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**Comparison of hypoxia among four river-dominated ocean margins: The Changjiang (Yangtze), Mississippi, Pearl, and Rhone rivers**

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1  
2 **Comparison of Hypoxia Among Four River-Dominated Ocean Margins: the**  
3 **Changjiang (Yangtze), Mississippi, Pearl, and Rhône Rivers**  
4

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25 **Abstract**

26 We investigated the occurrence of seasonal hypoxia ( $O_2 < 2\text{mg l}^{-1}$ ) in bottom waters of four  
27 river-dominated ocean margins (Changjiang, Mississippi, Pearl and Rhône Rivers) and  
28 compared the processes leading to the depletion of oxygen. Consumption of oxygen in bottom  
29 waters is linked to biological oxygen demand fuelled by organic matter from primary  
30 production in the nutrient-rich river plume. Hypoxia occurs when this consumption exceeds  
31 replenishment by turbulent mixing or lateral advection of water. After comparing the four  
32 systems, we concluded that Mississippi and Changjiang coastal systems are the most affected  
33 by summer hypoxia, while the Rhône and the Pearl rivers systems are less affected, although  
34 nutrient concentrations in the river water are similar for the four systems. Primary production  
35 is on the average very high for shelf adjacent to the Mississippi, Yangtze and Pearl ( $1\text{-}10\text{ g C}$   
36  $\text{m}^{-2}\text{ d}^{-1}$ ), and lower for the shelf off the Rhône ( $<1\text{ g C m}^{-2}\text{ d}^{-1}$ ) which could be one of the  
37 reasons why the shelf beyond the Rhone undergoes little hypoxia. The residence time of the  
38 bottom water is also related to the occurrence of hypoxia, with the Mississippi showing a long  
39 residence time and high occurrence of hypoxia over a very large spatial scale, whereas the  
40 East China Sea/Changjiang displays hypoxia less regularly way due to a shorter residence  
41 time of the bottom water. Physical stratification plays a major role since both the  
42 Changjiang and Mississippi shelf show strong thermohaline stratification during summer,  
43 whereas summer stratification is less permanent for the Pearl and Rhône. The shape of the  
44 shelf is another important factor since hypoxia occurs at intermediate depths (between 20 and  
45 50m) on broad shelves, or in bays with intermediate depths (Gulf of Mexico and East China  
46 Sea). Therefore, shallow estuaries with good flushing such as the Pearl River estuary show  
47 little hypoxia during the summer wet season when mixing and flushing are high, but there is  
48 severe hypoxia in the upper estuary during the winter dry season. Deeper shelves like the Gulf  
49 of Lion off the Rhone show little or no hypoxia.

50

51

52

53 **Keywords**

54 Oxygen, Hypoxia, Carbon cycle, coastal oceanography, estuaries, river plumes

55 **Regional index terms:**

56 China, Changjiang River, East China Sea

57 USA, Mississippi River, Gulf of Mexico

58 China, Pearl River, South China Sea

59 France, Rhône River, Gulf of Lion

60

61

62 **Introduction**

63 Eutrophication and its consequences are an increasing threat to coastal ecosystems  
64 through harmful algal blooms, altered plankton community structure and hypoxia in bottom  
65 waters (Cloern, 2001). These impacts are associated with high nutrient loads delivered by  
66 rivers to estuaries and coastal waters. Although the presence of hypoxia and anoxia has  
67 existed through geologic time, the occurrence in coastal waters has been accelerated by  
68 human activities (Diaz, 2001).

69 Large rivers exert a strong influence on the continental shelves over which they  
70 discharge, forming stratified and turbid plumes in their estuaries and outside on the shelves,  
71 either annually or during high discharge seasons (Dagg et al., 2004; McKee et al., 2004). In  
72 addition, elevated nutrient concentrations in river water often trigger high primary production  
73 and algal blooms in the river plume, and the adjacent shelf water (Lohrenz et al., 1997; Dagg  
74 and Breed, 2003). A portion of the organic matter that is produced in the plume, along with  
75 terrestrial inputs, settles to the seafloor where it is decomposed by benthic fauna and bacteria  
76 using oxygen and other equivalents. When vertical exchange of the water is limited, the  
77 oxidation process may reduce oxygen below 2 mg/l (62.5  $\mu\text{mol/l}$ ) producing a state of  
78 hypoxia (Rabalais et al., 2002) where benthic fauna become stressed or die due to the lack of  
79 oxygen (Diaz and Rosenberg, 1995). Hypoxia may ultimately lead to anoxia where oxygen  
80 completely disappears, and sulphide may diffuse from the sediment to the bottom water, both  
81 causing mass mortality of organisms (Smetacek et al., 1991).

82

83 Several estuaries and continental shelves of the world coastal ocean undergo severe hypoxia  
84 including the Chesapeake Bay, USA (Hagy et al., 2005), the Danish Straits (Conley et al.,  
85 2007), and the Mississippi River outlet in the Northern Gulf of Mexico which is the largest in  
86 area (Rabalais et al., 2002). Other estuaries such as the Changjiang (Yangtze) and Pearl Rivers

87 in China (Zhou and Shen, this issue; Yin et al., 2004a; Dai et al., 2006) and the St. Lawrence  
88 River in Canada (Gilbert et al., 2005), exhibit hypoxia in the inner or outer part of their  
89 estuary.

90

91 The decrease of oxygen from saturation (250-300  $\mu\text{mol/l}$ ) to hypoxic levels is a phenomenon  
92 that occurs when both thermal and haline stratification of the water due to freshwater  
93 discharge and summer warming, nutrient utilization by phytoplankton, and subsequent settling  
94 to bottom waters, occur in the right sequence. Yet, some estuaries of large rivers do not  
95 exhibit hypoxia and large variations in the volume of hypoxic waters are known to occur  
96 within hypoxic systems (Cloern 2001; Hetland and DiMarco, 2007) indicating that the  
97 processes causing and maintaining hypoxia in river-dominated ocean margins are not well  
98 understood.

99

100 In this paper, we compare the physical, chemical and biological processes leading to the  
101 formation, occurrence and intensity of hypoxia in four river-dominated ocean margins which  
102 receive large amounts of river-derived organic loading and dissolved nutrients: the  
103 Changjiang, Mississippi, Pearl and Rhône Rivers. These margins are all potentially impacted  
104 by their river inputs, but only some of these margins exhibit hypoxia. This paper compares  
105 these four estuaries with regards to their nutrient/organic inputs and their physical  
106 characteristics (tides, margin shape, shelf currents, water residence times), in order to better  
107 understand conditions for the establishment and maintenance of bottom water seasonal  
108 hypoxia (spring and summer).

109

## 110 ***Locations and characteristics of the four estuaries***

### 111 Geographic position and discharge

112

113 All four river systems are located in the northern hemisphere and three of them,  
114 discharge between 20 and 32°N (Table 1). Only one river (Rhône) is located north of 43°N  
115 and is thus a temperate river system, dominated in its southern part by Mediterranean climate.  
116 On a global basis, the Mississippi and the Changjiang are large rivers, while the Pearl is  
117 somewhat intermediate and the Rhone River is significantly smaller in discharge (Table 1).  
118 Although the three largest rivers (Changjiang, Mississippi and Pearl) discharge into a  
119 subtropical region, they are very different. The Mississippi is not a subtropical river since  
120 most of its drainage basin is located north of 35°N, whereas the drainage basins of the Pearl  
121 and Yangtze rivers are located below 30°N. However, the coastal zone located at the river  
122 mouth of the Mississippi is clearly a subtropical coastal zone with summer temperature  
123 reaching 30°C in surface waters. The seasonality of the discharge is clearly similar for the  
124 Pearl and Yangtze with high flows in summer during the monsoon season, whereas the  
125 Mississippi and Rhone show low water discharge in summer and high water fluxes in autumn  
126 and spring.

127 The Changjiang River (Yangtze) is the second longest river in China (6200 km) and  
128 drains a large portion of central continental China (Table 1). It discharges into the East China  
129 Sea mainly through its south branch which discharges more than 95% of the runoff (Cai et al.,  
130 this volume). Before the Three Gorges Dam was built, the annual freshwater discharge of the  
131 Changjiang River ranked fifth in the world and fourth for particle discharge (Milliman and  
132 Meade, 1983, Meade, 1996). This discharge is highly seasonal with 75% of the river runoff  
133 occurring during the flood/ rainy season between May and October. According to Yang et al.,



134 (2007), the building of the Three Gorges Dam has promoted a 30% decrease in discharge of  
135 sediments.

