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Sea-level responses to erosion and deposition of sediment in the Indus River basin and the Arabian Sea

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ABSTRACT

Changes in sea level are of wide interest because they shape the sedimentary geologic record, modulate flood-related hazards, and reflect Earth's climate. One driver of sea-level change is the erosion and deposition of sediment, which induces changes in sea level by perturbing Earth's crust, gravity field, and rotation axis. Here we use a gravitationally self-consistent global model to explore how sediment erosion and deposition affected sea level during the most recent glacial–interglacial cycle in the northeastern Arabian Sea and the Indus River basin, where fluvial sediment fluxes are among the highest on Earth. We drive the model with a widely used reconstruction of ice mass variations over the last glacial cycle and a sediment loading history that we constructed from published erosion and deposition rate measurements. Our modeling suggests that sediment fluxes from the Indus River are large enough to produce meter-scale changes in sea level near the Indus delta in as little as a few thousand years. These sea-level perturbations are largest closest to the center of the Indus delta, and they grow larger over time as sediment deposition increases. This implies that the elevation of sea-level markers near the Indus delta will be significantly altered by sediment transfer over millennial timescales, and that such deformation should be accounted for in studies that use paleo-sea-level markers to infer past ice sheet volume or explore local processes such as sediment compaction. Our analysis highlights the role that massive fluvial sediment fluxes play in driving sea-level changes over >1000-yr timescales from the Indus River, and, by implication, from other rivers with large sediment fluxes.

1. Introduction

Small increases in sea level prime coastlines for huge disasters. The flooding generated by Hurricane Sandy in November 2012, for instance, was responsible for tens of billions of dollars (US) of damage and the loss of ∼250 lives (Aerts et al., 2013; McNally et al., 2014). Flood-related damages of this scale will likely grow more frequent as a result of the anticipated changes in sea level over the coming century. Global mean sea level is projected to rise by 19–83 cm by 2100 relative to that in 1985–2005 (Church et al., 2013), which will reduce the size of the storm sufficient to inundate coastal cities and increase the frequency with which storms do so (e.g., Fitzgerald et al., 2008). With ∼10% of the world's population living at elevations of <10 m (McGranahan et al., 2007), these increases in sea level pose a particularly acute hazard. Such hazards motivate continued efforts to fully understand the physics of sea-level change.

In this paper we focus on sea-level responses to erosion and deposition of sediment over the most recent glacial–interglacial cycle (∼120 ka to the present). While sea-level change on short timescales (seconds to decades) is dominated by waves, tides, currents, thermosteric effects, and water fluxes between the oceans, ice sheets, atmosphere, and continents (e.g., Cazenave and Llovel, 2010), sea-level change on longer timescales (10^3–10^6 yr) is dominated by ice sheet growth, tectonics, and changes in surface loads, which perturb Earth's crustal elevation, its gravity field, and its rotation axis (e.g., Mitrovica et al., 2001; Mitrovica and Milne, 2002). This includes perturbations due to changes in sediment loads.

It has long been known that the transfer of sediment from continents to oceans affects sea level by perturbing the elevation of the seafloor (e.g., Bloom, 1964; Watts and Thorne, 1984; Simms et al., 2007, 2013; Ivins et al., 2007; Blum et al., 2008; Wolstencroft et al., 2014), but only recently have these and related

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effects been incorporated into a gravitationally self-consistent framework for modeling global sea-level variations (Dalca et al., 2013; Wolstencroft et al., 2014). Incorporating the impact of sediment redistribution in a gravitationally self-consistent fashion is complex because the associated redistribution of sediment and water alters Earth's shape and gravity field, which in turn induces further redistribution of water. Modeling sea-level changes thus requires accounting for water's gravitational attraction to itself (e.g., Farrell and Clark, 1976). In this paper we adopt the treatment of Dalca et al. (2013) to predict sea-level responses to the combined changes in ice, ocean, and sediment loads.

In considering the impact of sediment transfer on sea level, we focus on responses that occur over timescales of $\sim 10^3$–10^5 yr, because the viscoelastic deformation of the Earth is slow enough that sea level takes tens of thousands of years to completely equilibrate to changes in surface loads (e.g., Cathles, 1971; Peltier, 1974). Fully understanding sea-level variations at any moment in Earth's history thus requires accounting for changes in surface loads over the preceding tens of thousands of years. One implication of this is that sea level today is responding to sediment transfer that happened over ten thousand years ago, and that a complete understanding of what is driving modern sea-level changes requires quantifying how much past erosion and deposition continue to influence modern sea level.

Our goal in this study is to explore sea-level responses to erosion and deposition of sediment in the northeastern Arabian Sea and the Indus River basin. We choose this as a study area because sediment-driven effects on sea level in this area are large – fluvial sediment fluxes in the Indus River are among the highest on Earth (Milliman and Farnsworth, 2011) – and because the modeled sea-level history can inform studies of the response of local mid-Holocene human civilizations to changes in sea level (e.g., Giosan et al., 2012).

