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

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Abstract

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

Keywords

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

Regional index terms:

China, Changjiang River, East China Sea
USA, Mississippi River, Gulf of Mexico
China, Pearl River, South China Sea
France, Rhône River, Gulf of Lion

Introduction

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

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

Several estuaries and continental shelves of the world coastal ocean undergo severe hypoxia including the Chesapeake Bay, USA (Hagy et al., 2005), the Danish Straits (Conley et al., 2007), and the Mississippi River outlet in the Northern Gulf of Mexico which is the largest in area (Rabalais et al., 2002). Other estuaries such as the Changjiang (Yangtze) and Pearl Rivers in China (Zhou and Shen, this issue; Yin et al., 2004a; Dai et al., 2006) and the St. Lawrence River in Canada (Gilbert et al., 2005), exhibit hypoxia in the inner or outer part of their estuary.

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

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

Locations and characteristics of the four estuaries

Geographic position and discharge

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

The Changjiang River (Yangtze) is the second longest river in China (6200 km) and drains a large portion of central continental China (Table 1). It discharges into the East China Sea mainly through its south branch which discharges more than 95% of the runoff (Cai et al., this volume). Before the Three Gorges Dam was built, the annual freshwater discharge of the Changjiang River ranked fifth in the world and fourth for particle discharge (Milliman and Meade, 1983, Meade, 1996). This discharge is highly seasonal with 75% of the river runoff occurring during the flood/ rainy season between May and October. According to Yang et al., (2007), the building of the Three Gorges Dam has promoted a 30% decrease in discharge of sediments.

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

The Pearl River (or Zhujiang) is the 13th largest river in the world in terms of freshwater discharge and has an annual sediment delivery of ~80 Mt (Table 1; Zhao 1990; Tian 1994; Zhang et al. 1999). It discharges into the sub-tropical, oligotrophic South China Sea. Together with the Mekong River, they provide the largest freshwater input to the South China Sea (SCS), which is the largest marginal sea in the North Pacific. The Pearl River estuary is one of the most complex estuarine systems in the world (Cai et al., 2004; Gao et al., this issue). The Pearl River discharges into the South China Sea through three sub-estuaries, Lingdingyang, Maodaomen and Huangmaohai via eight main outlets, or distributaries, and is fed by three river tributaries, namely the Xi-jiang (West River), the Bei-jiang (North River) and the Dong-jiang (East River). The West River has the greatest freshwater discharge with about 67% of the total discharge (Zhou et al. 2006).

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

Nutrient discharge from the rivers

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

Dynamics of the bottom waters

The tidal range for the four estuaries is relatively small (Table 3). Only the Changjiang is mesotidal and slightly exceeds the 2 m range which is the upper limit of microtidal areas. The other coastal zones are characterised as microtidal, with the Pearl reaching the upper limit with a tidal range of 0.86 - 1.89 m for the main outlet. The tidal range is a very important characteristic as it shapes the development of the delta (Syvitski and Saito, 2007) and determines its exchange capacity with the coastal sea. All deltas and estuaries considered in this paper are only slightly influenced by tides, but some (like the Rhone or Pearl) are significantly affected by waves (Syvitski and Saito, 2007).

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

Bottom currents are variable for the four coastal zones (Table 3). On the Louisiana shelf away from the immediate plume area, surface current speeds are low (5-10 cm s^{-1}) and they reverse during the summer from westward to eastward (Zavala-Hidalgo et al., 2003). Bottom water currents in the inner shelf are even lower as measured by ADCP at 20 m (0.5-2 cm s^{-1}; (Wiseman et al., 2003). The current reversal occurring at the end of spring creates a temporary low in the transport rate in June, July and August (Smith and Jacobs, 2005). For the Changjiang, current speeds in the Taiwan Warm Current are on the order of 30 cm s^{-1} and occur throughout the year (Li et al., 2002; Zhu et al., 2004). This current occurs in intermediate and bottom waters along the 50 m isobath, and isolates bottom waters from the oxygen-rich surface waters (Wei et al., in press). The bottom current on the eastern part of the Gulf of Lion is mostly directed westward and shows intermediate speeds of 5-15 cm s^{-1} during the summer at 30 m over the Rhône prodelta (Lansard et al., in prep). Residence time in the Pearl River estuary is variable with a flushing time of a few days during the wet season (March-October, (Yin et al., 2004)), and a couple of weeks in the dry season (Dai, unpubl. data).

