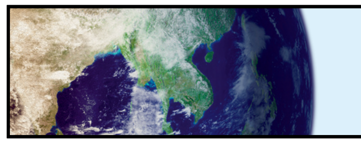

Vulnerability of coastlines - How do environmental changes affect coastlines and river deltas?

PRESENT PAST

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Most coastal zones of the world are ephemeral or sensitive to change, an exception being rocky shorelines that respond quite slowly to perturbations. Under the influence of long-term trends in Holocene sea level, coastlines have retreated, advanced or changed the nature of their land-sea interaction. But the human footprint is very large and growing in many places. For example the ocean volume is increasing due to human-induced global warming of the ocean (the steric effect) and the melt of our mountain and polar ice masses.

These modern trends are superimposed on regionally variable sea-level changes put in place prior to when humans began to have a significant impact. For coastlines undergoing uplift and where sea level continues to fall, for example those in the Pleistocene ice sheet zones, the rate will have slowed due to the more recent anthropogenic impact. For coastlines that were largely stable over the past few millennia, sea-level rise has begun to accelerate coastal retreat and is expected to do so in the foreseeable future.

In many of the world's deltas, human-induced subsidence – by water and petroleum mining, for example – now overwhelms the eustatic (global) sea level rise signal. In a study of 33 global deltas, relative sea-level rise was found to be four times larger on average than that for nearby bedrock shorelines (Syvitski et al. 2009). Tens of millions of hectares are flooded every year, and future flooding is only expected to get worse (Nicholls 2004; Syvitski et al. 2009).

Human activities further compound the problem of shoreline retreat (Fig. 1). For example, protective coastal mangrove forests or wetlands are removed, often to make room for shrimp farms (Woodroffe et al. 2006), accelerating coastal retreat from meters/year to kilometers/year. Coastal retreat in the arctic is also extremely high due to a combination of reduced summer sea-ice cover – which leads to increased wave energy – and a warmer coastal ocean. Together these processes combine to physically and thermally destroy thousands of kilometers of arctic coastal bluffs (Forbes 2010).

The great reduction in the sediment delivery to the world's coastal oceans is an important factor (Blum and Robert 2009) in coastal retreat. On average, there has been 1 major dam (>15 m in height) built every day for the last 110 years, sequestering hundreds of gigatons of sediment and carbon in reservoirs and greatly limiting the transport of sediment to the coast (Syvitski et al. 2005). Without this "fresh" sediment for tides and waves to rework, shoreline sediment is consumed and coastal retreat is accelerated.

