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2	DALROMS-NWA12 v1.0, a coupled circulation-ice-
3	biogeochemistry modelling system for the northwest Atlantic
4	<b>Ocean: Development and validation</b>
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13 Abstract. This study presents DalROMS-NWA12 v1.0, a coupled ocean circulation-sea ice-14 biogeochemistry modelling system for the northwest Atlantic Ocean (NWA) in which the 15 circulation and biogeochemistry modules are based on ROMS (Regional Ocean Modeling System). The circulation module is coupled to a sea ice module based on the Community Ice 16 CodE (CICE), and the physical ocean state simulated by the circulation module drives the 17 18 biogeochemical module. Study of the biological carbon pump in the NWA is one of the main 19 intended applications of this model. Global atmospheric and ocean reanalyses are used respectively to force DalROMS-NWA12 at the sea surface and as part of its lateral boundary 20 21 input. The modelling system is also forced by tides, riverine freshwater input, and continental 22 runoff. The physical ocean state and sea ice from two simulations of the period 2015-2018, with 23 and without nudging of the simulated temperature and salinity towards a blend of observations 24 and reanalysis, are examined in this study. Statistical comparisons between model results and 25 observations or reanalyses show the control (nudged) simulation outperforms the prognostic (un-26 nudged) simulation in reproducing the paths of the Gulf Stream and the West Greenland Current, 27 as well as propagation of the estuarine plume in the Gulf of St. Lawrence. The prognostic simulation performs better in simulating the sea ice concentration. The biogeochemical module, 28 29 which is run only in the control simulation, performs reasonably well in reproducing the 30 observed spatiotemporal variations of oxygen, nitrate, alkalinity, and total inorganic carbon. To 31 examine the effects of tides and sea ice on the physical fields in the study area, results of simulations from which either component is absent are compared to results of the prognostic 32 33 simulation. In the absence of tides, Ungava Bay in summer experiences a simulated surface salinity that is higher by up to  $\sim$ 7 than in the simulation with tides, as well as changes in 34 horizontal distributions of surface temperature and sea ice. Without coupling to the sea ice 35 36 module, the circulation module produces summertime sea surface temperatures that are higher by 37 up to  $\sim 5^{\circ}$ C in Baffin Bay.





#### 38 1 Introduction

39	The northwest North Atlantic Ocean (hereafter NWA) is characterized by interactions among
40	physical and biogeochemical processes that affect the global atmosphere-ocean system. Air-to-
41	sea flux of $CO_2$ per unit area is estimated to be largest in the world in the Atlantic Ocean north of
42	$50^{\circ}$ N, due to factors such as strong winds in winter and high primary production in spring
43	(Takahashi et al., 2009). The sinking of particles formed during primary production has the effect
44	of transporting atmospheric CO <sub>2</sub> to the deep ocean and is referred to as the biological carbon
45	pump (BCP; Volk and Hoffert, 1985). The BCP is influenced by various physical processes over
46	an annual cycle. The presence of sea ice in winter can, on one hand, drive upward transport of
47	nutrients through brine rejection-induced vertical mixing (Jin et al., 2018) but on the other hand
48	can reduce wind-induced mixing (Rainville et al., 2011) and attenuate the solar radiation
49	(Legendre et al., 1992) by isolating the water column from the atmosphere. Seasonal changes of
50	the mixed layer depth is another physical process that governs the BCP. Shoaling of the layer in
51	spring, driven by freshwater input from runoff and sea ice, promotes primary production (Wu et
52	al., 2007 and 2008; Frajka-Williams and Rhines, 2010), while deepening of the layer in winter
53	can result in entrainment of dissolved inorganic carbon and respiratory CO <sub>2</sub> that had been in
54	shallow sub-surface waters (Körtzinger et al., 2008). In the Labrador Sea, deep convection in
55	winter is thought to be an additional pathway for removal of carbon from near-surface waters
56	(Tian et al., 2004).

57 Several field programs have been conducted to quantify the major processes at work in the

58 NWA, such as the Labrador Sea Deep Convection Experiment (The Lab Sea Group, 1998),

59 which focused on atmospheric and physical oceanographic processes, and the Atlantic Zone

60 Monitoring Program (Pepin et al., 2005) and its off-shelf counterpart (e.g., Yashayaev and Loder,

- 61 2017), which have made regular shipboard measurements of physical and biogeochemical (BGC)
- 62 fields at fixed locations. Simultaneous measurements of physical and BGC fields at moorings
- 63 (e.g., Martz et al., 2009; Strutton et al., 2011) and by profiling floats (e.g., Yang et al., 2020;
- 64 Wang and Fennel 2022) have expanded the coverage of observations, which is crucial given the
- 65 spatiotemporal variability in the processes that govern the BCP (Garçon et al., 2001).





- 66 Processed-based numerical models can complement observations of oceanic processes by 67 providing four-dimensional estimates of relevant fields and by enabling experiments in which the effects of key inputs are isolated or the future state of oceans under various climate scenarios are 68 simulated (Fennel et al., 2022). Early numerical studies of the NWA using coupled ocean 69 70 circulation-sea ice models focused mainly on specific processes, such as climatological sea ice conditions (Mysak et al., 1991), sea ice variabilities on the interannual (Ikeda et al., 1996) and 71 72 intra-seasonal (Yao et al., 2000) time scales, and changes in sea ice and mixed layer properties 73 under different atmospheric conditions (Tang et al., 1999). As process-based numerical models 74 grew in complexity they yielded new insights, such as the role of sea ice's heat capacity in the 75 timing of ice melt (Zhang et al., 2004). Advances in computational power have led to realistic 76 simulations spanning a decade or more covering limited areas, such as the Canadian Arctic 77 Archipelago and Davis Strait (Lu et al., 2014) or the Labrador and Newfoundland Shelves (Ma et 78 al., 2016). Other ocean-ice models of areas within the NWA include that of the Gulf of St. 79 Lawrence and surrounding waters (Urrego-Blanco and Sheng, 2014; Wang et al., 2020), Hudson 80 Bay (Saucier et al., 2004), and the Labrador Sea (Pennelly and Myers, 2020). Canadian government agencies have developed coupled ocean-ice or atmosphere-ocean-ice models to 81 82 support activities such as hazard management, with domains ranging from the regional (e.g., Smith et al., 2013 for the Gulf of St. Lawrence) to basin-wide (Dupont et al., 2015; Wang et al., 83 84 2018). Other modelling studies have focused on hydrodynamics in coastal and shelf waters of the NWA, such as Han et al. (1997) for the Scotian Shelf, Wu et al. (2012) for the area between the 85 86 Gulf of Maine and Baffin Bay, and Chen and He (2015) for the Mid-Atlantic Bight and the Gulf 87 of Maine.
- 88 As for coupled physical-BGC modelling studies, three-dimensional models with high resolutions
- 89 have generally focused on the shelf and slope areas of the NWA. Pei (2022) used a simple
- 90 oxygen model to study seasonal changes in dissolved oxygen over the Scotian Shelf, while more
- 91 complex models have been used to study the biogeochemistry and plankton dynamics of the
- 92 Scotian Shelf and surrounding waters (Laurent et al., 2021, Rutherford and Fennel, 2022) and the
- 93 Gulf of St. Lawrence (LeFouest et al., 2010; Lavoie et al., 2021). Ross et al. (2023) developed a
- 94 coupled physical-BGC model for the North Atlantic Ocean from the Caribbean Sea to the
- 95 southern Labrador Sea, designed primarily for marine resource management.





96 As coupled simulations that include more processes and cover larger extents of space and time 97 become feasible, they are expected to enhance our understanding of how the ocean functions as an integrated system, as well as how this system might change under various scenarios of the 98 99 future climate. In this study, we present and assess a coupled ocean circulation-sea ice-BGC 100 model that has been developed recently with the primary goal of studying the interactions between physical and BGC processes in the NWA, including the BCP. Advantages of this 101 102 model's configuration include: (a) a domain that spans the area from the Mid-Atlantic Bight to 103 Baffin Bay, allowing for a wide range of oceanographic processes that can be examined; (b) a 104 horizontal grid size of O(km) that decreases with latitude, such that the first baroclinic Rossby 105 radius of deformation (Chelton et al., 1998) is spanned by about four grid boxes everywhere; (c) the use of a terrain-following vertical coordinate system, which can produce more realistic near-106 107 bottom vertical mixing and bottom boundary layer structures than the step-wise bottom 108 topography of z-level grids (Ezer and Mellor, 2004); (d) the inclusion of tides (as one of the 109 model inputs) and sea ice (through coupling between the circulation and sea ice modules), both 110 of which are important elements of the ocean system in this region, and (e) the inclusion of a BGC module, which enables the study of how processes such as the BCP are driven by the 111 112 coupled ocean circulation-sea ice system. This paper provides an assessment of the coupled 113 model's performance as well as sensitivity studies designed to elucidate the role of two physical processes, tides and sea ice. The components of the coupled model and the simulations are 114 115 described in the next section. In Sect. 3, the results of two simulations, with and without nudging 116 of the temperature and salinity towards a blend of observations and reanalysis (referred to respectively as the control and prognostic simulations), are described and quantitatively 117 compared to observations or reanalysis. In Sect. 4, the roles of tides and sea ice in the physical 118 fields of the NWA are examined by comparing the results of two additional simulations, one 119 120 without tidal forcing and the other without the simulation of sea ice, to results of the prognostic 121 simulation described in Sect. 3. A summary of our findings is presented in the concluding 122 section.





### 123 2 Model setup and forcing

- 124 The coupled circulation-sea ice-BGC modelling system used in this study consists of three
- 125 modules: an ocean circulation module based on ROMS (Regional Ocean Modeling System,
- version 3.9; Haidvogel et al., 2008), a sea ice module based on CICE (Community Ice CodE,
- version 5.1; Hunke et al., 2015), and a BGC module within ROMS based on the work of Fennel
- 128 et al. (2006, 2008) with updates as described by Laurent et al. (2021). The circulation and sea ice
- modules are coupled using the software MCT (Model Coupling Toolkit, version 2.10; Jacob et
- al., 2005; Larson et al., 2005) in a manner similar to Kristensen et al. (2017). Yang et al. (2023)
- 131 found good agreement between simulated and observed values of tides and storm surges
- simulated by a barotropic version of the ocean circulation module.
- 133 ROMS is a three-dimensional (3D) numerical circulation model with a free surface and the
- terrain-following S-coordinate system (originally developed by Song and Haidvogel (1994)) in
- the vertical. The vertical layers are placed more densely near the surface and bottom in deep
- 136 waters, and more uniformly in shallow waters. In this study ROMS has 40 vertical layers, whose
- 137 configuration is described in Appendix A. ROMS and CICE use the same horizontal grid and
- bathymetry, with the domain covering the area between  $\sim 81^{\circ}$  W and  $\sim 39^{\circ}$  W and between  $\sim 33.5^{\circ}$
- 139 N and  $\sim 76^{\circ}$  N (Fig. 1a). The grid resolution in the east-west direction is  $1/12^{\circ}$ , resulting in grid
- box dimensions of  $\sim 8$  km on each side near the grid's southern boundary and  $\sim 2$  km on each side
- 141 near the northern boundary.
- 142 The model bathymetry is derived from the 1/240°-resolution data set GEBCO 2019 (GEBCO
- 143 Compilation Group, 2019). After the GEBCO data were linearly interpolated onto the model
- 144 grid, the Shapiro filter (Shapiro, 1975) was applied to seamounts in deep waters from ~67.5° W
- 145 to  $\sim 42^{\circ}$  W and from  $\sim 34^{\circ}$  N to  $\sim 48^{\circ}$  N to reduce currents caused by spurious pressure gradients.
- 146 No other smoothing was applied to the bathymetry. To avoid model instability caused by strong
- 147 currents entering the model domain at an angle, the model bathymetry and land-sea mask in the
- 148 first four grid boxes from each lateral boundary were set to the same values as in the fifth grid
- box from the boundary.
- The advection schemes used in ROMS for physical fields are: (a) the third-order upstreamscheme for horizontal advection of physical tracers and 3D momentum and (b) the fourth-order





- 152 centered scheme for horizontal advection of two-dimensional momentum and for vertical
- advection of physical tracers and 3D momentum. The horizontal eddy viscosity and diffusivity
- are set to zero. Vertical mixing is parameterized using the "2.5-level" scheme of Mellor and
- 155 Yamada (1982) with modifications as described by Allen et al. (1995). The time step is 6 seconds
- 156 for the external (barotropic) mode and 120 seconds for the internal (baroclinic) mode.



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Figure 1. (a) Model domain and bathymetry. Locations of river mouths are indicated by red X marks. Abbreviations
are used for: Island (Is), Strait (Str.), Hudson Bay (HB), Ungava Bay (UB), Newfoundland (Nfd.), St. Lawrence
Estuary (SLE), Gulf of St. Lawrence (GSL), Cabot Strait (CS), Laurentian Channel (LC), Bay of Fundy (BoF), and
Gulf of Maine (GoM). (b) Regions in which metrics of model performance are calculated. The regions are: GRS
(Greenland Shelf), HST (Hudson Strait), BB (Baffin Bay), LS (Labrador Shelf), SPG (Subpolar Gyre), GSL (Gulf of
St. Lawrence), ScS/GB (Scotian Shelf/Grand Banks), MAB/GoM (Mid-Atlantic Bight/Gulf of Maine), and STG
(Subtropical Gyre). Areas within 10 grid points of lateral boundaries are excluded from the error metric calculations.

Atmospheric fields used to drive the coupled model are derived from the hourly reanalysis data
set ERA5 (Hersbach et al., 2018) which has a horizontal grid spacing of 1/4°. Within ROMS, the
bulk flux scheme of Fairall et al. (1996a, 1996b) is used to calculate the surface fluxes of heat





168 and fresh water. Lateral open boundary conditions are specified using the explicit scheme of 169 Chapman (1985) for sea surface elevation, the Shchepetkin scheme (Mason et al., 2010) for depth-averaged currents, and the adaptive scheme of Marchesiello et al. (2001) for depth-varying 170 171 currents and all tracers. In the adaptive boundary condition, the nudging time scale is three days 172 for inflow and 360 days for outflow. The values of currents, temperature, salinity, and sea surface 173 elevation specified at the lateral boundaries are derived from the daily reanalysis data set 174 GLORYS12V1 (hereafter GLORYS; Lellouche et al., 2021) which has a horizontal grid size of 175  $1/12^{\circ}$ . The lateral boundary conditions of currents, temperature, and salinity are supplemented by 176 nudging the simulated values near boundaries towards GLORYS values. The nudging time scale 177 is three days at the grid point closest to a lateral boundary and decreases linearly to zero over ten 178 grid points moving away from the boundary. Tidal elevation and currents are specified at the 179 lateral boundaries from the global tidal model solution TPXO9v2a (an updated version of the 180 model by Egbert and Erofeeva (2002)), with a horizontal grid size of 1/6° and 15 tidal 181 constituents.

182 Riverine freshwater input from 35 rivers (Table 1) is specified as volume flux through the bottom of a model grid cell. Each river is represented by a channel normal to the model's coastline, at 183 184 the head of which the surface elevation, vertical velocity, and tracer values are adjusted 185 according to the river discharge. The river water has a salinity of 0.4 and a temperature equal to 186 that of the GLORYS sea surface temperature at the grid point closest to the river mouth. For the 187 St. Lawrence River, we use the monthly-mean discharge at Quebec City estimated by the St. 188 Lawrence Global Observatory (2023) using the regression model of Bourgault and Koutitonsky 189 (1999). For all other rivers, we use the monthly-mean data set of Dai (2017) that was updated in 190 May 2019, substituting climatological values calculated over the period 1900-2018 for months with no data. Freshwater flux across coastlines due to the melting of ice and snow over land is 191 192 specified as an addition to the sea surface height and the surface freshwater flux at the 193 appropriate model grid boxes. This freshwater flux is derived from the monthly data set of 194 Bamber et al. (2018), who combined satellite observations of glaciers with the output of a 195 regional climate model. A monthly climatology of this data set, which covers the period 1958-196 2016, is used in simulations of the period after December 2016. Both the riverine and continental freshwater fluxes are converted to "pseudo-means" (monthly means that are adjusted such that 197





- 198 daily-mean values temporally interpolated from them, when summed over a month, results in the
- true monthly means) following Killworth (1996).

