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9 **Impacts of Sea-Level Rise on Hypoxia and Phytoplankton Production in**

10 **Chesapeake Bay: Model Prediction and Assessment**

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21 **Research Impact Statement**: This modeling study on the impacts of sea-level rise on the

22 seasonal hypoxia and phytoplankton production in Chesapeake Bay helps us better understand

23 the mechanisms that drive the changes.

24

25 **ABSTRACT**

26   In this study, the influence of sea-level rise (SLR) on seasonal hypoxia and

27 phytoplankton production in Chesapeake Bay is investigated using a 3D unstructured grid model.

28 Three SLR scenarios (0.17 m, 0.5 m, and 1.0 m) were conducted for 1991 to 1995. Results show

29 that the summer hypoxic volume (HV) increases about 2%, 8%, and 16%, respectively for these

30 three scenarios compared with Base Scenario. The contributions of physical and biological

31 processes on the increase in the HV were analyzed. With the projected SLR, enhanced

32 gravitational circulation transports more oxygen-rich water in the bottom layer from the mouth.

33 However, the pycnocline moves upwards along with increasing water depth, which largely

34 prolongs the time for dissolved oxygen (DO) to be transported to the bottom. The altered

35 physical processes contribute greatly to a larger HV bay-wide. Besides, SLR increases the whole

36 Bay phytoplankton production, with a larger increase in shallow areas (e.g. 53% in areas with

37 depth less than 1 m under SLR of 0.5 m). Enhanced light availability is suggested to be the major

38 driver of blooming phytoplankton under SLR in shallow areas. While increased DO production

39 over the euphotic zone is mostly released to the atmosphere and transported downstream, the

40 increase in settled organic matter greatly promotes DO consumption in the water column. The

41 increased respiration is another major cause of the HV increase besides the physical

42 contributions.

INTRODUCTION

44 Hypoxia (dissolved oxygen (DO) concentration $<= 2$ mg L^{-1}), occurs in deeper regions of

45 Chesapeake Bay (the Bay hereafter) in the summertime and has been recorded since the last

46 century (Seliger et al., 1985; Hagy et al., 2004). The hypoxic volume (HV) in Chesapeake Bay

47 ranges from 8 to 17 km^3, with larger HV observed in wet years (Bever et al., 2013; Hagy et al.,

48 2004). The observed large HV decreases habitats for fish, invertebrates, and benthic macrofauna

49 and therefore degrades the ecosystem by changing the food web and energy transfer between

50 different trophic levels (Diaz and Rosenberg, 1996; Vaquer-Sunyer and Duarte, 2008). Besides,

51 hypoxia changes nutrient cycling by inducing bottom nutrient release that further affects the

52 ecosystem (Kemp et al., 1990)

53 The primary cause of hypoxia in the Bay is that DO consumption exceeds replenishment

54 from the surface waters through the pycnocline. Net planktonic respiration, heterotrophic

55 respiration, and benthic consumption of deposited organic matter are major components of the

56 bottom water DO consumption (Kemp et al., 1992). The DO replenishment from the atmosphere

57 decreases when the vertical stratification is strengthened and the solubility is reduced in warmer

58 water in summer (Taft et al., 1980). For example, an increase in freshwater discharge from the

59   Susquehanna River, which also brings excess nutrients, leads to a stronger stratification and

60   therefore severe hypoxia (Seliger et al., 1985; Taft et al., 1980). Excessive anthropogenic loads

61   of nutrients are recognized to be a major cause of eutrophication. The onset of hypoxia in the

62   Bay usually starts after the spring algal bloom and the subsequent respiration of settled and

63   enhanced accumulation of organic matter in the water column and bottom sediment (Newcombe

64   and Horne, 1938; Murphy et al., 2011). After the initiation of hypoxia, increased nutrient flux

65   from the sediment supports the summer algal bloom which further increases the bottom water

66   column DO consumption (Kemp et al., 1992; Murphy et al., 2011).

67   Worldwide sea-level rise (SLR) has been accelerating over recent years from about 1.7

68   mm yr^{-1} between 1901 to 2010 to about 3.2 mm yr^{-1} between 1993 to 2010 (IPCC, 2014). In

69   Chesapeake Bay, the estimated trend of relative SLR, varying from 2.7 to 4.6 mm yr^{-1} for

70   different locations over 1955 to 2007, is larger than the estimation for global mean SLR (Boon et

71   al., 2010; Zervas, 2001). SLR is projected to be 0.3 - 0.7 m by 2050 and 0.7 - 1.6 m by 2100

72   (Rahmstorf, 2007; Najjar et al., 2010; Boesch et al., 2013). Under SLR, the bay-averaged salinity

73   is predicted to increase by 0.5 with an SLR of 0.2 m (Hilton et al. 2008). The bay-averaged

74   stratification is estimated to be strengthened under SLR, which reduces vertical exchange

75   through the pycnocline and tends to diminish the bottom DO supply from the surface layer

76   (Hong and Shen, 2012). Additionally, the residence time for substances discharged from the

77   Susquehanna River is prolonged due to larger water volume under SLR (Hong and Shen, 2012).

78   The changes in hydrodynamics could affect DO dynamics and hypoxic volume (HV).

79   Multiple numerical studies have been conducted to discuss the change in the

80   hypoxic/anoxia volume in response to SLR in the Bay. However, diverse changes have been

81   predicted. Both Wang et al. (2017) and Irby et al. (2018) showed an improvement in the DO

82   conditions whereas Ni et al. (2017) suggested an increase in the summer HV. St-Laurent et al.

83   (2019) made an explicit comparison between different models and showed that all the models

84   predict the same trend of change in DO but disagree on the changes in HV. This suggests large

85   uncertainties still exist in numerical modeling of the effects of SLR on hypoxia. The

86   uncertainties may be largely due to the differences in model kinetic parameters and grid

87   resolution. Another concern is the lack of a high-resolution grid that cannot well represent

88   shallow waters and tributaries in many of these models (Cai et al., 2020). There has been no

89   report on what and how much change will happen in shallow regions under SLR, though

90   tributaries and shallow water areas (water depths smaller than 2 m in this study) are expected to

91   experience larger changes compared with the main stem of the Bay.

92   In this study, a high-resolution three-dimensional unstructured-grid (UG) model is used

93   to investigate the effects of SLR on hypoxia. Besides studying the effects of SLR on the main

94   stem, we also explore the changes in HV, flushing time, and phytoplankton production, with a

95   focus on the tributaries and shallow water areas. This paper is organized as follows: a description

96   of the model, scenarios, and analysis methods are presented in Section 2. Results of changes in

97   hypoxic conditions and phytoplankton production are presented in Section 3. Section 4 presents

98   the discussions on the drivers of the changes for hypoxia including inside the tributaries and

99   shallow water areas. Section 5 summarizes the entire study.

100

101   **METHODS**

102   *SCHISM-ICM*

103   We use a fully coupled hydrodynamic and water quality model, SCHISM-ICM, which

104   couples the Semi-implicit Cross-scale Hydroscience Integrated System Model with the

105   Integrated Compartment Model (ICM) for water quality simulation (Cerco and Cole, 1994;

106   Zhang et al., 2016; Cai et al., 2020; schism.wiki). In addition, the sediment flux model which

107   simulates the diagenesis and recycling process is incorporated into ICM (DiToro and Fitzpatrick,

108   1993). SCHISM-ICM solves physical and biogeochemical processes simultaneously. There are

109   21 water quality state variables simulated by ICM: algal assemblage group, comprised of diatom,

110   green algae, and cyanobacteria, along with three groups of carbon, five groups of nitrogen, four

111   groups of phosphorus, chemical oxygen demand and DO. Local kinetic processes of these state

112   variables are simulated by ICM, while evolution and spatial distribution of these state variables

113   are simulated by SCHISM.

114   SCHISM uses a semi-implicit time-stepping scheme applied in a hybrid finite-element

115   and finite-volume framework to solve Navier-Stokes equations and uses an Eulerian-Lagrangian

116   method to treat the momentum advection. This numerical scheme ensures the time step is not

117   restricted by the CFL (Courant-Friedrichs-Lewy) condition. For shallow water areas where high-

118   resolution model grids are used, the time step can remain large in the hydrodynamic model. This

119   largely improves numerical efficiency. In the vertical dimension, the model uses a highly flexible

120   and efficient hybrid coordinate system LSC^2 (localized Sigma Coordinate with Shaved Cell),

121   which allows a varying number of vertical grids at each node (Zhang et al. 2015). The high-

122   resolution model grids, coupled with the hybrid vertical coordinate system for shallow water

123   areas allow for seamless spatial cross-scale simulations. This makes it feasible to study the

124   effects of SLR on shallow and deep areas as a whole.

125

126   *Design of Scenarios*

127   The model domain for Chesapeake Bay and its tributaries is shown in Figure 1. Base

128   Scenario uses the current mean sea level as a reference datum for model simulations, and the

129   model has been developed and calibrated by Cai et al. (2020). The simulation period is from

130   1991 to 1995, which is currently used as a reference period for management scenario simulations

131   by the Chesapeake Bay Program (CBP). Besides the Bay proper, the grid extends farther

132   offshore to the shelf break to minimize the influence of open ocean conditions on the interior of

133   the Bay. The grid resolution varies from 2.4 km on the continental shelf to less than 100 m in

134   tributaries. A flexible vertical grid system LSC2 (Localized Sigma Coordinates with Shaved

135   Cells) developed by Zhang et al. (2015) was applied in this study, which preserves the spatial

136   variation of bathymetry in high fidelity. The number of vertical layers varies from 11 to 52 (33

137   on average) for the whole system with resolution varying from 0.5 to 19 m. The model uses a

138   single non-split time step of 150 sec.

139   Interpolated elevations from two tidal gauges at Lewes, DE, and Beaufort, NC were used

140   to force elevations at the ocean boundary. We obtained the boundary temperature from Simple

141   Ocean Data Assimilation (SODA, Carton and Giese, 2008) from 01/01/1991 to 10/06/1992

142   (when HYCOM is not available) and hybrid coordinate ocean model (HYCOM, Chassignet et al.,

143   2007) from 10/07/1992 to 12/31/1995. World Ocean Atlas monthly climatological data provided

144   the ocean boundary salinity. We used constant values for the nutrients and other water quality

145   variables in the ocean boundary because the ocean boundary is far away from the Bay mouth and

146   the model simulation in the Bay was tested to be generally insensitive to the nutrient conditions

147   at the ocean boundary (Cai et al., 2020). Phase 6 Watershed Model of Chesapeake Bay

148   Assessment Tool (CAST) provided daily runoff and nutrient loads from the watershed for this

149   study (Shenk and Linker, 2013). The daily loadings are linearly interpolated into each time step

150   in this model. The atmospheric forcing and heat fluxes were obtained from the North American

151   Regional Reanalysis (Mesinger et al., 2006).

152   SLR of 0.17 m, 0.5 m, and 1.0 m were added to the sea surface height at the ocean

153   boundary of the Base Scenario, respectively for each SLR scenario. All scenarios share identical

154   oceanic, watershed, and atmospheric forcings. In this study, since we focus on the effects of SLR

155   as the sole driver to cause changes in transport and biochemical processes, all other processes,

156   such as river discharge, wind, solar radiation, and nutrient loadings remain unchanged.

