

Glacial isostatic adjustment as a control on coastal processes: An example from the Siberian Arctic

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ABSTRACT

The geomorphology of the western Siberian Arctic coast represents a significant departure from the global trend of Holocene delta formation by major rivers. The Ob' and Yenisei Rivers in western Siberia drain into the Arctic Ocean via estuaries ~900 and ~500 km long, respectively. Eastern Siberian rivers such as the Lena, Indigirka, and Kolyma terminate at significant marine deltas. We show that this spatial variation in coastal geomorphology can be explained by the glacial isostatic adjustment of the region. The development and collapse of a peripheral bulge in western Siberia, associated with the glaciation and subsequent deglaciation of the Eurasian ice sheets, led to a distinct spatial variation in sea-level change that continues to this day. In particular, since the marked decrease in global-scale ice melting ca. 7 ka, our model predicts a sea-level rise at the mouth of the Ob' River of ~14 m, compared to a rise of ~6 m at the mouth of the Lena River, which ceased at 3 ka. We propose that the enhanced sea-level rise in the western Siberian Arctic associated with peripheral bulge subsidence has prevented the establishment of marine deltas at the mouths of the Ob' and Yenisei Rivers. We conclude that regional variations in relative sea-level change driven by glacial isostatic adjustment should be considered when interpreting large-scale coastal morphology and deltaic stratigraphy, which is normally assumed to correlate with eustatic fluctuations.

Keywords: relative sea level, glacial isostatic adjustment, delta, Arctic, Siberia.

INTRODUCTION

Many of the largest rivers on Earth end at marine deltas, built since 6.5–8.5 ka (Stanley and Warne, 1994) when a marked decrease in ice melting occurred at the end of the most recent global deglaciation. Notable exceptions include the Ob' and Yenisei Rivers in western Siberia (Fig. 1), which flow across the low-relief landscape of the West Siberian Basin into the Arctic Ocean via estuaries ~900 and 500 km long, respectively (Fig. 2A). Small bayhead deltas are confined to the heads of these gulfs, with areas of 4500 and 3200 km². Both rivers have discharge rates comparable to that of the Mississippi, with values of 404 and 620 km³/yr for the Ob' and Yenisei, respectively (Peterson et al., 2002). Their combined rate is equivalent to 3% of the global runoff.

Numerous smaller rivers in western Siberia also end in long estuaries rather than marine deltas at the Arctic coastline (Walker, 1998). However, this pattern is not typical of the entire Eurasian Arctic coastline. In eastern Siberia, the largest river is the Lena, which is on the scale of the Ob' and Yenisei (discharge: 530 km³/yr) but ends at the largest delta in the Arctic (Fig. 2B). The deltaic plain is ~32,000 km², although only the eastern half of this region has been active in the Holocene (Schwamborn et al., 2002). The active Lena delta has prograded 150–200 km in the second half of the Holocene (Are and Reimnitz, 2000). Other rivers in eastern Siberia also end at active marine deltas, including the Indigirka and Kolyma (Walker, 1998). The transition between the two types of drainage, with or without marine deltas, occurs roughly at longitude 115°E.

These differences in the terminations of eastern and western Siberian rivers are not explained by differential vertical tectonic motion or underlying bathymetry. The basement blocks of Siberia vary enormously in

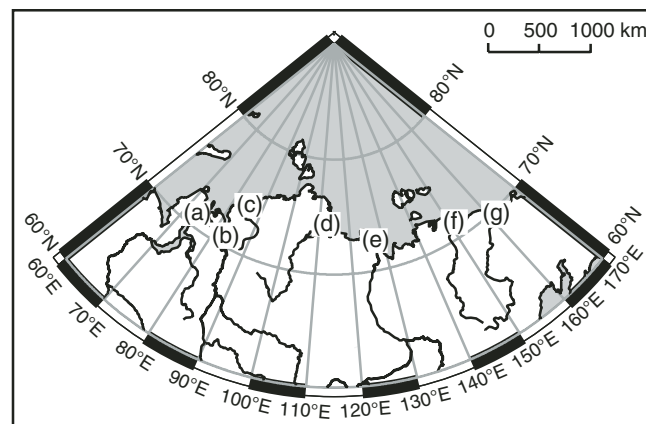


Figure 1. The Siberian Arctic coast. Letters are located at the mouths of the major Eurasian Arctic rivers. a—Ob'; b—Yenisei; c—Pyasina; d—Khatanga; e—Lena; f—Indigirka; g—Kolyma.

