Large-river delta-front estuaries as natural "recorders" of global environmental change

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Large-river delta-front estuaries (LDE) are important interfaces between continents and the oceans for material fluxes that have a global impact on marine biogeochemistry. In this article, we propose that more emphasis should be placed on LDE in future global climate change research. We will use some of the most anthropogenically altered LDE systems in the world, the Mississippi/Atchafalaya River and the Chinese rivers that enter the Yellow Sea (e.g., Huanghe and Changjiang) as case-studies, to posit that these systems are both ''drivers'' and ''recorders'' of natural and anthropogenic environmental change. Specifically, the processes in the LDE can influence (''drive'') the flux of particulate and dissolved materials from the continents to the global ocean that can have profound impact on issues such as coastal eutrophication and the development of hypoxic zones. LDE also record in their rapidly accumulating subaerial and subaqueous deltaic sediment deposits environmental changes such as continental-scale trends in climate and land-use in watersheds, frequency and magnitude of cyclonic storms, and sea-level change. The processes that control the transport and transformation of carbon in the active LDE and in the deltaic sediment deposit are also essential to our understanding of carbon sequestration and exchange with the world ocean—an important objective in global change research. U.S. efforts in global change science including the vital role of deltaic systems are emphasized in the North American Carbon Plan (www.carboncyclescience.gov).

carbon cycling | large-river-delta-front estuary | land-margin interactions | paleoreconstruction

Approximately 87% of Earth's land surface is connected to the ocean by rivers (1). Over the past 50 years increases in the human population have had severe global effects on rivers and deltaic systems through enhanced fertilizer usage, damming, deforestation, and many other land-use changes (2, 3). Many countries in the world are experiencing potable and agricultural water shortages (4). For example, although 30% (13,500 × 10^9 m^3·year^{-1}) of the world's (42,700 × 10^9 m^3·year^{-1}) renewable water resources are concentrated in Asia (5), countries like China are still experiencing water shortages in certain regions. Consequently, some of China's major river systems (e.g., Huanghe and Changjiag Rivers) have been dramatically altered by human activities in an attempt to remedy these water limitations (3). Recent work has documented global decreases in water and/or sediment discharge to the coastal ocean in numerous large-river deltaic estuaries (LDE) such as the Mississippi, Nile, Indus, Changjiang and Huanghe systems (6–8). Although humans have increased riverine sediment transport within the continents through soil erosion by an estimated 2.3 ± 0.6 Pg·year^{-1}, the actual amount reaching the ocean has decreased by 1.4 ± 0.3 Pg·year^{-1}, mainly due to dams and reservoirs (3, 9). These reductions play an important role in deltaic coastal retreat, where a large fraction of the human population lives, at a time when climate-driven acceleration in the rate of sea level rise threatens these low-elevation landscapes. Consequently, there has been increased interest in understanding how the flux of materials from rivers to the ocean have been altered, including global community programs such as the International Geosphere Biosphere Program (IGBP) and its major project, Land Ocean Interaction in the Coastal Zone (LOICZ) (3, 10).

Human Linkage

It has been estimated that ≈61% of the world population lives along the coastal boundary (11). By 2025, an estimated 75% of world's population is expected to live in the coastal zone, with many of the remaining 25% living near major rivers (12). The coastal ocean is a dynamic region where rivers, estuaries, ocean, land, and the atmosphere interact (13, 14). Although relatively small in area, this region (30% of the total net oceanic productivity) supports as much as 90% of the global fish catch (15). More specifically, LDE are typically some of the most productive regions in the coastal ocean so it is important to note that despite the limited areal extent, their role in commercially important fisheries cannot be over emphasized. Because of their ability to support large human populations, due to their enormously fertile agricultural potential and fisheries, LDE have historically played an important role in the advance of human civilizations (via trade and transportation) (ref. 12 and references therein). Demands of hydraulic power began some 5,000 years ago with the development of some of the first cities in human history in Mesopotamia, and the Nile, Huanghe, and Indus valleys (16). One of the most challenging issues concerning large river fluxes is to better understand the presumably major changes that they have undergone over the "Anthropocene" (16, 17) as a result of land-use changes (agriculture and urbanization) and river basin alterations, and the resultant impact of these changes on the land-ocean material transfer term, both quantitatively and qualitatively. For example, the "quality" of C being exported from rivers that have been impacted by dams will increase because there is likely to be more phytoplankton compared with terrestrially-derived vascular plant detritus exported to the LDE, which is more biologically available to coastal food webs (12, and reference therein)—further details on this later.