157   According to estimations from Dettmann (2001), the surface area of the Bay is 11,524 $\times$

158   10^6 m^2 and the mean depth of it is 6.8 m. SLR of 0.5 m will increase the Bay volume (ΔVol) by

159   5.764 km^3 (7.4%) without considering the changes in the surface area. The average volume or

160   depth increase is 7.4% of the original total volume and depth. For this study, the increase in the

161   surface area in the low-lying area of the Bay due to SLR was not considered for comparing the

162   model results with other published model results.

163

164   *Analysis Methods*

165   **Flushing Time** Flushing time is the time it takes to replace the water mass of a

166   waterbody and is often estimated by the ratio of the mass of a scalar in a reservoir to the rate of

167   renewal of the scalar (Monsen et al., 2002). We calculated the flushing time for the major

168   tributaries because the river discharge is estimated to be dominant for the water exchange in the

169   Chesapeake Bay (Xiong et al., 2021). Flushing time can be estimated numerically by calculating

170   the e-folding time. To calculate the e-folding time, passive tracers were released in each tributary

171   twice a month. The e-folding time for each release was calculated as the time it takes for tracer

172   concentration decreases to e^{-1} (about 37%) of the initial tracer concentration, and the values were

173   then averaged for the year 1992 (Monsen et al., 2002).

174

175   **Hypoxic Volume** The hypoxic volume estimation follows the method in Bever et al

176   (2013) for estimating the HV based on observations. Using the same method helps avoid any

177   bias introduced by the estimation method when comparing the modeled HV with observations.

178   The modeled DO profiles at major CBP stations (as used by Bever et al. 2013) were
179   interpolated/extrapolated onto the current SCHISM UG grid to cover the entire Chesapeake Bay
180   before the total HV was calculated. A linear interpolation was used at each vertical layer, and the
181   hypoxic layer thickness at each node was then calculated. The hypoxic layer thickness at each
182   element is the averaged value among its three/four surrounding nodes. The total HV is the sum
183   of HV in each element, which is the product of the element area and its hypoxic layer thickness.

184

185   **Phytoplankton Production** Local phytoplankton production was computed by
186   integrating local phytoplankton production in each water column for the element:

187    $$\text{GPP} = \sum_{i=1}^{n}(\text{C1}_i \cdot \text{G1}_i + \text{C2}_i \cdot \text{G2}_i + \text{C3}_i \cdot \text{G3}_i) \cdot \text{dep}_i \qquad (1)$$

188   where GPP is areal gross primary production of phytoplankton (g C m^{-2} day^{-1}), n is the number of
189   layers in each element, i is the vertical layer index, C1, C2, C3 are carbon-based phytoplankton
190   biomass of three groups (diatoms, green algae, and cyanobacteria) over each layer respectively
191   (g C m^{-3}), G1, G2, G3 are growth rates of the three phytoplankton groups (day^{-1}), and dep is layer
192   thickness (m).

193

194   **Comparison of DO Concentration and Local Change Rates** DO concentration and its
195   local change rate were calculated based on the absolute altitude in each vertical layer of the
196   model for both Base and SLR Scenarios. To better compare the vertical profiles of these values
197   between Base and SLR Scenarios, two references in the vertical coordinate were used. The first
198   reference was set to be the bottom, and its vertical position is unchanged in the model. This
199   reference helps to estimate the changes in DO in the bottom hypoxic layer. The second reference
200   was set to be the free water surface, which rises in each SLR Scenario. This reference helps to
201   compare the contributions of local biological processes in the upper layer, such as phytoplankton
202   growth.

203

204   **Oxygen and Nutrient Fluxes** Oxygen and nutrient fluxes were calculated at twelve
205   cross-sections from the Bay mouth to the head (Figure 1). Influx and outflux were calculated as

206   the sectionally-integrated products of along-channel flow velocity and concentration of DO or

207   nutrient where the velocity direction is upstream into the Bay (marked as negative) and

208   downstream (positive), respectively. The calculations of fluxes through each cross-section

209   follows:

210
$$\begin{cases} \text{influx} = \int_{A(u<0)}(u \cdot \text{Var})dA \\ \text{outflux} = \int_{A(u>0)}(u \cdot \text{Var})dA \end{cases} \tag{2}$$

211   where u is the along-channel velocity (m s^{-1}), Var is DO or nutrient concentrations (g m^{-3}), A is

212   the area of cross-sections (m^2). Five-year averages of monthly and annually influx, outflux, and

213   net flux at each cross-section were then calculated.

214

215   **RESULTS**

216   *Dissolved Oxygen Under SLR*

217   Changes in DO concentrations due to SLR (ΔDO; Δ = SLR Scenario – Base Scenario,

218   thereafter) can be either positive or negative, where positive values of ΔDO mean increases in

219   DO concentration after SLR and negative values mean decreases. For different SLR scenarios,

220   ΔDO has different magnitudes but shows a similar distribution in general. The magnitude of

221   ΔDO tends to increase linearly with the magnitude of SLR. The bottom ΔDO varies spatially,

222   and it is mostly negative in shallow areas but becomes positive in some hypoxic areas (DO

223   concentration is lower than 2 g m^{-3}) (Figure 2). From June to August, the bottom ΔDO

224   approaches zero in the upper and mid-Bay (between latitude 38.5 ^{o}N and 39 ^{o}N). A positive ΔDO

225   of 0.1 to 0.2 g m^{-3} can be seen in the region near 38 ^{o}N when SLR exceeds 0.17 m.

226

227   *The Hypoxic Volume Under SLR*

228   HV generally increases (ΔHV > 0) with some interannual variations (Figure 3). Take the

229   case of SLR = 0.5 m as an example, ΔHV ranges from 0.5 to 1.0 km^3 for different years. The

230   increase of HV is positively correlated to the magnitude of SLR. ΔHV is, on average, about 2%,

231   8%, and 16% of the current HV in Base Scenario, respectively, for the scenarios of SLR of 0.17

232   m, 0.5 m, and 1.0 m. In addition, although each case of SLR leads to a change in total water

233   volume (ΔVol), ΔHV maintains a relatively stable fraction (10% - 15%) of ΔVol.

234   As mentioned in the introduction, there are diverse predictions for ΔHV (Wang et al.,

235   2018; Ni et al., 2017; Irby et al., 2018). Our predicted ΔHV has the same trend as Ni et al. (2017).

236   St-Laurent et al. (2019) conducted a comparison between all the model predictions including the

237   SCHISM-ICM model and showed the predicted trends of ΔDO are the same for all the models –

238   positive ΔDO for the mid-lower Bay channel but negative for the shallow regions. The

239   magnitude of ΔDO for each SLR scenario is comparable (St-Laurent et al., 2019). Our model

240   result has a similar magnitude of ΔDO as ChesROMS-ECB (Irby et al., 2018), and lies between

241   the CH3D-ICM (Wang et al., 2017) and UMCES-ROMS-RCA (Ni et al. 2017).

242

243   *Phytoplankton Production Under SLR*

244   Changes in gross phytoplankton production (ΔGPP) have a significant impact on hypoxia

245   in the Bay (Murphy et al., 2011). ΔGPP corresponding to SLR in the water column is positive in

246   most areas of the Bay (Figs. 4d, 4e). For shallow areas, the magnitude of ΔGPP can reach as high

247   as 0.4 g C m^{-2} day^{-1} for the case of a 0.5 m SLR, i.e., a 50% increase in the phytoplankton

248   production (Figs. 4b, 4e). For the scenarios of 0.17 m and 1.0 m SLR, the increases in the local

249   production are up to about 18% and 80%, respectively (not shown in the figure). Large values of

250   ΔGPP (e.g. > 0.15 g C m^{-2} day^{-1}) generally occur in shallow areas (< 2 m) with relatively low

251   values of GPP (e.g. < 0.5 g C m^{-2} day^{-1}) in Base Scenario (Figs. 4b, 4c). In tributary channels

252   where the water depth ranges from 1 to 4 m, ΔGPP is up to 0.2 g C m^{-2} day^{-1}. In the deep areas

253   (e.g. > 8 m) where the GPP is large in Base Scenario (e.g. 0.8 to 1.4 g C m^{-2} day^{-1}), however,

254   ΔGPP is much smaller and can even be negative (e.g. < 0.02 g C m^{-2} day^{-1}) (Figs. 4b, 4c).

255   High depth-integrated chlorophyll-a concentrations (denoted by Tchla) are more

256   concentrated in deep areas in the upper-middle part of the main Bay and deep tributaries such as

257   the Potomac River (Figure 5a-1). In contrast, high depth-averaged chlorophyll-a concentrations

258   (denoted by Mchla) are located in shallow areas in the upper-middle Bay regions, including

259   shallow tributaries such as the Chester River (Figs. 5d, 5g). Changes in depth-integrated

260   chlorophyll-a concentrations (ΔTchla) generally show a similar spatial distribution as ΔGPP

261 (Figs. 5a-2, 5a-3). However, changes in depth-averaged chlorophyll-a concentrations (ΔMchla)

262 can be both positive and negative over the Bay (Figs. 5b-2, 5b-3).

263

264   **DISCUSSION**

265 *The Contributions of Physical and Biochemical Processes to DO Dynamics Under SLR*

266   **Physical Processes** SLR results in an increase in salinity throughout the Bay and the

267 deep channel (Figure 6a). Bay-averaged ΔS is about 0.7 for the case of a 0.5 m SLR, and ΔS

268 increases linearly with the magnitude of SLR. Results show that the length of salt intrusion also

269 increases with SLR and the seasonal pattern agrees with predictions in Hong and Shen (2012).

270 For example, a 0.5 m of SLR increases salt intrusion length by about 5 km on average (not

271 shown). The increase in salinity and salinity intrusion suggests that more DO-rich coastal water

272 can be transported into the Bay in the lower layer. This is supported by the upward oxygen at the

273 twelve cross-sections (Figure 7).

274   SLR drives stronger gravitational circulation, which inputs more oxygen-rich water into

275 the lower layer of the Bay from the coast, and exports more oxygen in the upper layer (Figure 7).

276 Although there is a net outflux of oxygen from the Bay annually (Figs. 7a-3, 7b-3), the elevated

277 bottom oxygen influx increases the bottom oxygen concentration over the lower Bay as shown in

278 Figs. 2b-2d. Compared with other model predictions for ΔDO in the Bay (e.g. Wang et al., 2017;

279 Ni et al., 2017; Irby et al. 2018; St-Laurent et al. 2019), our model shows the positive ΔDO is

280 more confined in the lower Bay due to the smaller influx of bottom oxygen at the location north

281 to the Rappahannock Shoal (Cross-section 5) (Figure 7b), which is different from other model

282 predictions (St-Laurent et al., 2019). This smaller upstream transport shown in our model could

283 result from the highly-resolved bathymetry in SCHISM relative to other models (Cai et al., 2020).