136 The Mississippi-Atchafalaya River basin drains approximately 41% of the USA and  
137 carries approximately 65% of all the suspended solids and dissolved solutes that enter the  
138 ocean from the USA. It effectively injects these materials onto the continental shelf as a point  
139 source in the northern Gulf of Mexico. The enormous discharge of freshwater, suspended  
140 sediment, and the associated particulate and dissolved carbon (C), nitrogen (N) and  
141 phosphorus (P) profoundly influences biological and geochemical processes in the plume and  
142 adjacent margin areas (Table 1). The Mississippi-Atchafalaya River system has the third  
143 largest drainage basin among the world major rivers (Milliman and Meade 1983; Meade  
144 1996). This river system also ranks seventh in freshwater discharge and fifth in sediment  
145 discharge. About two-thirds of the total flow passes through the Belize (or birdfoot) delta of  
146 the Mississippi River and discharges in the outer shelf region, with the remainder flowing into  
147 Atchafalaya Bay before entering the Gulf of Mexico on the coast (Wiseman and Garvine  
148 1995).

149 The Pearl River (or Zhujiang) is the 13<sup>th</sup> largest river in the world in terms of  
150 freshwater discharge and has an annual sediment delivery of ~80 Mt (Table 1; Zhao 1990;  
151 Tian 1994; Zhang et al. 1999). It discharges into the sub-tropical, oligotrophic South China  
152 Sea. Together with the Mekong River, they provide the largest freshwater input to the South  
153 China Sea (SCS), which is the largest marginal sea in the North Pacific. The Pearl River  
154 estuary is one of the most complex estuarine systems in the world (Cai et al., 2004; Gao et al.,  
155 this issue). The Pearl River discharges into the South China Sea through three sub-estuaries,  
156 Lingdingyang, Maodaomen and Huangmaohai via eight main outlets, or distributaries, and is  
157 fed by three river tributaries, namely the Xi-jiang (West River), the Bei-jiang (North River)

158 and the Dong-jiang (East River). The West River has the greatest freshwater discharge with  
159 about 67% of the total discharge (Zhou et al. 2006).

160 The Rhône River is located in the south of France and receives water from a drainage  
161 basin which spans several climatic regions including a temperate region with oceanic  
162 temperate influence in the north and a Mediterranean climate in the south (Table 1; Pont et al.,  
163 2002). Discharge is highly seasonal and fall and winter floods may reach  $>10,000 \text{ m}^3 \text{ s}^{-1}$ .  
164 Inputs from episodic floods are not well quantified, so annual inputs are uncertain, but the  
165 particle discharge at the mouth of the river is around  $10 \pm 5 \text{ Mt y}^{-1}$ .

#### 166 Nutrient discharge from the rivers

167

168 The amount of nutrients discharged by the four rivers is clearly linked to the water discharge  
169 volume (Table 2). The Changjiang has the largest input of dissolved inorganic nitrogen (DIN)  
170 and the Mississippi, Pearl and Rhône Rivers have lower values. Nitrogen inputs are due to  
171 sewage and industrial inputs as well as agricultural practices. All four basins are dominated by  
172 agriculture strongly affecting the relationship between freshwater and nutrient discharge. The  
173 DIN concentrations in the rivers are remarkably similar:  $130 \mu\text{M}$  for the Mississippi,  $75\text{-}110$   
174  $\mu\text{M}$  for the Pearl, and  $125 \mu\text{M}$  in the Changjiang and the Rhône. Dissolved inorganic  
175 phosphorus (DIP) fluxes show an interesting pattern with similar values for Changjiang and  
176 Pearl, although the Changjiang discharge is three times larger. This is due to the fact that,  
177 unlike nitrogen, phosphorus inputs are also linked to geological type of soils and their  
178 weathering, in addition to being impacted by fertilizer use. A similar explanation holds for  
179 dissolved silicate (DSi). DOC and POC inputs and have been reported only for the Rhône  
180 (Sempéré et al., 2000) and Mississippi (Trefry et al., 1994)

181 Dynamics of the bottom waters

182

183 The tidal range for the four estuaries is relatively small (Table 3). Only the Changjiang  
184 is mesotidal and slightly exceeds the 2 m range which is the upper limit of microtidal areas.

185 The other coastal zones are characterised as microtidal, with the Pearl reaching the upper limit  
186 with a tidal range of 0.86 - 1.89 m for the main outlet. The tidal range is a very important  
187 characteristic as it shapes the development of the delta (Syvitski and Saito, 2007) and  
188 determines its exchange capacity with the coastal sea. All deltas and estuaries considered in  
189 this paper are only slightly influenced by tides, but some (like the Rhone or Pearl) are  
190 significantly affected by waves (Syvitski and Saito, 2007).

191 Summer stratification is high for the Mississippi, Pearl and Changjiang estuaries as they lie at  
192 latitudes where heat exchange during summer promotes the development of thermal  
193 stratification (Table 3). Additionally, in the northern Gulf of Mexico, low wind speeds during  
194 summer help to support stratification and the horizontal spreading of the plume. In the case of  
195 the Changjiang and Pearl, the discharge peak occurs in summer, which also promotes density  
196 stratification due to freshwater inputs (Li et al., 2002) in the East China Sea close to the river  
197 mouth (Wei et al., in press). This is due to high salinity and high temperature water from the  
198 Taiwan Warm Current (TWC) which spreads at intermediate depths around 50 m (Li et al.,  
199 2002; Zhu et al., 2004). For the Rhône River, stratification is less established in summer due  
200 to high winds that may occur and disrupt stratification (Estournel et al., 2001).

201 Bottom currents are variable for the four coastal zones (Table 3). On the Louisiana  
202 shelf away from the immediate plume area, surface current speeds are low ( $5-10 \text{ cm s}^{-1}$ ) and  
203 they reverse during the summer from westward to eastward (Zavala-Hidalgo et al., 2003).  
204 Bottom water currents in the inner shelf are even lower as measured by ADCP at 20 m ( $0.5-2$   
205  $\text{cm s}^{-1}$ ; (Wiseman et al., 2003). The current reversal occurring at the end of spring creates a

206 temporary low in the transport rate in June, July and August (Smith and Jacobs, 2005). For the  
207 Changjiang, current speeds in the Taiwan Warm Current are on the order of  $30 \text{ cm s}^{-1}$  and  
208 occur throughout the year (Li et al., 2002; Zhu et al., 2004). This current occurs in  
209 intermediate and bottom waters along the 50 m isobath, and isolates bottom waters from the  
210 oxygen-rich surface waters (Wei et al., in press). The bottom current on the eastern part of the  
211 Gulf of Lion is mostly directed westward and shows intermediate speeds of  $5\text{-}15 \text{ cm s}^{-1}$  during  
212 the summer at 30 m over the Rhône prodelta (Lansard et al., in prep). Residence time in the  
213 Pearl River estuary is variable with a flushing time of a few days during the wet season  
214 (March-October, (Yin et al., 2004)), and a couple of weeks in the dry season (Dai, unpubl.  
215 data).

## 216 Shape of the estuaries

217

218 Most of the rivers in our comparison display large freshwater plumes that extend far onto the  
219 continental shelf and mix with seawater over the continental margin. The exception is the  
220 Pearl River with a seasonal plume that stretches onto the shelf only in the high discharge  
221 season in summer (Yin et al., 2001). At other times, the main open estuarine zone corresponds  
222 to a classical estuarine mixing zone. The input of particulate matter from these rivers has  
223 shaped the continental margin together with hydro-sedimentary processes (Saito and Sivitsky,  
224 2007) and most rivers display large flat shelves with depths shallower than 30 m for at least  
225 50 km and even more for the Changjiang which reaches 40 m at around 200 km from the river  
226 outlet (Fig. 2). The only exception to this shallow shelf pattern is the Rhône, where depths  
227  $>100 \text{ m}$  are encountered closer to the river mouth (40 km or less). The shape of the river  
228 mouths of the Rhône and Mississippi are different from the bathymetry of their adjacent  
229 shelves. Indeed, both rivers have built prodeltas which prograde onto the shelf and create

230 large slopes at the river mouth, with depths of around 100 m within 10 to 20 km off the river  
231 mouth and a clear difference on the bathymetric chart (Fig. 2).