200

201 Table 1. Names and discharge locations of rivers in the coupled model.

River	Lon.	Lat.	River	Lon.	Lat.
	(° W)	(° N)		(° W)	(° N)
Innuksuac	78.06	58.42	Saguenay	69.72	48.06
Nastapoca	76.56	56.91	St. Lawrence	70.81	46.94
Great Whale	77.81	55.28	Saint John	66.14	45.32
Roggan	79.56	54.37	Androscoggin	69.89	43.78
La Grande + Sakami	79.22	53.78	Saco	70.31	43.54
Eastmain	78.72	52.23	Merrimack +	70.81	42.87
Rupert	78.89	51.56	Pemigewasset		
Nottaway	78.89	51.51	Connnecticut	72.31	41.26
Harricana	79.89	51.30	Hudson	74.06	40.63
Arnaud	69.64	60.04	Passaic (Ramapo)	74.14	40.50
Leaf	69.39	58.90	Delaware + Beaver Kill	75.47	39.42
Koksoak (Caniapiscau	68.14	58.55	Susquehanna	76.22	39.35
+ Mélèzes)			Potomac	76.47	38.05
False + Whale	67.64	58.20	Rapidan +	76.39	37.59
George	66.14	58.77	Rappahannock		
Petit Mécatina	59.39	50.62	James	76.31	36.99
Natashquan	61.89	50.19	Roanoke	76.64	35.99
Moisie	65.97	50.24	Neuse (Contentnea)	76.64	35.04
Manicouagan +	68.22	49.17	Cape Fear	78.14	33.87
Outardes				1	<u> </u>

202 The sea ice model CICE consists of four main components: (a) a thermodynamic component that

203 calculates local growth or decay of sea ice due to snowfall and heat fluxes (Bitz and Lipscomb,

204 1999; Briegleb and Light, 2007); (b) a dynamic component that calculates the material properties





- of the ice (Hunke and Dukowicz, 1997; Bouillon et al., 2013); (c) a transport component that 206 calculates the horizontal advection of the ice (Lipscomb and Hunke, 2004); and (d) a component 207 that calculates the distribution of ice among thickness categories due to ridging and mechanical 208 processes (Hunke et al., 2015). There are seven ice layers and five ice thickness categories. We 209 implemented the clamped boundary condition, in which GLORYS-derived values of sea ice concentration (as a fraction of the model grid box area) and thickness are specified at the model's 210 211 lateral open boundaries. The sea ice specified at the lateral boundaries is uniformly covered with 212 snow of 0.2-m thickness. The time step in CICE is 1200 seconds.
- Coupling between ROMS and CICE via MCT occurs every 1200 seconds, equivalent to every 10 213
- internal time steps in ROMS and every time step in CICE. At each coupling step, ROMS sends 214
- 215 CICE the ERA5-derived atmospheric fields that drive both modules, as well as ROMS-simulated
- 216 values of currents, sea surface tilt, and sea-surface values of temperature and salinity. CICE
- 217 sends ROMS the ice-attenuated value of shortwave radiation and ice-ocean fluxes of stress, heat,
- 218 and salt or freshwater.
- 219 The BGC module includes the nitrogen cycle (Fennel et al., 2006), the carbonate system (Fennel
- 220 et al., 2008), and oxygen (Fennel et al., 2013). Particulate organic matter variables
- 221 (phytoplankton, zooplankton, and detritus) are split into small and large size classes, and rates of
- biological processes are temperature-dependent (Laurent et al., 2021). The HSIMT advection 222
- 223 scheme (Wu and Zhu, 2010), which ensures no spurious negative values occur, is used for both
- horizontal and vertical advection of BGC tracers. Initial and boundary conditions for nitrate, 224
- phosphate, dissolved inorganic carbon, alkalinity, and oxygen are interpolated from the 225
- climatology of GLODAP (Global Ocean Data Analysis Project; Lauvset et al., 2021) and set to a 226
- 227 small constant value for all other biogeochemical variables.
- 228 Four simulations will be examined in this paper. In the control simulation (hereafter Ctrl), the
- ocean temperature and salinity at all grid points are nudged with a restoring time scale of 60 days 229
- 230 toward the monthly data set of in situ observations known as CORA (COriolis dataset for Re-
- 231 Analysis; Cabanes et al., 2013) above the 2000-m depth and GLORYS below 2000 m (where
- CORA data are not available). The control simulation includes biogeochemistry. The second 232
- 233 simulation is a prognostic one (hereafter Prog), i.e., without any nudging of the simulation. There





- 234 are three reasons for presenting these simulations: 1) the ways in which either simulation 235 outperforms the other can shed light on potential ways in which the model can be improved; 2) Ctrl, by including nudging of the temperature and salinity, produces a physical state of the ocean 236 237 that is generally realistic and acts as a foundation for the biogeochemical simulation; and 3) this 238 modelling system is being used in regional climate simulations (Renkl et al., in prep.), and the lack of an option to nudge simulations of future conditions necessitates assessment of a 239 240 prognostic simulation. The performances of Ctrl and Prog will be evaluated in the next section. 241 Two more simulations are carried out for the sensitivity studies discussed in Sect. 4. Both are 242 identical to Prog but one is made without the specification of tidal elevation and currents at the 243 lateral boundaries (hereafter NoTides) and the other is made without coupling of ROMS to CICE 244 (hereafter NoIce). Configurations of the simulations are summarized in Table 2. All simulations 245 are made from 1 September 2013 to 31 December 2018 and are initialized with an ice-free ocean 246 in which the ocean's state consists of GLORYS fields for 1 September 2013 interpolated to the model grid. The simulation results of January 2015 onwards (December 2014 onwards in the 247 248 case of seasonal averages) will be discussed in the following sections.
- **Table 2**. Descriptions of the simulations discussed in this study.

Simulation	Description	Temperature &	Tidal forcing at	Coupling to
name		salinity nudging	lateral boundaries	sea ice model
Ctrl	Control	On	On	On
Prog	Prognostic	Off	On	On
NoTides	No tidal forcing	Off	Off	On
NoIce	No sea ice simulation	Off	On	Off

# 250 3 Model results and evaluation

# 251 **3.1 Simulated currents, temperature, and salinity**

- 252 We first examine four-year (1 January 2015–31 December 2018) averages of currents, salinity,
- and temperature produced by DalROMS-NWA12 v1.0 in runs Ctrl and Prog (Figs. 2 and 3
- respectively). Both model runs reproduce the major features of the circulation in this region.
- 255 They include: (a) the East and West Greenland Currents forming a clockwise flow around the





256 southern tip of Greenland; (b) bifurcation of the West Greenland Current, with one branch 257 continuing northward along the west coast of Greenland and the other flowing westward across the Labrador Sea; and (c) the westward flow across the Labrador Sea merging with the 258 259 southward Baffin Island Current out of Baffin Bay and southeastward flow out of Hudson Strait 260 to form the Labrador Current, the equatorward limb of the North Atlantic Subpolar Gyre. This 261 current has branches along the Labrador coast and the shelf break. Near the Grand Banks, the 262 Labrador Current meets the poleward Gulf Stream, the poleward limb of the North Atlantic 263 Subtropical Gyre. Both simulations also reproduce the relatively cold and fresh water over 264 continental shelves, with especially low values of salinity in Hudson Bay and the St. Lawrence Estuary. The three major differences between the simulations are that: (a) the bifurcation of the 265 266 West Greenland Current has a stronger northward branch in Prog; (b) the Gulf Stream in Prog is 267 closer to the continental shelf; and (c) the Gulf of St. Lawrence is warmer and saltier in Prog, 268 both at the surface and in model results interpolated to the 100-m depth. As discussed below, 269 comparison of model results to observations or reanalysis suggests the results of Ctrl are more 270 realistic than those from Prog. Seasonal-means of these simulated fields, shown in Appendix B, 271 indicate that differences between the simulations are more prominent in summer than in winter.

# 272 **3.2** Model performance for currents, temperature, and salinity

To assess the model's performance in simulating currents, temperature, and salinity, we divide the model domain into nine regions (Fig. 1b) and calculate metrics in each region for model results at the sea surface and interpolated to the 100-m depth. Within a given region, each model grid point is weighted by its horizontal area when regional averages are calculated. The areas along the model's lateral boundaries in which the simulated tracers and currents are nudged towards GLORYS are not included in the calculations.

- 279 To quantify model performance for temperature and salinity at the sea surface, root-mean-square
- errors (RMSE) of monthly-mean model results are calculated with respect to monthly means of
- 281 observations that are linearly interpolated to the model grid. Temperature and salinity at the
- surface are compared to 1/4°-grid analysed data sets that combine satellite and in situ
- 283 observations: the daily data set OISST (Optimum Interpolation Sea Surface Temperature, v2.0
- for 2015–2017 and v2.1 for 2018; Huang et al., 2021) for temperature and the weekly data set
- 285 SMOS (Soil Moisture Ocean Salinity; Buongiorno Nardelli et al., 2016) for salinity. For model







Figure 2. Temporal-mean salinity (a, c) and temperature (b, d) at the sea surface, averaged over 2015–2018, from
runs Ctrl (a, b) and Prog (c, d). Also shown in panels (a) and (c) are trajectories representing displacement over five
days due to currents at the sea surface averaged over 2015–2018, shown at every 24 model grid points. The gray

contour line represents the 1000-m water depth.







**Figure 3.** Similar to Fig. 2 but for model results interpolated to the 100-m depth.





295	results interpolated to the 100-m depth, where gridded observational data sets are not available,
296	root-mean-square differences (RMSD) of temperature and salinity are calculated with respect to
297	their respective GLORYS values. It should be noted that GLORYS is based on simulations that
298	do not include tides (Lellouche et al., 2018), which may affect the accuracy of its temperature
299	and salinity distributions in addition to that of its currents.
300	The RMSE and RMSD of temperature from the two simulations (Figs. 4–5) are similar over the
301	northern part of the model domain in that the largest errors tend to occur at the surface in GRS
302	(Greenland Shelf) throughout the year, and in HST (Hudson Strait) and BB (Baffin Bay) during
303	the summer. Within these three areas, the largest values of RMSE/RMSD occur in HST at the
304	surface (about 3.5 °C in Ctrl and 2.9 °C in Prog, both in July). The corresponding biases of
305	surface temperatures (not shown) indicate a tendency for overestimation (+0.3°C-+2.2°C in
306	GRS, and -0.4°C-+1.9°C and -0.5°C-+1.0°C during summer in HST and BB respectively for
307	Prog). Thus, the largest errors occur near the model's lateral open boundaries, during periods
308	when sea ice (which would tend to keep the temperature near freezing) is less in HST and BB,
309	and at the surface where the performance metrics are calculated with respect to an independent
310	observational data set instead of GLORYS which is also used as lateral boundary input. This
311	suggests GLORYS as a possible source of model errors, although a detailed examination is
312	beyond the scope of this study. The slightly larger RMSE of the simulated surface temperature in
313	Ctrl than in Prog over these areas may be related to the larger underestimation of sea ice in Ctrl,
314	which will be discussed in Sect. 3.3.

Further south, in SPG (Subpolar Gyre), the RMSE/RMSD are smaller in Ctrl than in Prog. The RMSE at the surface has the range 0.6–1.6 in Ctrl and 0.9–2.1 in Prog, and the RMSD for model results interpolated to the 100-m depth has the range 0.7–1.4 in Ctrl and 0.9–2.0 in Prog. This suggests the West Greenland Current simulated in Ctrl, in which the branch of the current that separates from the Greenland coast dominates, and its associated temperature distribution are more realistic. The RMSE/RMSD in LS (Labrador Shelf) are similar between the simulations, ranging from 0.4 to 1.9 in Ctrl and 0.4 to 1.4 in Prog.

The results of Ctrl clearly outperform those of Prog over the southern part of the model domain,
with a maximum RMSE/RMSD of ~2.5°C in the former and ~5.2°C in the latter, both occurring





- 324 in ScS/GB (Scotian Shelf/Grand Banks) for model results interpolated to the 100-m depth. This 325 indicates the Gulf Stream simulated in Ctrl, flowing further from the coast than in Prog (Figs. 2-3), is more realistic. In addition to STG (Subtropical Gyre) where the Gulf Stream itself flows, 326 the RMSE/RMSD in Ctrl are smaller both at the surface and the 100-m depth in ScS/GB, 327 328 MAB/GoM (Mid-Atlantic Bight/Gulf of Maine), and GSL (Gulf of St. Lawrence), all of which are influenced by the warm and salty slope water of which the Gulf Stream water is one 329 330 component (Gatien, 1976). The influence of the slope water extending into the GSL at the 100-m 331 depth (which can also be seen in Fig. 3) is consistent with the observed (e.g., Richaud et al., 332 2016) intrusion of slope water into the Gulf of St. Lawrence along the Laurentian Channel. 333 The RMSE and RMSD of salinity for both simulations (Figs. 6-7) in the northern part of the domain are similar to those of temperature in that they tend to be largest at the surface in 334 335 summer, especially in HST where the RMSE has maximum values of  $\sim 2.7$  in Ctrl and  $\sim 3.7$  in Prog. In contrast to the temperature metrics, the surface salinity metrics in GRS undergo an 336 annual cycle similar to those in HST and BB, being larger during summer and fall than during 337 338 the rest of the year. During the months when the RMSE are largest, the surface salinity biases for Prog are negative in GRS and BB ( $\sim$ -1.0) and positive in HST (up to  $\sim$ +1.5). In SPG and LS the 339 RMSE/RMSD are generally smaller in Ctrl than in Prog (0.1–0.8 for Ctrl and 0.4–1.5 in Prog for 340 341 the two regions combined), which is consistent with the metrics for temperatures discussed 342 above.
- 343 In the southern part of the domain, Ctrl has much smaller RMSE than Prog in GSL, ScS/GB, and
- 344 MAB/GoM (e.g., the maximum value is ~1.7 for Ctrl and ~3.7 for Prog in MAB/GoM). The
- 345 corresponding biases for Prog in these areas are consistently positive (up to  $\sim$ +3.3 in GSL),
- indicating overestimation. However, within GSL, the 2015–2018 mean of summer surface
- salinity simulated by Prog is lower than its counterpart from Ctrl by up to  $\sim$ 3.5 in the St.
- Lawrence Estuary, but higher by ~2 further downstream in the Gulf of St. Lawrence (not shown).
- 349 This suggests the model is not able to fully reproduce the propagation of low-salinity water from
- the St. Lawrence Estuary (where the salinity is underestimated) to areas downstream of it (where
- 351 the salinity is overestimated).





Temperature RMSE (°C)

