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The response of deltas to sea-level rise: Natural mechanisms and management options to adapt to high-end scenarios

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ABSTRACT

The response of deltas to sea level rise (SLR) has mostly been studied from a perspective of human impacts like global warming and impoundment, or from a perspective of natural changes associated with glacial cycles. Here we synthesize the response of deltas to SLR by integrating research looking at past and future evolution to improve the potential to manage deltas to adapt to high rates of SLR. We hypothesize that fluvial-dominated deltas can be managed to survive high rates of SLR (>1 cm year^{-1}) that characterized the post-glacial period and will likely characterize coming centuries due to global warming. There are three known mechanisms for deltas to cope with SLR that are self-reinforcing as the rates increase, tending to enhance the efficiency of the deltaic sedimentary trap:

(a) an increase in the frequency of delta lobe switching with accelerated SLR leading to the formation of new lobes in shallow areas
(b) an increase in the frequency and magnitude of flood events in the delta plain as a consequence of an increased crevassing through the river natural levees, leading to enhanced sediment deposition
(c) an increase in the frequency and magnitude of overwash events in the delta fringe enhancing the ability of sandy beaches to adapt to SLR.

The current view by much of the management community is that coastal protection is the best strategy for future SLR up to 2–5 m, and beyond 5 m that retreat would be the best (or the only) strategy. However, for the case of deltas a more functional adaptation strategy based on restoration can be envisioned provided that natural processes and ecosystem functions can be managed to increase system's resilience. The central element of this alternative strategy is the idea of "rising grounds" (vertical aggradation), instead of "rising dikes", but a combination of both can also be foreseen and may be needed in many cases. This means that "rising dikes" will be only feasible if "rising grounds" is also implemented; if not, retreat will be the only long-term alternative. We propose that "rising grounds" is the best adaptation strategy in most deltas for high-end scenarios of SLR, though in some cases the option of retreating may be necessary in combination with structural and functional measures.

1. Introduction

Deltas are river-dominated systems that are most prevalent in microtidal seas like the Mediterranean and the Gulf of Mexico. Their structure and functioning depends, in geomorphic, hydrological, biological and socio-economic terms, on the fluxes and pulses of water, sediments and dissolved materials delivered by rivers (Day et al., 1995). Most deltas, including their watersheds, are severely impacted by humans. These impacts range from rapid hydromorphological and ecological disruption due to alterations in river basins (i.e., flow regulation, sediment retention, etc.) and delta plains (i.e., dikes, altered hydrology, fluid withdrawals, etc.), to consequences of increased relative sea level rise (RSLR), such as increasing flooding risks (Ericson et al., 2006; Syvitski et al., 2009; Alvarado-Aguilar et al., 2012). Many deltas are heavily populated, especially in Asia (Marchand et al., 2012), which exacerbates the consequences of natural and anthropogenic impacts. Moreover, deltas undergo rapid changes at geological, ecological and human scales with strong feed-backs among these three levels, so their management and restoration must be based on a comprehensive

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understanding of delta functioning at a number of different temporal and spatial scales (Day et al., 1997).

A thorough understanding of the response of deltas to sea level rise (SLR) is important for designing adaptation strategies that may be sustainable in a context of high-end scenarios of climate change. SLR projections and assessments by IPCC (2007) are that sea level will rise by no more than a meter by 2100. However, recent studies suggest that eustatic sea level rise (ESLR) most likely will be between one and two meters (Pfeffer et al., 2008; Vermeer and Rahmstorf, 2009; Moser et al., 2012). Future projections of high-end scenarios of SLR up to 5 m beyond the present century (Jevrejeva et al., 2012; Schaeffer et al., 2012) probably equal or exceed tipping points for deltas and other coastal wetlands (Kirwan et al., 2010). Thus, there is a need to consider longer-term scenarios to analyze the evolution of deltas with high rates of SLR leading to high-end scenarios.

Linking past response of deltas to SLR to the future evolution of these systems under scenarios for the 21st century has proven complex. Until now the response of deltas to SLR has been either studied from a perspective of human impacts like global warming or from a perspective of natural changes associated with glacial cycles. The time scales, methods and disciplines of both approaches are different, and to date a comprehensive framework to analyze and compare the changes that deltas undergo due to SLR with natural and human-impacted conditions is lacking. Analyzing the response of deltas to natural scenarios of SLR implies looking at the past (i.e., last deglaciation), at scales of 1000s of years using geological methods (i.e., stratigraphy); whereas analyzing the response to human-impacted scenarios means looking at the present and future at scales of 10s to 100s years using diverse methods from different disciplines.

