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Spatial variability of sea level rise due to water impoundment behind dams

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[1] Dams have impounded ~10,800 km^3 of water since 1900, reducing global sea level by ~30.0 mm and decreasing the rate of sea level rise. The load from impounded water depresses the earth's surface near dams and elevates the geoid, which locally increases relative sea level (RSL). We computed patterns of dam-induced RSL change globally, and estimated that tide gauges, which are often close to dams, recorded only ~60% of the global average sea level drop due to reservoir building. Thus, RSL in the globally averaged ocean rose ~0.2 mm/yr more slowly than has been recorded by tide gauges, or ~10% slower than the measured rise rate of 1.5–2.0 mm/yr. Relative proximity to dams caused RSL to rise fastest in northeastern North America and slowest in the Pacific. This dam-induced spatial variability may mask the sea level "fingerprint" of melting sources, especially northern (Greenland) sources of glacial unloading.
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1. Introduction

[2] During the past century, average global sea level has risen 1.5–2 mm per year [*Douglas*, 1991; *Church and White*, 2006]. This rate may be currently accelerating due to an increased influence of climate change on sea level rise sources, which include thermal expansion of seawater and the melting of glaciers and ice sheets [*Douglas*, 1992; *Nerem et al.*, 2006]. Globally, sea level rise is not uniform but instead exhibits spatial variability that can be attributed to climatic variations, including wind patterns (such as El Niño), temperature variations, and freshwater-saltwater balance near melting glaciers [*Cazenave et al.*, 2003]. Spatial variations may also be attributed to geodynamic causes, including the Earth's elastic response to the redistribution of water mass on the Earth's surface [e.g., *Conrad and Hager*, 1997; *Mitrovica et al.*, 2001; *Tamisiea et al.*, 2001]. Because sea level rise significantly impacts coastal communities [*Pilkey and Cooper*, 2004], constraints on the patterns and causes of the spatial variability of sea level rise are essential for the mitigation of, and adaptation to, climate change.

[3] Recent work by *Chao et al.* [2008] suggests that ~10,800 km^3 of water has been impounded behind dams since 1900, leading to an equivalent sea level drop of ~30 mm. This transfer of water from oceans to continents emplaces water mass loads at the locations of continental reservoirs. These continental loads locally depress the Earth's surface and gravitationally attract seawater, thus elevating the sea surface. The accompanying unloading of water mass from the ocean basins should also induce oppositely-directed deflections of the solid Earth and ocean surfaces, but in a more geographically distributed pattern [e.g., *Farrell and Clark*, 1976; *Clark and Lingle*, 1977; *Conrad and Hager*, 1997; *Mitrovica et al.*, 2001; *Tamisiea et al.*, 2001]. Together, these perturbations result in a spatially-varying pattern of sea level change resulting from continental water storage. This sea level "fingerprint" should become exaggerated at coastlines nearest the largest dams, and will be detailed in this study.

[4] Globally, dam building was most prolific from 1950–1990 [*Chao et al.*, 2008] (Figure 1a). Global mean sea level (GMSL) for this time period is constrained primarily by tide gauges, which measure sea level relative to the solid Earth surface. Because both the sea surface and the solid earth surface are deflected by water impoundment, the pattern of these deflections should be recorded in the tide gauge records. Unlike mass movements associated with melting glaciers and ice sheets, the time-history of water impoundment by dams is constrained by historical records [*Vorosmarty et al.*, 1997; *International Commission on Large Dams* (*ICOLD*), 2007]. Thus, Earth's elastic response to these loads can be calculated directly. The resulting prediction of spatially-varying sea level change caused by dams and reservoirs may then be used to correct tide gauge records and estimates of GMSL change during the past century. Because these corrections affect constraints on sea level variability, they may also affect interpretations of the tide gauge data in terms of the "fingerprint" associated with various causes of recent sea level rise [*Mitrovica et al.*, 2001; *Tamisiea et al.*, 2001].