2015 2016	a) (	GR	Ss	urf	ac	е							b)	GR	S '	100	m									
2016	1.7	1.6	1.9	1.4	1.5	2.4	2.8	2.4	2.6	2.9	2.6	1.7	- 0.9	0.9	1.1	1.3	1.1	1.1	1.2	1.0	0.6	0.6	0.7	0.8		
	-1.4	1.8	2.0	2.0	2.2	2.8	2.1	2.0	1.9	1.9	1.6	1.5	0.8	0.9	1.2	1.0	0.7	1.0	1.1	1.0	0.7	0.7	0.6	0.6		
2017	2.6	2.0	1.4	1.6	1.9	2.4	2.4	3.0	2.5	3.0	2.5	2.7	- 0.8	0.8	0.9	0.9	0.9	1.1	1.1	0.9	0.7	0.6	0.7	0.8		6
2018	-2.2	1.7	2.2	2.2	1.8	2.4	1.7	1.6	2.0	2.0	1.7	2.0	-1.1	0.9	0.8	0.9	0.6	1.7	1.9	2.0	1.4	0.5	0.6	0.6		
	c)	HS.	Γs	urf	ace	ب			'	-		,	d)	нs	т 1	00	m			'	-			,		
2015	-0.4	0.2	0.2	0.3	0.5	1.5	2.4	2.0	1.1	0.6	0.7	0.9	-0.5	0.5	0.6	0.6	0.7	0.8	0.8	0.8	0.7	0.7	0.5	0.5		
2016	-0.5	0.3	0.3	0.3	0.6	1.6	27	2.0	1.0	0.6	0.7	0.9	-0.6	0.6	0.7	0.7	0.8	0.8	0.8	0.9	0.9	0.9	0.7	0.5		
2017	-0.7	0.3	0.3	0.4	0.7	1.7	2.3	1.8	1.1	0.7	0.8	0.8	-0.5	0.6	0.8	0.8	0.9	1.0	1.0	1.0	1.1	1.2	1.2	0.9		
2018	-0.1	0.2	0.2	0.2	0.4	1.7	3.5	2.4	1.2	0.6	0.5	0.2	-0.7	0.7	0.9	0.9	0.9	1.0	0.9	0.9	1.0	1.1	0.9	0.7		
2010	e)	BB	511	rfa	ce					-			f)	BB	10	0 m				'						5
2015	-0.6	0.4	0.3	0.4	0.4	1.2	2.0	1.5	0.9	0.7	0.9	0.7	-0.8	1.2	1.3	1.3	1.2	1.1	1.0	1.0	1.0	1.1	1.1	1.0		
2016	-0.5	0.5	0.5	0.5	0.5	11	17	12	0.8	0.7	0.8	0.9	-10	14	17	1.6	1.5	14	1.3	12	12	1.3	1.3	1 1		
2017	-0.6	0.5	0.5	0.5	0.6	1.0	1.5	1.4	0.7	0.7	0.8	0.9	-1.0	1.2	1.4	1.4	1.3	1.2	1.1	1.1	1.1	1.2	1.2	1.0		
2018	-0.6	0.5	0.4	0.4	0.4	1.1	1.8	1.2	0.6	0.6	0.5	0.5	- 0.9	1.0	1.2	1.1	1.1	1.1	1.1	1.0	1.1	1.1	1.0	0.8		
_0.0		I S	ein	fa				-	'	-			b)	19	10	0 m								1		
2015	9)	0.5	Sui	0.5		0.0	0.0	0.6	0.0	0.7	0.5	0.5		0.5	0.6		1.0	1 4	10	10	1.0	10	0.0	0.5		4
2013	0.0	0.5	0.0	0.0	1.4	1.6	1.1	0.0	0.9	1.0	0.5	0.5	0.4	0.5	0.0	1.0	1.2	1.4	1.5	1.0	1.2	1.3	1.5	0.5		4
2010	0.7	0.0	0.0	0.0	1.4	1.0	0.0	1.0	0.9	0.9	0.0	0.4	-0.4	0.5	0.7	1.0	1.4	1.0	1.5	1.5	1.5	1.7	1.5	1.0		
2017	-0.7	0.7	0.7	1.0	1.3	1.1	0.9	0.8	1.0	0.8	0.0	0.0	-0.7	0.5	0.7	0.0	1.4	1.3	1.3	1.0	1.7	1.5	1.0	0.8		
2010	0.7		0.7	1.0	1.5	1.5	0.9	0.8	1.0	0.0	0.0	0.0	0.7		0.7	0.9	1.1	1.5	1.2	1.2	1.4	1.5	1.2	0.0		
0015	1) 3	PG	I SL	urra	ace	0.0	0.0	0.0	• •	0.0	0.0	0.0	J) 3	580			m	0.0	10	10		10		10		
2015	-0.8	0.9	1.3	1.0	0.8	0.9	0.8	0.6	0.8	0.9	0.9	0.8	-0.8	0.8	0.9	0.7	0.8	0.9	1.0	1.2	1.1	1.2	1.1	1.0		
2010	1.0	1.1	1.2	1.0	1.1	0.7	0.8	0.8	0.7	0.7	0.7	0.8	-0.8	0.9	0.8	0.9	0.9	1.0	1.0	1.1	1.3	1.1	1.2	0.9	_	3
2017	1.0	1.1	1.2	1.1	0.9	0.9	0.9	1.0	0.6	0.8	0.7	0.8	1.1	0.8	0.8	0.8	0.7	0.8	0.8	1.9	1.2	1.1	1.0	0.9		
2010		1.0	1.4	1.0	0.8	0.8	0.6	0.6	0.8	0.7	0.7	0.7	-0.8	0.9	0.7	0.7	0.7	0.8	1.0	1.2	1.4	1.3	1.0	0.9		
	k) (	GSI	L S	urt	ace	•							I) (	GSI	- 10	1 00	n									
2015	-0.7	0.9	0.9	0.5	0.7	1.1	0.9	1.1	1.6	1.1	0.6	0.6	-0.9	0.8	0.8	0.8	0.7	0.8	1.0	1.0	1.1	1.4	1.2	1.0		
2016	-0.5	0.5	0.8	0.7	0.9	1.4	1.1	1.3	1.2	0.8	0.9	0.7	-0.6	0.6	0.8	1.0	0.8	0.8	0.9	1.0	1.0	1.2	1.1	0.9		
2017	-0.6	0.7	0.7	0.3	0.9	1.6	1.5	1.4	1.5	1.2	0.6	0.6	-0.5	0.6	0.8	1.3	1.2	1.3	1.3	1.2	1.3	1.5	1.6	1.4		
2018	-0.5	0.3	0.3	0.6	0.6	0.9	1.1	1.1	1.2	0.9	0.7	0.5	-1.2	1.0	0.7	0.8	1.1	1.3	1.4	1.5	1.6	1.7	1.3	1.0	-	2
	m)	Sc	S/(	GΒ	su	rfa	се						n)	Sc	S/C	зВ .	100	m								
2015	-1.1	1.0	1.2	1.0	0.7	0.8	0.7	0.8	1.7	1.7	1.5	1.0	- 1.7	2.1	2.4	2.5	2.0	1.9	2.1	2.1	1.6	1.7	1.7	1.5		
2016	-0.9	0.7	0.9	1.2	0.5	0.8	1.1	1.4	1.7	1.4	1.2	0.9	-1.1	1.2	1.4	1.7	1.4	1.3	1.6	1.5	1.8	1.7	1.8	1.9		
2017	-0.8	0.8	0.8	0.7	0.6	0.7	0.9	1.4	1.5	1.6	1.4	1.0	-1.8	1.8	1.8	1.5	1.3	1.2	1.6	1.7	1.9	2.1	2.5	2.1		
2018	0.7	0.8	0.7	0.6	0.8	0.8	0.9	0.9	1.3	1.5	1.1	0.8	-1.8	1.7	1.8	1.6	1.5	1.4	1.6	1.8	1.9	1.7	1.8	1.5		
	o)	MA	B/(	Go	M۹	sur	fac	е					p)	MA	B/	Go	M 1	00	m							
2015	- 1.0	1.5	1.2	1.1	0.9	0.9	1.2	1.2	1.0	0.7	0.6	0.8	-1.6	1.9	1.6	1.3	1.1	1.1	1.4	1.2	1.3	1.4	1.6	1.7	-	1
	-0.9	1.1	1.0	1.1	0.8	0.8	0.8	1.0	0.8	0.7	0.9	0.8	- 1.7	1.6	1.4	1.4	1.5	1.4	1.2	1.2	1.4	1.2	1.4	1.6		
2016	-1.1	1.1	0.9	1.3	0.8	0.8	1.0	1.0	0.7	0.7	0.7	1.0	-1.8	1.5	1.3	1.0	1.1	1.0	1.0	1.4	1.5	1.6	1.4	1.5		
2016 2017	- 1.5	1.3	1.1	0.7	0.7	0.9	0.9	1.1	0.9	0.7	0.7	1.0	- 1.5	1.4	1.2	1.0	0.8	0.7	0.9	1.0	1.1	1.0	1.2	1.0		
2016 2017 2018	_					-							r)	STO	G 1	00	m									
2016 2017 2018	q) :	STO	Gs	urf	ace	e																				
2016 2017 2018 2015	<b>q)</b> 1.4	STC 1.4	G s 1.5	<b>urf</b> 1.4	ace 1.2	<b>1</b> .0	0.8	0.8	1.0	1.1	1.3	1.5	-1.6	1.6	1.7	1.7	1.6	1.5	1.8	2.1	2.2	2.1	1.8	1.7		
2016 2017 2018 2015 2015 2016	<b>q)</b> 1.4 1.8	<b>ST</b> 1.4 1.6	<b>G S</b> 1.5 1.6	1.4 1.5	ace 1.2 1.4	1.0 1.2	0.8 1.0	0.8 0.9	1.0 0.9	1.1 1.2	1.3 1.3	1.5 1.3	- 1.6 - 1.7	1.6 1.7	1.7 1.6	1.7 1.8	1.6 1.9	1.5 1.6	1.8 1.9	2.1 2.0	2.2 2.2	2.1 2.2	1.8 2.1	1.7 1.5		0
2016 2017 2018 2015 2016 2017	<b>q)</b> 1.4 1.8 1.5	1.4 1.6 1.6	<b>G s</b> 1.5 1.6 1.7	1.4 1.5 1.6	ace 1.2 1.4 1.5	1.0 1.2 1.4	0.8 1.0 0.9	0.8 0.9 0.9	1.0 0.9 1.1	1.1 1.2 1.1	1.3 1.3 1.3	1.5 1.3 1.3	- 1.6 - 1.7 - 1.5	1.6 1.7 1.7	1.7 1.6 1.6	1.7 1.8 1.6	1.6 1.9 1.7	1.5 1.6 1.9	1.8 1.9 1.8	2.1 2.0 2.0	2.2 2.2 1.9	2.1 2.2 1.9	1.8 2.1 1.9	1.7 1.5 1.6		0
2016 2017 2018 2015 2016 2017 2018	<b>q)</b> - 1.4 - 1.8 - 1.5 - 1.4	1.4 1.6 1.6 1.7	G S 1.5 1.6 1.7 1.4	1.4 1.5 1.6 1.3	1.2 1.4 1.5 1.4	1.0 1.2 1.4 1.4	0.8 1.0 0.9 1.0	0.8 0.9 0.9 0.7	1.0 0.9 1.1 0.8	1.1 1.2 1.1 1.1	1.3 1.3 1.3 1.5	1.5 1.3 1.3 1.6	- 1.6 - 1.7 - 1.5 - 1.6	1.6 1.7 1.7 1.7	1.7 1.6 1.6 1.5	1.7 1.8 1.6 1.6	1.6 1.9 1.7 1.7	1.5 1.6 1.9 1.7	1.8 1.9 1.8 1.8	2.1 2.0 2.0 1.9	2.2 2.2 1.9 1.8	2.1 2.2 1.9 1.8	1.8 2.1 1.9 1.9	1.7 1.5 1.6 1.7		0

352 353

Figure 4. Root-mean-square-errors/differences of temperatures simulated in Ctrl, calculated for the regions shown
 in Fig. 1b with respect to the observation-derived OISST data set at the surface and GLORYS reanalysis for model

Month

Year





Temperature RMSE (<sup>o</sup>C)

	a) (	GR	Ss	urf	ac	е							b)	GR	S	100	m									
2015	1.6	1.4	1.4	1.1	1.3	2.0	2.3	1.9	1.9	2.5	2.5	1.6	- 0.9	1.0	1.1	1.2	1.0	0.9	0.9	1.0	1.1	1.0	0.8	0.9		
2016	1.1	1.3	1.4	1.5	1.7	2.4	1.8	1.5	1.5	1.6	1.4	1.3	- 0.9	0.9	1.1	0.9	0.9	0.7	0.9	0.8	0.9	1.1	0.6	0.6		
2017	2.4	1.8	1.0	1.2	1.5	1.9	1.9	2.3	1.8	2.3	2.0	2.3	- 0.8	0.8	0.9	1.0	0.7	0.7	0.8	0.9	1.1	1.2	0.7	0.7	•	6
2018	1.7	0.9	1.6	1.9	1.5	2.3	1.6	1.3	1.5	1.4	1.3	1.4	-0.9	1.1	1.0	0.9	0.7	1.6	1.7	1.6	0.9	0.7	0.6	0.6		
	c)	HS'	Γs	urf	ace	<u>,</u>			'		'	_	d)	HS	т 1	00	m			'	1			-		
2015	-0.4	0.2	0.2	0.4	0.6	1.1	2.1	2.1	1.5	0.7	0.7	1.0	-0.7	0.7	0.7	0.6	0.6	0.5	0.4	0.4	0.5	0.6	0.5	0.6		
2016	-0.5	0.3	0.4	0.4	0.5	1.3	2.3	2.2	1.3	0.6	0.7	1.0	-0.8	0.7	0.7	0.7	0.6	0.5	0.5	0.5	0.7	0.8	0.6	0.5		
2017	-0.7	0.3	0.4	0.4	0.6	1.6	2.1	2.1	1.3	0.7	0.9	0.9	-0.7	0.7	0.6	0.6	0.5	0.5	0.4	0.5	0.8	1.1	1.0	0.7		
2018	-0.1	0.1	0.1	0.2	0.2	1.2	2.9	2.1	1.2	0.6	0.5	0.2	-0.5	0.5	0.5	0.5	0.4	0.3	0.4	0.4	0.7	0.9	0.7	0.5		
2010	e)	BB	SU	rfa	ce					,	,		f) F	BB	10	0 m		,	,	,	,	,	,	-	ť	5
2015	-0.8	0.7	07	0.7	0.7	13	20	1.3	10	0.9	12	0.9	0.9	1.0	0.9	0.9	0.9	0.9	1.1	14	1.5	16	1.3	1.1		
2016	-0.8	0.6	0.7	0.7	0.8	14	21	14	0.9	0.9	0.9	1.0	-1.0	1.0	0.9	0.9	0.9	1.0	12	14	1.5	1.6	14	1.0		
2017	-0.8	0.7	0.6	0.6	0.8	1.3	1.6	14	0.8	0.8	0.0	1.0	-0.8	0.8	0.8	0.7	0.7	0.8	1.0	12	1.0	1.0	12	1.0		
2018	-10	1 1	1.0	0.9	0.8	14	1.9	12	0.7	0.7	0.9	0.9	-0.9	0.9	0.8	0.8	0.9	1.0	1 1	12	14	1.5	1.3	0.9		
2010	a)			fa	0.0							0.0	b)		10	0.0	0.0							0.0		
2015	9)	0.6	5ui			0.0	0.0	0.0	10	0.0	0 5	0.6	0.7	0.7	0.7		0.6	0.0	0.0	4.4	1 0	1.4	1.0	0.0		4
2015	0.9	0.0	0.7	0.0	0.5	0.9	0.0	0.0	1.0	0.0	0.5	0.0	0.7	0.7	0.7	0.0	0.0	0.0	0.9	1.1	1.0	1.4	1.2	0.9		+
2010	1.1	0.7	0.7	0.7	0.5	1.0	1.9	1.0	1.0	0.0	0.7	0.5	0.0	0.0	0.7	0.7	0.0	0.0	0.0	1.0	1.2	1.4	1.4	0.9		
2017	1.1	0.0	0.0	0.7	0.6	0.9	1.2	0.0	1.0	0.0	0.0	0.5	0.5	0.4	0.5	0.5	0.0	0.5	0.0	0.0	1.0	1.0	1.1	0.0		
2010	0.4	0.4	0.4	0.5	0.5	0.8		0.8		0.9	0.0	0.0	0.5	0.5	0.5	0.5	0.0	0.7	0.7	0.0	1.0	1.2	1.0	0.0		
0045	1) 3	PG	I SL	ILLE	ace							1.0	)) <b>z</b>	PC	1 1		m				1.0			1.0		
2015	1.4	1.8	2.0	2.1	1.6	1.3	1.2	1.0	1.1	1.4	1.3	1.3	-1.9	1.8	1.5	1.4	1.6	1.8	1.8	1.9	1.9	2.0	1.4	1.3		
2016	-1.3	1.4	1.4	1.3	1.4	0.9	1.1	1.1	0.9	1.0	1.0	1.1	-1.2	1.1	1.2	1.3	1.2	1.3	1.4	1.4	1.3	1.4	1.4	1.2	_ ;	3
2017	- 1.5	1.5	1.4	1.5	1.4	1.4	1.4	1.4	0.9	1.3	1.1	1.3	-1.3	1.1	1.0	1.0	1.1	1.0	1.2	1.3	1.6	1.4	1.4	1.4		
2018	1.5	1.6	1.4	1.3	1.4	1.3	0.9	0.9	1.1	1.1	1.0	1.0	1.5	1.2	0.9	1.0	1.0	1.2	1.3	1.5	1.6	1.6	1.3	1.0		
	k) (	GS	Ls	urf	ace	•							I) C	àSL	. 10	1 OO	n									
2015	1.7	1.2	1.4	1.3	1.0	1.0	1.0	1.3	1.6	0.8	1.0	1.2	-2.4	1.2	1.0	1.2	1.5	1.8	2.2	2.7	3.0	3.4	3.5	3.6		
2016	2.1	2.3	2.0	1.5	0.9	1.0	1.0	1.3	1.3	1.1	0.9	1.5	-2.4	1.6	1.6	1.7	1.8	2.1	2.5	2.6	2.9	3.3	3.8	3.5		
2017	1.9	1.9	1.9	1.6	0.9	1.2	1.4	1.1	1.2	1.1	1.8	2.1	-2.1	1.1	1.4	2.2	2.5	2.7	2.7	2.8	3.2	3.7	4.0	3.8		
2018	2.2	2.1	1.8	1.5	0.9	0.8	1.0	1.0	1.0	1.1	1.7	1.8	2.4	1.4	1.4	1.5	2.0	2.5	2.7	3.0	3.4	3.8	3.6	3.0	- :	2
	m)	Sc	S/(	GΒ	su	rfac	ce					_	n)	Sc	S/C	βB	100	m					_			
2015	2.1	2.6	2.5	2.1	1.3	0.9	0.8	0.9	1.4	1.4	1.4	2.1	- 3.5	2.7	2.5	2.6	2.5	3.2	3.5	3.9	4.2	4.8	5.2	4.8		
2016	2.7	3.0	2.3	1.7	1.8	1.3	0.9	1.1	1.3	1.2	0.9	1.8	- 3.4	2.4	2.1	2.0	2.4	2.6	2.6	3.2	4.0	4.2	4.2	3.8		
2017	2.3	2.2	2.2	2.1	1.3	0.7	0.8	1.2	1.3	1.4	1.1	1.1	3.2	2.6	2.4	2.3	2.5	2.5	2.6	2.9	3.2	3.8	4.4	4.1		
2018	1.8	1.8	1.8	1.2	0.7	0.8	0.9	1.0	1.3	1.3	1.2	1.5	3.0	2.6	2.5	2.6	2.7	2.5	2.4	2.6	2.7	3.2	3.3	2.6		
	<b>o)</b>	MA	B/(	Go	Ms	surf	fac	е					p)	MA	В/	Go	<b>M</b> 1	00	m							
2015	2.7	2.3	2.2	2.5	1.8	1.7	1.5	1.4	1.2	1.7	2.2	2.2	- 1.8	1.8	1.7	1.5	1.5	1.2	1.3	1.3	1.7	1.6	2.0	2.1	-	1
2016	2.8	3.3	3.7	3.3	2.7	1.7	1.4	1.8	1.5	2.2	3.2	3.2	1.9	1.9	1.6	1.5	1.5	1.2	1.2	1.4	1.2	1.2	1.5	1.6		
2017	4.0	4.2	4.5	4.7	4.1	2.8	2.3	2.1	2.1	2.4	2.8	2.9	- 1.8	1.8	1.5	1.5	1.3	1.3	1.4	1.4	1.3	1.4	1.6	1.8		
2018	3.9	4.3	4.6	3.5	2.8	2.6	2.0	1.9	2.1	2.1	2.5	3.3	-2.0	1.8	1.3	1.4	1.2	1.1	1.0	1.1	1.5	1.5	1.5	1.3		
	a) :	STO	Gs	urf	ace	ə					'	_	r) \$	STO	<b>à</b> 1	00	m	'		'						
2015	2.4	2.6	2.8	2.5	2.3	1.8	1.4	1.1	1.3	1.5	2.1	2.6	2.0	2.1	2.0	2.0	2.3	2.5	2.7	2.9	3.3	3.4	3.2	2.7		
2016	2.9	2.8	2.8	2.6	2.4	2.1	1.4	1.2	1.4	1.9	2.0	2.4	-2.5	2.5	2.2	2.3	2.3	2.6	2.7	2.9	3.2	3.2	3.1	2.6		_
2017	3.0	3.2	3.0	3.0	2.7	2.2	1.4	1.2	1.4	1.7	2.0	2.1	2.5	2.3	2.4	2.5	2.4	2.7	2.8	3.1	3.2	2.9	3.0	2.5	_ (	D
2018	2.5	2.7	2.4	2.6	2.3	2.1	1.5	1.2	1.2	1.6	2.2	2.5	-2.4	2.5	2.3	2.5	2.6	2.8	3.0	3.1	3.1	3.1	2.9	2.6		
_0.0		-	-		-					10		10	_				_	-	-	-	-	10		10		
	٦	2	3	4	5	ы Мо	/ nth	่ช เ	9	10	11	12	1	2	3	4	5	6	1	8	9	10	11	12		

