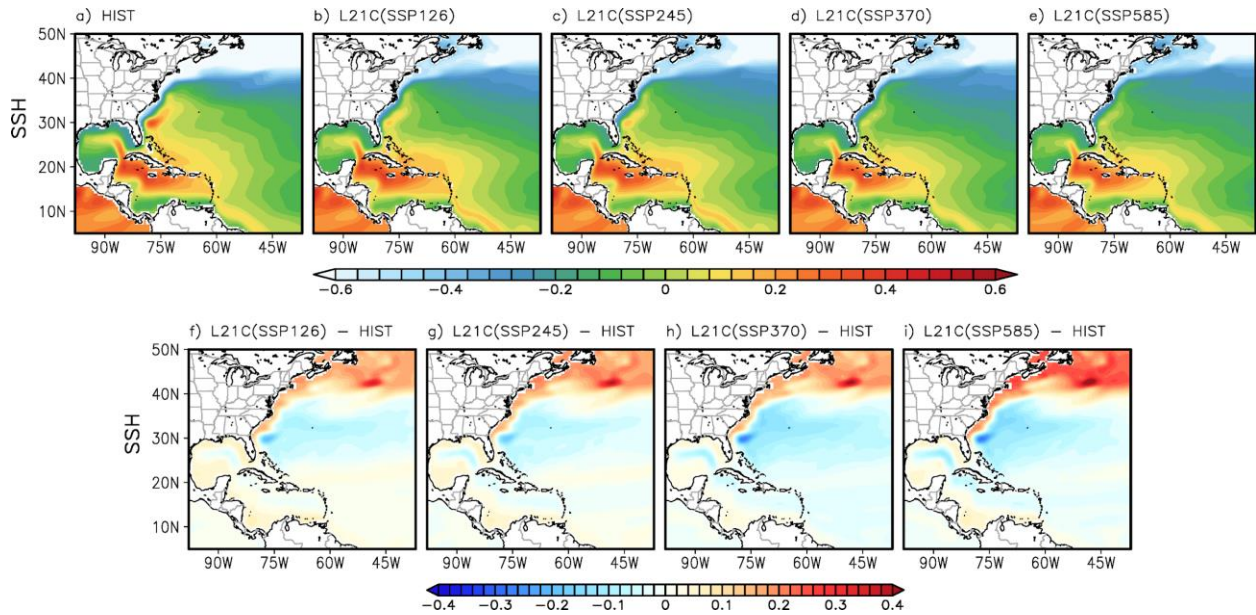
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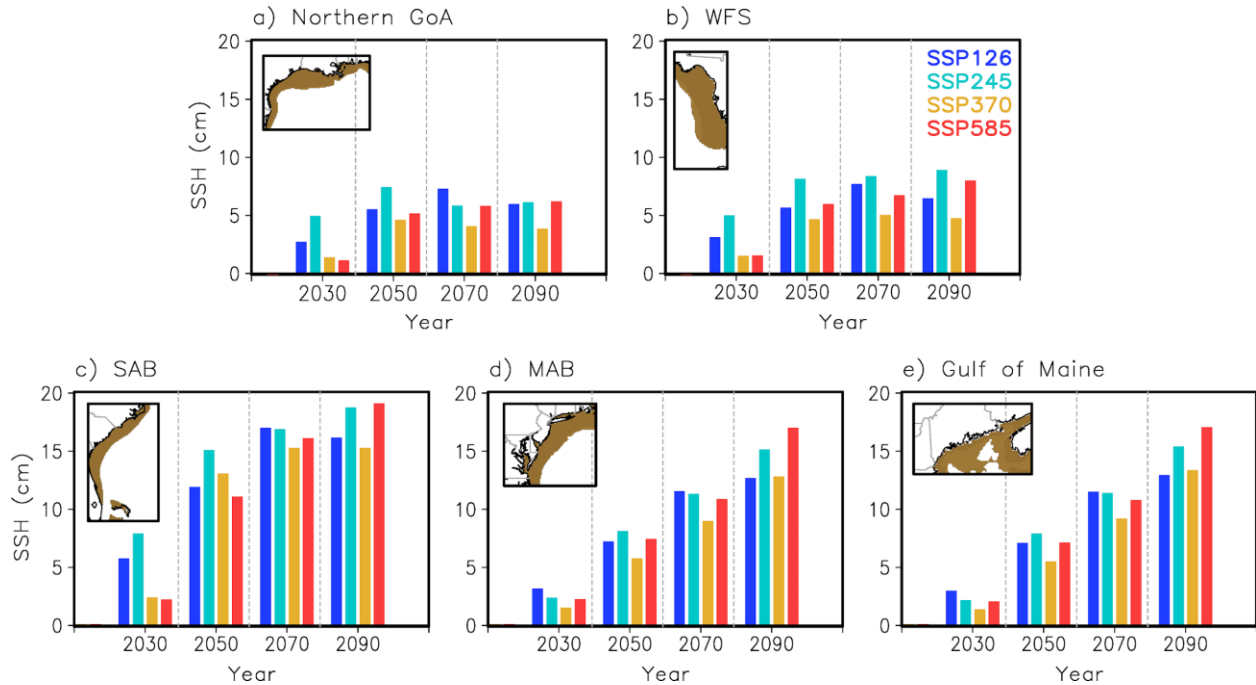
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Fig. 11. Spatial sea surface height (SSH, m) patterns derived from MOM6-NWA12 during (a) the historical (1993-2020) period, and future (2073-2100) period from (b) SSP-126, (c) SSP-245, (d) SSP-370 and (e) SSP-585 simulations. The difference in SSH between the future and historical periods from (f) SSP-126, (g) SSP-245, (h) SSP-370, and (i) SSP-585 simulations, respectively. The black dotted lines in (a) indicate the locations of vertical cross-section used in Fig.15-17 and 18.