2. Computing the Elastic Earth Response

[5] To compute the deflections of the solid earth and sea surfaces that result from water impoundment by dams, we used the same method as that of *Conrad and Hager* [1997]. In doing so, we convolved dam loads with Green's functions for vertical displacement and gravitational potential. These Green's functions are based on those defined by *Farrell* [1972], but include degree one terms that utilize a reference frame based on the center of mass of the Earth-load system [*Conrad and Hager*, 1997]. After similarly applying negative loads consistent with removal of water from the oceans, we then interpolated radial displacement and gravitational potential from the load points over an ocean grid with a resolution of 0.5 degrees. These displacements effectively redistribute mass within the ocean, creating new loading and unloading points that we then applied. We repeated the process for 5 iterations, until the solution converged to within a few

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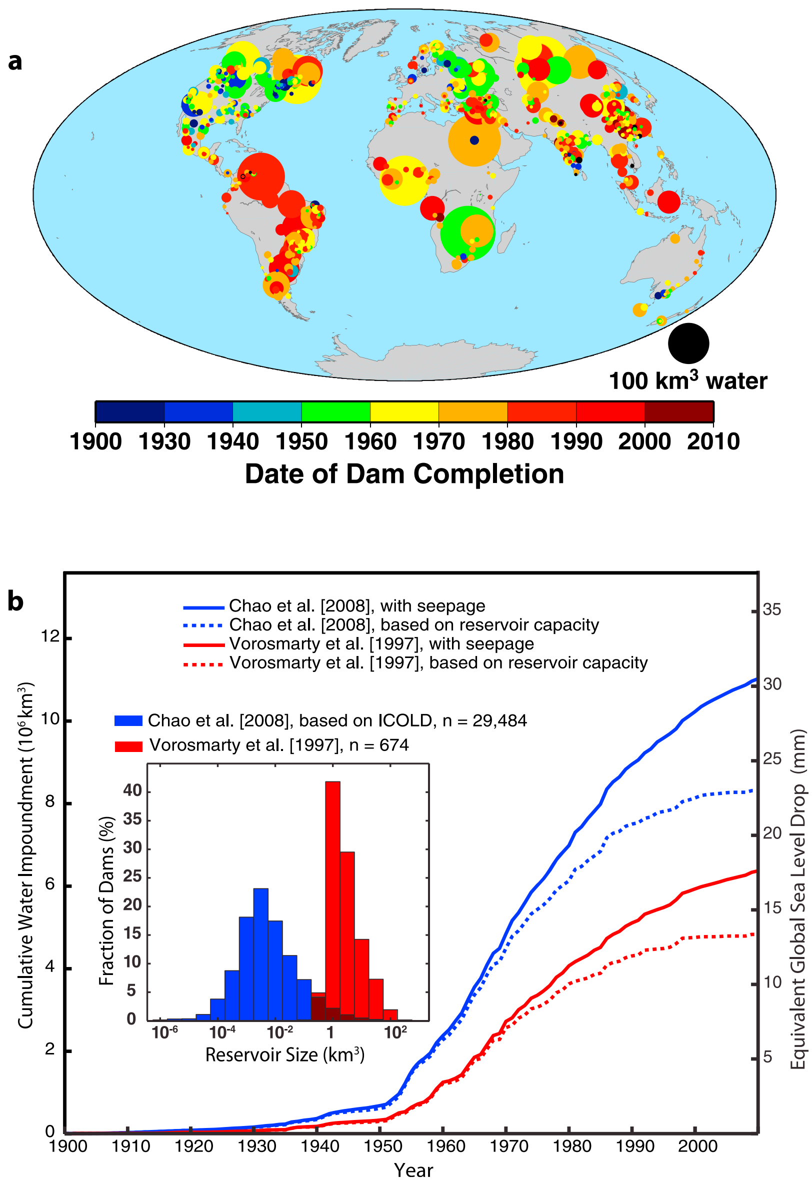

