



HAL
open science

Future intensification of summer hypoxia in the tidal Garonne River (SW France) simulated by a coupled hydro sedimentary-biogeochemical model

Katixa Lajaunie-Salla, Aldo Sottolichio, Sabine Schmidt, Xavier Litrico, Guillaume Binet, Gwenaël Abril

► **To cite this version:**

Katixa Lajaunie-Salla, Aldo Sottolichio, Sabine Schmidt, Xavier Litrico, Guillaume Binet, et al.. Future intensification of summer hypoxia in the tidal Garonne River (SW France) simulated by a coupled hydro sedimentary-biogeochemical model. *Environmental Science and Pollution Research*, 2018, 25 (32), pp.31957-31970. 10.1007/s11356-018-3035-6 . hal-02104899

HAL Id: hal-02104899

<https://hal.science/hal-02104899>

Submitted on 21 Feb 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

[Click here to view linked References](#)

1 **Future intensification of summer hypoxia in the Tidal Garonne River (SW France) simulated by a coupled**
2 **hydro sedimentary-biogeochemical model**

3 Katixa Lajaunie-Salla^{1,2}, Aldo Sottolichio¹, Sabine Schmidt¹, Xavier Litrico², Guillaume Binet², Gwenaël Abril^{1,3,4}.

4 ¹ Laboratoire EPOC, Environnements et Paléoenvironnements Océaniques et Continentaux UMR 5805, CNRS –
5 Université de Bordeaux – Pessac, France

6 ² LyRE, SUEZ research center, Bordeaux, France

7 ³ Departamento de Geoquímica, Universidade Federal Fluminense, Niterói, RJ, Brazil.

8 ⁴ Biologie des Organismes et Ecosystèmes Aquatiques (BOREA), Muséum National d'Histoire Naturelle, 61 rue
9 Buffon, 75231, Paris cedex 05, France.

10 **Corresponding Author:** katixa.lajaunie@gmail.com

11
12 **Acknowledgments**

13 This study was funded by the Aquitaine Region and LyRE (SUEZ research center) who provided a PhD grant to K.
14 Lajaunie-Salla. This research was also supported by the Cluster of Excellence COTE at the Université de Bordeaux
15 (ANR-10-LABX-45). The authors are also grateful to the MAGEST network for the availability of data and to the
16 SGAC and Bordeaux Metropole for providing urban effluent data and fruitful discussions.

17

18 **Abbreviations**

1 19 DO: dissolved oxygen
2 20 DOC: dissolved organic carbon
3 21 POC: particulate organic carbon
4 22 SSC: suspended sediment concentration
5 23 SO: sewage overflow
6 24 TGR: Tidal Garonne River
7 25 TMZ: turbidity maximum zone
8 26 WS: watershed
9 27 WW: wastewater
10 28 WWTP: wastewater treatment plant
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

30 **Abstract**

1
2 31 Projections for the next 50 years predict a widespread distribution of hypoxic zones in the open and coastal ocean due
3 32 to environmental and global changes. Previously, the Tidal Garonne River (SW France) has experienced few episodic
4 33 hypoxic events. However, predicted future climate and demographic changes suggest hypoxia could become more
5 34 severe near the city of Bordeaux in the next few decades. A 3D model, which couples hydrodynamic, sediment
6 35 transport and biogeochemical processes, is applied to assess the impacts of global and regional changes on
7 36 oxygenation in the turbidity maximum zone (TMZ) of the Tidal Garonne River during low-discharge periods. The
8 37 model predicts an intensification of summer hypoxia with an increase in temperature, a decrease in river flow or an
9 38 increase in the local population but not with sea level rise, which has a negligible impact on dissolved oxygen. We
10 39 tested different scenarios by combining these different factors according to the regional projections for 2050 and
11 40 2100. All simulations predict a spatial and temporal extension of summer hypoxia that needs to be considered by local
12 41 water authorities to impose management strategies to protect the ecosystem.

13
14
15 42 **Keywords:** future changes, hypoxia, modeling, Tidal Garonne River, wastewater, water quality
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

43 1 Introduction

1
2 44 Climate models predict a general decrease in dissolved oxygen (DO) and a widespread distribution of hypoxia in the
3 45 ocean (Cocco et al. 2013). Hypoxic waters are defined by a concentration of DO lower than 2 mg.L⁻¹ (or < 30%
4 46 saturation, e.g., Rabalais et al. (2010)). Hypoxia exposes marine organisms to environmental stress and could have
5 47 dramatic effects on coastal ecosystems; it increases fish mortality and consequently reduces the commercial fisheries
6 48 (de Jonge et al. 2002; Vaquer-Sunyer and Duarte 2008). The comparison of observations between 1976 and 2000 has
7 49 revealed a faster decline in DO concentrations in the coastal ocean than in the open ocean due to eutrophication
8 50 (Gilbert et al. 2010).

9
10 51 Global change promotes coastal hypoxia due to a combination of different mechanisms. First, an increase in
11 52 temperature decreases oxygen solubility in surface water and favors thermal stratification of the water column, which
12 53 limits reaeration (Conley et al. 2009; Lehmann et al. 2014). Global models predict for the year 2100 an increase in
13 54 oceanic water temperature of 2°C to 3°C (Cocco et al. 2013; IPCC 2013). In addition, Seneviratne et al. (2014)
14 55 showed that future heat waves will be more frequent and intense than today. Water warming also accelerates
15 56 biogeochemical processes that consume DO (Goosen et al. 1999). Second, global change affects coastal ecosystems
16 57 by decreasing river flow in some regions and, more precisely, through an intensification of summer droughts. A
17 58 reduction in summer river discharge is in fact due to a combination of climatic and anthropogenic factors including
18 59 lower precipitation, hydroelectric power dams and irrigation within watersheds (Boé and Habets 2014). The river
19 60 flow change could alter coastal estuarine tidal currents, sediment transport, and the transit and mineralization of
20 61 terrestrial organic material in estuaries (Abril et al. 1999; Howarth et al. 2000). Third, climate models project a sea
21 62 level rise between 0.5 and 1 m in 2100 (IPCC 2013). In estuaries, a consequence could be an increased propagation of
22 63 the tide, leading to an upstream extension of the marine influence (Robins et al. 2016).

23
24
25 64 These climatic changes interact with the population and activity development in the coastal zone. Human activities
26 65 enrich coastal waters with nutrients and organic matter (OM) and contribute to hypoxia through eutrophication (Diaz
27 66 and Rosenberg 2008; Cotovicz et al. 2017). The organic matter of wastewater effluents is very labile and is quickly
28 67 degraded, which consumes DO (Lajaunie-Salla et al. 2017). Wastewaters are also a source of ammonium that is
29 68 nitrified in waters, which also consumes DO. The development of large cities in coastal areas thus has negative
30 69 impacts on water quality (Zhao et al. 2015). For example, hypoxia events have been recorded in estuaries with nearby
31 70 important urban areas such as the Thames Estuary (Tinsley 1998), the Yangtze Estuary (Li et al. 2002), and the
32 71 Chesapeake Bay (Hagy et al. 2004).

33
34
35
36
37 72 In macrotidal estuaries, summer hypoxia is usually associated with the presence of a turbidity maximum zone (TMZ),
38 73 which limits primary production and favors organic matter degradation (Thouvenin et al. 1994; Talke et al. 2009;
39 74 Etcheber et al. 2011). Deoxygenation in a TMZ is the result of complex interactions between processes consuming
40 75 oxygen, such as the degradation of organic matter or nitrification, and processes supplying oxygen, such as gas
41 76 exchange at the water-air interface or the advection of DO-rich waters from upstream and downstream (Soetaert et al.
42 77 2006; Talke et al. 2009; Lanoux et al. 2013). These processes are highly variable in time, depending on
43 78 hydrodynamics, particle settling/resuspension with semidiurnal and fortnightly tidal cycles (Abril et al. 1999), and
44 79 sporadic storm overflow of urban water (Etcheber et al., 2011; Lanoux et al., 2013). Global and local changes are
45 80 likely to increase temperature and wastewater discharges, to modify river flow and TMZ dynamics and, therefore, to
46 81 amplify hypoxia events in macrotidal estuaries. However, this hypothesis needs to be quantified in order to allow
47 82 preventive strategy management. For this purpose, it is necessary to estimate the expected minimum DO levels
48 83 (DO_{min}), the duration and extension of future hypoxia events, and to identify the contribution of each forcing factor.
49 84 This requires a model coupling hydrodynamic, sediment transport and biogeochemical processes to predict DO
50 85 variations according to the environmental conditions (Talke et al. 2009; Peña et al. 2010; Testa et al. 2014).
51 86 Numerical models are the only method to assess DO sensitivity to forcing factor variations and to test DO changes
52 87 under scenarios of climate and local changes (Justić et al. 2007; Vanderborgh et al. 2007; Cox et al. 2009; Wild-
53 88 Allen et al. 2009; Skerratt et al. 2013). For example, a modeling study has shown that climate change could increase
54 89 hypoxia events in the Oyster Grounds (North Sea) and that DO_{min} could decrease by 0.8 mg.L⁻¹ in 2100 (Meire et al.
55 90 2013). Such numerical models are also management tools to help water policymakers maintain good water quality in
56 91 coastal environments (Kemp et al. 2009).