284   The overall Bay-averaged stratification is strengthened with the enhanced gravitational

285 circulation. Under SLR, the pycnocline rises *relative to the bottom* (Figure 6b). Meanwhile, the

286 vertical salinity gradient (dS/dz) *relative to the sea surface* decreases, which indicates a slight

287 increase in the mixing of DO near the surface (Figure 6c). However, this does not necessarily

288 mean that there is a higher DO flux transported from the upper layer into the lower layer of the

289 water column. Previous studies suggest that the time for water parcels transported from the

290   surface to the bottom, the vertical exchange time (VET), becomes longer in estuaries under SLR

291   (Hong and Shen, 2012). This is caused by the pycnocline rise and the increased volume below

292   the pycnocline. Thus, although the mixing of DO may be enhanced above the pycnocline, the

293   overall time required for the DO in the upper layer to be transported to the lower layer increases.

294   As a result, the oxycline rises *relative to the bottom* under SLR (Figure 6d), which mainly drives

295   the overall increase of HV (Figure 3). On the other hand, the DO concentration increases under

296   SLR at the same distance below the surface (Figure 6e). This could be a result of enhanced

297   mixing in the upper layer as discussed above, but could also be a result of the increased

298   phytoplankton production, which will be discussed in the next sections.

299   The contribution of lateral circulation is also studied. Under SLR, the increase in water

300   depth in shallow areas is more pronounced than the deep channel, which can alter the lateral

301   circulation. The model simulation shows that the lateral channel-shore exchange is strengthened

302   along the lateral cross-section under SLR. For example, the averaged surface velocity along the

303   cross-channel direction over section 9 (see Figure 1) increases 2.35% when SLR is 1 m. The

304   increased channel-shore exchange is expected to transport more oxygen from shallow areas to

305   deep channels to decrease HV. However, the lateral circulation induced DO supply is minor,

306   which is unable to offset baseline hypoxic conditions. On the other hand, the lateral advection of

307   low-oxygen water contributes to the decrease in the bottom DO concentration in the shallow

308   areas (Figure 2).

309

310   **Biochemical Processes** The enhanced gravitational circulation, strengthened

311   stratification, and increased water depth/volume caused by SLR, as discussed in section 4.1,

312   cannot fully explain the overall increased HV in the Bay since DO concentration increased in the

313   deep channel of the mid-lower Bay. The model also suggests that the phytoplankton production

314   increases under SLR, which produces more oxygen through photosynthesis, but consumes more

315   DO through respiration. Surface DO for both deep (Figs. 6d, 6e) and shallow areas (Figure 8a)

316   changes little resulting from the air-sea equilibrium and advection. The local net rate of change

317   in DO at the surface (1.1 g m^{-3} day^{-1}, Figure 8b) is smaller than the difference between DO

318   production rate and respiration rate (1.7 g m^{-3} day^{-1}, Figs. 8c, 8d), which suggests there is a net

319   transport of DO from the water to the atmosphere. The outflux of DO by gravitational circulation

320 near the surface also increases. Therefore, more oxygen produced by the increased

321 phytoplankton production under SLR does not help much to increase the bottom oxygen

322 concentration. Furthermore, the settled organic matter, from increased phytoplankton production

323 under SLR, contributes to more water column respiration (Figure 8d). The vertical distributions

324 of local biochemical processes share the same trend as shown in Figure 8 for both deep and

325 shallow areas. The increased phytoplankton production under SLR increases the settling of

326 organic matter, resulting in the sediment oxygen demand. Also, the deepened water column and

327 increased residence time prolong the retention time of increased organic matters in the water

328 column, resulting in increased water column respirations.

329

330 **DO Budget** We used a simple DO budget model to evaluate the contributions of both the

331 physical transport and local biochemical processes to hypoxia in the region between cross-

332 sections 7 and 8 (Figure 1), and quantitatively compared the contribution of each process for

333 Base and SLR scenarios (Figure 9). The dominant processes are phytoplankton production,

334 heterotrophic respiration, and net flux physical transport. Other processes, such as air-sea

335 exchange and nitrification, have relatively fewer contributions to the budget. Under SLR of 1 m,

336 contributions of all dominant processes on DO budget increase. The total DO consumption

337 increases by 11.2% (Figure 9b). Although the DO influx in the bottom layer increases under SLR

338 (Figure 7), the increased net flux transports more DO out of the Bay. The increased total

339 respiration and DO outflux overwhelm the increased DO production, which leads to more loss of

340 DO and an enlarged HV.

341

342 *Changes in Phytoplankton Production Under SLR*

343 Since both Tchla and local depth increase, the positive ΔMchla shown in certain areas

344 indicates that the local production, especially the local growth, is enhanced due to the effect of

345 SLR (Figure 5). In other areas, especially the main stem, the local Tchla is usually at a high level

346 though ΔMchla is negative, implying that other local processes limiting the accumulation or

347 growth of phytoplankton. For example, Mchla is diluted by increased water depth. Also, the

348 increased water depth and enhanced stratification reduce the upward flux of recycled nutrients

349 from the lower layer, which reduces the nutrients supply in the surface layer for phytoplankton to
350 take up.

351   The enhanced gravitational circulation affects both the transports of nutrients and
352 phytoplankton. To quantify the export and retention of substances affected by SLR in the Bay,
353 the freshwater age of the Bay was computed following the method in Shen and Hass (2004). The
354 overall water age of the Bay increases with SLR. With an SLR of 0.5 m, the annual freshwater
355 age of the Bay mouth increased by 20 to 60 days for different years from the value of about 200
356 days in Base Scenario (Cai et al., 2020). An increased freshwater age suggests that more
357 nutrients will be retained inside the Bay for phytoplankton growth (Nixon et al., 1996), which is
358 also supported by the changes in nutrient flux under SLR (Figure 10). The net outfluxes of both
359 total nitrogen (TN) and dissolved inorganic nitrogen (DIN) decrease in all the seasons (Figs. 10a-
360 1,2; 10b-1,2); and the net influx of total inorganic phosphorus (TIP) increases during most time
361 of a year under SLR (Figs. 10a-3, 10b-3). Besides, the Bay-wide stronger stratification tends to
362 maintain phytoplankton in the euphotic zone.

363   Besides the direct effects on phytoplankton growth, accumulation and distribution, it
364 appears that SLR reduces the growth limitations of phytoplankton in many tributaries or certain
365 regions of large tributaries (e.g. the Choptank River, the upstream of the Potomac River). The
366 changes of water volume (water column depth), transport and circulation, flushing time, as well
367 as the nonlinear interactions among them, influence the local phytoplankton growth by changing
368 the local nutrient and light availabilities, and the detailed discussion about these interactions will
369 be presented in section 4.3.

370

371 *Changes in Tributaries and Shallow Areas*

372 **Changes of Flushing Time of Major Tributaries** As discussed above, model results
373 show that phytoplankton production increases significantly in tributaries and shallow areas under
374 SLR. The increase in the GPP, however, is not proportional to the volume increase in most areas.
375 Since nutrient loadings from the watershed are unchanged, the nutrient limitation for
376 phytoplankton growth is mainly influenced by physical processes and nutrient consumption, and
377 nutrient is less limited in tributaries. In this case, change in nutrient limitation under SLR for
378 phytoplankton growth is expected to be minor in tributaries and shallow areas. Flushing time was

379   computed for each major tributary to explore the local retention and dynamic processes that

380   affect the dynamics of phytoplankton and nutrients.

381   Opposite to the situation that residence time of the Bay increases under SLR, the flushing

382   time in most tributaries in the upper Bay (e.g. the Chester River) tends to decrease with SLR

383   (Figure 11a); however, this seems a relatively minor factor (see discussions below).

384   The flushing time of a tributary can be expressed as

385    $$\tau = \frac{V}{Q} \qquad (3)$$

386   where V is the total volume and Q is the flux out of tributary (Monsen et al., 2002). The change

387   in flushing time depends on the net effect of increases in volume and flux. Although SLR

388   increases water volume, V, which tends to increase the flushing time, it also increases flux Q, as

389   suggested by the classic estuarine circulation theory. According to the classic estuarine

390   circulation theory (Hansen and Rattray, 1965; MacCready and Geyer, 2009), the velocity of the

391   exchange flow is quantified by the expression:

392    $$u_E = \frac{g\beta \overline{s_x} H^3}{48 K_m} \qquad (4)$$

393   where g is the gravitational acceleration constant, $\beta \cong 7.7 \times 10^{-4}$ PSU^{-1}, $\overline{s_x}$ is depth-averaged

394   salinity gradient in the along-channel direction, H is water depth, and K_m is the vertical eddy

395   viscosity. The outflux can be expressed by the production of u_E and the cross-section area. This

396   suggests that the increase of water depth increases both the velocity of the exchange flow and

397   cross-section area. Therefore the increase of water depth increases the water exchange and

398   shortens the flushing time (Hansen and Rattray, 1965; Shen and Lin, 2001). Since the outflux can

399   increase if the exchange flow increases due to the enhanced gravitational circulation, the change

400   in flushing time ($\Delta\tau$) depends on the competition between the increases in the volume and the

401   increase in the flux resulting from increased gravitational circulation. $\Delta\tau$ can be either positive or

402   negative for different tributaries.

403

404   **Effects of Sea-level Rise on Light Supply in Tributaries** The areal phytoplankton

405   primary production is the integration of productivity over the water column. In estuaries,

406   phytoplankton is distributed vertically in the upper mixed layer while photosynthesis occurs in

407   the euphotic zone. The ratio of the depth of the euphotic zone (1% of the surface irradiance) to

408   the depth of the mixed layer can alter the light availability in the water column and hence

409   regulate the areal phytoplankton production (Cloern, 1987; Smith and Kemp, 1995). In deep

410   areas where the depth of the euphotic zone is greater than the depth of the mixed layer, light is

411   fully utilized in the water column and leads to maximum phytoplankton production. However, in

412   areas where the depth of the euphotic zone is less than the depth of the mixed layer, light cannot

413   be fully utilized and may prevent full growth of the phytoplankton production from reaching its

414   maximum productivity (Brawley et al., 2003; Brush and Brawley, 2009; Cloern, 1987). In these

415   shallow areas, the whole water column is usually within the euphotic zone and hence the light

416   availability can often be limited by the water depth. This has been widely observed in different

417   estuaries that phytoplankton production is often less than the maximum values in the areas where

418   the water depth is shallower than the euphotic depth (e.g., Boyer et al., 1993; Mallin et al., 1991;

419   Cloern, 1987). Thus, in some shallow areas of the tributaries, the increase in water depth and

420   change in hydrodynamics as a result of SLR can have a nontrivial impact on light supply for

421   phytoplankton growth and hence on primary production. This can be examined quantitively

422   using the equation for primary production. The phytoplankton productivity can be expressed as

423   gross primary production and phytoplankton biomass (Cloern et al., 2014; Qin and Shen, 2017),

424   and the depth-integrated phytoplankton gross primary production (GPP) is the integral of

425   productivity from the surface to the bottom:

426             $GPP = \int_0^H G_z C_z dz$ (5)

427   where G_z and C_z are the gross growth rate and volumetric biomass at each depth z, respectively.