Figure 1. Total impounded water as a function of year. The majority of dam building occurs in the years from 1950–1990. (a) Locations, date of completion, and relative sizes of the largest reservoirs (based on the work by *Vorosmarty et al.* [1997]), which are used in this paper's calculations. (b) The total water impounded by *Vorosmarty et al.*'s [1997] dams (expressed in km^3 and equivalent global sea level drop) and by *Chao et al.*'s [2008] dams, which include smaller reservoirs. Solid lines represent the total expected impoundment for each data set, which accounts for groundwater seepage and less than maximum reservoir capacity. The inset shows the relative distribution of reservoir sizes in each data set.

tenths of a percent. Although a pseudospectral solution to the sea level equation [e.g., *Milne et al.*, 1999] is computationally more efficient, the Green's functions approach used here is simpler to implement because it does not require transformation to the spectral domain. Because we can ignore the Earth's viscous response for the ~100 yr timescales considered here, both methods should yield the same solution.

[6] Additional terms in the sea level equation were considered but not implemented, including a time-varying shoreline and perturbations of the Earth's rotation vector. Shoreline inundation only becomes important for large water volume displacements. For example, assuming an exceptionally flat average shoreline slope of 1/2000 (the average value for North Carolina [*Pilkey and Cooper*, 2004]), the ~356,000 km of global shoreline would be inundated by only 0.6 km^3 of water, which is >10^4 smaller than the total impounded water volume, and thus insignificant. Sea level change induced by rotation perturbations [*Milne and Mitrovica*, 2005] scales with the off-diagonal terms of the moment of inertia tensor of the surface mass load [*Mitrovica et al.*, 2005]. We computed these terms for the dam loads, and found their magnitude to be ~44% of those associated with melting of the West Antarctic Ice Sheet (WAIS) because they are more globally distributed. Since rotational perturbations associated with WAIS unloading induce sea level deviations with maximum amplitudes ~15% of eustatic change [*Gomez et al.*, 2010], we estimate the corresponding maximum deviations for dam loading to be ~2 mm, or