Deltaic "System"

A delta (typically, but not always showing a shoreline protuberance) forms because river-derived sediments accumulate faster in a coastal/river water body than they can disperse from marine redistribution processes (18) (Fig. 1). More specifically, Wright (18) has defined a delta as "coastal accumulations, both subaqueous and subaerial, of river-derived sediments adjacent to, or in close proximity to, the source stream, including the deposits that have been secondarily molded by various marine agents, such as waves, currents, or tides." LDE include a subset of the subaerial and subaqueous delta systems of large rivers (Fig. 2). The subaerial LDE

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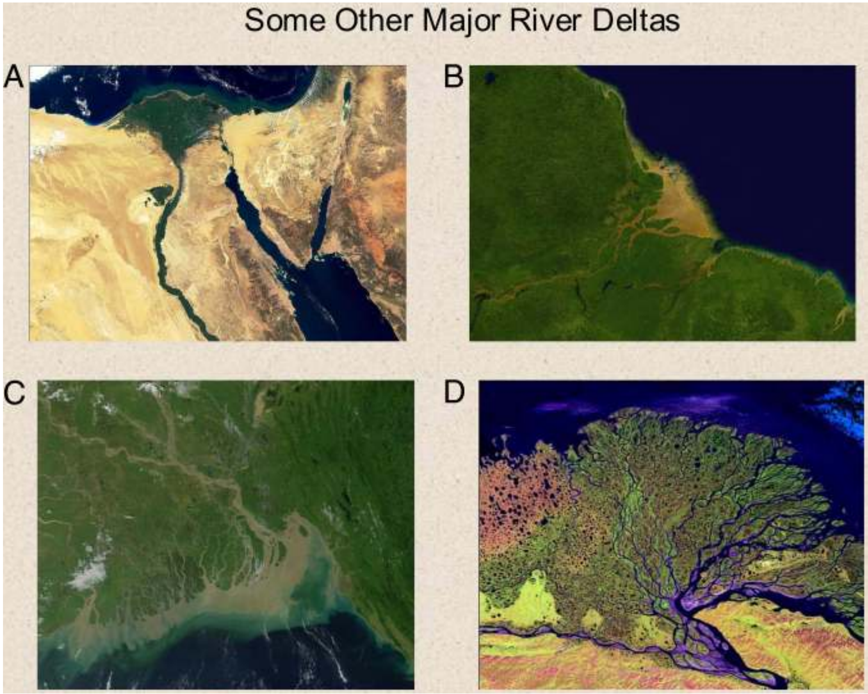

Fig. 1. Some other major deltas of the world. (*A*) Nile. (*B*) Amazon. (*C*) Ganges–Brahmaputra. (*D*) Lena.

extends inland along the deltaic plain and lowland floodplain (inland of the delta) to the limit of the tidal and/or saline intrusion in the adjacent river channel, and includes large river mouths without a shoreline protuberance (12, 19). In the subaqueous, the LDE extends onto the continental shelf where the initial fallout of river particulates takes place, and the bulk of long-term sediment accumulation is found. This deltaic subzone is where increased sedimentation, organic matter deposition, burial, transformation and occur—the primary reasons LDE are important in the context of global C cycling. It has been estimated that 80% of the total organic carbon preserved in marine sediments occurs in "terrigenous-deltaic" regions near river mouths (20, 21), which we have referred to as the subaqueous LDE. We have included the lowland floodplain in the LDE because studies in systems like the Amazon (22) and Ganges–Brahmaputra (23) have shown that as much as 30% of some river's sediment load is trapped here above the delta plain and land-sea interface. Finally, it should be noted that the aforementioned boundaries of an LDE (as defined here) are different from what has commonly been referred to as river-dominated margins (RiOMars), because RiOMars generally do not include the lowland floodplain and extend much farther across the continental margin (including submarine canyons constructed by the river) and alongshore for hundreds to thousands of kilometers, as defined by the limits of the low salinity plume (24). The defined upper margin of the large Chinese and Mississippi–Atchafalaya River LDEs are shown in Fig. 3.

Fluxes and Cycling of Materials to LDE

The coastal ocean and in particular LDE represent active interfaces between terrestrial and oceanic environments (the 2 largest global sinks for atmospheric CO_2) where CO_2 fluxes as either source or sink have been estimated to be 1 Pg of C per year (25). The world's 25 largest rivers drain approximately half of the continental surface and transport ≈50% of the fresh water and 40% of the particulate materials entering the ocean (2, 25–27); once again it is important to remember that this is a considerable amount given the relatively small areal extent of the LDE—as mentioned earlier (Table 1). Rivers transport an estimated 20 $\text{Pg}\cdot\text{year}^{-1}$of fluvial sediments to the coastal zone (3, 27, 28); associated with this sediment loading is an estimated 0.21 Pg of particulate organic carbon (POC) per year (ref. 24; see also ref. 29 and references therein). They are also the major contributers of dissolved organic carbon (DOC) to the oceans: Global estimates of riverine flux of DOC generally range from ≈0.25 to 0.36 $\text{Pg}\cdot\text{year}^{-1}$ (28, 30, 31); more recent estimates by Richey (32) suggest that total global river POC+DOC export may need to be revised upward, closer to ≈0.8 Pg of C per year. Much of the POC in rivers is derived from both allochthonous (e.g., soil organic matter, algal inputs from streams, and from aquatic emergent and submergent wetland vegetation) and autochthonous material. Interestingly, recent estimates indicate that inland waters receive an annual loading of 1.9 Pg of C per year from anthropogenically altered sources of the terrestrial system, of which 0.2 is buried in aquatic systems, with ≈0.8 Pg C possibly returned to the atmosphere through gas exchange and the remaining 0.9 Pg C being delivered to oceans (33). One point of interest here is that ≈1 to 3 Pg C (as POC) has been trapped in reservoirs over the past 50 years (3). One of the most challenging issues concerning large river organic carbon (OC) and organic matter (OM) fluxes is to better understand the presumably major changes that they have undergone over the Anthropocene as a result of land use changes (agriculture and urbanization) and river basin alterations, and the resultant impact of these changes on the land-ocean-atmosphere C transfer terms, both quantitatively and qualitatively.