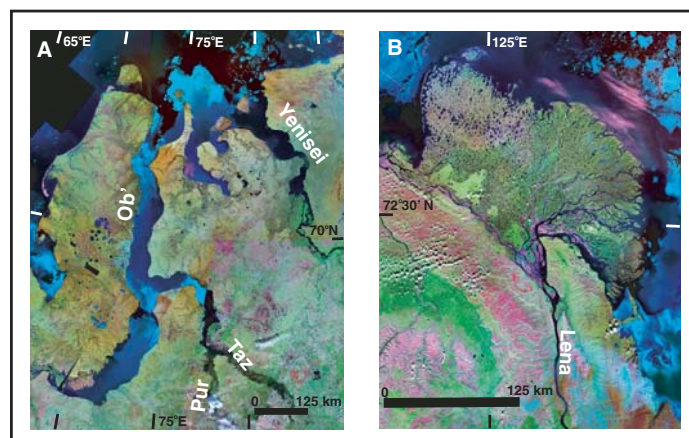


Figure 2. Contrasting geomorphology along the Siberian Arctic coastline. A: The estuaries of the Ob' and Yenisei Rivers. B: The Lena River delta. Both images are derived from multiresolution seamless image database (MrSID) mosaics of Landsat 7 satellite imagery, bands 2, 4, and 7 (source: <https://zulu.ssc.nasa.gov/mrsid>).

age and type but are not undergoing deformation that can be detected by global positioning system (GPS)-derived velocity fields or seismicity; Siberia forms “stable Eurasia” with respect to the India-Eurasia collision system to the south (Zhang et al., 2004; Bayasgalan et al., 2005). The northern Eurasian Arctic continental margin was created during the early Cenozoic rifting of the Eurasia Basin (Jokat et al., 1995). The Lena River enters the Arctic Ocean near the onshore continuation of the ultraslow Arctic mid-ocean ridge (Dick et al., 2003), but areas to its east and west are tectonically quiescent. At present, the mainland Eurasian coastline lies 200–1500 km from the continental margin. Paleovalleys, presumably associated with the Last Glacial Maximum (LGM), extend up to 200–300 km north of the modern Arctic shoreline in both eastern and western Siberia

(Bauch et al., 2001; Polyak et al., 2002). Thus there is no appreciable difference between the paleovalley systems of the major Siberian rivers that could have affected the presence or absence of present-day marine deltas. The Ob' estuary itself is not a pronounced topographic feature. South of 72.4°N, water depths across the ~50 km wide estuary are never greater than 10 m, and the adjacent topography is subdued, typically with a gradient of ~1 m/km, hence bathymetry is not the restricting factor that has prevented the Ob' from prograding to the Arctic coast.

The three largest rivers in Siberia have comparable sediment fluxes as well as discharge rates. Sediment yields are 16, 13, and 12 Mt/yr for the Ob', Yenisei, and Lena (Milliman and Syvitski, 1992). For comparison, the total load of all three rivers is roughly 10% of the value for the Mississippi. Therefore, it does not appear that sediment load governs the presence or absence of Eurasian Arctic marine deltas. No climatic or environmental factors have been identified that are significantly different between eastern and western Arctic Siberia—not enough to cause the presence or absence of coastal deltas.

An additional process that could account for the observed east-west variation in coastal morphology is the ongoing deformation of this region due to the relatively recent deglaciation of the Eurasian ice sheets. We modeled the glacial isostatic adjustment (GIA) of the Eurasian Arctic for the period following the LGM, and our results demonstrate that the predicted variations in Holocene relative sea level (RSL) can account for the observed differences.

There are two more general aspects to our results. First, significant (mm/yr) RSL variations occur hundreds of kilometers from ice sheet margins, and they persist for thousands of years after the peak in global meltwater influx toward the end of the most recent deglaciation (ca. 7 ka). Second, if spatial variations in GIA-induced RSL changes can override eustatic control on coastal sedimentation patterns, there are implications for high-resolution stratigraphic correlation throughout the Quaternary, or any pre-Quaternary glacial epoch.

METHODS

RSL is a measure of the change in ocean depth, due to changes in both the height of the land and the sea surface. We compute RSL changes for the last glacial cycle throughout the Eurasian Arctic in a gravitationally self-consistent fashion by solving the sea-level equation (Farrell and Clark, 1976). Furthermore, we solve a generalized version of this equation (Mitrovica and Milne, 2003; Kendall et al., 2005) in order to incorporate changes in shoreline geometry and the RSL signal associated with GIA-induced perturbations in Earth rotation (e.g., Milne, 2002). The isostatic effects of erosion/sedimentation are not accounted for in the calculations, nor are tectonic effects. Given the low erosion/sedimentation rates observed for the study region, and the lack of significant tectonic activity (see above), we believe that these omissions are not significant. We use a radially varying Earth model consisting of a Maxwell viscoelastic body, with elastic and density structure derived from seismic constraints (Dziewonski and Anderson, 1981).