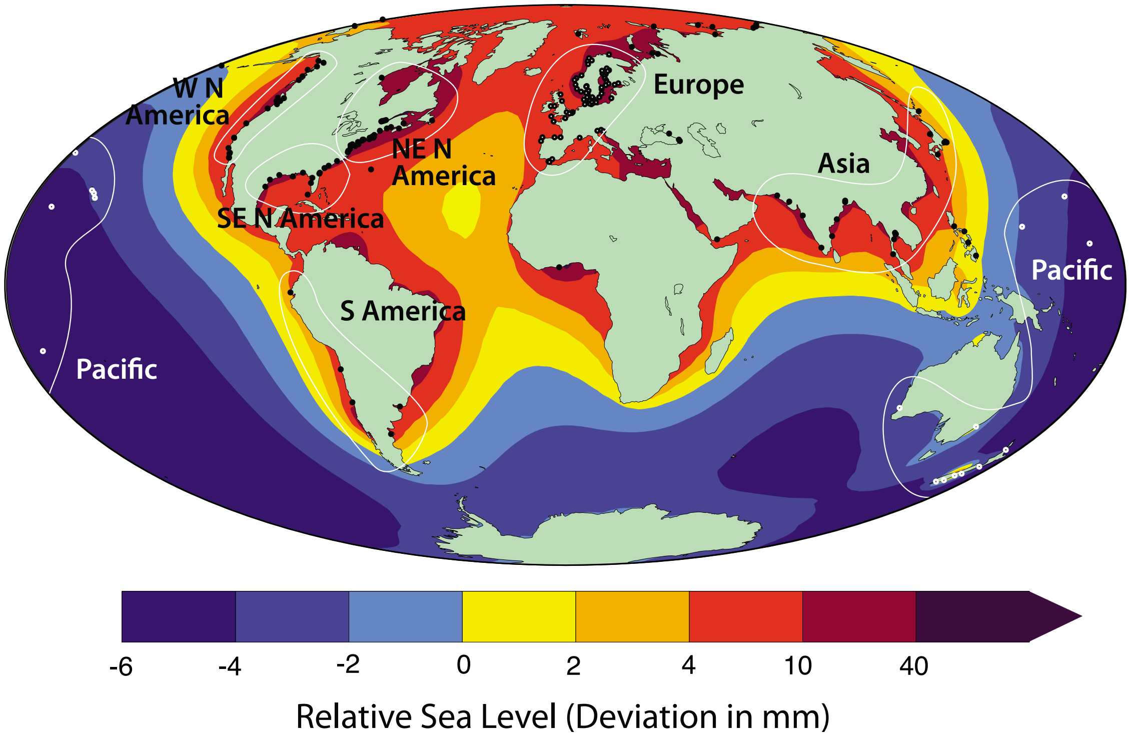

Figure 2. Spatial variations in relative sea level due to water impoundment behind dams, as well as tide gauge locations (black and white dots). Note that although reservoir building causes sea level to decrease globally by 30 mm [*Chao et al.*, 2008], we remove this static sea level drop so that deviations from global trends are more apparent. Thus, the average relative sea level change shown here is zero.

6.6% of the 30 mm eustatic change. Furthermore, the average deviation over the Earth's surface is only ~0.4 mm, and therefore significantly smaller than deviations associated with uncertainty in the dam loads, described below.

[7] We obtained reservoir data from *Vorosmarty et al.* [1997] for volumes and locations of impounded water (Figure 1a), and added six additional post-1997 dams from *Chao et al.* [2008] (specifically, the Three Gorges, Longtan, Luoyang, and Longyangxia dams in China; the Pati dam in Argentina; and the Balambano dam in Indonesia). Although the reservoir data from *Chao et al.* [2008] is more complete (29,484 named reservoirs obtained from *ICOLD* [2007] and other sources), we used *Vorosmarty et al.*'s [1997] smaller data set because, unlike *Chao et al.*'s [2008] data, it includes latitude and longitude locations of reservoirs. In total, we used 674 of the world's largest reservoirs, comprising a net load of ~4,834 km^3 of water, equating to ~13 mm of sea level drop. Employing the same method as that of *Chao et al.* [2008] to include the effect of groundwater seepage and less than maximal reservoir capacity, these 674 reservoirs sum to ~6300 km^3 of water, or ~17 mm of sea level drop (Figure 1b). This is roughly 57% of the ~30 mm sea level drop associated with the complete *Chao et al.* [2008] dam dataset.

[8] Although *Vorosmarty et al.*'s [1997] dataset is just over 2% of the size of *Chao et al.*'s [2008] set, it represents only the largest dams (Figure 1b, inset), and over half the estimated volume of water impounded during the 20th century. By assuming that the spatial distribution of water in smaller dams and associated seepage is similar to the spatial distribution of loads from the largest reservoirs, we calculated Earth's elastic response to all dams by computing the response to *Vorosmarty et al.*'s [1997] loads, and applied a simple linear scaling. This scaling is simply the ratio of the *Chao et al.* [2008] water volumes to those of *Vorosmarty et al.*'s [1997] dataset (Figure 1b).

[9] Magnitudes of radial displacement and gravitational potential decrease rapidly with distance from the load [*Farrell*, 1972]. Consequently, using a single location to express a reservoir's load exaggerates deflections very near that location and disregards the lateral span of the reservoir. To simulate loading from a large reservoir instead of a single point, we distributed each reservoir's capacity load within a circle of 20 km radius centered on the dam location (but did not apply loads in oceanic areas for dams located near coastlines). Although this approximation does not utilize information regarding the shape of the flooded area [*Boy and Chao*, 2002], it does prevent load-proximal singularities in our calculations associated with concentrated point loads. Differences in simulated reservoir area have a minimal effect on predicted relative sea level variability (e.g., differs by <0.05 mm for 10 km radii).