In modern marine environments, riverine delivery of OC to LDE is the dominant means by which terrigenous production is preserved, thereby influencing global biogeochemical cycles and the ocean's ability to sequester atmospheric CO_2. Yet, there remains considerable uncertainty in our ability to adequately quantify carbon exchange from land to the coastal ocean and in our understanding of the processes influencing the fate of terrigenous carbon in coastal sediments (20, 29). Recent work has shown that areas of low $p\text{CO}_2$ in the Mississippi River plume were associated with high phytoplankton productivity—driven by high river nutrient loading (34). More recently, estimates of air-to-sea fluxes in the Mississippi River plume (2–4.2 mmol of C per square meter per day) were made using satellite ocean color assessment (MODIS-Aqua L1B) (35), are consistent with previous field measurements. Air-to-sea exchanges near the Changjiang River delta also reflect carbon sequestration from enhanced phytoplankton production due to nutrient loading (36). Similarly, the flux of other important greenhouse gases like CH_4 and N_2O have been shown to be important in these dynamic regions, particularly where hypoxic zones have developed (ref. 12 and reference therein).

The importance of LDE to global OC burial (29) is evidenced by the tremendous magnitude of material fluxes to these regions. Yet, despite the importance of these environments, there remains a fundamental lack of understanding about OC dynamics operating within these regions. This lack of understanding largely results from the high degree of spatial and

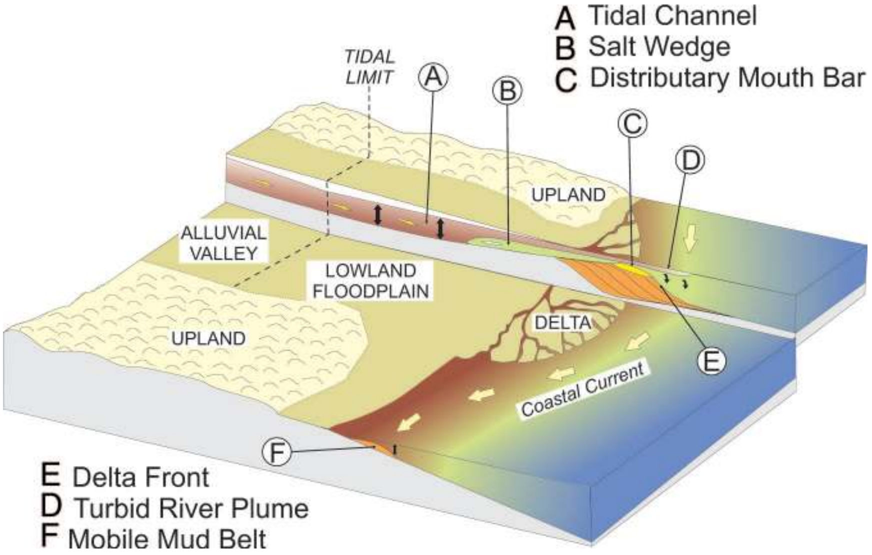

Fig. 2. Regional geomorphogical boundaries and associated sedimentary deposits within an LDE.

temporal variability in the sources of OC: (*i*) primary production by phytoplankton and (*ii*) discharge of terrestrially-derived organic carbon by rivers and from deltaic sediments reworked by marine processes. Additional variability on OC dynamics is induced by the OC diagenetic effects of mobility of recently deposited riverine muds on the inner shelf. Successive resuspension and deposition episodes of these "mobile muds" may also act to enhance the degradation of terrestrially-derived OC, which is generally assumed to be very decay-resistant. The pioneering work of Aller and his associates (e.g., refs. 37–39) has shown the importance of mobile muds as an "incinerator" of terrestrially-derived OC in other deltaic systems that have mobile mud belts, such as the Amazon and Fly rivers. Thus, although it can be established that LDE are globally important zones of organic carbon input with enhanced burial and carbon remineralization, further work is needed to better understand the relative role of these processes in the context of the global carbon cycle. As we will show in the case studies below, this understanding is further complicated by human-induced changes in material fluxes now being carried by these systems to the oceans.

Case Studies in the Impact of Watershed Land Use Change on Global Fluxes

Mississippi-Atchafalaya River System. The Mississippi River flows 3,780 km from its source to the Gulf of Mexico (GOM) and has the largest of all North American watersheds (3.3×10^6 km^2) (40), draining 40% of the continental United States and parts of 2 Canadian provinces (Fig. 4*A*). The Mississippi has a mean annual water discharge of $\approx$18,400 m^3·s^{-1}. The distribution of this water at the coast is divided because of the presence of a major distributary of the Mississippi, the Atchafalaya River, which contains $\approx$30% of the total system flow. On average, Mississippi–Atchafalaya River (MAR) discharge is strongest during the spring flood (January-June); low discharge is only $\approx$30% of this springtime high. The hydrographic structure and dynamics of the plumes emitted from these 2 river mouths differ because the Mississippi discharges into deep water near the continental shelf edge, whereas the Atchafalaya discharges into shallow water onto a 150-km-wide shelf. Both rivers generate physical and biogeochemical impacts in the coastal and deep water ocean far beyond the region of the easily identifiable turbid water plume that defines the LDE seaward boundary.