428   For shallow areas where the water depth is less than the depth of the mixed layer depth, the

429   phytoplankton can be assumed to be homogeneously distributed at each depth (for the sake of

430   analytical solutions), and the biomass C_z can be assumed to be independent of depth and equal to

431   the depth-averaged biomass. Therefore, depth-integrated phytoplankton production can be

432   expressed as:

433             $GPP = G \cdot C \cdot H$ (6)

434   where G is depth-averaged gross growth rate (day^{-1}), C is depth-averaged phytoplankton biomass

435   (g C m^{-3}), and H is water depth (m). Under light limitation, gross growth rate $G = G_m \cdot f(I)$,

436   where G_m is the temperature-dependent maximum growth rate (day^{-1}) and $f(I)$ is the daily-

437   averaged growth-limitation function for light (Chapra, 1997):

$$f(I) = \frac{e}{K_d \cdot H} \cdot (e^{-\frac{I_0}{I_{opt}} \cdot e^{-K_d \cdot H}} - e^{-\frac{I_0}{I_{opt}}}) \tag{7}$$

438

439

440   K_d is light attenuation coefficient (m^{-1}), I_0 is incident light irradiance at the surface and I_{opt} is

441   optimal light intensity (langleys day^{-1}). Eqs. (6) and (7) suggest that under SLR, a possible

442   change in GPP can result from changes in water depth, H, light attenuation, K_d, or phytoplankton

443   biomass, C. Substituting Eq. (7) into Eq. (6) reads:

$$GPP = G_m \cdot C \cdot \frac{e}{K_d} \cdot (e^{-\frac{I_0}{I_{opt}} \cdot e^{-K_d \cdot H}} - e^{-\frac{I_0}{I_{opt}}}) \tag{8}$$

444

445   The effect of water depth on GPP is through its comparison with the depth of the

446   euphotic zone (denoted by H_u). If water depth $H \geq H_u$, the utilization of the light by

447   phytoplankton in the water column is not limited by the water depth. In this case, light irradiance

448   approaches zero at the bottom. Since light irradiance at each depth z can be described by the

449   Beer-Lambert law, $I(z) = I_0 e^{-k_d \cdot z}$, we have $I(H) = I_0 e^{-k_d \cdot H} \approx 0$. This results that $e^{-k_d \cdot H}$

450   ≈ 0 and $e^{-\frac{I_0}{I_{opt}} \cdot e^{-K_d \cdot H}} \approx 1$. Therefore, the daily-averaged growth-limiting function for light can

451   be simplified as:

$$f^*(I) = \frac{e}{K_d \cdot H}(1 - e^{-\frac{I_0}{I_{opt}}}) \tag{9}$$

452

453   We used $f^*(I)$ to denote the $f(I)$ when the utilization of the light by phytoplankton in

454   the water column is not limited by the water depth. If the water depth is less than the depth of the

455   euphotic zone, $H < H_u$, i.e., light can penetrate ultimately to the bottom. In this case, the

456   utilization of the light by phytoplankton in the water column is limited by the water depth, $I(H)$

457      $= I_0 e^{-k_d \cdot H} > 0$ and $e^{-\frac{I_0}{I_{opt}} \cdot e^{-K_d \cdot H}}$ is less than 1. Obviously, $f(I) < f^*(I)$.

458   To describe $f(I)$ in the two cases $H \geq H_u$ and $H < H_u$, the daily-averaged growth-

459   limiting function for light may be expressed as:

$$f(I) = r \cdot f^*(I) \tag{10}$$

460

461   where r is a factor ranging from 0 to 1, and it has the expression:

462
$$r = \frac{e^{-\frac{I_0}{I_{opt}} \cdot e^{-K_d \cdot H}} - e^{-\frac{I_0}{I_{opt}}}}{1 - e^{-\frac{I_0}{I_{opt}}}}$$
(11)

463   For the case $H \geq H_u$, $r = 1$ and $f(I) = f^*(I)$. For the case $H < H_u$, $r < 1$, and Eq. (11)

464   suggests a positive correlation between r and $K_d \cdot H$. Over shallow areas where the whole water

465   column is within the euphotic zone when the water becomes deeper, more light energy can be

466   utilized in the water column until the local depth exceeds the 1% light level.

467   Correspondingly, Eq. (6) can be expressed explicitly as

468
$$GPP = G_m \cdot r \cdot \frac{e}{K_d}(1 - e^{-\frac{I_0}{I_{opt}}}) \cdot C$$
(12)

469   Eq. (12) suggests that the change of GPP under light limitation due to SLR can be

470   explained quantitatively by the changes in r, C, and K_d.

471   Among the three factors r, C, and K_d, the increase in GPP is mainly driven by the

472   increase in r under SLR in the Bay. The model results show that K_d is not a major factor in

473   changing GPP. Except in certain areas with an extreme high phytoplankton biomass and

474   particulate organic matter, the main stem and the channel areas of most tributaries exhibit a

475   decrease in light attenuation ($\Delta K_d < 0$) under SLR, but the magnitude of ΔK_d is small (<1%;

476   Figure 11a) and its impact on phytoplankton is minor. Changes in phytoplankton biomass C are

477   also not likely a determining factor leading to an increase in GPP in the scenarios. Model results

478   show that the percentage increase in C after SLR is not as high as that in GPP in tributaries, and

479   C even decreases in some locations. The change of biomass C is determined by local and

480   transport processes (Qin and Shen, 2017; Qin and Shen, in revision):

481
$$\frac{dC}{dt} = GC - R_r C - R_m C - \frac{\omega_c}{H}C - FC$$
(13)

482   where R_r and R_m are respiration rate (day^{-1}) and mortality rate (day^{-1}), respectively, ω_c is the

483   settling velocity of phytoplankton (m day^{-1}), and F is the flushing rate due to transport processes

484   (day^{-1}). In the tributaries, the overall changes in flushing in tributaries are not large compared

485   with their values in Base Scenario, suggesting the increase in C is mainly due to changes in local

486　processes. Among the local processes, respiration and grazing rates are kept unchanged in the

487　model, and the increase in C can only be through an increase in production or a decrease in

488　settling due to an increase in water depth. While it is not clear if the increase in C is mainly due

489　to the increase in GPP or the decrease in settling, the model results show that the increase in C is

490　not the major factor in increasing GPP. Take the Choptank River, which has the largest positive

491　ΔMchla, as an example. The mean water depth of the Choptank River is about 3.95 m, so the

492　change of water depth is about 12.7% under the case of a 0.5 m SLR. In this river, ΔK_d is less

493　than 0.005 m^{-1} over the river channel, which is a small value compared to K_d of about 0.4 m^{-1},

494　and K_d decreases less than 1%. Hence, the combined change in $K_d \cdot H$ increases about 11.6%,

495　which corresponds to an increase in r. Calculations of model results show that GPP increases

496　about 25% and C increases about 10% after a 0.5 m SLR (Figures 4, 5), so Eq. (12) suggests that

497　the increase in r is about 13.6% under SLR, which is more than that in C or K_d. Thus, in those

498　areas where the water depth is less than the depth of the euphotic zone, the increase in GPP is

499　mainly due to the increase in r, and the mechanism that SLR increases GPP is mainly through

500　the increase in the percent of light utilized by phytoplankton in the water column.

501　　　　The current model does not simulate benthic algae or submerged vegetation. For the areas

502　with abundant benthic producers, the interactions between pelagic and benthic producers can

503　alter the results (Qin and Shen, 2019). Under SLR, the elevated depth enhanced GPP in the water

504　column, which could decrease the light supply to the benthic producers. When the SLR is 0.5 m,

505　the overall decrease in light availability at the bottom ranges from 10% to 25% in the shoals

506　where the benthic producers are supported by excess light before SLR (Figure 11b). Bottom light

507　supply experiences little change in deep regions where the benthic producer cannot survive

508　anyway because of the limited light supply. Although the current model does not couple a

509　benthic algal model (e.g. Cerco and Seitzinger, 1997) to explicitly estimate the response of the

510　benthic producers to SLR, a reduction of less than 25% on benthic production is estimated based

511　on the PI curve for benthic algae (Pinckney and Zingmark, 1993; Dodds et al., 1999). However,

512　the reduction of benthic production also relies on the nutrient supply and the real irradiance

513　reaching the bottom, so future work is required for this direction.

514

SUMMARY AND CONCLUSION

515
516   We utilized a 3D unstructured-grid model (SCHISM-ICM) to evaluate the influence of

517 sea-level rise (SLR) on seasonal hypoxia and phytoplankton production in Chesapeake Bay.

518 Three scenarios (SLR = 0.17 m, SLR = 0.5 m and SLR = 1.0 m) were assessed based on the

519 calibrated current condition (Base Scenario) (Cai et al., 2020) for the period from 1991 to 1995.

520 Under SLR, the bottom DO was predicted to increase in the deep channel of the mid-lower Bay,

521 but to decrease in other areas. Peak summer hypoxic volume (HV) is estimated to increase by

522 about 2%, 8%, and 16% for these three scenarios, respectively, compared with Base Scenario.

523 SLR drives a total volume change (ΔVol) of 1.96 km^3, 5.76 km^3, and 11.52 km^3, respectively;

524 and the changes in hypoxia volume (ΔHV) account for about 10% -15% of ΔVol.

525   Different physical and biological drivers are found to have diverse effects, either positive

526 or negative, on the DO budgets and HV. SLR increases the flux of oxygen-rich water from the

527 ocean into the Bay due to increased gravitation circulation and this tends to improve bottom DO.

528 On the other hand, the enhanced stratification and the enlarged volume below the pycnocline will

529 make it take a longer time for oxygen to be transported from the upper layer to the lower layer of

530 the water column. SLR slightly increases lateral circulation but the minor increase fails to

531 significantly enhance the channel-shoal exchange that refuels oxygen in the channel. In addition

532 to the physical contributions, SLR increases phytoplankton production as a result of longer

533 residence times, stronger stratification, and increased light supply in shallow waters; and the

534 production increases up to 15%, 40%, and 80% for these three SLR scenarios, respectively,

535 which in turn increases the water column DO respiration. The increased phytoplankton

536 production and residence time enhance the settling of organic matter to the lower layer.

537 Consequently, more oxygen is consumed that contributes to the increase in the HV. Overall, this

538 model study suggests that both the altered physical processes and the higher respiration under

539 SLR contribute to the enlarged HV.

540   Shallow areas in tributaries are highly impacted by SLR since the increased water depths

541 are proportionally large compared with the original depths. The model result shows the largest

542 increase in phytoplankton production occurs in the shallow water regions. The analysis shows

543 that the increase in water depth increases light utilization in shallow areas of many tributaries

544 where the whole water column is within the euphotic zone. This facilitates phytoplankton growth
545 and therefore increases the local production in those areas.

546   For the sake of simplicity and comparison to other studies, the current study only
547 considered the impact of SLR. For shallow areas and tributaries, other factors can be important
548 as well. Four such factors are the land use (that affects nutrient supply), presence of vegetation
549 (either submerged or emergent), presence of benthic algae, and change in temperature. These
550 complications are left to future studies.