Shape of the estuaries

Most of the rivers in our comparison display large freshwater plumes that extend far onto the continental shelf and mix with seawater over the continental margin. The exception is the Pearl River with a seasonal plume that stretches onto the shelf only in the high discharge season in summer (Yin et al., 2001). At other times, the main open estuarine zone corresponds to a classical estuarine mixing zone. The input of particulate matter from these rivers has shaped the continental margin together with hydro-sedimentary processes (Saïto and Sivitsky, 2007) and most rivers display large flat shelves with depths shallower than 30 m for at least 50 km and even more for the Changjiang which reaches 40 m at around 200 km from the river outlet (Fig. 2). The only exception to this shallow shelf pattern is the Rhône, where depths >100 m are encountered closer to the river mouth (40 km or less). The shape of the river mouths of the Rhône and Mississippi are different from the bathymetry of their adjacent shelves. Indeed, both rivers have built prodeltas which prograde onto the shelf and create large slopes at the river mouth, with depths of around 100 m within 10 to 20 km off the river mouth and a clear difference on the bathymetric chart (Fig. 2).

Occurrence of hypoxia

Changjiang:

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

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

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

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

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

In contrast, in the upper estuary during the winter dry season, downstream of the city of Guangzhou with salinities between 1-5, persistently low dissolved oxygen, down to < 1 mg L^{-1}, was documented in the water column (Dai et al, 2006; Zhai et al, 2005). This severe hypoxia is due to poor flushing during the dry season. These strongly hypoxic waters occur 30 km upstream of the river outlet and are due to organic matter decomposition supplemented by high nitrification rates due to high organic loads from agricultural runoff and sewage inputs (Dai et al., 2006). A strong transition from hypoxic to low oxygen waters occurs at salinity 5 to 15 between 30 and 20 km upstream of the open part of the estuary. Shelf water is stratified during spring-summer when the estuarine plume forms, but the stratification does not appear to induce the formation of hypoxia perhaps due to the fact that the estuary is quite shallow (5-20 m). There is little or no stratification in winter due to wind mixing and average winter wind speeds (10 m s^{-1}.) are four times higher than summer (2.5 m s^{-1}) (Yin 2002).

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

Discussion

The occurrence of hypoxic conditions in coastal regions connected to large rivers is due to an interplay between water column production, which supplies organic matter to bottom water and sediment generating oxygen consumption, and physical forcings (stratification, the circulation pattern in the region, and residence time of the water in the mixing zone) which prevent oxygenation of bottom waters. We examined these physical and biogeochemical factors separately for the four systems where data are available. All four river/coastal sea systems show different physical characteristics, yet the two largest systems (Yangtze and Mississippi) undergo seasonal hypoxia at intermediate depths on the shelf, whereas the Pearl system displays low oxygen (within the estuarine zone), but no hypoxia over the shelf, and the Rhone continental shelf is largely oxygenated. The nutrient inputs to the coastal zone are different between systems (varying with the water flux), but nutrient concentrations are elevated in all systems (>= 100 µM for DIN) and it is clear that nutrients alone do not determine hypoxia.

Physical forcings

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

Shape of the estuary

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

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

Residence time of the bottom water

Residence time of bottom waters may be an important factor for hypoxia development because it directly affects the duration of oxygen consumption during organic matter decomposition and thus the degree of O_2 depletion. A long residence time may allow complete decomposition of organic matter and large oxygen consumption. Residence time of bottom waters is controlled by horizontal advection of the water under the influence of intermediate and bottom shelf currents.