Suspended sediment concentrations have been decreasing in the main stem of the MAR since the 1950s as the largest natural sources of sediment in the drainage basin were cut off from the MAR main stem by the construction of large reservoirs on the Missouri and Arkansas Rivers (41, 42). Before creation of dams and reservoirs beginning in the 19th century, the average annual sediment discharge to the Gulf of Mexico (GOM) by the MAR is estimated to have been $\approx$0.4 Pg (40). These factors, combined with the implementation of soil conservation practices since the 1930s in the drainage basin and meander cutoffs and bank revetments (41, 43), have reduced the present MAR sediment load to $\approx$0.2 Pg·year^{-1} (26, 44) since the 1950s and to 0.1 Pg·year^{-1} during the last 2 decades (1987–2006) (45, 46). This reduction in loading has reduced sediment and organic carbon accumulation on the subaqueous LDE by an estimated factor of 2 to 3 (47). Conversely, the flux of nitrate has approximately tripled in the last 40 years with most of the increase occurring between 1970 and 1983 due to chemical fertilizer loss from agricultural lands of the upper drainage basin (48).

As total suspended solid (TSS) loads have fallen in the MAR, increases in light availability appear to have stimulated phytoplankton production, particularly in regions of the river within the upper drainage basin, where nutrients remain high (49, 50, 51). For example, many regions in the upper drainage basin of the MAR that have been dammed contain reservoirs where sediment particles have settled out of the water (under lower flow regimes), allowing for greater light levels and phytoplankton production. Thus, phytoplankton inputs from reservoirs (and navigation locks), and in some cases from oxbow lakes and adjacent wetlands—primarily within the Missouri and upper Mississippi River (52, 53), may be important in "seeding" phytoplankton populations in the mainstem Mississippi River (54). In fact, high chlorophyll concentrations have been observed in both the Upper Mississippi River (up to 190 μg·L^{-1}) and the Missouri River (4.5–107 μg·L^{-1}) (55), compared with relatively lower chlorophyll-a concentrations observed in the deeper Ohio River (1.1–17.7 μg·L^{-1}) (56). High phytoplankton biomass in some oxbow lakes in the upper river (e.g., in the Missouri Basin) (55) is likely an important source of phytoplankton to the lower river. Finally, in addition to reductions in TSS load in the MAR, there has actually been an increase in river discharge over the past few decades (56). This has resulted in the enhancement of carbonate alkalinity export and has been linked with land-use changes. Thus, the spatial and temporal complexity of separating natural and anthropogenic changes in a large drainage basin of this size (3rd largest in the world), can be very challenging. However, the delta has the potential to act as a recorder of many of these diverse and extant events.

Approximately 60% of the total suspended matter and 66% of the total dissolved materials transported from the continent to the GOM are carried by the MAR alone (57). It was recently estimated that the annual input of DOC and POC delivered to the GOM from the MAR was of 3.1×10^{-3} Pg and 9.3×10^{-4} Pg, respectively (58, 59). However, there are likely significant alterations occurring through the tidal zone and, further downstream, in the salt wedge (e.g., flocculation and low discharge channel bed storage) that may affect the composition and magnitude of DOC and POC fluxes (60–62). Understanding these changes within the lower river as it enters the

