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River Deltas and Sea-Level Rise

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Keywords

river delta, sea-level rise, geomorphology, climate change, coast, sedimentary geology, shoreline

Abstract

Future sea-level rise poses an existential threat for many river deltas, yet quantifying the effect of sea-level changes on these coastal landforms remains a challenge. Sea-level changes have been slow compared to other coastal processes during the instrumental record, such that our knowledge comes primarily from models, experiments, and the geologic record. Here we review the current state of science on river delta response to sea-level change, including models and observations from the Holocene until 2300 CE. We report on improvements in the detection and modeling of past and future regional sea-level change, including a better understanding of the underlying processes and sources of uncertainty. We also see significant improvements in morphodynamic delta models. Still, substantial uncertainties remain, notably on present and future subsidence rates in and near deltas. Observations of delta submergence and land loss due to modern sea-level rise also remain elusive, posing major challenges to model validation.

- There are large differences in the initiation time and subsequent delta progradation during the Holocene, likely from different sea-level and sediment supply histories.

- Modern deltas are larger and will face faster sea-level rise than during their Holocene growth, making them susceptible to forced transgression.
- Regional sea-level projections have been much improved in the past decade and now also isolate dominant sources of uncertainty, such as the Antarctic ice sheet.
- Vertical land motion in deltas can be the dominant source of relative sea-level change and the dominant source of uncertainty; limited observations complicate projections.
- River deltas globally might lose 5% (~35,000 km^2) of their surface area by 2100 and 50% by 2300 due to relative sea-level rise under a high-emission scenario.

1. INTRODUCTION

River delta: a landform built by fluvial sediments in a standing body of water (lake or sea)

River deltas are global hotspots for major and rapidly growing population centers (Edmonds et al. 2020) with their associated economic activity, alongside agriculture and fisheries, and transportation. They are the cradles of human civilization (Bianchi 2016) yet also possess exceptional ecological value as well as abundant natural resources (oil, gas, freshwater). These assets are increasingly in conflict, and delta sustainability has evolved into a major priority for the future well-being of humankind.

In a world of accelerating sea-level rise, the future of river deltas is increasingly uncertain. Deltas form where river currents slow down as they approach the ocean and their sediments settle. Changes in sea level are therefore a first-order control on delta evolution, along with river sediment supply (**Figure 1**). Deltas are found along the vast majority of the world's shorelines, but their density varies, with hotspots of delta formation occurring in Southeast Asia (Caldwell et al. 2019), where sediment supply is high and relative sea level (RSL) has generally been falling during

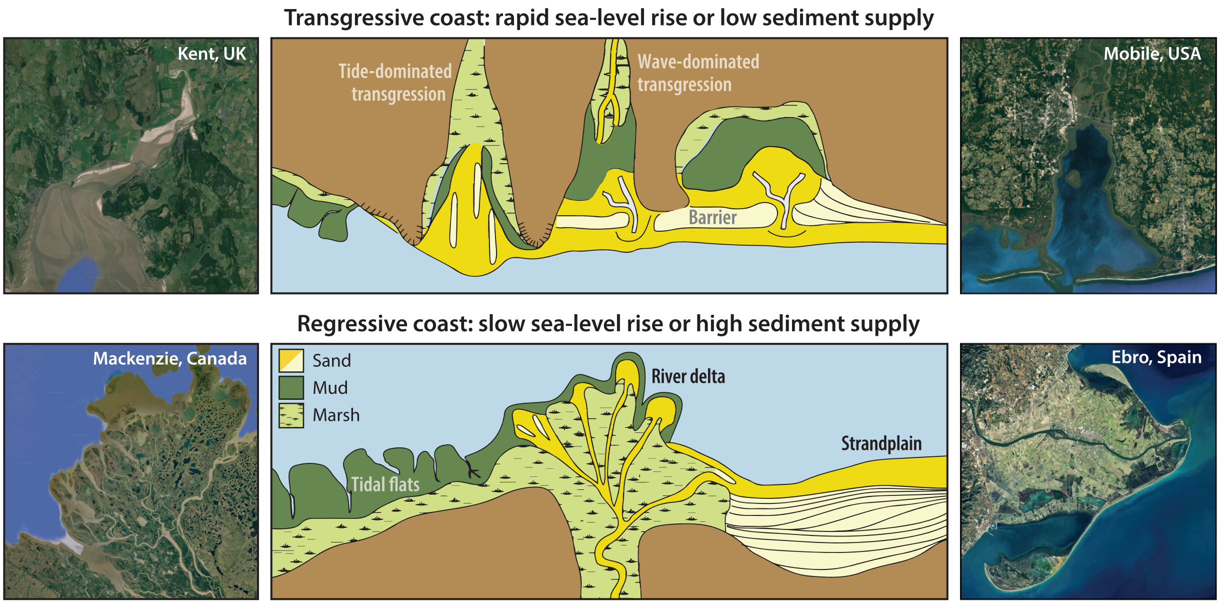


Figure 1

The effect of sea-level rise and sediment supply on delta geomorphology, with (*top*) transgressive, rapid sea-level rise and low sediment supply examples and (*bottom*) regressive, slow sea-level rise and high sediment supply examples. Satellite images are from Google Earth; conceptual art adapted from Harris (2020) and Boyd et al. (1992).

the mid-to-late Holocene. At the most basic level, knowledge of the relative roles of RSL rise and sediment supply is key to meaningful projections of future delta change (e.g., Ericson et al. 2006, Giosan et al. 2014).

While pioneering investigations of deltas were carried out by G.K. Gilbert in the 1800s, the onset of modern delta studies has been credited to H.N. Fisk (Miall 1978). For example, Fisk & McFarlan (1955) highlighted the intimate relationship between delta evolution and RSL change. Nevertheless, most delta studies through the 1960s to 1980s focused heavily on other aspects (e.g., bedforms and facies models) with little attention to the role of RSL change. It is perhaps somewhat ironic that the impetus for examining delta evolution within the context of RSL change came from Exxon Production Research in Houston, Texas—the birthplace of sequence stratigraphy. The emergence of sequence stratigraphy was motivated by hydrocarbon exploration and led to a more holistic view of sedimentary systems (also called source-to-sink systems), much of which revolves around shoreline changes (Jervey 1988, Posamentier & Vail 1988). Given the key role of deltaic depocenters herein, river deltas found themselves receiving renewed interest. These early sequence-stratigraphic models have subsequently undergone substantial revisions (e.g., Schumm 1993, Helland-Hansen & Martinsen 1996, Posamentier & Allen 1999, Blum & Törnqvist 2000, Strong & Paola 2008), providing a valuable framework for the more recent focus on delta sustainability within the context of climate-driven RSL rise (e.g., Kim et al. 2006, Jerolmack 2009, Nienhuis & Van de Wal 2021).

In this review we consider recent advances in our understanding of RSL change and its effect on river deltas, from both a theoretical and an observational perspective. We focus on past changes during the Holocene but also on future responses, on timescales of 10–1,000 years, for deltas worldwide with a delta plain larger than 10 km^2. All years are noted in Common Era (CE) unless specified. For extensive discussions on processes responsible for sea-level rise or subsidence, we refer readers to recent reviews by Horton et al. (2018), Hamlington et al. (2020), and Shirzaei et al. (2021). We limit ourselves to natural delta morphologic responses and refer readers to overviews of human management strategies for deltas by Paola et al. (2011) and Cox et al. (2022). Hoitink et al. (2020) discuss the importance of tipping points within the context of a range of deltaic processes, and Bianchi & Allison (2009) provide more details on the role of deltas in global biogeochemical cycles (notably carbon), while Bhattacharya (2006) focuses extensively on deltas in the stratigraphic record. Straub et al. (2020) highlight the critical role of deltas in reading Earth history, including a detailed assessment of the associated caveats.