In most systems where the river discharges onto the continental shelf (Rhone, Yangtze, Mississippi), the margin is dominated by an alongshore current. For each of these river systems, this current has different intensities (discussed above and reproduced in Table 4). In order to calculate the residence time of the bottom water, one must define the box over which it is calculated. The box that we chose has the approximate size of the zone where primary production from the river plume in surface water is dominant (Table 4). Although occurring in surface waters rather than bottom water where our calculation applies, primary production is a primary driver of hypoxia through the transfer of organic matter to bottom waters (Green et al., 2006) and thus the size of its area of influence determines potential hypoxic areas. The residence time of the water is calculated as the ratio between the volume of the water in this box to the flux of water through the lateral surface of the box.

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

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

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

$$V_{hypoxic} = S_{box} * L$$

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

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

$$\tau_{res} = L / \omega$$

As a first order approximation, the results from Table 4 show that hypoxia is somehow related to the residence time as the Mississippi system with the longest bottom water residence time showing the strongest and largest hypoxia, while the Rhône with a short residence time and the Pearl in the lower estuary has no hypoxia. ECS/Changjiang displays hypoxia in a less regularly and often of a shorter duration which might be due to more vigorous replacement of its bottom water by bottom currents.

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

Tidal regime, summer stratification

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

The strength of summer stratification is another variable which may promote hypoxia since it restricts oxygenation of the water by reducing contact between the bottom water and the atmosphere. For the Mississippi shelf, a correlation between summer stratification and hypoxia has been proposed (Wiseman et al., 1997), Rowe and Chapman, 2002). This situation is exemplified on Fig. 5, where a large decrease in temperature and an increase in salinity of the bottom waters produces high density bottom waters and hence strong stratification in August. A higher surface temperature is due to heat exchange with the atmosphere and a lower surface salinity is related to the input of freshwater from the river in the Louisiana current. If wind and tidal mixing are low, then hypoxia can occur over a large area. Amon and Benner (1998) calculated that bacterial oxygen consumption alone could reduce the oxygen concentration to hypoxic levels within 1 – 7 weeks during the summer. Chin-Leo and Benner (1992) calculated that 26 - 56 days of sub-pycnocline respiration (excluding benthic respiration) could lead to hypoxia. Large oxygen demands ranging from 20-50 mmol O_2 m^{-2} d^{-1} (Morse and Rowe, 1999) indicate that the sediment may constitute a large sink. Dortch et al. (2004) included both water and benthic respiration and calculated that bottom water oxygen depletion would take about 1 month in the summer. These different calculations indicate organic matter sedimentation into the sub-pycnocline layer is sufficient to consume oxygen and create hypoxia if oxygen is not replenished.

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

These observations on the Mississippi and Changjiang where hypoxia is recurrent, suggest that stratification plays a key role in hypoxia development. Indeed, oxygen depletion is very sensitive to cross pycnocline exchange (Rowe 2001) and O_2 replenishment either vertically through the pycnocline or laterally, must be properly quantified if calculations of “time to hypoxia” are to be used to make predictions.

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

Nutrient and organic matter discharge

As hypoxia is the result of the interplay between oxygen supply from surface water and atmosphere and oxygen consumption from degrading organic matter, nutrient inputs which generate algal production and subsequent settling to the bottom waters are a primary forcing factor on the system. River estuaries and deltas are regions of very high productivity sustained by nutrients of terrestrial origin and rainfall. In this section, we examine nutrient discharge, and N/P and N/Si nutrient ratios when available. We also examine the delivery of particulate and dissolved organic matter and their role in oxygen consumption.

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

In all four systems, the nutrient concentration in the river input is high during all seasons (Table 5). Indeed, DIN concentrations are around 100 µM on average for all systems, while DIP concentrations are much more variable. DIN and DIP input fluxes (Table 2) are related to water discharge and are maximal for the Mississippi and Yangtze and lower for the Pearl and Rhône Rivers.