In this paper, we review the theory underlying sediment-driven changes in sea level and describe how we constructed a sediment loading history for the study area. Our analysis suggests that sediment fluxes from the Indus River are large enough to generate meter-scale sea-level perturbations near the Indus delta over timescales as short as a few thousand years, and that these perturbations grow larger over time. This implies that any paleo-sea-level markers older than a few thousand years near the Indus delta are likely to be significantly deformed by sediment fluxes, and that accurately inferring paleo-ocean water (or, equivalently, ice) volume from such markers requires accounting for the deforming effects of sediment transfer.

2. A brief review of static sea-level theory and model implementation

2.1. Theory

Modern theories for post-glacial sea-level change are built on the work of Farrell and Clark (1976), who derived expressions for the gravitationally self-consistent redistribution of water during the growth and melting of ice sheets. These expressions were based on an equilibrium sea-level theory in which the redistribution of water is determined by perturbations in the elevation of the Earth's crust and the gravitational equipotential that defines the sea surface. This equilibrium sea level is commonly known as static sea level, and may be understood as the background sea level upon which short-term perturbations caused by waves, tides, and currents are superimposed.

Farrell and Clark (1976) developed their static sea-level theory for a viscoelastic non-rotating Earth with fixed shorelines, a theory that has since been generalized to include sea-level responses to changes in Earth's rotation (e.g., Milne and Mitrovica, 1996, 1998), shoreline migration (e.g., Johnston, 1993; Mitrovica and Milne, 2003; Kendall et al., 2005), and sediment transfer (Dalca et al., 2013). Extensive descriptions of the sea-level theory and its numerical implementation may be found in Dalca et al. (2013). Here we briefly describe the central aspects of the sea-level theory.

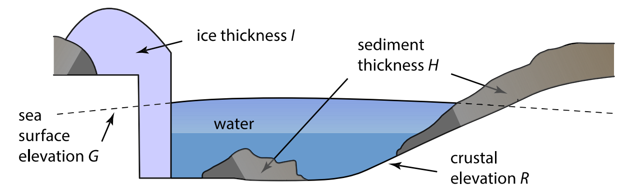

Fig. 1. Schematic of sea level in the presence of sediments and ice. Changes in sediment thickness, ΔH, and ice thickness, ΔI, produce changes in the elevation of the sea surface equipotential (ΔG) and the crust (ΔR), and thereby induce changes in sea level (ΔSL), as defined in Eq. (2). Modified from Dalca et al. (2013).

We first define what we mean by sea level. Consider the schematic in Fig. 1. Sea level in ice age theory is defined as the elevation difference between two globally defined surfaces. The first is the equipotential height G, which is the elevation above an arbitrary datum of the gravitational equipotential that defines the sea surface. The second is Earth's solid surface, which is defined as the sum of the crustal elevation R above the same arbitrary datum, the sediment thickness H, and the grounded ice thickness I (Fig. 1). Thus, sea level is given by:

$$SL = G - R - H - I. \tag{1}$$

Because each term on the right side of Eq. (1) is defined over the whole planet, the sea-level field SL is also defined globally. That is, sea level is defined over continents as well as over oceans. At a site in the ocean, for example, sea level is the thickness of sea water, while at a continental site with no sediment or grounded ice, sea level is the elevation difference between the sea surface equipotential and the surface of the crust. Following Eq. (1), sea level is the negative of the topography, under the usual definition of topography as the elevation of the crustal surface relative to the local sea surface equipotential.

Eq. (1) follows the traditional geological definition of sea level. It is useful for interpreting the sedimentary rock record because it considers the sea surface elevation relative to the ground, which is where the sedimentary record is formed. It is also useful for studies that use past indicators of global ocean water volume to infer ancient ice volumes, because the global ocean water volume is the thickness of the water column – i.e., sea level in Eq. (1) – integrated over the ocean area. This definition differs from geodetic studies that define sea level as the elevation of the sea surface equipotential relative to another datum, such as satellite ranging measurements of sea surface height.

The sea-level theory developed by Farrell and Clark (1976) computes the total change in sea level, ΔSL, in response to changes in mass loading on the Earth's surface between an initial time and a later time. Using Eq. (1), we may write:

$$\Delta SL = \Delta G - \Delta R - \Delta H - \Delta I, \tag{2}$$

where ΔH and ΔI are changes in the thickness of sediment and grounded ice, respectively, since the onset of loading, and ΔG and ΔR are the resulting perturbations in the elevation of the sea surface equipotential and crust, respectively.

Eq. (2) is commonly known as the sea-level equation, and it is what we use to compute changes in sea level in this paper. The changes in sea level in Eq. (2) are driven by changes in surface loading ΔL, which we compute as the total change in water, sediment, and ice mass loads:

$$\Delta L = \rho_w \Delta S + \rho_s \Delta H + \rho_I \Delta I \tag{3}$$