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Key Points:
- Groundwater depletion elevates average sea level but also deforms the solid Earth and sea surfaces, causing spatial variations in sea level
- Models predict depressed sea level in western North America and southern Asia, where groundwater loss is most significant
- Groundwater depletion has slowed sea level rise in California and India by ~0.4 mm/yr since 1930, consistent with tide gauge observations

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The impact of groundwater depletion on spatial variations in sea level change during the past century

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Abstract Continental groundwater loss during the past century has elevated sea level by up to ~25 mm. The mass unloading associated with this depletion locally uplifts Earth's solid surface and depresses the geoid, leading to slower relative sea level rise near areas of significant groundwater loss. We computed spatial variations in sea level using a model of the solid Earth's response to estimates of groundwater depletion during the past century and find large negative deviations of ~0.4 mm/yr along the coastlines of western North America and southern Asia. This approximately corresponds to the difference between rates of sea level rise measured by tide gauges in these regions since 1930 and average rates inferred from global reconstructions. Groundwater-induced regional variations in sea level can be larger than those due to postglacial rebound and interseismic deformation and should become increasingly important in the future as both groundwater depletion and sea level rise accelerate.

1. Introduction

Sea level rise will likely be one of the most important environmental problems of our century [e.g., *Church et al*., 2013] and can be better understood given knowledge of past patterns and sources of sea level change. Since the 1930s, tide gauge constraints suggest that global mean sea level (GMSL) rose by an average of ~1.8 ± 0.3 mm/yr [*Church and White*, 2011], with slower twentieth century rates accelerating significantly during the last two decades [*Cazenave and Llovel*, 2009]. Recent and future sea level rise is primarily associated with global climatic warming via melting of glaciers and ice sheets and thermal expansion of seawater [*Cazenave and Nerem*, 2004; *Church et al*., 2013]. Terrestrial hydrological changes also contribute to the global sea level budget [*Sahagian*, 2000]. For example, *Chao et al*. [2008] showed that dam building during the last half of the twentieth century likely decreased sea level by ~30 mm. An opposite behavior may be expected from continental groundwater depletion [*Huntington*, 2008], which is estimated to have raised sea level ~0.4–0.6 mm/yr recently [*Konikow*, 2011; *Wada et al*., 2012].

Any redistribution of mass on Earth's surface instantaneously creates spatial variations in sea level associated with both elastic deformation of Earth's solid surface and perturbations to the gravitational equipotential surface that defines sea level [e.g., *Conrad and Hager*, 1997; *Farrell and Clark*, 1976; *Mitrovica et al*., 2001; *Tamisiea et al*., 2001]. Together, these deflections tend to cause slower relative sea level rise near areas of continental mass loss. Such regional variations have been estimated to be as large as few mm/yr due to recent melting of glaciers and ice sheets [e.g., *Conrad*, 2013; *Stammer et al*., 2013]. Spatial variations in sea level should also result from the transfer of groundwater to the oceans and have been estimated for the past few decades based on global hydrological models and observations [*Jensen et al*., 2013] and for longer timescales in conjunction with other hydrological mass transfers [*Slangen et al*., 2014]. However, the particular impact of groundwater depletion on the past century of sea level change has not been evaluated. Here we quantify the regional and temporal patterns of sea level change associated particularly with groundwater depletion during the past ~80 years and evaluate their impact on the tide gauge record of sea level change during this period. These estimates can be used to correct tide gauge records of sea level change near areas of significant groundwater depletion and could help to characterize changes in GMSL during the past century.

2. Sea Level Variations Due To Past Groundwater Depletion

To estimate spatial variations in sea level rise associated with groundwater depletion, we need constraints on the temporal and spatial patterns of depletion during the past century. Since 2003 the Gravity Recovery and Climate Experiment (GRACE) satellites have provided constraints on terrestrial water storage variations with a