Relative sea-level (RSL) change: the change in local mean sea level compared to the local solid surface (geocentric sea-level change minus vertical land motion)

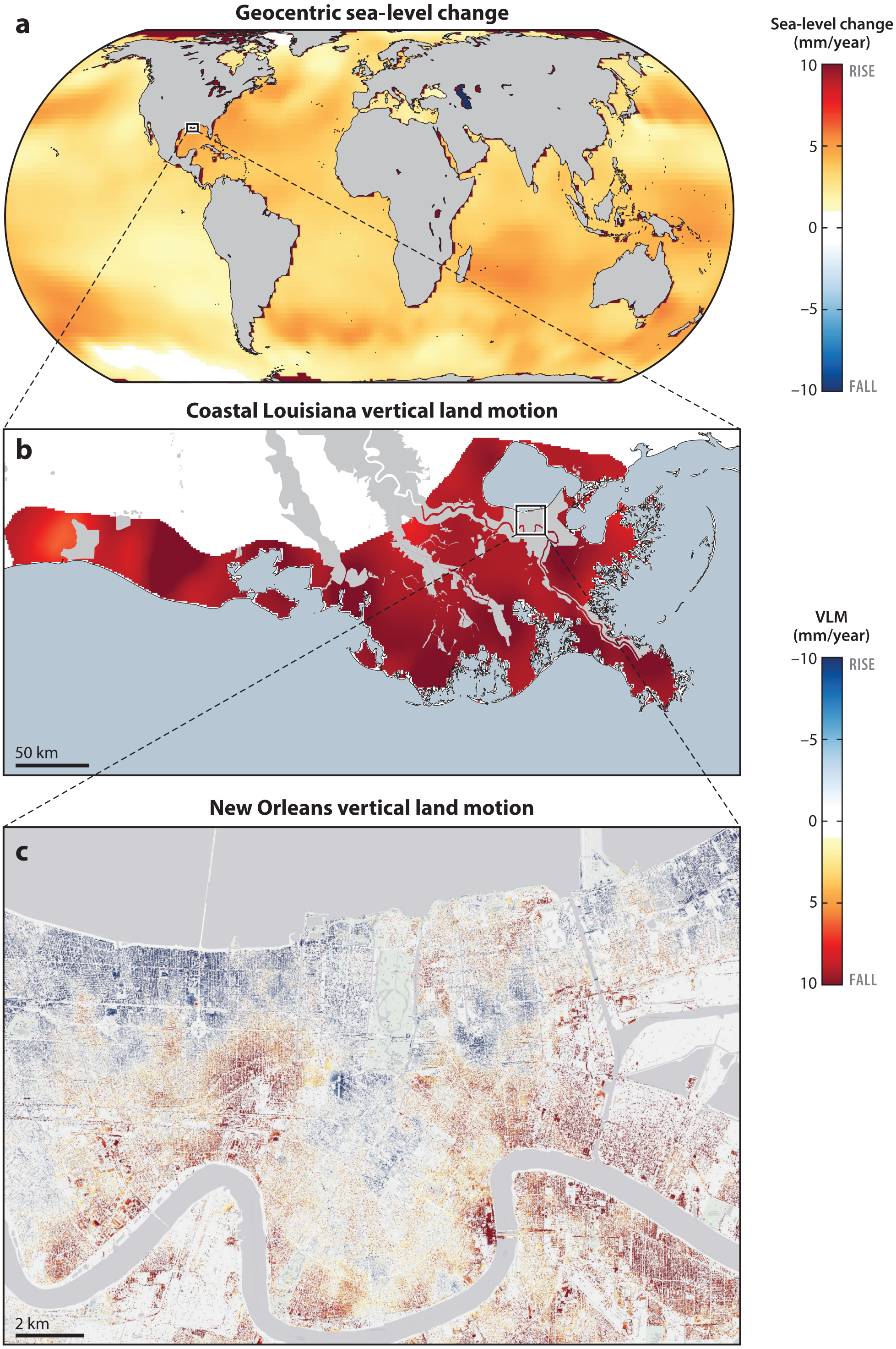
Geocentric sea-level change: the change in local mean sea level with respect to the center of Earth

Vertical land motion (VLM): vertical movement (uplift or subsidence) of the solid surface with respect to the center of Earth

2. RELATIVE SEA-LEVEL CHANGE NEAR DELTAS

Sea level varies on a range of temporal and spatial scales caused by different processes with origins both local and distant to deltas (Gregory et al. 2019, Hamlington et al. 2020, Fox-Kemper et al. 2021) (**Figure 2**). Sea-level change can be geocentric when measured with respect to the reference ellipsoid (e.g., the ocean surface with respect to the center of mass of Earth), but of primary importance for delta geomorphology is RSL change, which is geocentric sea-level change corrected for the vertical land motion (VLM) of the delta surface.

Sea-level change can arise from ocean density changes as a result of temperature or salinity variations, affecting the volume of the ocean water (called steric sea-level change). It can also arise from differences in the amount of water in the ocean (called barystatic sea-level change) due to changes in glaciers, ice sheets, or land water storage. Sea level is also affected by ocean circulation (ocean dynamic effects) and changes in the gravitational field, Earth rotation, and solid Earth deformation as a result of surface mass redistribution. The spatial scales of the sea-level changes associated with most of the above processes are considerably larger than that of deltas



(*Caption appears on following page*)

Figure 2 (*Figure appears on preceding page*)

Spatial scales of (*a*) geocentric sea-level change rates from satellite altimetry, 1993–2019 (Prandi et al. 2021), (*b*) coastal VLM rates from surface-elevation table–marker horizon and GPS measurements, ∼2006–2015 (Nienhuis et al. 2017), and (*c*) delta urban VLM rates from InSAR measurements, 2009–2012 (Jones et al. 2016). Abbreviations: InSAR, Interferometric Synthetic Aperture Radar; VLM, vertical land motion.

(**Figure 2*a***). Sea level also varies as a result of storm surges, tides, and waves, but the response of deltas to these shorter timescale changes is typically considered separately to that associated with the longer-term sea-level processes described above.

Of primary importance for deltas is RSL change, which includes local VLM (**Figure 2*b*,*c***). VLM includes contributions from a number of processes, such as (*a*) tectonic movement; (*b*) isostatic adjustment due to sediment, ice, and ocean (un)loading; (*c*) sediment compaction and oxidation; and (*d*) (artificial) drainage and fluid extraction. Note that some studies consider sedimentation and erosion to be contributors to VLM and, therefore, RSL (e.g., Dalca et al. 2013). Here we follow the geomorphologic literature and consider sedimentation and erosion to be separate from VLM such that surface-elevation change is the sum of VLM, sedimentation, and erosion.

It has long been recognized that deltas—particularly large deltas—experience greater downward VLM (subsidence) than nondeltaic coastal zones (e.g., Fisk & McFarlan 1955, Bijlsma et al. 1995). This is generally the result of a multitude of processes that collectively often exceed the rate of regional geocentric sea-level rise (Jelgersma 1996). These processes operate over a wide range of spatiotemporal scales (Yuill et al. 2009, Allison et al. 2016, Shirzaei et al. 2021). As a general rule, shallow processes (e.g., sediment compaction) exhibit large spatial variability (e.g., Nienhuis et al. 2017) (**Figure 2*b***) and dissipate over relatively short (10^1–10^3 year) timescales, whereas deep processes (e.g., lithospheric flexure due to sediment loading) have wide spatial footprints and comparatively slow rates that do not change appreciably over human-relevant timescales (typically less than 1 mm/year as found for the Mississippi Delta) (Yu et al. 2012, Wolstencroft et al. 2014, Kuchar et al. 2018). VLM as observed at the delta surface is the result of the sum of these processes across all depths. A comprehensive review of coastal subsidence and its driving mechanisms is provided by Shirzaei et al. (2021).

Studies that have integrated multiple measurement techniques across depths into delta deposits (i.e., stratigraphic as well as space-geodetic methods) to capture the range of processes that drive VLM have found that a large component usually occurs in the shallowest (Holocene) strata. Delta-plain sedimentation tends to result in deposits with very high water content, regardless of whether they are dominated by mud or organic matter. Delta deposits therefore lose volume rapidly in the uppermost ∼10 m or less, depending on organic content, when pore water is expelled and/or additional sediment is deposited (Keogh et al. 2021). This has been demonstrated both in the passive margin setting of the Mississippi Delta (Meckel et al. 2006, Törnqvist et al. 2008, Wolstencroft et al. 2014, Karegar et al. 2015) and in foreland basins such as those occupied by the Po Delta (Teatini et al. 2011) and the tectonically active Ganges-Brahmaputra Delta (Steckler et al. 2022), where deeper subsidence rates—partly due to sediment loading—tend to be higher (Karpytchev et al. 2018).

Surface-elevation change: net elevation change of the land surface due to VLM, sedimentation, and erosion

While naturally occurring sediment compaction may cause rapid subsidence rates (van Asselen et al. 2011, Zoccarato et al. 2018), human action—notably fluid extraction—has led to rates that can be an order of magnitude more rapid than the present-day rate of global mean sea-level rise across some large deltas such as the Mekong (Erban et al. 2014). At more local scales and in highly urbanized deltas, subsidence rates due to groundwater pumping can even be two orders of magnitude higher (Abidin et al. 2011).