357 358

**359** Figure 5. Similar to Fig. 4 but for temperatures simulated in Prog.

Year





3.5

3

2.5

Salinity RMSE

2

1.5

1

0.5

0

	a) (	GR	Ss	urf	ac	е								b) (	GR	S 1	00	m							
2015	-0.6	0.6	0.7	0.7	0.8	1.0	1.5	1.1	0.8	1.0	0.8	0.6	.	0.3	0.3	0.4	0.4	0.3	0.3	0.4	0.2	0.2	0.3	0.4	0.3
2016	-0.5	0.5	0.5	0.6	0.8	0.9	1.4	1.0	0.9	0.7	0.7	0.5	١.	0.3	0.3	0.4	0.4	0.3	0.3	0.4	0.3	0.2	0.3	0.4	0.4
2017	-0.5	0.6	0.5	0.5	0.6	1.0	1.2	1.1	0.9	1.0	0.7	0.7	١.	0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.3	0.5	0.6
2018	0.8	0.8	0.8	0.8	0.6	0.7	1.0	0.9	0.8	0.7	0.7	0.5	١.	0.6	0.5	0.4	0.4	0.3	0.4	0.3	0.3	0.3	0.4	0.5	0.4
		HC.	Te	urf	200	<u> </u>	,		'	,	,	,		4)   	ЦĊ	т 1	nn.	m		,		,	,		-
2015	1 2	1 2	1 2	1 /	20	27	27	20	1 2	1 2	10	1 2	١.		0.7	0.7	00	0.6	0.5	0.4	0.4	0.3	0.4	0.4	0.4
2010	-1.0	1.0	1.0	1.4	2.0	2.7	2.7	2.0	1.5	1.2	1.2	1.2	١.	0.5	0.6	0.7	0.0	0.5	0.0	0.3	0.4	0.3	0.4	0.4	0.4
2010	-13	1.0	1.2	1.4	2.0	2.7	2.7	2.0	1.5	1.2	1.2	1.2	١.	0.5	0.0	0.6	0.0	0.5	0.4	0.0	0.0	0.0	0.4	0.4	0.6
2018	-1.3	1.2	1.2	1.3	2.1	2.5	2.7	1.9	1.0	1.2	1.2	1.2		0.5	0.0	0.6	0.0	0.5	0.4	0.4	0.0	0.4	0.5	0.5	0.5
2010			-1.2 CU	rfa	2.2	2.0	2.0	1.0		1.2				6.0 A E		100	) m	0.0	0.0	0.4	0.4	0.4	0.0	0.0	0.0
2015		00	Su	11a		0.6	16	10	0.7	0.0	0.5	0.4	1.	1 <b>)</b> L		100	0.4	0.4	0.4	0.2	0.0	0.0	0.0	0.0	0.0
2015	0.3	0.3	0.3	0.3	0.2	0.0	1.0	1.0	0.7	0.0	0.5	0.4		0.3	0.4	0.4	0.4	0.4	0.4	0.3	0.2	0.2	0.2	0.2	0.2
2010	0.3	0.3	0.3	0.3	0.3	0.9	1.0	1.0	1.0	0.7	0.5	0.4	1.	0.2	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2
2017	0.3	0.3	0.3	0.3	0.2	0.8	1.3	1.0	1.0	0.8	0.5	0.3		0.3	0.3	0.4	0.4	0.4	0.4	0.3	0.3	0.2	0.3	0.4	0.4
2018	0.5	0.4	0.3	0.3	0.3	0.5	1.4	1.1	0.8	0.6	0.4	0.4		0.4	0.5	0.6	0.6	0.6	0.6	0.5	0.4	0.4	0.3	0.3	0.3
	g)	LS	su	rta	ce								1	n)	LS	100	Jm								
2015	-0.3	0.3	0.5	0.5	0.5	0.5	0.5	0.2	0.3	0.4	0.4	0.4	1	0.3	0.5	0.5	0.5	0.5	0.4	0.3	0.2	0.2	0.2	0.2	0.2
2016	-0.4	0.4	0.4	0.4	0.7	0.7	0.4	0.5	0.5	0.5	0.4	0.4	1	0.3	0.4	0.4	0.5	0.5	0.4	0.3	0.3	0.2	0.2	0.3	0.2
2017	-0.4	0.4	0.4	0.5	0.7	0.7	0.6	0.4	0.4	0.6	0.5	0.3	ŀ	0.4	0.5	0.5	0.5	0.5	0.4	0.2	0.3	0.3	0.2	0.3	0.3
2018	0.3	0.4	0.5	0.7	0.8	0.6	0.5	0.4	0.3	0.5	0.4	0.4	•	0.4	0.5	0.5	0.5	0.5	0.5	0.4	0.3	0.3	0.3	0.3	0.3
	i) S	SPC	à si	urfa	ace	•								j) S	SPC	à 10	)0 I	m							
2015	-0.3	0.3	0.3	0.4	0.3	0.4	0.4	0.3	0.3	0.3	0.4	0.3	ŀ	0.1	0.1	0.2	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2
2016	-0.3	0.3	0.3	0.3	0.4	0.3	0.4	0.3	0.4	0.3	0.3	0.3	ŀ	0.1	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.1	0.2	0.2
2017	-0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.3	0.4	0.4	0.3	0.3	ŀ	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.2
2018	0.4	0.3	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.2	ŀ	0.2	0.2	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0.2
	k) (	GS	Ls	urf	ace	Э								I) G	SL	. 10	)0 r	n							
2015	0.8	0.7	0.7	0.8	1.1	0.8	1.0	0.6	0.8	0.9	0.9	0.8	.	0.3	0.3	0.3	0.3	0.2	0.2	0.3	0.3	0.2	0.2	0.2	0.2
2016	0.7	0.8	0.6	0.9	1.2	1.1	1.2	0.9	0.8	0.8	0.7	0.8	.	0.3	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.3
2017	0.7	0.7	0.7	0.8	1.0	0.9	1.2	1.1	0.9	1.0	0.9	0.8	·	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.3	0.2	0.3	0.3	0.3
2018	0.8	0.7	0.5	0.5	1.2	1.3	1.5	0.9	0.8	0.9	0.9	0.9	ŀ	0.4	0.4	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.4
	m)	Sc	s/(	GВ	su	rfa	ce			'	'	'		n) :	Scs	s/G	iΒ·	100	) m	'	'	'			'
2015	-0.6	0.6	0.6	0.4	0.4	0.5	0.4	0.4	0.4	0.5	0.4	0.5	.	0.5	0.6	0.6	0.6	0.5	0.6	0.6	0.5	0.4	0.4	0.4	0.4
2016	0.5	0.4	0.4	0.4	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.6	.	0.4	0.5	0.4	0.4	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4
2017	0.5	0.4	0.3	0.3	0.5	0.7	0.5	0.5	0.5	0.5	0.5	0.4	.	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4
2018	0.5	0.4	0.4	0.3	0.4	0.5	0.4	0.5	0.4	0.6	0.9	0.8	.	0.4	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.4
	o)	MA	B/0	Go	M٤	sur	fac	e			'			(a	MA	B/(	Gol	M 1	100	m	· · ·		_	_	_
2015	0.8	0.8	1.0	1.4	1.7	1.3	1.2	0.9	0.8	0.9	0.9	0.6	.	0.4	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.4	0.4
2016	0.8	0.9	1.0	1.4	1.7	1.5	0.9	0.6	1.2	1.5	1.2	1.0	١.	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.4
2017	0.8	0.6	0.7	1.7	1.6	1.3	1.1	1.2	1.4	1.2	1.1	0.9	١.	0.4	0.3	0.3	0.4	0.4	0.4	0.3	0.4	0.4	0.4	0.4	0.4
2018	0.7	0.8	0.8	1.2	1.2	1.3	1.1	1.2	1.0	1.0	1.2	1.0		0.4	0.4	0.4	0.3	0.2	0.2	0.3	0.3	0.3	0.2	0.3	0.2
	a) (	eŤ	Ge	urf	200	- -		-	'	,		,		r\ <	et o	2 10	י הר	m	-				,	-	-
2015	4)	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.4	۱.	0.2	0.2	0.2	0.2	0.2	0.2	0 2	0.2	0 2	0 2	0.3	03
2010	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.4		0.3	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.3	0.0	0.0
2017	0.5	0.5	0.5	0.4	0.5	0.4	0.0	0.5	0.0	0.5	0.4	0.4		0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.0	0.0	0.0	0.2
2018	0.5	0.5	0.0	0.0	0.0	0.5	0.0	0.5	0.5	0.4	0.5	0.4	1	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.3
_0.0				- · · ·	- · · ·		- · · ·			- · · ·			1	0.0					0.0		0.0				0.0

.5 0.6 .5 0.4 .4 0.4 .4 0.5 .6 0.6 .5 0.5 .2 0.2 .2 0.2 .4 0.4 .3 0.3 .2 0.2 .3 0.2 .3 0.3 .3 0.3 .2 0.2 .2 0.2 .2 0.2 .1 0.2 .2 0.2 .2 0.3 .3 0.3 .3 0.4

- .3 0.4 .4 0.4 .3 0.2 .3 0.3 .3 0.2
- .3 0.3 .3 0.3 5 0.4 0.5 0.5 0.3
- 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 Month

360 361

362 Figure 6. Root-mean-square-errors/differences of salinity simulated in Ctrl, calculated for the regions shown in Fig.

363 1b with respect to the observation-derived SMOS data set at the surface and GLORYS reanalysis for model results

364 interpolated to the 100-m depth.

