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Trajectories of nutrients concentrations and ratios in the French coastal ecosystems: 20 years of changes in relation with large-scale and local drivers

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5 Authors: Lheureux Arnaud(1) ¹, David Valérie(1), Del Amo Yolanda(1), Soudant
6 Dominique(2), Auby Isabelle(3), Bozec Yann(4), Conan Pascal(5), Ganthy Florian(3),
7 Grégori Gérard(6), Lefebvre Alain(7), Leynart Aude(8), Rimmelin-Maury Peggy(8),
8 Souchu Philippe(9), Vantrepote Vincent(10), Blondel Camille(7), Cariou Thierry(4,11),
9 Crispi Olivier(5), Cordier Marie-Ange(1), Crouvoisier Muriel(10), Duquesne Vincent(7),
10 Ferreira Sophie(1), Garcia Nicole(6), Gouriou Laure(3), Grosteffan Emilie(8), Le Merrer
11 Yoann(9), Meteigner Claire(3), Retho Michael(9), Tournaire Marie-Pierre(3), Savoye
12 Nicolas(1)

13
14 (1) Université de Bordeaux-CNRS, UMR 5805, Environnement Paléoenvironnement Océaniques
15 et Côtiers (EPOC), 2 Rue du Professeur Jolyet, 33120 Arcachon, France

16 (2) Ifremer Nantes, Valorisation de l'Information pour la Gestion Intégrée Et la Surveillance
17 (VIGIES), 44311 Cedex 03, Rue de l'Île d'Yeu, 44980 Nantes, France

18 (3) Ifremer, LER AR 1 Quai du Commandant Silhouette, 33120 Arcachon, France

19 (4) Sorbonne Université, UPMC Univ. Paris 06, CNRS, UMR 7144 AD2M, Station Biologique de
20 Roscoff, 29680 Roscoff, France

21 (5) Sorbonne Université, UPMC Univ. Paris 06, CNRS, UMR7621 LOMIC, Observatoire
22 Océanologique, F-66650 Banyuls sur Mer, France

23 (6) Aix-Marseille Université, Univ. de Toulon, CNRS, INSU, IRD, UM 110 MIO, 163 Avenue de
24 Luminy, 13288, Marseille, France

25 (7) Ifremer, Unité Littoral, Laboratoire Environnement Ressources, 150 Quai Gambetta, 62320
26 Boulogne-sur-Mer, France

27 (8) IUEM-UAR 3113, rue Dumont d'Urville, 29280 Plouzané, France

28 (9) Ifremer, LER MPL Rue de l'Île d'Yeu, BP 21105, 44311, Cedex 03, Nantes, France

29 (10) Univ. Littoral Côte d'Opale, Univ. Lille, CNRS, UMR 8187 LOG, F-62930 Wimereux, France

30 (11) IRD, UAR191, Instrumentation, Moyens Analytiques, Observatoires en Géophysique et
31 Océanographie (IMAGO), Technopôle de Brest-Iroise, Plouzané, France

32

¹ Corresponding author: arnaud.lheureux@sorbonne-universite.fr
Campus Buffon, 17 allée des Crapauds 2ème étage - CP 53 - 75005 Paris Cedex 05

* Colors should be used for all figures.

33 Keywords: nutrients concentrations, long-term changes, global change, ecosystem
34 trajectories, multi-ecosystem

35

36 Highlights

- 37 • Most ecosystems showed overall decreasing nutrients concentrations
- 38 • Both climatic changes and human activities drove nutrients concentrations
- 39 • Ecological ecosystem trajectories are useful tools to study ecosystems changes
- 40 • Ecosystems had similar trajectories based on their continental influence
- 41 • Ecosystems internal functioning had a non-negligible importance on trajectories

42

43 Abstract

44 Along with their important diversity, coastal ecosystems receive various amounts of
45 nutrients, principally arising from the continent and from the related human activities
46 (mainly industrial and agricultural activities). During the 20th century, nutrients loads
47 have increased following the increase of both the global population and need of services.
48 Alongside, climate change including temperature increase or atmospheric circulation
49 change has occurred. These processes, Ecosystem state changes are hard to monitor and
50 predict. To study the long-term changes of nutrients concentrations in coastal ecosystems,
51 eleven French coastal ecosystems were studied over 20 years as they encompass large
52 climatic and land pressures, representative of temperate ecosystems, over a rather small
53 geographical area. Both univariate (time series decomposition) and multivariate
54 (relationships between ecosystems and drivers) statistical analyses were used to
55 determine ecosystem trajectories as well as typologies of ecosystem trajectories. It
56 appeared that most of the French coastal ecosystems exhibited trajectories toward a
57 decrease in nutrients concentrations. Differences in trajectories mainly depended on
58 continental and human influences, as well as on climatic regimes. One single ecosystem
59 exhibited very different trajectories, the Arcachon Bay with an increase in nutrients

60 concentrations. Ecosystem trajectories based on ordination techniques were proven to be
61 useful tools to monitor ecosystem changes. This study highlighted the importance of local
62 environments and the need to couple uni- and multi-ecosystem studies. Although the
63 studied ecosystems were influenced by both local and large-scale climate, by
64 anthropogenic activities loads, and that their trajectories were mostly similar based on
65 their continental influence, non-negligible variations resulted from their internal
66 functioning.

67

68 Graphical abstract

69

70 **1. Introduction**

71 External inputs from the lithosphere, anthroposphere and atmosphere as well as the
72 recycling of nitrogen (N), phosphorus (P) and silicon (Si) by the biosphere are among the
73 main factors controlling the primary production in the hydrosphere and particularly in
74 the marine temperate coastal ecosystems (Bouwman et al. 2013; Nixon et al. 1986). In
75 these ecosystems, nutrients mainly come from rivers and other continental run-off
76 (Seitzinger et al. 2002). Other processes participate in the input of nutrients such as
77 vertical advection from deep water, benthic advection in shallow ecosystems, organic
78 matter remineralisation or atmospheric deposition. Indubitably, nutrients are influenced
79 by a set of marine biogeochemical processes — e.g., recycling, consumption, tidal pumping
80 — and drivers — e.g. climate, human activities (Deborde et al. 2008; Bouwman et al.
81 2013). In most coastal areas, N and P mainly come from anthropogenic activities on land
82 — e.g., urban expansion, industrial effluents or intensive agriculture — that considerably
83 alter their natural cycles (Galloway et al. 2004, Metson et al. 2017). Si principally comes
84 from natural weathering (Tréguer et al. 1995) but its cycle can be altered by modifications
85 on lands like the creation of dams (Papush and Danielsson, 2006). The export of nutrients
86 from the continent to the coastal ecosystems has almost doubled at the global scale
87 between 1901 and 2000 (Beusen et al. 2016), in response to human activities (Paerl
88 2009).

89

90 Temperate coastal ecosystems are very diversified (as seen in Duarte et al. 2008) and this
91 diversity is expressed at different scales. Coastal ecosystems are characterised by
92 different geomorphologies defining their intrinsic characteristics. Geomorphology shapes
93 their shoreline, influences their internal processes (Adame et al. 2010) and thus affects

94 exchanges with contiguous ecosystems. Coastal ecosystems are also characterised by
95 their “trophic status” (from oligo- to eutrophic): they experience various levels of nutrient
96 concentrations and phytoplankton biomass. Moreover, coastal ecosystems struggle with
97 different tidal regimes or continental influences and are under different anthropogenic
98 pressures and climatic conditions. Such diversity in coastal ecosystems characteristics
99 may drive the multiplicity of nutrients origins, dynamics as well as their concentrations
100 and ratios. For instance, among the well-studied ecosystems, Chesapeake Bay (USA) is a
101 mesotrophic bay facing a macro-tidal regime (in its meso- and polyhaline zones). It
102 experiences important freshwater discharges: $86 \text{ km}^3 \cdot \text{yr}^{-1}$, (Yang et al. 2015) with 96 000
103 tons of dissolved inorganic nitrogen per year (Feng et al 2015) coming from its large
104 watershed ($166\,000 \text{ km}^2$). In contrast, Venice Lagoon (Italy) is a mesotrophic semi-
105 enclosed bay facing a micro-tidal regime with only few freshwater discharges $-1 \text{ km}^3 \cdot \text{yr}^{-1}$
106 and 4 000 tons of dissolved inorganic nitrogen per year (Solidoro et al. 2010) from its
107 small watershed (1840 km^2). Both ecosystems have similar nutrients concentrations
108 (Facca et al. 2011, Harding et al. 2019) but with different watershed surface areas and
109 supplying origins: nutrients are mainly brought by the rivers all along the watershed in
110 Chesapeake Bay *versus* run-off through highly industrialised urban lands in the vicinity of
111 the bay in the Venice lagoon (Pastres et al. 2004, Sfriso et al. 1992).

112

113 In addition to the natural geomorphology and to the nutrient supply origins, the climatic
114 pressures applied to coastal ecosystems play a role on nutrients concentrations in several
115 ways and at different scales (Bouwman et al. 2013). Temperature has effects on benthic
116 fluxes and remineralisation — through its influence onto the biological compartment —
117 as well as on nutrient vertical fluxes — i.e., through the stratification (Doney 2006).

118 Precipitations influence not only continental inputs of nutrients but also the atmospheric
119 deposition (Durrieu de Madron et al. 2011). Winds and tides influence currents and thus
120 the horizontal nutrients advection as well as the hydro- and sediment dynamics
121 (Christiansen et al. 2006). Moreover, light availability might favour specific
122 phytoplankton, macroalgae or angiosperms taxa and thus might influence nutrients
123 uptake, and therefore modify nutrients concentrations and ratios (Litchman et al. 2007).

124 Anthropogenic pressures can be different depending on the human activities and on the
125 nature of the ecosystems (Borja et al. 2010). In addition to the increasing direct
126 anthropogenic pressures on the coast due to both the growing agricultural and industrial
127 activities to fulfil humans needs, the increasing population and human modifications
128 made on the watersheds directly impact and modify the coastal ecosystems. For instance,
129 some major Asian deltas have been losing their geomorphological features due to a
130 reduced load of sediments from the rivers following the implementation of dams
131 (Mimura, 2006). Another example of rather unexpected human-induced change in coastal
132 nutrient concentrations is that management policies implemented to reduce N and P loads
133 in the Rhine and Meuse Rivers had induced an increase of Si concentrations in the coastal
134 North Sea (Prins et al. 2012). It was shown that the retention of Si in the rivers decreased
135 with decreasing eutrophication resulting in increased continent to ocean Si fluxes.

136

137 Within a restricted geographical area, French coastal ecosystems display a wide range of
138 characteristics such as a high range of salinity, low to high continental influence, micro- to
139 megatidal regime in estuaries, semi-enclosed bays, open littorals, etc. Within this context,
140 the objective was to examine how nutrients concentrations and their respective ratios in
141 different, although contiguous, coastal ecosystems responded to global change during the

142 past two decades by investigating (i) the overall ecosystems characteristics based on
143 nutrients concentrations and ratios in relation with their potential drivers and (ii) by
144 establishing a typology of ecosystems according to their temporal trajectories of the
145 nutrients concentrations and ratios.

146

147 **2. Material and methods**

148 **2.1. Ecosystems**

149 Eleven contrasted French coastal ecosystems were considered. The diversity of these
150 ecosystems (Figure 1; Table 1) relies on their geomorphologies (estuary to open
151 systems), tidal regime (micro- to mega-tidal), trophic status (oligo- to eu-trophic as stated
152 in Liénart et al. 2017, 2018) and continental influences (annual salinity mean from 3 to
153 38) including river flow (from 1 to 1650 m³.s⁻¹) and watershed area (470 to 127535 km²).
154 Seven of the eleven ecosystems are represented by more than one sampling stations,
155 enabling to point out potential continent-ocean gradients within ecosystems. In addition,
156 the climatic conditions of these ecosystems are different: annual air temperature averages
157 range from 11 to 16°C and annual monthly precipitation from 50 to 83 mm.

158

159 **2.2. Stations and data**

160 The coastal parameters were retrieved from two French monitoring programs: the
161 SOMLIT and the REPHY (including regional sub-programs ARCHYD and SRN) (red dots
162 on Figure 1) at twenty-nine stations located in the eleven coastal ecosystems. These two
163 monitoring programs produce sub-surface data (although one station was sampled at 5m
164 depth for 6 years) for more than twenty years, at a weekly to monthly frequency. The two
165 programs participated to annual inter-laboratory exercises at the national scale (Belin et
166 al, 2021; Breton et al. in prep). For more information regarding these programs, see
167 Cocquempot et al. (2019), Goberville et al. (2010), Liénart et al. (2017, 2018) and
168 Lheureux et al. (2021) for SOMLIT, and Belin et al. (2021) for REPHY. The data retrieved

169 for this study run from January 2000 to December 2019. Different databases were used
170 for gathering data regarding nutrients — the core parameters — and parameters arising
171 from the lithosphere and atmosphere potentially forcing coastal ecosystems such as
172 parameters indicative of hydrological, continental and climate drivers (Table 1).