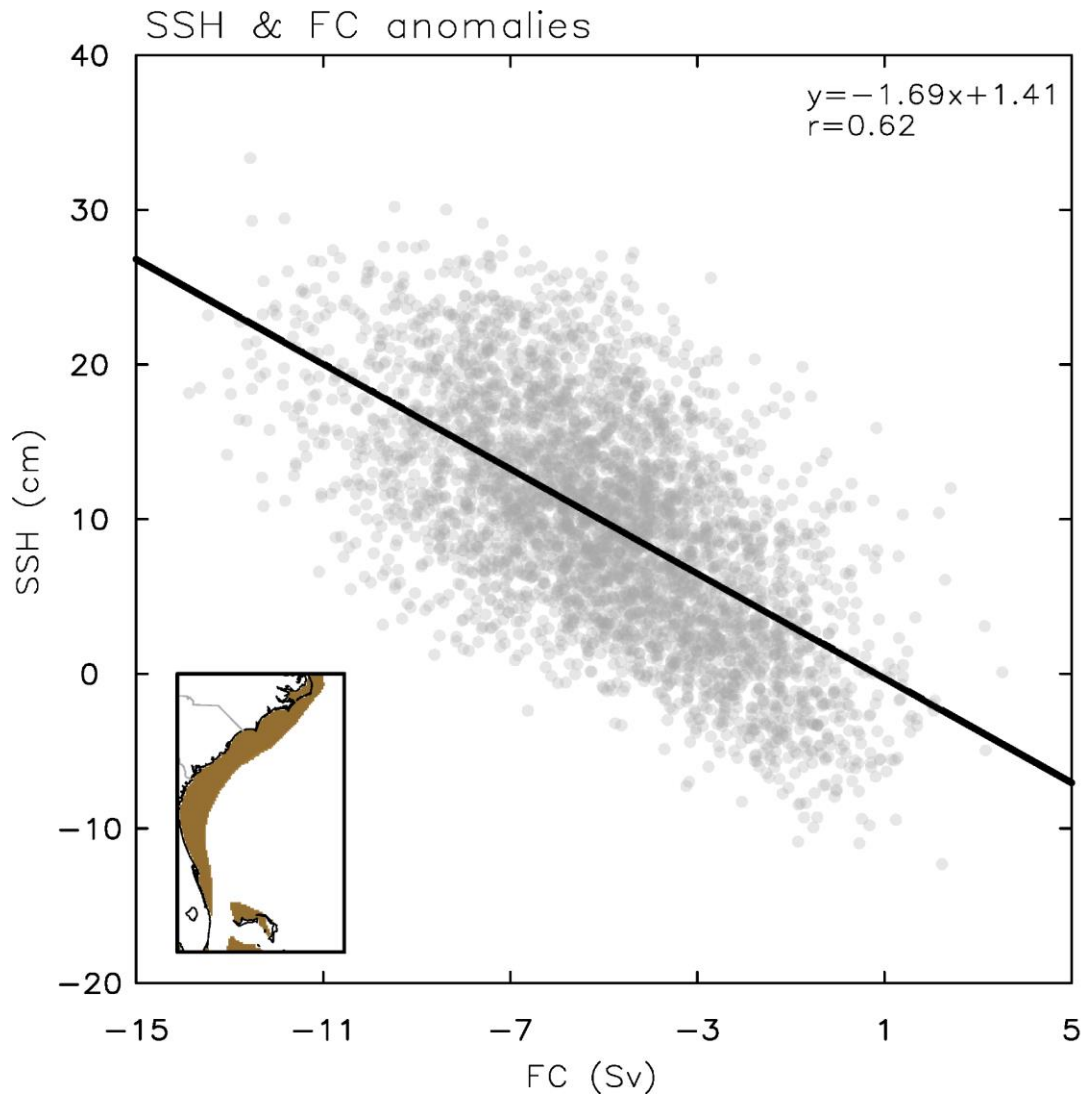
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Fig. 12. Spatial SSH patterns derived from GFDL-ESM4.1 during (a) the historical (1993-2020) period, and future (2073-2100) period from (b) SSP-126, (c) SSP-245, (d) SSP-370, and (e) SSP-585 simulations, respectively. The difference in SSH between the future and historical periods from (f) SSP-126, (g) SSP-245, (h) SSP-370 and (i) SSP-585 simulations, respectively.



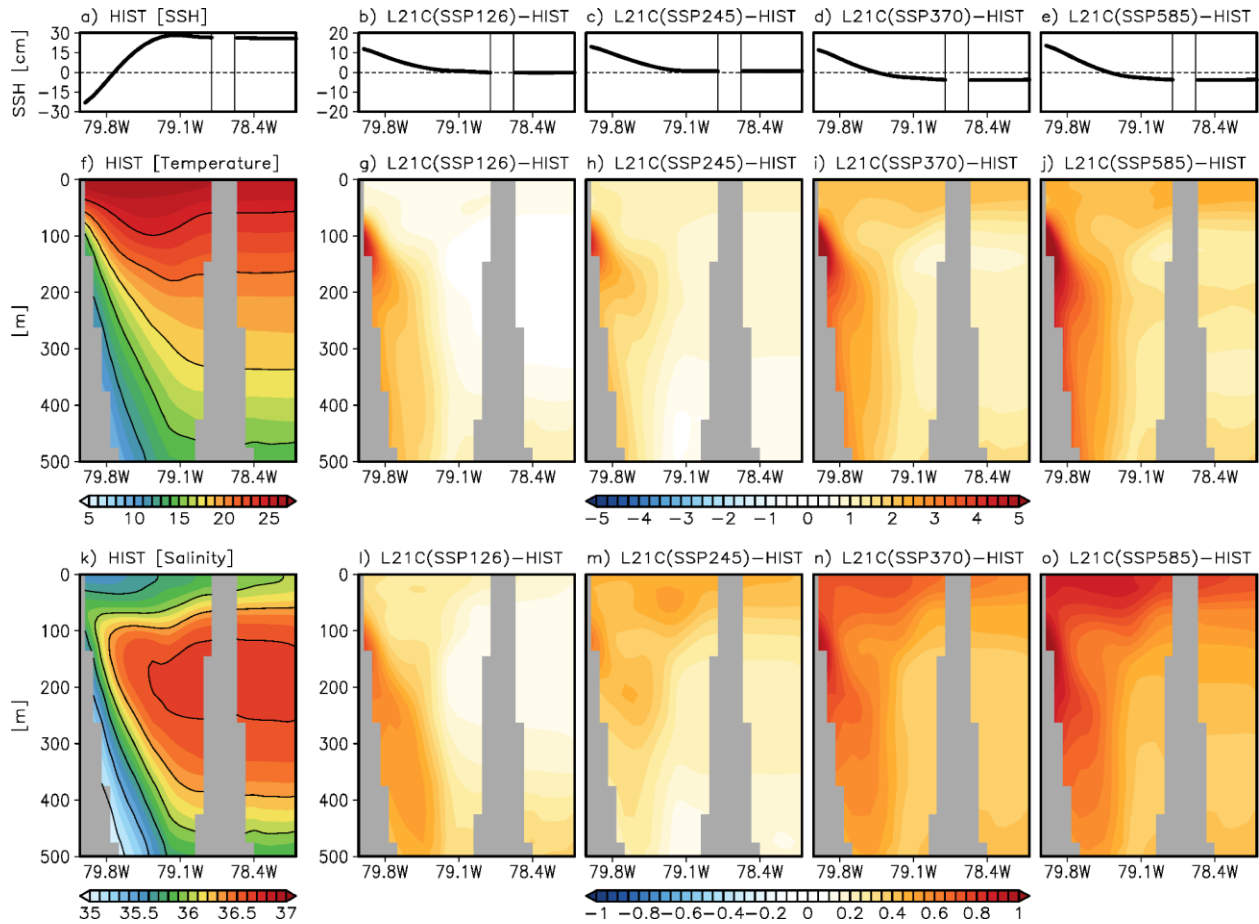
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 1159 **Fig. 13.** Spatially averaged sea level changes (cm) from historical period (1993-2020) in (a) the