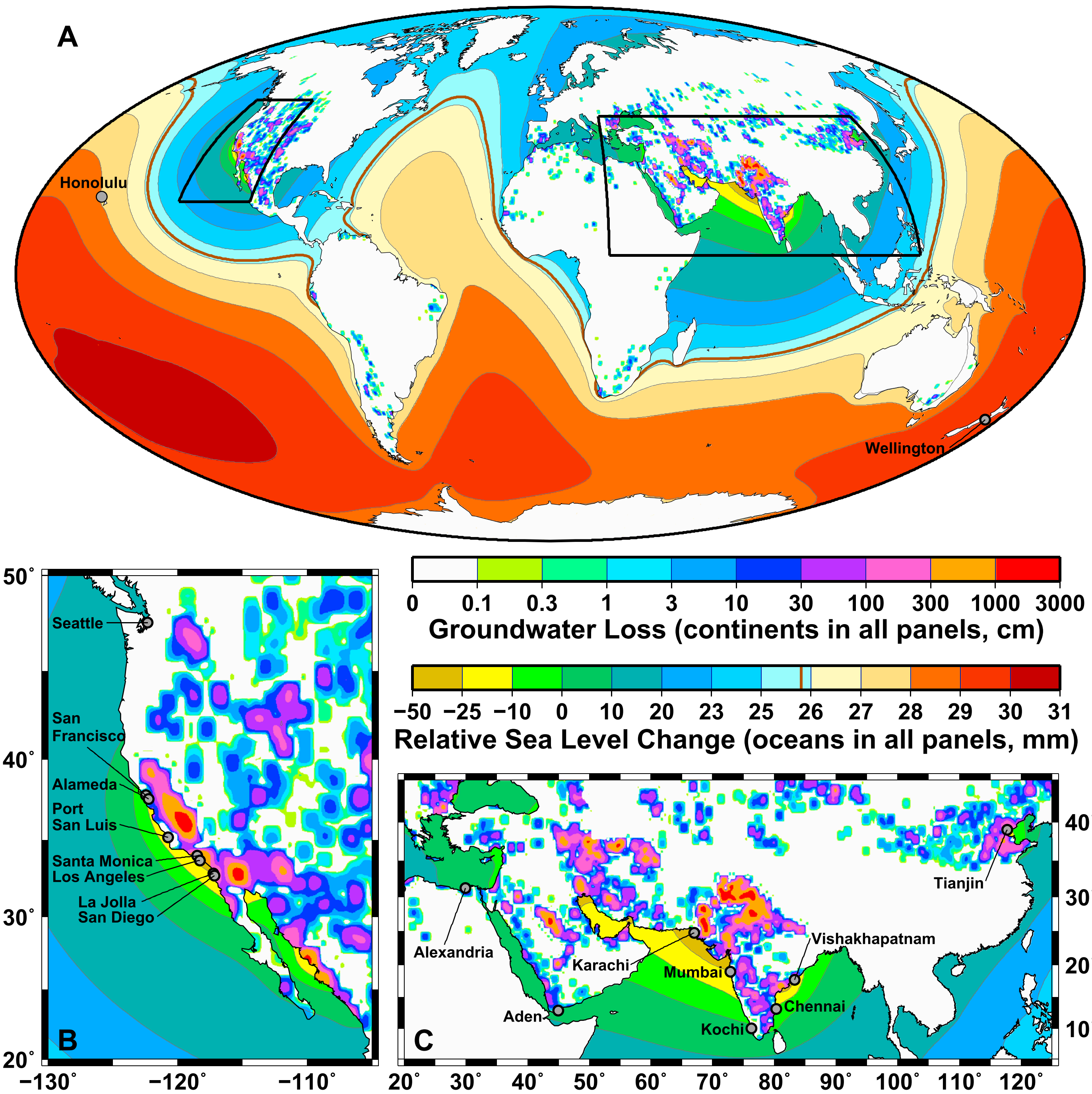

Figure 1. Cumulative groundwater loss from the continents from 1930 to 2015 (shown as colors in continental regions as a thickness of equivalent water layer removed, based on updated data from *Wada et al.* [2012]), and the spatially varying relative sea level rise that results from this groundwater loss to the oceans (shown as colors in oceanic regions, global average of 25.8 mm denoted by brown line). (a) Global patterns and details of (b) western North America and (c) southern Asia show depressed relative sea level near regions of large groundwater loss. Grey circles give locations of tide gauge stations examined for this study (Table 1).

monthly time resolution and a spatial resolution of hundreds of kilometers [*Tapley et al.*, 2004]. Here we examine a time period that starts before the launch of the GRACE satellites and also strive for global coverage. For this, *Wada et al.* [2012] used a global hydrological model to estimate past groundwater depletion as the difference between natural groundwater recharge and human-induced extraction, using the assumption that groundwater is extracted close to where it is most needed. We used an updated version of this model (Y. Wada, personal communication, 2015), which expresses depletion yearly with $0.5° \times 0.5°$ resolution.