173 Continental variables were provided by EauFrance and the French water agencies (blue
174 and green dots on Figure 1). The meteorological variables were obtained from MERRA-2
175 for the local scale (see Gelaro et al. 2017) and by the National Centers for Environmental
176 Protection and the National Center for Atmospheric Research (NCEP/NCAR) for the
177 regional scale. The hydro-climatic teleconnection indices were provided by the US
178 National Oceanic and Atmospheric Administration (NOAA), National Center for
179 Atmospheric Research (NCAR), Climate Prediction Center (CPC) and National Centers for
180 Environmental Information (NCEI).

181 **2.2.1. Core parameters: nutrient concentrations and ratios**

182 Four nutrients (nitrate + nitrite (NO_x), ammonium (NH_4^+), orthophosphate (PO_4^{3-}), and
183 silicic acid ($\text{Si}(\text{OH})_4$) concentrations and their corresponding ratios (N:P, Si:N, Si:P) were
184 used.

185 **2.2.2. Environmental drivers**

186 **2.2.2.1. Local bio-physical data**

187 Three bio-physical parameters (water temperature, salinity, chlorophyll-a) were also
188 considered. Instead of using raw salinity measures, salinity was standardised according
189 the 3 French facades. Each observation was divided by the facade percentile 97.5 (North
190 Sea / English Channel = 35.40, Atlantic Ocean = 35.29, Mediterranean Sea = 38.36).

191 Hence, this salinity index (i.e., standardised salinity) can be used as a proxy of marine
192 *versus* continental water body influence. It varies between 0 (freshwater) and 1 (marine
193 water).

194 **2.2.2.2. Continental data**

195 Four continental variables were collected (three nutrient concentrations (NO_x , NH_4^+ and
196 PO_4^{3-}) and the river flows). The nutrient concentrations and the river flows were
197 monitored upstream the dynamic influence of the tide, when any. When more than one
198 river influenced a given ecosystem, river flows were weighted by the distance between
199 the river mouth and the station while associated nutrients concentrations were weighted
200 by the river flow and the distance between the river mouth and the station (see Liénart et
201 al. 2018).

202 **2.2.2.3. Local-scale climate data**

203 Seven meteorological variables were used: four atmospheric circulation variables (the
204 atmospheric pressure, the wind intensity and its meridional and zonal components — see
205 Lheureux et al. (2022) for more details on the components positive or negative values
206 meaning), along with the air temperature, the short-wave irradiation and the monthly
207 accumulated precipitation.

208 **2.2.2.4. Large-scale climate**

209 The same parameters but the short-wave irradiation were collected at regional scale
210 (30°N to 60°N and 15°W to 15°E). Datasets were derived from reanalysis procedures and
211 improved statistical methods had been applied to produce stable monthly reconstruction

212 on a $2.5^\circ \times 2.5^\circ$ spatial grid, but on a $1^\circ \times 1^\circ$ spatial grid for SST (see Betts et al. (1996),
213 Kalnay et al. (1996) and Kistler et al. (2001) for further details on the methodology).
214 Empirical orthogonal functions (EOF) were applied on each of these parameters to extract
215 the temporal changes (the two first principal components) and the spatial extent of the
216 changes (eigenvalues) over the geographical window. The extracted temporal
217 components originating from two gridded climate data providers were correlated
218 (Pearson's $\rho > 0.940$, raw data not shown) regardless of the data sets (NOAA *vs*
219 Copernicus) or the data spatial resolution ($> 1^\circ \times > 1^\circ$ *vs* $< 1^\circ \times < 1^\circ$).

220 Five hydro-climatic teleconnection indices were used: the AO) and the Arctic Oscillation
221 (AO). The AMO (Enfield et al. 2001) represents the Atlantic Multidecadal Oscillation
222 (AMO), the Northern Hemisphere Temperature anomalies (NHT), the East Atlantic
223 Pattern (EAP), the Northern Atlantic Oscillation (NAO) in the north Atlantic Ocean
224 surface temperature after removing the human impact whereas the NHT anomalies is an
225 index based on the 1901-2000 north Atlantic temperature average. The NAO (Hurrell
226 1995; Hurrell & Deser 2009) and the EAP (Barnston & Livezey 1987) are the two most
227 predominant mode of low-frequency variability over the north Atlantic. While the NAO
228 tracks the movements of the Azores high, the EAP values consist of a north-south dipole
229 of pressure anomalies centred on the north Atlantic, from east to west. Finally, the AO is
230 based on atmospheric pressures and is related to the Arctic climate and its southern
231 incursions (Higgins et al. 2000).

232 **2.3. Statistical analyses**

233 **2.3.1. Step 1: Data pre-treatment**

234 All the time series were reduced to one data per month by applying a median if more than
235 one observation were available for each month. Nutrients (concentrations and ratios),
236 chlorophyll-a and river flow data were log-transformed before any other statistical
237 analysis. More details regarding the whole statistical pathway can be found in
238 Supplementary material A.

239 To only consider the year-to-year changes, the interannual component was extracted for
240 each time series, except for the large-scale hydro-climatic indices, using dynamic linear
241 models (DLM, West and Harrison, 1997). DLMs have already been used in ecological
242 studies dealing with nutrients, phytoplankton and climate data (Hernández-Fariñas et al
243 2014, Ratmaya et al. 2019, Lheureux et al. 2022).

244 To detect monotonic significant changes across the whole time period (20 years),
245 modified Mann-Kendall tests (Hamed and Rao, 1998) were performed on each time series.
246 Additionally, three modified Mann-Kendall were performed on three 10-year drifting
247 windows: 2000-2009, 2005-2014, 2010-2019 on each time series. Using the sign of the
248 associated Sen-Theil slopes, it was possible to detect trend inversions (inversion of sign)
249 or trends that occurred during a specific span along the 20-year studied period.

250 **2.3.2. Step 2: Co-inertia analysis (COIA)**

251 Between-Group COInertia Analysis (BGCOIA, Franquet et al. 1995) and Within-Group
252 COInertia Analysis (WGCOIA, Franquet and Chessel 1994) are traditionally used to study
253 the changes in species-environment relationships (Thioulouse et al. 2018) by analysing

254 series of pairs of tables. In this study, they were used to study changes in nutrients
255 concentrations and ratios *versus* drivers relationships. The COIA was used to reveal the
256 main co-structures — i.e., common structures to the nutrients and to the drivers data sets
257 — by combining the two separate PCAs (Principal Component Analysis) into a single
258 analysis (Thioulouse et al. 2018).

259

260 .

261 **2.3.3. Step 3: Overall characteristics of the nutrients concentrations and ratios** 262 **in the ecosystems (BGCOIA)**

263 The BCA allowed to focus on the ecosystems overall nutrients concentrations and ratios
264 along the French coast by pointing out the different responses of each station to the
265 environmental drivers. The BCA was computed so that each station is a group. This final
266 BGCOIA analysis enabled to point out the overall characteristics and co-structures at each
267 station, hence for each ecosystem.

268 **2.3.4. Step.4: Bi-decadal changes of the nutrients concentration and ratios per** 269 **stations (WGCOIA)**

270 The WCA focussed on the remaining co-structure in the data sets at each station, hence
271 for each ecosystem (i.e., temporal changes). An extra standardisation by station was
272 applied on the results of the two PCAs and the two tables of group averages were
273 subtracted by the corresponding DLMS inter-annual components. Thus, the analysis
274 enabled to focus on the long-term responses of nutrients to drivers during the two past
275 decades for each station and compare them.

276 **2.3.5. Step.5: Typology of stations according to the bi-decadal response of**
277 **nutrients concentrations and ratios to the drivers**

278 An Euclidean distance matrix was computed for each month, so a total of 240 distance
279 matrices (240 dates) were computed, each giving the Euclidean distances between each
280 station at a given month. The « station x station » couples were then ranked based on their
281 distance before being summed over the months to constitute a global distance matrix. A
282 fuzzy partitioning coupled to a silhouette analysis were then computed on this global
283 distance matrix to find out the relevant number of clusters and the percentage of chance
284 of each station to belong to each identified cluster (Borcard et al, 2011).

285 **2.3.6. Softwares**

286 DLMS (package “dlm” (Petris, 2010)), BGC0IA and WGC0IA (package “ade4” (Bougeard
287 and Dray, 2018; Chessel et al. 2004; Dray and Dufour, 2007; Dray et al. 2007; Thioulouse
288 et al. 2018)), fuzzy partitioning (package “cluster” (Maechler et al. 2021)) and associated
289 figures (packages “ggplot2”(Wickham, 2016), “ggrepel” (Slowikowski 2021),
290 “rnatuarearth” (South, 2017), “rnatuarearthhires”, (South, 2021), “rgdal” (Bivand and
291 al., 2021), “scatterpie” (Yu, 2021) and “wesanderson” (Ram and Wickham, 2018) were
292 performed using the R software (R Development Core Team, 2021). The map (Figure 1)
293 was created with QGIS (QGIS Development Team, 2021).

294 **3. Results**

295 **3.1. Overall characteristics of the ecosystems based on nutrient** 296 **concentrations and ratios**

297 **3.1.1. Mean levels and temporal trends**

298 NO_x concentrations ranged between nearly 0 and 385 μM (Figure 3). The highest and
299 lowest annual average concentrations were recorded in the Gironde Estuary at station 18
300 (127 μM) and in the Bay of Marseille at station 27 (0.834 μM), respectively. NH₄⁺
301 concentrations ranged between nearly 0 and 14.0 μM. The highest and lowest annual
302 mean concentrations were recorded in the Arcachon Bay at station 21 (4.38 μM) and in
303 the Bay of Banyuls at station 28 (0.187 μM), respectively. PO₄³⁻ concentrations ranged
304 between nearly 0 and 7.76 μM. The highest and lowest annual average concentrations
305 were recorded in the Gironde Estuary at station 19 (2.18 μM) and in the Bay of Banyuls at
306 station 28 (0.0320 μM), respectively. Si(OH)₄ concentrations ranged between nearly 0
307 and 264 μM. The highest and lowest annual mean concentrations were recorded in the
308 Gironde Estuary at station 18 (120 μM) and in the Bay of Banyuls at station 28 (1.49 μM),
309 respectively. N/P ratio highest and lowest average were recorded in the Arcachon Bay
310 (194) and in the EEC (15) respectively. Si/N ratio highest and lowest mean were recorded
311 in the Arcachon Bay (27) and in the WEC (0.75) respectively. Si/P ratio highest and lowest
312 mean were recorded in the Arcachon Bay (302) and in the North Sea (10) respectively.
313 All nutrients related models can be found in Supplementary material B.

314 Although the four nutrients concentrations tended to show either no or decreasing trends
315 at most of the stations within the studied period, their changes as well as changes in ratios,

316 differed both between and within ecosystems. Most of the time (except for NO_x), when no
317 significant changes were detected over the bi-decadal period, a trend inversion was
318 highlighted (Figure 4), meaning that some changes occurred during the study period.

319 Overall, NO_x significantly increased only in the Gironde Estuary (station 18) and in the
320 Arcachon Bay (stations 21, 22, 23, 26) and NH_4^+ increased only in the Western English
321 Channel (station 14). PO_4^{3-} significantly increased at a few scattered stations, one station
322 out of four in the Bay of Somme (station 12), the two stations of the Western English
323 Channel (stations 13 and 14), the Bay of Brest station (station 15), one out of three
324 stations sampled in the Gironde Estuary (station 20) and the one station recorded in the
325 Bay of Banyuls (station 28). Si(OH)_4 significantly increased in the inner Bay of Somme
326 (station 9), in the Bay of Quiberon (station 16), in the Bay of Vilaine (station 17), in the
327 Gironde Estuary (stations 18 to 20) and in the Arcachon Bay (stations 21, 22, 23 and 26).

328 The inner Arcachon Bay (stations 21 to 26) was one of the scarce ecosystems where NO_x
329 and Si(OH)_4 significantly increased at most stations: NO_x concentrations tripled at some
330 stations and Si(OH)_4 was multiplied by 1.5 on average. However, NH_4^+ showed no
331 significant monotonic trend and PO_4^{3-} decreased by almost two folds at all the stations of
332 this ecosystem.

333 Following these nutrients concentrations changes, ratios significantly increased or
334 showed no significant monotonic trends at most stations. In the Eastern English Channel,
335 N/P decreased at two (stations 7 and 8) out of five stations (stations 4 to 8) and was
336 associated with significant decreasing NO_x and NH_4^+ concentrations and stable PO_4^{3-}
337 concentrations with no inversion. The same patterns were spotted for the Si/P and Si/N
338 as the Si(OH)_4 concentrations significantly decreased. In the Western English Channel and
339 the Bay of Brest (stations 13, 14 and 15), N/P and Si/P decreased following the PO_4^{3-}

340 concentrations increase and Si/N decreased at the one station where NH_4^+ concentrations
341 increased. In the Arcachon Bay (stations 21 to 27), Si/N significantly decreased because
342 the NO_x concentrations increase was higher than for $\text{Si}(\text{OH})_4$. N/P also decreased in the
343 Bay of Banyuls (stations 28) due to the decreasing NO_x and NH_4^+ and increasing PO_4^{3-} .