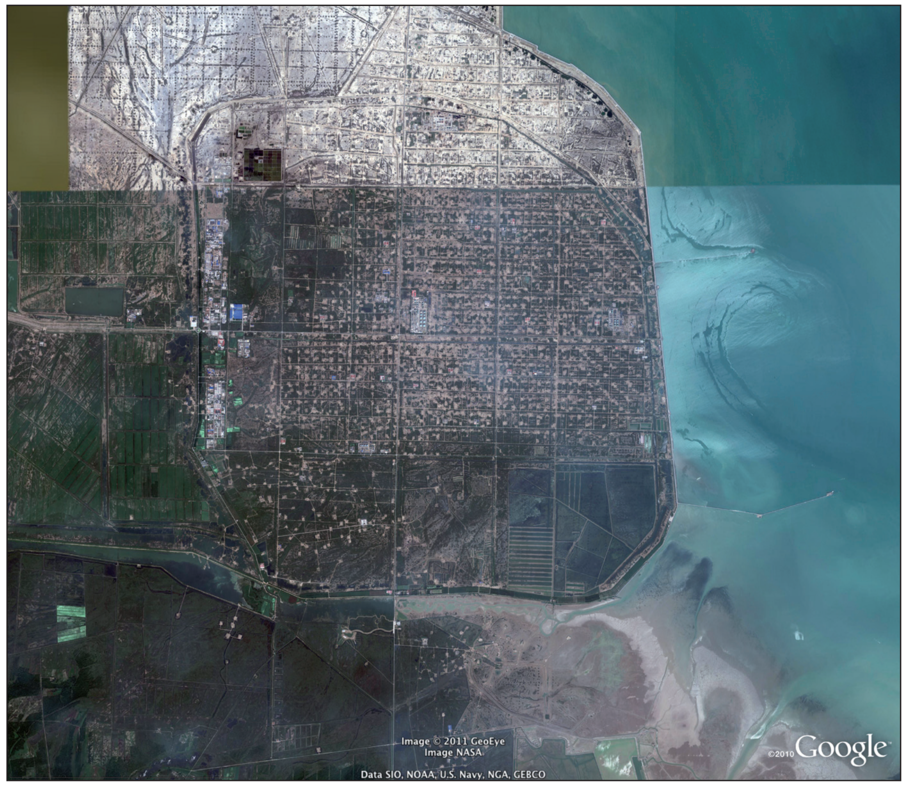

Figure 1: GEO-EYE satellite image of the Yellow River (Huanghe) delta. Each year 33.6 Mt of crude oil are extracted from the delta. The Gudong Seawall, built 1985-1988 to protect the oil fields from inundation, is 10 m thick at its top and 38 m at its bottom. The oilrigs are laid out on a grid pattern. The field is presently below sea level by 1 to 2 m, protected from the sea by the Seawall. Image from Google Earth Pro; pixel resolution is ~1 m.

The combination of decreased vegetation, reduced coastal sediment delivery and higher sea levels makes coastlines more susceptible to tropical storms and their surges: latest research shows that the frequency of the most intense storms will increase throughout this century (Knutson et al. 2010; Tom Knutson, this issue). The result is an ever-increasing reliance on engineering structures to protect infrastructure (e.g. cities, industry, transportation facilities, agriculture) that is found increasingly at elevations below sea level. These engineering structures can be overwhelmed with devastating consequences, as in the case of Hurricane Katrina and the Sendai Tsunamis.

Human activity has also lead to the formation of many coastal features: for example the deltas of rivers such as the Po and Rhone were formed due to anthropogenic acceleration of soil erosion by deforestation and farming activities. The deltas were inherently unstable. When soil erosion was reduced or sediment delivery was reduced with the proliferation of dams, these unstable deltas were the first to enter the destructive phase affecting much of the world's coastlines. A combination of modern and historical perspectives can help understand the global footprint of humans on our world's coastlines. And this can help us develop effective policies and protocols for learning to live in such transient environments.

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Coastal changes have occurred throughout geological time due to tectonic and isostatic processes as well as sea level changes induced (primarily) by climatic changes. During the Quaternary, one of the main controls on coastal evolution was sea-level changes through the exchange of mass between ice sheets and oceans. However, local and regional changes are superimposed on the global signal. These local/regional changes become more important as the temporal scale resolution increases, producing substantial spatial and temporal variability in sea-level changes, even when localities lie close to each other. This becomes even more complex as humans occupied the coastal zone (e.g. Syvitski, this issue).

Furthermore, it seems that the overall warming and sea-level rise of the Holocene was punctuated by climatic events and, apparently, impacted the coastal evolution. In fact, a correlation between marsh evolution and rapid climatic changes (RCCs) in the Delaware Bay has been established at a millennial scale. The idea of coastal evolution linked to climatic changes is supported by stratigraphic sequences occurring simultaneously with RCCs recognized in the western Gulf of Mexico, in the Trinity/Sabine River incised valley system and in northern Spain. Among the RCCs identified during the Holocene, an event at 750-950 AD was characterized by polar cooling, tropical aridity and major atmospheric circulation changes. Although this event was global in scale, records of it are poorly correlated due to its different behavior between regions (Mayewski et al. 2004).

Concomitant with these reported RCC events, major coastal geomorphological changes have been identified. For instance, recent work undertaken in the US North Carolina estuaries and barrier islands suggests that the period ca. 750-1400 AD was characterized by a high degree of barrier island segmentation and open marine influence in areas now occupied by the modern estuaries. Figure 1B shows the interpretation of the environmental change that occurred in the southern part of the Pamlico Sound at 850 AD, reflecting the destruction of large segments of the barriers compared to the current situation (Fig. 1A) (Grand Pre et al. 2011). Estuaries along the southern Bay of Biscay reflect similar changes associated with RCCs. These changes might have impacted the tidal frame, currents and sediment transport. In fact, dramatic changes in the tidal frame have been modeled for the Bay of Fundy in response to the catastrophic breakdown of a barrier system (Shaw et al. 2010). Also, tidal changes have been recorded in Delaware Bay over the last 4000 years in response to the change of the basin shape during the late Holocene sea-level rise (Leorri et al. 2011).