We use an ice model that combines the Eurasian ice history from Lambeck et al. (1998) with a global ice model (with the Eurasian component removed) that was derived from the ICE-3G deglaciation history (Tushingham and Peltier, 1991) and tuned to fit far-field RSL data (Bassett et al., 2005; we adopt the optimum model from this study, which includes an Antarctic contribution of 15 m [eustatic equivalent] to meltwater pulse 1A). In the Eurasian component of this model, there is no ice over the Kara Sea east of Novaya Zemlya, consistent with the rebound analysis for Arctic Europe (Lambeck, 1995). The Eurasian component has been calibrated using an extensive regional sea-level data set (Lambeck et al., 1998) and is consistent with GPS observations of crustal motion in Fennoscandia (Milne et al., 2004). Furthermore, we have adjusted the global component of the ice model to account for the estimated ~3 m eustatic

increase in ocean volume during the period 7–3 ka (Lambeck, 2002). The Earth model used with this ice history comprises a 71 km elastic lithosphere, an upper mantle of viscosity 0.5×10^{21} Pa s, and a lower mantle of viscosity 10^{22} Pa s. This viscosity model is compatible with the Eurasian ice history we have adopted (Lambeck et al., 1998).

RESULTS

The rate of change of RSL is shown for 10 ka, 5 ka, and 0 ka in Figure 3. At 10 ka (Fig. 3A), rapid RSL rise is predicted at all locations outside the formerly glaciated regions. RSL change is dominated by the eustatic signal due to the melting of both Northern and Southern Hemi-

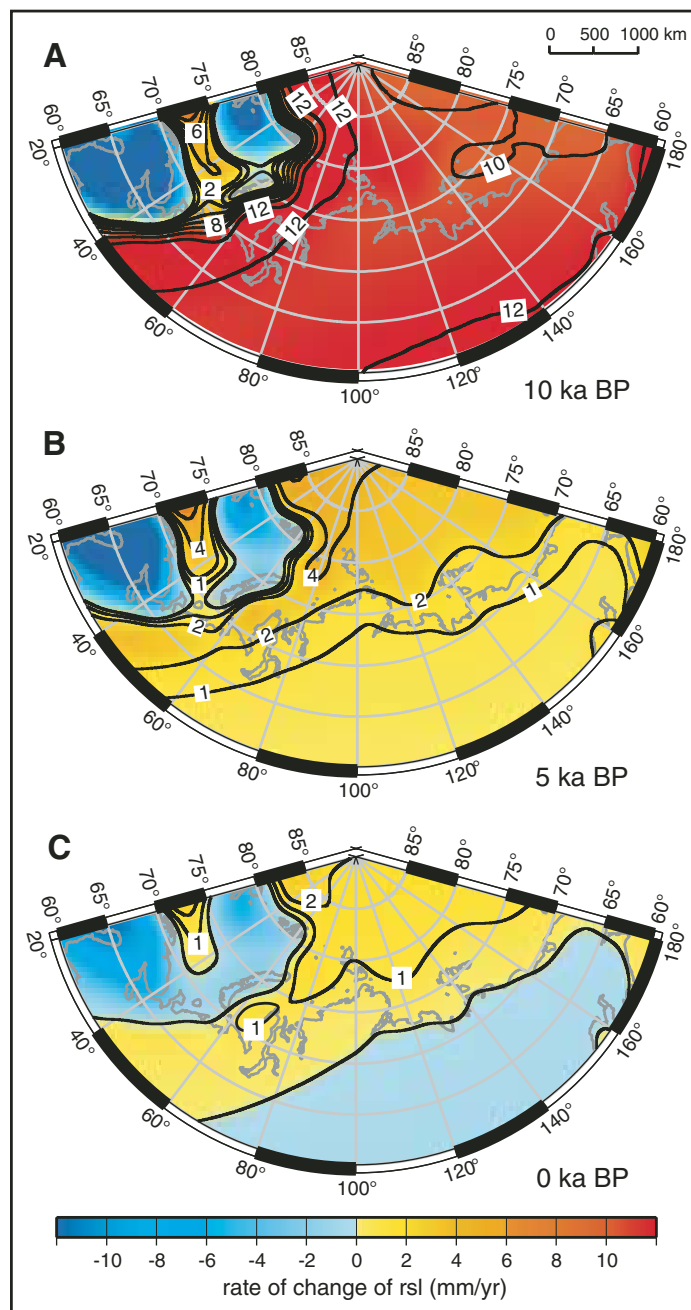


Figure 3. Rate of change of relative sea level (RSL) in mm/yr at 10 ka (A), 5 ka (B), and 0 ka (C). Positive contours are given every 2 mm/yr, with an additional contour at 1 mm/yr. Note that positive rates identify a sea-level rise, and vice versa.