344 **3.1.2. Spatial discrimination and drivers**

345 Because it was complicated to synthesise the observed diversity in terms of nutrients
346 concentrations and their bi-decadal variability, ordination techniques such as the BGCIOA
347 enabled to discriminate the coastal ecosystems to have an overall image.

348 The BGCIOA discriminates the stations along a 'nutrients ratio axis' (first axis on Figure
349 5a) from the English Channel (lower Si/P ratio) to the Arcachon Bay (higher Si/P ratio)
350 and along a 'concentration axis' (second axis on Figure 5a) from the Gironde estuary
351 (higher concentrations) to the Mediterranean Sea (lower concentrations) (Figure 5a and
352 b). Also, the BGCIOA discriminates the stations along a 'temperature axis' (first axis on
353 Figure 5c) from the northern (lower temperature) to the southern (higher temperature)
354 stations and along a 'salinity axis' (second axis on Figure 5c) from the Gironde estuary
355 (lower salinity) to the Mediterranean Sea (higher salinity) (Figure 5c and d).

356 Two ecological gradients were highlighted by both the nutrients and drivers. First, a
357 latitudinal-like gradient expressed through temperatures, nutrient ratios, and wind
358 directions that opposed the warm southernmost stations located in the Gironde Estuary,
359 the Arcachon Bay and the Mediterranean Sea, which exhibited a high Si/P ratio, to the cold
360 northernmost stations located in the North Sea, the English Channel and the northern Bay
361 of Biscay, which exhibited a low Si/P ratio. Secondly, a 'trophic status' gradient expressed
362 through continental inputs (river flow, nutrient concentration) and chlorophyll *a*

363 concentrations opposed the eutrophic Gironde Estuary to the oligotrophic Mediterranean
364 ecosystems. High nutrient concentrations were thus associated with low salinity and high
365 precipitations, river flow and chlorophyll *a* concentrations. Apart from wind intensity,
366 only local drivers showed up in the expression of these gradients and therefore
367 discriminated the stations and ecosystems from one another.

368

369 **3.2. Ecosystem trajectories and typologies**

370 **3.2.1. Nutrient trajectories**

371 Four groups of stations were identified based on the observed temporal variability.
372 Nutrients concentrations and ratios changes were expressed as trajectories and mean
373 trajectories for each of the four identified groups. These trajectories were projected onto
374 the correlation circle. They indicate the changes in nutrients concentrations and ratios.
375 When a trajectory is directed towards a parameter, it means that this parameter
376 increased. Inversely, when a trajectory is directed away from a parameter, it means that
377 this parameter decreased.

378 NO_x , NH_4^+ and $\text{Si}(\text{OH})_4$ were opposed to the Si/N ratio on the first axis and PO_4^{3-} was
379 opposed to both the N/P and Si/P ratios on the second axis. N and Si both being opposed
380 to Si/N indicated that N-changes range were relatively wider than Si changes. P being
381 opposed to both N/P and Si/P indicated that P-changes range were relatively wider than
382 for N and Si.

383

384 *The Arcachon Bay group*

385 Group A (Figure 6b top left, purple in Figure 6c) encompassed all the stations of the
386 Arcachon Bay (stations 21 to 27). Thus, group A was defined as “The Arcachon Bay group”.
387 This group was characterised by increasing NO_x and Si(OH)_4 , rather stable NH_4^+ and
388 decreasing PO_4^{3-} concentrations (Figure 4) and by increasing N/P and Si/P ratio as well
389 as decreasing Si/N (Figure 4). The trajectories of the six inner stations were very close
390 one from another and were directed from the top right corner to the bottom left, meaning
391 that the stations were mostly characterised by increasing NO_x , Si(OH)_4 and N/P as well as
392 decreasing Si/N (Figure 6a and b).

393

394 *The group of strong continental influence*

395 Group B (Figure 6b top left, blue in Figure 6c) encompassed the two inner-most stations
396 of the Bay of Somme (stations 9 and 10), Ouest Loscolo (station 17) in the Bay of Vilaine,
397 the Gironde Estuary (stations 18, 19 and 20) and Frioul (station 29) in the Bay of
398 Marseille. This group was characterised by rather stable NO_x and PO_4^{3-} , rather decreasing
399 NH_4^+ and rather increasing Si(OH)_4 (Figure 4). Regarding nutrients ratios, this group was
400 characterized by stable N/P and increasing Si/N and Si/P. Including the estuarine stations
401 and the closest stations to the river mouths, apart from Frioul, it was defined as “The
402 group of strong continental influence”. Frioul apart (mean salinity index: 0.991), the mean
403 salinity index of each station ranges between 0.080 and 0.922. The trajectories of the
404 stations within this group were all directed along the horizontal axis, from left to right,
405 with variations on the vertical axis. The stations within this group were mostly
406 characterised by decreasing ammonium, by increasing Si/N for the first half of the period
407 and increasing Si/P for the second half (Figure 6a and b).

408

409 *The group of moderate continental influence*

410 Group C (Figure 6b bottom left, red in Figure 6c) encompassed six out of eight stations of
411 the North Sea (stations 1, 2 and 3) and the Eastern English Channel (stations 4, 5 and 6),
412 the two outermost stations of the Bay of Somme (stations 11 and 12) and station Men er
413 Roue (station 16) in the Bay of Quiberon. This group was characterised by decreasing NO_x ,
414 NH_4^+ and Si(OH)_4 and rather stable PO_4^{3-} concentrations (Figure 4). Regarding the
415 nutrients ratios, this group was characterized by increasing Si/P and Si/N as well as rather
416 stable N/P (Figure 4) so that it was defined as “The group of moderate continental
417 influence”. The mean salinity index of each station ranges between 0.937 and 0.973. The
418 trajectories of all the stations were close from one another and were positioned along the
419 horizontal axis, from left to right with very little variations along the vertical axis. The
420 stations within this group were mostly characterised by decreasing NO_x and NH_4^+ as well
421 as increasing Si/N and Si/P (Figure 6).

422

423 *The group of poor continental influence*

424 Group D (Figure 6b bottom right, green in Figure 6c) encompassed the remaining two
425 stations of the Eastern English Channel (stations 7 and 8), the two stations of the Western
426 English Channel (13 and 14), Portzic (station 15) in the Bay of Brest and Sola (station 28)
427 in the Bay of Banyuls. This group was characterised by decreasing NO_x , NH_4^+ and Si(OH)_4 ,
428 and increasing PO_4^{3-} concentrations. Regarding the nutrients ratios, this group was
429 characterized by rather stable or decreasing Si/P and Si/N as well as decreasing N/P. It
430 was thus defined as “The group of poor continental influence”. Except for Point C (station
431 7; mean salinity index: 0.963) the mean salinity index of each station ranges between
432 0.980 and 0.994. The trajectories of the stations were not very close from one another, but

433 the mean trajectory was directed from the bottom left to the top right corner. All the
434 stations were mostly characterised by decreasing NO_x , $\text{Si}(\text{OH})_4$ and N/P.

435

436 **3.2.2. Drivers changes**

437 Similarly to nutrients, it was possible to project the drivers changes once the spatial effect
438 was removed (Figure 7a) and to group the stations by common trajectories (Figure 7b).

439 Two groups with different drivers changes were detected (Figure 7c). Unlike for
440 nutrients, these drivers segregated the stations along a north-south gradient. Group A
441 gathered the northern stations from the North Sea to the Bay of Vilaine (stations 1 to 17)
442 apart from the Bay of Quiberon (station 16), whereas group B gathered the southern
443 stations from the Gironde Estuary to the Mediterranean Sea (stations 18 to 29) in addition
444 to the Bay of Quiberon (station 16). The northern stations exhibited a V-shaped trajectory
445 and the southern stations a more linear trajectory. Despite the differences in trajectories,
446 precipitations, wind-speed and direction, as well as pressure were the most involved
447 drivers. Temperature also accounted through the NHT but to a lesser extent. It should be
448 noticed that local drivers, apart from local wind intensity (l_{wind}), are poorly represented
449 on the correlation circle of the WGCIOA (Figure 7a) in contrast to the correlation circle of
450 the BGCIOA (Figure 5c and section 3.1.2.).

451

452 **4. Discussion**

453 **4.1. Differences between ecosystems**

454 Although the studied ecosystems are not very distant from one another, various studies
455 pointed out their contrasted characteristics. Using a panel of particulate, dissolved and
456 hydro-physical parameters, it was showed that the French coastal ecosystems
457 experienced both similar (salinity) or opposed (dissolved and particulate organic matter)
458 changes during the last two decades (Goberville et al. 2010, Lheureux et al. 2021). At an
459 annual timescale, the contribution of organic matter sources to coastal particulate organic
460 matter along the French coast (including common stations with the present study)
461 followed a continent-ocean gradient (Liénart et al. 2017, 2018). In other French coastal
462 ecosystems where phytoplankton biomass was used as a proxy of ecosystems trophic
463 status, their eutrophication trajectories were different (Derolez et al. 2020, Le Fur et al.
464 2019; Ratmaya et al. 2019). The bay of Vilaine showed trajectories towards
465 eutrophication despite decreasing continental discharges (Ratmaya et al. 2019), whereas
466 the French Mediterranean lagoons showed trajectories towards oligotrophication. The
467 latter were mainly influenced by air temperature, winds and rainfall (Derolez et al. 2020).
468 At a higher trophic level and at a wider spatial scale, different trophic pathways structures
469 and fish assemblages were identified between the three French ecoregions: the English
470 Channel Bay, the Bay of Biscay and the Gulf of Lions (Cresson et al. 2020). These
471 differences were mainly driven by primary production and environmental drivers,
472 highlighting the contrast between the French ecosystems.

473

474 The *in-situ* parameters used in the present study highlighted the patent contrasts
475 between the studied ecosystems in terms of temperature or continental discharges, in
476 addition with their differences in geomorphology, tidal regime and trophic status (Table
477 1).

478 First, the studied stations and ecosystems were segregated along a temperature gradient
479 (Figure 5). Indeed, there is a patent contrast between the French local climatic
480 characteristics (Joly et al. 2010): the Mediterranean climate experiences higher
481 temperatures (e.g., yearly average temperature of 16°C in the Bay of Marseille) than the
482 oceanic climate of northern France (e.g. yearly average temperature of 11°C in the North
483 Sea). Differences in wind conditions were also pointed out (Figure 5b). The latter two
484 ecoregions (Mediterranean Sea and North Sea) were two extremes between which the
485 other ecosystems, all under oceanic climate (Joly et al. 2010) were gradually characterised
486 by higher temperatures and lower precipitations (from the Eastern English Channel in the
487 North to the Bays of Marseille and Banyuls in the South). The gradient in nutrients ratios
488 was in the same direction: higher ratios values were recorded in the Mediterranean
489 ecosystems than in the northern ecosystems.

490 Secondly, the stations and ecosystems were segregated along a continental influence and
491 trophic status gradient (i.e., the eutrophic Gironde Estuary was opposed to the
492 oligotrophic Mediterranean bays). Both river flows and salinity were proxies of
493 continental discharges. These two parameters were related to the differences in trophic
494 status as illustrated by the nutrients and chlorophyll *a* concentrations. Analysis 1 (Figure
495 5) also highlighted the fact that nutrients were mainly brought by rivers in the French
496 temperate coastal ecosystems. The other studied ecosystems were gradually distributed
497 between the Gironde Estuary and the Mediterranean bays. Such a gradient in trophic

498 status of ecosystems has also been previously pointed out as a driver of the composition
499 of the particulate organic matter for similar ecosystems (Liénart et al. 2017, 2018).