Much of the remaining uncertainties around the magnitude and drivers of RSL in deltas stem from the fact that deltas are particularly challenging places to measure RSL changes. Geocentric sea-level rise can be measured by satellite altimetry (**Figure 2*a***). This provides near-global coverage, but disadvantages are that these measurements are only available from 1993 and that near-shore rates may be less accurate due to land contamination, although recent work (Cazenave et al. 2022) has made progress on this aspect. The forthcoming Surface Water and Ocean Topography (SWOT) satellite mission will further improve coastal altimetry (Fu et al. 2012). The VLM component of RSL can be measured by GPS, surface-elevation table–marker horizons (**Figure 2*b***), Interferometric Synthetic Aperture Radar (InSAR) (**Figure 2*c***), and Light Detection and Ranging (LIDAR) (Shirzaei et al. 2021), but long-term measurements are scarce and often complicated by simultaneous delta sedimentation and erosion, which can make it challenging to extract the VLM component of surface-elevation change. RSL itself can be measured by tide gauges. Some tide-gauge records extend well over 100 years and provide high-resolution temporal data, but a disadvantage is that these measurements are confined to coastal regions where they are influenced by river outflow hydrology or harbor activity. Longer time series typically exist only in the Northern Hemisphere, and tide gauges in deltas often fail to capture shallow subsidence and can therefore miss its large spatial variability (**Figure 2*b*,*c***) and underestimate total subsidence rates (Keogh & Törnqvist 2019).

3. THE EFFECTS OF RELATIVE SEA-LEVEL CHANGE ON DELTAS

3.1. A Simple but Useful 2D Model

The effect of RSL change on deltas is multifaceted. RSL rise influences delta surface water flows, with increased salinities and delta flooding probabilities (Yu et al. 2018), including the likelihood of compound events from storm surges and river flooding (Moftakhari et al. 2017). RSL rise affects coastal waves, for example, from reduced bottom friction (Smith et al. 2010), and affects coastal tidal heights, with the sign of the change depending on the magnitude of coastal retreat because of changes to the natural period of oscillation of the tidal basin (Pickering et al. 2017). RSL change also alters delta ecology, from changes to tidal inundation periods to salinity levels.

On top of all the short-term adjustments, RSL change affects delta morphology. This has been extensively studied in the field (e.g., Blum & Price 1998, Shen et al. 2012, Amorosi et al. 2016), with mathematical models (e.g., Leeder & Stewart 1996, Swenson 2005a), and with laboratory experiments (e.g., Wood et al. 1993, Li et al. 2016), or combinations thereof (Parker et al. 2008). Generally, studies can be split into 2D (dip-oriented cross-sectional deltas) (e.g., Muto & Steel 2002, Kollegger et al. 2022); quasi-3D, which assume some shape as deltas grow (e.g., Kim et al. 2009); and fully 3D, for both experiments (e.g., Li et al. 2016) and models (e.g., van de Lageweg & Slangen 2017).

Many fundamental insights are derived from cross-sectional 2D studies (**Figure 3**). At a basic level, they assume a constant width and simplify delta geometry into two surfaces: the topset (above sea level) and the foreset (below sea level). The topset, or delta plain for geomorphologists, is the relatively low-gradient onshore surface and is riverine or tidal. The foreset, or delta front for geomorphologists, has a higher gradient and is constructed by a mix of both downslope (e.g., gravity flow) and transverse (e.g., longshore drift) transport processes. In the most basic 2D model, the equilibrium condition between sediment supply and RSL change can be approximated by the following equation (Paola et al. 2011):

$$Q_{\text{river}} \cdot f_{\text{r}} = \dot{S} \cdot A_{\text{delta}}, \qquad 1.$$

where the fluvial sediment supply Q_{river} (m^3/year) that is retained on the delta (f_{r}, between 0 and 1) is balanced by the rate of RSL rise ($\dot{S}$) (m/year) across the delta surface area (A_{delta}, m^2), which is

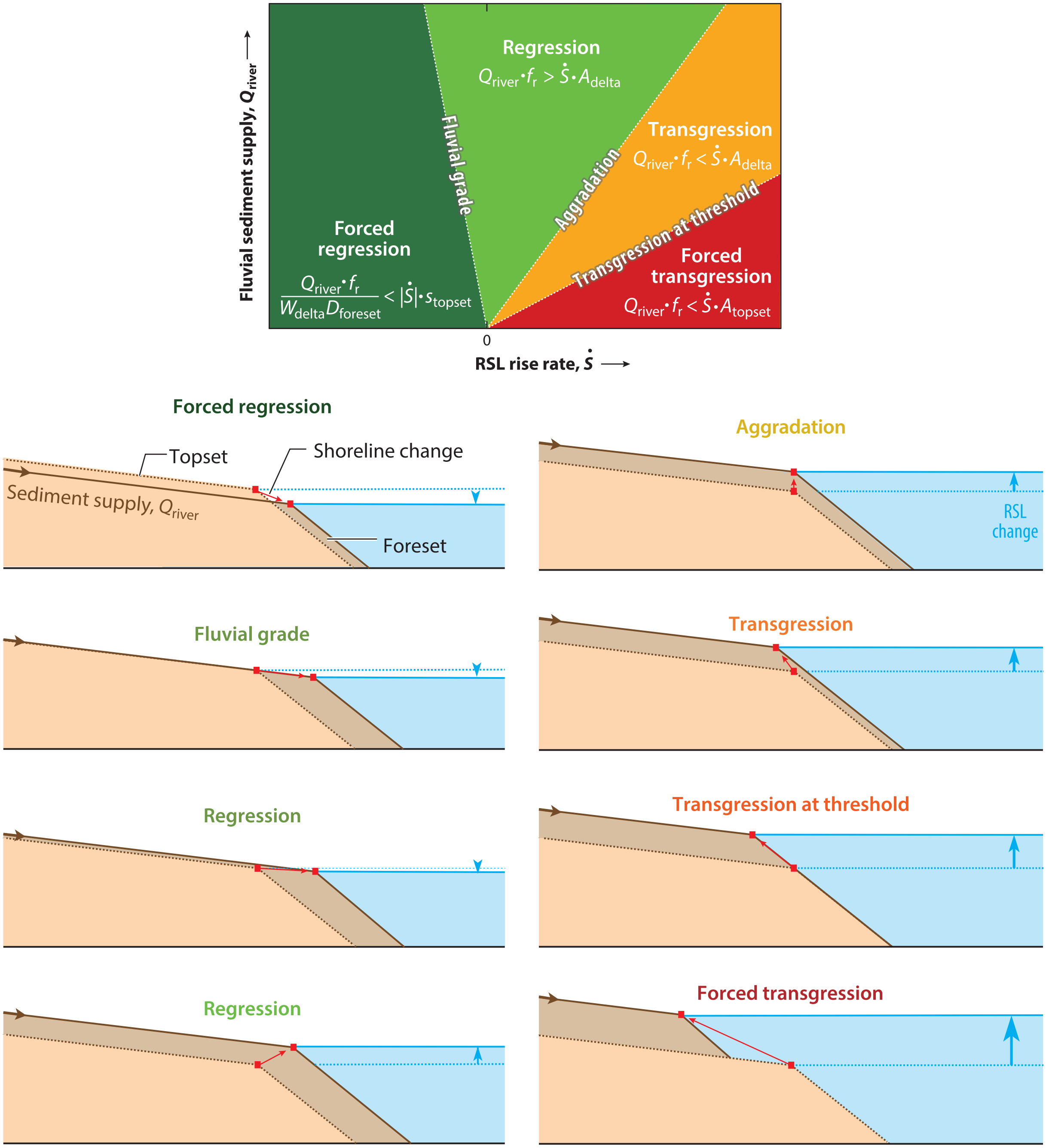


Figure 3

Thresholds and character of delta response to RSL change and sediment supply from the viewpoint of a delta cross section with constant width (derivations can be found in **Supplemental Text 1**). Examples of resulting plan-view change are shown in **Figure 1**. Note that these relatively simple models do not capture more complex morphologies, such as the subaqueous deposits that are found in large deltas such as the Amazon and Ganges-Brahmaputra (Nittrouer et al. 1986, Kuehl et al. 1997). Abbreviation: RSL, relative sea level.

Supplemental Material >

the sum of the delta topset area (A_{topset}, m^2) and foreset area ($A_{foreset}$, m^2). When Equation 1 is balanced, the delta aggrades vertically with RSL rise, and there is no horizontal shoreline movement. Deviations from this balance result in delta shoreline change, which includes seaward migration (i.e., regression or progradation) or landward migration (i.e., transgression or retrogradation).