sphere ice sheets during the early Holocene. Maximum rates of RSL rise are >12 mm/yr in an ~ 400 -km-wide zone surrounding the position of the former Eurasian ice sheet. At 5 ka (Fig. 3B), a sea-level rise of 2 mm/yr persists within this region of western Siberia, while a value closer to 1 mm/yr is predicted along much of the eastern Siberian coast (which reached its present-day configuration by ca. 5 ka). At the present day (Fig. 3C), this differential in rates of RSL change between eastern and western Siberia continues; the 0 mm/yr contour follows the eastern Siberian coast, implying a stable RSL, while positive rates of RSL change are predicted for western Siberia between 60°E and 110°E .

The continued rise in RSL across western Siberia is explained by a lowering of the land as opposed to a rise in the height of the sea surface. During the loading of Earth by an ice sheet, GIA models predict the development of a region of uplift peripheral to the ice margin (a so-called “peripheral bulge”; e.g., Peltier, 1974). A peripheral bulge is predicted to have formed adjacent to the area loaded by the Eurasian ice sheets. Following deglaciation, the isostatic adjustment of this bulge resulted in the subsidence of the land in this region. This process continues in the present day.

In order to study the time-dependent behavior of RSL in the Siberian Arctic (Fig. 1), RSL curves are plotted for seven major rivers (Fig. 4). Specifically, the seven sites are located at the mouths of the rivers where a marine delta would be expected to form given suitable conditions. At all sites, there is a marked decrease in the rate of RSL rise as global melting slowed down, ca. 7 ka. However, as indicated in Figure 3, there is a distinct increase in the rate of RSL rise since this time as one moves progressively west from the Lena delta. In particular, we note that at the mouths of the Ob’ and Yenisei Rivers, the total rise in RSL has been two to three times greater than that at the three eastern rivers (Lena, Indigirka, and Kolyma)

since the initiation of sedimentation in the Lena delta at 6–5 ka (Schwamborn et al., 2002). Furthermore, the model predictions show that RSL has been constant at the mouths of these three eastern rivers for the past 3 k.y., whereas RSL at the mouths of the Khatanga, Pyasina, Yenisei, and Ob’ Rivers has continued to rise by up to 3 m since this time.

The spatial trend in RSL change identified in Figures 3 and 4 has decreased over time and can be traced back to ca. 15 ka (see inset, Fig. 4) when the peripheral bulge is predicted to have reached its maximum height. (The bulge does not reach its maximum height at the LGM as a consequence of the delay in the viscous response of the solid Earth to mass changes in the ice sheets.) The difference between western and eastern Siberian curves progressively decreases from west to east, reflecting the decay in the height of the peripheral bulge in this direction.

The model predictions shown in Figure 4 are consistent with geomorphic and sedimentological evidence for late Holocene transgression in the western Siberian Arctic (Svendsen et al., 2004). There are fewer data for eastern Siberia, but our predicted rates of RSL change and resultant shoreline migration history are in agreement with a reconstruction of the marine transgression in this area based on cores from the Laptev Sea (Bauch et al., 2001). In addition, the study by Bauch et al. (2001) shows that sea level reached its present height by 6–4 ka, with no evidence for significant subsequent change, which is in agreement with our predictions.

DISCUSSION AND CONCLUSIONS

Deceleration of sea-level rise was the controlling factor on the global initiation of marine deltas at ca. 6.5–8.5 ka (Stanley and Warne, 1994). The Arctic rivers of western Siberia depart from this pattern, terminating in estuaries that are up to 900 km long. There are no regional tectonic effects or variations in fluvial sediment input that can account for this difference. Moreover, eastern Siberian rivers typically end in marine deltas, in keeping with global patterns in the Holocene. Our modeling of the spatial variation in RSL over time provides a viable explanation: that the positive RSL change in western Siberia during the middle to late Holocene has prevented the establishment of marine deltas in this region. The underlying cause is GIA. The isostatic signal related to the development and collapse of a peripheral bulge in western Siberia, associated with the glaciation and subsequent deglaciation of the Eurasian ice sheet, perturbs the RSL history of western Siberia. The eustatic meltwater signal dominates the Siberian RSL curves from the LGM until 7 ka. As global melting slows, RSL change becomes negligible in eastern Siberia, whereas isostatic effects dominate the RSL signal in western Siberia, thus prolonging the situation of RSL rise in this region.