232

### 233 ***Occurrence of hypoxia***

234

#### 235 Changjiang:

236 Early hydrological surveys off the Changjiang River reported the occurrence of  
237 hypoxic waters about 100 km from the river mouth along 123°E and oxygen concentrations  
238 were 1.5 to 2 mg l<sup>-1</sup> (Tian et al., 1993). In a subsequent larger survey on the east China Sea  
239 (ECS) and its continental shelf in 1999 (Li et al., 2002), the extension of the hypoxic zone was  
240 defined. This low oxygen zone (defined in these papers as < 3 mg l<sup>-1</sup>) extends over 55 km in  
241 the W-E and 250 km N-S direction. It covers a region of 13000 km<sup>2</sup> and a thickness of 20 m  
242 at a depth between 30 and 50 m (Li et al., 2002). It was also reported that the oxygen  
243 concentration in the core of this hypoxic region was lower in 1999 (Li et al., 2002) than in  
244 earlier studies performed in the 1980s, suggesting that hypoxia was larger in 1999 than in  
245 previous decades. More recent studies (Chen et al., 2005; Wei et al., in press) suggest that the  
246 hypoxic zone was larger in 2003 (20,000 km<sup>2</sup> with <3 mg l<sup>-1</sup> of oxygen) and displays the  
247 largest seasonal hypoxia in August. Both thermal and haline stratifications are present in late  
248 summer (Li et al., 2002) in the ECS close to the mouth of the Changjiang River and correlate  
249 well with the hypoxic areas (Wei et al., in press). This is related to high salinity, high  
250 temperature water from the Taiwan Warm Current (TWC) which spreads at intermediate  
251 depths, which further limits oxygen exchange with the surface waters (Li et al., 2002; Zhu et  
252 al., 2004).

253

254 Mississippi: The shelf region of the northern Gulf of Mexico that is impacted by the  
255 Mississippi and Atchafalaya River systems is the best documented example of hypoxia  
256 (Rabalais and Turner, 2001; Rabalais et al. 2002; Dagg et al. 2007). Since 1993, an extensive  
257 zone of bottom water hypoxia, typically  $> 15,000 \text{ km}^2$ , develops during most years (Rabalais  
258 et al. 2002).

259 In the northern Gulf of Mexico, hypoxia is seasonal. It starts in late spring and reaches its  
260 maximum in late August or September before fall wind mixing and destratification. Hypoxia  
261 occurs in shallow bottom waters (10-50 m) along the coast of Louisiana in regions affected by  
262 nutrient inputs from the Mississippi/Atchafalaya River discharge. The oxygen concentration  
263 in bottom waters in the centre of this hypoxic zone is frequently  $<1 \text{ mg l}^{-1}$  of oxygen ( $31 \text{ } \mu\text{mol}$   
264  $\text{l}^{-1}$ ). The main driving forces for hypoxia in the northern Gulf of Mexico are believed to be  
265 stratification by the freshwater flux which decreases oxygen replenishment to bottom waters  
266 because of decreased vertical mixing (Wiseman et al., 1997); Hetland and DiMarco, 2007)  
267 and nutrient input from the river which creates high algal biomass that sinks, decomposes and  
268 uses up oxygen in the bottom waters. Models (Justić et al. 2002; Scavia et al. 2003; Turner et  
269 al. 2005) have utilized statistical relationships between hypoxia and riverine nutrient inputs to  
270 the shelf to predict or hindcast hypoxia. These models reinforce the view that nutrient  
271 stimulated production from the Mississippi and Atchafalaya Rivers drives the development  
272 and maintenance of coastal hypoxia. Generally, there is a strong correlation between the  
273 volume of river discharge in spring and summer and the extent of hypoxic waters. During two  
274 severe droughts of the Mississippi River in 1988 and 2000, the surface area of hypoxic bottom  
275 water was  $<5000 \text{ km}^2$  (Rabalais 2002, Rabalais and Turner, in press). In contrast, the  
276 maximum extent of the hypoxic zone occurred from 1993 to 1997 ( $>15,000 \text{ km}^2$ ) and in 1999  
277 and 2001, it was  $>20,000 \text{ km}^2$ . The impact on the living resources is high in terms of stress  
278 and mortality when the concentration of oxygen in the bottom waters decreases to  $<2 \text{ mg l}^{-1}$

279 (Gray et al., 2002; Rabalais and Turner, 2001; Diaz and Rosenberg, 1995). It is believed that  
280 motile organisms (fish, crabs, shrimp, squid) escape these waters, but can be displaced from  
281 their preferred habitat (Craig and Crowder, 2005). When exposed to long periods of low  
282 oxygen, burrowing invertebrates display stressed behaviours and eventually die, leaving  
283 benthic regions of low infaunal diversity, biomass and abundance (Rabalais et al., 2002).

284

285

286 Pearl River: Hypoxic conditions rarely occur in the lower Pearl River estuary and adjacent  
287 shelf despite the high nutrient load in the river water (Yin et al., 2004a) This is primarily due  
288 to its shallow depth (Table 1) and rapid flushing and mixing during the summer wet season  
289 (Table 4). In the summer of 1999 (high river flow), a survey of the estuary showed oxygen-  
290 depleted waters (around 3-4 mg l<sup>-1</sup>) occurred in several areas of the estuary, but hypoxic  
291 waters (<2 mg l<sup>-1</sup>) occurred only around the turbidity maximum at one station (Yin et al.,  
292 2004a). A monthly, 10 year (1990-1999) time series around Hong Kong Island (in the eastern  
293 part of the estuary and the nearby shelf) also showed low oxygen waters, but no hypoxia in  
294 the bottom waters (Yin et al., 2004a).

295 In contrast, in the upper estuary during the winter dry season, downstream of the city of  
296 Guangzhou with salinities between 1-5, persistently low dissolved oxygen, down to < 1 mg L<sup>-1</sup>,  
297 was documented in the water column (Dai et al, 2006; Zhai et al, 2005). This severe  
298 hypoxia is due to poor flushing during the dry season. These strongly hypoxic waters occur 30  
299 km upstream of the river outlet and are due to organic matter decomposition supplemented by  
300 high nitrification rates due to high organic loads from agricultural runoff and sewage inputs  
301 (Dai et al., 2006). A strong transition from hypoxic to low oxygen waters occurs at salinity 5  
302 to 15 between 30 and 20 km upstream of the open part of the estuary. Shelf water is stratified  
303 during spring-summer when the estuarine plume forms, but the stratification does not appear

304 to induce the formation of hypoxia perhaps due to the fact that the estuary is quite shallow (5-  
305 20 m). There is little or no stratification in winter due to wind mixing and average winter wind  
306 speeds ( $10 \text{ m s}^{-1}$ ) are four times higher than summer ( $2.5 \text{ m s}^{-1}$ ) (Yin 2002).

307

308 Rhône River: On the continental shelf near the Rhône, high oxygen concentrations have been  
309 reported throughout the year. In the Gulf of Lions, near saturation values in bottom waters  
310 were reported in January, March and June (Denis and Grenz, 2003) including the Rhone  
311 prodelta. In the same area, datasets for the summer of 2005 and 2006, showed oxygenated  
312 water down to 1 m above the seabed (Fig. 3). In August 2006, oxygen content in a bay located  
313 west of the Rhône was near-saturation under very windy conditions (Lansard, 2004). Hence,  
314 the continental shelf near the Rhône River does not appear to exhibit significant hypoxia, but  
315 further systematic investigations (time series and spatial surveys) are needed.

316

## 317 **Discussion**

318

319 The occurrence of hypoxic conditions in coastal regions connected to large rivers is due to an  
320 interplay between water column production, which supplies organic matter to bottom water  
321 and sediment generating oxygen consumption, and physical forcings (stratification, the  
322 circulation pattern in the region, and residence time of the water in the mixing zone) which  
323 prevent oxygenation of bottom waters. We examined these physical and biogeochemical  
324 factors separately for the four systems where data are available. All four river/coastal sea  
325 systems show different physical characteristics, yet the two largest systems (Yangtze and  
326 Mississippi) undergo seasonal hypoxia at intermediate depths on the shelf, whereas the Pearl  
327 system displays low oxygen (within the estuarine zone), but no hypoxia over the shelf, and the  
328 Rhone continental shelf is largely oxygenated. The nutrient inputs to the coastal zone are



329 different between systems (varying with the water flux), but nutrient concentrations are  
330 elevated in all systems ( $\geq 100 \mu\text{M}$  for DIN) and it is clear that nutrients alone do not  
331 determine hypoxia.