500

501 The fact that the studied ecosystems are subjected to different drivers and / or to their
502 different magnitudes implies local consequences, either directly or indirectly due to the
503 drivers. For example, the western Mediterranean Sea is subjected to direct atmospheric
504 deposition with a higher N/P ratio than the seawater (Durrieu de Madron et al. 2011).
505 Differences in wind and precipitation regimes could therefore modify the atmospheric
506 deposition, which could have major consequences on the functioning of Mediterranean
507 ecosystems due to their oligotrophic conditions (Durrieu de Madron et al. 2011). In meso-
508 or eutrophic ecosystems, such differences might not have similar consequences on
509 nutrients concentrations and ratios. The influence of precipitations on nutrients
510 concentrations and ratios does not only stand at local scale but also at the scale of the
511 watershed through a combination of processes. Precipitation leads to nutrient leaching
512 from the soils toward the rivers and contributes to river flow (Blöschl et al. 2007).
513 Differences in precipitations then resulted in differences in continental discharges, and
514 consequently in nutrients concentrations and ratios due to the strong connection between
515 rivers and coastal ecosystems (Seitzinger et al. 2002). The consequences of such
516 differences depend on the continental influence in each ecosystem but also on the land
517 use and the associated run-off waters in the watersheds. The consequences were thus
518 expected to be very different between the agricultural lands of French Brittany including
519 the Western English Channel (stations 13 and 14) and Bay of Brest (station 15), both
520 under lower continental influence, and the urban and yet subjected to low continental
521 discharges Bay of Marseille (station 29). At last, differences in water temperature may

522 induce differences in nutrients concentrations and ratios because higher water
523 temperatures induce stronger stratification that can disrupt vertical nutrient inputs and
524 remineralisation processes (Doney, 2006).

525

526 **4.2. Temporal changes of ecosystems**

527 Despite the importance of local drivers to characterise the French coastal ecosystems, it
528 appeared that regional and large-scale drivers were involved in the temporal changes.
529 Ecosystem responses to large-scale climate and anthropogenic drivers are complex to
530 assess because of their non-linearity. This non-linearity can be attributed to the involved
531 processes (Cloern et al. 2010) and to the rather indirect influence of the drivers. For
532 example, precipitation rates and rivers discharge as well as the Eastern Atlantic Pattern
533 (EAP) influenced winter nutrients concentrations in the Bay of Brest (Tréguer et al. 2014).
534 Yet, river discharge is locally influenced by local precipitations (Blöschl et al. 2007),
535 themselves under the spectrum of large-scale precipitations and wind circulation and
536 thus under the prism of the teleconnection indices that summarize climate at a large scale
537 (Kingston et al. 2006, Steirou et al. 2017).

538 In addition, ecosystems answers can follow different pathways: ecosystems can come
539 back to a previous state or switch to another equilibrium (Scheffer & Carpenter 2003,
540 Scheffer et al. 2009). Many studies detected abrupt changes during the late 1990s and
541 early 2000s in the western Europe and French coastal ecosystems either using
542 biogeochemical parameters (Goberville et al. 2010, Lheureux et al. 2021), phytoplankton
543 communities (David et al. 2012; Hernández-Fariñas et al 2014), zooplankton
544 communities (Richirt et al. 2019), fish assemblages (Chaalali et al. 2013) or birds (Luczak

545 et al. 2011). Although the processes that triggered these changes had not been explicitly
546 described as a whole, it appeared that it was due to a combination of both climatic and
547 direct anthropogenic pressures that were hard to disentangle. The obvious assessment
548 was that the French coastal ecosystems were struggling with obvious changes during the
549 past decades.

550

551 **4.2.1. Overall changes in nutrients and drivers**

552 Along the 20-year studied period the overall nutrients concentrations in the French
553 coastal ecosystems tended to decrease. The main exception was the Arcachon Bay where
554 inorganic dissolved nitrogen and silicic acid concentrations increased due to internal
555 ecosystem functioning (Lheureux et al. 2022).

556 The overall decrease in nutrients concentrations could be attributed to both changes in
557 climatic and continental drivers as well as to management policies. Local and regional
558 precipitations appeared to be decreasing and changes in regional winds were also spotted
559 (Supplementary material C and D). Rainfall decline (except in south-western France) and
560 changes in winds affected continental discharges (Blöschl et al. 2007) at local (i.e., local
561 run-off) and larger (i.e. watershed) scale and might be responsible for continental
562 discharges overall stability or decrease (Supplementary material E; Friedland et al. 2021),
563 which might have induced the overall decrease in nutrients concentrations in the coastal
564 ecosystems (Seitzinger et al. 2002). In addition, continental nutrients concentrations also
565 decreased (Supplementary material E) probably due to such decreases of precipitations
566 and continental discharges, as reported in the North Sea (Radach & Pätsch 2007) and of
567 management policies.

568 Indeed, France had reduced the use of phosphate in domestic detergent from the middle
569 of year 2007 (Decree n°2007-491, March 29, 2007). During the studied period, PO_4^{3-}
570 concentrations dropped in many of the studied ecosystems. This could be a consequence
571 of this decree although such decreasing trends were observed from the 1990 in numerous
572 south-western Europe rivers, including the biggest French rivers (Romero et al. 2013).
573 This highlights the importance and the need of appropriate management policies and
574 mitigation to fight against eutrophication (Friedland et al. 2021) as PO_4^{3-} was often the
575 limiting nutrient in the French coastal ecosystems at the beginning of the productive
576 period considering the Redfield ratio as the reference value (Glé et al. 2008, Souchu et al.
577 2010) as PO_4^{3-} limitation could arise during the spring period during dry years. However,
578 it was hard to disentangle the real impact of this measure from the change in precipitation
579 and associated river discharge that occurred at the same period.

580 Changes in regional climate and atmospheric circulation had already been raised and
581 suspected to have caused an abrupt change *ca* 2005 in the French coastal ecosystems
582 (Goberville et al. 2010; Lheureux et al, 2021). Our study was framed by the above
583 mentioned early 2000s abrupt changes as it was noticeable in the nutrients and drivers
584 groups mean trajectories between 2005 and 2010. It was also probable that the Atlantic
585 Meridional Overturning Circulation (AMOC) played a role in the regional climate changes.
586 The AMOC was reported to be decreasing with a starting point between 2005 (Chen &
587 Tung 2018) and 2009/2010 (Roberts et al. 2013). A decreasing AMOC leads to a decrease
588 of precipitations and changes in the atmosphere circulation patterns over Europe
589 (Jackson et al. 2015), as seen above. A decreasing AMOC would also alter the heat transfer
590 from the tropical regions to Europe and would result in decreasing temperature as seen
591 from 2000 to *ca* 2010. The increase in temperature from 2010 onwards should also

592 participate in strengthening water stratification and thus might have reduced the vertical
593 advection of nutrients from deeper waters.

594 However, quantifying the importance of the AMOC was not the goal of this study but not
595 mentioning a potential role of the AMOC would have been a shortage as it is known that
596 the hydrosphere and the atmosphere are connected.

597

598 In theory, following these climatic and anthropogenic changes, nutrients concentrations
599 decrease (or trend inversions) as well as changes in their ratios should arise. This
600 happened in most but not all the studied ecosystems. Such discrepancies highlight the
601 need to focus on the local scale with local climatic variations, land use in the watersheds
602 and ecosystems functioning in multi-ecosystemic studies.

603

604 **4.2.2. Typology of ecosystem trajectories based on changes in nutrients** 605 **concentrations and ratios**

606 Ecological trajectories are useful tools to analyse and compare changes between
607 ecosystems (Lamothe et al. 2019). They do not only provide synthetic information
608 regarding changes, e.g., in nutrients concentrations and ratios, but also enables to
609 characterize ecosystem status and to identify its potential changes. Ecosystem state
610 changes could either be inexistent, linear, abrupt and sustained or abrupt and temporary
611 (Ratajczak et al. 2018). Identifying state changes could greatly help to understand the
612 temporal variability and its implications for ecosystems.

613

614 The Arcachon Bay Group

615 The Arcachon Bay was the only ecosystem where both N- and Si-nutrients concentrations
616 increased during the studied period. The processes involved in these changes are only
617 summarized here as they are deeply described and discussed in Lheureux et al. (2022).
618 The main hypothesis behind the increase in N- and Si-nutrients concentrations is linked
619 to the decrease in the biomass and sediment surface coverage of the seagrass (*Zostera*
620 *noltii*) meadow (Plus et al. 2010). This decrease led to a lowered nutrients consumption
621 by the seagrass as well as, on the other hand, to wobblier sediments, the latter causing an
622 increase in benthic nutrient advection and particulate resuspension. Both processes
623 explained the increase in N- and Si-nutrients concentrations, which led to an increase in
624 phytoplankton biomass (Lheureux et al. 2022). Because of both the difference in nutrients
625 needs between *Zostera* and phytoplankton and the higher need in P relatively to N and Si
626 for the phytoplankton than for *Zostera*, the increase in N- and Si-nutrients concentrations
627 and in phytoplankton biomass induced a decrease in PO_4^{3-} concentrations in this
628 ecosystem where the phytoplankton production is mainly P-limited (Glé et al. 2008).
629 Consequently, the N/P and Si/P ratios increased.

630 Following the classification of Ratajczak et al. (2018), the mean trajectory of the Arcachon
631 Bay group can be considered as a potential sustained change of state: the ecosystem
632 shifted between 2002 and 2013 before stabilising in a rotating movement indicating a
633 relative stability during the last years of the studied period. The *Zostera* meadow decrease
634 is likely responsible for the nutrients changes (Lheureux et al. 2022). Studying the
635 Arcachon Bay using this statistical approach enabled to detect a potential beginning of the
636 abrupt change in 2002. It might have been triggered by the extremely low river discharges
637 in 2002 that could then have induced a disequilibrium in the bay.

638

639 *The group of strong continental influence*

640 All stations of this group, except Frioul (station 29) in the Bay of Marseille, were either in
641 an estuary or close to an estuary within a bay. It is important to note that station Frioul is
642 the station with the lowest affiliation to this group compared to the six others.

643 Frioul is geographically close to the Rhône river (40 km eastward the delta) but is in fact
644 slightly under its influence: 1) the Coriolis acceleration flushes the Rhône plume
645 westward, 2) the intrusion of Rhône water in the Bay of Marseille is scarce (up to 8 times
646 a year and for less than three days each time) and mainly limited to the northern part of
647 the bay while Frioul is located in its southern part and is protected on its west-side by the
648 Frioul island (Frayse et al. 2014). It is more likely that the proximity of the city of
649 Marseille is a factor explaining the presence of station Frioul into this group. The
650 Huveaune river (Marseille's river) is a small stream with low continental inputs but with
651 the greatest urban lands share among the studied watersheds. In addition, some of the
652 Huveaune river waters are derived to an outlet in the south of the city (5km eastward the
653 bay of Marseille) and mixed with effluents from waste-water treatment plants (WWTPs).
654 Although the outlet flow is composed by equal proportions of WWTPs and Huveaune
655 waters, more than 80% of the NH_4^+ , NO_2^- and PO_4^{3-} concentrations come from the urban
656 effluents (Oursel et al. 2013). It was therefore possible that the "estuarine-like"
657 characteristics of the trajectory of station Frioul were due to this outlet influence.

658 The stations of the group of the strong continental influence were the only stations (with
659 the Arcachon Bay stations) where $\text{Si}(\text{OH})_4$ concentrations increased. $\text{Si}(\text{OH})_4$ main origin
660 in the coastal ecosystems is continental, mainly due to rock weathering. Thus $\text{Si}(\text{OH})_4$
661 concentrations should have decreased following the decrease of both global precipitation

662 and river discharge. The increase in Si(OH)_4 concentrations might have been due to the
663 recovery from eutrophication processes in the rivers, which can induce the release of the
664 retained Si(OH)_4 and consequently can result in the increase in Si(OH)_4 export to the
665 coastal ecosystems (Prins et al. 2012). Similar hypotheses have been pointed out for the
666 Bay of Vilaine (station 17), and for the Bay of Somme (station 9 and 10). Regarding the
667 Bay of Vilaine, PO_4^{3-} and chlorophyll-*a* concentrations decreased in the Loire and Vilaine
668 rivers as well as in the bay, whereas Si(OH)_4 concentrations increased in the bay, in line
669 with internal benthic regeneration (Ratmaya et al. 2019). The eutrophication processes
670 also decreased upstream the Bay of Somme with an increase in Si(OH)_4 concentrations in
671 the inner bay (Lefebvre et al. unpublished). We assume that similar hypotheses also stand
672 for the Gironde estuary.

673 The mean trajectory of this group enabled to detect a potential abrupt and temporary
674 change of state in 2005. The mean trajectory indicated a shift from the direction towards
675 lower NO_x concentrations and higher Si/P ratio to the direction towards lower PO_4^{3-}
676 concentration and higher Si/P ratio, with an overall net trajectory toward lower
677 ammonium concentrations. The shift is coherent with both the start of the AMOC decrease
678 (see section 4.2.1) and the removal of PO_4^{3-} from public detergents. However, this abrupt
679 change was not obvious in the trajectories of all the stations of this group, probably
680 because of the high diversity of local drivers encountered in the concerned ecosystems.

681

682 *The group of medium continental influence*

683 All stations of this group belong to four ecosystems located in the northern half of the
684 study area. The nutrient concentrations changes of this group were the closest to the
685 expected changes following the decrease of precipitations, continental discharges and the

686 implementation of management policies on land. The mean trajectory is linear and
687 seemed to indicate relatively slow changes at the beginning of the study period (small
688 gaps between points). It exhibited an overall change towards a decrease of the N- and Si-
689 nutrients, indicating changes towards mesotrophy, and an increase of Si/N and Si/P
690 ratios. The fact that eight (over nine) stations of the group of medium continental
691 influence belong to drivers group “1” indicates that changes in nutrients concentrations
692 and ratios are clearly in relation to the decrease in precipitations and to changes in wind
693 intensity and directions. The year of inflexion corresponds to the period of change of the
694 AMOC (see section 4.2.1).