567 **LITERATURE CITED**

568 Bever, A.J., M.A. Friedrichs, C.T. Friedrichs, M.E. Scully, and L.W. Lanerolle. 2013.
569   "Combining Observations and Numerical Model Results to Improve Estimates of
570   Hypoxic Volume Within the Chesapeake Bay, USA." *Journal of Geophysical Research:*
571   *Oceans*, 118(10), pp.4924-4944. https:// doi.org/10.1002/jgrc.20331
572 Boesch, D.F., L.P. Atkinson, W.C. Boicourt, J.D. Boon, D.R. Cahoon, R.A. Dalrymple, T. Ezer,
573   B.P. Horton, Z.P. Johnson, R.E. Kopp, and M. Li. 2013. "Updating Maryland's sea-level
574   rise projections." https://digitalcommons.odu.edu/ccpo_pubs/154/

575 Boon, J.D., J.M. Brubaker, and D.R. Forrest. 2010. "Chesapeake Bay land subsidence and sea
576   level change: An evaluation of past and present trends and future outlook."
577   https://scholarworks.wm.edu/reports/706/

578 Boyer, J.N., R.R. Christian, and D.W. Stanley. 1993. "Patterns of phytoplankton primary
579   productivity in the Neuse River estuary, North Carolina, USA." *Marine ecology progress*
580   *series. Oldendorf*, 97(3), pp.287-297. https://www.int-
581   res.com/articles/meps/97/m097p287.pdf

582 Brawley, J.W., M.J. Brush, J.N. Kremer, and S.W. Nixon. 2003. "Potential applications of an
583   empirical phytoplankton production model to shallow water ecosystems." *Ecological*
584   *modelling*, 160(1-2), pp.55-61. https://doi.org/10.1016/S0304-3800(02)00310-1

585 Cai, X., Y.J. Zhang, J. Shen, H. Wang, Z. Wang, Q. Qin and F. Ye. 2020. "A Numerical Study of
586   Hypoxia in Chesapeake Bay Using an Unstructured Grid Model: Validation and
587   Sensitivity to Bathymetry Representation." *Journal of the American Water Resources*
588   *Association* 1–24. https://doi.org/10.1111/1752-1688.12887.

589 Carton, J.A. and B.S. Giese. 2008. "A reanalysis of ocean climate using Simple Ocean Data
590   Assimilation (SODA)." *Monthly weather review*, 136(8), pp.2999-3017.
591   https://doi.org/10.1175/2007MWR1978.1

592 Cerco, C.F. and T.M. Cole. 1994. "CE-QUAL-ICM: a three-dimensional eutrophication model,
593   version 1.0. User's Guide." *US Army Corps of Engineers Waterways Experiments Station,*
594   *Vicksburgh, MS.*

595 Cerco, C.F. and S.P. Seitzinger. 1997. "Measured and modeled effects of benthic algae on
596   eutrophication in Indian River-Rehoboth Bay, Delaware." *Estuaries*, 20(1), pp.231-248.
597   https://doi.org/10.2307/1352733

598 Chapra, S.C. 1997. "Surface Water-Quality Modeling, McGraw-Hill Series in Water Resources
599   and Environmental Engineering."

600 Chassignet, E.P., H.E. Hurlburt, O.M. Smedstad, G.R. Halliwell, P.J. Hogan, A.J. Wallcraft, R.
601   Baraille, and R. Bleck. 2007. "The HYCOM (hybrid coordinate ocean model) data
602   assimilative system." *Journal of Marine Systems*, 65(1-4), pp.60-83.
603   https://doi.org/10.1016/j.jmarsys.2005.09.016

604 Cloern, J.E. 1987. "Turbidity as a control on phytoplankton biomass and productivity in
605   estuaries." *Continental shelf research*, 7(11-12), pp.1367-1381.
606   https://doi.org/10.1016/0278-4343(87)90042-2

607 Cloern, J.E., S.Q. Foster, and A.E. Kleckner. 2014. "Phytoplankton primary production in the
608   world's estuarine-coastal ecosystems." *Biogeosciences*, 11(9), p.2477.
609   https://doi.org/10.5194/bg-11-2477-2014

610 Dettmann, E.H. 2001. "Effect of water residence time on annual export and denitrification of
611   nitrogen in estuaries: a model analysis." *Estuaries*, 24(4), pp.481-490.
612   https://doi.org/10.2307/1353250

613 Diaz, R.J. and R. Rosenberg. 1995. "Marine benthic hypoxia: a review of its ecological effects
614   and the behavioural responses of benthic macrofauna." *Oceanography and Marine*
615   *biology: an Annual Review*, 33, pp.245-03.

616 Di Toro, D.M. and J.J. Fitzpatrick. 1993. "*Chesapeake Bay sediment flux model. Final*
617   *report* (No. AD-A-267189/9/XAB)." Hydroqual, Inc., Mahwah, NJ (United States).

618 Dodds, W.K., B.J. Biggs, and R.L. Lowe. 1999. "Photosynthesis-irradiance patterns in benthic
619   microalgae: variations as a function of assemblage thickness and community
620   structure." *Journal of phycology*, 35(1), pp.42-53. https://doi.org/10.1046/j.1529-
621   8817.1999.3510042.x

622 Du, J. and J. Shen. 2015. "Decoupling the influence of biological and physical processes on the
623   dissolved oxygen in Chesapeake Bay." *Journal of Geophysical Research: Oceans*, 120(1),
624   pp.78-93. https://doi.org/10.1002/2014JC010422

625 Hagy, J.D., W.R. Boynton, C.W. Keefe, and K.V. Wood. 2004. "Hypoxia in Chesapeake Bay,
626   1950–2001: long-term change in relation to nutrient loading and river
627   flow." *Estuaries*, 27(4), pp.634-658. https://doi.org/10.1007/BF02907650

628 Hansen, D.V. and M. Rattray Jr. 1966. "Gravitational circulation in straits and estuaries."
629   https://digital.lib.washington.edu/researchworks/bitstream/handle/1773/16068/M66-
630   76.pdf?sequence=1

631 Hilton, T.W., R.G. Najjar, L. Zhong, and M. Li. 2008. "Is there a signal of sea-level rise in
632   Chesapeake Bay salinity?" *Journal of Geophysical Research: Oceans*, 113(C9).
633   https://doi.org/10.1029/2007JC004247

634   Hong, B. and J. Shen. 2012. "Responses of estuarine salinity and transport processes to potential
635   future sea-level rise in Chesapeake Bay." *Estuarine, Coastal and Shelf Science*, 104,
636   pp.33-45. https://doi.org/10.1016/j.ecss.2012.03.014

637   Irby, I.D., M.A. Friedrichs, F. Da, and K.E. Hinson. 2018. "The competing impacts of climate
638   change and nutrient reductions on dissolved oxygen in Chesapeake
639   Bay." *Biogeosciences*, 15(9), pp.2649-2668. https://doi.org/10.5194/bg-15-2649-2018

640   Kemp, W.M., P. Sampou, J. Caffrey, M. Mayer, K. Henriksen, and W.R. Boynton. 1990.
641   "Ammonium recycling versus denitrification in Chesapeake Bay sediments." *Limnology*
642   *and Oceanography*, 35(7), pp.1545-1563. https://doi.org/10.4319/lo.1990.35.7.1545

643   Kemp, W.M., P.A. Sampou, J. Garber, J. Tuttle, and W.R. Boynton. 1992. "Seasonal Depletion
644   of Oxygen from Bottom Waters of Chesapeake Bay: Roles of Benthic and Planktonic
645   Respiration and Physical Exchange Processes." *Marine Ecology Progress Series*, pp.137-
646   152. www.jstor.org/stable/24829928

647   MacCready, P. and W.R. Geyer. 2009. "Advances in estuarine physics." *Annual Review of*
648   *Marine Science*, Vol. 2: 35-58. https://doi.org/10.1146/annurev-marine-120308-081015

649   Mallin, M.A., H.W. Paerl, and J. Rudek. 1991. "Seasonal phytoplankton composition,
650   productivity and biomass in the Neuse River estuary, North Carolina." *Estuarine, Coastal*
651   *and Shelf Science*, 32(6), pp.609-623. https://doi.org/10.1016/0272-7714(91)90078-P

652   Mesinger, F., G. DiMego, E. Kalnay, K. Mitchell, P.C. Shafran, W. Ebisuzaki, D. Jović, J.
653   Woollen, E. Rogers, E.H. Berbery, and M.B. Ek. 2006. "North American Regional
654   Reanalysis." *Bulletin of the American Meteorological Society*, *87*(3), pp.343-360.
655   https://doi.org/10.1175/BAMS-87-3-343

656   Monsen, N.E., J.E. Cloern, L.V. Lucas, and S.G. Monismith. 2002. "A comment on the use of
657   flushing time, residence time, and age as transport time scales." *Limnology and*
658   *oceanography*, 47(5), pp.1545-1553. https://doi.org/10.4319/lo.2002.47.5.1545

659   Murphy, R.R., W.M. Kemp, and W.P. Ball. 2011. "Long-term Trends in Chesapeake Bay
660   Seasonal Hypoxia, Stratification, and Nutrient Loading." *Estuaries and Coasts*, *34*(6),
661   pp.1293-1309. doi: 10.1007/s12237-011-9413-7

662   Najjar, R.G., C.R. Pyke, M.B. Adams, D. Breitburg, C. Hershner, M. Kemp, R. Howarth, M.R.
663   Mulholland, M. Paolisso, D. Secor, and K. Sellner. 2010. "Potential climate-change

664   impacts on Chesapeake Bay." *Estuarine, Coastal and Shelf Science*, 86(1), pp.1-20.

665   https://doi.org/10.1016/j.ecss.2009.09.026

666   Newcombe, C.L. and W.A. Horne.1938. Oxygen-poor Waters of the Chesapeake

667   Bay. *Science*, *88*(2273), pp.80-81. doi: 10.1126/science.88.2273.80

668   Ni, W., M. Li, A. Ross, and R.G. Najjar. 2017. "Downscaling climate projections for

669   Chesapeake Bay hypoxia in the mid-21st century." 24th Biennial CERF Conference.

670   CERF.

671   Nixon, S.W., J.W. Ammerman, L.P. Atkinson, V.M. Berounsky, G. Billen, W.C. Boicourt, W.R.

672   Boynton, T.M. Church, D.M. Ditoro, R. Elmgren, and J.H. Garber. 1996. "The Fate of

673   Nitrogen and Phosphorus at the Land-Sea Margin of the North Atlantic

674   Ocean." *Biogeochemistry*, *35*(1), pp.141-180. https://doi.org/10.1007/BF02179826

675

676   Pinckney, J. and R.G. Zingmark. 1993. "Photophysiological responses of intertidal benthic

677   microalgal communities to in situ light environments: methodological

678   considerations." *Limnology and oceanography*, 38(7), pp.1373-1383.

679   https://doi.org/10.4319/lo.1993.38.7.1373

680   Qin, Q. and J. Shen. 2017. "The contribution of local and transport processes to phytoplankton

681   biomass variability over different timescales in the Upper James River, Virginia."

682   *Estuarine, Coastal and Shelf Science*, *196*, pp.123-133.

683   https://doi.org/10.1016/j.ecss.2017.06.037

684   Scully, M.E. 2010. "Wind modulation of dissolved oxygen in Chesapeake Bay." *Estuaries and*

685   *Coasts*, 33(5), pp.1164-1175. https://doi.org/10.1007/s12237-010-9319-9

686   Scully, M.E. 2013. "Physical controls on hypoxia in Chesapeake Bay: A numerical modeling

687   study." *Journal of Geophysical Research: Oceans*, 118(3), pp.1239-1256.