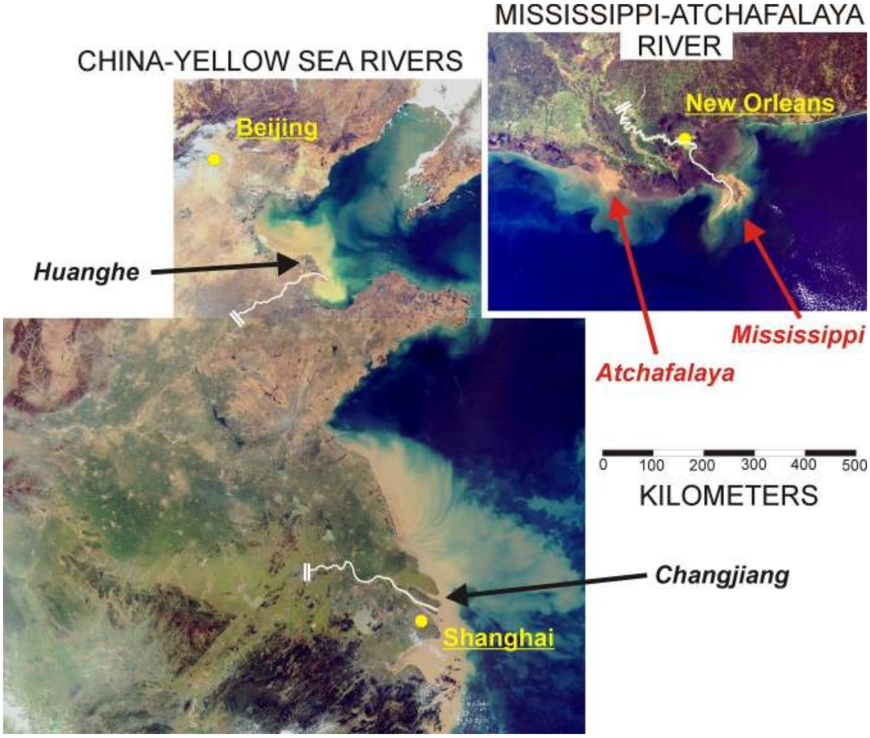

Fig. 3. The Huanghe, Changjiang and Mississippi–Atchafalaya River deltas from NASA MODIS imagery from the Terra satellite. The upper reaches of the LDE are defined by the limit of tides in the river channel (white bar). The limits of the turbid surface plume approximate the outer limits of the LDE zone of rapidly accumulating sediments on the underlying seafloor.

LDE is critical if we are to better understand the fluxes of materials from large rivers into the global ocean and the potential role of greenhouse gas fluxes (e.g., N_2O, CH_4, CO_2) in LDE, because the amount and quality of DOC and POC are critical in controlling microbial pathways linked with these greenhouse gas fluxes (ref. 25 and references therein).

China-Yellow Sea River System. Asian rivers discharge an estimated 70% of total sediments delivered to ocean by all rivers in the world because of the preponderance of high elevation and geologically young watersheds (3). The Chinese (western) side of the shallow Yellow Sea receives the discharge from 2 of the 25 largest river systems: the Changjiang (Yangtze) and Huanghe (Yellow). In contrast to the MAR, these systems are marked by increasing sediment loads to the LDE until very recently in the Anthropocene.

The Changjiang (Yangtze) River is ranked globally as the 4th and 5th largest river in water and sediment discharge, 944 $km^3 \cdot year^{-1}$ and 0.5 $Pg \cdot year^{-1}$, respectively (Table 1), and the longest river (6,300 km) in Asia (40). The river originates in the Tibetan Plateau at an elevation of 6,600 m and flows to the east where it is discharged in the East China Sea (Fig. 4*B*). This river has a major role in the flux of terrestrial material from the Chinese mainland to the western Pacific (ref. 63 and references therein). Recent work has shown the Changjiang River has accumulated $\approx$1,200 Pg of sediment in the deltaic plain and subaqueous estuary of this LDE (64, 65). Much of this sediment accumulation along the shoreline of the Changjiang LDE began $\approx$2,000 yB.P., when increased human activities enhanced catchment erosion from farming and deforestation increased the river's sediment load. These sediments and POC have remained trapped on the inner shelf of this LDE because of the net effects of shear forces from coastal currents (e.g., China Coastal, Taiwan Warm, and Kuroshio Currents) (65). However, over the past 5 decades there has been a significant ($\approx$40%) decrease in the sediment discharge because of dam construction (8). The drainage basin (1.8×10^6 km^2) of the river is populated by 400 million people (8) and contains 45,628 reservoirs (as of 1995) (66, 67), which are estimated to retain 90% of the sediment load. The situation has recently been exacerbated by the construction of the 175-m-high Three Gorges Dam, which is not anticipated to be fully operational until 2009 (8), but which began to retain water and sediment in June 2003 as the dam rose to 135 m (8). Projected estimates indicate that 70% of the sediment (and associated POC) discharge will be trapped for the first 2 decades (in the upper reaches), and that $\approx$44% of the river's sediment will be stored behind the dam after 100 years (8, 68, 69). Such changes in sediment loading are likely to be recorded in the sediments of Changjiang LDE, where invaluable historical information (e.g., contaminants and natural organic carbon inputs) linked with land-use change can be reconstructed and compared with ongoing changes.

The Huanghe (Yellow) River was, until recently, the second largest river in the world in terms of sediment discharge with an annual average of 1.1 Pg ($\approx$6% of the total global sediment discharge of all rivers) (26). The Huanghe was very different from the Changjiang in that it had twice the sediment discharge carried by only 5% of the Changjiang's water discharge (26). Some of the reasons for such high sediment loading are the high erodability of the heavily cultivated soils of the Loess Plateau through which it passes, and massive flooding events in the past—before dam construction. In fact, many thousands of lives have been lost from catastrophic flooding events in this drainage basin recorded over the past millennia (70). As a result of dam construction in the 1950s, and enhanced water consumption in the 1970s because of rising populations in the basin, overlapped with climate change that has reduced precipitation, the sediment load has been decreasing (7, 67, 71). Global climate change is believed to have reduced precipitation in northern China, which has resulted in significant decreases in river water discharge from the Hunaghe drainage basin (7, 72). The annual sediment discharge of the Huanghe to the Bohai Sea (Fig. 3*B*) was measured from 2000 to 2005 and was shown to have decreased to only 0.15 $Pg \cdot year^{-1}$ values close to that in the pre-Anthropocene (71). These changes in rainfall and land-use practices with farming in upper basin have dramatically altered the morphology, ecology, and biogeochemical dynamics on the lower estuarine deltaic plain of this LDE (71). These dramatic alterations in the Huanghe River basin represent perhaps one of the best cases of how stored sediments in the LDE can be used as recorders of climate and human changes (71).