Regression/Progradation: seaward migration of a shoreline in response to changes in the balance between RSL change and sediment input

Transgression/Retrogradation: landward migration of a shoreline in response to changes in the balance between RSL change and sediment input

In cases of RSL rise, delta submergence results in additional space for sediment to be deposited on the topset, commonly referred to as accommodation (Jervey 1988). This enhances aggradation rather than transport of riverine sediment across the shoreline to the foreset, which reduces shoreline regression (**Figure 3**). For a low sediment supply or large delta area, the space on the delta plain generated by the RSL rise cannot be filled and the delta will transgress ($Q_{river} \cdot f_r < \dot{S} \cdot A_{delta}$) (Muto & Steel 1992, 2002). Transgression can occur with and without continuous foreset deposition, depending on the sediment supply and the RSL rise rate. The latter is often described as a shoreline back step or as sediment-starved autoretreat, as the delta becomes detached from its original foreset due to lack of sediment available for the foreset ($Q_{river} \cdot f_r < \dot{S} \cdot A_{topset}$; herein referred to as forced transgression). The river mouth is abandoned, and the delta becomes an estuary (**Figures 1**, **3**). Although this transformation has been well described (e.g., Boyd et al. 1992), the timescales and spatial configurations of these transformations are poorly known for modern deltas.

For sufficient sediment supply, a delta can also maintain its size (aggradation, $Q_{river} \cdot f_r = \dot{S} \cdot A_{delta}$) or prograde seaward even with fast RSL rise (regression, $Q_{river} \cdot f_r > \dot{S} \cdot A_{delta}$). However, there is a time dependence that will disrupt this balance. Continuous RSL rise and sediment supply over time will make a delta advance seaward, resulting in delta plain (A_{topset}) and delta front ($A_{foreset}$) growth. Aggradation and regression cannot be sustained and will eventually reverse into transgression when the delta grows too large. This autogenic behavior is termed autoretreat. Studies have discussed the stratigraphic implications (Muto & Steel 1992, 2002), but how close modern deltas are to autoretreat remains unknown.

In cases of RSL fall, delta topsets still can aggrade and experience progradation if the sediment supply is sufficiently high so the shoreline progradation rate is fast enough (Leeder & Stewart 1996) (**Figure 3**). Otherwise, delta channels will feel base-level drop at the shoreline, steepen beyond the equilibrium topset slope, and incise into the delta topset. This state is known as forced regression, and it occurs if $Q_{river} \cdot f_r < |\dot{S}| \cdot s_{topset} W_{delta} D_{foreset}$, where s_{topset} is the topset slope, W_{delta} is the delta width (m), and $D_{foreset}$ is the foreset depth (m). Finally, a condition of fluvial grade can be achieved when the sediment supply is just enough to maintain the topset slope in the newly prograded delta plain (**Figure 3**).

Changes to delta area have also been explored based on the deviation from equilibrium (Equation 1). Nienhuis & Van de Wal (2021) formulated the following relation for delta area change:

$$\frac{dA_{delta}}{dt} = \frac{Q_{river} \cdot f_r - \frac{1}{2} A_{delta} \cdot \dot{S}}{D_{foreset}}, \qquad 2.$$

where the foreset depth should be viewed as an active delta height across which the delta can migrate landward (transgression) or seaward (regression).

3.2. Delta Dynamics Beyond 2D

Linear cross-sectional models in 2D and quasi-3D (Jerolmack 2009) have been extensively tested in the laboratory (Muto & Steel 2002) and the field (Nienhuis & Van de Wal 2021), but a comparison to natural deltas remains challenging because of the many simplifications. Many cross-section models assume deltas respond instantly to changes in sea level or sediment supply. In reality, the topset can be slow to adjust, driving upstream river-to-delta transitions that can be out of phase and erode while RSL is rising (Schumm 1993, Kollegger et al. 2022). Delta sedimentation is also not uniform and instantaneous across the delta plain. This is particularly true on short (e.g., below channel migration rate) timescales (Sheets et al. 2002, Wickert et al. 2013, Ganti et al. 2014), shorter than what is known as the compensation timescale in stratigraphy (Straub et al. 2020).

RSL rise can affect abrupt changes in the course of delta distributaries (known as avulsion), leading to sudden redistribution of sediment across the delta plain, alongside flood hazard. A more detailed review of river avulsions is provided by Slingerland & Smith (2004). Within the context of the present review, the following elements stand out. First, accelerated RSL rise may increase the frequency of avulsions as shown theoretically (Mackey & Bridge 1995), experimentally (Bryant et al. 1995), and in the geologic record (Törnqvist 1994). However, this merely constitutes a first-order control that neglects the role of waves and tides in delta evolution, which is not yet well understood. For example, for wave-dominated deltas, arguments have been made both in favor of (Ratliff et al. 2018) and against (Swenson 2005b) increased avulsion frequency with increased wave reworking. In tide-influenced deltas, their deep and stable distributary channels may lead to a decrease in avulsion frequency, although effects of RSL change are untested (Rossi et al. 2016). More widely accepted is the finding that avulsion sites are likely to migrate landward as a function of RSL rise, as observed throughout the mid-to-late Holocene in the Rhine-Meuse Delta (Stouthamer & Berendsen 2000) and in recent decades in a lacustrine delta (Li et al. 2022). A variety of studies (e.g., Chatanantavet et al. 2012, Chadwick et al. 2020, Brooke et al. 2022) suggest that this is associated with landward migration of the backwater zone and associated avulsion nodes.

Cross-section delta models also do not usually include relevant (nondeltaic) topography that can shape deltas during regression and transgression. Many coastal deltas retreat into valleys where they are protected from waves and, to a lesser extent, tides. Changes in delta width, foreset depth, and the potential for valley infilling with marine sediment greatly alter their response to sea-level rise (**Figure 1**), but relevant models remain conceptual (Boyd et al. 1992).

Not all fluvial sediment that is transported to the delta apex contributes to delta building, as is shown by the sediment retention fraction (f_r) in Equation 1. For example, Allison et al. (1998) estimated values ranging from 40% to 70% for the Ganges-Brahmaputra Delta. Esposito et al. (2017) showed that sediment retention on a delta plain can vary greatly depending on location, with values approaching 100% in inland settings and much lower retention on the open coast where waves, tides, and currents carry sediment offshore. Retention of sediment may also be significantly lower considering human impacts on deltas (e.g., flood-control infrastructure, damming of distributaries) or higher considering enhanced trapping due to RSL rise.

There are also other mechanisms of delta plain aggradation beyond clastic fluvial sediment input. Delta plains can grow vertically by the accumulation of organic matter (i.e., peat beds) that in some cases can account for a large portion of the delta stratigraphy (e.g., Rhine-Meuse Delta). Organic matter accretion can be included into Equations 1 and 2 by increasing f_r, and insights into relevant dynamics can come from studies of coastal wetlands (mangroves, marshes, freshwater swamps) that often occupy substantial portions of delta plains. For example, as demonstrated by Morris et al. (2002), coastal wetland accretion is intimately related to tide levels, with an optimum between mean high tide and mean tide level. This capacity of coastal wetlands to grow independently from clastic sediment supply can make them less sensitive to RSL rise, especially with a high tidal range (Stevenson et al. 1986, Kirwan & Guntenspergen 2010). Given their role in maintaining delta plain elevation, this can also result in nonlinear delta responses. One of the implications of the Morris model is that if a delta plain falls below the elevation window for organic matter accumulation, it may cross a threshold (tipping point) and drown rapidly. For example, it has been shown that the marshes that occupy much of the Mississippi Delta are likely to drown when the rate of RSL rise exceeds 3 mm/year (Törnqvist et al. 2020). Delta plains with a low tidal range and thus low elevations (e.g., ~0.2 m above mean sea level in the Mississippi Delta) would be most vulnerable to such rapid retreat due to RSL rise. Although such tipping points may exist in deltas, care must be taken in translating these local concepts to larger scales. For example, the exceptionally large sediment supply in the Ganges-Brahmaputra Delta renders this system comparatively less sensitive to RSL rise (e.g., Wilson & Goodbred 2015) (**Figure 4**).