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

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

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

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

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

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

Phytoplankton Productivity and Community Structure

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

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

For the Rhône River, a contrasting situation is found. The primary production encountered in the transition zone between the near- and mid-fields (<1 g C m^{-2} d^{-1}) is much lower than for the other river systems, although the structure of the ecosystem is similar. Within the turbid plume where production is low, 50% of the chlorophyll *a* and 80% of the primary production is attributed to pico- and nanoplankton (Videau and Leveau, 1990; Woodward *et al.*, 1990). In the transition area between the plume and the marine system, microplankton represented 50% of the chlorophyll *a* and primary production, largely due to diatoms during spring.

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

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

1.80 g C m^{-2} d^{-1} during spring, but rates are lower during other seasons (0.29 – 0.95 g C m^{-2} d^{-1}), and even lower away from the immediate plume (0.18 – 0.40 g C m^{-2} d^{-1}) (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).

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

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

The Pearl River System

(I believe it is still the key to hypoxia, unfortunately, I have just started to look into this issue for the Pearl but have not yet systematic data set. My impression is that DOC is probably pretty much similar everywhere and thus POC loading and bacterial respiration of POC make the difference and is essential to maintain hypoxia. MH)

Based on a cruise in Nov 2002 to the Pearl River Estuary, POC (%OC_{org}) of SPM gives lower value in estuary and high value on the shelf. In the estuary, the lowest value of POC is at the turbidity maximum. In the upper estuary, POC decreased withTSM. While from turbidity maximum to the shelf, POC increased with the decreasing of TSM. In upper estuary, POC%= 2.06 ~ 2.60%， and in lower estuary，POC%= 0.80 ~ 1.58%，while on the shelf, POC% =1.63 ~ 10.34%，(TSM= 0.64 ~ 8.72mgL^{-1}) (Dai et al., unpublished data).

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

Summary

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

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

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

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

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Figure Captions

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

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

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

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

Tables

Table 1: Major characteristics of the four river systems.

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

Table 2: Annual nutrient discharge from the four rivers.

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

[1] Goolsby et al., 1999

[2] Shen et al., 2005

[3] Cai et al., 2004

[4] De Madron et al., 2003

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

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

[1] Zavala-Hidalgo et al., 2003; Wiseman et al., 2004

[2] Yin et al., 2000

[3] Zhu et al., 2004

[4] Lansard et al., in prep

5 Gan Unpubl. results

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

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

[a] Zhu et al., 2004

[b,c] Zavala-Hidalgo et al., 2003; Wiseman et al., 2004

[d] Lansard et al., in prep.

[e] Yin et al., 2000

[f] Gan (unpubl. Results)

Table 5: Average summer nutrient concentrations (µM) in four rivers and the nutrient atomic ratio.

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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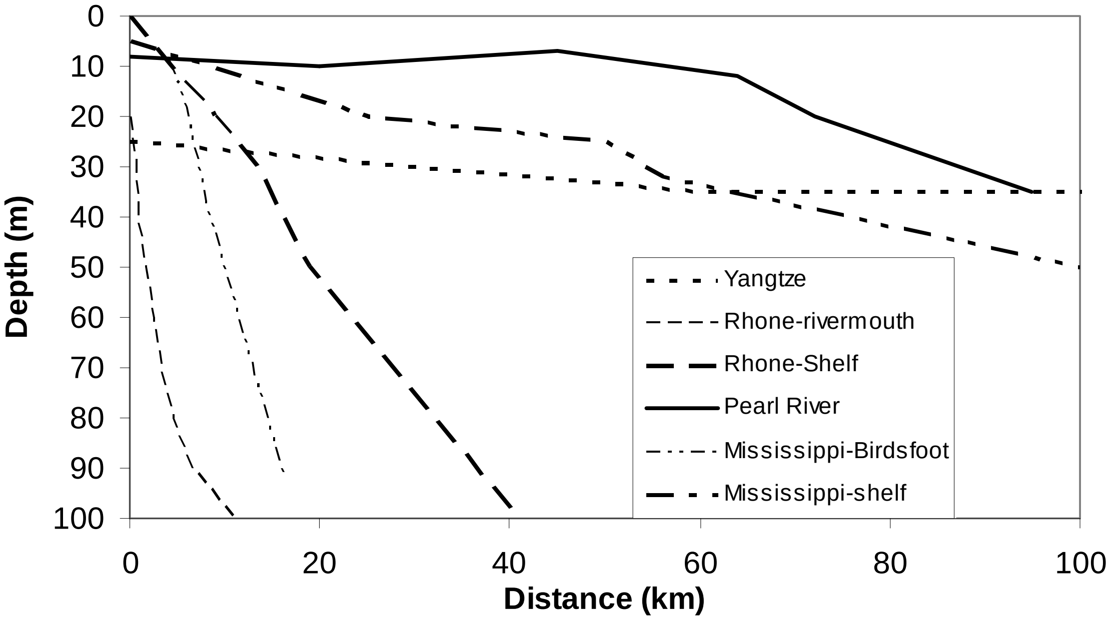