 1160 northern Gulf of America, (b) West Florida shelf, (c) the South Atlantic Bight, (d) the Middle
 1161 Atlantic Bight, and (e) the Gulf of Maine under the SSP-126 (blue bars), SSP-245 (green bars),
 1162 SSP-370 (orange bars) and SSP-585 (red bars) simulations. The dynamic sea level changes are
 1163 spatially averaged over the shelf regions below 200 m depth (brown-colored area in the maps).
 1164 The years on the x-axis represent the center of a 20-year averaging period (e.g., the value for
 1165 2030 represents the average from 2021 to 2040).

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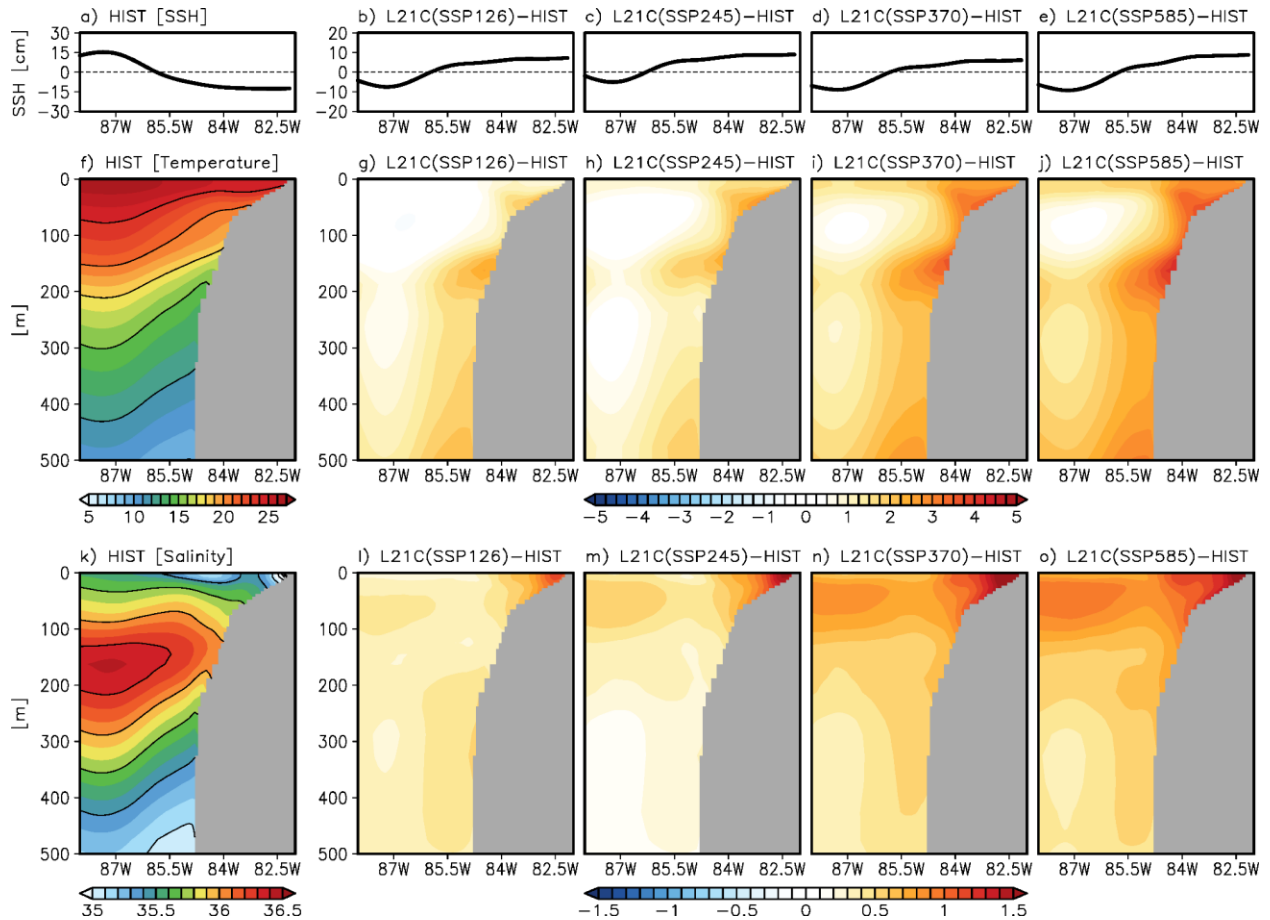