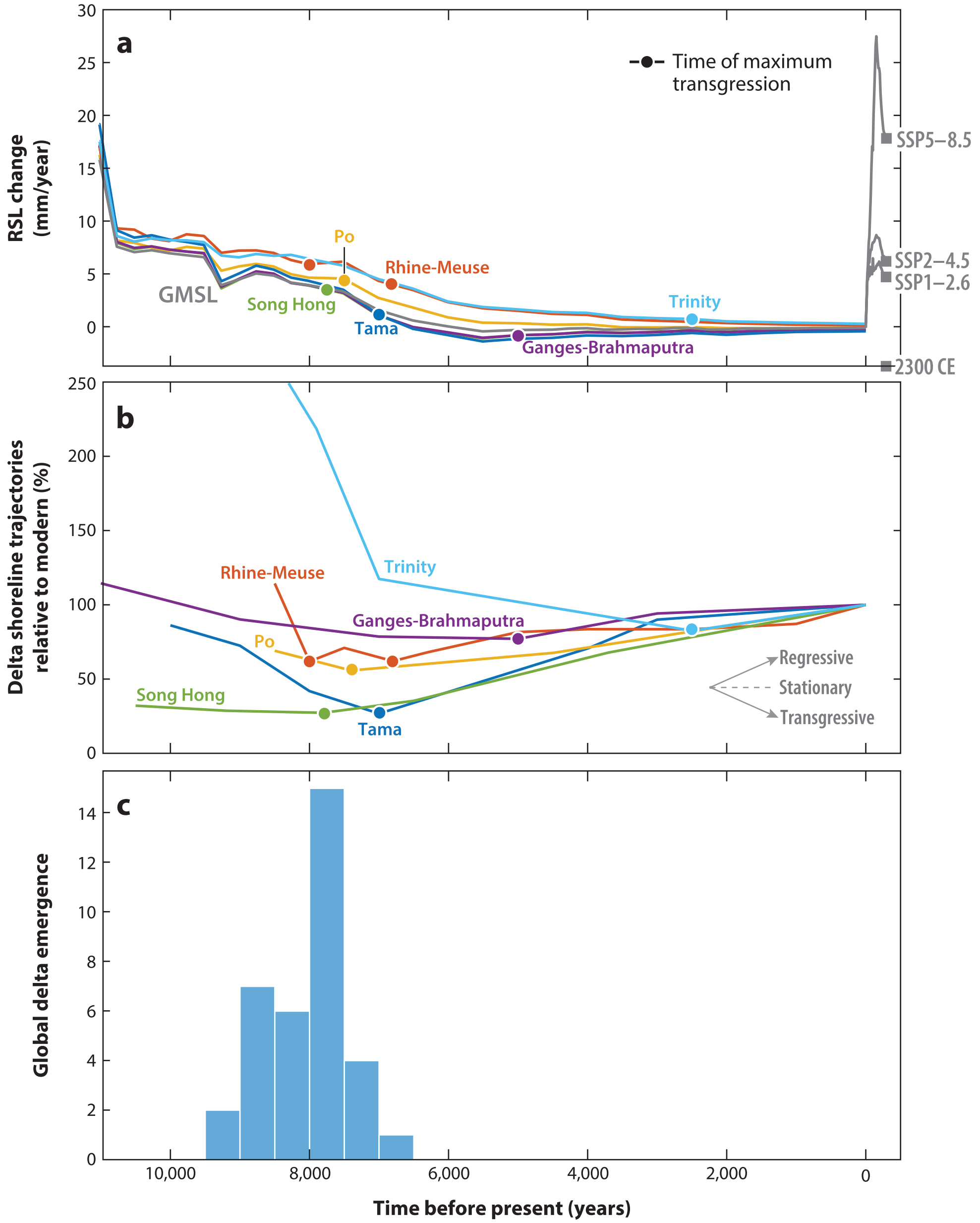


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Figure 4 (*Figure appears on preceding page*)

(*a*) Past and future rates of RSL change for a selection of deltas based on a glacial isostatic adjustment model [specifically, the ICE-6G ice model and VM5a Earth viscosity model (Peltier et al. 2015) and IPCC-AR6 projections until 2300 (Fox-Kemper et al. 2021)]. Markers show the time of maximum delta transgression. RSL change from an alternative glacial isostatic adjustment model (Lambeck et al. 2014) is shown in **Supplemental Figure 1**. (*b*) Holocene deltaic shoreline trajectories of select deltas, relative to the delta apex, nondimensionalized using the present-day shoreline position (details in **Supplemental Text 2**), based on paleogeographic maps from Amorosi et al. (2019), Anderson et al. (2008), Berendsen & Stouthamer (2000), Duong et al. (2020), Goodbred & Kuehl (2000), Hijma & Cohen (2011), and Tanabe et al. (2022). (*c*) Time of emergence of global deltas (Stanley & Warne 1994), with ages calibrated using IntCal20. Abbreviations: GMSL, global mean sea level; IPCC-AR6, Intergovernmental Panel on Climate Change 6th Assessment Report; RSL, relative sea level; SSP, Shared Socioeconomic Pathway.

Supplemental Material >

4. FROM THE HOLOCENE TO THE PRESENT

4.1. Holocene Relative Sea-Level Change

Modern deltas are, to a large extent, the product of sedimentation and RSL change during the Holocene. Reconstructions of Holocene RSL changes indicate considerable temporal and spatial variability (e.g., Shennan 1989, Khan et al. 2019). Melting of the Laurentide Ice Sheet dominated rates of sea-level rise during the early Holocene, with barystatic rates exceeding 10 mm/year (multicentury average) (Whitehouse & Bradley 2013, Peltier et al. 2015) (**Figure 4*a***). Following the demise of the Laurentide Ice Sheet ~7,000 years ago (Fleming et al. 1998, Carlson & Clark 2012, Dalton et al. 2020), rates of barystatic sea-level rise show a marked deceleration. Since then, the barystatic signal has steadily declined to submillimeter/year values during the late Holocene until the distinct acceleration to modern rates in the nineteenth century (Kopp et al. 2016). Thus, global mean sea levels were remarkably stable during most of the mid-to-late Holocene.

On regional scales, away from tectonically active margins, glacial isostatic adjustment has been the dominant contributor to RSL change during the mid-to-late Holocene (e.g., Clark et al. 1978, Milne & Mitrovica 2008). Broadly speaking, areas well within the maximum ice limit at the Last Glacial Maximum (LGM) exhibit an RSL fall while areas beyond the ice margin show an RSL rise that exceeds that of the barystatic signal, primarily due to subsidence of these (ice) peripheral regions (**Figure 5**). The spatial gradients in RSL change are largest within and adjacent to previously glaciated areas, and so potential impacts of this variability would be most apparent on delta evolution in the Arctic (e.g., Whitehouse et al. 2007, Overeem et al. 2022). In regions more distant from the ice sheets, the influence of water loading is an important but more subtle control on the spatial variability (e.g., Nakada & Lambeck 1989). This is highlighted by the relatively small contrast between Holocene RSL change for six deltas from the ICE-6G glacial isostatic adjustment model (Peltier et al. 2015) (**Figure 4*a***). Results based on a different model (described in Lambeck et al. 2014) show marked differences compared to those shown in **Figure 4*a*** (**Supplemental Figure 1**); however, the general characteristic of high RSL rates during the early Holocene (order ~10 mm/year) reducing to much lower rates by the mid-to-late Holocene (order ~1 mm/year) is the same. Neither of these models include the influence of sediment compaction, a component of VLM, on rates of RSL rise during the Holocene, but this could vary greatly between deltas. Rapid subsidence is expected in the first centuries postdeposition, and rates generally increase with deposition rate (Meckel et al. 2006, Teatini et al. 2011).

4.2. Holocene Delta Growth

Despite the diversity in delta sizes and shapes, striking similarities exist in their Holocene growth patterns and their relationship with RSL rise (**Figure 4*b*,*c***). A foundational study by Stanley & Warne (1994), who compiled basal ^{14}C ages from delta successions worldwide, suggests that the