Figure 2 – Rabouille et al.

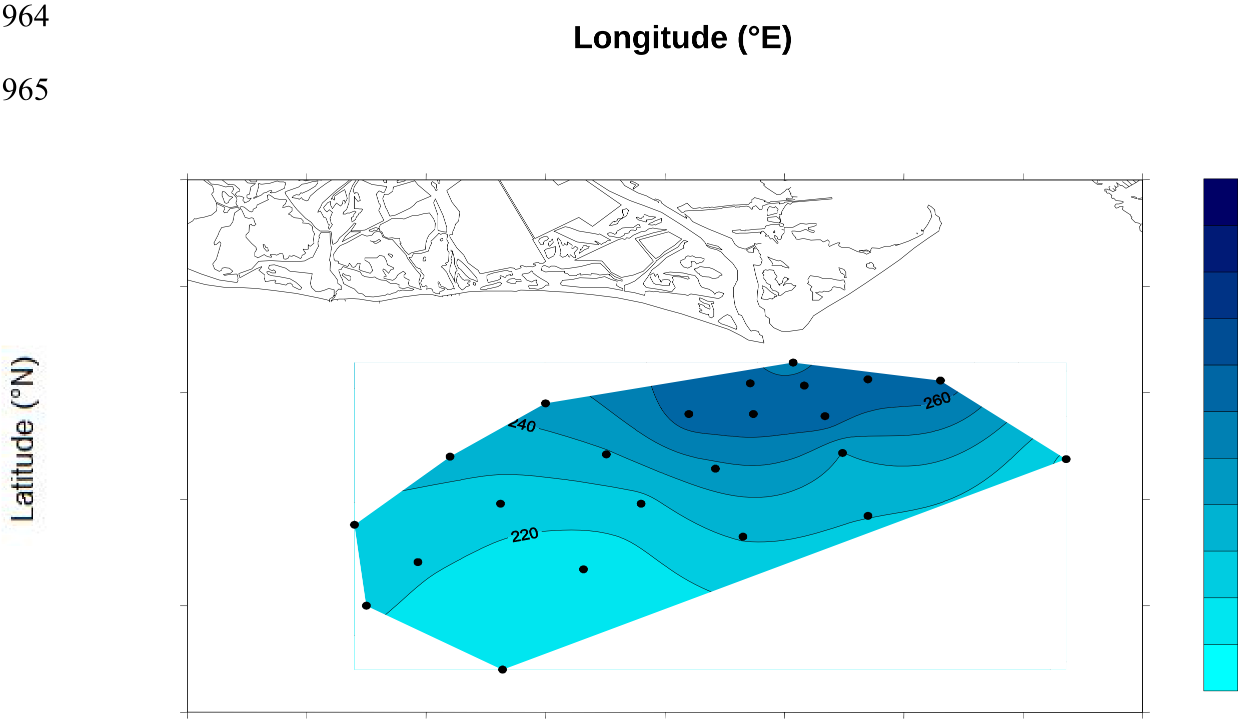

Figure 3 – Rabouille et al.