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Fig. 14. Scatter plot of anomalous Florida Current (FC) transport (Sv) versus dynamic sea level (cm) change along the South Atlantic Bight derived from all four SSP simulations. The dynamic sea level change is spatially averaged over the shelf regions below 200 m (brown-colored area in the map).



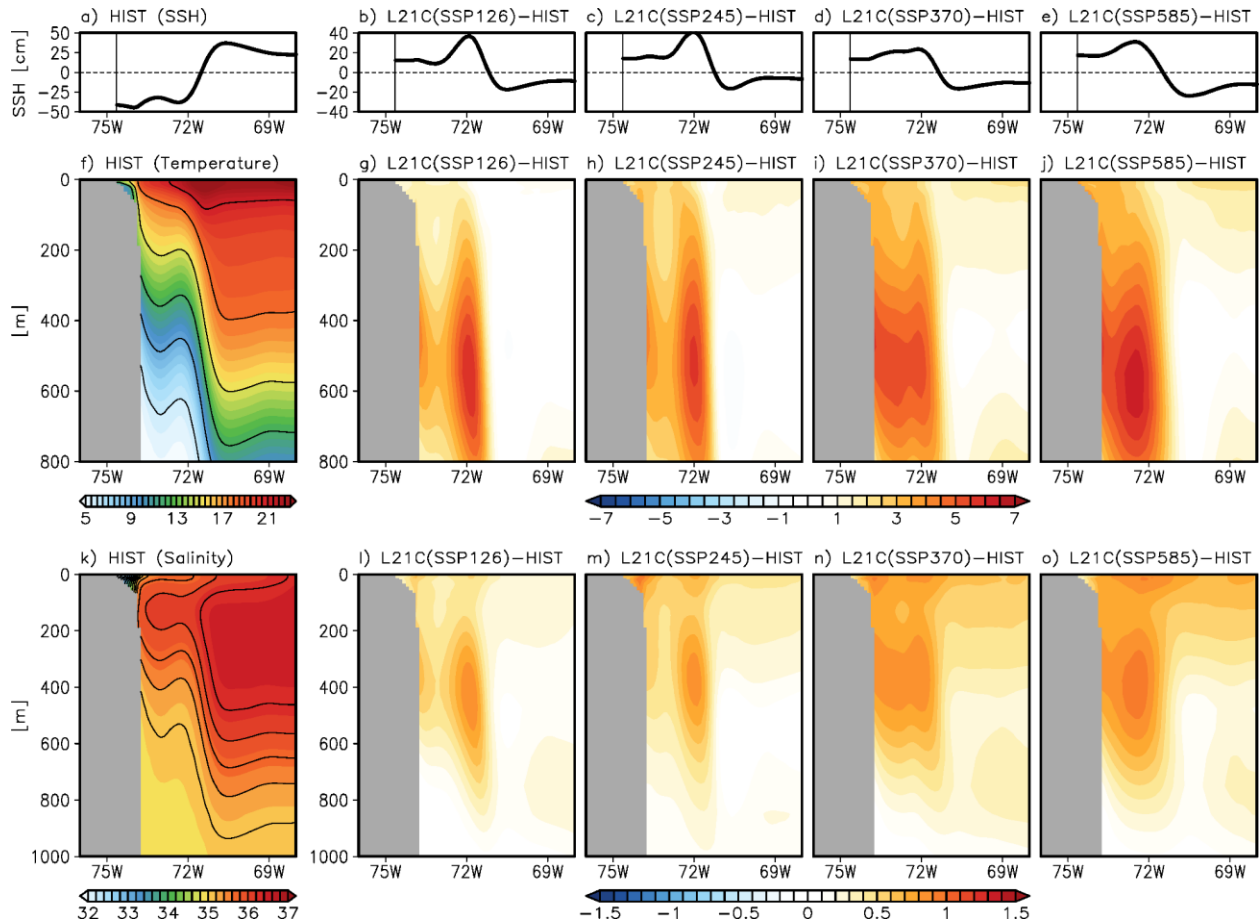
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Fig. 15. (a) Sea level at the east coast of Florida (26.5°N , 79.7°W - 78.0°W) during the historical period. Future change in the sea level at the east coast of Florida from (b) SSP-126, (c) SSP-245, (d) SSP-370, (e) SSP-585, and (c) SSP-585 simulations. (f) The vertical