695 Since the trajectory of this group exhibited a “smooth” shape, it could be interesting to
696 have a look at the speed of the changes in order to check if the ecosystems of this group
697 are potentially rather moving away or drawing near a state of “stability”. Stability has lots
698 of different definitions due to its different aspects and thus different index to define it (e.g.
699 resistance, resilience, robustness; Saint-Béat et al. 2015). One way to check this is to study
700 the distance between each observation. If the distance is decreasing, it indicated that the
701 ecosystems might draw near a state of ‘stability’ (Lamothe et al. 2019). The distance
702 between each observation were greater at the beginning of the study and kept decreasing
703 between 2016 and 2019. Although declaring that these ecosystems are approaching a
704 period of higher stability was not possible by lack of time span, it would be interesting to
705 test the hypothesis in the upcoming years.

706

707 *The group of poor continental influence*

708 The stations of this group belong to four ecosystems distributed along the French coasts.
709 Despite Point C in the Eastern English Channel (station 7; discussed below), the stations

710 of this group are under poor continental influence. Estacade and Astan in the Western
711 English Channel (stations 13 and 14) are subjected to very poor continental influence
712 from the Penzé river, a small stream which nutrients concentrations and discharge data
713 were not available for the studied period. Portzic in the inlet of the Bay of Brest (Station
714 15) is located in a semi-enclosed ecosystem receiving freshwater from the Aulne River
715 and the Elorn River. However, its location in the inlet of a macrotidal bay combined with
716 the fact that the samplings have been performed at high tide, implies that the sampling
717 water mass is mainly influenced by oceanic waters (Le Pape & Menesguen, 1997). This is
718 well illustrated by the averaged salinity index of 0.981, indicating that on average over the
719 study period, the sampled water is composed at 98% of marine water. Sola in the Bay of
720 Banyuls (station 28) is under a very low influence of some Southern France rivers (mean
721 salinity index of 0.98) since it is southward because of the overall water circulation in the
722 continental shelf of the Gulf of Lion. Point C and L, found in the Eastern English Channel
723 (stations 7 and 8), such as stations 4, 5 and 6 but these five stations were segregated into
724 two groups: the groups of poor and medium continental influence, respectively. In
725 contrast to station 8, which showed a mean salinity index of 0.980 characteristic of this
726 group of 'poor continental influence', station 7 in the English Channel exhibited an
727 averaged salinity index of 0.963, which is rather characteristic of the group of 'moderate
728 continental influence'. In fact, this station is located within the 'coastal flow' — a water
729 mass composed by the diluted river plumes of the Seine River, the Somme River and other
730 minor rivers — that is directed eastward along the French coast because of the overall
731 water circulation (Brylinski et al. 1991). Station 7 shared the same characteristics than
732 the other stations of this group (stations 8, 14, 15 and 28), i.e., the only group where the
733 N/P ratio decreased over the study period. Surprisingly, stations 4; 5 and 6 do not belong
734 to the same group as stations 7 and 8. This is probably because the former stations are

735 under the influence of the Liane River, a small stream (38 km) pouring in the city of
736 Boulogne-Sur-Mer.

737 The group of poor continental influence was the only group encompassing stations at
738 which the N/P ratio decreased during the study period. This decrease was due to the
739 increase in PO_4^{3-} concentration and/or the decrease in DIN concentration. Interestingly,
740 these stations exhibited, among all other stations, the lowest mean PO_4^{3-} concentrations
741 over the study period (except Frioul). The concerned ecosystems were characterised by
742 low human population density and watershed made of slow-weathering and nutrient-
743 poor bedrock from which low P pattern should result (Farmer et al. 2018).

744 The mean trajectory of this group displayed overall changes towards decreasing NO_x ,
745 NH_4^+ and $\text{Si}(\text{OH})_4$ concentrations and N/P ratio as well as increasing PO_4^{3-} concentrations.
746 The hypotheses explaining these changes in nutrient concentrations and ratios are not
747 straightforward yet. Since these stations are of poor continental influence, possible
748 explanation had to be found among internal processes of the water masses. However,
749 from our data sets, there is no straightforward evidence of specific higher or lower
750 remineralization processes and because changes may be due to other reasons, e.g.,
751 changes in phytoplankton community that may have different needs in N/P/Si ratios
752 nowadays compared to the beginning of the study period.

753

754 **4.3. Conclusion**

755 The nutrients concentrations and their ratios in the studied French coastal ecosystems
756 were influenced both by local and large-scale drivers, as well as by climatic and
757 anthropogenic drivers (e.g., AMOC decrease and its implications on temperature and

758 atmospheric circulation, as well as the PO_4^{3-} regulation policies). Although it was hard to
759 truly ascertain the role of one specific driver at one given scale because they are all inter-
760 networked, it was possible to point out significant cascade effects. Such effects resulted
761 from the non-linear and dynamic characteristics of the drivers (Cloern et al. 2010) and
762 were previously reported in some of our studied ecosystems (i.e., Chaalali et al. 2013). In
763 addition, studying a longer time period (at least 30 years) might have enabled to have
764 better large-scale climate signals and thus to point out better connections between the
765 different spheres. Unfortunately, such long time periods data sets are not yet available for
766 these ecosystems. Interestingly, the data sets showed that the spatial variability of
767 nutrients concentrations and ratios mainly depended on local drivers (local climate and
768 river flow) while their overall bi-decadal variability depends on large-scale drivers
769 (mainly regional climate). Nevertheless, a form of geographical typology of the bi-decadal
770 variability appeared and was linked to local drivers: e.g., the seagrass meadow for the
771 Arcachon Lagoon and the freshwater influence for the other groups of stations. In
772 different words, while large-scale drivers were tangled with local drivers in the definition
773 of the overall nutrients concentrations and ratios changes, it seemed that even under
774 different local characteristics and influences the ecosystems responded in a similar way
775 in function of their continental influence.

776 The need for multi-scaled data in environmental studies to identify as many patterns as
777 possible is therefore highlighted. However, studying one ecosystem at a time (e.g.,
778 Lheureux et al. 2022) remained important as it allowed going deeper into the local
779 processes that were of importance to understand ecosystems functioning.

780 Nutrients concentrations and ratios are essential drivers of phytoplankton production
781 (and primary production as a whole). Their (pluri-)decadal change should undoubtedly

782 affect phytoplankton production and probably phytoplankton diversity, and subsequent
783 trophic levels, which have been reported to change at this time scale (David et al. 2012;
784 Hernández-Farinas et al. 2014). Coupling studies of (pluri-)decadal changes of nutrients
785 concentrations and ratios with phytoplankton diversity would allow to have a broader
786 view and understanding of the ecosystem functioning and its changes in the era of global
787 change.

788

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799

800 **References**

- 801 Anderson, M.J., Thompson, A.A., 2004. Multivariate Control Charts for Ecological and
802 Environmental Monitoring. *Ecol Appl* 14, 1921–1935. [https://doi.org/10.1890/03-](https://doi.org/10.1890/03-5379)
803 5379
- 804 Arcese, P., Sinclair, A.R.E, 1997. The Role of Protected Areas as Ecological Baselines. *J Wildl*
805 *Manage* 61, 587–602. <https://doi.org/10.2307/3802167>
- 806 Barnston, A.G., Livezey, R.E., 1987. Classification, Seasonality and Persistence of Low-
807 Frequency Atmospheric Circulation Patterns. *Mon. Weather Rev.*
808 [https://doi.org/10.1175/1520-0493\(1987\)115<1083:CSAPOL>2.0.CO;2](https://doi.org/10.1175/1520-0493(1987)115<1083:CSAPOL>2.0.CO;2)
- 809 Belin, C., Soudant, D., Amzil, Z., 2021. Three decades of data on phytoplankton and
810 phycotoxins on the French coast: Lessons from REPHY and REPHYTOX. *Harmful*
811 *Algae* 102, 101733. <https://doi.org/10.1016/j.hal.2019.101733>
- 812 Betts, A.K., Hong, S.-Y., Pan, H.-L., 1996. Comparison of NCEP-NCAR Reanalysis with 1987
813 FIFE Data. *Mon. Weather Rev.* 124, 1480–1498. [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0493(1996)124<1480:CONNRW>2.0.CO;2)
814 0493(1996)124<1480:CONNRW>2.0.CO;2
- 815 Beusen, A.H.W., Bouwman, A.F., Beek, L.P.H. Van, Mogollón, J.M., Middelburg, J.J., 2016.
816 Global riverine N and P transport to ocean increased during the 20th century despite
817 increased retention along the aquatic continuum 2441–2451.
818 <https://doi.org/10.5194/bg-13-2441-2016>
- 819 Bivand, R., Keitt, T., Rowlingson, B., 2021. rgdal: Bindings for the 'Geospatial' Data
820 Abstraction Library. R package version 1.5-23. [https://CRAN.R-](https://CRAN.R-project.org/package=rgdal)
821 [project.org/package=rgdal](https://CRAN.R-project.org/package=rgdal)

822 Blöschl, G., Ardoin-Bardin, S., Bonell, M., Dorninger, M., Goodrich, D., Gutknecht, D.,
823 Matamoros, D., Merz, B., Shand, P., Szolgay, J., 2007. At what scales do climate
824 variability and land cover change impact on flooding and low flows? *Hydrol. Process.*
825 21, 1241–1247. <https://doi.org/10.1002/hyp.6669>

826 Borcard, D., Gillet, F., Legendre, P. (2001). *Numerical Ecology with R*. Elsevier.
827 <https://doi.org/10.1007/978-1-4419-7976-6>

828 Bougeard, S., Dray, S., 2018. Supervised multiblock analysis in R with the ade4 package. *J.*
829 *Stat. Softw.* 86, 1–17. <https://doi.org/10.18637/jss.v086.i01>

830 Bouwman, A.F., Bierkens, M.F.P., Griffioen, J., Hefting, M.M., Middelburg, J.J., Middelkoop,
831 H., Slomp, C.P., 2013. Nutrient dynamics, transfer and retention along the aquatic
832 continuum from land to ocean: Towards integration of ecological and biogeochemical
833 models. *Biogeosciences* 10, 1–23. <https://doi.org/10.5194/bg-10-1-2013>

834 Brun, F.G., Hernández, I., Vergara, J.J., Peralta, G., Pérez-Lloréns, J.L., 2002. Assessing the
835 toxicity of ammonium pulses to the survival and growth of *Zostera noltii*. *Mar. Ecol.*
836 *Prog. Ser.* 225, 177–187. <https://doi.org/10.3354/meps225177>

837 Chaalali, A., Beaugrand, G., Boët, P., Sautour, B., 2013. Climate-Caused Abrupt Shifts in a
838 European Macrotidal Estuary. *Estuaries and Coasts* 36, 1193–1205.
839 <https://doi.org/10.1007/s12237-013-9628-x>

840 Chen, X., Tung, K.K., 2018. Global surface warming enhanced by weak Atlantic overturning
841 circulation. *Nature* 559, 387–391. <https://doi.org/10.1038/s41586-018-0320-y>

842 Chessel, D., Dufour, A.B., Thioulouse, J., 2004. The ade4 Package - I: One-table Methods. *R*
843 *News* 4, 5–10.

844 Christiansen, C., Vølund, G., Lund-Hansen, L.C., Bartholdy, J., 2006. Wind influence on tidal
845 flat sediment dynamics: Field investigations in the Ho Bugt, Danish Wadden Sea. *Mar.*
846 *Geol.* 235, 75–86. <https://doi.org/10.1016/j.margeo.2006.10.006>

847 Cloern, J.E., Hieb, K.A., Jacobson, T., Sansó, B., Di Lorenzo, E., Stacey, M.T., Largier, J.L.,
848 Meiring, W., Peterson, W.T., Powell, T.M., Winder, M., Jassby, A.D., 2010. Biological
849 communities in San Francisco Bay track large-scale climate forcings over the North
850 Pacific. *Geophys Res Lett* 37:L21602. <https://doi.org/10.1029/2010GL044774>

851 Cocquempot, L., Delacourt, C., Paillet, J., Riou, P., Aucan, J., Castelle, B., Charria, G., Claudet,
852 J., Conan, P., Coppola, L., Hocdé, R., Planes, S., Raimbault, P., Savoye, N., Testut, L.,
853 Vuillemin, R., 2019. Coastal ocean and nearshore observation: À French case study.
854 *Front. Mar. Sci.* 6, 1–17. <https://doi.org/10.3389/fmars.2019.00324>

855 Cresson, P., Chouvelon, T., Bustamante, P., Bănaru, D., Baudrier, J., Le Loc'h, F., Mauffret, A.,
856 Mialet, B., Spitz, J., Wessel, N., Briand, M.J., Denamiel, M., Doray, M., Guillou, G., Jadaud,
857 A., Lazard, C., Prieur, S., Rouquette, M., Saraux, C., Serre, S., Timmerman, C.A., Verin,
858 Y., Harmelin-Vivien, M., 2020. Primary production and depth drive different trophic
859 structure and functioning of fish assemblages in French marine ecosystems. *Prog.*
860 *Oceanogr.* 186, 102343. <https://doi.org/10.1016/j.pocean.2020.102343>

861 Culhane, C.A., Perrière, G., Considine, E.C., Cotter, T.G., Higgins, D.G., 2002. Between-group
862 analysis of microarray data. *Bioinformatics* 18, 1600–1608.
863 <https://doi.org/10.1093/bioinformatics/18.12.1600>

864 David, V., Ryckaert, M., Karpytchev, M., Bacher, C., Arnaudeau, V., Vidal, N., Maurer, D.,
865 Niquil, N., 2012. Spatial and long-term changes in the functional and structural
866 phytoplankton communities along the French Atlantic coast. *Estuarine, Coastal and*
867 *Shelf Science* 108, 37–51. <https://doi.org/10.1016/j.ecss.2012.02.017>

868 Deborde, J., Anschutz, P., Auby, I., Glé, C., Commarieu, M-V., Maurer, D., Lecroart, P., Abril,
869 G. 2008. Role of tidal pumping on nutrient cycling in a temperate lagoon (Arcachon
870 Bay, France). *Marine Chemistry* 109, 98–114.