92 The objective of this work is to evaluate the potential impacts of global and local changes on the oxygenation of the
93 Tidal Garonne River (SW France). Continuous monitoring data (Lanoux et al. 2013; Schmidt et al. 2017) have
94 revealed that the Tidal Garonne River (TGR) had previously experienced few hypoxic events. However, continuing
95 changes (temperature increase, increase in TMZ duration and concentration, development of the Bordeaux
96 Metropolis) suggest that summer hypoxia near the city of Bordeaux could be more pronounced in the next decades. In
97 this work, we use a recently developed 3D numerical model of dissolved oxygen (Lajaunie-Salla et al., 2017) to
98 estimate the influence of the main identified factors likely to evolve in the next 50–100 years (fluvial discharge,
99 temperature, urban development, and sea level rise) that may affect DO. The aim of the study is to simulate the
100 probable future summer oxygenation according to the influence of these pressures, considered alone or combined, and
101 to discuss the future risk of hypoxia in the TGR.

102 2 Materials and Methods

103 2.1 Study Area

104 The Gironde Estuary, located in southwestern France on the Atlantic coast, is formed by the confluence of the
105 Garonne and the Dordogne Rivers. This macrotidal fluvio-estuarine system is characterized by the presence of a TMZ
106 with suspended sediment concentration (SSC) $> 1 \text{ g.L}^{-1}$ (Allen 1972). The TMZ is formed by the so-called tidal
107 pumping effect (Uncles et al., 1985), consisting of mud trapping due to tidal asymmetry, i.e., the flood phase is
108 shorter but with more intense currents than the ebb phase (Allen et al. 1980). The TMZ moves seasonally along the
109 estuary axis according to fluvial discharges. In summer, when river flows decrease, the TMZ moves toward the tidal
110 Dordogne and Garonne rivers, i.e., the portions of the rivers where the tidal waves propagate. A TMZ is present in the
111 Tidal Garonne River between 3 and 8 months per year (Jalón-Rojas et al. 2015).

112 The Garonne River is the main tributary of the Gironde Estuary: it drains a watershed of 55 000 km²; the mean annual
113 discharge is 600 m³.s⁻¹, ranging between extreme daily values of 54 and 4720 m³.s⁻¹. The Bordeaux Metropolis is
114 located 25 km from the confluence. The sewage system of the metropolis drains an urban surface area of 578 km² and
115 serves a population estimated at 749 595 inhabitants in 2015. Two wastewater treatment plants (WWTPs, Clos de
116 Hilde and Louis Fargue) continuously discharge treated wastewater into the TGR (Fig. 1); in addition, nine sewage
117 overflows (SOs) occasionally discharge untreated wastewater into the TGR.

118 DO levels in the TGR are strongly influenced by water temperature, river flow, TMZ occurrence and urban effluents
119 (Lajaunie-Salla et al., 2017; Lanoux et al., 2013; Schmidt et al., 2017). Hypoxia events preferentially occur during
120 summer, when water temperature is increased to 24°C, a few days after a spring tide (Lanoux et al., 2013), as the
121 result of an increased oxygen demand followed by reduced reaeration due to high turbidity (Lajaunie-Salla et al.,
122 2017). Lajaunie-Salla et al. (2017) highlighted that wastewater effluents during deoxygenation events decreased the
123 DO_{min} at Bordeaux by 10 %sat ($\sim 0.8 \text{ mg.L}^{-1}$). The projected development of Bordeaux Metropolis will lead to an
124 increase in effluents, which would contribute to an intensification of the summer hypoxia in the Tidal Garonne River.
125 To limit this risk in the TGR, a challenging objective of a minimum daily mean DO of 5 mg.L⁻¹ has been enforced by
126 the local water agency to attain a good ecological status. Schmidt et al. (2017) highlighted that an increase of 2°C in
127 summer leads to a daily average DO level below this threshold.

128 2.2 Model description

129 We used the three-dimensional SiAM-3D model coupling hydrodynamic, sediment transport and biogeochemical
130 models recently developed by Lajaunie-Salla et al. (2017). The hydrodynamic and sediment transport models, initially
131 developed by Brenon and Hir (1999) and Cugier and Le Hir (2002) for the Seine Estuary, were implemented in the
132 Gironde Estuary by Sottolichio et al. (2000). The hydrodynamic model is based on the Navier-Stokes equations under
133 the Boussinesq approximation and hydrostatic assumptions. The transport model solves the advection/dispersion
134 equations for dissolved and particulate variables, i.e., suspended sediment, salinity and biogeochemical variables. For
135 suspended sediment, the main cohesive sediment processes are taken into account to appropriately reproduce the
136 dynamics of the TMZ (Van Maanen and Sottolichio, in revision). The hydrodynamic model is forced by tidal
137 elevation at the shelf and by daily river flow of the Garonne and Dordogne Rivers at the upstream boundary (from
138 French national hydrological data, www.hydro.eaufrance.fr).

139 We recently implemented the biogeochemical model for the Gironde Estuary to simulate biogeochemical processes
140 that produce or consume oxygen in the water column, taking into account different types of dissolved and particulate
141 organic matter (Lajaunie-Salla et al., 2017). These biogeochemical processes include the degradation of organic
142 matter (mineralization of organic carbon and ammonification using the C/N ratio), nitrification, photosynthesis,
143 respiration and mortality of phytoplankton, and DO gas exchange with the atmosphere. The model includes 11 state
144 variables: dissolved oxygen (DO), ammonia (NH₄⁺), nitrate (NO₃⁻) and particulate and dissolved organic carbon (POC
145 and DOC) from the watershed (POC from litter, DOC from rivers) and wastewater (from wastewater treatment plants
146 and from sewage overflows), and POC from phytoplankton and detritus. The biogeochemical model requires inputs of
147 the seasonal water temperature (data from MAGEST, a high-frequency water quality monitoring network,
148 <http://www.magest.u-bordeaux1.fr>), wind and incident light intensity (from French meteorological office, Météo
149 France). Urban wastewater discharge points are included in the model based on measurements provided by the
150 operator of the sewer system, both regarding rejects of WWTP and SO (Fig.1).

151 The computational domain of the model extends from the 200 m isobath on the continental shelf to the upstream
152 limits of the tidal propagation, at 170 km from the mouth (La Réole and Pessac-sur-Dordogne; Fig. 1) (Sottolichio et
153 al. 2000). The 3D model is implemented for the Gironde Estuary on an irregular Cartesian grid with 2421 wet cells in
154 the horizontal plane. In the vertical plane, the water column is split into 12 layers. The grid cell lengths progressively
155 increase in the upstream direction from 500 m to 2 km. In the TGR, the width is described by three cells in the
156 downstream section and by one cell in the upstream section. However, the average width and depth are rigorously
157 well represented at all the cross sections along the tidal rivers, ensuring a good calculation of the oscillating volumes
158 of water and tidal currents.

159 The originality of this biogeochemical model is to rely on extensive local data, particularly in the Tidal Garonne
160 River. Except for nitrification, the degradation kinetics of different organic matter were measured for mixtures of
161 estuarine turbid waters, riverine waters rich in phytoplankton or terrestrial litter, and domestic waters from SOs and
162 WWTPs (Veyssey 1998; Lemaire et al. 2002; Etcheber et al. 2007; Lanoux et al. 2013).

163 In addition to temperature, the MAGEST network has recorded turbidity, salinity and DO every 10 minutes at
164 different sites since 2005 (Fig. 1). The model was compared with data available for the TGR and tested on the basis of
165 three criteria: i/ the ability to reproduce the observed DO variability at a seasonal scale; ii/ the ability to reproduce the
166 spring-neap tidal cycle; and iii/ a statistical evaluation based on the Willmott skill score (WSS, Willmott (1982)). In
167 summary, the model performed well (WSS > 0.7) in the lower TGR around Bordeaux but had lower performance
168 levels at the upper section (WSS < 0.5) (for details, see Lajaunie-Salla et al. (2017)).

169 2.3 Reference year

170 The simulations were compared to a reference simulation, which corresponds to the year 2006 (Fig. 2). This year was
171 chosen as a relatively critical reference simulation from the point of view of river discharge, temperature and hypoxia.
172 The summer water temperature was on average 24.6°C, with a maximum of 29.4°C during a 21-day heat wave event.
173 The mean summer Garonne River flow was 145 m³.s⁻¹ (minimum of 54 m³.s⁻¹) with 60 continuous days of river flow
174 below 100 m³.s⁻¹. In 2006, WWTP and DO discharges of urban water to the Garonne River were 51.2 and 9.6 Mm³,
175 respectively.

176 2.4 Scenarios

177 Different simulations were carried out to study the DO sensitivity of the Tidal Garonne River to the evolution of the
178 main forcing factors: water temperature, river flow, sea level and population growth of Bordeaux Metropole. Present-
179 day trends were used to extrapolate the expected values for 2050 and 2100:

- 180 - the water temperature increases following a mean rate of 0.06°C year⁻¹ (Le Treut 2013), suggesting an increase
181 of +2°C in 2050 and +5°C in 2100;
- 182 - the mean Garonne river flow is expected to be reduced by 30 to 40% in 2050 and by 50 to 60% in 2100
183 (Etcheber et al. 2013; Schmidt et al. 2016);

- in the Bay of Biscay, the sea level has increased at a mean rate of 2 mm year⁻¹ over the last few decades and should increase by 0.14 to 0.24 m in 2050 and by 0.28 to 0.48 m in 2100 (Le Treut, 2013);
- Bordeaux Metropolis is taking advantage of its attractiveness by implementing a dynamic policy to develop the city with the objective of reaching 1 million inhabitants by 2030 and then stabilizing the population until the end of the 21st century. (<http://www.bordeaux-metropole.fr>).