688   https://doi.org/10.1002/jgrc.20138

689   Seliger, H.H., J.A. Boggs, and W.H. Biggley. 1985. "Catastrophic Anoxia in the Chesapeake

690   Bay in 1984." *Science*, *228*(4695), pp.70-73. doi: 10.1126/science.228.4695.70

691   Shen, J. and L. Haas. 2004. "Calculating Age and Residence Time in the Tidal York River Using

692   Three-Dimensional Model Experiments." *Estuarine, Coastal and Shelf Science*, *61*(3),

693   pp.449-461. https://doi.org/10.1016/j.ecss.2004.06.010

694 Shen, J., B. Hong, and A.Y. Kuo. 2013. "Using timescales to interpret dissolved oxygen
695   distributions in the bottom waters of Chesapeake Bay." *Limnology and*
696   *Oceanography*, 58(6), pp.2237-2248. https://doi.org/10.4319/lo.2013.58.6.2237

697 Shenk, G.W. and L.C. Linker. 2013. "Development and Application of the 2010 Chesapeake Bay
698   Watershed Total Maximum Daily Load Model." *JAWRA Journal of the American Water*
699   *Resources Association*, *49*(5), pp.1042-1056. https://doi.org/10.1111/jawr.12109

700 Smith, E.M. and W.M. Kemp. 1995. "Seasonal and regional variations in plankton community
701   production and respiration for Chesapeake Bay." *Marine ecology progress series.*
702   *Oldendorf*, 116(1), pp.217-231. http://www.int-res.com/articles/meps/116/m116p217.pdf

703 St-Laurent, P., M.A.M. Friedrichs, M. Li, and W. Ni. 2019. "Impacts of sea level rise on hypoxia
704   in Chesapeake Bay: A model intercomparison." Report to Virginia Tech and Chesapeake
705   Bay Program, October 2019, 34 pp. https://scholarworks.wm.edu/reports/2310/

706 Taft, J.L., W.R. Taylor, E.O. Hartwig, and R. Loftus. 1980. "Seasonal Oxygen Depletion in
707   Chesapeake Bay." *Estuaries*, *3*(4), pp.242-247. http://www.jstor.com/stable/1352079

708 Wang, P., L. Linker, H. Wang, G. Bhatt, G. Yactayo, K. Hinson, and R. Tian. 2017. "Assessing
709   water quality of Chesapeake Bay by the impact of sea level rise and warming." In IOP
710   Conference Series: Earth and Environmental Science(Vol. 82, No. 1, p. 012001).
711   https://iopscience.iop.org/article/10.1088/1755-1315/82/1/012001/meta

712 Vaquer-Sunyer, R. and C.M. Duarte. 2008. "Thresholds of hypoxia for marine
713   biodiversity." *Proceedings of the National Academy of Sciences*, 105(40), pp.15452-
714   15457. https://doi.org/10.1073/pnas.0803833105

715 Xiong, J., J. Shen, Q. Qin, and J. Du. 2021. "Water exchange and its relationships with external
716   forcings and residence time in Chesapeake Bay." *Journal of Marine Systems*, 215,
717   p.103497. https://doi.org/10.1016/j.jmarsys.2020.103497

718 Zervas, C. 2001. "Sea level variations of the United States, 1854-1999 (Vol. 36)". US
719   Department of Commerce, National Oceanic and Atmospheric Administration, National
720   Ocean Service.

721 Zhang, Y.J., E. Ateljevich, H.C. Yu,, C.H. Wu and C.S. Jason. 2015. "A New Vertical
722   Coordinate System for a 3D Unstructured-Grid Model." *Ocean Modelling*, *85*, pp.16-31.
723   https://doi.org/10.1016/j.ocemod.2014.10.003

724   Zhang, Y.J., F. Ye,, E.V. Stanev and S. Grashorn. 2016. "Seamless Cross-Scale Modeling with

725   SCHISM." *Ocean Modelling*, *102*, pp.64-81.

726   https://doi.org/10.1016/j.ocemod.2016.05.002

727

728   Figure 1: Model domain for Chesapeake Bay and its tributaries, with the 12 cross channel sections (red

729   lines). Two blue triangles denote the locations used for vertical profile analysis.

730

731   Figure 2: (a) Five-year averaged bottom DO concentrations in Base Scenario, and (b, c, and d) absolute

732   differences between SLR (0.17 m, 0.5 m, and 1 m) to Base Scenarios from June to August.

733

734   Figure 3: Hypoxic volume and difference under SLR scenarios of 0.17 m, 0.5 m, and 1.0 m. The black

735   line in the upper panel is from Base Scenario.

736

737   Figure 4: Five-year averages of gross phytoplankton production (depth-integrated) from April to June: (a)

738   horizontal distribution in Base Scenario, (b) averages in areas of different water depths for Base Scenario

739   and SLR = 0.5 m, (c) relative difference between Base Scenario and SLR = 0.5 m at different water

740   depths, and horizontal distribution of (d) absolute difference and (e) relative difference caused by SLR =

741   0.5 m on Base Scenario.

742

743   Figure 5: Five-year averages of (a) depth-integrated and (b) depth-averaged chlorophyll-a concentration

744   from April to June, respectively, for (a, b-1) Base Scenario, (a, b-2) absolute difference and (a, b-3)

745   relative difference caused by SLR = 0.5 m on Base Scenario.

746

747   Figure 6: Five-year averages of the vertical distribution of (a) salinity (b, c) dS/dz, and (e,f) DO at a deep

748   location in the hypoxic zone (Figure 1) from June to August. Profiles (a, b, and d) relative to the bottom

749   and (c, e) relative to the water surface are provided.

750

751   Figure 7: (a) Five-year averages of oxygen flux for each month from 1991 to 1995 at cross-section 4 near

752   Rappahannock Shoal (Figure 1); (b) Five-year averages of annual oxygen flux from 1991 to 1995 at the

753   12 cross-sections Bay mouth to head. Panels (a, b-1) are influx, panels (a, b-2) are outflux, and panels (a,

754   b-3) are the net oxygen flux. Negative values mean flux into the Bay while positive values refer to outflux.

755

756   Figure 8: (a) Five-year averages of the vertical distribution of DO at a shallow location in cross-section 9

757   (Figure 1). (b) The local net rate of change resulting from the local processes controlling the DO budget,
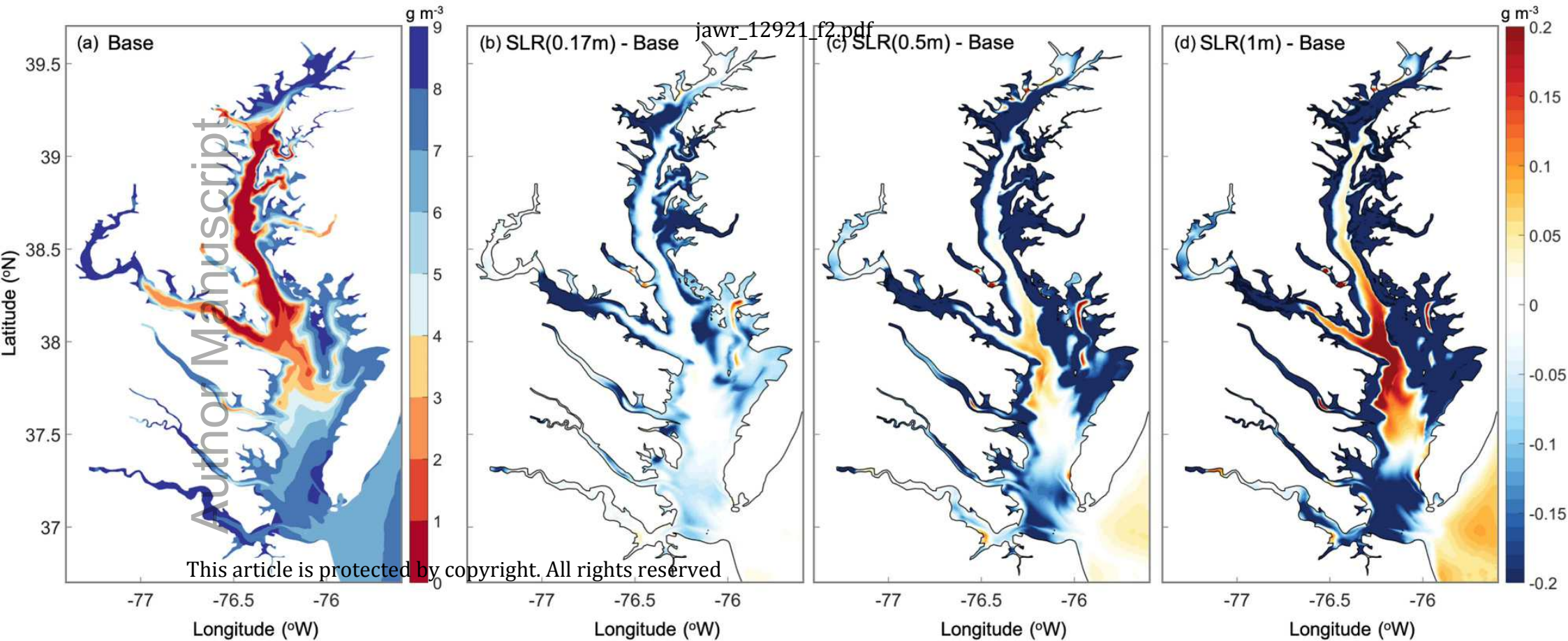
758   including reaeration, phytoplankton photosynthesis, basal respiration, heterotrophic respiration,

759   nitrification, sulfide oxidation, and sediment oxygen demand. (c) The rate of local oxygen productions. (d)