871 Decret n°2007-491 du 29 mars 2007

872 Derolez, V., Bec, B., Munaron, D., Fiandrino, A., Pete, R., Simier, M., Souchu, P., Laugier, T.,
873 Aliaume, C., Malet, N., 2019. Recovery trajectories following the reduction of urban
874 nutrient inputs along the eutrophication gradient in French Mediterranean lagoons.
875 *Ocean Coast Manage* 171, 1–10. <https://doi.org/10.1016/j.ocecoaman.2019.01.012>

876 Derolez, V., Malet, N., Fiandrino, A., Lagarde, F., Richard, M., Ouisse, V., Bec, B., Aliaume, C.,
877 2020. Fifty years of ecological changes: Regime shifts and drivers in a coastal
878 Mediterranean lagoon during oligotrophication. *Sci. Total Environ.* 732.
879 <https://doi.org/10.1016/j.scitotenv.2020.139292>

880 Dolédec, S., Chessel, D., 1987. Rythmes saisonniers et composantes stationnelles en milieu
881 aquatique. I- Description d'un plan d'observations complet par projection de
882 variables. *Acta Oecol Oecol Generalis* 8:403–426

883 Dolédec, S., Chessel, D., 1994. Co-inertia analysis: an alternative method for studying
884 species–environment relationships. *Freshw. Biol.* 31, 277–294.
885 <https://doi.org/10.1111/j.1365-2427.1994.tb01741.x>

886 Doney, S.C., 2006. Oceanography: Plankton in a warmer world. *Nature* 444, 695–696.
887 <https://doi.org/10.1038/444695a>

888 Dray, S., Chessel, D., Thioulouse, J., 2003. Co-inertia analysis and the linking of ecological
889 data tables. *Ecology* 84, 3078–3089. <https://doi.org/10.1890/03-0178>

890 Dray, S., Dufour, A.B., 2007. The ade4 package: Implementing the duality diagram for
891 ecologists. *J. Stat. Softw.* 22, 1–20. <https://doi.org/10.18637/jss.v022.i04>

892 Dray S., Dufour A.B., Chessel D., 2007. “The ade4 Package - II: Two-Table and K-Table
893 Methods.” *R News*, 7(2), 47-52. URL:<https://cran.r-project.org/doc/Rnews/>.

894 Duarte, C.M., Dennison, W.C., Orth, R.J.W., Carruthers, T.J.B., 2008. The charisma of coastal
895 ecosystems: Addressing the imbalance. *Estuaries and Coasts* 31, 233–238.
896 <https://doi.org/10.1007/s12237-008-9038-7>

897 Durrieu de Madron, X., Guieu, C., Sempéré, R., Conan, P., Cossa, D., D’Ortenzio, F., Estournel,
898 C., Gazeau, F., Rabouille, C., Stemmann, L., Bonnet, S., Diaz, F., Koubbi, P., Radakovitch,
899 O., Babin, M., Baklouti, M., Bancon-Montigny, C., Belviso, S., Bensoussan, N., Bonsang,
900 B., Bouloubassi, I., Brunet, C., Cadiou, J.F., Carlotti, F., Chami, M., Charmasson, S.,
901 Charrière, B., Dachs, J., Doxaran, D., Dutay, J.C., Elbaz-Poulichet, F., Eléaume, M.,
902 Eyrolles, F., Fernandez, C., Fowler, S., Francour, P., Gaertner, J.C., Galzin, R., Gasparini,
903 S., Ghiglione, J.F., Gonzalez, J.L., Goyet, C., Guidi, L., Guizien, K., Heimbürger, L.E.,
904 Jacquet, S.H.M., Jeffrey, W.H., Joux, F., Le Hir, P., Leblanc, K., Lefèvre, D., Lejeusne, C.,
905 Lemé, R., Loÿe-Pilot, M.D., Mallet, M., Méjanelle, L., Mélin, F., Mellon, C., Mérigot, B.,
906 Merle, P.L., Migon, C., Miller, W.L., Mortier, L., Mostajir, B., Mousseau, L., Moutin, T.,
907 Para, J., Pérez, T., Petrenko, A., Poggiale, J.C., Prieur, L., Pujo-Pay, M., Pulido-Villena,
908 Raimbault, P., Rees, A.P., Ridame, C., Rontani, J.F., Ruiz Pino, D., Sicre, M.A., Taillandier,
909 V., Tamburini, C., Tanaka, T., Taupier-Letage, I., Tedetti, M., Testor, P., Thébault, H.,
910 Thouvenin, B., Touratier, F., Tronczynski, J., Ulses, C., Van Wambeke, F., Vantrepotte,
911 V., Vaz, S., Verney, R., 2011. Marine ecosystems’ responses to climatic and
912 anthropogenic forcings in the Mediterranean. *Prog. Oceanogr.* 91, 97–166.
913 <https://doi.org/10.1016/j.pocean.2011.02.003>

914 Enfield, D.B., Mestas-Nuñez, A.M., Trimble, P.J., 2001. The Atlantic multidecadal oscillation
915 and its relation to rainfall and river flows in the continental U.S. *Geophys. Res. Lett.*
916 28, 2077–2080. <https://doi.org/10.1029/2000GL012745>

917 Facca, C., 2011. Trophic Conditions in the Waters of the Venice Lagoon (Northern Adriatic
918 Sea, Italy). *Open Oceanogr. J.* 5, 1–13.
919 <https://doi.org/10.2174/1874252101105010001>

920 Farmer, A.M., 2018. Phosphate pollution: A global overview of the problem. In: Schaum,
921 C., (Ed), *Phosphorus: Polluter and Resource of the future. Removal and Recovery*
922 *from Wastewater*. IWA Publishing.

923 Feng, Y., Friedrichs, M.A.M., Wilkin, J., Tian, H., Yang, Q., Hofmann, E.E., Wiggert, J.D., Hood,
924 R.R., 2015. Chesapeake Bay nitrogen fluxes derived from a land-estuarine ocean
925 biogeochemical modeling system: Model description, evaluation, and nitrogen
926 budgets. *J. Geophys. Res. G Biogeosciences* 120, 1666–1695.
927 <https://doi.org/10.1002/2015JG002931>

928 Franquet, E., Chessel, D., 1994. Approche statistique des composantes spatiales et
929 temporelles de la relation faune-milieu. *Comptes Rendus de l'Académie des sciences*
930 *Série 3* 317:202–206

931 Franquet, E., Dolédec, S., Chessel, D., 1995. Using multivariate analyses for separating
932 spatial and temporal effects within species-environment relationships.
933 *Hydrobiologia* 300–301, 425–431. <https://doi.org/10.1007/BF00024484>

934 Fraysse, M., Pairaud, I., Ross, O.N., Faure, V.M., Pinazo, C., 2014. Generation processes and
935 impacts on ecosystem functioning. *J. Geophys. Res. Ocean.* 6535–6556.
936 <https://doi.org/10.1002/2014JC010022>.Received

937 Friedland, R., Macias, D., Cossarini, G., Daewel, U., Estournel, C., Garcia-Gorriz, E., Grizzetti,
938 B., Grégoire, M., Gustafson, B., Kalaroni, S., Kerimoglu, O., Lazzari, P., Lenhart, H.,
939 Lessin, G., Maljutenko, I., Miladinova, S., Müller-Karulis, B., Neumann, T., Parn, O.,
940 Pätsch, J., Piroddi, C., Raudsepp, U., Schrum, C., Stegert, C., Stips, A., Tsiaras, K., Ulses,
941 C., Vandenbulcke, L., 2021. Effects of Nutrient Management Scenarios on Marine
942 Eutrophication Indicators: A Pan-European, Multi-Model Assessment in Support of
943 the Marine Strategy Framework Directive. *Front. Mar. Sci.* 8, 1–22.
944 <https://doi.org/10.3389/fmars.2021.596126>

945 Galloway, J.N., Dentener, F.J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S.P.,
946 Asner, G.P., Cleveland, C.C., Green, P.A., Holland, E.A., Karl, D.M., Michaels, A.F., Porter,
947 J.H., Townsend, A.R., Vörösmarty, C.J., 2004. Nitrogen cycles: Past, present, and future,
948 *Biogeochemistry*. <https://doi.org/10.1007/s10533-004-0370-0>

949 Gelaro, R., McCarty, W., Suárez, M.J., Todling, R., Molod, A., Takacs, L., Randles, C.A.,
950 Darmenov, A., Bosilovich, M.G., Reichle, R., Wargan, K., Coy, L., Cullather, R., Draper,
951 C., Akella, S., Buchard, V., Conaty, A., da Silva, A.M., Gu, W., Kim, G.K., Koster, R.,
952 Lucchesi, R., Merkova, D., Nielsen, J.E., Partyka, G., Pawson, S., Putman, W., Rienecker,
953 M., Schubert, S.D., Sienkiewicz, M., Zhao, B., 2017. The modern-era retrospective
954 analysis for research and applications, version 2 (MERRA-2). *J. Clim.* 30, 5419–5454.
955 <https://doi.org/10.1175/JCLI-D-16-0758.1>

956 Glé, C., Del Amo, Y., Sautour, B., Laborde, P., Chardy, P., 2008. Variability of nutrients and
957 phytoplankton primary production in a shallow macrotidal coastal ecosystem
958 (Arcachon Bay, France). *Estuar. Coast. Shelf Sci.* 76, 642–656.
959 <https://doi.org/10.1016/j.ecss.2007.07.043>

960 Goberville, E., Beaugrand, G., Sautour, B., Tréguer, P., Team, S., 2010. Climate-driven
961 changes in coastal marine systems of western Europe 8187.

962 Goldfeld, S.M., Quandt, R.E., 1965. Some Tests for Homoscedasticity. *J. Am. Stat. Assoc.* 60,
963 539–547. <https://doi.org/10.1080/01621459.1965.10480811>

964 Harding, L.W., Mallonee, M.E., Perry, E.S., Miller, W.D., Adolf, J.E., Gallegos, C.L., Paerl, H.W.,
965 2019. Long-term trends, current status, and transitions of water quality in
966 Chesapeake Bay. *Sci. Rep.* 9, 1–19. <https://doi.org/10.1038/s41598-019-43036-6>

967 Hernandez-Farinas, T., Soudant, D., Barillé, L., Belin, C., Lefebvre, A., Bacher, C., 2014.
968 Temporal changes in the phytoplankton community along the French coast of the
969 eastern English Channel and the southern Bight of the North Sea. *Encycl. Environ.*
970 *Soc.* 71, 821–833. <https://doi.org/10.4135/9781412953924.n678>

971 Higgins, R. W., Leetmaa A., Xue, Y., Barnston, A., 2000. Dominant factors influencing the
972 seasonal predictability of U.S. precipitation and surface air temperature. *J. Climate*,
973 13, 3994–4017.