These expected trends were used to perform 14 simulations, including sensitivity analysis and two combined scenarios (Tab. 1), as follows:

- four simulations to test the impact of increasing temperature by adding a constant value (2, 3, 4 and 5°C) to the reference year (2006);
- four simulations to test the impact of a decrease in the Garonne flow, consisting of 78 days of constant river flow (100, 80, 60 and 40 m³.s⁻¹) during the driest season, from July 15 to September 30. The selected values correspond to a decrease in the reference summer flow by 24%, 36%, 46% and 57%, respectively.
- three simulations to test the impact of sea level rise by +10, +20 and +40 cm.
- one simulation to test the impact of the increase in population assuming an associated increase in wastewater discharge by 50% and in a theoretical case of uncontrolled increase of urban discharges.
- the four forcing factors were combined to produce academic scenarios close to the expected scenarios for the years 2050 and 2100 (Table 1).

Each of the 14 simulations were run over 10 months, from January 1 to October 31. To form a TMZ, a stock of deposited mud was introduced in the estuary at the start of each simulation, which was easily resuspended during the first tidal cycle (see Lajaunie-Salla et al., 2017 for details). The mass of the TMZ was therefore the same for all the simulations, including those with a decreasing summer river flow, which did not significantly change the total mass of mud in the estuary. We used three quantitative indicators to assess the oxygenation state of the TGR waters: (1) the minimum DO value attained (DO_{min}); (2) the number of hypoxia days, i.e., DO < 2 mg.L⁻¹; and (3) the rates of biogeochemical processes consuming DO near Bordeaux and Portets, averaged for the summer months. The grid cells in front of Bordeaux and Portets were chosen because Bordeaux is under the impact of urban effluents and Portets represents the upstream presence of a TMZ.

3 Results and Discussion

3.1 Reference year

The reference simulation highlights the occurrence of the TMZ at Bordeaux from June to September, a summer DO decrease and two events of low DO, which were close to hypoxia (end of July and mid-September) (Fig. 2b). In fact, in summer, when the river flow decreases, the TMZ arrival in the tidal Garonne is always accompanied by a simultaneous decline in DO in Bordeaux waters (Etcheber et al., 2011; Schmidt et al, 2017). The lowest DOs occur at the end of July during a period characterized by a persistent low river flow, a heat wave and a sewage overflow discharge (Fig. 2). Moreover, as detailed in Lajaunie-Salla et al. (2017), the reference simulation shows that lower DO levels occur a few days after the spring tide peak and the deoxygenated zone moves between PK-10 and PK-20. In fact, at spring tide, the highest tidal currents promote resuspension and advection of suspended sediment, and the TMZ moves upstream of Bordeaux. Then, heterotrophic processes are favored and DO depletion is more intense in the upper TGR section than near Bordeaux. At neap tides, suspended matter settles, as well as organic matter coming from the watershed, and consequently reduces the mineralization of organic matter in the water column. Considering that at Bordeaux 32% of the DO consumption is due to wastewater effluents versus 4% at Portets (Lajaunie-Salla et al., 2017), at neap tides, DO depletion is more intense in Bordeaux waters than in the upper section of the TGR. In fact, in the area of Bordeaux, nitrification processes account for 19% of the DO consumption, and the watershed, 49%. Whereas in the area of Portets, nitrification accounts for 1% and the watershed for 95% of the DO consumption. At Bordeaux, the hypoxia threshold is not reached (DO > 2 mg.L⁻¹); however, at Portets, the hypoxia event lasted 3 days during this reference year (Tab. 2 & Fig. 4c).

3.2 Impact of increasing temperatures

230 The impact of an increase in temperature is negligible during winter and spring. From June, modeled scenarios show
1 231 a reduction in DO_{min} at Bordeaux and Portets when the temperature is higher than 20°C (Fig. 3; Tab. 2). For a
2 232 temperature increase of 5°C, at Bordeaux station, DO_{min} decreases from 28.9 to 14.3 %sat, and 26 days of hypoxia are
3 233 simulated, whereas at Portets, DO_{min} decreases from 22.4 to 15.8 %sat, and 11 days of hypoxia are simulated (Tab. 2).
4 234 At Bordeaux station, the deoxygenation observed in 2006 is amplified to hypoxia at the end of July when the
5 235 temperature increases by +2°C. An increase of +4°C is required to observe hypoxia in mid-September (Tab. 2 and
6 236 Fig. 3a).

8
9 237 In the area near Bordeaux, for the scenario of +2°C, DO consumption rates by nitrification and the mineralization of
10 238 urban OM and watershed OM increase by 12%, 7% and 4%, respectively, whereas with an increase of 5°C, the
11 239 consumption rates increase by 28%, 11% and 16%, respectively (Tab. 3). The results highlight that an increase in
12 240 temperature affects biogeochemical processes and accelerates reactions. However, in the area of Portets, although the
13 241 nitrification processes increase with temperature, DO consumption by urban OM decreases. This is explained by a
14 242 more intense degradation of the urban OM close to its source, i.e., Bordeaux, leading to a lower amount of OM being
15 243 transported to Portets.

17 18 244 3.3 Impact of population growth

19
20 245 The increase in wastewater discharge with demographic growth also results in lower DO values compared with those
21 246 of the reference year only in summer (Fig. 3b). At Bordeaux, the model simulates 3 days of hypoxia with a DO_{min} of
22 247 23.6 %sat, whereas at Portets, urban effluents have less impact because DO_{min} decreases by only 1 %sat (DO_{min} = 21.3
23 248 %sat, Tab. 2). Close to Bordeaux, DO consumption due to urban OM degradation and nitrification increases by 50%
24 249 and 42%, respectively (Tab. 3). At Portets, the same processes increase by 65% and 7%, respectively (Tab. 3),
25 250 whereas the impact of the mineralization of OM from the watershed remains constant (Tab. 3). Population growth in
26 251 Bordeaux Metropole moderately affects the oxygenation status of the TGR, despite the increase in urban labile
27 252 organic matter inputs and then in DO consumption.

29 30 253 3.4 Impact of a long period of low river flow

31
32 254 Recent observations have shown an influence of the multidecadal discharge decrease on the intensification of the
33 255 TMZ in the Tidal Garonne River (Jalón-Rojas et al., 2015). The model was thus used to test whether a discharge
34 256 decrease also influences DO. The model simulates a marked saline intrusion (>4 at Bordeaux) and an obvious TMZ
35 257 intensification and extension in the upper section of the TGR with a long period of low to very low water discharge
36 258 (Fig. 4). DO_{min} decreases and the number of hypoxic days increases with the river flow reduction (Fig. 4; Tab. 2).
37 259 This is explained by the TMZ development and its high SSC, which favors DO consumption by heterotrophic
38 260 processes. Indeed, the strongest deoxygenation occurs when the river flow is the lowest and SSC is the highest (Fig.
39 261 4o). In the case of a discharge of 40 $m^3.s^{-1}$, a DO_{min} of 13.5 %sat and 8 %sat and 13 and 52 days of hypoxia are
40 262 simulated at Bordeaux and Portets, respectively (Tab. 2). However, the comparison of low river flow scenarios
41 263 suggests that heterotrophic processes are not the only controlling factor of DO distribution (Fig. 4). First, in the
42 264 reference simulation, a short event of increasing river flow occurred at the end of July, which resulted in a temporary
43 265 downstream relocation of a low-DO core near Bordeaux (Fig. 4c). For 100 $m^3.s^{-1}$, the hypoxia is also located close to
44 266 Bordeaux, whereas the waters of the upper tidal river (PK -10 to -20) are still reoxygenated by fluvial inputs (Fig. 4f).
45 267 In contrast, for the lowest simulated river flow (40 $m^3.s^{-1}$), the dilution of the upper Tidal Garonne River waters by
46 268 oxygenated freshwaters becomes negligible, and then, several successive hypoxia events spread from PK-10 to PK-25
47 269 (Fig. 4o). This indicates that the upper section could be reoxygenated by the input of oxygenated advected freshwater.
48 270 At Bordeaux, hypoxia is reached for the four simulated scenarios, whereas at Portets, it occurs only when the river
49 271 discharge is lower than 60 $m^3.s^{-1}$ (Tab. 2).

53
54 272 We calculated the input of oxygenated freshwater (with a typical DO concentration of approximately 90 %sat)
55 273 introduced by the Garonne River into the tidal river during a semidiurnal tidal cycle: the volume is 4.3 $10^6 m^3$ for a
56 274 discharge of 100 $m^3.s^{-1}$, and 1.7 $10^6 m^3$ for 40 $m^3.s^{-1}$. This represents 3.8 and 1.5% of the average water volume
57 275 between La Réole (the river end-member) and Bordeaux; and 22% and 9.3% of the averaged volume between La
58 276 Réole and Portets (Fig. 1). The time to renew half of the water volume is shorter at Portets (between 1.1 and 2.7 days)
59 277 than at Bordeaux (from 6.7 to 16.3 days). At Bordeaux, a water initially at 30 %sat would increase after one tidal
60

278 cycle by +2.3 %sat for a river flow of $100 \text{ m}^3 \cdot \text{s}^{-1}$, but only by +0.9 %sat for a river flow of $40 \text{ m}^3 \cdot \text{s}^{-1}$ (Portets, +13.2
1 279 %sat for $100 \text{ m}^3 \cdot \text{s}^{-1}$ and +5.6 %sat for $40 \text{ m}^3 \cdot \text{s}^{-1}$). Then, the fluvial DO renewal effect is reduced when the river flow
2 280 decreases.

3
4 281 The last consequence of a lower fluvial discharge is an increase in DO consumption by nitrification and
5 282 mineralization of OM from wastewater, whereas there is a decrease in the mineralization of OM from watersheds near
6 283 Bordeaux and Portets (Tab. 3). This is a consequence of i/ a lower downstream dispersion of urban inputs, which tend
7 284 to remain concentrated near Bordeaux and ii/ an upstream displacement of the TMZ to the upper section (PK-25, Fig.
8 285 4). The strongest deoxygenation observed for the simulation of a river flow of $40 \text{ m}^3 \cdot \text{s}^{-1}$ is thus a consequence of
9 286 combined factors: reduced wastewater dispersion and dilution with oxygenated freshwaters and an increase in
10 287 heterotrophic processes in the uppermost section where large amounts of fine sediments are trapped during summer.