760   The rate of total local oxygen consumption, including basal respiration, heterotrophic respiration,

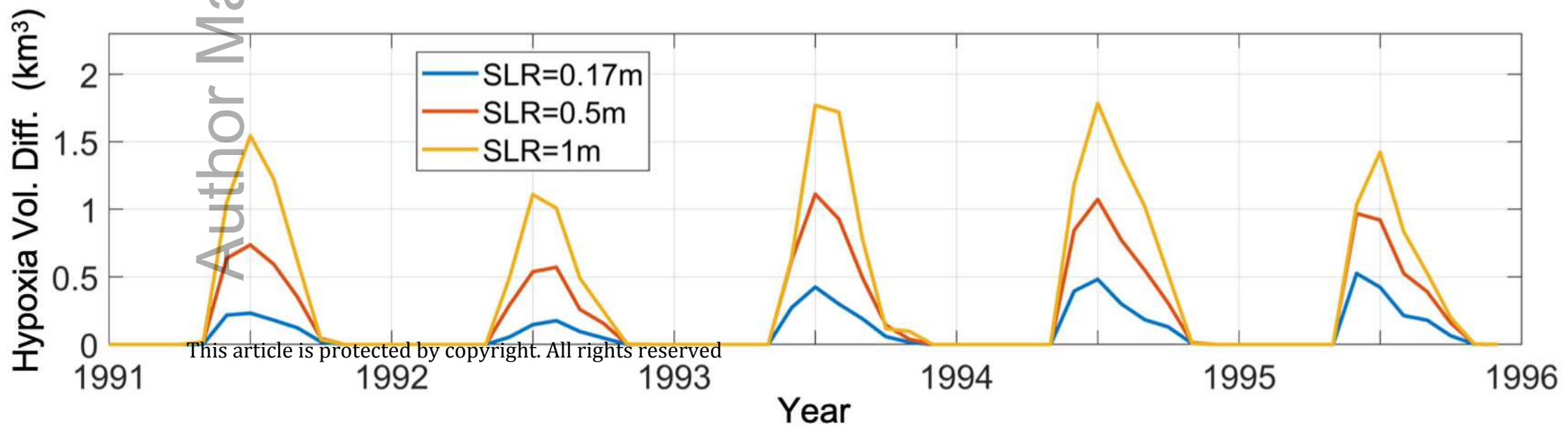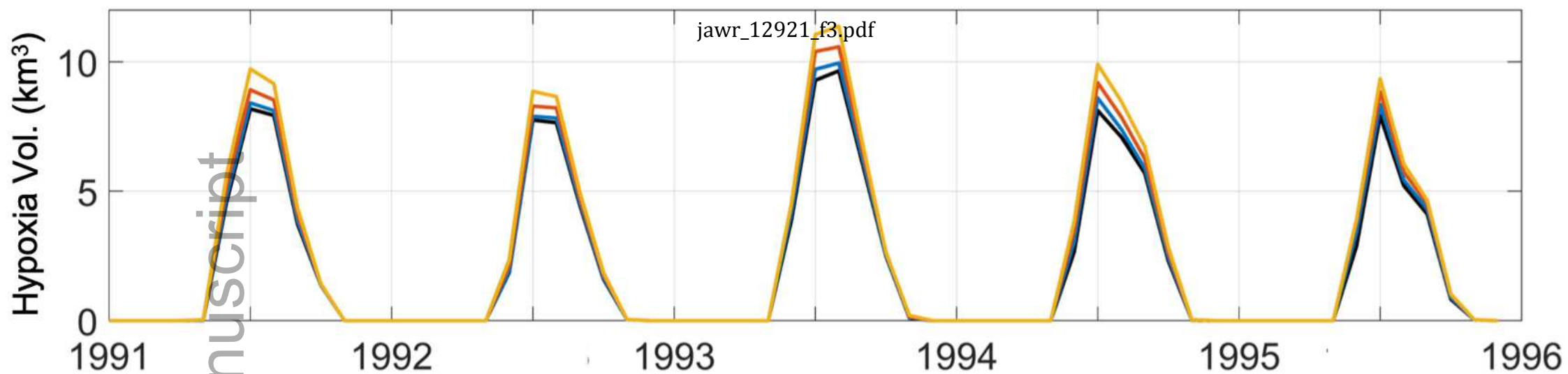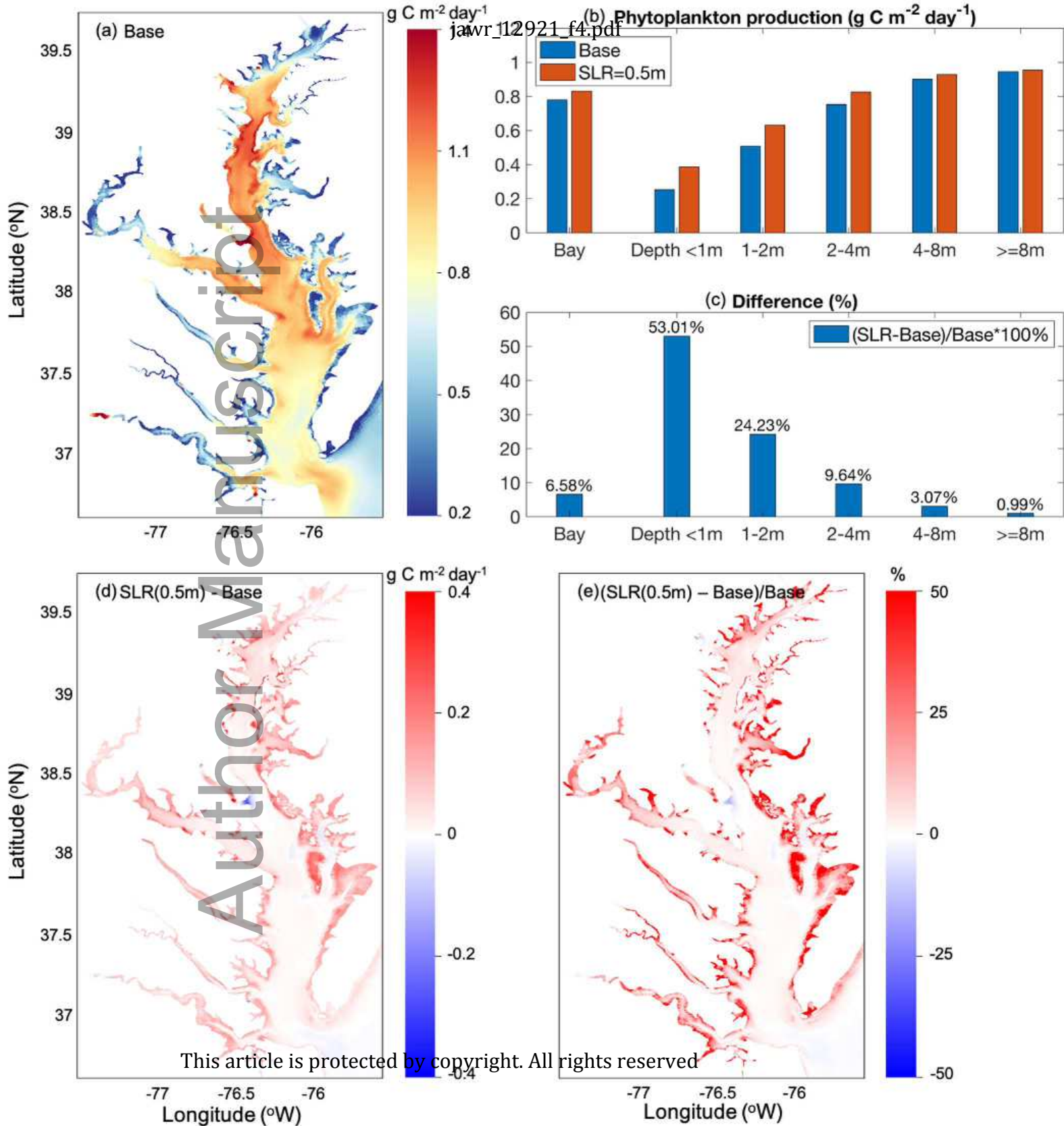761   nitrification, sulfide oxidation, and sediment oxygen demand. The averages are calculated for July.

762

763   Figure 9: Five-year averages of the contribution of each physical or biological process to the DO budget

764   in the area between cross-sections 7 and 8 (Figure 1) from June to August, for Base and SLR Scenarios.

765   (a) Diagram of the contribution of each process to the DO budget, where the width of the arrow is

766   generally proportional to the averaged contribution. Blue arrows indicate source terms of the DO budget

767   and yellow arrows indicate sink terms of the DO budget. (b) Bar plots of each term in the DO budget,

768   with the change percentages (SLR-Base)/Base labeled.

769

770   Figure 10: (a) Five-year averages of net nutrient flux for each month from 1991 to 1995 at cross-section 4

771   near Rappahannock Shoal (Figure 1); (b) Five-year averages of annual net nutrient flux from 1991 to

772   1995 at the 12 cross-sections Bay mouth to head. Panels (a, b-1) are total nitrogen, panels (a, b-2) are

773   dissolved inorganic nitrogen (DIN) and panels (a, b-3) are total inorganic phosphorus. Negative values

774   mean flux into the Bay while positive values refer to outflux.

775

776   Figure 11: (a) Difference of depth-averaged light attenuation coefficient (K_d) caused by SLR of 0.5 m

777   from April to June. Side labels in days indicate the estimated change of flushing time caused by an SLR