3. Sea Level Response to Water Impoundment

[10] The impoundment of water behind dams places new mass loads at the dam locations, which are largely in the northern hemisphere, and removes seawater from the ocean basins, which are positioned, on average, in the southern hemisphere. In response to this load redistribution, the solid earth becomes depressed in the vicinity of impounded water, and moves toward the South Pacific to maintain the center of mass of the Earth-load system. Absolute sea level (ASL),

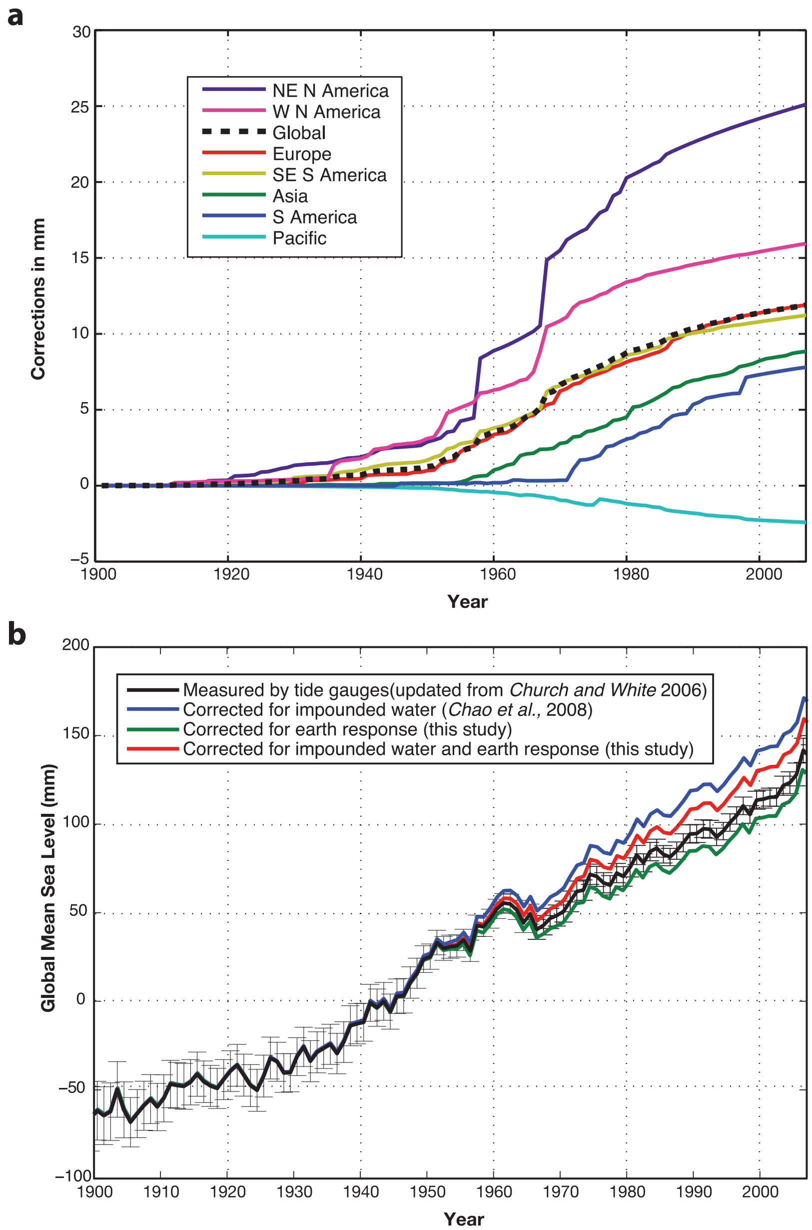

Figure 3. Effect of Earth's response to dam loading on tide gauge measurements, as a function of calendar year. Shown are (a) dam-loading corrections for individual regions with long-running tide gauges (regional groupings are denoted with white circles in Figure 2), assuming impoundment of 30.0 mm of equivalent sea level drop [*Chao et al.*, 2008], and (b) global average corrections applied to *Church and White*'s [2006] sea level curve for the past century (black line), which was constrained by tide gauge measurements. Correcting *Church and White*'s [2006] curve (black line) for water impoundment only (blue line) increases the estimated rate of sea level rise from remaining sources by about 0.55 mm/yr [*Chao et al.*, 2008]. However, dam loading causes additional sea level rise near dam loading locations, which are often near coastlines. By correcting both *Chao et al.*'s [2008] impoundment-corrected curve (blue line) and *Church and White*'s [2006] measured RSL curve (black line) using our estimate of the average RSL response at tide gauge locations (black dashed line, part a), we estimate that both curves should be diminished by about 0.2 mm/yr during the dam-building period when applied to the average global ocean (red and green lines, respectively).

which is the sea surface in the center of mass frame, (e.g., as observed by satellites such as TOPEX/Poseidon and Jason-1 and -2 [*Nerem et al.*, 2006]) drops everywhere due to reservoir water removal, but the amplitude of drop varies spatially. Seawater is gravitationally drawn toward continental loads and is generally removed from nearby basins. This causes the sea surface to become elevated near dam-proximal shorelines and relatively depressed in the middle of ocean basins that are surrounded by dam loads (e.g., North Pacific, Indian, Arctic, and (especially) Atlantic basins). Relative sea level (RSL) change, which has been measured by tide gauges during the past century of dam building, is the difference between ASL change and solid earth surface displacement.