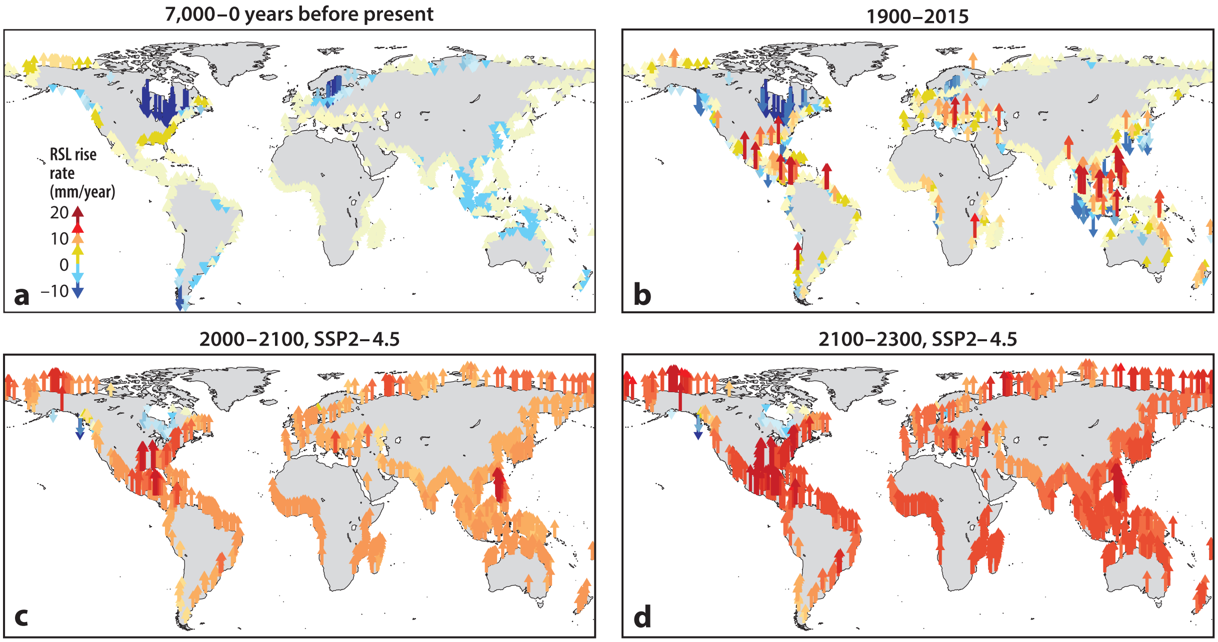

Figure 5

Rate of RSL change (mm/year) for 933 global deltas for (*a*) the past 7,000 years (based on the model of Lambeck et al. 2014), (*b*) from 1900 to 2015 (Dangendorf et al. 2019, Nienhuis & Van de Wal 2021), (*c*) from 2000 up to 2100 following SSP2–4.5, and (*d*) from 2100 to 2300, projections from IPCC-AR6 (Fox-Kemper et al. 2021). Sources of VLM data vary between subplots, which contributes to the RSL estimates. Panels *a* and *b* use a glacial isostatic adjustment model; panel *b* further includes GPS records, and panels *c* and *d* use tide-gauge records. All these sources likely miss shallow subsidence and therefore underestimate deltaic RSL rise. Abbreviations: IPCC-AR6, Intergovernmental Panel on Climate Change 6th Assessment Report; RSL, relative sea level; SSP, Shared Socioeconomic Pathway; VLM, vertical land motion.

initiation of 36 deltas (that is, in their present location) occurred 9,500–6,500 years ago (all ages are expressed here in calendar years with respect to 1950 CE) (**Figure 4*c***). It is conceivable that this is, to a large extent, driven by the reduction in the rate of global mean sea-level rise around this time (**Figure 4*a***). This would have allowed deltas to transition from transgression to regression (**Figure 3**), possibly including a transition in delta plain channel dynamics from avulsions to a mode dominated by bifurcation (Jerolmack 2009). It has also been linked to coincident major changes to human civilizations, including the appearance of the first cities and irrigation-based agriculture (Bianchi 2016).

However, Stanley & Warne (1994) did not consider the stratigraphic context of basal ^{14}C ages beyond the fact that they represent the base of the Holocene deltaic succession. As shown by Fisk & McFarlan (1955) along with numerous subsequent studies (e.g., Zaitlin et al. 1994, Simms et al. 2006; reviewed in Blum et al. 2013), the base of a delta varies spatially. Some of the delta ages from Stanley & Warne (1994) represent deposition onto deeply buried floodplain surfaces in paleovalleys from the time around the LGM, whereas other ages were reported from delta deposits on paleovalley flanks. These deposits can be more than 30 m above the LGM floodplain in the Mississippi Delta (Blum & Roberts 2012). Even for smaller systems such as the Trinity River in Texas, this elevation difference can easily exceed 10 m (Blum et al. 2013), resulting in age differences that can amount to thousands of years. Put differently, the morphologic definition of when delta growth begins, and therefore the reported age of a delta, is somewhat arbitrary.

A compilation of shoreline trajectories from more recent studies provides a more nuanced assessment of global delta response to Holocene RSL change. For the limited number of deltas for which sufficiently detailed paleogeographic reconstructions are available, trajectory analysis (following Helland-Hansen & Hampson 2009) shows that delta shorelines transgressed landward of the present-day shoreline in association with rapid RSL rise (**Figure 4*b***; for retrieval details, see the **Supplemental Text**). This is consistent with observations of backstepping of Asian deltas by Hori & Saito (2007) during rapid RSL rise 9,000–8,000 years ago. Maximum shoreline transgression was generally reached between 8,000 and 5,000 years ago. This partially postdates delta initiation as inferred by Stanley & Warne (1994). For example, for the Rhine-Meuse Delta the delta initiation was inferred to occur 9,000–8,000 years ago by Stanley & Warne (1994), yet the inflection of the shoreline trajectory took place 8,000–7,000 years ago (**Figure 4*c***). With generally decreasing RSL rise throughout this period, shoreline trajectories could therefore indicate a lower RSL rise rate threshold for delta progradation, perhaps about 5 mm/year (**Figure 4*a***).

Supplemental Material >

There are distinct differences in the timing and magnitude of Holocene shoreline migration between different deltas (**Figure 4*c***). When normalized against the modern (backwater) delta length, delta lengths declined to between ~30% (Song Hong, Tama) and ~80% (Trinity, Ganges-Brahmaputra) of the modern length following Holocene RSL rise. Subsequent regression is limited in the Ganges-Brahmaputra Delta but much more significant in the Song Hong Delta, Vietnam. This can likely be attributed to the interplay of sediment supply and the local RSL history. The monsoon-driven large sediment supply of the Ganges-Brahmaputra system during the early Holocene is well documented and explains the comparatively stationary shoreline in this delta (Goodbred & Kuehl 2000). In the case of the Song Hong, the substantial progradation may be in part due to the RSL fall after the Holocene RSL highstand, which has occurred throughout Southeast Asia (**Figure 5**). The Trinity is a comparatively small river with a lower sediment flux. Its bayhead delta (Galveston Bay, Texas) started to grow only ~2,500 years ago. It is likely that the differences in rate and timing of the progradation of deltas show that other factors besides RSL, such as sediment supply, control delta growth. For example, the Trinity and Rhine-Meuse stand out by exhibiting very rapid transgression ~8,000 years ago (**Figure 4*b***), which may be due to a comparatively low sediment supply. There are implications for human settlement and agricultural practices on deltas. These are affected by environmental change (Giosan et al. 2012) and may therefore have responded differently between deltas throughout this period.

More detailed records from deltas during the past 2,000 years show responses to changes in sediment supply. For example, there has been rapid growth of Mediterranean deltas during times of deforestation but also delta erosion following subsequent reforestation (Maselli & Trincardi 2013). The key point though is that in a broad sense, the Holocene record shows that RSL change is a first-order control on delta growth versus retreat.

4.3. Sea-Level Change and Deltas During the Twentieth Century

Global mean sea-level rise during the twentieth century has started to show an acceleration. Reconstructions using tide-gauge measurements find an average sea-level rise of 1.7 (1.3–2.2) mm/year between 1901 and 2018 (Fox-Kemper et al. 2021) (median and very likely range), with an acceleration of 0.0053 (0.0042–0.0073) mm/year^2 for the period 1902–2010 (Palmer et al. 2021). For the satellite era (1993–2018), the rate increased to 3.25 (2.88–3.61) mm/year (Fox-Kemper et al. 2021), with an acceleration of 0.094 (0.082–0.115) mm/year^2 (Cazenave et al. 2018). These changes are primarily driven by ocean warming and continental ice mass loss.

VLM rates have also accelerated in many deltas, as human activity on delta plains has increased local land subsidence. For instance, the Tama Delta (Tokyo Bay) has been subsiding at an average rate of 38 mm/year between 1900 and 2013 (Kaneko & Toyota 2011). The Ciliwung Delta

(Jakarta) has been subsiding at 18 mm/year between 1900 and 2013, a rate that has accelerated to 179 mm/year between 2000 and 2013 (Bakr 2015).

A global compilation of recent delta plain area changes indicates that, despite global sea-level rise, deltas worldwide are growing at 54 km^2/year from 1985 to 2015, or 0.008% of their surface area per year (Nienhuis et al. 2020). This rate is broadly expected for steady delta area gain over the past 7,000 years if deltas on average have gained 40% of their present-day surface area, although in the past as well as in the present, there are large differences in delta growth rates (**Figure 4*b***).

Detecting a signature of RSL change in modern delta growth is challenging. A model-based estimate suggests that, without RSL change, global deltas would have gained 67% more land area between 1985 and 2015, but a comparison against observations is weak (R^2 is ∼0.4) (Nienhuis & Van de Wal 2021). Observations of the effects of accelerating RSL rise on deltas do not yet exist. This is largely because land area change measurements are difficult, because acceleration in local RSL rise is not yet statistically significant everywhere, and because of many other components that drive delta change that are unrelated to RSL change, including human activities, sediment supply, and autogenic delta dynamics. A net delta area gain of 54 km^2/year is the result of 181 km^2/year of gains versus 127 km^2/year of losses, most of which is unrelated to RSL change. Other studies have found a net loss of tidal wetlands on deltas globally [gains of 105 km^2/year versus losses of 115 km^2/year (Murray et al. 2022)] as well as a net loss of tidal flats (Murray et al. 2019). These losses are predominantly caused by human development and therefore do not constitute delta land area loss. More efforts should be made to define and quantify delta land area change, especially in relation to RSL rise.