332

### 333 **Physical forcings**

334 Various physical factors, including the shape of the estuary, the residence time of the water on  
335 the shelf, the summer stratification, rainfall, and the tidal regime all influence the occurrence  
336 and intensity of hypoxia. Hypoxia of the coastal shelf near river mouths occurs when oxygen  
337 consumption from the decomposition of organic inputs to the bottom waters exceeds  
338 replacement of oxygen in bottom waters. Thus, conditions affecting the rate of oxygen  
339 replenishment to sub-pycnocline waters, by either horizontal advection of water through  
340 circulation on the shelf, or turbulent vertical mixing by surface cooling and wind mixing, are  
341 key to determining the development, duration and extent of bottom water hypoxia (Rowe et  
342 al., 2001). Hypoxia occurs most strongly in summer due to several physical factors. Summer  
343 warming of the water decreases the oxygen saturation and an increase in the temperature of  
344 seawater from 10 to 20°C decreases the oxygen solubility from 280 to 230  $\mu\text{mol l}^{-1}$  (a  
345 decrease of nearly 2 mg  $\text{l}^{-1}$ ). Additionally, vertical mixing is also affected by summer  
346 warming of the surface waters and induced stratification. Mixing and advection efficiency are  
347 also largely influenced by the shape of the estuary/delta on which these phenomena occur.  
348 Shallow versus deep shelves will allow winds to more completely mix the water column,  
349 whereas shallow shelves can “isolate” estuaries from main shelf circulation compared to  
350 deeper shelves.

351

### 352 ***Shape of the estuary***

353           As shown in Figure 2, the shapes of the continental shelves near the four rivers are  
354 different. The Pearl River is an open estuary in which most of the mixing occurs except in the  
355 flushing season, whereas the Rhone, Mississippi and Yangtze Rivers discharge directly onto  
356 the shelf. The Mississippi and Changjiang have broad, shallow shelves with depths < 40 m  
357 which extend over 60 km or more from the coast. The Rhône system has a steeper slope with  
358 depths of 100 m observed within 40 km of the coastline. These bathymetric features certainly  
359 have an influence on water warming, with shallower depths being more subject to summer  
360 warming and thus stronger stratification. These shallow shelves may also have more intense  
361 pelagic-benthic coupling and higher export of more degradable organic matter to the  
362 sediments which locally enhance sediment oxygen demand. On the other hand, shallower  
363 depths will also facilitate wind-driven vertical mixing of oxygen from the atmosphere to the  
364 bottom waters, thereby tending to reduce hypoxia. For the four systems, the broad shallow  
365 shelf feature seems to be linked with hypoxia. Indeed, the Yangtze and Mississippi show  
366 seasonal hypoxia, whereas the Rhône, which has a deeper shelf, does not. This feature is  
367 certainly not a unique criterion, and is indeed not valid for classical estuaries, like the Pearl  
368 River which has a very shallow wide estuary and displays no hypoxia. In spite of its  
369 shallowness however, the Pearl has moderately strong physical dynamics associated with tidal  
370 mixing (reaching 2 m tidal height), monsoon winds and occasional typhoons in summer (Yin,  
371 2002, 2003; Yin et al., 2004c; Harrison et al., this issue). Therefore, a broad shallow shelf  
372 seems to be an important precursor to hypoxia, but is not a sufficient characteristic in itself for  
373 hypoxia development associated with rivers carrying high nutrients that discharge onto the  
374 shelf.

375           Another feature which may influence the development or intensity of hypoxia is the  
376 existence of a prodelta (as in the Mississippi and Rhône) which progrades, resulting in the  
377 input of river water well beyond the coastal and shallow shelf region. In the current physical

378 configuration of an intensively leveed Mississippi River, it appears that direct sedimentation  
379 of terrestrial organic matter from this plume has a relatively small contribution to the  
380 development of hypoxia on the shelf (Green et al., 2006) with a large fraction of water and  
381 sediments instead delivered directly to a deep offshore canyon. Rather, hypoxia may be  
382 related to recycled nutrients from this plume that are transported over the broad shallow shelf  
383 to the west, or it may be related to organic matter inputs from coastal bays and marshes.  
384 Physical conditions contributing to the transport of Mississippi River water from its discharge  
385 site at the shelf break to the coastal region are key for hypoxia development. In the case of the  
386 Rhône, where a prodelta also exists, the main plume is diverted to the south-west over the  
387 deeper shelf and rarely penetrates in a shallower coastal bay. Thus no hypoxia occurs which  
388 indicates that the existence of a prodelta does not ultimately control the formation of hypoxic  
389 bottom water. The shape of the shelf and the circulation of the plume over the shelf is  
390 certainly one of the determinants of the potential for hypoxia.

391

### 392 ***Residence time of the bottom water***

393 Residence time of bottom waters may be an important factor for hypoxia development  
394 because it directly affects the duration of oxygen consumption during organic matter  
395 decomposition and thus the degree of O<sub>2</sub> depletion. A long residence time may allow  
396 complete decomposition of organic matter and large oxygen consumption. Residence time of  
397 bottom waters is controlled by horizontal advection of the water under the influence of  
398 intermediate and bottom shelf currents.

399 In most systems where the river discharges onto the continental shelf (Rhône, Yangtze,  
400 Mississippi), the margin is dominated by an alongshore current. For each of these river  
401 systems, this current has different intensities (discussed above and reproduced in Table 4). In  
402 order to calculate the residence time of the bottom water, one must define the box over which

403 it is calculated. The box that we chose has the approximate size of the zone where primary  
404 production from the river plume in surface water is dominant (Table 4). Although occurring in  
405 surface waters rather than bottom water where our calculation applies, primary production is a  
406 primary driver of hypoxia through the transfer of organic matter to bottom waters (Green et  
407 al., 2006) and thus the size of its area of influence determines potential hypoxic areas. The  
408 residence time of the water is calculated as the ratio between the volume of the water in this  
409 box to the flux of water through the lateral surface of the box.

410

$$411 \quad \tau_{\text{res}} = V_{\text{hypoxic}} / F_{\text{water}}$$

412

413 where  $\tau_{\text{res}}$  is the residence time of the bottom water in the hypoxic part of the shelf with  
414 regards to lateral current,  $V_{\text{hypoxic}}$  is the volume of potential hypoxic waters, and  $F_{\text{water}}$  the  
415 flux of water through that volume.

416 If the geometry is rectangular, this problem can be simplified since:

$$417 \quad V_{\text{hypoxic}} = S_{\text{box}} * L$$

$$418 \quad \text{and} \quad F_{\text{water}} = S_{\text{box}} * \omega$$

419  $S_{\text{box}}$  being the lateral surface area of the box considered,  $\omega$  the current speed ( $\text{cm s}^{-1}$ ) and  $L$  the  
420 extension of the system alongshore (km). The residence time can thus be expressed by

$$421 \quad \tau_{\text{res}} = L / \omega$$

422

423 As a first order approximation, the results from Table 4 show that hypoxia is somehow  
424 related to the residence time as the Mississippi system with the longest bottom water  
425 residence time showing the strongest and largest hypoxia, while the Rhône with a short  
426 residence time and the Pearl in the lower estuary has no hypoxia. ECS/Changjiang displays

427 hypoxia in a less regularly and often of a shorter duration which might be due to more  
428 vigorous replacement of its bottom water by bottom currents.

429 Rainfall – should you have a short section of rainfall – how much and when it occurs. Pearl  
430 and Yangtze is in summer and the rainfall/snow melt in the Mississippi is in spring. Or this  
431 information could be with the section of river discharge.

### 432 *Tidal regime, summer stratification*

433 Tidal mixing of water can disrupt density stratification which promotes the isolation of  
434 bottom water from the atmosphere and the subsequent occurrence of hypoxia (Wiseman et al.,  
435 1997). The tidal regime of the four estuaries varies from the micro- to the meso tidal, with  
436 ranges varying between <1 m for the Rhône and Mississippi, about 2 m for the Pearl River,  
437 and 2.5 m for the Changjiang (Table 3). Apparently, there is no correlation between the tidal  
438 regime and the occurrence of hypoxia since the Mississippi and the Changjiang undergo  
439 seasonal hypoxia, but they have very different tidal regimes. It is noteworthy that the tidal  
440 range in the four systems examined is rather narrow, only the Changjiang slightly exceeds the  
441 microtidal threshold of 2 m. For the four systems with relatively low to intermediate tides,  
442 tidal mixing by itself does not seem to be a dominant feature for controlling hypoxia, except  
443 maybe for the Pearl River although tidal mixing may act with other physical factors such as  
444 wind to enhance vertical mixing in relatively shallow waters of this estuary. However, the  
445 tidal range during spring tides should be examined, rather than the average tidal range. If  
446 hypoxia occurs in deeper waters as in the case of Changjiang at 30-50 m, the mixing by tides  
447 may be less efficient compared to shallow estuaries like the Pearl River estuary.