778   of 0.5 m for each major tributary. (b) The relative difference of bottom light supply from April to June
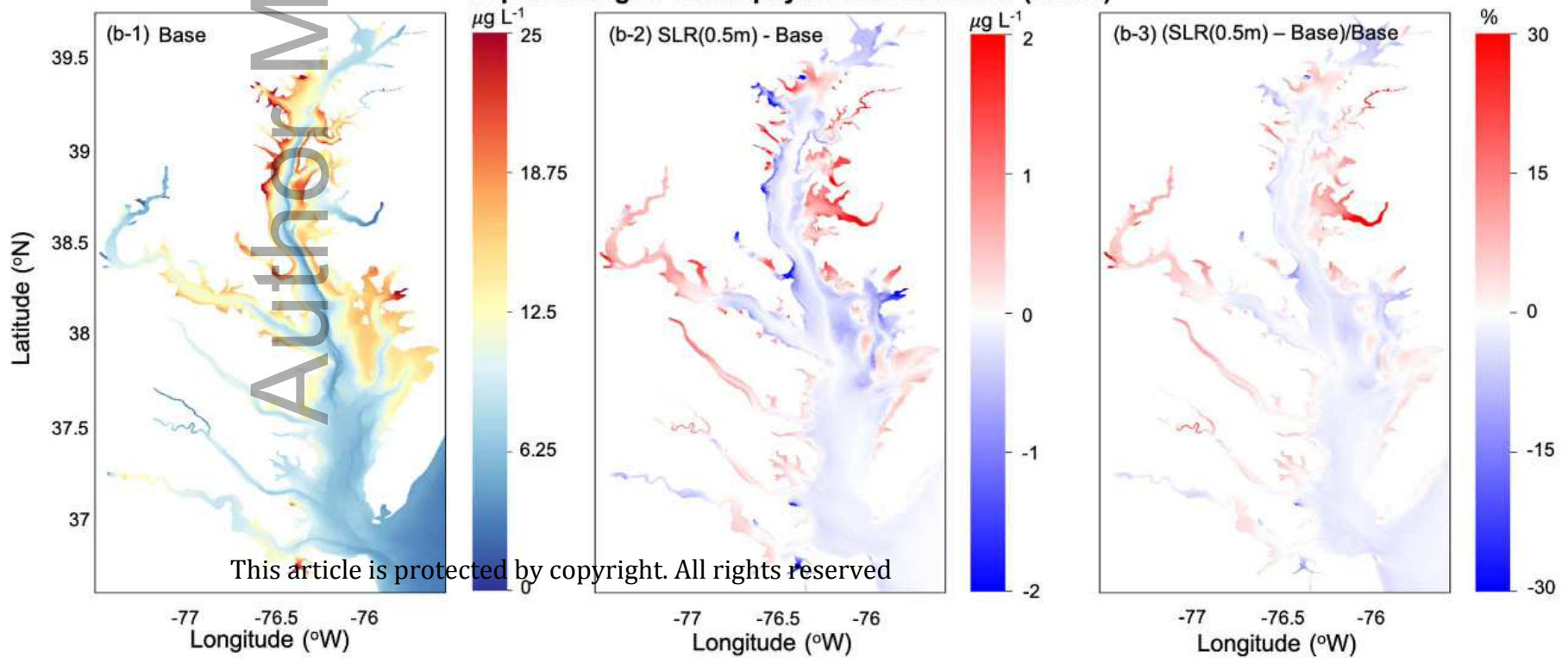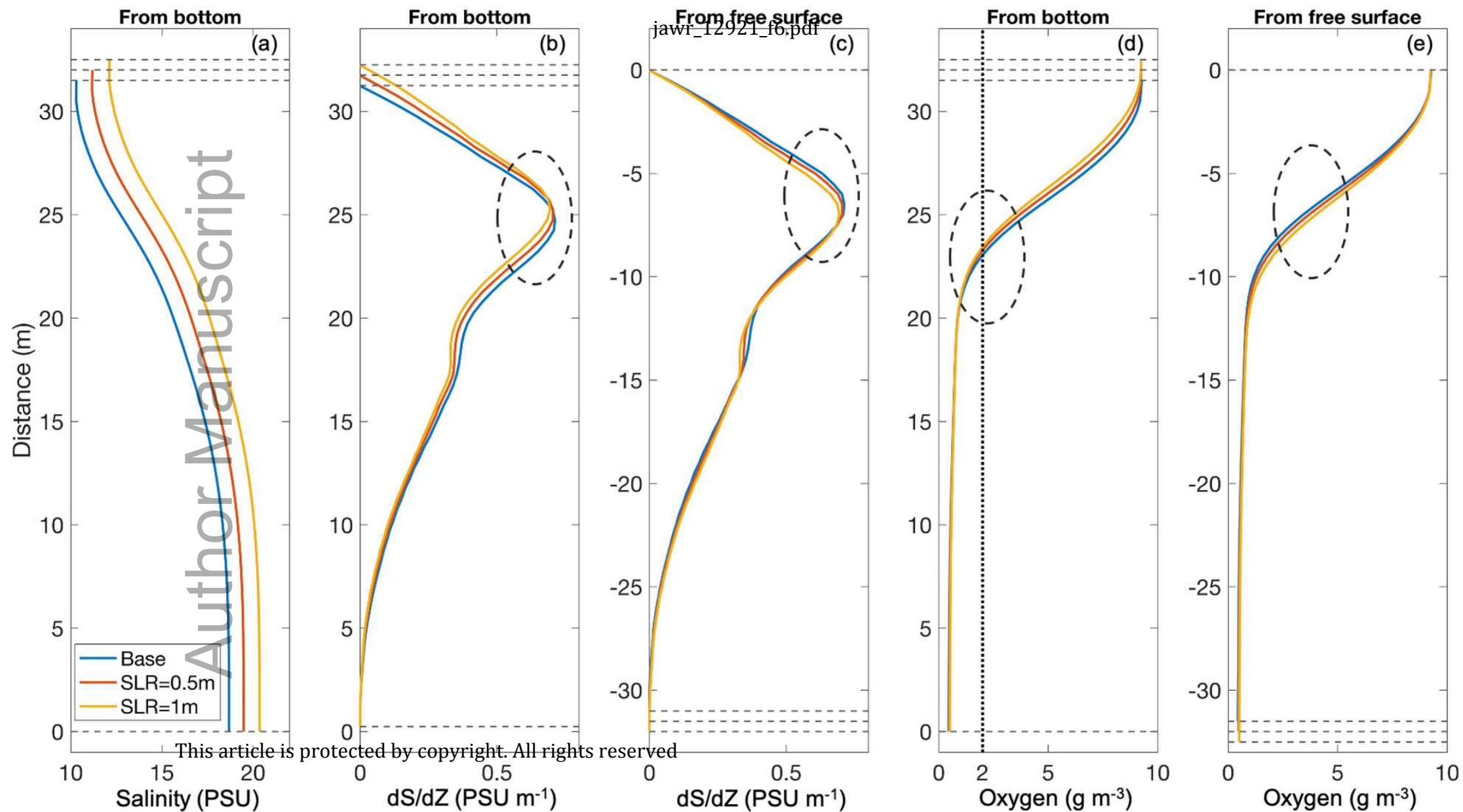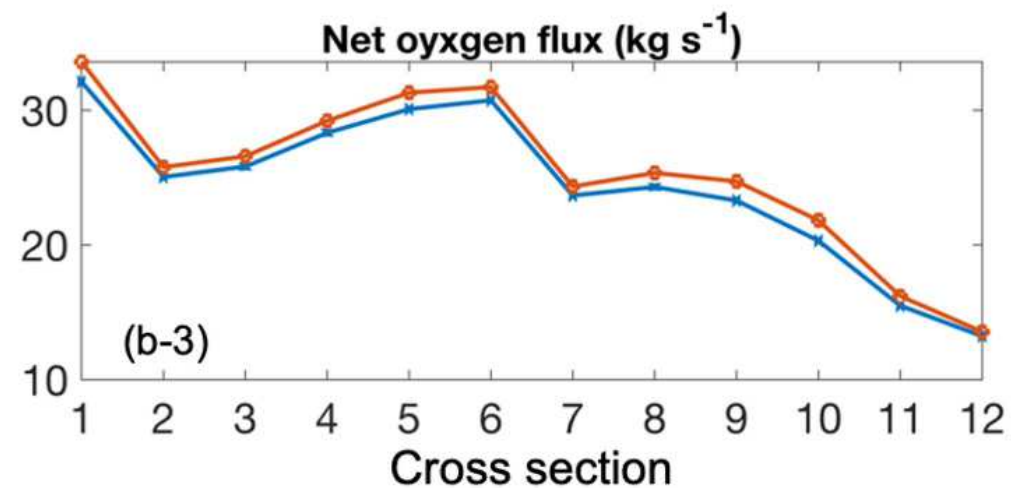
779   caused by SLR = 0.5 m on Base Scenario

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(a) Base

g C m^{-2} day^{-1}

(b) Phytoplankton production (g C m^{-2} day^{-1})

Base
SLR=0.5m

Bay   Depth <1m   1-2m   2-4m   4-8m   >=8m

(c) Difference (%)

(SLR-Base)/Base*100%

53.01%

24.23%

6.58%   9.64%   3.07%   0.99%

Bay   Depth <1m   1-2m   2-4m   4-8m   >=8m

(d) SLR(0.5m) - Base

g C m^{-2} day^{-1}

(e) (SLR(0.5m) - Base)/Base

%

Longitude (°W)

Longitude (°W)

Depth-integrated Chlorophyll a Concentration (Tchla)

(a-1) Base

(a-2) SLR(0.5m) – Base

(a-3) (SLR(0.5m) – Base)/Base

Depth-averaged Chlorophyll a Concentration (Mchla)

(b-1) Base

(b-2) SLR(0.5m) – Base

(b-3) (SLR(0.5m) – Base)/Base

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(a) From bottom

(b) From bottom

Local net rate of change= reaeration + photosynthesis - basal respiration - heterotrophic respiration – nitrification - sulfide oxidation - sediment oxygen demand

(c) From free surface

2.35   2.37

(d) From free surface

Base
SLR=1m

Distance (m)

Oxygen (g m^{-3})

Local net rate of change (g m^{-3} day^{-1})

Oxygen production (g m^{-3} day^{-1})

Total respiration (g m^{-3} day^{-1})

(a) Change in light attenuation coefficient (Kd) m⁻¹

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SLR(0.5m) - Base

-1 day

-1 day

+0.5 day

+2 day

-1 day

+4 day

+4 day

+2 day
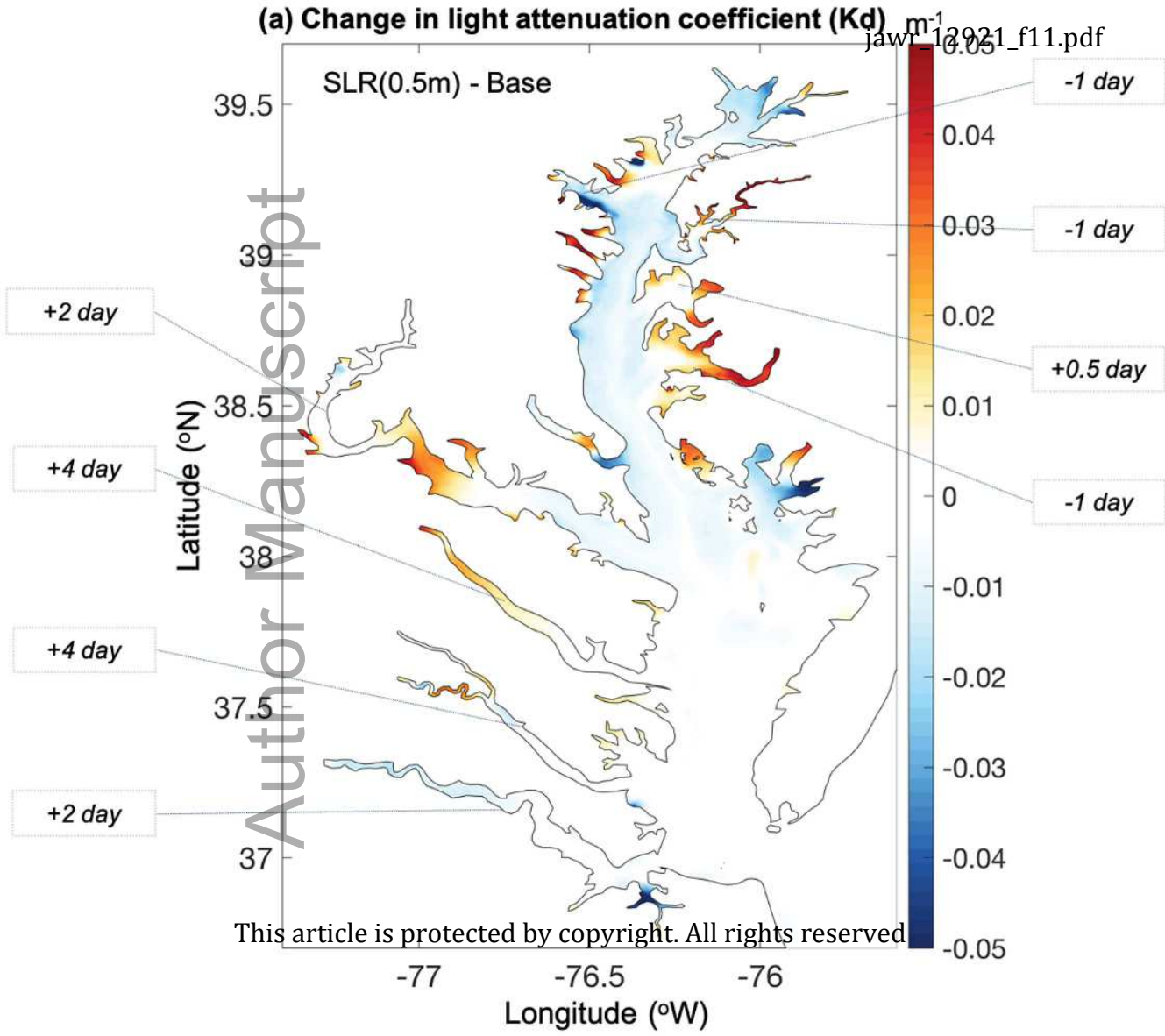
(b) Change in bottom light supply

(SLR(0.5m) − Base)/Base