Year





3.5

2.5

Salinity RMSE 2

1.5

1

0.5

a) GRS surface	b) GRS 100 m
2015 -0.7 0.7 0.7 0.7 0.8 1.3 2.3 1.7 0.8 0.9 0.8 0.7	1.2 1.4 1.2 1.2 1.2 1.2 1.2 1.3 1.4 1.3 1.2 1.3
2016 - 0.6 0.5 0.5 0.7 1.0 1.4 2.3 1.7 0.7 0.6 0.8 0.6	-1.2 1.3 1.2 1.2 1.3 1.2 1.2 1.2 1.4 1.2 1.0 1.1
2017 - 0.6 0.7 0.6 0.6 0.8 1.6 2.2 2.0 0.8 0.9 0.7 0.8	-1.2 1.3 1.2 1.3 1.2 1.2 1.3 1.4 1.4 1.2 1.1 1.1
2018 -0.9 1.0 0.9 0.9 0.6 1.0 1.8 1.6 0.7 0.6 0.7 0.6	1.1 1.4 1.2 1.2 1.1 1.0 1.0 1.1 1.3 1.2 1.2 1.2
c) HST surface	d) HST 100 m
2015 - 1.7 1.9 2.0 2.1 2.7 3.4 3.1 2.2 1.8 1.8 1.8 1.8	-1.3 1.3 1.2 1.2 1.1 1.1 1.1 1.1 1.1 1.1 1.2 1.3 1.2
2016 - 1.8 1.9 1.9 2.1 2.7 3.4 3.1 2.4 2.0 1.9 1.9 1.9	-1.2 1.2 1.1 1.1 1.1 1.1 1.0 1.0 1.1 1.2 1.3 1.2
2017 -2.0 2.1 2.1 2.2 2.9 3.3 3.1 2.3 1.9 1.8 1.7 1.7	-1.2 1.2 1.1 1.1 1.1 1.1 1.1 1.2 1.3 1.4 1.5 1.5
2018 -1.9 2.1 2.2 2.4 <mark>3.1 3.7 3.4</mark> 2.3 1.8 1.8 1.7 1.8	-1.4 1.4 1.2 1.1 1.1 1.2 1.1 1.2 1.4 1.4 1.4 1.4
e) BB surface	f) BB 100 m
2015 -0.7 0.7 0.6 0.6 0.6 0.8 1.7 1.5 1.1 1.2 0.9 0.7	0.9 1.0 0.9 0.9 0.9 0.9 0.8 0.8 0.9 0.8 0.9 0.9 0.9
2016 - 0.6 0.6 0.6 0.6 0.6 0.9 1.8 1.6 1.0 1.0 0.8 0.7	-0.9 1.0 0.9 0.9 0.9 0.9 0.9 0.8 0.9 0.9 0.9 0.9 0.9
2017 - 0.7 0.7 0.6 0.6 0.6 1.1 1.5 1.3 1.1 1.0 0.8 0.7	-0.9 1.0 0.9 0.9 0.9 0.9 0.9 0.9 0.9 0.9 0.9 0
2018 -0.8 0.8 0.7 0.6 0.6 0.9 1.5 1.3 1.1 0.9 0.8 0.8	0.8 0.9 0.7 0.8 0.7 0.8 0.7 0.7 0.8 0.8 0.8 0.8 0.8
g) LS surface	h) LS 100 m
2015 -0.4 0.5 0.6 0.6 0.8 0.9 0.6 0.5 0.6 0.6 0.6 0.6	-0.9 1.1 1.0 1.0 1.0 1.1 1.1 1.0 1.0 1.0 0.9 0.9
2016 -0.6 0.6 0.6 0.6 0.8 1.0 0.9 0.9 0.9 0.9 0.7 0.7	-0.9 1.0 0.9 1.0 1.0 1.0 1.0 0.9 1.0 1.1 1.2 1.0
2017 -0.6 0.6 0.6 0.7 0.8 1.5 0.9 0.6 0.5 0.8 0.7 0.5	-0.9 1.0 0.9 1.0 1.0 1.1 1.1 0.9 1.0 1.1 0.9 0.8
2018 0.4 0.5 0.6 0.7 0.7 0.7 0.7 0.7 0.5 0.6 0.6 0.7	0.8 1.0 0.9 1.0 0.9 0.9 0.9 1.0 1.0 1.0 1.0 1.0
i) SPG surface	j) SPG 100 m
2015 - 0.4 0.4 0.4 0.5 0.5 0.6 0.6 0.6 0.6 0.6 0.6 0.6 0.5	-1.2 1.3 1.2 1.2 1.1 1.2 1.1 1.1 1.1 1.1 1.1 1.1
2016 - 0.4 0.3 0.4 0.4 0.4 0.5 0.5 0.6 0.7 0.6 0.6 0.5	-1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1
2017 - 0.5 0.4 0.4 0.4 0.4 0.6 0.6 0.6 0.6 0.7 0.6 0.4	-1.0 1.1 1.0 1.0 1.0 1.0 1.0 1.0 1.1 1.0 1.0
2018 -0.4 0.4 0.4 0.4 0.5 0.6 0.6 0.6 0.6 0.5 0.4 0.3	1.1 1.2 1.0 1.0 1.0 1.0 1.0 1.1 1.1 1.1 1.1 1.0
k) GSL surface	l) GSL 100 m
2015 - 2.0 1.9 2.0 2.3 2.6 2.4 2.8 2.6 2.7 2.7 2.6 2.5	0.5 0.7 0.6 0.6 0.5 0.5 0.6 0.5 0.4 0.4 0.4 0.3
2016 -2.4 2.4 2.3 2.6 3.0 3.0 3.4 3.3 3.1 2.9 2.7 2.6	-0.3 0.4 0.5 0.6 0.5 0.5 0.5 0.4 0.4 0.4 0.3 0.4
2017 - 2.3 2.2 2.2 2.3 2.4 2.4 3.0 3.0 3.0 2.6 2.4 2.3	
2018 2.2 2.0 1.7 1.8 2.4 2.7 3.1 2.7 2.6 2.4 2.3 2.3	0.4 0.5 0.4 0.4 0.4 0.4 0.3 0.3 0.3 0.3 0.4 0.3
m) ScS/GB surface	n) ScS/GB 100 m
2015 - 1.7 1.7 1.6 1.6 1.6 1.7 1.8 1.9 2.1 2.2 2.1 2.1	-1.0 1.3 1.2 1.1 1.0 1.0 1.0 1.0 0.9 0.8 0.8 0.8
2016 - 1.9 1.8 1.8 1.7 2.0 2.0 2.1 2.1 2.2 2.2 2.1 1.9	-0.8 0.9 0.8 0.8 0.8 0.7 0.7 0.7 0.8 0.8 0.8 0.8 1
2017 - 1.7 1.6 1.5 1.4 1.5 1.7 1.6 1.6 1.6 1.5 1.7 1.5	0.8 0.9 0.9 0.9 0.8 0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7
2018 - 1.5 1.4 1.3 1.2 1.3 1.4 1.4 1.6 1.6 1.7 2.1 1.9	0.9 1.0 0.8 0.9 0.9 0.8 0.7 0.8 0.8 0.8 0.8 0.8
o) MAB/GoM surface	p) MAB/GoM 100 m
2015 -1.8 1.9 2.1 2.6 2.9 2.6 2.7 2.5 2.3 2.2 2.2 2.0	1.1 1.2 1.0 0.9 0.8 0.8 0.8 1.0 1.2 1.0 0.9 0.8
2016 -2.2 2.4 2.6 2.9 3.2 3.1 2.7 2.7 3.0 3.1 2.8 2.7	-0.8 0.8 0.7 0.6 0.6 0.6 0.6 0.6 0.7 0.6 0.7 0.7
2017 -2.6 2.5 2.6 3.4 3.7 3.4 3.2 3.2 3.2 2.9 2.8 2.4	0.6 0.6 0.4 0.4 0.5 0.5 0.5 0.6 0.6 0.5 0.6 0.8
2018 - 2.4 2.6 2.7 3.1 3.2 3.1 2.9 2.9 2.7 2.6 2.9 2.7	0.8 0.8 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.6 0.7 0.7
q) STG surface	r) STG 100 m
2015 -0.9 0.8 0.7 0.8 0.9 0.8 1.0 0.9 1.0 1.0 0.9 0.9	-1.2 1.3 1.1 1.2 1.2 1.2 1.2 1.3 1.3 1.3 1.3 1.2
ਲ੍ਹੇ 2016 -0.9 0.9 0.9 0.9 1.0 1.0 1.0 1.0 1.0 0.9 0.8 0.8	-1.2 1.2 1.1 1.2 1.2 1.2 1.2 1.2 1.3 1.3 1.3 1.2
✓ 2017 0.9 0.8 0.8 0.8 0.9 1.0 1.0 0.9 1.0 1.0 0.9 0.8	1.2 1.3 1.2 1.3 1.2 1.2 1.2 1.2 1.3 1.2 1.3 1.2 1.3 1.2
2018 -0.9 0.9 0.7 0.7 0.8 0.8 0.8 1.0 0.8 0.8 0.9 0.8	1.2 1.3 1.1 1.2 1.2 1.2 1.3 1.3 1.3 1.2 1.3 1.2
1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12

365 366

367 Figure 7. Similar to Figure 6 but for salinity simulated in Prog.





- A possible cause of this discrepancy between observed and simulated salinity values in the St. 369 370 Lawrence Estuary-Gulf system is spurious diapycnal mixing generated by the third-order upstream advection scheme used for tracers in this study (Marchesiello et al., 2009). We found 371 372 that switching to the fourth-order Akima scheme produced salinity and sea ice distributions in the 373 Gulf that were generally more realistic, but this option was not pursued further because the scheme is prone to over- or under-shooting, which resulted in patches of unrealistic tracer values 374 375 in areas such as the Grand Banks where strong horizontal gradients occur. (This problem has 376 been reported by Naughten et al. (2017), who simulated the Southern Ocean using ROMS and 377 CICE). A potential solution is a fourth-order advection scheme in which spurious values are 378 reduced with a flux limiter, as has been demonstrated by Sheng (2002) for a z-level model.
- For currents, the model performance is evaluated using a metric known as ε<sup>2</sup> (Schwab et al.,
  1989; Urrego-Blanco and Sheng, 2014):

$$\epsilon^{2} = \frac{\sum_{i=1}^{N} \left[ \left( U_{i}^{O} - \overline{U}_{i}^{O} - U_{i}^{M} + \overline{U}_{i}^{M} \right)^{2} + \left( V_{i}^{O} - \overline{V}_{i}^{O} - V_{i}^{M} + \overline{V}_{i}^{M} \right)^{2} \right]}{\sum_{i=1}^{N} \left[ \left( U_{i}^{O} - \overline{U}_{i}^{O} \right)^{2} + \left( V_{i}^{O} - \overline{V}_{i}^{O} \right)^{2} \right]},$$
(1)

where the superscripts *O* and *M* denote observed and simulated values respectively, overbars denote spatial averaging over each validation region, and the summation is made over the validation region. Thus, this metric combines errors for the zonal and meridional current components and assesses model performance in terms of spatial averages as well as at individual points, with a value of zero corresponding to perfect agreement between model results and observations. The metric is calculated with respect to GLORYS both at the surface and for model results interpolated to the 100-m depth.

389 For both simulations, values of  $\varepsilon^2$  (Figs. 8–9) in the southern part of the model domain are generally smaller in Ctrl than in Prog (e.g., about 0.7–1.3 for Ctrl vs. 1.0–2.2 for Prog in STG), 390 391 consistent with the more realistic simulation of the Gulf Stream due to the nudging of salinity and temperature in Ctrl. In SPG and LS, values of  $\varepsilon^2$  are similar between the regions and smaller 392 in Ctrl than in Prog (about 0.4–1.1 in Ctrl and 0.5–1.6 in Prog for the two regions combined). 393 394 This suggests the Labrador Current is more realistic in Ctrl than in Prog, which is consistent with the conclusion drawn from the temperature metrics that the separation of the West Greenland 395 396 Current from the Greenland coast is simulated more accurately in Ctrl.





- 397 The model errors for both runs are largest in HST, mostly due to the southeastward flow along 398 the south side of Hudson Strait being stronger in the model than in GLORYS (not shown). Taking as an example the 2015–2018 mean of monthly-mean currents produced by Prog in 399 400 September, the southeastward flow is stronger than that in GLORYS by  $\sim 0.25$  m s<sup>-1</sup> at the surface 401 and  $\sim 0.15$  m s<sup>-1</sup> at the 100-m depth. One possible reason for this large discrepancy is that the model is likely to be unable to accurately simulate the circulation in Hudson Bay, which is the 402 403 source of the southeastward flow through Hudson Strait. Circulation in the Bay consists of several gyres and is sensitive to river discharge (Ridenour et al., 2019). Our model domain 404 405 includes only the eastern part of the Bay (Fig. 1a) and, due to a lack of observations, we use 406 climatological discharge (mostly calculated from observations in the 1960s or 1970s) for all but 407 one of the ten rivers emptying into the eastern Bay; these factors cast doubt on the model's 408 ability to realistically simulate the flow within and out of the Bay. It should also be noted that Hudson Strait is characterized by tides of typically 3-6 m in 409 amplitude (Drinkwater, 1988). While our model includes tidal forcing, GLORYS, as stated 410 411 above, does not. This raises questions about how appropriate GLORYS is as a basis of evaluating simulated currents in this area. Drinkwater (1988) deployed an array of current meters across 412 Hudson Strait between August and October of 1982. While exact coordinates of this array are not 413
- available, the grid point in our model closest to the southwestern end of the array (station HS1)
- 415 can be approximated as (69.47° W, 61.15° N), with a water depth of 272 m, from Figs. 1-2 of
- 416 Drinkwater (1988). The eight-week average of residual current speeds at this location was
- 417 observed to be about  $0.29 \text{ m s}^{-1}$  and  $0.12 \text{ m s}^{-1}$  at the 30-m and 100-m depths respectively. The
- 418 2015–2018 average of September-mean current speeds simulated by Prog and from GLORYS at
- the corresponding model grid point are similar to each other and somewhat less than the
- 420 observed value at the 30-m depth (about 0.24 m s<sup>-1</sup> and 0.23 m s<sup>-1</sup> respectively vs. 0.29 m s<sup>-1</sup>).
- 421 However, at the 100-m depth, the simulated mean current speed  $(0.10 \text{ m s}^{-1})$  is more similar to
- 422 the observation  $(0.12 \text{ m s}^{-1})$  than the GLORYS value  $(0.03 \text{ m s}^{-1})$ . This points to the possibility
- 423 that the inclusion of tides in our model may result in a more realistic vertical structure of currents
- 424 in areas where both tides and baroclinity play significant roles. The role of tides in the NWA is
- 425 explored further in Sect. 4.1.





	a) GRS surface	b) GRS 100 m	
2015	0.6 0.5 0.6 0.6 0.5 0.5 0.6 0.5 0.5 0.5 0.6 0.8	0.6 0.6 0.7 0.8 0.8 0.9 1.0 0.8 0.7 0.8 0.6 0.7	
2016	0.6 0.5 0.6 0.5 0.6 0.6 0.5 0.4 0.6 0.7 0.5 0.6	0.7 0.7 0.7 0.8 0.9 1.0 1.0 0.9 0.8 0.8 0.7 0.6	
2017	0.5 0.7 0.7 0.6 0.6 0.5 0.5 0.6 0.6 0.5 0.4 0.4	0.6 0.7 0.8 0.8 0.8 0.9 0.7 0.9 0.8 0.9 0.7 0.7	5
2018	0.6 0.5 0.7 0.6 0.4 0.4 0.4 0.4 0.5 0.6 0.6 0.6	0.7 0.6 0.9 0.9 0.6 0.7 0.7 0.9 1.2 0.8 0.7 0.8	
	c) HST surface	d) HST 100 m	
2015	-3.1 5.5 7.2 6.7 3.8 3.1 1.9 1.8 2.2 1.0 1.0 2.1	6.0 6.6 7.2 6.8 7.2 6.1 5.5 4.3 4.0 2.8 4.0 8.0	
2016	4.3 5.0 6.6 7.3 5.1 3.7 2.7 1.2 1.6 1.8 1.0 1.7	-9.6 8.5 10.910.89.6 7.1 6.6 3.9 4.8 3.3 3.3 5.7	4.5
2017	-2.7 5.3 5.4 5.7 5.5 3.3 2.2 1.9 1.0 0.8 0.6 0.9	-6.8 8.8 11.3 8.3 8.2 5.5 4.2 <mark>3.8 3.5 3.0 2.4</mark> 5.9	
2018	- <b>4.6</b> 6.4 8.6 7.4 4.8 <b>3.3</b> 3.0 <b>1.7 1.2</b> 0.9 0.7 <b>1.1</b>	-12.4 9.3 10.416.011.8 6.6 3.8 4.5 3.7 2.6 2.7 5.2	
	e) BB surface	f) BB 100 m	
2015	0.8 0.8 0.8 1.0 1.3 1.3 1.2 1.3 1.2 1.1 1.1 1.0	-1.1 1.2 1.2 1.7 1.7 1.5 1.2 1.2 1.1 1.0 0.9 1.0	4
2016	1.0 1.1 1.3 1.4 1.3 1.2 1.2 1.2 1.0 1.0 0.8 0.8	-1.1 1.5 1.7 1.6 1.4 1.2 1.1 1.0 0.9 0.9 0.8 0.7	
2017	0.7 0.7 0.9 1.0 1.0 1.1 1.1 1.0 1.1 1.3 1.1 0.9	-0.8 0.8 1.0 1.1 1.1 1.1 1.2 1.1 1.2 1.2 1.1 1.1	
2018	0.9 1.0 1.2 1.1 1.1 1.2 1.1 1.1 1.0 0.9 1.0 0.8	1.1 1.1 1.3 1.3 1.4 1.2 1.2 1.2 1.2 1.0 1.1 1.0	
	g) LS surface	h) LS 100 m	3.5
2015	0.7 0.8 0.7 0.7 0.7 0.7 1.0 0.6 0.5 0.6 0.5 0.8	0.8 1.1 0.7 0.7 0.6 0.8 1.1 0.6 0.6 0.7 0.6 1.0	
2016	0.6 0.9 0.8 0.8 0.8 0.9 0.8 0.6 0.6 0.6 0.6 0.6	0.7 1.0 0.9 0.8 0.7 1.0 0.9 0.7 0.7 0.7 0.5 0.6	
2017	0.7 0.8 0.6 0.6 0.7 0.6 0.6 0.7 0.7 0.6 0.7 0.6	- <mark>0.8 0.9 0.7 0.5 0.6 0.5 0.6 0.8 0.8 0.6 0.9 0.6</mark>	
2018	0.4 0.5 0.6 0.5 0.5 0.5 0.6 0.6 0.6 0.5 0.4 0.5	0.5 0.5 0.7 0.6 0.4 0.5 0.6 0.7 0.6 0.6 0.5 0.6	3
	i) SPG surface	j) SPG 100 m	
2015	0.4 0.5 0.6 0.7 0.7 0.8 0.9 1.0 0.6 0.4 0.6 0.6	0.5 0.6 0.7 0.7 0.8 0.8 0.9 1.0 0.6 0.5 0.7 0.7	
2016	0.5 0.5 0.6 0.7 0.7 0.8 0.7 0.6 0.8 0.6 0.6 0.5	0.5 0.6 0.7 0.7 0.7 0.9 0.7 0.7 0.9 0.6 0.6 0.6	
2017	- <mark>0.7</mark> 0.4 0.6 0.9 0.7 0.5 0.5 0.7 0.7 0.5 0.5 0.5	- <mark>0.7 0.5 0.7 0.9 0.6 0.5 0.5 0.8 0.7 0.5 0.6 0.6</mark>	2.5 ∾₀
2018	0.5 0.7 0.6 0.5 0.6 0.5 0.7 0.6 0.6 0.6 0.5 0.5	0.6 0.8 0.7 0.6 0.6 0.5 0.8 0.6 0.6 0.6 0.6 0.6	
	k) GSL surface	l) GSL 100 m	
2015	-1.8 2.6 2.0 2.6 1.9 2.3 2.5 1.7 2.2 2.0 2.4 1.6	-5.1 7.1 5.5 5.6 5.9 4.6 2.1 1.8 2.6 2.8 2.2 2.0	
2016	-1.8 2.0 1.6 2.0 2.3 2.2 1.4 1.6 1.9 2.3 2.0 1.1	-5.5 3.6 2.0 1.9 2.1 2.3 1.5 1.5 1.7 2.2 4.6 3.1	2
2017	-1.8 1.7 1.7 2.9 3.5 2.1 2.0 2.3 2.2 1.7 1.8 2.0	4.4         3.3         3.2         4.0         4.5         2.7         1.5         1.6         3.0         2.6         2.6	
2018	1.9       2.2       2.3       1.8       2.6       2.3       2.2       2.4       1.6       1.2       1.0	2.3 3.4 1.5 4.2 4.6 2.5 2.5 2.2 2.3 1.9 3.6 1.6	
	m) ScS/GB surface	n) ScS/GB 100 m	15
2015	- <mark>0.6 0.8 0.8 1.3</mark> 1.6 1.4 1.4 1.5 1.4 0.7 0.6 0.4	0.7 0.9 0.9 1.3 2.0 1.5 1.9 1.7 1.7 0.6 0.5 0.3	1.5
2016	0.5 0.7 0.7 1.1 1.0 0.8 1.0 1.0 0.9 0.5 0.6 0.4	0.5 0.6 0.6 1.5 1.0 0.8 1.0 1.1 0.8 0.5 0.6 0.3	
2017	-0.5       0.4       0.5       0.6       0.8       0.9       1.1       0.8       0.5       0.5       0.7	0.4 0.3 0.4 0.5 0.6 0.9 0.9 0.7 0.5 0.4 0.4 0.6	
2018	0.7 0.7 0.6 0.5 0.7 0.7 1.0 0.8 0.6 0.6 0.5 0.4	0.6 0.5 0.6 0.6 0.7 0.7 1.0 0.8 0.5 0.6 0.5 0.4	1
	o) MAB/GoM surface	p) MAB/GoM 100 m	ľ.
2015	0.8 0.9 1.1 0.8 0.8 1.1 1.2 1.4 2.4 1.9 1.2 0.8	-0.3 0.3 0.6 0.6 0.5 1.0 1.2 1.1 1.9 1.1 0.4 0.3	
2016	0.8 0.8 0.6 1.0 0.8 0.7 0.8 1.4 2.2 1.1 1.2 0.9	0.3 0.5 0.5 0.5 0.8 0.7 1.1 1.4 1.9 0.5 0.7 0.7	
2017	1.6         0.8         1.0         0.7         0.8         1.3         0.8         1.0         1.2         2.5         1.4         1.2	-1.3 0.4 0.6 0.6 1.1 1.9 0.5 0.5 1.0 3.0 1.2 0.6	0.5
2018	0.9 0.7 0.5 0.9 0.7 1.2 0.9 0.8 1.1 1.0 0.7 1.0	0.3 0.3 0.3 0.4 0.7 1.1 0.5 1.0 0.7 0.6 0.5 0.8	0.0
	q) STG surface	r) STG 100 m	
2015	-1.1 1.0 1.0 1.2 1.1 1.1 1.0 0.9 0.9 1.1 1.1 1.1	1.0 1.0 1.0 1.1 1.0 1.0 1.0 0.9 0.9 1.0 1.1 1.1	
ਲੂ 2016	1.2 1.0 1.1 1.2 1.0 0.9 0.9 1.0 1.1 1.3 1.3 1.0	1.1 0.9 1.1 1.2 1.0 0.9 0.8 1.0 1.0 1.3 1.2 0.9	0
۶ 2017 ∽	1.1 1.2 1.0 0.9 1.0 1.1 1.0 1.3 1.0 1.0 1.0 0.9	1.0 1.1 1.0 0.9 1.0 1.1 0.9 1.2 1.0 1.0 1.0 0.8	
2018	0.9 1.0 0.8 0.7 0.9 0.9 1.1 1.0 1.1 0.9 1.0 1.1	0.9 0.9 0.8 0.7 0.9 0.9 1.1 1.0 1.1 0.8 1.0 1.1	
	1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12	
	Month		