13 288 3.5 Impact of sea level rise

14
15 289 Finally, we tested the potential impact of sea level rise (SLR) on DO. The simulations do not show a clear trend
16 290 among the 3 scenarios (+10 cm; +20 cm; +40 cm) (Fig. 5). In the simulation SLR+10 cm, the TMZ is intensified and
17 291 DO_{\min} decreases from 28.9%sat to 25.6%sat at Bordeaux, but never reach the hypoxia threshold (Tab.2). At Portets
18 292 the impact seems more critical with a DO_{\min} decline from 22.4 %sat to 15.0 %sat, reaching 5 days of hypoxia
19 293 (instead of 3 days for the reference year, Tab.2). But, surprisingly, in the simulation SLR+20 cm, the trend is
20 294 reversed: the TMZ is attenuated and DO_{\min} remains similar to the reference year values, with only two days of
21 295 hypoxia at Portets (Tab.2). For the scenario SLR+40 cm, there is an amplification of deoxygenation at Portets: DO_{\min}
22 296 decreases at 14.7% and hypoxia occurs 6 days (Tab.2). The intensification of hypoxia for a sea level rise of 10 cm and
23 297 40 cm is explained by an increase of the tidal range and asymmetry in the Tidal Garonne River due to an overall
24 298 higher depth, as observed in other urbanized estuaries (Winterwerp et al., 2013). These changes in tide are likely to
25 299 increase the tidal pumping effect and therefore sediment resuspension and upstream transport (Winterwerp et al.,
26 300 2013). For the simulation SLR+20 cm, flood dominance increases also, but simulated SSC decreases, which creates
27 301 better conditions for oxygenation. As tidal currents are not expected to reduce, we hypothesize this could be attributed
28 302 to a dilution effect due to a larger water volume in the tidal Garonne section (compared to SLR+10 cm). Indeed, the
29 303 fate of suspended sediments in the water column of shallow tidal rivers results from a complex interaction between
30 304 the tide, river flow, sediment supply and morphology (Robins et al., 2016). In particular, the evolution of the flood
31 305 dominance depends on the relative importance of the local tidal range, the cross-section averaged depth, and the
32 306 presence of channel and intertidal flats (Dronkers, 1986, Friedrichs et Aubrey, 1988). For the TGR, a sea level rise of
33 307 approximately 20 cm seems to be a threshold value from which the effects of morphology and estuarine volume
34 308 counteract the effects of increased tidal pumping and flood dominance. Then, at higher SLRs, the amplification of
35 309 tidal pumping prevails over the dilution effect. Unfortunately, the description of lateral flats and channel bathymetry
36 310 in the present model is not robust enough to make conclusions for these opposing effects. This implies the
37 311 implementation of a morphodynamic model that more precisely describes the lateral flats and, eventually, the
38 312 morphological evolution, which is far beyond the scope of the present study. Indeed, simulated results demonstrate
39 313 this factor does not induce major changes in oxygenation compared with temperature and fluvial discharge changes
40 314 (Tab. 2).

46 315 3.6 Scenarios of the combined effects for 2050 and 2100

47
48 316 To produce more realistic simulations, we combined the forcing factors to produce expected scenarios for 2050 and
49 317 2100. When compared to the reference scenario (Fig. 6a), the 2050 scenario shows no upstream TMZ migration nor
50 318 extension, only a slight increase in SSC and a longer duration until October near Bordeaux (Fig. 6c). Simultaneously,
51 319 there is a clear DO decrease and an increase in the hypoxia duration in Bordeaux (29 days). Conversely, the hypoxia
52 320 threshold is never attained at Portets (Tab. 2). This is caused by two processes: the summer river flow is fixed at 80
53 321 $\text{m}^3 \cdot \text{s}^{-1}$, water in the upper sections is still reoxygenated by dilution with freshwater (Fig. 4i/6d), and there is no TMZ
54 322 intensification (Fig. 6c).

55
56
57 323 For the 2100 scenario, the TMZ is far more concentrated until October compared with the reference, and it extends up
58 324 to Portets in September (Fig. 6e). In the meantime, high and continuous DO depletion occurs over the entire section,
59 325 from PK-15 to PK-25 (Fig. 6f). The extremely low summer river flow ($40 \text{ m}^3 \cdot \text{s}^{-1}$) promotes an increased intensity and

326 duration of the TMZ. In addition, the input of well-oxygenated freshwater is limited, as already discussed in section
1 327 3.4. The duration of hypoxia increases at Bordeaux and Portets (91 and 78 days, respectively, Tab. 2). DO in the TGR
2 328 decreases far below the threshold of 2 mg.L⁻¹ (DO_{min} at Bordeaux and Portets is less than 0.3 mg.L⁻¹) and almost
3 329 reaches anoxia in early August (Tab. 2). Then, the hypoxia area extends over 40 km during the entire summer season.
4 330 As these low DO values are modeled for surface waters, we assume a “dead zone” (Diaz and Rosenberg, 2008) could
5 331 appear in the Tidal Garonne River near Bordeaux.

7 332 The average summer rates of biogeochemical processes impacting DO near Bordeaux and Portets show a significant
8 333 increase (more than twice) in nitrification and degradation of urban OM in the 2050 and 2100 simulations due to the
9 334 combined effect of increased temperature and population growth (Tab. 3). An increase in DO consumption rates of
10 335 urban substrates (ammonia and urban matter) occurs for both scenarios (Tab. 3): in Bordeaux close to the urban
11 336 source and at Portets 25 km upstream. In the case of Bordeaux, DO consumption by wastewater organic matter is
12 337 higher for the 2050 scenario than for 2100, probably due to a stronger upstream dispersion of urban effluents from
13 338 Bordeaux to Portets (Tab. 3).

16 339 The presence of a permanent summer hypoxia may cause serious ecological problems in the TGR, and in particular
17 340 could perturb benthic and pelagic fauna (Diaz and Rosenberg 2008; Vaquer-Sunyer and Duarte 2008). A permanent
18 341 seasonal hypoxia could have serious repercussions for the downstream migration of juvenile fishes (shad or sturgeon)
19 342 (Lanoux et al. 2014). These ecological problems could also impact the economy of the fishing sector. Moreover, the
20 343 potential formation of a « dead zone » would have an impact on atmospheric chemistry, causing greenhouse gas
21 344 emissions (Naqvi et al. 2010; Howarth et al. 2011).

24 345 **4 Summary and conclusions**

26 346 The newly developed 3D biogeochemical model of the Tidal Garonne River coupling hydrodynamic and sediment
27 347 transport models was particularly useful for understanding the future evolution of DO under global and local changes.
28 348 An increase in temperature accelerates oxygen consumption by biogeochemical reactions. Population growth supplies
29 349 additional labile organic matter in the Tidal Garonne River. A reduction in the river flow during summer droughts
30 350 reduces the dilution of estuarine water with oxygenated freshwater and the downstream dispersion of the TMZ. Sea
31 351 level rise can intensify mud trapping and oxygen consumption, but the competition between dilution and tidal
32 352 pumping remain unclear and need specific investigations with high-resolution models.

35 353 The simulations of the combined effects of temperature, river flow, sea level and urban effluent changes predict a
36 354 probable critical to very critical hypoxic state of the Tidal Garonne River for 2050 and 2100. A severe and permanent
37 355 summer hypoxia is likely to develop between Bordeaux and Portets, reaching DO levels close to anoxia and
38 356 potentially causing substantial repercussions on the ecosystem. These model results indicate the need for management
39 357 actions to maintain the water quality of the Tidal Garonne River in the future. Possible actions could be to provide
40 358 low river flow support, while still minimizing the impact of population growth through even more stringent
41 359 wastewater treatment objectives. Moreover, the DO response to fluvial discharge highlights the need to maintain river
42 360 discharge at a minimal threshold during summer, for example, by improving the release of water stored in dams or by
43 361 limiting irrigation in the watershed during drought periods.