Coastal Eutrophication and Hypoxic Zones

Recent work has shown that the number of hypoxic zones globally in the coastal margin is doubling every decade, primarily because of land-use changes that result in enhanced nutrient loading (eutrophication) (73), which is particularly widespread in LDE. For example, summer hypoxic (defined as oxygen concentrations <2 $mg \cdot L^{-1}$) events in the northern GOM on the Louisiana/Texas inner shelf have been

Table 1. Basin area, discharge, runoff and basin latitude for the 25 world's largest rivers [modified from Cai (28)]

No.	River name	Basin area, 10^3 km^2	Discharge, km^3·year^{-1}	Runoff, mm·year^{-1}	Basin latitude
1	Amazon	5,854	6,642	1,135	2
2	Congo	3,699	1,308	354	4
3	Orinoco	1,039	1,129	1,087	7.5
4	Changjiang	1,794	944	526	30
5	Brahmaputra	583	628	1,077	25
6	Mississippi	3,203	610	190	36
7	Yenisei	2,528	599	232	60
8	Parana	2,661	568	213	23
9	Lena	2,418	531	220	63
10	Mekong	774	525	678	20
11	Ob	2,570	412	160	60
12	Ganges	956	404	423	26
13	St Lawrence	1,267	363	287	47
14	Pearl River	477	343	719	23
15	Xijiang	409	270	660	23
16	Mackenzie	1,713	290	169	64
17	Columbia	724	252	348	42
18	Ubangi	356	228	640	2.5
19	Yukon	852	212	249	64
20	Danube	788	202	256	48
21	Niger	2,240	193	86	10
22	Kolyma	666	118	177	67
23	Indus	1,143	104	91	29
24	Godavari	312	97	311	21
25	Huanghe	894	47	53	36

observed every year since the 1990s, owing to water stratification and decay of accumulated organic matter during phytoplankton blooms (74). Temporal variability of the distribution of these hypoxic events is, at least partially, related to the amplitude and phasing of the Mississippi and Atchafalaya River water discharge and nutrient loading (54, 75, 76). The maximal water discharge generally occurs in April, but the peaks in nutrient (e.g., nitrate) concentration and fluxes are somewhat delayed with respect to the peak in runoff (76, 77). The areal extent of the summer hypoxic zone on the shelf has been found to be coupled to riverine nitrate input in May (and June) linked with water column stratification (limited vertical mixing by waves and currents) during the low-energy summer season, and this flux has been used to estimate the magnitude and size of the hypoxic zone in the GOM in the last few decades (76, 77). Although it is clear primary productivity in the Gulf hypoxic zone is coupled with riverine nutrient inputs (74) and water column stratification in the near field reaches of the plume, the role of organic carbon from eroding wetlands in fueling hypoxia outside the particle plume regions are still poorly understood (78–81), as is the reason for the apparently negligible effects of hypoxia on local fisheries (79) in the area.

The long-term history of hypoxia in the MAR has been established by examining changes in the benthic foraminiferal community in dated sediment cores (82–84), once again proving the utility of LDE sediments as recorders of anthropogenically-driven change in both terrestrial and aquatic/coastal systems ecosystems. The relative abundance of 3 low-oxygen tolerant benthic foraminifers (*Pseudononion atlanticum*, *Epistominella vitrea*, and *Buliminella morgani*) has recently been used as a proxy (PEB index) for the past and present hypoxic conditions on the Louisiana shelf (84). The PEB index (82) and the A/P ratio—the ratio of agglutinated to porcellaneous foraminifera orders (85)—indicate that increases in the intensity of hypoxic events began during the past 50 years. Osterman et al. (83) also showed that several probable low oxygen events occurred in the past 180 years that were likely associated with high Mississippi River discharge rates and changes in land-use patterns (e.g., deforestation) in the upper basin. Most recently it was established, using the PEB index that hypoxia events may have occurred as far back as 1000 yB.P. (86).

Over the past 2 decades China has also become the largest global consumer of fertilizers, which has resulted in eutrophication in the Changjiang estuary (87, 88). The area of this hypoxic zone in the East China Sea is 2×10^4 km^2 (89), comparable to that off Louisiana (USA). Although nutrient inputs from the Changjiang River have doubled in the past 2 decades and do, in part, contribute to the low oxygen conditions in this LDE, maintenance of hypoxia is believed to be largely controlled by density stratification caused by the salinity differences between the freshwater plume and the more saline waters of the Taiwan Straight (89). The occurrence of typhoons in this region can range between 3 to 6 per summer, which results in significant mixing and oxidizing of the hypoxic waters. To better understand when hypoxia first began off the Changjiang, sediment coring in the LDE is needed, as previously described off the Louisiana coast (82–86).