426 427

429 reanalysis. See Equation 1 for the definition of  $\varepsilon^2$ .

<sup>428</sup> Figure 8.  $\varepsilon^2$  of currents simulated in Ctrl, calculated for the regions shown in Fig. 1b with respect to GLORYS





a) GRS surface	b) GRS 100 m
2015 -0.6 0.6 0.6 0.7 0.6 0.6 0.6 0.6 0.5 0.5 0.6 0.8	0.6 0.7 0.6 0.8 0.8 0.9 1.0 0.8 0.7 0.7 0.6 0.7
2016 - 0.7 0.6 0.6 0.5 0.6 0.6 0.6 0.6 0.7 0.7 0.5 0.6	-0.7 0.6 0.6 0.7 0.9 1.0 1.0 0.9 0.9 0.8 0.6 0.6
2017 -0.6 0.7 0.7 0.7 0.6 0.6 0.6 0.8 0.7 0.6 0.4 0.4	-0.6 0.7 0.7 0.7 0.7 0.8 0.8 1.0 0.8 0.8 0.7 0.6
2018 -0.6 0.5 0.7 0.6 0.5 0.4 0.6 0.5 0.6 0.6 0.6 0.6	-0.6 0.6 0.8 0.8 0.6 0.6 0.7 1.0 1.2 0.8 0.7 0.7
c) HST surface	d) HST 100 m
2015 - 2.7 2.6 2.5 2.9 2.6 2.7 2.2 1.9 2.7 1.2 1.2 2.3	-4.8 4.0 3.6 4.1 5.7 6.3 8.5 6.1 5.2 3.4 4.4 7.7
2016 - 3.8 2.6 2.9 3.5 3.4 3.8 3.0 1.3 1.9 2.4 1.2 1.7	-7.9 5.4 5.8 6.5 6.9 6.7 8.0 4.6 5.8 4.2 3.9 5.2 4.5
2017 - 1.9 1.8 1.4 1.9 3.0 2.7 2.3 2.0 1.2 1.0 0.7 1.0	-5.6 4.0 4.2 4.0 4.8 4.4 4.2 4.3 4.1 3.4 2.8 6.4
2018 - 3.5 3.2 4.1 3.6 3.6 2.9 2.9 1.7 1.4 1.0 0.9 1.1	9.2 5.9 6.4 9.6 7.9 5.1 3.5 4.5 3.7 2.6 2.8 5.0
e) BB surface	f) BB 100 m
2015 - 1.2 1.3 1.4 1.9 2.1 1.6 1.6 1.6 1.7 1.4 1.4 1.5	-1.8 2.0 1.8 2.8 2.5 1.9 1.7 1.7 1.7 1.4 1.4 1.6
2016 - 1.6 1.9 1.7 1.6 1.3 1.4 1.7 1.5 1.3 1.1 1.0 1.2	-1.7 2.1 2.0 1.6 1.4 1.2 1.4 1.4 1.4 1.1 1.2 1.2
2017 - 1.3 1.3 1.4 1.5 1.5 1.5 1.7 1.5 1.4 1.5 1.3 0.9	-1.3 1.2 1.4 1.6 1.6 1.4 1.6 1.5 1.6 1.6 1.6 1.6 1.2
2018 - 1.2 1.5 1.8 1.7 1.5 1.4 1.4 1.4 1.4 1.2 1.4 1.5	-1.7 1.8 2.1 2.1 2.0 1.6 1.4 1.4 1.5 1.3 1.7 1.8
q) LS surface	h) LS 100 m
2015 -1.0 1.1 0.9 0.8 0.7 0.8 1.3 0.8 0.8 0.8 0.7 1.1	
2016 -10 15 14 12 09 12 10 07 08 08 06 07	
2017 -0.9 1.0 0.8 0.7 0.7 0.6 0.7 0.8 0.7 0.6 0.7 0.6	
2018 -0.5 0.7 0.8 0.8 0.7 0.5 0.6 0.7 0.7 0.7 0.5 0.6	
i) SPG surface	i) SPG 100 m
2015 -0.8 0.9 0.9 1.1 1.2 1.4 1.3 1.2 1.1 1.3 0.9 0.9	
2016 -0.8 0.8 1.0 0.9 1.1 1.1 1.0 0.9 1.1 1.2 1.0 0.9	
2017 - 1.1 0.8 1.0 1.6 1.3 1.0 0.9 1.1 1.1 0.8 0.7 0.8	-1.2 0.8 1.1 1.6 1.3 1.0 1.0 1.2 1.1 0.9 0.8 0.9 - 2.5 ∾
2018 - 1.0 1.1 1.1 0.9 0.9 0.9 1.2 0.9 0.8 0.7 0.9 0.7	-1.2 1.2 1.1 1.1 1.0 1.0 1.4 1.0 0.9 0.8 1.0 0.8
k) GSL surface	I) GSL 100 m
2015 -1.6 3.0 2.0 2.5 1.6 2.2 2.9 2.1 2.6 2.0 2.4 1.4	3.5 5.1 4.1 4.1 4.7 4.1 2.3 2.4 2.4 2.4 1.8 1.5
2016 - 1.8 1.9 1.6 2.7 2.6 3.1 2.1 2.0 2.5 2.9 2.6 1.3	- <u>3.4</u> 2.6 1.9 2.1 2.1 2.8 2.1 1.8 2.0 2.5 <mark>5.2 3.3</mark> <sup>-</sup> 2
2017 - 2.0 2.0 2.0 3.7 4.7 2.6 1.8 2.3 2.6 2.1 1.8 1.8	4.3 3.4 2.9 3.7 4.9 3.1 1.7 2.1 2.3 3.9 3.0 2.4
2018 -1.5 2.2 2.9 1.9 2.5 2.4 1.9 2.1 2.7 2.1 1.4 1.0	-1.9 2.8 1.3 2.9 3.4 2.4 2.5 2.8 3.1 2.8 3.9 1.2
m) ScS/GB surface	n) ScS/GB 100 m
2015 -0.9 1.1 1.1 1.8 2.0 1.7 2.1 2.2 1.7 1.1 0.9 0.6	1.0 1.1 1.3 2.2 2.2 2.2 3.3 2.9 1.7 1.0 0.8 0.5
2016 -0.7 0.9 0.8 1.1 1.3 1.3 1.3 1.3 1.1 0.7 1.0 0.5	-0.6 0.9 0.8 1.3 1.3 1.3 1.5 1.3 1.0 0.7 0.9 0.5
2017 - 0.8 0.6 0.5 0.8 0.9 0.9 0.9 1.2 1.0 0.6 0.6 0.7	-0.8 0.6 0.5 0.7 0.8 1.1 0.9 0.8 0.6 0.5 0.5 0.6
2018 - 0.7 0.7 0.7 0.6 0.9 0.9 1.1 1.0 0.8 0.7 0.6 0.6	-0.5 0.6 0.6 0.6 0.8 0.8 1.1 0.8 0.6 0.7 0.7 0.6
o) MAB/GoM surface	p) MAB/GoM 100 m
2015 -0.7 0.8 1.2 1.7 1.2 1.4 1.9 4.0 7.3 4.4 5.0 2.0	0.4 0.4 0.7 2.2 0.9 1.8 2.9 4.2 7.4 3.3 2.5 1.4
2016 - 3.4 3.4 1.8 4.7 2.5 1.4 2.6 6.0 2.5 1.5 3.0 3.2	-2.1 2.2 1.3 3.4 2.2 1.3 3.0 5.0 1.9 1.0 1.8 2.1
2017 - 8.4 3.1 2.5 2.3 2.9 5.9 2.3 2.6 4.4 8.0 4.9 2.5	9.2 2.4 1.6 2.1 3.2 6.5 1.6 1.8 2.8 10.7 4.8 2.0
2018 -2.5 1.2 1.2 2.7 2.5 3.9 1.8 2.6 5.4 3.0 3.1 4.5	-1.6 0.7 1.1 2.0 2.8 3.3 1.0 3.0 3.3 1.8 2.0 3.0
q) STG surface	r) STG 100 m
2015 - 1.2 1.0 1.3 1.7 1.7 1.6 1.8 1.6 1.7 1.8 1.7 1.6	1.2 1.0 1.3 1.7 1.6 1.6 1.8 1.6 1.7 1.7 1.7 1.5
ਲ 2016 -1.6 1.7 1.8 2.0 1.4 1.4 1.5 1.8 1.6 1.7 1.7 1.6	-1.6 1.6 1.8 2.0 1.4 1.3 1.5 1.8 1.6 1.7 1.7 1.5
∞ 2017 -2.1 1.6 1.6 1.9 1.9 2.0 1.6 1.7 1.5 1.4 1.4 1.4	-2.1 1.6 1.6 1.9 1.9 2.0 1.7 1.8 1.5 1.4 1.4 1.4
2018 -1.4 1.6 1.6 1.6 1.5 1.5 1.7 1.8 1.9 2.2 1.9 2.1	-1.3 1.6 1.6 1.7 1.6 1.5 1.7 1.8 1.8 2.1 1.8 2.0
1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12
Month	

Figure 9. Similar to Fig. 8 but for currents simulated in Prog.





434 The temperature and salinity simulated in Prog have also been compared to observations made 435 along transects from the Atlantic Zone Monitoring Program and its off-shelf counterpart (not 436 shown). RMSE along the AR7W transect, which spans the Labrador Sea between southern 437 Labrador and southern Greenland, are largest near the surface, reaching  $\sim 2^{\circ}$ C for temperature and ~0.5 for salinity. The errors are larger in transects across Cabot Strait and across the Scotian 438 Shelf (up to ~4°C for temperature and ~3 for salinity), reflecting the difficulty Prog has in 439 440 reproducing the estuarine circulation in the Gulf of St. Lawrence and the positions of the Gulf Stream and slope waters. 441 442 The preceding description and evaluation of the simulated circulation and hydrography have highlighted two features in which the nudging of temperature and salinity in Ctrl leads to 443 444 improved model performance: (a) the separation of currents (the Gulf Stream and West 445 Greenland Current) from their respective coasts and (b) propagation of the low-salinity plume from the St. Lawrence Estuary. Chassignet and Xu (2017) and Pennelly and Myers (2020) 446 447 showed respectively that increasing the horizontal resolution of their model grids from  $1/12^{\circ}$  to 448 1/50° or 1/60° resulted in more realistic representations of the Gulf Stream or the West Greenland Current. Given the computational costs of making coupled physical-biogeochemical simulations 449 with a finer horizontal grid than what we currently use, a possible way to improve our modelling 450 451 system's performance in prognostic simulations would be to nest a finer-resolution grid covering an area of particular interest (e.g., the Labrador Sea) within the existing 1/12° grid. As discussed 452 453 earlier, a fourth-order horizontal advection scheme with a flux limiter is a possible way to 454 improve our model's simulation of estuarine plumes in prognostic simulations.

#### 455 **3.3 Sea ice**

456 February-mean values of sea ice cover and effective sea ice thickness (sea ice cover multiplied

457 by thickness), averaged over 2015–2018, are shown in Fig. 10. Model results from Ctrl and Prog

458 are similar in that the ice cover spans Hudson Strait and adjoining areas to its west as well as

- 459 most of Baffin Bay, and the thickest ice (thickness  $>\sim 3$  m) occurs along the coasts of those areas.
- 460 The two runs are different in that Ctrl produces more ice along the west coast of Greenland and
- 461 in the northwest Gulf of St. Lawrence, while Prog produces more ice along the north side of
- 462 Hudson Strait and on the Labrador Shelf. The larger sea ice production by Ctrl for the west coast
- 463 of Greenland and the northwest GSL is consistent with the lower sea-surface salinity and





- temperature in this simulation due to the nudging (Fig. 2). For northern Hudson Strait and the
  Labrador Shelf, a possible factor in the larger sea ice production by Prog is the fact that, in these
- areas, offshore winds tend to cause ice divergence, which in turn leads to new ice formation
- 467 (Babb et al., 2021; Prinsenberg and Peterson, 1992). The cycle of open water formation,
- 468 freezing, and ice divergence implies changes in the surface temperature and salinity over
- 469 relatively small spatiotemporal scales, which could be dampened by the nudging of Ctrl to the
- 470 monthly CORA data set which has a horizontal resolution of  $0.2^{\circ}-0.5^{\circ}$  in our study area
- 471 (Szekely, 2023). The role of sea ice on the physical oceanography of our study area is studied
- 472 further in Sect. 4.2.
- 473 The ice model's performance is evaluated in terms of RMSE with respect to daily AMSR2
- 474 (Advanced Microwave Satellite Radiometer) observations, available on a 6.5-km grid
- 475 (Melsheimer and Spreen, 2019). The model errors in HST, BB, and LS are generally larger in
- 476 Ctrl (Fig. 11) than in Prog (Fig. 12), consistent with the smaller sea ice production in these areas
- 477 by the former. In HST, the increase in model error during May for both runs is mostly due to
- 478 underestimation, indicating a too-early melting of the ice. Given that this seasonal increase in
- 479 model error occurs in both runs, the cause of the underestimation may be related to ice advection
- 480 instead of thermodynamics. Examination of sea ice budgets for areas within the NWA is a
- 481 possible topic of future studies.