362 **5 References**

- 1
2 363 Abril G, Etcheber H, Le Hir P, et al (1999) Oxidic/anoxic oscillations and organic carbon mineralization in an estuarine
3 364 maximum turbidity zone (The Gironde, France). *Limnol Oceanogr* 44:1304–1315
4
5 365 Allen GP (1972) Étude des processus sédimentaires dans l'estuaire de la Gironde. Université de Bordeaux, p.314.
6
7 366 Allen GP, Salomon J, Bassoullet P (1980) Effects of tides on mixing and suspended sediment transport in macrotidal
8 367 estuaries. *Sediment Geol* 26:69–90
9
10 368 Boé J, Habets F (2014) Multi-decadal river flow variations in France. 691–708. doi: 10.5194/hess-18-691-2014
11
12 369 Brenon I, Hir P Le (1999) Modelling the Turbidity Maximum in the Seine Estuary (France): Identification of
13 370 Formation. 525–544
14
15 371 Cocco V, Joos F, Steinacher M, et al (2013) Oxygen and indicators of stress for marine life in multi-model global
16 372 warming projections. *Biogeosciences* 10:1849–1868. doi: 10.5194/bg-10-1849-2013
17
18 373 Conley DJ, Carstensen J, Vaquer-Sunyer R, Duarte CM (2009) Ecosystem thresholds with hypoxia. *Hydrobiologia*
19 374 629:21–29. doi: 10.1007/s10750-009-9764-2
20
21 375 Cotovicz LC, Knoppers BA, Brandini N, et al (2017) Aragonite saturation state in a tropical coastal embayment
22 376 dominated by phytoplankton blooms (Guanabara Bay - Brazil). *Mar Pollut Bull* 0–1. doi:
23 377 10.1016/j.marpolbul.2017.10.064
24
25 378 Cox TJS, Maris T, Soetaert K, et al (2009) A macro-tidal freshwater ecosystem recovering from hypereutrophication:
26 379 the Schelde case study. *Biogeosciences* 6:2935–2948. doi: 10.5194/bg-6-2935-2009
27
28 380 Cugier P, Le Hir P (2002) Development of a 3D Hydrodynamic Model for Coastal Ecosystem Modelling. Application
29 381 to the Plume of the Seine River (France). *Estuar Coast Shelf Sci* 55:673–695. doi: 10.1006/ecss.2001.0875
30
31 382 Dronkers J (1986) Tidal asymmetry and estuarine morphology. *Neth. J. Sea Res.* 20, 117-131
32
33 383 de Jonge VN, Elliott M, Orive E (2002) Causes , historical development , effects and future challenges of a common
34 384 environmental problem : eutrophication. 1–19
35
36 385 Diaz RJ, Rosenberg R (2008) Spreading dead zones and consequences for marine ecosystems. *Science* (80-)
37 386 321:926–929. doi: 10.1126/science.1156401
38
39 387 Etcheber H, Coupry B, Coynel A, et al (2013) Disponibility of surficial continental waters. In: Le Treut H (ed) Impact
40 388 of climate change in the Aquitaine region. Scientific Report., resses Uni. Pessac, p 365
41
42 389 Etcheber H, Schmidt S, Sottolichio A, et al (2011) Monitoring water quality in estuarine environments: lessons from
43 390 the MAGEST monitoring program in the Gironde fluvial-estuarine system. *Hydrol Earth Syst Sci* 15:831–840.
44 391 doi: 10.5194/hess-15-831-2011
45
46 392 Etcheber H, Taillez A, Abril G, et al (2007) Particulate organic carbon in the estuarine turbidity maxima of the
47 393 Gironde, Loire and Seine estuaries: origin and lability. *Hydrobiologia* 588:245–259. doi: 10.1007/s10750-007-
48 394 0667-9
49
50 395 Friedrichs CT, Aubrey DG, (1988). Non-linear tidal distortion in shallow well-mixed estuaries: a synthesis. *Estuar.*
51 396 *Coast. Shelf Sci.* 27, 521-545.
52
53 397 Gilbert D, Rabalais NN, Díaz RJ, Zhang J (2010) Evidence for greater oxygen decline rates in the coastal ocean than
54 398 in the open ocean. *Biogeosciences* 7:2283–2296. doi: 10.5194/bg-7-2283-2010
55
56 399 Goosen NK, Kromkamp J, Peene J, et al (1999) Bacterial and phytoplankton production in the maximum turbidity
57 400 zone of three European estuaries: the Elbe, Westerschelde and Gironde. *J Mar Syst* 22:151–171
58
59 401 Hagy JD, Boynton WR, Keefe CW, Wood K V. (2004) Hypoxia in Chesapeake Bay, 1950–2001: Long-term change
60 402 in relation to nutrient loading and river flow. *Estuaries* 27:634–658. doi: 10.1007/BF02907650
61
62
63
64
65

1 403 Howarth R, Chan F, Conley DJ, et al (2011) Coupled biogeochemical cycles: eutrophication and hypoxia in temperate
2 404 estuaries and coastal marine ecosystems. *Front Ecol Environ* 9:18–26. doi: 10.1890/100008

3 405 Howarth RW, Swaney DP, Butler TJ, Marino R (2000) Rapid Communication: Climatic Control on Eutrophication of
4 406 the Hudson River Estuary. *Ecosystems* 3:210–215. doi: 10.1007/s100210000020

5 407 IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth*
6 408 *Assessment Report of the Intergovernmental Panel on Climate Change*. 1535

7
8 409 Jalón-Rojas I, Schmidt S, Sottolichio A (2015) Turbidity in the fluvial Gironde Estuary (southwest France) based on
9 410 10-year continuous monitoring: sensitivity to hydrological conditions. *Hydrol Earth Syst Sci* 19:2805–2819.
10 411 doi: 10.5194/hess-19-2805-2015

11
12 412 Justić D, Bierman Jr. VJ, Scavia D, Hetland RD (2007) Forecasting Gulf ’ s Hypoxia : The Next 50 Years ? *Estuaries*
13 413 *and Coasts* 30:791–801

14
15 414 Kemp WM, Testa JM, Conley DJ, et al (2009) Coastal hypoxia responses to remediation. *Biogeosciences Discuss*
16 415 6:6889–6948. doi: 10.5194/bgd-6-6889-2009

17
18 416 Lajaunie-Salla K, Wild-Allen K, Sottolichio A, et al (2017) Impact of urban effluents on summer hypoxia in the
19 417 highly turbid Gironde Estuary , applying a 3D model coupling hydrodynamics , sediment transport and
20 418 biogeochemical processes. *J Mar Syst* 174:89–105. doi: 10.1016/j.jmarsys.2017.05.009

21
22 419 Lanoux A, Etcheber H, Schmidt S, et al (2013) Factors contributing to hypoxia in a highly turbid, macrotidal estuary
23 420 (the Gironde, France). *Environ Sci Process Impacts* 15:585–595. doi: 10.1039/c2em30874f

24
25 421 Lanoux A, Lepage M, De Watteville J, et al (2014) Effects of hypoxia on the fish and crustacean fauna in the Gironde
26 422 Estuary. In: *The 46th International Liege Colloquium*. Liege, Belgium

27
28 423 Le Treut H (2013) *Impact of climate change in the Aquitaine region*. Scientific Report., Presses Un. Pessac

29
30 424 Lehmann A, Hinrichsen HH, Getzlaff K, Myrberg K (2014) Quantifying the heterogeneity of hypoxic and anoxic
31 425 areas in the Baltic Sea by a simplified coupled hydrodynamic-oxygen consumption model approach. *J Mar Syst*
32 426 134:20–28. doi: 10.1016/j.jmarsys.2014.02.012

33
34 427 Lemaire E, Abril G, De Wit R, Etcheber H (2002) Effet de la turbidité sur la dégradation des pigments
35 428 phytoplanctoniques dans l’estuaire de la Gironde. *Geoscience* 334:251–258

36
37 429 Li D, Zhang J, Huang D, et al (2002) Oxygen depletion off the Changjiang (Yangtze River) Estuary. *Sci China Ser D*
38 430 45:1137. doi: 10.1360/02yd9110

39
40 431 Meire L, Soetaert KER, Meysman FJR (2013) Impact of global change on coastal oxygen dynamics and risk of
41 432 hypoxia. 2633–2653. doi: 10.5194/bg-10-2633-2013

42
43 433 Naqvi SWA, Bange HW, Fariás L, et al (2010) Marine hypoxia/anoxia as a source of CH₄ and N₂O. *Biogeosciences*
44 434 7:2159–2190. doi: 10.5194/bg-7-2159-2010

45
46 435 Peña M, Katsev S, Oguz T, Gilbert D (2010) Modeling dissolved oxygen dynamics and coastal hypoxia: a review.
47 436 *Biogeosciences ...* 6:9195–9256. doi: 10.5194/bgd-6-9195-2009

48
49 437 Rabalais NN, Levin LA, Turner RE, et al (2010) Dynamics and distribution of natural and human-caused coastal
50 438 hypoxia. *Biogeosciences* 7:585–619. doi: 10.5194/bgd-6-9359-2009

51
52 439 Robins PE, Skov MW, Lewis MJ, et al (2016) Impact of climate change on UK estuaries: A review of past trends and
53 440 potential projections. *Estuar Coast Shelf Sci* 169:119–135. doi: 10.1016/j.ecss.2015.12.016

54
55 441 Schmidt S, Bernard C, Escalier J-M, et al (2017) Assessing and managing the risks of hypoxia in transitional waters:
56 442 a case study in the tidal Garonne River (South-West France). *Environ Sci Pollut Res*. doi: 10.1007/s11356-016-
57 443 7654-5

58
59 444 Schmidt S, Etcheber H, Sottolichio A, Castaing P (2016) Le réseau MAGEST: bilan de 10 ans de suivi haute-
60 445 fréquence de la qualité des eaux de l’estuaire de la Gironde. In: Schmitt FG, Lefevre A (eds) *Mesures haute*
61 446 *résolution dans l’environnement marin côtier*. Presses du CNRS