Sea-Level Change

The majority of global climate models for the next century forecast planetary warming in response to anthropogenic and natural forcing (90). Although eustatic (global) sea level rose ≈15 to 20 cm in the last century (91), projections for the 21st century range from 20 to 60 cm (multiple climate model means) (90) to as much as 1 m (92). Coastal wetlands (both saline marsh and mangrove and freshwater marsh and swamps), which make up most of the subaerial portion of deltas, maintain their viability and stave off conversion to open water in these conditions by having combined organic and mineral accumulation rates minus local subsidence rates (compaction or tectonic-induced) (93) that meet or exceed the rate of eustatic sea level rise (94–96). In the coastal zone, 3 of the most important impacts of this predicted warming are (*i*) accelerated rates of eustatic sea level rise, (*ii*) a potential increase in cyclonic storm frequency and/or intensity, and (*iii*) a shift in the latitudinal ranges of flora and fauna. Coastal saline wetlands, defined here as coastal wetlands exposed to brackish-to-marine salinities and vegetated by salt-tolerant flora (salt marsh grasses and mangroves), are generally those immediately adjacent to the terrestrial-marine interface, and hence, are extensive in LDE and most vulnerable to these 3 factors. Mangroves, which are confined to lower-latitude coastal saline wetlands in LDE and elsewhere by freeze-effects, might be expected to increase in latitudinal importance with climate amelioration.

The MAR LDE is one of the most modified aquatic coastal ecosystems in the world, and experiences as much as 80% of the wetland loss in the USA (peak rates of 60–90 km^2·year^{-1}) (97). These wetland losses in the deltaic plain between the 1930s and 1990 exceeded 2,972 km^2 (98). Extensive studies of the causes of this loss have determined that it is a combination of anthropogenic (e.g., artificial canal cut-

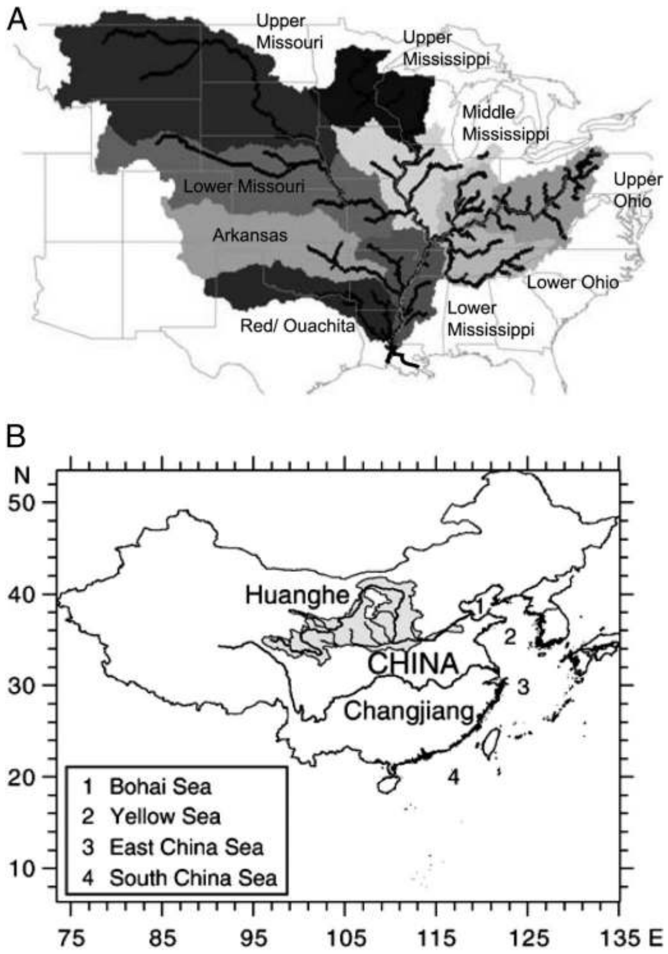

Fig. 4. Map showing the drainage basin of the Mississippi River (USA) (*A*) (from ref. 119) and the Huanghe (Yellow) and Changjiang (Yangtze) Rivers (China) (*B*) (from ref. 71).

ting and subsequent expansion, pond creation, etc.), and natural mechanisms involving relative sea level rise (RSLR) and wave attack of open-water fronting marshes (ref. 98 and reference therein). However, the overriding factor in "natural" wetland loss are thought to be the effects of compaction-induced sediment subsidence exacerbated by a starvation of new sediment to wetland surfaces that resulted from levee construction along the lower Mississippi River (ref. 99 and references therein). Given the consensus by the community of the importance of subsidence-induced RSLR to coastal zone management worldwide, it has been suggested that the timing of the peak wetland loss rates in the 1950s to 1970s (present rates are estimated to be 26–30 $km^2 \cdot year^{-1}$) (100) coincides with the maximum rates of oil and gas extraction from the lower deltaic plain. More recent stratigraphic comparisons in the Terrebonne area show the timing of subsidence "hotspots" is closely related to the local production history (101, 102). There is also controversy to what extent crustal (deep) subsidence and growth-faulting of the sedimentary basin package are contributing factors (103–106). Thus, understanding the dynamics of wetland loss in relation to RSLR in LDE, where major population centers are situated [e.g., Bangkok, Calcutta (Kolkata), Karachi, New Orleans, Shanghai, etc.] that are shielded from storm surges by wetlands, is important for future coastal management strategies.