5. PROJECTIONS TOWARD 2300 AND BEYOND

5.1. Relative Sea-Level Change

In the coming century and beyond, global mean sea level will continue to rise, primarily driven by mass loss of glaciers and ice sheets, and thermosteric sea-level rise due to ocean warming (Fox-Kemper et al. 2021). Building on a wide range of global and regional projection studies, the Intergovernmental Panel on Climate Change 6th Assessment Report (IPCC-AR6) assessed that under a greenhouse gas reduction scenario with net-zero emissions in 2050 [Shared Socioeconomic Pathway (SSP) 1–1.9], the projected RSL rise rate is 4.1 (2.8–6.0) mm/year in 2040–2060 and 4.2 (2.4–6.6) mm/year in 2080–2100 (median and very likely range). Under a greenhouse gas increase scenario with doubling of CO_2 emissions by 2050 (SSP5–8.5), the projected rate is 7.2 (5.6–9.7) mm/year in 2040–2060 and 12.1 (8.6–17.6) mm/year in 2080–2100 (Fox-Kemper et al. 2021) (**Figure 4*a***). These projections include a steady (constant in time) background RSL change component derived from tide-gauge records (following Kopp et al. 2014).

Beyond 2100, there is deep uncertainty around the amount of mass loss from, in particular, the Antarctic Ice Sheet. Several studies provide global and regional sea-level projections up to 2300 (Kopp et al. 2014, Nauels et al. 2017, Bamber et al. 2019, Horton et al. 2020, Palmer et al. 2020) (**Figure 5**). Combining this information with the current understanding of ice sheet evolution, the IPCC-AR6 assessed the projected range of RSL rise at 0.3–3.1 m under the SSP1–2.6 scenario, with a global mean rise rate of 4.8 (1.8–12.6) mm/year in 2300. Projections under the SSP5–8.5 scenario are 1.7–6.8 m, but up to 16 m when marine ice-cliff instabilities are considered, with global mean rates covering a very wide range of 17.5 (3.6–61.4) mm/year in 2300.

Most RSL projections use spatially varying but steady VLM rates for the timescale considered (typically centuries) (**Figure 5**). Indeed, steady and comparatively low rates of subsidence and uplift owing to tectonic processes and glacial isostatic adjustment can be assumed for the twenty-first century (Whitehouse et al. 2007). By contrast, much higher and variable subsidence rates occur owing to compaction associated with sediment loading and fluid extraction (**Figure 5**), as well as large earthquakes. Projecting future delta subsidence is still in its infancy and requires the integration of a wide range of models that capture both deep and shallow processes (Allison et al. 2016, Shirzaei et al. 2021). Because subsidence (notably sediment compaction) cannot be viewed in isolation from delta aggradation, recent work has started to integrate deposition and subsidence (Nienhuis et al. 2018, Chamberlain et al. 2021, Keogh et al. 2021, Dunn & Minderhoud 2022), providing opportunities for projections for individual deltas. While this is a useful advance, it is still a relatively small step; given the strong anthropogenic imprint on delta subsidence, these models must eventually incorporate socioeconomic factors.

5.2. Delta Change

Projections of future delta change from sea-level changes and subsidence have been developed in recognition of potential flooding hazards and other threats. One class of projections comes from so-called bathtub models. These use a static elevation model to project when parts of a delta become submerged due to sea-level rise. Bathtub models offer high spatial detail and are rapidly becoming more precise as delta elevation maps improve (e.g., MERIT digital elevation model in Yamazaki et al. 2017; CoastalDEM in Kulp & Strauss 2019). They also use increasingly detailed RSL projections including storm surge and wave setup, validated against tide-gauge data (Kirezci et al. 2020), as well as improved data on global delta flood-protection levees (O'Dell et al. 2021). Kirezci et al. (2020) project that between 176 and 287 million people will be exposed to floods by 2100 under a high-emission scenario (assuming no coastal protection), and 32% of flooded land will be below mean sea level.

Despite these improvements, bathtub projections remain of limited use in deltas because of the assumption of no morphologic change, which cannot be neglected on timescales relevant for RSL change (>10 years). This is illustrated by a lack of model skill. Comparisons between observed delta change from 1985 to 2015 and reanalysis using bathtub models are poor (Nienhuis & Van de Wal 2021), although this could also be the result of uncertain delta change observations. Improved satellite data covering flood events (Tellman et al. 2021) and long-term surface water change (Pekel et al. 2016) as well as other big data flood observations (De Bruijn et al. 2019) can greatly aid the validation and calibration of delta models.

Another class of delta projections has resulted in improvements over bathtub models. Minderhoud et al. (2020) used spatially explicit subsidence projections to find that 56% of the Mekong Delta will be below mean sea level by 2100 under a median subsidence scenario. Blum & Roberts (2009) allowed for delta sedimentation to compensate for RSL change and found that an additional 30% of the Mississippi Delta plain could be lost by 2100. Other advances include the study by Nienhuis & Van de Wal (2021), who used a simple morphodynamic model (Equation 2) and performed a cross-delta validation by comparing different responses from different RSL rise rates between 5,000 deltas (**Figure 6**). Their results suggest that future deltas will lose land on average: 2% of their surface area by 2100 under SSP2–4.5, increasing to 10% by 2300 (**Figure 6*e***). For the 933 deltas with a delta plain exceeding 10 km^2, 526 deltas will transgress by 2100 under SSP2–4.5. Projections under the high-emission but low-confidence scenario of SSP5–8.5 up to 2300 suggest losses will continue and may increase to 50% of global delta area (**Figure 6*e***). These numbers remain uncertain, primarily because of unknown future sediment supply, uncertainties in future VLM and sea-level rise, and poorly constrained sediment retention on delta plains.

Morphodynamic projections for wetlands and beaches, many of which are found in deltas, can also help to provide insights into the fate of deltas. Wetland and beach land area change is also controlled by the ratio of accommodation, created by RSL rise, versus sediment supply. Projections for wetlands suggest that long-term sustainability is unlikely and that global wetlands may lose