- 447 Seneviratne SI, Donat MG, Mueller B, Alexander L V. (2014) No pause in the increase of hot temperature extremes.
1 448 Nat Clim Chang 4:161–163. doi: 10.1038/nclimate2145
- 2
3 449 Skerratt J, Wild-Allen K, Rizwi F, et al (2013) Use of a high resolution 3D fully coupled hydrodynamic, sediment and
4 450 biogeochemical model to understand estuarine nutrient dynamics under various water quality scenarios. Ocean
5 451 Coast Manag 83:52–66. doi: 10.1016/j.ocecoaman.2013.05.005
- 6
7 452 Soetaert K, Middelburg JJ, Heip C, et al (2006) Long-term change in dissolved inorganic nutrients in the
8 453 heterotrophic Scheldt estuary (Belgium, The Netherlands). Limnol Oceanogr 51:409–423
- 9
10 454 Sottolichio A, Hir P Le, Castaing P (2000) Modeling mechanisms for the stability of the turbidity maximum in the
11 455 Gironde estuary, France. Proc Mar Sci 3:373–386
- 12
13 456 Talke SA, Swart HE, de Jonge VN (2009) An Idealized Model and Systematic Process Study of Oxygen Depletion in
14 457 Highly Turbid Estuaries. Estuaries and Coasts 32:602–620. doi: 10.1007/s12237-009-9171-y
- 15
16 458 Testa JM, Li Y, Lee YJ, et al (2014) Quantifying the effects of nutrient loading on dissolved O₂ cycling and hypoxia
17 459 in Chesapeake Bay using a coupled hydrodynamic–biogeochemical model. J Mar Syst 139:139–158. doi:
18 460 10.1016/j.jmarsys.2014.05.018
- 19
20 461 Thouvenin B, Le Hir P, Romana LA (1994) Dissolved oxygen model in the Loire estuary. Chang fluxes estuaries
21 462 Implica- tions from Sci to Manag Acad 169–178
- 22
23 463 Tinsley D (1998) The Thames estuary: a history of the impact of humans on the environment and a description of the
24 464 current approach to environmental management. In: Attrill M (ed) A Rehabilitated Estuarine Ecosystem SE - 2.
25 465 Springer US, pp 5–26
- 26
27 466 Uncles RJ, Elliott TCA, Weston SA (1985) Observed fluxes of water and suspended sediment in a partly mixed
28 467 estuary. Estuar. Coast. Shelf Sci. 20, 147-167
- 29
30 468 Van Maanen B, Sottolichio A (in revision). Hydro- and sediment dynamics in the Gironde estuary (France):
31 469 sensitivity to seasonal variations in river inflow and sea level rise. Continental Shelf Research.
- 32
33 470 Vanderborcht J-P, Folmer IM, Aguilera DR, et al (2007) Reactive-transport modelling of C, N, and O₂ in a river–
34 471 estuarine–coastal zone system: Application to the Scheldt estuary. Mar Chem 106:92–110. doi:
35 472 10.1016/j.marchem.2006.06.006
- 36
37 473 Vaquer-Sunyer R, Duarte CM (2008) Thresholds of hypoxia for marine biodiversity. Proc Natl Acad Sci U S A
38 474 105:15452–15457. doi: 10.1073/pnas.0803833105
- 39
40 475 Veyssy E (1998) Transferts de matière organiques des bassins versants aux estuaires de la Gironde et de l'Adour
41 476 (Sud-Ouest de la France). Université de Bordeaux, p.262.
- 42
43 477 Wild-Allen K, Herzfeld M, Thompson PA., et al (2009) Applied coastal biogeochemical modelling to quantify the
44 478 environmental impact of fish farm nutrients and inform managers. J Mar Syst 81:134–147. doi:
45 479 10.1016/j.jmarsys.2009.12.013
- 46
47 480 Willmott CJ (1982) Some comments on the evaluation of model performance. Bull Am Meteorol Soc 63:
- 48
49 481 Winterwerp JC, Wang ZB, van Braeckel A, van Holland G, Kösters F (2013). Man-induced regime shifts in small
50 482 estuaries-II: A comparison of rivers. Ocean Dynamics, 63(11–12), 1293–1306. doi:10.1007/s10236-013-
51 483 0663-8
- 52
53 484 Zhao W, Zhu X, Sun X, et al (2015) Water quality changes in response to urban expansion: spatially varying relations
54 485 and determinants. Environ Sci Pollut Res 22:16997–17011. doi: 10.1007/s11356-015-4795-x
- 55
56
57
58
59
60
61
62
63
64
65

16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Table 1: Forcing of the different scenarios simulated with the model.

Scenarios	Temperature	River flow	Water level	Wastewater flow	
Reference	Ref	T 2006	$Q_{G/D}$ 2006	3.24 m	Q_{WW} 2006
Effect of temperature	+2°C	T2006 +2°C	$Q_{G/D}$ 2006	3.24 m	Q_{WW} 2006
	+3°C	T2006 +3°C	$Q_{G/D}$ 2006	3.24 m	Q_{WW} 2006
	+4°C	T2006 +4°C	$Q_{G/D}$ 2006	3.24 m	Q_{WW} 2006
	+5°C	T2006 +5°C	$Q_{G/D}$ 2006	3.24 m	Q_{WW} 2006
Effect of demographic growth	+POP	T2006	$Q_{G/D}$ 2006	3.24 m	Q_{WW} 2006 +50%
Effect of river flow	100 m³.s⁻¹	T2006	$Q_{G/D}$ 2006; $Q_G = 100 \text{ m}^3 \cdot \text{s}^{-1}$ from 15/07 to 30/09	3.24 m	Q_{WW} 2006
	80 m³.s⁻¹	T2006	$Q_{G/D}$ 2006; $Q_G = 80 \text{ m}^3 \cdot \text{s}^{-1}$ from 15/07 to 30/09	3.24 m	Q_{WW} 2006
	60 m³.s⁻¹	T2006	$Q_{G/D}$ 2006; $Q_G = 60 \text{ m}^3 \cdot \text{s}^{-1}$ from 15/07 to 30/09	3.24 m	Q_{WW} 2006
	40 m³.s⁻¹	T2006	$Q_{G/D}$ 2006; $Q_G = 40 \text{ m}^3 \cdot \text{s}^{-1}$ from 15/07 to 30/09	3.24 m	Q_{WW} 2006
Effect of sea level	+10 cm	T2006	$Q_{G/D}$ 2006	3.34 m	Q_{WW} 2006
	+20 cm	T2006	$Q_{G/D}$ 2006	3.44 m	Q_{WW} 2006
	+40 cm	T2006	$Q_{G/D}$ 2006	3.64 m	Q_{WW} 2006
Combined effect	2050	T2006 +2°C	$Q_{G/D}$ 2006; $Q_G = 80 \text{ m}^3 \cdot \text{s}^{-1}$ from 15/07 to 30/09	3.44 m	Q_{WW} 2006 +50%
	2100	T2006 +5°C	$Q_{G/D}$ 2006; $Q_G = 40 \text{ m}^3 \cdot \text{s}^{-1}$ from 15/07 to 30/09	3.64 m	Q_{WW} 2006 +50%

16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Table 2: Minimum simulated DO (in % of saturation and in mg.L⁻¹), the corresponding temperature and the number of hypoxia days in Bordeaux and Portets for each scenario.

Scenarios		Bordeaux				Portets			
		T (°C)	DO _{min} (%)	DO _{min} (mg.L ⁻¹)	Days of hypoxia	T (°C)	DO _{min} (%)	DO _{min} (mg.L ⁻¹)	Days of hypoxia
Reference	Ref	27.2	28.9	2.3	0	24	22.4	1.8	3
Effect of temperature	+2°C	29.2	22.8	1.7	5	26	18.9	1.5	7
	+3°C	30.2	19.8	1.5	9	27	18.5	1.4	8
	+4°C	31.2	17.0	1.2	15	28	16.5	1.3	13
	+5°C	32.2	14.3	1.0	26	29	15.8	1.2	14
Effect of demographic growth	+POP	27.2	23.6	1.9	3	24	21.3	1.7	4
Effect of river flow	100 m³.s⁻¹	26.9	23.7	1.9	4	24	33.5	2.8	0
	80 m³.s⁻¹	26.8	19.5	1.5	8	23.7	32.2	2.7	0
	60 m³.s⁻¹	26.8	15.6	1.2	11	24.4	19.5	1.6	12
	40 m³.s⁻¹	27.4	13.5	1.0	13	24.4	8	0.7	52
Effect of sea level	+10 cm	27.2	25.6	2.0	0	23.1	15	1.2	5
	+20 cm	26.4	33	2.6	0	24.6	22.5	1.9	2
	+40 cm	23.7	29.7	2.3	0	22.6	14.7	1.2	6
Combined impact	2050	28.9	14	1.1	29	26.7	29.1	2.4	0
	2100	32.4	2.8	0.2	91	29.7	3.4	0.3	78

16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Table 3: Differences (in %) of biogeochemical process rates impacting DO between the scenarios and reference simulations during summer at Bordeaux.

Scenarios	Bordeaux			Portets			
	nitrification	mineralization TOC _{WS}	mineralization TOC _{WW}	nitrification	mineralization TOC _{WS}	mineralization TOC _{WW}	
Effect of temperature	+2°C	+12%	+7%	+4%	+15%	-3%	-2%
	+3°C	+17%	+11%	+6%	+22%	-2%	-7%
	+4°C	+23%	+13%	+9%	+30%	-3%	-11%
	+5°C	+28%	+16%	+11%	+37%	-2%	-15%
Effect of demographic growth	+POP	+42%	-1%	+50%	+7%	-3%	+65%
Effect of river flow	100 m ³ .s ⁻¹	+8%	-1%	+4%	-4%	-8%	+20%
	80 m ³ .s ⁻¹	+25%	0	+3%	+15%	-9%	+29%
	60 m ³ .s ⁻¹	+45%	-4%	+6%	+67%	-14%	+41%
	40 m ³ .s ⁻¹	+66%	-14%	+6%	+159%	-18%	+52%
Effect of sea level	+10 cm	+3%	+3%	-7%	+4%	-4%	+14%
	+20 cm	0	0	0	-26%	-19%	-5%
	+40 cm	+3%	-13%	-12%	+11%	+3%	+18%
Combined effect	2050	+86%	-8%	+59%	+44%	-5%	+65%
	2100	+144%	-28%	+52%	+241%	-15%	+131%

1 **Figure 1:** The Tidal Garonne River in southwestern France. “PK” denotes the distances in km from the city center of
2 Bordeaux; the control grid cell at Bordeaux is at PK-4 and Portets is at PK-20. In insert A, the purple triangles
3 represent the position of sewage overflows (SOs) and the green squares represent the position of wastewater treatment
4 plants (WWTPs). The area in orange represents the area of Bordeaux where the biogeochemical fluxes are calculated.
5 In inset B, the purple line represents the 200 m isobath.
6