[11] The transfer of seawater from oceans to continental reservoirs causes global RSL drop [*Chao et al.*, 2008], but the spatial variability of this drop (Figure 2) is large. In order to make this variability more apparent, we remove the static sea level drop (30 mm), and denote the resulting variations as deviations in mm. Because most large dams are located on the northern continents, as well as Africa and South America, the solid earth near these continents drops, causing a positive deviation of RSL. By contrast, the southern hemisphere and the Pacific, which are generally far from dam loads, experience a negative average RSL deviation because the solid Earth moves away from the northern dam loads and toward the South Pacific sea surface. Positive sea level deviations become highly exaggerated at coastlines nearest the largest dams, particularly in northeast North America (Daniel Johnson Dam) and Ghana (Akosombo), where deviations actually exceed 30 mm indicating an *increase* in RSL due to dam building. These two dams impound water for the 4th and 5th largest reservoirs in the world, respectively, and are located relatively close to coastlines. Thus, they create large local vertical subsidence while gravitationally attracting ocean water; the result is increased dam-proximal RSL.

[12] In order to determine the effect of dam loads on recent estimates of GMSL, we selected the 204 tide gauges with records longer than 50 years from the *Permanent Service for Mean Sea Level* [2009] database (dots in Figure 2). Our selected tide gauges have a relatively similar spatial distribution to the long-duration gauges used to estimate trends in past global and regional sea level rise [*Church and White*, 2006]. The average dam-induced deviation of RSL for these 204 tide gauges is positive (elevating sea level) and roughly 12.0 mm, or ~40% of the magnitude of global average sea level drop. This is because most tide gauges are located on continental coastlines and therefore closer to dam loads than most ocean locations. Thus, the local subsidence and elevated sea level near dams prevents tide gauges from experiencing the entire sea level drop associated with continental water storage. The average RSL deviation for European tide gauges is also ~40%, whereas the northeastern North American tide gauges show average deviations of ~25.4 mm, or ~85% of the magnitude of the average drop, due to the high number of continental reservoirs near tide gauges in this area. This implies that the northeastern coastline of North America largely missed the 30 mm RSL drop experienced elsewhere in the global oceans because of the past century of dam building. In contrast, Australia, New Zealand, Hawaii, and other Pacific locations show deviations of −2.5 mm, or ~8% *more* RSL drop than the global average because they are far removed from locations of dam loading (Figure 3a).