# 482 **3.4 Biogeochemistry**

- 483 Snapshots of surface nitrate and subsurface oxygen in the Labrador Sea and surrounding areas at
- the time of the Atlantic Zone Off-Shelf Monitoring Program (AZOMP) cruise in May 2015 are
- shown in Fig. 13. The simulation indicates that nitrate starts to be depleted in the northern
- 486 Labrador Sea and along the Labrador shelf at this time but remains high in the deep central
- 487 Labrador Sea. Surface and shelf waters are well oxygenated and subsurface conditions along the
- 488 AR7W transect are characteristic of the water masses: oxygenated Labrador Sea Water
- (depth<2000 m), lower-oxygen Northeast Atlantic Deep Water (2000–3000 m), and the more
- 490 oxygenated Denmark Strait Overflow Water (>3000 m), which is in line with the observations
- 491 along the AR7W transect (Fig. 14a). Simulated nitrate is also characteristic of the three water
- 492 masses (Fig. 14b). As also shown in Fig. 13, surface nitrate remains high in the central Labrador





- 493 Sea but is low or depleted on the West Greenland and Labrador Shelves, respectively. These
- 494 patterns agree with the observations. The spatial variability in alkalinity (Fig. 14c) and total
- 495







- 498 Figure 10. Monthly-mean simulated sea ice concentration (a, c) and effective sea ice thickness (sea ice cover
- 499 multiplied by thickness) (b, d) for February, averaged over 2015–2018, from Ctrl (a, b) and Prog (c, d). The gray
- 500 contour line represents the 1000-m water depth.



501 502

503 Figure 11. Root-mean-square-errors of ice concentration simulated in Ctrl, calculated for the regions shown in Fig.

**504** 1b with respect to AMSR2 satellite observations.





		a) Gl	RS						b) H	ST						
	'14-'15 ·	10	11	16	17	23	19		16	7	10	8	14	29		_ 40
	'15-'16 ·	10	15	16	23	17	18		13	8	8	10	13	28		40
	'16-'17 ·	9	16	16	14	18	22		17	10	7	9	13	30		
	'17-'18 ·	10	11	15	22	22	12		14	8	8	10	14	23		35
		c) B	в						d) LS	3						
	'14-'15 ·	17	22	23	27	26	28		9	13	20	23	20	22		- 30
	'15-'16 ·	14	21	22	21	22	25		10	15	20	28	24	24		
	'16-'17 ·	16	14	19	19	21	24		11	13	24	23	19	23		- 25
ason	'17-'18 ·	14	17	23	26	23	22		5	11	25	18	14	18		
e sea		e) SF	PG						f) GS	;L						- 20 :
<u>ö</u>	'14-'15 ·	0	2	4	11	15	5		7	16	44	41	23	6		
	'15-'16 ·	3	5	9	8	7	1		7	13	14	19	9	6		45
	'16-'17 ·	1	2	3	5	8	4		6	10	17	23	11	7		- 15 .
	'17-'18 ·	0	1	8	12	5	3		7	19	46	21	11	5		
		g) So	cS/G	В					h) M	AB/C	àoM					- 10
	'14-'15 ·	3	3	6	12	8	2		4	4	7	5	3	2		
	'15-'16 ·	2	3	3	3	2	2		3	3	3	2	2	4		- 5
	'16-'17 ·	3	3	3	3	3	2		2	3	3	3	3	3		
	'17-'18 ·	3	3	6	4	2	2		3	5	3	4	3	2		0
		12	1	2	3	4	5	1	12	1	2	3	4	5	1	
							Μ	on	th							

505 506

507 Figure 12. Similar to Fig. 11 but for ice concentration simulated in Prog.









511

512 Figure 13. Three-dimensional view of simulated surface nitrate and subsurface oxygen for May 15, 2015. The black

- 513 dots at the surface correspond to the AR7W transect stations and the black line indicates the location of the bottom
- 514 for the transect.
- 515



516 517

Figure 14. Comparison of simulated (background) versus observed (dots) for: oxygen (a), nitrate (b), alkalinity (c),
and total inorganic carbon (d) during the AR7W transect in May 2015. Note: the y-axis has higher resolution in the

520 upper 200 m.





521



522 523

Figure 15. Comparison between simulated values and AZMP/AZOMP bottle observations during 2014–2018 for:
oxygen (a), nitrate (b), alkalinity (c), and total inorganic carbon (d). N is the number of observations used for the
comparison.

527

inorganic carbon (TIC; Figure 14d) along the AR7W transect is also well represented. The largest
mismatch occurs for TIC which is underestimated in the subsurface layers (depths>200 m).

530 Comparison of simulated oxygen, nitrate, alkalinity, and TIC to AZMP/AZOMP in situ

observations, at locations ranging from the Gulf of Maine to the Labrador Shelf, was carried out

- 532 for the period 2014–2018 (Fig. 15). The model simulates reasonably well the spatial and
- temporal variability in biogeochemical variables ( $0.65 \le r^2 \le 0.81$ ). Simulated oxygen has a small
- 534 positive bias (10.8 mmol m<sup>-3</sup>, Fig. 15a) but otherwise agrees with observations. Nitrate has the
- best match with observations ( $r^2=0.81$ ) but with a small positive bias (Fig. 15b), possibly driven





- 536 by excess vertical mixing or by a delay in the seasonal uptake. The small bias at low TIC (i.e.,
- 537 surface) is likely to have the same source (Fig. 15d).

#### 538 4 Sensitivity studies

- 539 The ocean circulation and sea ice modules of DalROMS-NWA12 v1.0 are used in this section to
- 540 examine the roles of tides and sea ice in the hydrodynamics of the NWA. This is done by
- 541 comparing the model results from Prog to those from two additional simulations that are
- identical to Prog but with the tidal forcing absent from one (NoTides) and sea ice absent from the
- 543 other (NoIce). In NoIce, the net surface heat flux is set to zero if it would cool the ocean and the
- sea surface temperature is already at or below the local freezing temperature. The difference
- 545 between surface temperatures simulated in Prog and in NoTides (Prog minus NoTides) will be
- 546 denoted  $\Delta T_{sfc}^{P-NT}$  and the difference in bottom temperatures will be denoted  $\Delta T_{btm}^{P-NT}$ . Similar
- 547 notations will be used for differences in salinity (e.g.,  $\Delta S_{sfc}^{P-NT}$ ) and current speed (e.g.,
- 548  $\Delta |\vec{V}|_{sfc}^{P-NT}$ ) and for differences between model results from Prog and NoIce (e.g.,  $\Delta T_{sfc}^{P-NI}$ ).

#### 549 4.1 The effect of tides

- 550 Differences between Prog and NoTides (Prog minus NoTides) in sea surface salinity, currents,
- and temperature over Baffin Bay and the Labrador Sea, averaged over the winters (December-
- 552 February) and summers (June-August) of December 2014-August 2018, are shown in Fig. 16. In
- 553 winter (Fig. 16a-b), differences between the simulations of temperature and salinity over this
- area are relatively small generally within  $\pm 1$  for salinity, and up to  $\sim +1.5^{\circ}$ C for temperature. In
- summer (Fig. 16c–d),  $\Delta S_{sfc}^{P-NT}$  is positive along most of the Baffin Island coast, in Ungava Bay,
- and on the northern Labrador Shelf (up to ~7 in Ungava Bay) while  $\Delta T_{sfc}^{P-NT}$  is mostly negative
- throughout the area but especially over shelves (~-1°C). These differences between Prog and
- 558 NoTides are consistent with the presence of sea ice over large portions of this area during winter,
- 559 given that sea ice can modulate tidal mixing and thus tend to reduce the differences between the
- 560 ocean states simulated with and without tides. In summer, the presence of tidal mixing in Prog
- 561 contributes to vertical mixing over shelf areas, resulting in surface waters that are saltier and
- 562 colder than if there were no tides and the water column were more highly stratified. There are,
- bowever, areas in which the inclusion of tides results in positive  $\Delta T_{sfc}^{P-NT}$  during the summer,





- notably along the coast of Ungava Bay. Given that  $\Delta S_{sfc}^{P-NT}$  is positive throughout the Bay, the contrast between positive  $\Delta T_{sfc}^{P-NT}$  along the coast and negative  $\Delta T_{sfc}^{P-NT}$  near the Bay's mouth
- suggests air-sea fluxes might differ between the two parts of the Bay.
- 567 The effect of tides on water temperature within Ungava Bay is explored in Figs. 17 and 18. In
- 568 winter, the models results from Prog and NoTides are similar not only in terms of the surface
- temperature (Fig. 17a), but also in terms of bottom temperature ( $|\Delta T_{btm}^{P-NT}| \ll 1^{\circ}$ C, Fig. 17b) and
- 570 current speeds at both the surface and bottom  $(\Delta |\vec{V}|_{sfc}^{P-NT} \text{ and } \Delta |\vec{V}|_{btm}^{P-NT} < 0.1 \text{ m s}^{-1}$ , Fig. 17a–b).
- 571 In summer at the sea surface (Fig. 17c), both  $\Delta |\vec{V}|_{sfc}^{P-NT}$  and  $\Delta T_{sfc}^{P-NT}$  are positive along the coast
- 572 but generally negative in the outer bay. Along the bottom in summer (Fig. 17d),  $\Delta T_{btm}^{P-NT}$  is
- 573 positive and as large as ~+4°C along the coast, while in the outer bay  $\Delta T_{btm}^{P-NT}$  is small
- 574  $(|\Delta T_{btm}^{P-NT}| < 1^{\circ}C)$  and the currents are generally weak in both simulations. The patterns of mean
- 575 summer sea ice concentration are also different between the two simulations, with the ice cover
- 576 produced in Prog (Fig. 18a) being highest over the outer bay (up to  $\sim 40\%$ ) and low near the
- 577 coast, while NoTides (Fig. 18b) produces a wide area of high ice cover along the coast (up to
- $\sim$  90%). The patterns of mean summer sea surface temperature from the two simulations (Fig.
- 579 18c-d) correspond to those of the sea ice cover, with areas of higher (lower) ice cover
- 580 corresponding to lower (higher) temperatures. Given that the only difference between the Prog
- and NoTides simulations is the inclusion of tides in the former, these results suggest that tides
- along the coast of Ungava Bay promotes an earlier disappearance of ice there during the summer,
- and this in turn leads to a larger flux of solar radiation into the ocean and a less impeded flow.
- 584 The effect of tides is also evident in the region surrounding two other areas with large tidal
- ranges, the St. Lawrence Estuary and the Bay of Fundy. In both winter and summer,  $\Delta S_{sfc}^{P-NT}$  in
- the St. Lawrence Estuary (Fig. 19a,c) is positive (up to ~6), suggesting that tidal mixing brings
- 587 higher-salinity subsurface water towards the surface. In summer (Fig. 19c), the influence of this
- 588 higher salinity due to tidal mixing spreads into the northwest Gulf of St. Lawrence due to the
- 589 propagation of the estuarine plume. The role of tidal mixing is also evident in the patterns of sea
- surface temperatures (Fig. 19b,d), with  $\Delta T_{sfc}^{P-NT}$  positive in winter and negative in summer.
- 591 Differences between the simulations are also visible over the open ocean for all three fields. As









Figure 16. Differences in seasonal-mean simulated sea surface salinity and currents (a, c) and temperature (b, d)
over Baffin Bay and the Labrador Sea when model results from NoTides are subtracted from those from Prog,
averaged over winters (a, b) and summers (c, d) of 2015–2018. Difference vectors are shown at every 12th model
grid point. The gray contour line represents the 1000-m water depth.







Figure 17. Differences between Prog and NoTides over Ungava Bay: 2015–2018 averages of seasonal-mean
simulated currents (thick magenta arrows: Prog, thin green arrows: NoTides) and temperature difference (Prog
minus NoTides) at the sea surface (a, c) and bottom layer (b, d) in winter (a–b) and summer (c–d). Current vectors
are shown at every sixth model grid point. The gray contour line represents the 100-m water depth.







606

**607** Figure 18. 2015–2018 averages of seasonal-mean sea ice concentrations in Ungava Bay during summer simulated

in runs Prog (a) and NoTides (b); seasonal-mean sea surface temperature for summer simulated by runs Prog (c) and
 NoTides (d).







610 611

612 Figure 19. Similar to Fig. 17, but for the area between the Gulf of Maine and the southern Labrador Sea.

Wang et al. (2020) have suggested, this may be caused by internal tides that are generated nearthe shelf break and propagate offshore.

615 **4.2** The effect of sea ice

616 The effect of sea ice is examined next by comparing simulated surface fields from Prog to those

- from the simulation in which ROMS is run without coupling to CICE (NoIce). A prominent
- feature in winter is the horizontal gradient in  $\Delta S_{sfc}^{P-NI}$ , approximately aligned with the 1000-m
- 619 isobath, in western Baffin Bay (Fig. 20a).  $\Delta S_{sfc}^{P-NI}$  is positive on the shelf (~0.2) but negative
- 620 offshore of the shelf break (~-0.3). In the zone where  $\Delta S_{sfc}^{P-NI}$  changes signs,  $\Delta |\vec{V}|_{sfc}^{P-NI}$  is positive
- 621 (up to ~0.3 m s<sup>-1</sup>). The area on the shelf where  $\Delta S_{sfc}^{P-NI}$  is positive coincides with the highest
- 622 average sea ice thickness in the domain (Fig. 10d), which makes the higher salinity in Prog





623 consistent with brine rejection at the time of sea ice formation. Values of  $|\Delta T_{sfc}^{P-NI}|$  in winter (Fig. 624 20b) tend to be largest over the parts of Baffin Bay and the northern Labrador Shelf where the 625 ice edge occurs in Prog (Fig. 10c).  $\Delta T_{sfc}^{P-NI}$  in these areas are negative (as low as ~-1.9°). Surface

heat flux is expected to result in positive  $\Delta T_{sfc}^{P-NI}$ , given that in winter it is expected to cool the

627 ocean surface while sea ice can insulate the ocean surface below from cold air. Another possible 628 factor in  $\Delta T_{sfc}^{P-NI}$  is vertical mixing, which is examined later.

In summer,  $\Delta S_{sfc}^{P-NI}$  and  $\Delta T_{sfc}^{P-NI}$  (Fig. 20c and 20d respectively) are lowest in western Baffin Bay, 629 with the former as low as  $\sim$ -4 (reflecting the input of freshwater due to melting sea ice) and the 630 latter as low as ~-4.7°C (reflecting the blocking of shortwave radiation by the sea ice that 631 remains in summer). These results suggest that, as sea ice in areas such as Baffin Bay and the 632 633 Labrador Shelf decline in a warming climate, areas downstream from them such as the Scotian Shelf and the Gulf of Maine will experience changes in the temperature and salinity of the water 634 that is brought there by the Labrador Current. The effect of changes in water masses advected 635 into a given area, in combination with changes that occur in situ due to climate change, is 636

another possible topic of future research.

638 Differences in the wintertime vertical stratification and vertical mixing between Prog and NoIce

are examined further using vertical profiles of four-year mean wintertime temperature, salinity,

640 and vertical eddy viscosity produced by the two runs, as well as the squared buoyancy frequency

 $(N^2)$  calculated from the mean wintertime temperature and salinity using the Gibbs-SeaWater

642 Oceanographic Toolbox (McDougall and Barker, 2011). The profiles represent temporal averages

over the same period as in Figs. 20a–b (winters of 2015–2018) and are calculated at 1-m depth

644 intervals for two locations: location A (62.56° W, 67.60° N), indicated by the square in Fig. 20b,

- 645 where  $\Delta T_{sfc}^{P-NI}$  is small and the 2015–2018 mean of the February-mean sea ice cover is ~95%
- 646 (Fig. 10c), and location B (57.64° W, 67.60° N), indicated by the circle in Fig. 20b, where
- 647  $\Delta T_{sfc}^{P-NI}$  has a large magnitude (~-1.9°C) and the four-year mean of the February-mean sea ice
- 648 cover is ~84%. The model's water depths at the two locations are similar (231 m and 218 m).









Figure 20. Differences in seasonal-mean simulated sea surface salinity and currents (a, c) and temperature (b, d)
over Baffin Bay and the Labrador Sea when results of NoIce are subtracted from those of Prog, averaged over
winters (a, b) and summers (c, d) of 2015–2018. Difference vectors are shown at every 12th model grid point. The

- gray contour line represents the 1000-m water depth. Locations A and B, for which the vertical profiles of model
- variables are shown in Figs. 21 and 22, are indicated in panel (b) with a square and a circle respectively.