974 Hurrell, J.W., 1995. Decadal trends in the North Atlantic oscillation: Regional
975 temperatures and precipitation. *Science* (80-.). 269, 676–679.
976 <https://doi.org/10.1126/science.269.5224.676>

977 Hurrell, J.W., Deser, C., 2009. North Atlantic climate variability: The role of the North
978 Atlantic Oscillation. *J. Mar. Syst.* 78, 28–41.
979 <https://doi.org/10.1016/j.jmarsys.2008.11.026>

980 Jackson, L.C., Kahana, R., Graham, T., Ringer, M.A., Woollings, T., Mecking, J. V., Wood, R.A.,
981 2015. Global and European climate impacts of a slowdown of the AMOC in a high

982 resolution GCM. *Clim. Dyn.* 45, 3299–3316. <https://doi.org/10.1007/s00382-015->
983 2540-2

984 Joly, D., Brossard, T., Cardot, H., Cavailhes, J., Hilal, M., Wavresky, P., 2010. Les types de
985 climats en France, une construction spatiale. *CyberGeo* 2010, 0–25.
986 <https://doi.org/10.4000/cybergeogeo.23155>

987 Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S.,
988 White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., J, J., Mo, K.C.,
989 Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., Joseph, D., 1996. The
990 NCEP/NCAR 40-Year Reanalysis Project. *Bull. Am. Meteorol. Soc.* 77, 437–471.

991 Kingston, D.G., Lawler, D.M., McGregor, G.R., 2006. Linkages between atmospheric
992 circulation, climate and streamflow in the northern North Atlantic: Research
993 prospects. *Prog. Phys. Geogr.* 30, 143–174.
994 <https://doi.org/10.1191/0309133306pp471ra>

995 Kistler, R., Kalnay, E., Collins, W., Saha, S., White, G., Woollen, J., Chelliah, M., Ebisuzaki, W.,
996 Kanamitsu, M., Kousky, V., Van Den Dool, H., Jenne, R., Fiorino, M., 2001. The NCEP-
997 NCAR 50-year reanalysis: Monthly means CD-ROM and documentation. *Bull. Am.*
998 *Meteorol. Soc.* 82, 247–267. <https://doi.org/10.1175/1520->
999 0477(2001)082<0247:TNNYRM>2.3.CO;2

1000 Kolmogorov, A., "Sulla Determinazione Empirica di una Legge di Dis tribuzione," *Giornale*
1001 *dell'Istituto Italiano degli Attuari*, 4 (1933), 1-11

1002 Labry, C., Herbland, A., Delmas, D., 2002. The role of phosphorus on planktonic production
1003 of the Gironde plume waters in the Bay of Biscay. *J Plankton Res* 24, 97–117.
1004 <https://doi.org/10.1093/plankt/24.2.97>

1005 Lamothe, K.A., Somers, K.M., Jackson, D.A., 2019. Linking the ball-and-cup analogy and
1006 ordination trajectories to describe ecosystem stability, resistance, and resilience.
1007 *Ecosphere* 10(3):e02629. [10.1002/ecs2.2629](https://doi.org/10.1002/ecs2.2629)

1008 Lanoux, A., Etcheber, H., Schmidt, S., Sottolicho, A., Chabaud, G., Richard, M., Abril, G., 2013.
1009 Factors contributing to hypoxia in a highly turbid, macrotidal estuary (the Gironde,
1010 France). *Environ Sci Pollut Res Int* 15, 585–595. [https://doi.org/doi:](https://doi.org/doi:10.1039/c2em30874f)
1011 [10.1039/c2em30874f](https://doi.org/doi:10.1039/c2em30874f)

1012 Le Pape, O., Menesguen, A., 1997. Hydrodynamic prevention of eutrophication in the Bay
1013 of Brest (France), a modelling approach. *J Mar Syst* 12, 171–186.
1014 [https://doi.org/10.1016/S0924-7963\(96\)00096-6](https://doi.org/10.1016/S0924-7963(96)00096-6)

1015 Lefebvre, A., Devreker, D., 2020. First comprehensive quantitative multi-parameter
1016 assessment of the eutrophication status from coastal to marine french waters in the
1017 english channel, the celtic sea, the bay of biscay, and the mediterranean sea. *J. Mar.*
1018 *Sci. Eng.* 8. <https://doi.org/10.3390/JMSE8080561>

1019 Lheureux, A., Savoye, N., Del Amo, Y., Goberville, E., Bozec, Y., Breton, E., Conan, P.,
1020 L'Helguen, S., Mousseau, L., Raimbault, P., Rimelin-Maury, P., Seuront, L., Vuillemin,
1021 R., Caparros, J., Cariou, T., Cordier, M., Corre, A., Costes, L., Crispi, O., Crouvoisier, M.,
1022 Crouvoisier, M., Derriennic, H., Devesa, J., Durozier, M., Ferreira, S., Garcia, N.,
1023 Grossteffan, E., Gueux, A., Lafont, M., Lagadec, V., Lecuyer, E., Leroux, C., Macé, E.,
1024 Maria, E., Mornet, L., Nowaczyk, A., Parra, M., Petit, F., David, V., 2021. Bi-decadal
1025 variability in physico-biogeochemical characteristics of temperate coastal
1026 ecosystems: from large-scale to local drivers. *Mar. Ecol. Prog. Ser.* 660, 19–35.
1027 <https://doi.org/10.3354/meps13577>

1028 Lheureux, A., David, V., Del Amo, Y., Soudant, D., Auby, I., Ganthy, F., Blanchet, H., Cordier,
1029 M-A., Costes, L., Ferreira, D., Mornet, L., Nowaczyk, A., Parra, M., D'Amico, F., Gouriou,
1030 L., Meteigner, C., Oger-Jeanneret, H., Rigoin, L., Rumebe, M., Tournaire, M-P., Trut, F.,
1031 Trut, G., Savoye, N. 2022. Bi-decadal changes in nutrient concentrations and ratios in
1032 marine coastal ecosystems: The case of the Arcachon Bay, France. *Progress in*
1033 *Oceanography* 201, 102740. <https://doi.org/10.1016/j.pocean.2022.102740>

1034 Liénart, C., Savoye, N., Bozec, Y., Breton, E., Conan, P., David, V., Feunteun, E., Grangeré, K.,
1035 Kerhervé, P., Lebreton, B., Lefebvre, S., L'Helguen, S., Mousseau, L., Raimbault, P.,
1036 Richard, P., Riera, P., Sauriau, P.G., Schaal, G., Aubert, F., Aubin, S., Bichon, S., Boinet,
1037 C., Bourasseau, L., Bréret, M., Caparros, J., Cariou, T., Charlier, K., Claquin, P., Cornille,
1038 V., Corre, A.M., Costes, L., Crispi, O., Crouvoisier, M., Czamanski, M., Del Amo, Y.,
1039 Derriennic, H., Dindinaud, F., Durozier, M., Hanquiez, V., Nowaczyk, A., Devesa, J.,
1040 Ferreira, S., Fournier, M., Garcia, F., Garcia, N., Geslin, S., Grossteffan, E., Gueux, A.,
1041 Guillaudeau, J., Guillou, G., Joly, O., Lachaussée, N., Lafont, M., Lamoureux, J., Lecuyer,
1042 E., Lehodey, J.P., Lemeille, D., Leroux, C., Macé, E., Maria, E., Pineau, P., Petit, F., Pujon-
1043 Pay, M., Rimelin-Maury, P., Sultan, E., 2017. Dynamics of particulate organic matter
1044 composition in coastal systems: A spatio-temporal study at multi-systems scale. *Prog.*
1045 *Oceanogr.* 156, 221–239. <https://doi.org/10.1016/j.pocean.2017.03.001>

1046 Liénart, C., Savoye, N., David, V., Ramond, P., Rodriguez Tress, P., Hanquiez, V., Marieu, V.,
1047 Aubert, F., Aubin, S., Bichon, S., Boinet, C., Bourasseau, L., Bozec, Y., Bréret, M., Breton,
1048 E., Caparros, J., Cariou, T., Claquin, P., Conan, P., Corre, A.M., Costes, L., Crouvoisier, M.,
1049 Del Amo, Y., Derriennic, H., Dindinaud, F., Duran, R., Durozier, M., Devesa, J., Ferreira,
1050 S., Feunteun, E., Garcia, N., Geslin, S., Grossteffan, E., Gueux, A., Guillaudeau, J., Guillou,
1051 G., Jolly, O., Lachaussée, N., Lafont, M., Lagadec, V., Lamoureux, J., Lauga, B., Lebreton,

1052 B., Lecuyer, E., Lehodey, J.P., Leroux, C., L'Helguen, S., Macé, E., Maria, E., Mousseau, L.,
1053 Nowaczyk, A., Pineau, P., Petit, F., Pujo-Pay, M., Raimbault, P., Rimmelin-Maury, P.,
1054 Rouaud, V., Sauriau, P.G., Sultan, E., Susperregui, N., 2018. Dynamics of particulate
1055 organic matter composition in coastal systems: Forcing of spatio-temporal variability
1056 at multi-systems scale. *Prog. Oceanogr.* 162, 271–289.
1057 <https://doi.org/10.1016/j.pocean.2018.02.026>

1058 Le Fur, I., De Wit, R., Plus, M., Oheix, J., Derolez, V., Simier, M., Malet, N., Ouisse, V., 2019.
1059 Re-oligotrophication trajectories of macrophyte assemblages in Mediterranean
1060 coastal lagoons based on 17-year time-series. *Mar. Ecol. Prog. Ser.* 608, 13–32.
1061 <https://doi.org/10.3354/meps12814>

1062 Luczak, C., Beaugrand, G., Jaffré, M., Lenoir, S., Supplement, D., 2011. Climate change
1063 impact on Balearic shearwater through a trophic cascade Subject collections Email
1064 alerting service Climate change impact on Balearic shearwater through a trophic
1065 cascade. *Biol. Lett.* 7, 702–705. <https://doi.org/10.1098/rsbl.2011.0225>

1066 Madsen, J.D., Chambers, P.A., James, W.F., Koch, E.W., Westlake, D.F., 2001. The interaction
1067 between water movement, sediment dynamics and submersed macrophytes.
1068 *Hydrobiologia* 444, 71–84. <https://doi.org/10.1023/A:1017520800568>

1069 Maechler, M., Rousseeuw, P., Struyf, A., Hubert, M., Hornik, K., 2021. cluster: Cluster
1070 Analysis Basics and Extensions. R package version 2.1.2.

1071 Metson, G.S., Lin, J., Harrison, J.A., Compton, J.E., 2017. Linking terrestrial phosphorus
1072 inputs to riverine export across the United States. *Water Res.* 124, 177–191.
1073 <https://doi.org/10.1016/j.watres.2017.07.037>

1074 Milner, A.M., Woodward, A., Freilich, J.E., Black, R.W., Resh, V.H., 2016. Detecting
1075 significant change in stream benthic macroinvertebrate communities in wilderness
1076 areas. *Ecol Indic* 60, 524–537.

1077 Mimura, N. (2006). State of the environment in the Asia and Pacific coastal zones and
1078 effects of global change. In: *Global Change and Integrated Coastal Management, The*
1079 *Asia-Pacific Region*. Ed Harvey, N. Springer.

1080 Muylaert, K., Sanchez-Pérez, J.M., Teissier, S., Sauvage, S., Dauta, A., Vervier, P., 2009.
1081 Eutrophication and its effects on dissolved Si concentrations in the Garonne River
1082 (France). *J Limnol* 68, 368–374. <https://doi.org/10.3274/JL09-68-2-19>

1083 Nixon, S.W., 1981. Remineralization and nutrient cycling in coastal marine ecosystems, in:
1084 (eds.), B.J.N. et al (Ed.), *Estuaries and Nutrients*. The Humana Press Inc.

1085 Oursel, B., Garnier, C., Durrieu, G., Mounier, S., Omanović, D., Lucas, Y., 2013. Dynamics and
1086 fates of trace metals chronically input in a Mediterranean coastal zone impacted by a
1087 large urban area. *Mar. Pollut. Bull.* 69, 137–149.
1088 <https://doi.org/10.1016/j.marpolbul.2013.01.023>

1089 Paerl, H.W., 2009. Controlling eutrophication along the freshwater-Marine continuum:
1090 Dual nutrient (N and P) reductions are essential. *Estuaries and Coasts* 32, 593–601.
1091 <https://doi.org/10.1007/s12237-009-9158-8>

1092 Papush, L., Danielsson, Å., 2006. Silicon in the marine environment: Dissolved silica trends
1093 in the Baltic Sea. *Estuar. Coast. Shelf Sci.* 67, 53–66.
1094 <https://doi.org/10.1016/j.ecss.2005.09.017>

1095 Pastres, R., Solidoro, C., Ciavatta, S., Petrizzo, A., Cossarini, G., 2004. Long-term changes of
1096 inorganic nutrients in the Lagoon of Venice (Italy). *J. Mar. Syst.* 51, 179–189.
1097 <https://doi.org/10.1016/j.jmarsys.2004.05.011>

1098 Petris, G., 2010. An R package for dynamic linear models. *J. Stat. Softw.* 36, 1–16.
1099 <https://doi.org/10.18637/jss.v036.i12>

1100 Plus, M., Dalloyau, S., Trut, G., Auby, I., de Montaudouin, X., Emery, E., Noël, C., Viala, C.,
1101 2010. Long-term evolution (1988-2008) of *Zostera* spp. meadows in Arcachon Bay
1102 (Bay of Biscay). *Estuar. Coast. Shelf Sci.* 87, 357–366.
1103 <https://doi.org/10.1016/j.ecss.2010.01.016>

1104 Plus, M., Jeunesse, I. La, Bouraoui, F., Zaldívar, J.M., Chapelle, A., Lazure, P., 2006. Modelling
1105 water discharges and nitrogen inputs into a Mediterranean lagoon: Impact on the
1106 primary production. *Ecol. Modell.* 193, 69–89.
1107 <https://doi.org/10.1016/j.ecolmodel.2005.07.037>

1108 Prins, T.C., Desmit, X., Baretta-Bekker, J.G., 2012. Phytoplankton composition in Dutch
1109 coastal waters responds to changes in riverine nutrient loads. *J Sea Res* 73, 49–62.