Within the Siberian Arctic, the modeled rate of change of RSL decays eastward along the coast, in keeping with the presence of marine deltas east of $\sim 115^\circ\text{E}$. The influence of the isostatic RSL signal on coastal geomorphology therefore extends 500–1000 km east of the LGM boundary of the Eurasian ice sheet. At present, it is difficult to place a tighter constraint upon this range; the inclusion of lateral Earth structure would perturb the RSL signal (e.g., Kendall et al., 2006), and there are uncertainties in the extent of the ice sheet. However, even with these uncertainties our modeling demonstrates the potential for regional GIA effects to influence coastal deposition over millions of square kilometers, on the time scale of a glacial cycle.

The RSL differences between eastern and western Siberia are equivalent to differences in accommodation space creation on the order of 1 mm/yr. This is the scale of rate modeled to have significant impacts on deltaic and coastal morphology (Ritchie et al., 2004).

The global relationships between GIA-induced RSL changes and coastal geomorphology are ripe for further study, not least because they bear on some of the most important population centers and food-producing areas on Earth. For example, peripheral bulge subsidence associated with the melting of the Laurentide ice sheet is predicted to occur as far south as northernmost South America (Milne et al., 2005), implying that the sub-

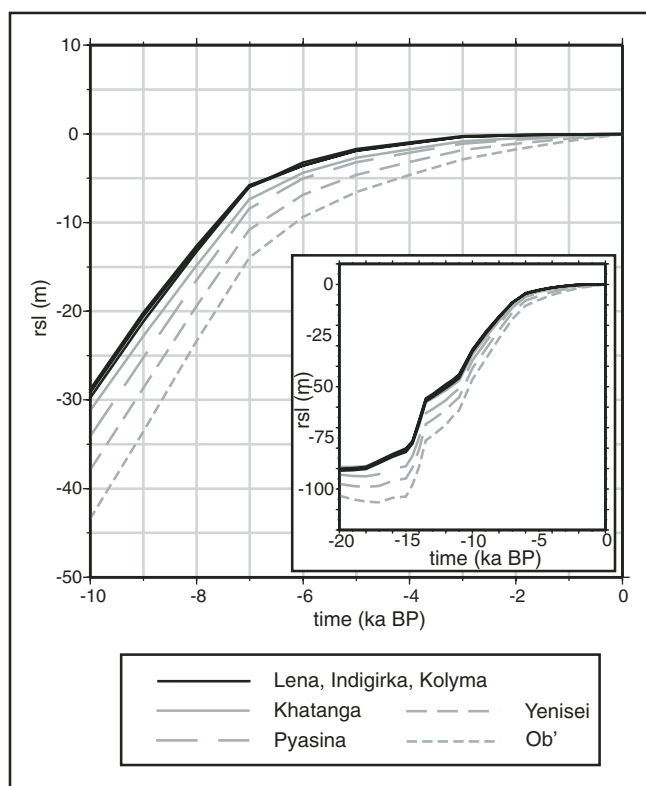


Figure 4. Relative sea level (RSL) between 10 ka and the present for sites at the mouth of seven major Siberian rivers (see Fig. 1 for locations). Inset: Relative sea-level curves for the same sites between 20 ka and the present.

sidence and wetland loss of the Mississippi delta may be influenced by GIA-driven changes in RSL. However, there remains considerable debate on this issue (e.g., Törnqvist et al., 2006; Sella et al., 2007). Furthermore, our results have clear implications for sequence stratigraphy: Higher-order deltaic depositional cycles, which might be expected to correlate with eustatic fluctuations, may be diachronous between different localities, depending on position with respect to former and contemporary ice sheets.

In summary, we find that perturbations to RSL change associated with GIA dominate variations in sea-level change across the Siberian Arctic. We propose that the contribution of peripheral bulge subsidence to the predicted sea-level rise in western Siberia during the middle to late Holocene has been a principal control on regional coastal morphology and has prevented the evolution of large marine deltas in the last 7 k.y., in contrast to the global trend.

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