Over the Holocene, coastal environments have moved across the landscape. However, accelerated rates of climate change and sea-level rise could affect coastal environments by overcoming the natural mechanisms of self-maintenance. The impact of these changes might be considered significant since there are more than 20,000 km of barrier islands along the world's open ocean coast, and they represent the front line to impacts of projected climate change. This may alter coastal systems from current conditions in a number of ways by: 1) increasing salt water intrusion landward, producing more rapid salinization; 2) altering the species composition through modified migration and other mechanisms; 3) enhancing tidal erosion, potentially forcing a coastal retreat; and 4) increasing the potential impact of future storms.

In the case of North Carolina, it has been suggested that hurricanes impacted the barrier islands at ca. 850 AD, causing the destruction of large segments of barriers. These barrier destruction events are essentially synchronous with intervals of RCCs at 750-950 AD and are coincident with transgressive surfaces in Delaware Bay, highlighting the importance of environmental changes in coastal evolution and suggesting their potential impact for future coastal evolution.

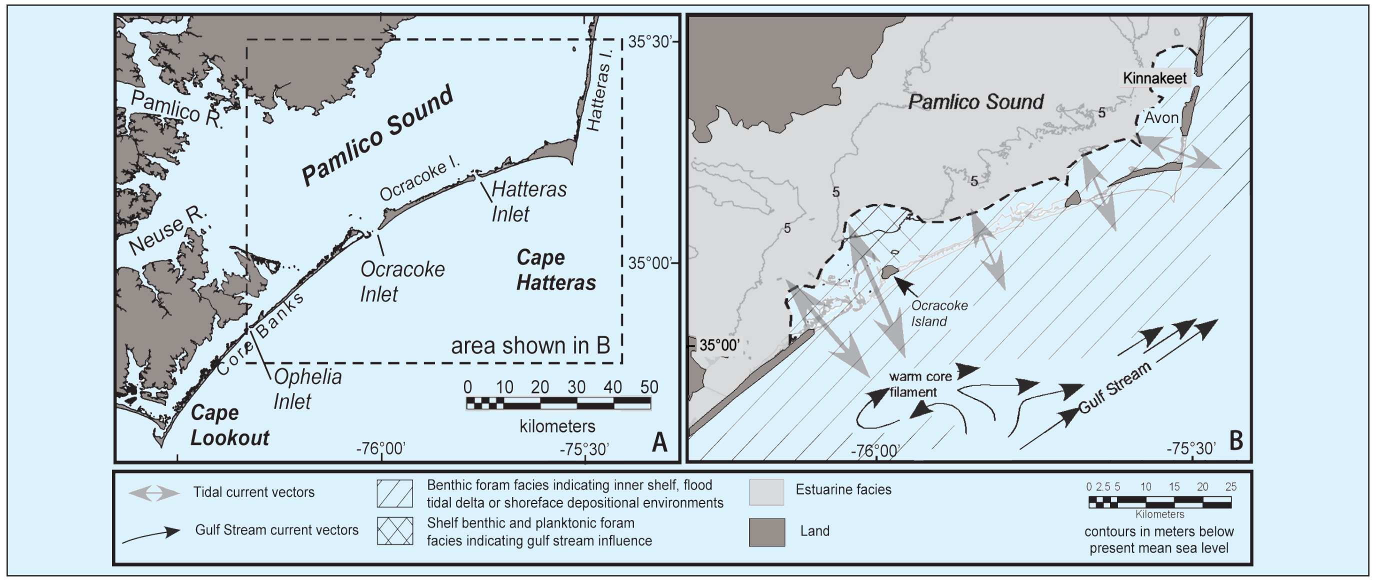

*Figure 1: **A**) Map of the Pamlico estuarine system in North Carolina showing the location of the main active inlets. **B**) Paleoenvironmental reconstruction of the southern Pamlico Sound region ca. 850 AD (modified from Grand Pre et al. 2011). Barrier island destruction along the southern Outer Banks resulted in a shallow, submarine sand shoal and localized deeper tidal channels over which normal marine waters were advected. The Cape Hatteras region exhibited several inlets with large flood-tide deltas.*

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