1110 QGIS Development Team, 2021. QGIS Geographic Information System. Open Source
1111 Geospatial Foundation Project. <http://qgis.osgeo.org>"

1112 R Core Team, 2021. R: A language and environment for statistical computing. R
1113 Foundation for Statistical Computing, Vienna, Austria. URL [https://www.R-](https://www.R-project.org/)
1114 [project.org/](https://www.R-project.org/).

1115 Radach, G., Pätsch, J. 2007. Variability of Continental Riverine Freshwater and Nutrient
1116 Inputs into the North Sea for the Years 1977–2000 and Its Consequences for the
1117 Assessment of Eutrophication. *Estuaries and Coasts* 30, 66–81.

1118 Ram, K., Wickham, H., 2018. wesanderson: A Wes Anderson Palette Generator. R package
1119 version 0.3.6. <https://CRAN.R-project.org/package=wesanderson>

1120 Ratmaya, W., Soudant, D., Salmon-Monviola, J., Plus, M., Cochenec-Laureau, N., Goubert,
1121 E., Barillé, L., Souchu, P., 2019. Reduced phosphorus loads from the Loire and Vilaine
1122 rivers were accompanied by increasing eutrophication in the Vilaine Bay (south
1123 Brittany, France). *Biogeosciences* 16, 1361–1380. [https://doi.org/10.5194/bg-16-](https://doi.org/10.5194/bg-16-1361-2019)
1124 1361-2019

1125 Richirt, J., Goberville, E., Ruiz-Gonzalez, V., Sautour, B., 2019. Local changes in copepod
1126 composition and diversity in two coastal systems of Western Europe. *Estuar. Coast.*
1127 *Shelf Sci.* 227. <https://doi.org/10.1016/j.ecss.2019.106304>

1128 Roberts, C.D., Waters, J., Peterson, K.A., Palmer, M.D., McCarthy G.D., Frajka-Williams E.,
1129 Haines, K., Lea, D.J., Martin, M.J., Storkey, D., Blockley, E.W., Zuo, H., 2013. Atmosphere
1130 drives recent interannual variability of the Atlantic meridional overturning
1131 circulation at 26.5°N. *Geophys Res Lett.* 40:5164–5170.
1132 <https://doi.org/10.1002/grl.50930>

1133 Romero, E., Garnier, J., Lassaletta, L., Billen, G., Le Gendre, R., Riou, P., Cugier, P. 2013.
1134 Large-scale patterns of river inputs in southwestern Europe: seasonal and
1135 interannual variations and potential eutrophication effects at the coastal zone.
1136 *Biogeochemistry* 113, 481–505. <https://doi.org/10.1007/s10533-012-9778-0>

1137 Saint-Béat, B., Baird, D., Asmus, H., Asmus, R., Bacher, C., Pacella, S. R., Johnson, G. A., David,
1138 V., Vézina, A. F., Niquil, N., 2015. Trophic networks: How do theories link ecosystem
1139 structure and functioning to stability properties? A review. *Ecological Indicators* 52,
1140 458–471. <https://doi.org/10.1016/j.ecolind.2014.12.017>

1141 Scheffer M., Carpenter S.R., 2003. Catastrophic regime shifts in ecosystems: linking theory
1142 to observation. *Trends Ecol Evol* 18:648–656.
1143 <https://doi.org/10.1016/j.tree.2003.09.002>

1144 Scheffer M., Bascompte J., Brock W.A., Brovkin V., Carpenter, S.R., Dakos, V., Held, H., van
1145 Nes, E.H., Rietkerk, M, Sugihara, G., 2009. Early-warning signals for critical
1146 transitions. *Nature* 461:53–59. <https://doi.org/10.1038/nature08227>

1147 Seitzinger, S.P., Kroeze, C., Bouwman, A.F., Caraco, N., Dentener, F., Styles, R. V., 2002.
1148 Global patterns of dissolved inorganic and particulate nitrogen inputs to coastal
1149 systems: Recent conditions and future projections. *Estuaries* 25, 640–655.
1150 <https://doi.org/10.1007/BF02804897>

1151 Sen, 1968. Estimates of the Regression Coefficient Based on Kendall's Tau. *Journal of the*
1152 *American Statistical Association* 63, 1379–1389.

1153 Sfriso, A., Pavoni, B., Marcomini, A., Orio, A.A., 1992. Macroalgae, nutrient cycles, and
1154 pollutants in the Lagoon of Venice. *Estuaries* 15, 517–528.
1155 <https://doi.org/10.2307/1352394>

1156 Shein, K.A., 2006. State of the climate in 2005. *Bull. Am. Meteorol. Soc.* 87.
1157 <https://doi.org/10.1175/BAMS-87-6-shein>

1158 Slowikowski, K., 2021. ggrepel: Automatically Position Non-Overlapping Text Labels with
1159 'ggplot2'. R package version 0.9.1. <https://CRAN.R-project.org/package=ggrepel>

1160 Smirnov, H., "Sur les Ecart de la Courbe de Distribution Empirique" *Recueil*
1161 *Mathématique (Matematicheskii Sbornik)*, N.S. 6 (1939), 3–26

1162 Solidoro, C., Bandelj, V., Aubrey Bernardi, F., Camatti, E., Ciavatta, S., Cossarini, G., Facca,
1163 C., Franzoi, P., Libralato, S., Melaku Canu, D., Pastres, R., Pranovi, F., Raicevich, S., Socal,

1164 G., Sfriso, A., Sigovini, M., Tagliapietra, D., Torricelli, P. (2010). Response of the Venice
1165 Lagoon Ecosystem to Natural and Anthropogenic Pressures over the Last 50 Years. In:
1166 Coastal Lagoons, Critical Habitats of Environmental Change, eds: Kennish, M. J. Paerl,
1167 H. W., 483–511

1168 Somavilla, R., González-Pola, C., Rodríguez, C., Josey, S.A., Sánchez, R.F., Lavin, A., 2009.
1169 Large changes in the hydrographic structure of the Bay of Biscay after the extreme
1170 mixing of winter 2005. *J. Geophys. Res. Ocean.* 114, 1–14.
1171 <https://doi.org/10.1029/2008JC004974>

1172 Somavilla, R., González-Pola, C., Schauer, U., Budeús, G., 2016. Mid-2000s North Atlantic
1173 shift: Heat budget and circulation changes. *Geophys. Res. Lett.* 43, 2059–2068.
1174 <https://doi.org/10.1002/2015GL067254>

1175 Souchu, P., Bec, B., Smith, V.H., Laugier, T., Fiandrino, A., Benau, L., Orsoni, V., Collos, Y.,
1176 Vaquer, A., 2010. along an anthropogenic eutrophication gradient in French
1177 Mediterranean coastal lagoons. *Can. J. Fish. Aquat. Sci.* 67, 743–753.

1178 Souissi, S., Yahia-Kéfi, O.D., Daly Yahia, M.N., 2000. Spatial characterization of nutrient
1179 dynamics in the Bay of Tunis (south-western Mediterranean) using multivariate
1180 analyses: Consequences for phyto- and zooplankton distribution. *J. Plankton Res.* 22,
1181 2039–2059. <https://doi.org/10.1093/plankt/22.11.2039>

1182 South, A., 2017. *rnaturalearth*: World Map Data from Natural Earth. R package version
1183 0.1.0. <https://CRAN.R-project.org/package=rnaturalearth>

1184 South, A., 2021. *rnaturalearthhires*: High Resolution World Vector Map Data from Natural
1185 Earth used in *rnaturalearth*. <https://docs.ropensci.org/rnaturalearthhires>,
1186 <https://github.com/ropensci/rnaturalearthhires>.

1187 Steirou, E., Gerlitz, L., Apel, H., Merz, B., 2017. Links between large-scale circulation
1188 patterns and streamflow in Central Europe: A review. *J. Hydrol.* 549, 484–500.
1189 <https://doi.org/10.1016/j.jhydrol.2017.04.003>

1190 Stoffer, D.S., Toloi, C.M.C., 1992. A note on the Ljung-Box-Pierce portmanteau statistic with
1191 missing data. *Stat. Probab. Lett.* 13, 391–396. [https://doi.org/10.1016/0167-](https://doi.org/10.1016/0167-7152(92)90112-1)
1192 [7152\(92\)90112-1](https://doi.org/10.1016/0167-7152(92)90112-1)

1193 Theil, 1950a. A Rank-Invariant Method of Linear and Polynomial Regression Analysis Part
1194 I. *Proceedings of the Royal Netherlands Academy of Sciences* 53, 386–392

1195 Theil, 1950b. A Rank-Invariant Method of Linear and Polynomial Regression Analysis Part
1196 II. *Proceedings of the Royal Netherlands Academy of Sciences* 53, 521–525

1197 Theil, 1950c. A Rank-Invariant Method of Linear and Polynomial Regression Analysis Part
1198 III. *Proceedings of the Royal Netherlands Academy of Sciences* 53, 1397–1412

1199 Thioulouse, J., Dray, S., Dufour, A.B., Jombart, T., Dray, S., Siberchicot, A., Pavoine, S., 2018.
1200 Multivariate analysis of ecological data with ade4, *Multivariate Analysis of Ecological*
1201 *Data with ade4*. <https://doi.org/10.1007/978-1-4939-8850-1>

1202 Tréguer, P., Goberville, E., Barrier, N., L’Helguen, S., Morin, P., Bozec, Y., Rimmelin-Maury,
1203 P., Czamansli, M., Grossteffan, E., Cariou, T., Répécaud, M., Guéméner, L. 2014. Large
1204 and local-scale influences on physical and chemical characteristics of coastal waters
1205 of Western Europe during winter. *Journal of Marine Systems* 139, 79–90.
1206 <http://dx.doi.org/10.1016/j.jmarsys.2014.05.019>

1207 Tréguer, P., Nelson, D.M., Van Bennekom, A.J., Demaster, D.J., Leynaert, A., Quéguiner, B.,
1208 1995. The silica balance in the world ocean: A reestimate. *Science* (80-.). 268, 375–
1209 379. <https://doi.org/10.1126/science.268.5209.375>

1210 Wainright, S., 1990. Sediment-to-water fluxes of particulate material and microbes by
1211 resuspension and their contribution to the planktonic food web. *Mar. Ecol. Prog. Ser.*
1212 62, 271–281. <https://doi.org/10.3354/meps062271>

1213 Wasserman, J.-C., Dumon, J.-C., Latouche, C., 1992. Bilan de 18 éléments-trace et de 7
1214 éléments majeurs dans un environnement peuplé de zostères *Zostera noltii*. *Vie*
1215 *milieu* 42, 15–20.

1216 West, M., Harrison, J., 1997. *Bayesian Forecasting & Dynamic Models*, Springer S. ed.
1217 Springer-Verlag New York, Inc., 175 Fifth Avenue, New York, NY 10010, USA, New-
1218 York.

1219 Wickham, H., 2016. *ggplot2-Elegant Graphics for Data Analysis*. Springer International
1220 Publishing. Cham, Switz.

1221 Willems, J.L., 1970. *Stability theory of dynamical systems*. Wiley and Sons, New- York,
1222 USA. <https://doi.org/10.1109/TSMC.1971.4308335>

1223 Wright, S., 1931. Evolution in Mendelian populations. *Genetics* 16, 97–159.

1224 Yang, Q., Tian, H., Friedrichs, M.A.M., Liu, M., Li, X., Yang, J., 2015. Hydrological
1225 responses to climate and land-use changes along the north american east
1226 coast: A 110-Year historical reconstruction. *J. Am. Water Resour.*
1227 *Assoc.* 51, 47–67. <https://doi.org/10.1111/jawr.12232>

1228 Yu, G., 2021. scatterpie: Scatter Pie Plot. R package version 0.1.7. [https://CRAN.R-](https://CRAN.R-project.org/package=scatterpie)
1229 [project.org/package=scatterpie](https://CRAN.R-project.org/package=scatterpie)

1230

1231