[13] Unfortunately, detecting specific dam loading events using individual tide gauge records is difficult in practice because of fluctuations and interruptions of the tide gauge data on sub-decadal time scales. Water impoundment by a large dam near a coastline should produce a sea level increase over a period of years as the reservoir fills. We expect such an increase for the St. Lawrence River in Canada (Daniel Johnson dam, 141.9 km^3, completed in 1968) and near Accra, Ghana (Akosombo Dam, 148 km^3, completed in 1965). We estimate that these two dams should have separately induced over their lifetimes up to ~18 mm of RSL rise along the St. Lawrence River and ~22 mm of RSL rise along the Ghanaian coastline. Unfortunately, tide gauge data in these locations (Baie Comeau, Rivière-du-Loup, Ste-Anne-des-Monts, Pointe-au-Père, and Tadoussac gauges on the St. Lawrence and Tema and Takoradi gauges near Accra) are not continuous over a long enough period of time or are too fragmented to detect sea level changes of this magnitude.

4. Conclusions

[14] Climate-change induced sea level rise has been partially mitigated during the past century by the impoundment of water on land, which decreases the apparent rate of relative sea level rise globally [*Chao et al.*, 2008]. Considering only the volume of water associated with the building of continental reservoirs, *Chao et al.* [2008] estimated that sea level dropped 0.55 mm yr^{-1} due to dam building during the past half century. Adding this water back to the oceans would indicate a nearly constant background rise rate of ~2.5 mm/yr during this time period (Figure 3b, blue line). On most coastlines, however, this protection from sea level rise is partially diminished because continental water storage depresses the Earth's surface and gravitationally attracts seawater, inducing relative sea level rise. Our results show that the average long-running tide gauge would record only ~60% of the average global sea level drop associated with the past century of reservoir development, or about 0.35 mm yr^{-1}. Thus, tide gauges, and shorelines on all continents, recorded a rate of RSL rise (Figure 3b, solid black line) that is ~0.2 mm yr^{-1} faster than the ocean average during the dam building period (Figure 3b, green line). After accounting for the correction for both water impoundment and the associated spatial variations in rise rates, we estimate a background rise rate of ~2.3 mm/yr (Figure 3b, red line), which is ~20% faster than direct estimates from tide gauges (Figure 3b, black line) [*Douglas*, 1991; *Church and White*, 2006], and 10% slower than *Chao et al.*'s [2008] estimate that includes impoundment but not spatial variations (Figure 3b, blue line). These estimates, of course, depend on our assumption that smaller dams [*Chao et al.*, 2008] are distributed similarly in space and time as the large dams on which our calculations are based. Future constraints on the volumes and locations of artificial reservoirs may influence estimates of sea level variability and associated corrections to tide gauge records.

[15] Spatial variations in rates of relative SLR caused by the solid earth's response to dam building may hold important significance for coastal communities. The ~0.2 mm/yr average coastal enhancement cannot be expected to continue, however, now that dam constructions rates have diminished. Thus, future predictions of sea level in coastal areas based on past observations may benefit by accounting for the influence of past dam loading on local sea level.

[16] Tide gauge records are not currently corrected for non-uniform rise rates associated with water impoundment on land, as they are for other processes that affect sea level observations such as postglacial rebound [*Church et al.*, 2004; *Douglas*, 2008]. Such corrections would remove variations ranging from ~0.47 mm/yr of additional RSL rise for northeastern North America to ~0.04 mm/yr of extra RSL drop for the Pacific. These corrections to tide gauge data should affect estimates of the 20th century sources of sea level rise [e.g., *Miller and Douglas*, 2004], as well as estimates of the sea level "fingerprint" of glacial and ice sheet melting [e.g., *Douglas*, 2008]. Northern sources, such as Greenland, diminish relative sea level rise in northern hemisphere, whereas southern sources, such as Antarctica, achieve

the opposite effect [*Conrad and Hager*, 1997; *Mitrovica et al.*, 2001]. Correcting tide gauge data for dam loading would increase southern hemisphere tide gauge measurements and decrease those from NE North America and Europe. These changes are consistent with a larger than previously estimated contribution from a northern source of glacial unloading, such as Greenland.

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