Effects of Cyclonic Storms

Tropical cyclones, because of the enormous wave orbital velocities and strong mean flows they create that impact sediment erodibility, have a disproportionate impact on the erosion and transport, deposition and burial of sediments in the LDE where they are active. Of the 25 LDE shown in Table 1, 11 low-to-mid latitude systems have been impacted by tropical cyclones in historical times, including the MAR and Chinese Yellow Sea systems. LDE are generally the only shelf type where modern fine-grained sediment deposition is taking place on the inner to mid-shelf region (24). The transport of sediments in these regions is strongly impacted by storm-induced waves and surge-induced currents. As such, large reservoirs of soft sediments are available for mobilization in these areas, and organic-rich wetland sediments are subjected to the surge and wave attack, which may have significant implications for controlling the geometry and location of the shelf sediment depocenter and carbon sequestration/export/diagenesis. Much of the limited research on these processes to date that has been conducted on the MAR margin (107–110) following several recent hurricanes (e.g., Lili, Katrina, Rita) has shown that these storms scour the seabed to water depths of up to 40 m and then deposit event layers (on the shelf/slope) of cm to decimeter thickness that reflect multiple sediment and OM sources (e.g., shelf and riverine deposits and coastal wetlands). Interannual preservation of tropical cyclone event layers recorded in LDE could be used for studies of paleo-hurricane frequency and intensity.

Future Studies Documenting Climate Change

Because long-term preservation of high-resolution sedimentary records on eroding continental platforms is rare, and where present, often integrates conditions from only a limited region (e.g., lakes), we must rely on coastal marine sediments (particularly in LDE) to better supplement our understanding of continental climatic history. Projections of anthropogenic (greenhouse gas emission) global warming by 2100 suggest the largest increases (3–6 °C) will take place in the highest latitudes, particularly in the Arctic (111–113). This warming will be coupled with global changes in precipitation patterns and river runoff: Again the Arctic is predicted to see among the largest increase in precipitation, evaporation, and runoff (114, 115). Beginning in the later half of the 20th century (approximately the time span of the instrumented record), widespread and rapid climate change effects have been observed in the Arctic, including increased melting of permafrost and glacial ice, increased shoreline erosion of permafrosted coastal tundra due to lengthening of the open water season and potentially increased "storminess," decreasing summer sea ice, increasing surface air temperatures, and changing ocean circulation. Approximately 90% of the total organic C in the Arctic tundra resides in the organic horizons and permafrost (116). In fact, the North American tundra has been estimated to have 98.2 Pg C, which can then be extrapolated to 160 Pg C for the entire Arctic tundra (117)—which is equivalent to 2.5% of the annual increase in atmospheric C. Moreover, because the northern permafrost region extends 3 to 4 times beyond the tundra biome it has been estimated that the organic C in permafrost soils to a depth of 3 m is as much as 1,204 Pg C (118). So, as these systems warm and permafrosted soils thaw, much of the fluvial transport of organic C in soils will drain through the LDE into the Arctic Ocean. This, and increasing coastal erosion will likely increase sediment and OC burial as well in the LDE.

As we have shown, the LDE sediment record, because of its rapid burial rates and sensitivity to both source and marine basin fluctuations, contains an under-exploited record of Holocene climate on a par with well-studied and important records in ice cores, lakes, tree rings and deep marine sediments. Although all LDE records potentially have value in documenting continental-scale climate change, we suggest the Arctic should be a particular focus. Specifically, new high-resolution Arctic paleoclimate sediment records near LDE like the Colville and Mackenzie Rivers on the North American Arctic margin would serve (*i*) to extend the limited instrument record of high Arctic climate change on the adjacent continent and terrestrial-marine linkages and (*ii*) would serve as baseline localities for monitoring future change.

Understanding LDE sediment records of continental weathering and climate is vital because of its primacy in receiving, processing and burying a significant portion of the global carbon record. River systems play an important role (via the carbon cycle) in the natural self-regulation of Earth's surface conditions by serving as a major sink for anthropogenic CO_2. Changes in climate and human changes in the watersheds may lead to LDE changes in factors that change the net production to burial ratio on these margins, such as nutrient input, plume turbidity, and greater storm intensity, which may result in greater remineralization rates of OC with less burial and OC being dispersed over a broader area—more research is clearly needed to address these issues. LDEs are dynamic regions that can be used as a "litmus test" for global climate change.

Conclusions

In summary, we propose that if we are to use LDE as natural recorders of environmental change in 21st century, and want to better understand the changes being induced by the dense human populations inhabiting these dynamic systems, we need a greater understanding of: (*i*) the net impact of LDE on the global carbon budget in the context of them being sources and/or sinks of greenhouse gases (e.g., CO_2, CH_4, N_2O), (*ii*) sediment fluxes through LDE and their effects on global carbon budgets, (*iii*) the resilience of LDE wetlands in the face of accelerating RSLR and its linkage to the changing riverine sediment input; (*iv*) wetland-river-shelf OM and nutrient inputs to LDE and their role in producing hypoxic zones; (*v*) vegetational species migration and implications for deltaic sustainability (e.g., mangroves, marshes, and exotic marine species); (*vi*) impact of the lower (tidal/saline) river on the flux, timing, and transformation of OM in the LDE); (*vii*) impact of climate and land-use changes in the drainage basin (e.g., precipitation, soil/agriculture practices) on the stability of deltas); and (*viii*) the importance of human-induced changes in LDE evolution in higher latitudes, which are among the most poorly studied systems and predicted to be most severely impacted by climate change.

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