448 The strength of summer stratification is another variable which may promote hypoxia  
449 since it restricts oxygenation of the water by reducing contact between the bottom water and  
450 the atmosphere. For the Mississippi shelf, a correlation between summer stratification and  
451 hypoxia has been proposed (Wiseman et al., 1997), Rowe and Chapman, 2002). This situation

452 is exemplified on Fig. 5, where a large decrease in temperature and an increase in salinity of  
453 the bottom waters produces high density bottom waters and hence strong stratification in  
454 August. A higher surface temperature is due to heat exchange with the atmosphere and a  
455 lower surface salinity is related to the input of freshwater from the river in the Louisiana  
456 current. If wind and tidal mixing are low, then hypoxia can occur over a large area. Amon and  
457 Benner (1998) calculated that bacterial oxygen consumption alone could reduce the oxygen  
458 concentration to hypoxic levels within 1 – 7 weeks during the summer. Chin-Leo and Benner  
459 (1992) calculated that 26 - 56 days of sub-pycnocline respiration (excluding benthic  
460 respiration) could lead to hypoxia. Large oxygen demands ranging from 20-50 mmol O<sub>2</sub> m<sup>-2</sup>  
461 d<sup>-1</sup> (Morse and Rowe, 1999) indicate that the sediment may constitute a large sink. Dortch et  
462 al. (2004) included both water and benthic respiration and calculated that bottom water  
463 oxygen depletion would take about 1 month in the summer. These different calculations  
464 indicate organic matter sedimentation into the sub-pycnocline layer is sufficient to consume  
465 oxygen and create hypoxia if oxygen is not replenished.

466 In the case of the Changjiang, permanent stratification is present when the Taiwan  
467 Warm Current (TWC) spreads at mid-depths below the Changjiang Diluted Water (CDW).  
468 The difference in salinity between these two water masses creates a strong barrier to oxygen  
469 replenishment in the Changjiang coastal region (Chen et al., 2003; Li et al., 2002; Zhu et al.,  
470 2004). This stratification coupled with the phytoplankton production and settling linked to  
471 nutrient discharge from the river is believed to be a major driver of hypoxia in the Changjiang  
472 coastal region, despite the strong currents transporting water from the south in the East China  
473 Sea. A major geographical correlation is described in Wei et al. (in press) between  
474 thermohaline stratification, Chl-*a* concentration and hypoxia occurrence in late summer at the  
475 Changjiang mouth.

476 These observations on the Mississippi and Changjiang where hypoxia is recurrent, suggest  
477 that stratification plays a key role in hypoxia development. Indeed, oxygen depletion is very  
478 sensitive to cross pycnocline exchange (Rowe 2001) and O<sub>2</sub> replenishment either vertically  
479 through the pycnocline or laterally, must be properly quantified if calculations of “time to  
480 hypoxia” are to be used to make predictions.

481 The situation is completely different for the Pearl River which has an open delta, but  
482 an inland estuary. Because of the monsoon regime in southern China, the highest discharge in  
483 the Pearl River occurs during summer (July) together with warmest temperatures. During this  
484 high discharge period, the flushing time of the estuary is short (3-5 days, (Yin et al., 2000))  
485 preventing the occurrence of hypoxic conditions. For the Rhône, which has similar  
486 hydrographical characteristics as the Mississippi (microtidal sea, low bottom currents at the  
487 river mouth), the mixing situation is quite different. Indeed, the northern Mediterranean Sea is  
488 characterised by elevated summer air temperature (around 30°C) and by the occurrence of  
489 strong north-western winds occurring half of the year with wind speeds > 10 m s<sup>-1</sup> and  
490 alternating with strong south-eastern winds. The occurrence of these wind reversals  
491 throughout the year with lower frequency in summer, promotes small scale circulation and  
492 inertial waves and provides oxygen to the bottom waters in the zone located around the plume  
493 area (Estournel et al., 2001; Estournel et al., 1997). Therefore in the Rhône coastal region,  
494 stratification occurs during summer warming, but it is counteracted by secondary wind-  
495 induced circulation which acts as an oxygen provider to the potential hypoxic zone. It is  
496 noteworthy that the Rhone shelf does not undergo summer hypoxia.

497

## 498 **Nutrient and organic matter discharge**

499 As hypoxia is the result of the interplay between oxygen supply from surface water and  
500 atmosphere and oxygen consumption from degrading organic matter, nutrient inputs which

501 generate algal production and subsequent settling to the bottom waters are a primary forcing  
502 factor on the system. River estuaries and deltas are regions of very high productivity sustained  
503 by nutrients of terrestrial origin and rainfall. In this section, we examine nutrient discharge,  
504 and N/P and N/Si nutrient ratios when available. We also examine the delivery of particulate  
505 and dissolved organic matter and their role in oxygen consumption.

506

507 ***Nitrogen, phosphorus and silicon inputs and nutrient ratios of the river discharge***

508 In all four systems, the nutrient concentration in the river input is high during all seasons  
509 (Table 5). Indeed, DIN concentrations are around 100  $\mu\text{M}$  on average for all systems, while  
510 DIP concentrations are much more variable. DIN and DIP input fluxes (Table 2) are related to  
511 water discharge and are maximal for the Mississippi and Yangtze and lower for the Pearl and  
512 Rhône Rivers.

513 The nutrient export to the coastal zone fuels a very intense primary production in the adjacent  
514 coastal zone. The nutrient load is the parameter generally associated with impacts in the  
515 estuary and surrounding waters as it is the total quantity of nutrients delivered and its  
516 utilization by the ecosystem which ultimately controls the total production of the delta and  
517 coastal system. Positive correlations exist between DIN discharge and primary productivity  
518 for the Mississippi (Lohrenz et al., this issue). Therefore, for potential hypoxia formation, the  
519 total flux of nutrients is a primary driver of the algal biomass formed and the potential oxygen  
520 consumption in bottom waters. However, when comparing river-coastal systems with  
521 different discharge volumes where the area of freshwater influence shows a wide range of  
522 variation and is related to the water discharge like the nutrient flux, it might be also interesting  
523 to consider nutrient concentration. This may provide a way to compare systems with very  
524 different discharge and discuss nutrient ratio.



525 Data from a suite of studies assessing nutrient limitation of phytoplankton production  
526 (summarized in Rabalais et al., 2002), indicate that, in the case of the Mississippi, either N, P,  
527 or Si can limit phytoplankton growth in the system, depending on the conditions and time of  
528 year. This is due to the low DIN:TP (15) or DIN:DSi (~ 1) ratios which are similar to nutrient  
529 utilization ratios by marine phytoplankton (DIN:DSi:DIP 16:16:1). In fact, N limitation  
530 appears most common during low flow periods and at higher salinities, particularly during late  
531 summer and fall. N is generally believed to be the main limiting nutrient, due to efficient  
532 recycling of P and loss of N to denitrification (Rabalais et al., 2002). During spring and early  
533 summer, P limitation may play an important role in primary production. Evidence from  
534 nutrient ratios and bioassays show that P limitation can occur during high flow and at  
535 intermediate salinities (Smith and Hitchcock, 1994; Lohrenz et al., 1997; Lohrenz et al., 1999;  
536 Sylvan et al., 2006a). Si limitation is more variable and most pronounced in the spring  
537 (Dortch and Whitley, 1992). Si limitation impacts diatoms (Nelson and Dortch, 1996;  
538 Lohrenz et al., 1999; Rabalais et al., 1999), which are an important fraction of the biomass of  
539 sinking particles (Redalje et al., 1994). Hence, Si dynamics are especially significant for  
540 hypoxia formation.

541 In the Pearl River during the summer, nutrient loads are high due to inputs from the river  
542 (DIN ~100  $\mu$ M, DIP ~1  $\mu$ M and DSi ~50  $\mu$ M) and rain (DIN ~50  $\mu$ M, DIP ~1  $\mu$ M and DSi  
543 ~50  $\mu$ M) (Yin, this issue; Yin et al., 2000, 2004b). The nutrient ratio of 100N: 100Si :1P is  
544 about 7 times the Redfield ratio required for phytoplankton growth and hence P potentially  
545 limits biomass production in the summer (Yin et al. 2000, 2004b; Yin 2002, 2003). The Pearl  
546 is similar to the Mississippi since Si limitation may occur before the river discharge begins to  
547 increase in May and potential nitrogen limitation may occur in the winter dry season due to  
548 the monsoon-driven invasion of coastal water. This is also the case for the Rhône and  
549 Changjiang Rivers where the DIN:DIP ratio is clearly higher than the utilisation ratio (16:1).