7 **Figure 2:** Influencing factors of the reference simulation (year 2006): time series of river flow (a, $\text{m}^3 \cdot \text{s}^{-1}$), water
8 temperature (b, $^{\circ}\text{C}$), discharge of sewage overflow (SO) and of wastewater treatment plants (WWTPs) (c, $\text{m}^3 \cdot \text{s}^{-1}$),
9 simulated DO saturation (d, %), and SSC (d, $\text{g} \cdot \text{L}^{-1}$) and tidal range (d, m) from January 1 to October 31. In figure b,
10 the blue line and the green area show the median and the envelope of measured temperature for the period 2005-2015,
11 respectively.
12

13 **Figure 3:** Temporal evolution of DO_{\min} (over tidal cycle in %sat) at Bordeaux, from January to October, according to
14 the scenarios of temperature increases (from 2°C to 5°C , a) or population growth (b). The blue line represents the
15 2006 reference simulation.
16

17 **Figure 4:** Spatiotemporal evolution of simulated surface daily average parameters along the Tidal Garonne River
18 section: salinity (left), SSC (middle, in $\text{g} \cdot \text{L}^{-1}$) and DO (right, in %sat). The simulations correspond to the reference
19 with a summer mean Garonne discharge of $145 \text{ m}^3 \cdot \text{s}^{-1}$ (a, b and c) and to the following four scenarios: $100 \text{ m}^3 \cdot \text{s}^{-1}$ (d, e
20 and f), $80 \text{ m}^3 \cdot \text{s}^{-1}$ (g, h and i), $60 \text{ m}^3 \cdot \text{s}^{-1}$ (j, k and l) and $40 \text{ m}^3 \cdot \text{s}^{-1}$ (m, n and o). The y-axis represents the kilometric
21 points, and the white lines represent Bordeaux and Portets.
22
23

24 **Figure 5:** Spatiotemporal evolution of simulated surface daily average parameters along the Tidal Garonne River
25 section: salinity (left), SSC (middle, in $\text{g} \cdot \text{L}^{-1}$) and DO (right, in %sat). The simulations correspond to the three
26 scenarios of SLR: +10 cm (a, b and c), +20 cm (d, e and f) and +40 cm (g, h and i). The y-axis represents the
27 kilometric points, and the white lines represent Bordeaux and Portets.
28
29

30 **Figure 6:** Spatiotemporal evolution of daily average surface SSC (left, in $\text{g} \cdot \text{L}^{-1}$) and DO (saturation, right in %) along
31 the Tidal Garonne River section for the reference year 2006 (a and b) and the scenarios of 2050 (c and d) and 2100 (e
32 and f). The y-axis represents the kilometric points, and the white lines represent Bordeaux and Portets.
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Figure 1:

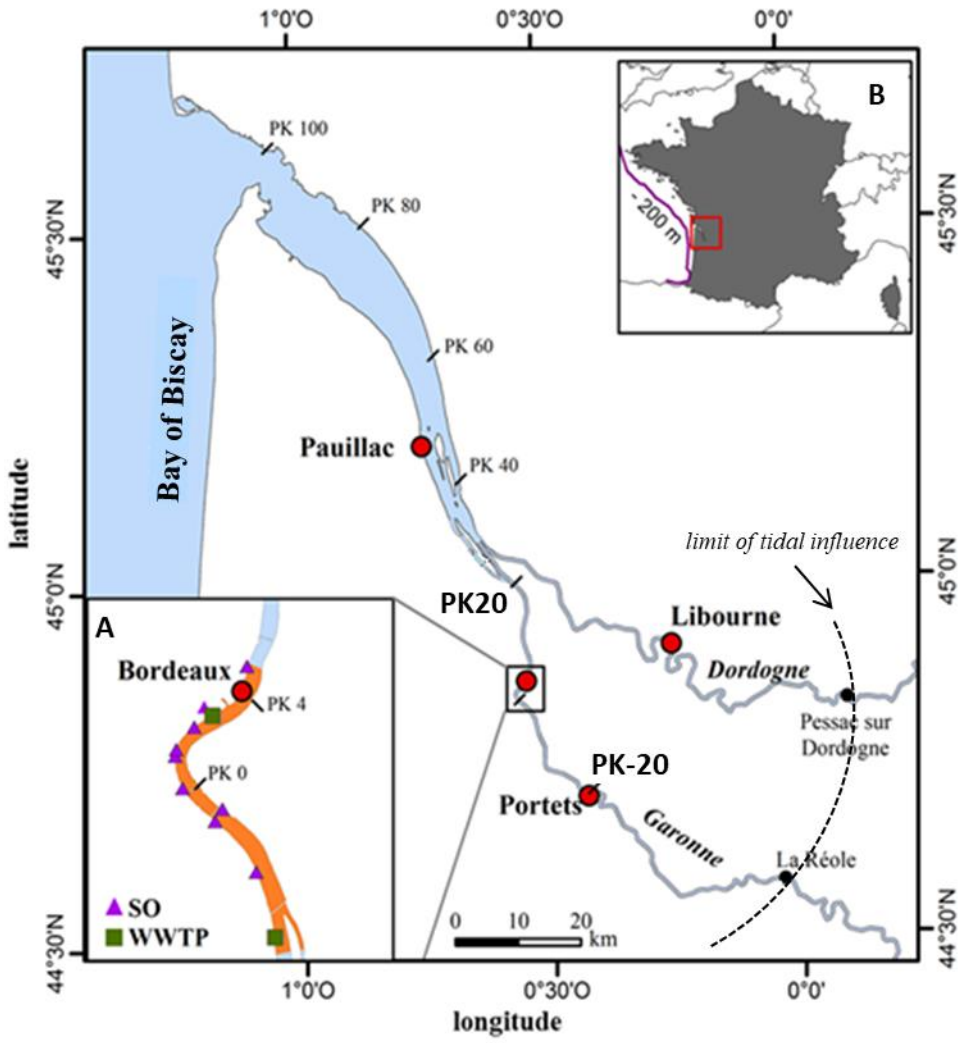


Figure 2:

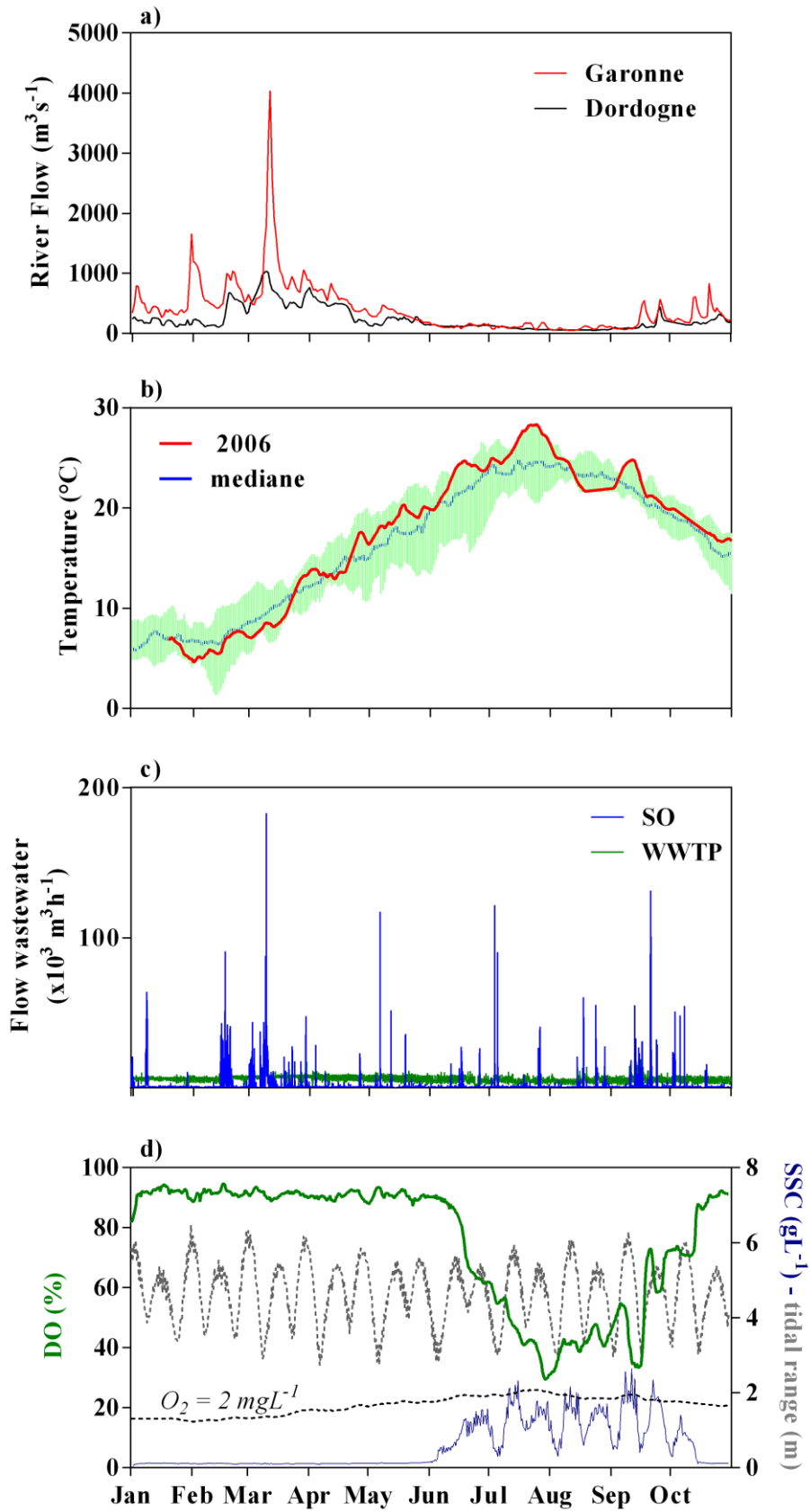


Figure 3:

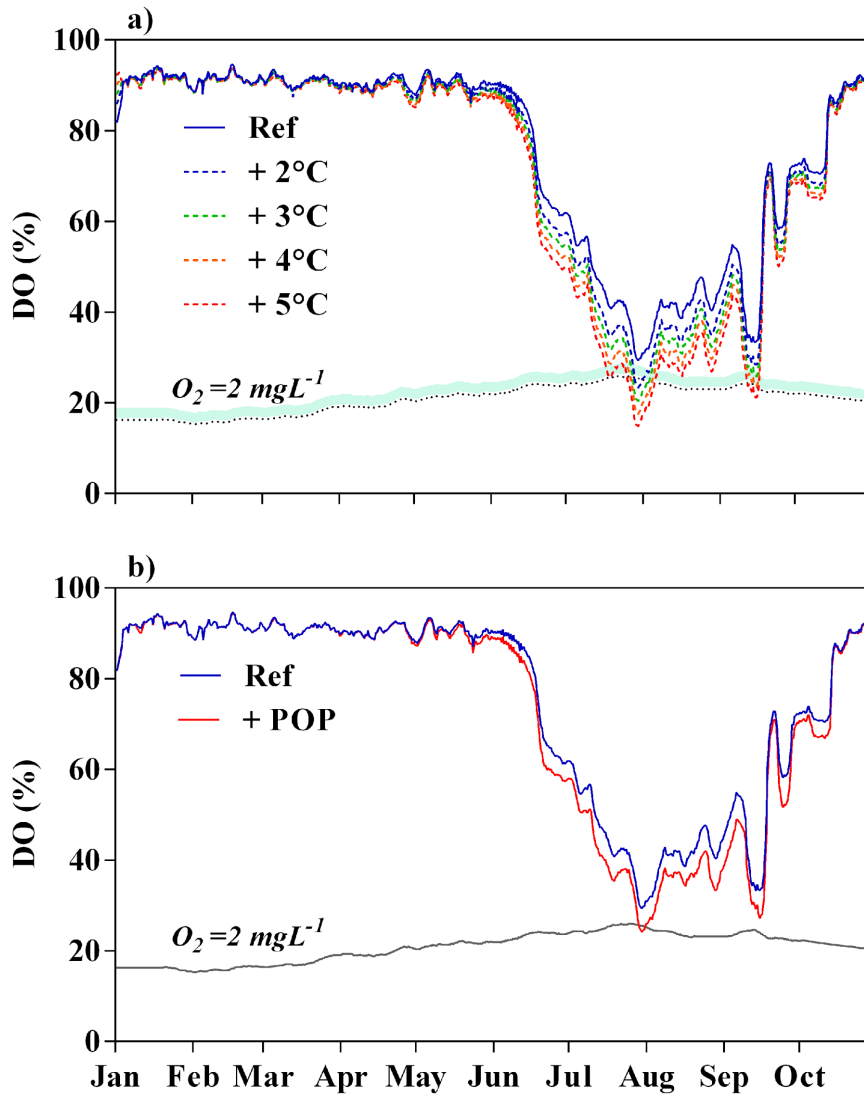


Figure 4:

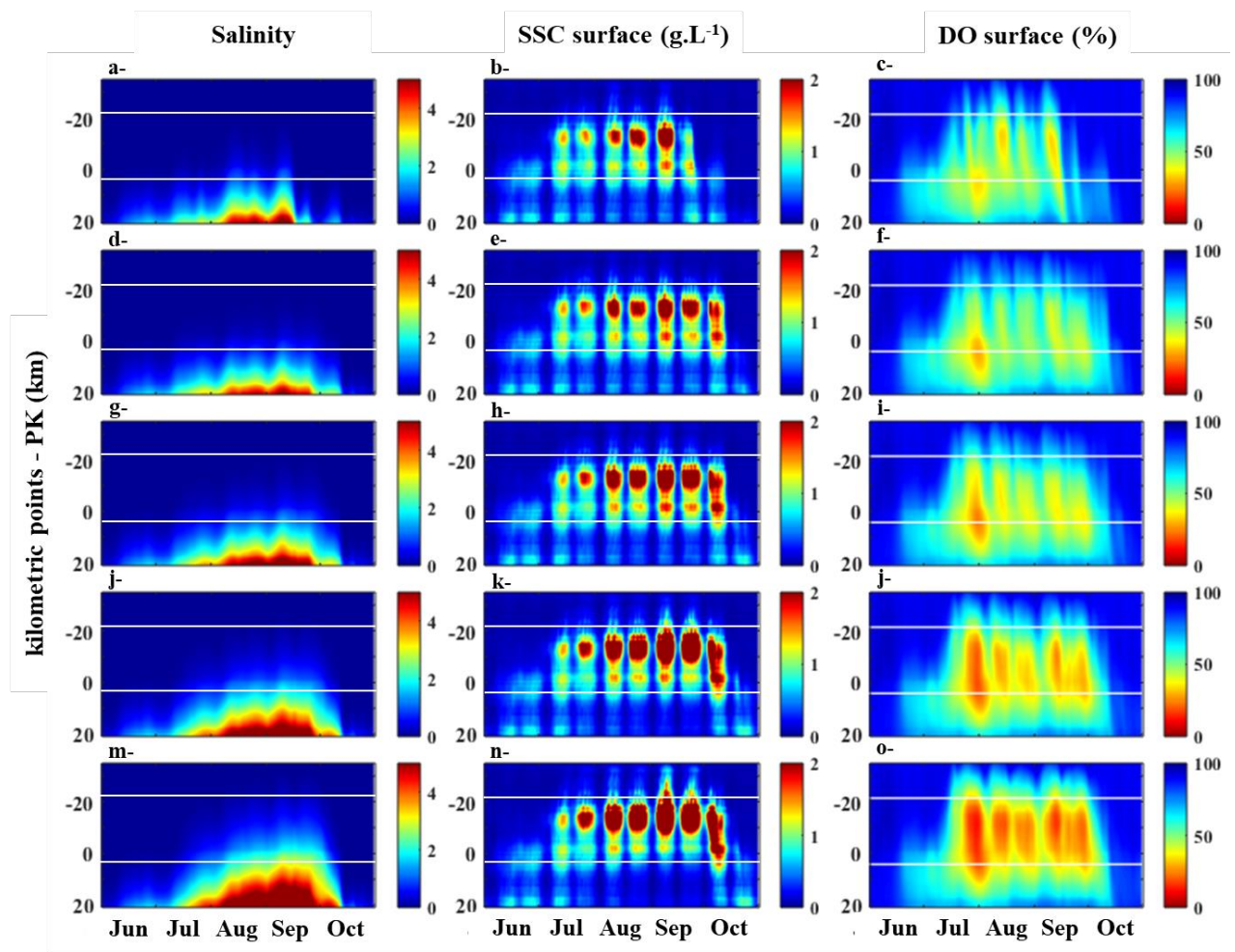
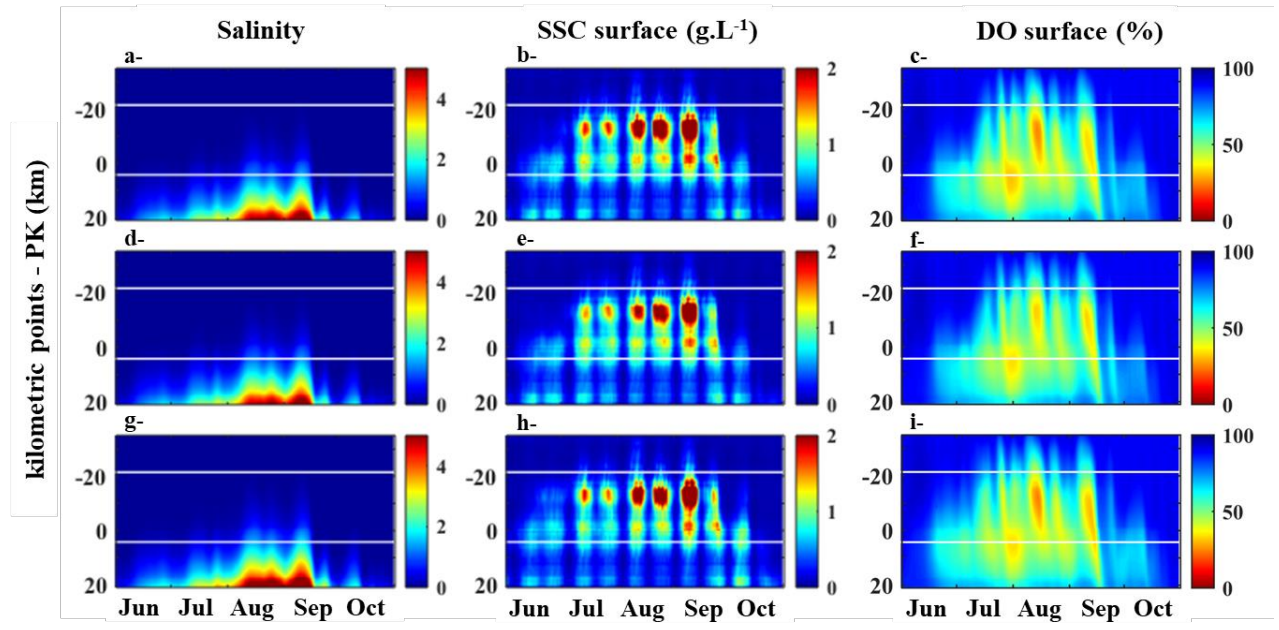


Figure 5:



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Figure 6