Coastal scientists, engineers, managers, and planners face important challenges in interpreting the impact of SLR on coasts because of inherent synergistic processes that produce responses over different temporal and spatial scales (FitzGerald et al., 2008). An improved understanding of the response of deltas to climate change requires integrative approaches from sedimentology, geomorphology, stratigraphy, coastal engineering, and ecology. The literature concerning models of delta evolution is abundant (see Fagherazzi and Overeem, 2007), but most of them consider sea level changes in a limited way. Some conceptual models describe the response of delta channel networks to Holocene sea level rise (e.g., Jerolmack, 2009). Models dealing with delta construction and evolution often do not incorporate long-term sea level changes (Sun et al., 2002; Seybold et al., 2007; Ashton et al., 2013), whereas models dealing with long-term sea level changes do not fully consider all feedbacks between river inputs and delta plain processes (Ritchie et al., 2004, Swenson, 2005). Some models at shorter time scales incorporate sea level changes, rules for channel switching and delta floodplain sedimentation (Overeem et al., 2000). Steel et al. (2008) produced a comprehensive review of the state-of-the-art in modeling the response of deltas and other shoreline systems to sea level changes across the shelf platform.

Several basic aspects of the response of coastal systems to SLR remain unclear, including what will be the survival of deltas under high rates of SLR (i.e., >1 cm year^{-1}) similar to those that occurred at the end of glacial periods, and that may occur in the next century. FitzGerald et al. (2008) pointed out that coastal systems could adjust to SLR dynamically while maintaining a characteristic geometry that is typical of a particular coast. However, the current scientific paradigm states that high rates of SLR lead to a destructive phase of deltas, suggesting that deltas did not exist, or existed only to a limited extent, during the pre-Holocene and early Holocene marine transgression (Stanley and Warne, 1994; McManus, 2002; Porebski and Steel, 2006; Hanebuth et al., 2012). Some authors have further concluded that some deltas, such as the Ebro, were estuaries until Roman times (Guillén and Palanques, 1997; Maselli and Trincardi, 2013), though according to Canicio and Ibáñez (1999) this conclusion is based on a misinterpretation of historical documents.

In this paper we synthesize information on the response of deltas to SLR by looking at past and future evolution to improve the ability to manage deltas to adapt to high rates of RSLR. We hypothesize that deltas can withstand high rates of SLR (>1 cm year^{-1}) under certain natural and human-managed scenarios, based on specific mechanisms that make them more resilient to SLR than non-deltaic coastal systems. The main goals of the paper are:

(a) to review the scientific literature concerning the effects of SLR on deltas under both natural and human-impacted scenarios;
(b) to develop a general framework on the response of deltas to SLR according to the mechanisms linking deltaic and fluvial processes;
(c) to propose restoration and management strategies based on system functioning to better adapt delta management to high-end scenarios of RSLR.

2. The role of humans in the formation of deltas

Presently the scientific paradigm interprets modern deltas as primarily formed recently (early to mid Holocene; Stanley and Warne, 1994), where some authors stress the idea that deltas are largely human-made constructs as a consequence of the exacerbation of sediment fluxes (Maselli and Trincardi, 2013). Stanley and Warne (1994) further concluded that the formation of most modern deltas began in the mid Holocene epoch about 5–7 Ka BP; as the rate of eustatic SLR declined, inputs of fluvial sediment began to accumulate along many coasts creating deltas throughout the world. According to this paradigm, deltas started to form under a relatively stable SLR, and thus they are not resistant to high rates of SLR (resulting in high vulnerability). Maselli and Trincardi (2013) concluded that the largest southern European deltas formed almost synchronously during two short intervals of enhanced anthropogenic pressure (i.e., enhanced sediment load in rivers due to land clearing). Other studies suggest that river-dependent coastal wetland area is much greater than would be under natural conditions, as consequence of the enhanced erosion caused by deforestation and farming in the watershed (Giosan et al., 2012; Kirwan et al., 2011). According to this, present deltas would be much smaller without past human intervention (though paradoxically, the Mississippi and numerous other deltas have shrunk since strong human impact began, and the Mississippi formed largely before strong human impact), and it has been suggested that the retreat of some deltas due to sediment retention in the reservoirs is in fact a return to more original conditions (Guillén and Palanques, 1997). According to this, deltas may not survive accelerated SLR, because the expected rates are beyond their adaptation capacity (Blum and Roberts, 2009), even if sediment supply from the river is not drastically reduced.

The evolution of deltas along the last glacial cycles can be typified by three stages (McManus, 2002; Porebski and Steel, 2006):

(1) During the repeated glaciations of the past 2.5 Ma, sea level fell by 100–150 m from near present mean sea level (MSL); any river-borne sediment would have been deposited in distal areas, possibly creating deltas at such sites (self-edge deltas) which would have been drowned as sea level continued to rise. These early deltas would have been much smaller than deltas that formed during high stands of sea level fully on the continental shelves.