550 In contrast, the DIN/DSi ratio is close to the utilisation ratio (~1) which indicates that Si may  
551 not be limiting, except in the case of the Rhône River. These patterns, based on annually  
552 averaged concentrations, are only indicative of the potentially limiting nutrient as  
553 concentrations, and phytoplankton species vary during the seasons and might provide  
554 different situations for different seasons.

555 Regeneration processes are crucial for transporting nutrients as part of the buoyant plume that  
556 forms from the discharging river water. In the case of the Mississippi, respiration accounts for  
557 65% of the fate of the fixed carbon in the plume (Green et al. 2006) and recycling of plume  
558 nitrogen is a major pathway for nitrogen flow (Cotner and Gardner 1993; Gardner et al. 1994).  
559 This nitrogen recycling and associated production of organic matter provides an important  
560 mechanism for transporting a portion of the river nitrogen load and resultant organic matter  
561 production to the shallow regions susceptible to hypoxia development. This process is  
562 certainly acting in all systems as nitrogen recycling is very intense in river plumes.

563 The concentration of the most limiting nutrient ultimately determines the magnitude of  
564 primary productivity especially through the N:P and N:Si ratio. The functioning of the pelagic  
565 ecosystem (recycling versus downward export) determines the magnitude and location of  
566 organic matter deposition and they are both determine of the occurrence of hypoxia. Because  
567 ratios of N, P and Si have changed in most rivers during the past 50 years due to changes in  
568 land use, and dam building, the limiting nutrient has likely shifted also. For example, P  
569 limitation is likely more important now because of increased N input from the Mississippi  
570 River over the past 50 years (Turner and Rabalais, 1991). Nitrogen inputs have also increased  
571 in the Pearl (Yin et al., 2001), the Changjiang (Zhou and Shen, this issue) and other coastal  
572 areas of China (Harrison et al., 1990) over the last few decades. For the Rhône, nitrogen has  
573 increased during the seventies and stabilized since the early 80's (Moutin et al., 1998)

574

575 ***Phytoplankton Productivity and Community Structure***

576 As the river mixes with the coastal water, light is further enhanced by dilution and sinking of  
577 large lithogenic particles and particulate organic material and phytoplankton growth increases  
578 dramatically (Dagg and Breed 2003). In the Mississippi, phytoplankton growth rates approach  
579 theoretical maxima in the mid-salinity region, and can be as high as  $3 \text{ d}^{-1}$  at summer  
580 temperatures of  $30^{\circ}\text{C}$  (Fahnenstiel et al. 1995). In this region, primary production can reach  $10$   
581  $\text{g C m}^{-2} \text{ d}^{-1}$  (Lohrenz et al., 1999) during early summer. Both grazing and dilution by physical  
582 mixing tend to reduce phytoplankton concentration, but the growth rates typical of mid-  
583 salinity regions are so high that phytoplankton biomass rapidly accumulates in spite of these  
584 loss terms (Lohrenz et al. 1999). These high stocks of phytoplankton are often visible in  
585 satellite images (Reference??). Large phytoplankton cells are subject to lower grazing  
586 mortality in the low- and mid-salinity regions because of the relatively slow numerical  
587 response by their major grazers, the copepods (Liu and Dagg 2003). Consequently, large cells,  
588 especially diatoms, typically dominate the phytoplankton community in the mid-salinity  
589 region (Bode and Dortch 1996; Liu and Dagg 2003).

590 In the Pearl River estuary during the summer, large chain-forming diatoms such as  
591 *Skeletonema*, *Thalassiosira* and *Chaetoceros* dominate and Chl *a* ranges from  $20$  to  $>100 \text{ mg}$   
592  $\text{m}^{-2}$  (Yin 2002, 2003). The Pearl River estuary is very productive with values ranging from  $1$   
593 to  $5 \text{ g C m}^{-2} \text{ d}^{-1}$  due to high surface temperatures of about  $27^{\circ}\text{C}$  (Yin et al., 2000). The fate of  
594 this fixed carbon is not well understood in terms of how much sinks and how much is grazed  
595 by zooplankton.

596 For the Rhône River, a contrasting situation is found. The primary production  
597 encountered in the transition zone between the near- and mid-fields ( $<1 \text{ g C m}^{-2} \text{ d}^{-1}$ ) is much  
598 lower than for the other river systems, although the structure of the ecosystem is similar.  
599 Within the turbid plume where production is low, 50% of the chlorophyll *a* and 80% of the

600 primary production is attributed to pico- and nanoplankton (Videau and Leveau, 1990;  
601 Woodward *et al.*, 1990). In the transition area between the plume and the marine system,  
602 microplankton represented 50% of the chlorophyll *a* and primary production, largely due to  
603 diatoms during spring.

604 Primary production in the Changjiang-influenced coastal zone ranges from 1.5 to 4.5 g  
605 C m<sup>-2</sup> d<sup>-1</sup> (Chen *et al.*, 2004) during summer. This high primary production is highly seasonal  
606 with values falling to 0.04 g C m<sup>-2</sup> d<sup>-1</sup> during winter (Chen *et al.*, 2001). During the summer,  
607 primary and new production is largely driven by diatoms in the coastal zone influenced by the  
608 river. In the case of the Changjiang, coastal upwelling plays an important role in supplying  
609 deficient phosphorus to the surface waters during the summer (Chen *et al.*, 2004). In the turbid  
610 area of the plume, flagellates may photosynthesize and accumulate due to their ability to swim  
611 upward during the day (Chen *et al.*, 2003).

612 Except in the case of the Rhône River, high primary production during spring and summer (1-  
613 10 g C m<sup>-2</sup> d<sup>-1</sup>) is due to large fast-growing diatoms which can be exported through direct  
614 sinking at the end of the bloom and contribute to large inputs of labile organic matter to  
615 bottom waters. Large phytoplankton cells can sink at rates of several meters per day, and  
616 aggregates of cells or mixtures of cells and detritus at rates of 10 – 100 m d<sup>-1</sup>. At these rates,  
617 direct sinking of phytoplankton from the most productive layer of the plume, typically only 1-  
618 10 m thick, can easily provide a large input of organic matter to the sub-pycnocline layer that  
619 fuels hypoxia formation. Rapidly sinking (10 - 100 m d<sup>-1</sup>) fecal pellets provide an additional  
620 source of organic matter to the sub-pycnocline layer. If a significant fraction (~50%) of the 5  
621 g C m<sup>-2</sup> d<sup>-1</sup> reaches the sediment or bottom waters, this may cause oxygen consumption in  
622 bottom waters of up to 200 mmol m<sup>-2</sup> d<sup>-1</sup> which may create hypoxia in days to weeks if the  
623 replenishment of oxygen through the pycnocline is decreased by stratification. As an example,  
624 vertical flux of organic carbon in various parts of the Mississippi River plume is as high as

625 1.80 g C m<sup>-2</sup> d<sup>-1</sup> during spring, but rates are lower during other seasons (0.29 – 0.95 g C m<sup>-2</sup> d<sup>-1</sup>), and even lower away from the immediate plume (0.18 – 0.40 g C m<sup>-2</sup> d<sup>-1</sup>) (Redalje et al. 1994). This vertical flux is equivalent to approximately 10-25% of phytoplankton production in mid-salinity regions of the plume (Breed et al. 2004).

629

630

631 ***DOC and POC loading: what is their role in generating/sustaining hypoxia?***

632

633 The contribution of organic matter directly discharged by rivers to hypoxia is currently  
634 unknown. Most of the particulate organic carbon from the river is deposited close to the river  
635 mouth. Contrary to the paradigm of the terrigenous organic matter being largely refractory,  
636 this organic matter can be mineralized in the sediment giving rise to large oxygen demands  
637 (Morse and Rowe, 1999; Lansard et al., this volume). The demand of oxygen created by the  
638 direct deposition of organic matter can add to the oxygen demand generated by the settling of  
639 local primary production, reaching a threshold which might trigger hypoxia in bottom waters.  
640 Even less clear is the role of DOC in generating hypoxia. Some DOC from rivers is believed  
641 to be degradable (Raymond and Bauer, 2001), and Benner and Opsahl, (2001) estimated that  
642 the portion of Mississippi DOC that is labile was 2-4%. If DOC is labile, it would then  
643 contribute to oxygen consumption if entrained in coastal bottom waters. Significant processes  
644 such as adsorption on particulates (minerals or organic) in the water column can contribute to  
645 this transfer, but little is known about these processes near the river mouth. Cross pycnocline  
646 exchanges will also promote the introduction of labile DOC in bottom waters together with  
647 oxygen, thereby reducing the net oxygenation of the waters.