cross-sections of the mean temperature across the east coast of Florida during the historical period. The difference in temperature between the future and historical periods from (g) SSP-126, (h) SSP-245, (i) SSP-370, and (j) SSP-585 simulations, respectively. (k)-(o) are the same as (f)-(j) but for salinity.



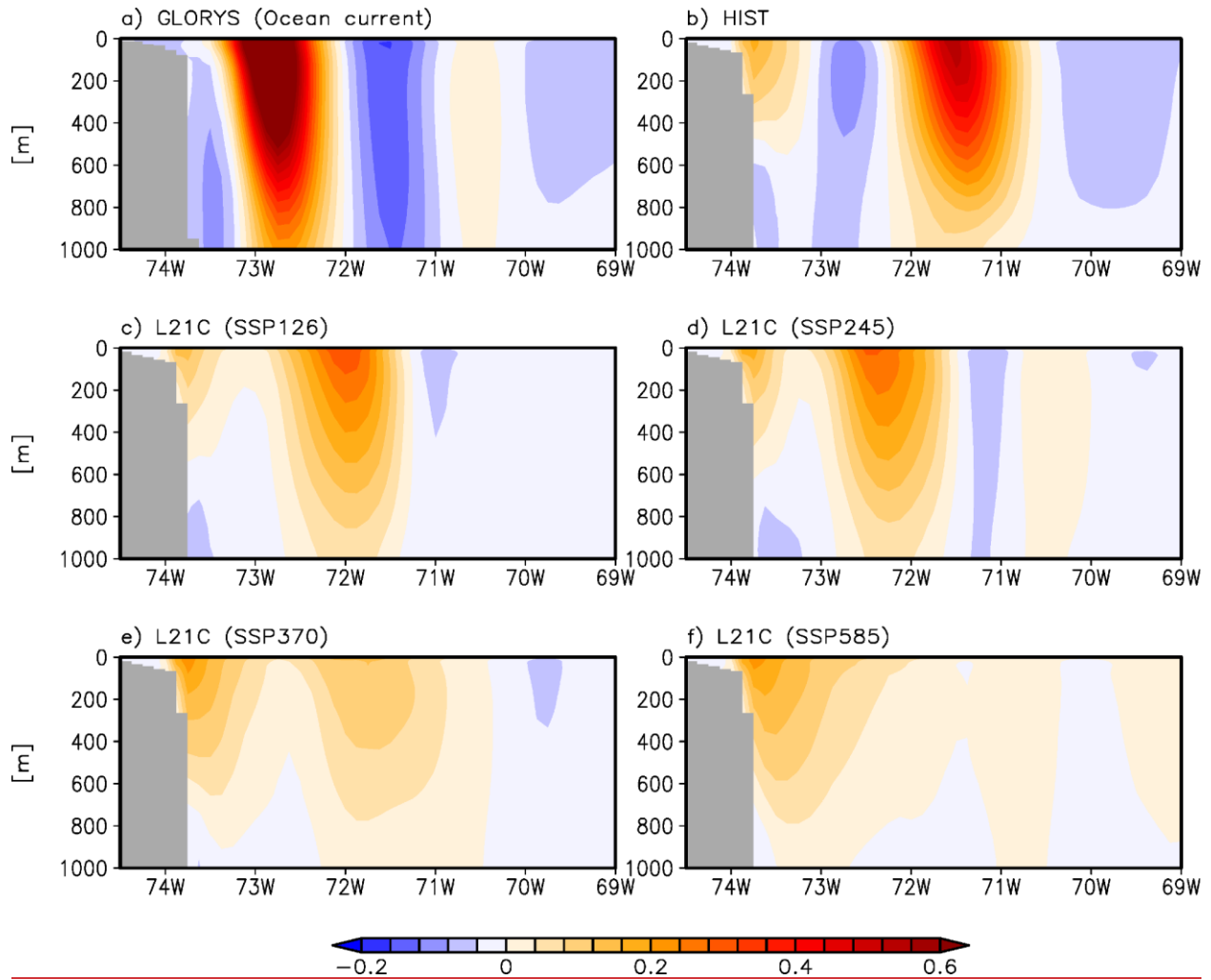
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Fig. 16. (a) Sea level at West Florida (26.5°N , 88°W - 81°W) during the historical period. Future change in the sea level at West Florida from (b) SSP-126, (c) SSP-245, (d) SSP-370, (e) SSP-585, and (c) SSP-585 simulations. (f) The vertical cross-sections of the mean