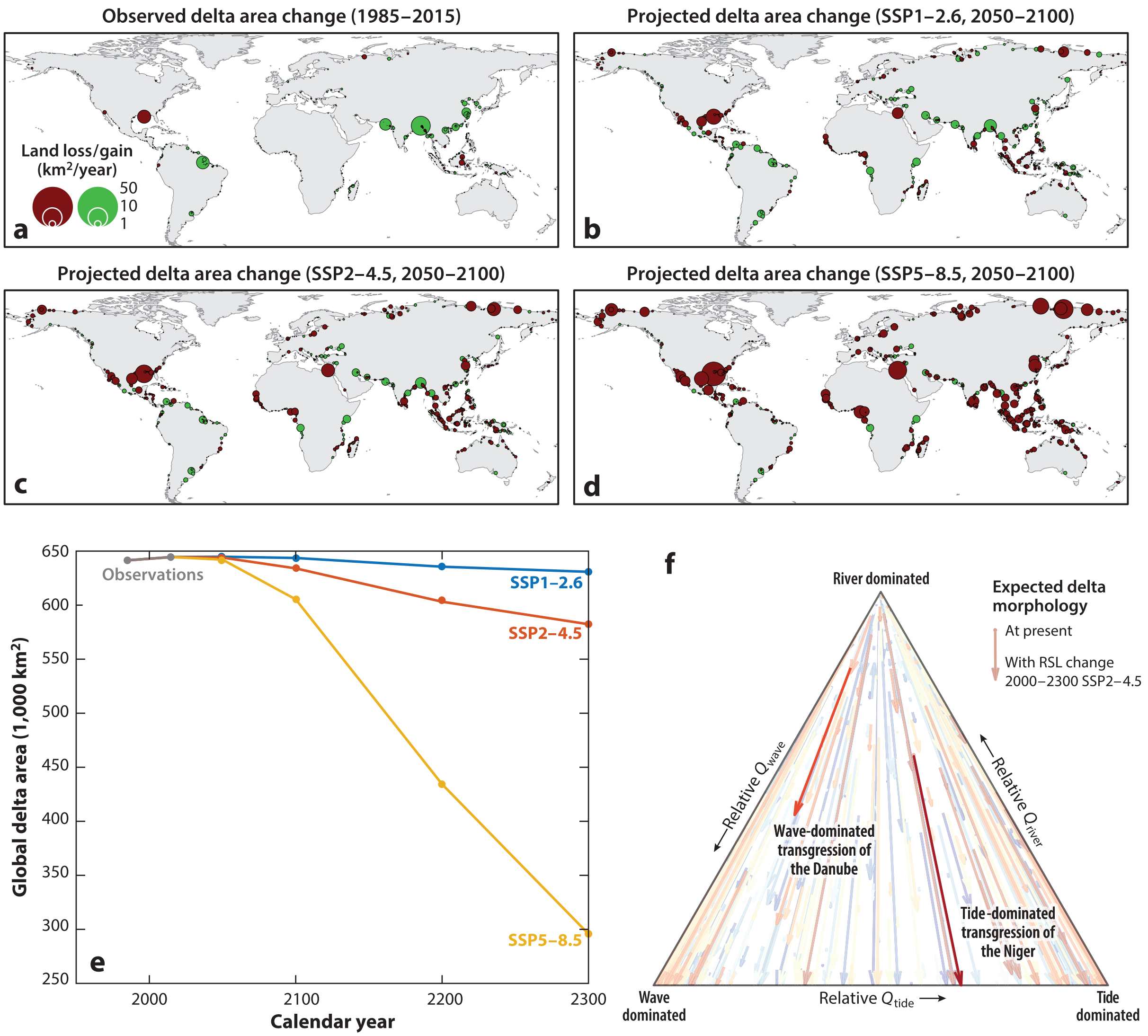

Figure 6

Delta land area change of 933 deltas larger than 10 km^2, showing (*a*) observations and (*b*,*c*,*d*) projections up to 2100 for three climate scenarios. (*e*) Time series of delta area change for 933 deltas, including observed growth from 1985 to 2015 and projected change up to 2300 for three climate scenarios. (*f*) Projected direction of morphologic change under RSL rise from 2000 to 2300 under SSP2–4.5, based on a ternary diagram for delta morphology, with transformation to the bottom left (e.g., Danube) and right (e.g., Niger) indicative of wave- and tide-dominated transgression, respectively (cf. **Figure 1**). Panels *a*–*d* and *f* adapted from Nienhuis & Van de Wal (2021). Abbreviations: RSL, relative sea level; SSP, Shared Socioeconomic Pathway.

375,000 km^2, or 50% of their surface area, by 2100 under a medium emissions scenario (Spencer et al. 2016). Beaches may erode up to 37,500 km^2 under the same scenario (Vousdoukas et al. 2020), although both projections are sensitive to the potential for landward creation of wetlands and beaches in response to RSL rise (Cooper et al. 2020). Timescales from models also remain uncertain. A stratigraphic study in the Mississippi Delta indicates that it may take about 50 years with RSL rise exceeding 6–9 mm/year before marshes drown (Törnqvist et al. 2020).

5.3. Effect of Relative Sea-Level Change on Delta Geomorphology

Beyond delta relative elevation change and land loss, other types of delta morphologic response to RSL change are also expected. River-level rise will accompany RSL rise and lead to increased delta flooding; an upstream migration of river delta avulsions, potentially with increasing avulsion frequency; and upstream conversion of nondeltaic land to deltaic floodplain (Li et al. 2022). An increasing proportion of fluvial sediments sequestered on delta plains will starve delta river mouths. Deltas will transform from a regressive state into a state of (forced) transgression (**Figure 1**), where sedimentation will move upstream and may become detached from the old delta front (**Figure 3**). From a global database of deltas and RSL rise rates (Nienhuis & Van de Wal 2021), it is projected that 85% of deltas larger than 10 km^2 will evolve into a state of forced transgression by 2300, assuming modern fluvial sediment supply and RSL change under SSP2–4.5 (**Figure 6**). Coastal rivers will transform to estuaries, and whether resulting estuaries will remain fully alluviated or become underfilled will depend on the fluvial sediment supply but also the marine sediment supply into the estuary (Boyd et al. 1992, Simms et al. 2006).

When deltas detach from the coast and migrate upriver, wave and tidal forces will rework abandoned delta deposits. For deltas where wave-driven sediment transport exceeds tide-driven sediment transport, strandplains and barrier islands may emerge, and protruding deltas may retreat and become bayhead deltas (Boyd et al. 1992) (**Figure 1**). If tidal fluxes dominate, deltas will transform into alluvial estuaries by tidal reworking of delta deposits. Which of these two transformations will dominate has been predicted using simple models (**Figure 6*f***). For the 791 deltas distributed globally that are expected to enter a state of forced transgression, 546 will be predominantly reworked by waves, and 245 will be predominantly reworked by tides (Nienhuis & Van de Wal 2021). When these transitions would occur is uncertain, and no observations exist (yet) to validate the model outcomes, so predictions should be interpreted with caution.

5.4. Human Response

RSL rise will pose major sustainability challenges for deltas but also for their inhabitants. It will increase delta flooding and the associated exposure and risk. Salinization will decrease the productivity of the delta's arable lands. Land loss will decrease the available habitable area, which might lead to conflict. Human short-term response might exacerbate long-term risks: Dams and dredging have led to decreases in sediment supply to many deltas, which will amplify the effects of RSL change (Dethier et al. 2022) and is expected to be the dominant cause of land loss in 1,487 deltas (Nienhuis & Van de Wal 2021).

From a broad perspective, delta populations will face three possibilities: (*a*) large-scale inland relocation (retreat), (*b*) construction and expansion of flood-protection infrastructure (protect), and (*c*) adoption of sedimentation-enhancing strategies to counteract RSL rise (mitigate).

RSL rise can cause large-scale relocation from deltas and subsequent loss of population, although observations are scarce and strongly influenced by broader regional or national trends. Currently, population growth on deltas is still higher than the global average, at 1.59% versus 1.11% per year (Edmonds et al. 2020). Thresholds for migration may appear when the costs of exposure to hazards exceed the benefits that coastal environments offer (Hauer et al. 2020). A broad coastal study for the European Union indicates that forced migration due to coastal land loss will be a major contributor to climate change damage toward the end of the century (Hinkel et al. 2010).

The construction of flood-protection infrastructure is a widely adopted alternative to relocation. Early levee building along the Nile River has offered protection against fluvial and coastal flooding and allowed deltas and delta societies to develop (Macklin & Lewin 2015). A synthesis of levees on 153 major deltas suggests that around 17% of the modern delta plain area is embanked, protecting 26% of its population (O'Dell et al. 2021). Levees in the Rhine-Meuse Delta are constructed to provide sufficient protection up to 1 m (and potentially 2 m) of RSL rise (van den Top 2019). However, levee design and protection levels vary greatly between deltas (Scussolini et al. 2016).

Despite short-term gains, flood-protection infrastructure can, counterintuitively, also increase future risks by preventing delta plain aggradation while also increasing subsidence rates through surface drainage (Middelkoop et al. 2010). The result is known as a lock-in. It occurs when there is increasing dependence on engineering, and it becomes impossible, or too expensive, to return to a natural state (Santos & Dekker 2020). A synthesis of 48 deltas by Santos & Dekker (2020) found that 46 percent are locked in.

In response to the challenges that traditional flood defenses bring, new approaches are sought to protect delta populations against the risks of RSL rise. Many of these approaches aim to restore natural delta hydrology and delta plain sedimentation—that is, utilize and enhance natural processes that lead to flood protection. A review of 21 sedimentation-enhancing strategies in deltas globally found that strategies range from river diversions, where sluice gates are built to mimic crevasse splay sedimentation, to salt marsh restoration that enhances vegetation-induced sedimentation (Cox et al. 2022). Many strategies outpace RSL rise, although it could be challenging to keep up sedimentation rates, which can be rapid initially but generally decrease over time. Collectively, these strategies comprise only 0.1% of the global delta area.

Increased RSL rise and increased delta development might promote and justify future delta sustainability (Moodie & Nittrouer 2021) despite the human need for stability (Passalacqua et al. 2021). We hope future delta studies will integrate the best available understanding of morphodynamic processes with increasingly site-specific RSL projections, alongside the socioeconomic impacts and responses of these densely populated landforms at the forefront of climate change.

FUTURE ISSUES

1. Stratigraphic models of delta change as a function of relative sea level (RSL) and sediment supply change are well established and validated, but a translation to provide modern delta projections remains challenging.
2. Possible time lags between modern RSL change and delta morphological adjustments such as autoretreat remain mostly unknown.
3. Global insights and observations of delta change during the Holocene should be exploited to further improve projections of future change.
4. It remains challenging to isolate the effect that RSL rise had on deltas over the past decades because of poor delta change observations and a multitude of other factors influencing delta change.
5. Despite recent advances, further improvements to digital elevation models of deltas are critical to rigorously model the impacts of RSL rise.
6. Rates and patterns of sediment retention on delta plains are uncertain but should be included in delta change projections.
7. Future projections of delta change should be based on Shared Socioeconomic Pathways and include feedbacks with delta management.

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IPCC AR6 data: **https://doi.org/10.5281/zenodo.5914709** and **https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool**. Sea-level change projections up to 2150.

Global Surface Water Explorer: **https://global-surface-water.appspot.com/#**. Observations of surface water dynamics from 1985 to 2021.

Global Delta Dataset: **https://github.com/jhnienhuis/GlobalDeltaChange** (**https://doi.org/10.5281/zenodo.7044706**). Observations and model projections from 1985 to 2300, including data to reproduce findings of this study.

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