648

649 **The Pearl River System**

650 (I believe it is still the key to hypoxia, unfortunately, I have just started to look into this  
651 issue for the Pearl but have not yet systematic data set. My impression is that DOC is  
652 probably pretty much similar everywhere and thus POC loading and bacterial respiration  
653 of POC make the difference and is essential to maintain hypoxia. MH)  
654 Based on a cruise in Nov 2002 to the Pearl River Estuary, POC (%OC<sub>org</sub>) of SPM gives lower  
655 value in estuary and high value on the shelf. In the estuary, the lowest value of POC is at the  
656 turbidity maximum. In the upper estuary, POC decreased with TSM. While from turbidity  
657 maximum to the shelf, POC increased with the decreasing of TSM. In upper estuary, POC%=  
658 2.06 ~ 2.60% , and in lower estuary , POC%= 0.80 ~ 1.58% , while on the shelf, POC%=  
659 =1.63 ~ 10.34% , (TSM= 0.64 ~ 8.72mgL<sup>-1</sup>) (Dai et al., unpublished data).

660 **Minhan, I do not get your point here. Can you include in text or remove? Thank**  
661 **you.**

662 Summary

663 The comparison of four river-ocean systems provided some insights into the major factors  
664 influencing hypoxia on river-dominated ocean margins. Efficient nutrient utilization by  
665 primary producers on the shelf is an important process for providing organic matter to bottom  
666 waters. The impact of this production on hypoxia generation is certainly modulated by the  
667 food web structure (export-regeneration), although our study is not conclusive on that  
668 particular point. Physical constraints such as summer thermohaline stratification and long  
669 residence time are required for maintaining the isolation of bottom waters during oxygen  
670 consumption. Broad intermediate depth shelves (40-50 m) are also a condition where tidal and  
671 wind mixing are damped while a strong pelagic-benthic coupling is effective in the vertical  
672 transport of the algal biomass to depth.

673           The Mississippi and Rhône Rivers and their shelves are at the two extremes of this  
674 classification. The Mississippi has a long residence time, strong summer stratification, a broad  
675 intermediate shelf and high primary production in its plume. This river-coastal system  
676 displays the largest area of hypoxia. Mediterranean waters close to the Rhône River have a  
677 low residence time, summer stratification can be broken by wind reversals primary,  
678 production on the shelf is low and the shelf is deep. Therefore it shows no evidence of  
679 hypoxia.

680           The Changjiang and adjacent East China Sea are intermediate with a broad shelf, strong  
681 summer stratification and high primary production, but also high advection of water from the  
682 southern shelf which makes summer hypoxia less important in this area and less recurrent.  
683 The Pearl River estuary is shallow (<10 m) and wind and tidal mixing can reduce  
684 stratification. It has a short residence time during the summer wet season and flushing is high,  
685 and hence little hypoxia occurs in the lower estuary. In contrast, during the winter dry season,  
686 when the residence time is much longer (low flushing), severe hypoxia occurs in the upper  
687 part of the estuary.

688           The importance of the physical constraints on the occurrence of hypoxia points towards a  
689 potential risk of an increase in hypoxic areas due to a changing climate. Indeed, warmer  
690 summers and weaker winds during these summers, or changes in coastal water circulation  
691 could lead to enhanced stratification or decreased open-water intrusion on the shelf. In the  
692 future, this could lead to an increase in the potential of hypoxia in coastal areas which are, at  
693 present, impacted by high nutrient discharge, but have sufficient summer mixing to prevent  
694 complete oxygen consumption. Clearly further research is needed on this topic to assess the  
695 vulnerability of coastal zones located near a eutrophic river to climate change.

696

697

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910 **Figure Captions**

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912 Figure 2: Approximate bathymetry for the four river systems. The four thick lines represent  
 913 the very shallow estuary of the Pearl River, the shelf of the Yangtze, the Louisiana shelf west  
 914 of the Mississippi and the shelf west of the Rhône. Thinner lines (Rhône and Mississippi)  
 915 display bathymetric features at the river mouth, which are characterized by a prodelta and thus  
 916 steep slopes.

917 Figure 3: Oxygen distribution in the bottom waters off the Rhône River (June 2005).

918 Figure 4: Schematic diagram of alongshore circulation in intermediate and bottom waters.

919 Figure 5: Typical profiles of T, S and oxygen during hypoxic conditions in the Mississippi  
 920 system showing strong thermo-haline stratification (August 12, 2004, at 28° 32.86'N, 90°  
 921 54.62'W; M. Dagg unpublished).

922 **Tables**

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925 Table 1: Major characteristics of the four river systems.

	Length	Latitude of river mouth	Drainage basin	Freshwater discharge	Annual sediment discharge (Mt)
	(km)	(°N)	(1000 km <sup>2</sup> )	(10 <sup>9</sup> m <sup>3</sup> /y)	
Changjiang	6200	31°30' N	1800	924	486
Mississippi	6300	29°00' N	3210	530	210
Pearl	2200	22°30' N	450	330	80
Rhône	800	42°50' N	100	53	10

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929 Table 2: Annual nutrient discharge from the four rivers.

	Freshwater	Nutrient Input ( $10^9 \text{ mol y}^{-1}$ )				
	discharge ( $10^9 \text{ m}^3 \text{ y}^{-1}$ )	DIN	DIP	DSi	DOC	POC
Changjiang <sup>2</sup>	924	116	0.3	100	/	/
Mississippi <sup>1</sup>	530	68	1.3	72	150	317
Pearl <sup>3</sup>	330	28	0.3	46	/	/
Rhône <sup>4</sup>	53	8.8	0.08	4.8	11	16

930 <sup>1</sup> Goolsby et al., 1999

931 <sup>2</sup> Shen et al., 2005

932 <sup>3</sup> Cai et al., 2004

933 <sup>4</sup> De Madron et al., 2003

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937 Table 3 : Tidal range, summer stratification, bottom current speed and wind speed.

	Average	Stratification	Bottom current	Wind speed in
	Tidal range (m)		( $\text{cm s}^{-1}$ )	summer ( $\text{m s}^{-1}$ )
Changjiang <sup>3</sup>	2.5	Strong	25-30	
Mississippi <sup>1</sup>	1	Strong	2-5	4
Pearl <sup>2</sup>	1.4	Strong	25-50 <sup>5</sup>	2.5
Rhône <sup>4</sup>	0.4	Medium	10-15	

938 <sup>1</sup> Zavala-Hidalgo et al., 2003; Wiseman et al., 2004

939 <sup>2</sup> Yin et al., 2000

940 <sup>3</sup> Zhu et al., 2004

941 <sup>4</sup> Lansard et al., in prep

942 <sup>5</sup> Gan Unpubl. results

943 Table 4: Current speed in intermediate and deep waters near the river mouths, the extension of  
 944 the mixing system and the calculated residence time.

River	Alongshore current speed $\omega$ (cm s <sup>-1</sup> )	Extension of the system – L (km)	Residence time $\tau_{res}$ (d)
Changjiang	Taiwan Warm Current 30 cm s <sup>-1</sup> <sup>a</sup>	300	11
Mississippi	Louisiana bottom Current 2-5 cm s <sup>-1</sup> <sup>b, c</sup>	400	95
Pearl	China Coastal Current 10 cm s <sup>-1</sup> <sup>f</sup>	50	3-5 <sup>e</sup>
Rhône	Ligurian bottom Current 10 cm s <sup>-1</sup> <sup>d</sup>	50	6

945 <sup>a</sup> Zhu et al., 2004

946 <sup>b, c</sup> Zavala-Hidalgo et al., 2003; Wiseman et al., 2004

947 <sup>d</sup> Lansard et al., in prep.

948 <sup>e</sup> Yin et al., 2000

949 <sup>f</sup> Gan (unpubl. Results)

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952 Table 5: Average summer nutrient concentrations ( $\mu$ M) in four rivers and the nutrient atomic  
 953 ratio.