temperature ($^{\circ}\text{C}$) across West Florida during the historical period. The difference in temperature between the future and historical periods from (g) SSP-126, (h) SSP-245, (i) SSP-370, and (j) SSP-585 simulations, respectively. (k)-(o) are the same as (f)-(j) but for salinity (psu).



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Fig. 17. (a) Sea level at the MAB (30°N - 41°N , 76°W - 67°W) during the historical period. Future change in the sea level at the MAB from (b) SSP-126, (c) SSP-245, (d) SSP-370, (e) SSP-585, and (f) SSP-585 simulations. (f) The vertical cross-sections of the mean temperature ($^{\circ}\text{C}$) across the MAB during the historical period. The difference in temperature between the future and historical periods from (g) SSP-126, (h) SSP-245, (i) SSP-370, and (j) SSP-585 simulations, respectively. (k)-(o) are the same as (f)-(j) but for salinity (psu).



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1236 **Fig. 18.** (a) Vertical cross-section of the mean alongshore current across the MAB (30°N-41°N,
 1237 76°W-67°W) during the historical period (1993-2020) from GLORYS12. (b) Same as (a), but for
 1238 MOM6-NWA12. (c)-(f) are the same as (b), but for the future period (2073-2100) from the (c)
 1239 SSP1-2.6, (d) SSP2-4.5, (e) SSP3-7.0, and (f) SSP5-8.5 simulations, respectively.