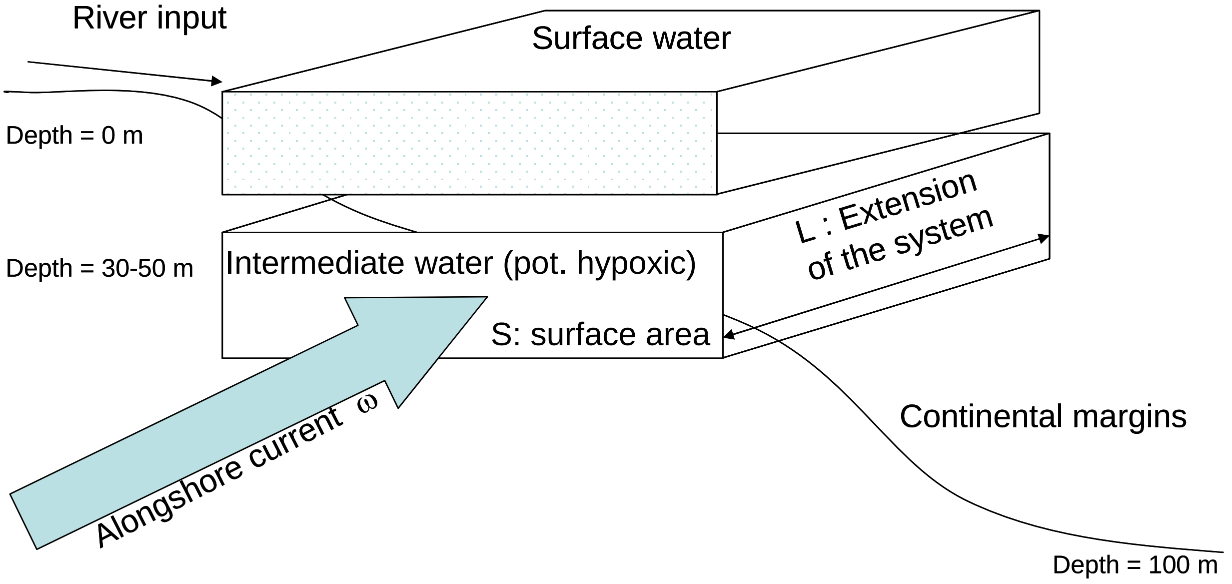

Figure 4 – Rabouille et al.

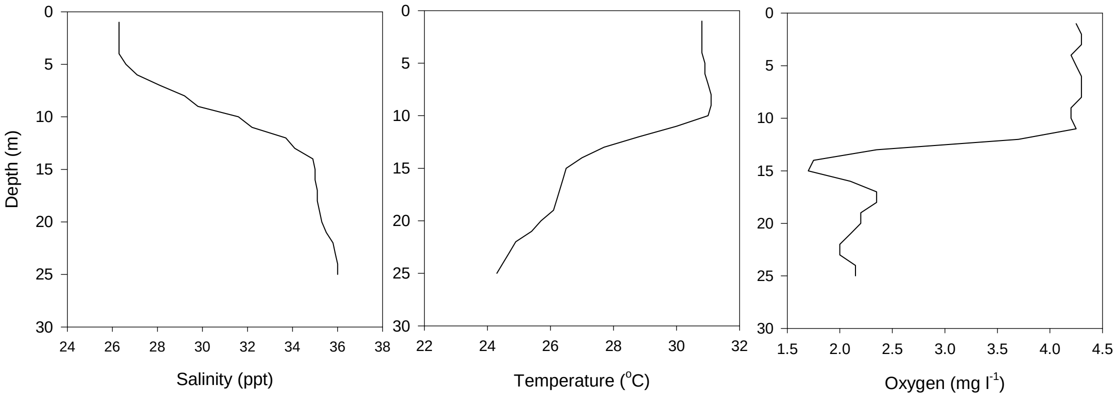

Figure 5 – Rabouille et al.