- 656 The vertical profiles of mean wintertime temperature (Fig. 21a) and salinity (Fig. 21b) at location A are similar between runs Prog and NoIce, with a vertical range of <1.4°C for temperature and 657 <0.8 for salinity in both runs. The profiles of N<sup>2</sup> (Fig. 21c) are thus also similar between the runs, 658 with maximum values of  $\sim 6 \times 10^{-5}$  s<sup>-2</sup> about 40 m below the sea surface. Negative values of N<sup>2</sup>, 659 indicating instability, are limited to the top few metres of the water column. Values of the 660 Richardson number (not shown) below 0.25, including negative values, are limited to the top 5 m 661 of the water column, again indicating a mostly stable water column and weak convection in both 662 Prog and NoIce. The mean wintertime vertical mixing below the surface is very weak in both 663 runs (Fig. 21d), with the vertical eddy diffusivity from both runs having maximum values of 664  $\sim 0.02 \text{ m}^2 \text{ s}^{-1}$  about 10 m below the surface and having values  $< 0.002 \text{ m}^2 \text{ s}^{-1}$  in  $\sim 80\%$  of the water 665 column. It should be noted that the mean wintertime stress exerted on the sea surface (by winds 666 and/or sea ice in Prog and by winds in NoIce) differs significantly between the two runs (Fig. 667 21d). The surface stress has a much smaller magnitude in Prog (0.02 N m<sup>-2</sup>) than in NoIce (1.0 N 668 669  $m^{-2}$ ), which can be explained by the buffering effect of sea ice on the wind stress in Prog. Due to this buffering effect of sea ice, the wind-induced vertical mixing in the surface layer (Fig. 21d) is 670 671 weaker in Prog than in NoIce, as expected.
- 672 In contrast to location A, the vertical profiles of mean wintertime model results at location B
- 673 differ significantly between runs Prog and NoIce. The mean wintertime temperature (Fig. 22a)
- has a vertical range of  $>3^{\circ}$ C in Prog (about -0.9°C near the surface and 2.4°C near the bottom)
- but  $<1^{\circ}$ C in NoIce (about 1.1°C near the surface and 1.7°C near the bottom). The mean
- 676 wintertime salinity (Fig. 22b) has a vertical range of ~0.5 in Prog (about 34.0 near the surface
- and 34.5 near the bottom) but just ~0.1 in NoIce (about 34.5 near the surface and 34.6 near the
- bottom). Values of  $N^2$  (Fig. 22c) from both runs are lower than at location A; with a maximum of
- $\sim 1.9 \times 10^{-5}$  s<sup>-2</sup> in Prog and  $\sim 2.1 \times 10^{-6}$  s<sup>-2</sup> in NoIce. In addition, the N<sup>2</sup> in NoIce is negative in the
- 680 top ~20 m of the water column and between depths of ~40 and ~50 m, indicating unstable
- stratification and unrealistically strong convection. The Richardson number is <0.25 in the top  $\sim 5$
- m of the water column in Prog, and at approximately the same depths as the negative values of
- 683 N<sup>2</sup> in NoIce. The maximum vertical eddy diffusivity coefficient is  $\sim 0.3 \text{ m}^2 \text{ s}^{-1}$  in NoIce, which is
- much larger than the maximum values of  $\sim 0.06 \text{ m}^2 \text{ s}^{-1}$  in Prog, while the surface stress is similar
- $685 \qquad at \sim 0.1 \ N \ m^{-2} \ in \ both \ runs.$









Figure 21. Vertical profiles of wintertime temperature (a), salinity (b), squared buoyancy frequency (c), and vertical
eddy diffusivity (d) simulated by the model in Prog (blue solid line) and NoIce (red dashed line), averaged over
2015–2018, interpolated to 1-m depth intervals, at location A, indicated by the square in Fig. 20b (62.56° W, 67.60°
N). Also shown in panel (d) is the stress exerted on the sea surface by sea ice and/or winds in the Prog (thick arrow)
and NoIce (thin arrow) runs, averaged over the same period as the other fields. The x- and y-axes for the surface
stress range from -0.1 to 0.1 N m<sup>-2</sup>.









Figure 22. Similar to Fig. 21 but for location B, indicated by the circle in Fig. 20b (57.64° W, 67.60° N). Note the
change from Fig. 21 in the x-axis limits for the squared buoyancy frequency (c) and the vertical eddy diffusivity (d).

699 A possible explanation for the relatively warm ( $\geq 2^{\circ}$ C) and salty ( $\geq 34$ ) subsurface water in the 700 lower water column at location B in Prog (solid blue lines in Fig. 22a,b) is the horizontal 701 advection of relatively warm and salty waters from the south to this location. In Prog, the ocean-702 to-air heat flux in winter results in cooling of the near-surface water as well as sea ice formation, 703 and subsurface ablation of the sea ice can be a source of fresh water that contributes to vertical 704 stability. The advection of relatively warm, salty subsurface waters from the south would also 705 occur in NoIce, but in this case the near-surface water would be cooled to the freezing point 706 without an accompanying reduction in salinity, which may explain the very large vertical mixing and nearly uniform vertical profiles of temperature and salinity in this run. 707





#### 708 **5** Conclusions

709	In this study, a newly-developed, fully-coupled modelling system for simulating the ocean
710	circulation, sea ice, and biogeochemistry of the northwest North Atlantic Ocean (DalROMS-
711	NWA12 v1.0) was described. The model domain covers the area from Cape Hatteras to Baffin
712	Bay with a horizontal resolution of $\sim$ 2 to $\sim$ 8 km, making this modelling system highly suitable
713	for a range of research topics, including study of the biological carbon pump and quantification
714	of the major physical and biogeochemical (BGC) processes influencing the ocean carbon cycle
715	over the region. The results of two simulations using this modelling system, with and without
716	nudging of the simulated temperature and salinity towards a blend of observations and
717	reanalysis, were compared to observations and reanalysis. We found that results of the control
718	run, which included the nudging, are more realistic than results of the prognostic (un-nudged)
719	simulation for several important physical features observed in this region, such as separation of
720	the Gulf Stream and the West Greenland Current from their respective coasts, as well as
721	propagation of low-salinity waters from the St. Lawrence Estuary. These results demonstrate the
722	utility of simple data assimilation in reducing the systematic model errors that can be attributed
723	to model configuration (such as horizontal grid resolution in the case of currents' separation from
724	coasts and the choice of tracer advection scheme in the case of estuarine plume propagation) and
725	unresolved or parameterized physical and BGC processes. The prognostic simulation, while
726	having difficulties with the above-mentioned features, was able to reproduce the general
727	spatiotemporal patterns of the physical fields and outperformed the control run in terms of the
728	sea ice concentration. The major differences between the simulations in the sea ice extent
729	highlight the complex nature of interactions among the atmosphere, ocean, and sea ice.
730	The modelling system was able to reproduce the general patterns of BGC variables over the
731	northwest Atlantic shelves and in the Labrador Sea. Further validation will include comparisons
732	with observations made by BGC Argo floats (Johnson and Claustre, 2016). Future work will use
733	this modelling system to investigate the biological carbon pump in the Labrador Sea including
734	vertical flux estimates derived from BGC Argo (Wang and Fennel, 2022 and 2023). The addition

735 of silicate as a state variable will also be tested.

As an example of application of this modelling system, sensitivity studies were made in which
results of the prognostic simulation were compared to those from similar simulations from which





- either the tides or simulation of sea ice were excluded. The comparisons suggest that tides and
  sea ice strongly affect the physical oceanography of the NWA in several ways. These include the
  combined effects of tides and sea ice (in Ungava Bay) as well as individual effects (e.g., higher
  surface salinity in summer when sea ice is not simulated).
- 742 In addition to studies of the biological carbon pump and of the downstream effects of changes in
- the water transported by the Labrador Current, another possible direction of future research is to
- vue the ocean state simulated by this model as input for numerical particle-tracking experiments
- to investigate connectivity among different areas of the NWA. The resulting metrics of
- 746 connectivity under current and projected future climate conditions can support decision-making
- 747 processes concerning conservation measures. The model will also be used to compare
- 748 approaches to reducing bias in long-term simulations (Renkl et al., in prep.).
- 749 The high air-to-sea flux of CO<sub>2</sub> and the subsequent downward export of fixed carbon make the
- 750 NWA a key component in the global climate system, but it is a remote region where seasonal
- transitions can take place in just a few weeks (e.g., in terms of pCO<sub>2</sub>; Körtzinger et al., 2008) and
- 752 details of the interactions between physical and biogeochemical processes are still unknown or
- remain poorly integrated into models (e.g., the sea-ice carbon pump; Richaud et al., 2023). The
- four-dimensional ocean states produced by numerical models can aid in the interpretation of
- observations as well as enable experiments that elucidate the roles of various processes in the
- ocean and how those processes might change under future climate scenarios.

# 757 Appendix A: The vertical coordinate system in ROMS

ROMS uses a generalized terrain-following vertical coordinate system with several options
for vertical transformation equations and vertical stretching functions. In this study the default
configuration is used, with the vertical coordinate *S* defined as (Hedstrom, 2018):

761 
$$z(x, y, \sigma, t) = \zeta(x, y, t) + [\zeta(x, y, t) + h(x, y)]S(x, y, \sigma)$$
 (A1)

762 
$$S(x, y, \sigma) = \frac{h_c + h(x, y)C(\sigma)}{h_c + h(x, y)}$$
(A2)

763 
$$C(\sigma) = \frac{\exp\left(\theta_B C'(\sigma) - 1\right)}{1 - \exp\left(-\theta_B\right)}$$
(A3)

764 
$$C'(\sigma) = \frac{1 - \cosh(\theta_S \sigma)}{\cosh(\theta_S) - 1}$$
(A4)





- where  $\sigma$  ranges from 0 at the free surface to -1 at the ocean bottom,  $\zeta$  is the free surface, h is the
- undisturbed water column thickness,  $h_c$  is the value of h below which the vertical layers are more
- uniformly spaced, and  $\theta_s$  and  $\theta_b$  are parameters that control the vertical resolution near the
- surface and the bottom respectively. In this study ROMS has 40 layers and the parameters  $h_c$ ,  $\theta_s$ ,
- and  $\theta_b$  are set to 100 m, 5.0, and 0.5 respectively.

# 770 Appendix B: Seasonal-mean simulated fields

Seasonal means of salinity and currents in Baffin Bay and the northern Labrador Sea

- simulated in Ctrl and Prog, averaged over December 2014–December 2018, are shown in Figs.
- 773 B1 and B2. Differences between the simulations are more evident in summer (June–August;
- Figs. B1c-d and B2c-d than in winter (December–February; Figs. B1a–b and B2a–b). The
- northward branch of the West Greenland Current and the Baffin Island Current are stronger in
- Prog by up to  $\sim 0.25$  m s<sup>-1</sup> at the surface and  $\sim 0.15$  m s<sup>-1</sup> for model results interpolated to the 100-
- m depth. In the area between the southern Labrador Sea and the Gulf of Maine (Figs. B3 and
- B4), the difference in salinity between the simulations is more prominent in summer, following
- the annual peak in freshwater discharges from the St. Lawrence and other rivers. In the St.
- 780 Lawrence Estuary, the 2015–2018 mean of summer surface salinity simulated in Prog is lower
- than that from Ctrl by up to ~3.5, but further downstream in the Gulf of St. Lawrence, the
- 782 salinity from Prog is higher by  $\sim 2$ .









Figure B1. Seasonal-mean simulated salinity and currents at the sea surface (a, c) and interpolated to the 100-m
depth (b, d) from Ctrl averaged over the winters (a, b) and summers (c, d) of 2015–2018 in Baffin Bay and the
Labrador Sea. Winters are defined as December of the previous year to February of that year. Summers are defined
as June to August. Current vectors are shown at every 12th grid point. The 1000-m depth contour is shown in gray.







791 Figure B2. Similar to Figure B1 but for Prog.







**Figure B3.** Seasonal-mean simulated salinity and currents at the sea surface (**a**, **c**) and interpolated to the 100-m

depth (**b**, **d**) from Ctrl averaged over the winters (**a**, **b**) and summers (**c**, **d**) of 2015–2018 over the area between the

Gulf of Maine and the southern Labrador Sea. Current vectors are shown at every 12th grid point. The 1000-m depthcontour is shown in gray.







**800** Figure B4. Similar to Fig. B3 but for Prog.

# 801 Appendix C: Datasets used in model performance assessment

802 Online sources of the datasets used to assess the model performance are listed below in the order

- they are discussed in Section 3.
- 1. <u>Sea surface temperature</u>: OISST v2.1 (Huang et al., 2021), a daily dataset on a 1/4° grid that
- incorporates satellite and in situ observations. A combination of v2.0 and v2.1 was used in this
   study; v2.0 is now retired. <a href="https://www.ncei.noaa.gov/products/optimum-interpolation-sst">https://www.ncei.noaa.gov/products/optimum-interpolation-sst</a>
- 807 2. Sea surface salinity: MULTIOBS GLO PHY S SURFACE MYNRT 015 013 (Buongiorno
- 808 Nardelli et al., 2016), a dataset that incorporates satellite and in situ observations. At the time
- 809 of this study, it was a weekly dataset on a  $1/4^{\circ}$  grid; now it is a daily dataset on a  $1/8^{\circ}$  grid.





810 https://data.marine.copernicus.eu/product/MULTIOBS GLO PHY S SURFACE MYNRT

811	015	013/description
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- 812 3. Currents: GLOBAL\_MULTIYEAR\_PHY\_001\_030, also known as GLORYS12V1
- 813 (Lellouche et al., 2021), a daily reanalysis dataset on a  $1/12^{\circ}$  grid.
- 814 <u>https://data.marine.copernicus.eu/product/GLOBAL\_MULTIYEAR\_PHY\_001\_030/descripti</u>
- 815 <u>on</u>
- 816 4. <u>Shipboard observations of physical and biogeochemical variables</u>: Atlantic Zone Monitoring
- 817 Program (Pepin et al., 2005) cruises take place seasonally and Atlantic Zone Off-Shelf
- 818 Monitoring Program (e.g., Yashayaev and Loder, 2017) cruises take place annually.
- 819 <u>https://catalogue.cioosatlantic.ca/dataset/ca-cioos\_9a4bd73f-12a2-40ff-a7c7-b961a1d11311</u>
- 820 <u>https://catalogue.cioosatlantic.ca/dataset/ca-cioos\_15f90eab-21ed-447d-aea7-8fe98ea27fe5</u>
- 5. <u>Sea ice</u>: AMSR2 ASI sea ice concentration data for the Arctic, v5.4 (Melsheimer and Spreen,
- 822 2019), a daily dataset on a 6.5-km grid derived from satellite observations.
- 823 https://doi.pangaea.de/10.1594/PANGAEA.898399

# 824 Code and Data Availability

- 825 The model codes, scripts for compiling the model, and sample CPP header and runtime
- 826 parameter files for physics-only simulations are available at
- 827 https://doi.org/10.5281/zenodo.12752091 (Ohashi et al., 2024a). Input files used by the ocean
- 828 circulation and sea ice modules in a simulation of September December 2013 are available at
- 829 https://doi.org/10.5281/zenodo.12752190 (Ohashi et al., 2024b),
- 830 https://doi.org/10.5281/zenodo.12734049 (Ohashi et al., 2024c), and
- https://doi.org/10.5281/zenodo.12735153 (Ohashi et al., 2024d). Daily-mean output files from
- the ocean circulation, sea ice, and biogeochemistry modules are available for September 2013
- 833 (beginning of simulation period) at https://doi.org/10.5281/zenodo.12744506 (Ohashi et al.,
- 834 2024e) and for January 2015 (beginning of model validation period) at
- https://doi.org/10.5281/zenodo.12746262 (Ohashi et al., 2024f). Input and output files for the
- remainder of the simulation period, as well as CPP header, runtime parameter, and input files for
- the biogeochemistry module, are available from the corresponding author KO upon request.





### 838 Author contributions

- 839 KO configured the ocean circulation model; prepared the model bathymetry, freshwater input
- 840 files, atmospheric forcing files, and some of the lateral boundary input files; and carried out the
- 841 Prog, NoTides, and NoIce runs. AL prepared input files for and configured the biogeochemical
- 842 module; and carried out the Ctrl run. CR configured the sea ice model and its coupling to the
- 843 ocean circulation model; prepared some of the lateral boundary input files and the pseudo-mean
- versions of freshwater input files; configured the regions used to evaluate model performance;
- 845 processed the observations used in model evaluation; and calculated the model errors with
- respect to AZMP observations. AL carried out the analyses for and prepared Figs. 13–15; and
- 847 wrote the text describing the biogeochemical module, the Ctrl run, and Figs.13–15. KO prepared
- 848 the rest of the manuscript with advice from JS. JS, KF, and EO provided advice throughout
- 849 development and evaluation of the model and provided funding to KO, AL, and CR respectively.

# 850 Competing interests

851 The authors declare that they have no conflicts of interest.

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