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River	DIN conc	DIP Conc	DSi conc	PIP conc	DIN/DIP	DIN/TP	DIN/DSI
Changjiang	125	0.3	110		417		1.13
Mississippi	128	2.5	136	5.8	51	15	0.9
Pearl	85	1	140		85		0.6
Rhône	164	1.6	90	3.1	103	35	1.8

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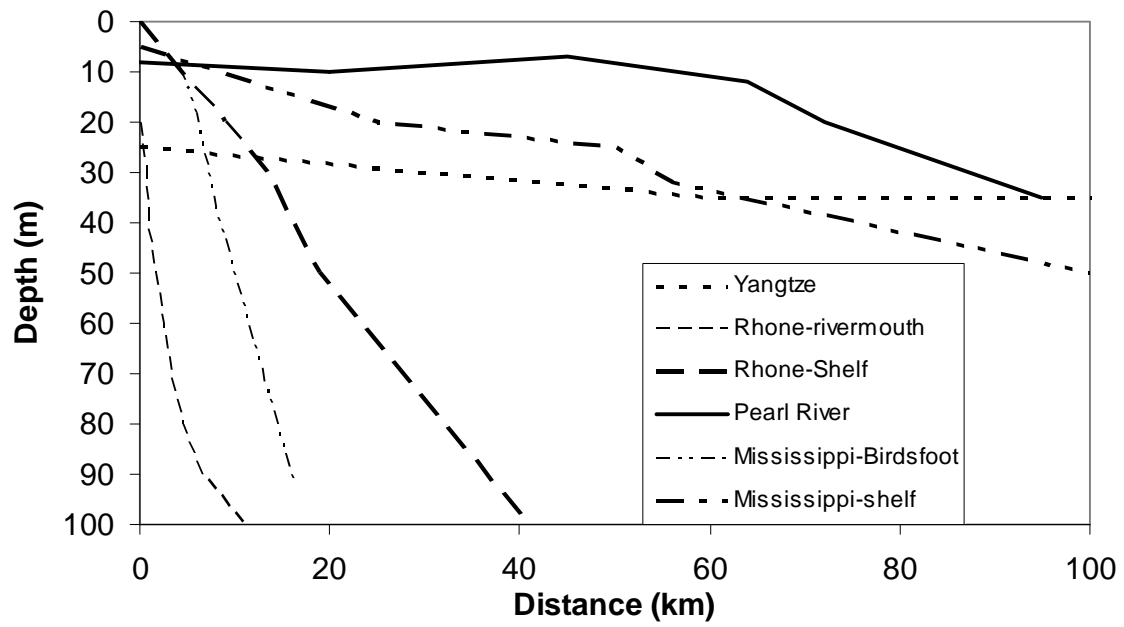




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961 Figure 2 – Rabouille et al.

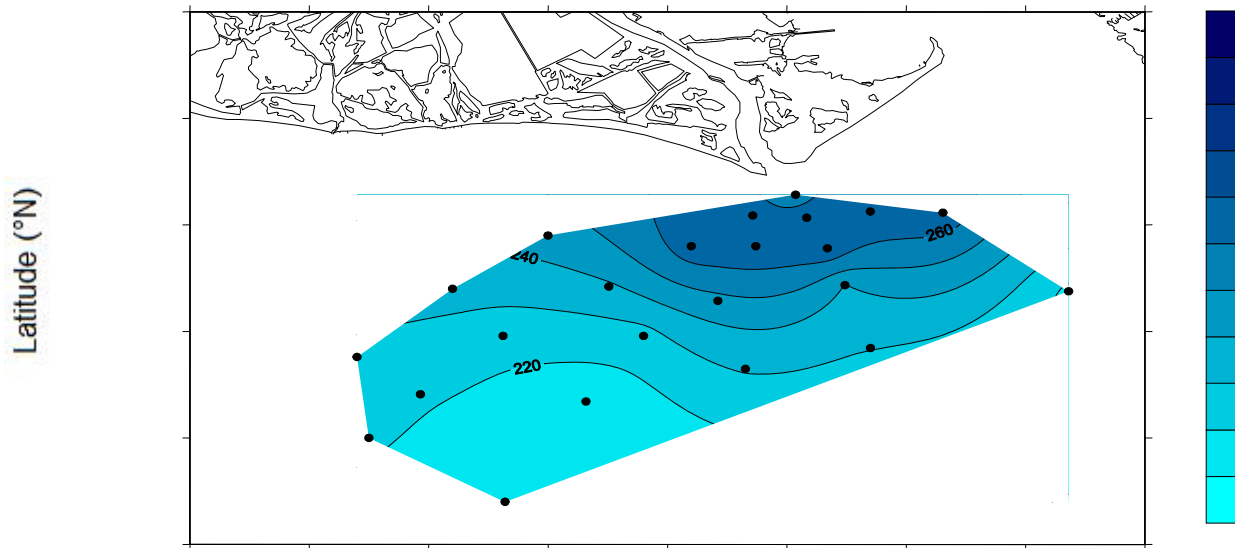
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Longitude (°E)



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967 Figure 3 – Rabouille et al.

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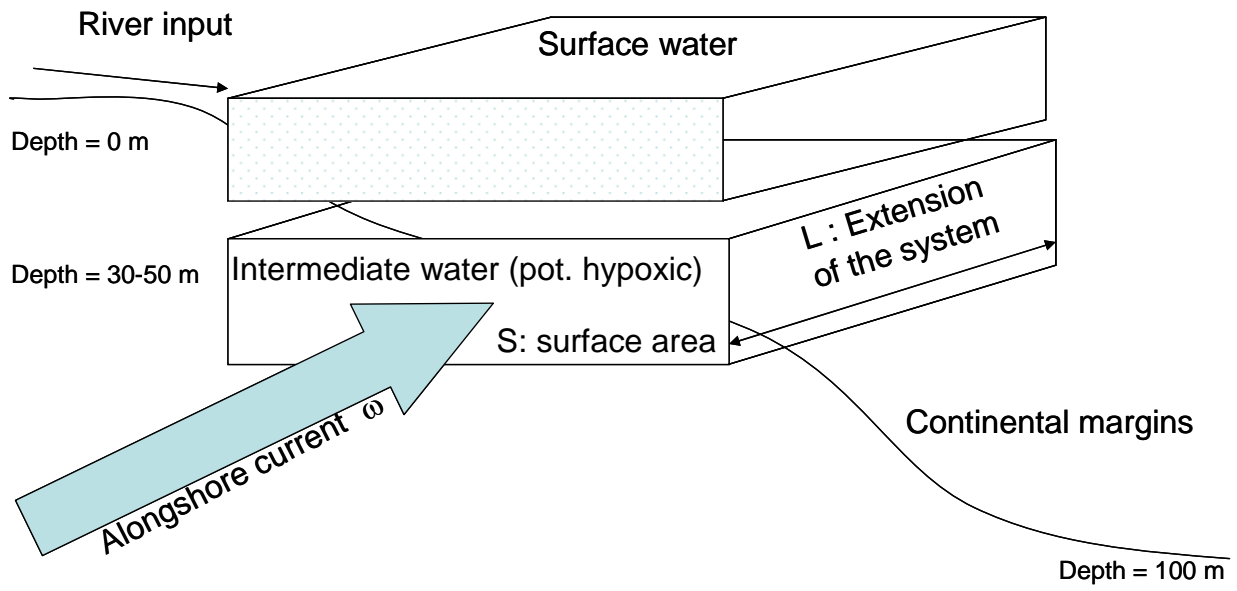
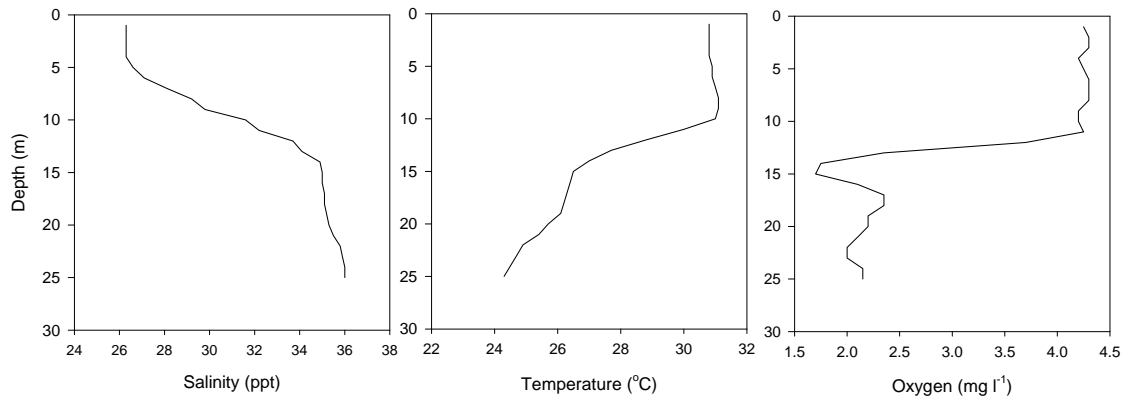


Figure 4 – Rabouille et al.

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993 Figure 5 – Rabouille et al.

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