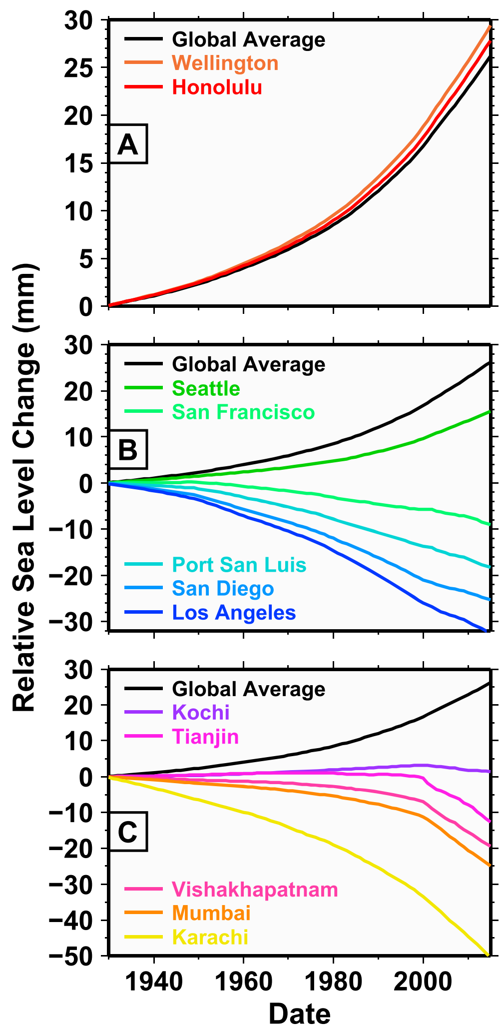

Figure 2. Model prediction of the relative sea level change caused by groundwater depletion since 1930. Here global average rise (black curves) is compared with trends at individual tide gauges (colored curves, labeled in order, locations in Figure 1) that are (a) far from depletion zones or close to regions of intense groundwater depletion in (b) western North America and (c) southern Asia.

Major hot spots of depletion can be seen in maps of cumulative groundwater depletion from 1930 to 2015 (Figure 1a) and include western North America, particularly California (Figure 1b), and southern Asia, particularly Northwest India, Northeast Pakistan, the Arabian Peninsula, and Northeast China (Figure 1c). Regional studies confirm significant groundwater depletion in these regions [e.g., *Famiglietti et al.*, 2011; *Rodell et al.*, 2009].

We compute deflections of the solid Earth and sea surfaces that result from groundwater depletion by following *Farrell*'s [1972] Greens function approach, which *Fiedler and Conrad* [2010] used to estimate the sea level impact of water impoundment behind dams. We did not include the effects of seashore inundation or changes in Earth's rotation axis, although both can induce additional spatial variations in sea level [e.g., *Kendall et al.*, 2005]. Seashore inundation is not significant for water displacements distributed across continents [e.g., *Fiedler and Conrad*, 2010]. Perturbations to Earth's rotation axis may induce more significant sea level variations, but their geographic pattern depends significantly on the spatial pattern of mass redistributions. We show below that rotation-induced sea level variations may have amplitudes up to ~5 mm, which is smaller than the uncertainty associated with the groundwater model.

Between 1930 and 2015, we computed the annual deflection of the solid Earth and sea surfaces that result from *Wada et al.*'s [2012] yearly groundwater depletion rates. Cumulative relative sea level rise, averaged over the ocean basins (Figure 2a), is equivalent to the cumulative total global groundwater depletion and has accelerated for nearly the entire period. Indeed, the groundwater model adds 0.16 mm/yr to sea level before 1980 and 0.50 mm/yr afterward. The cumulative global average sea level rise since 1930 is 25.8 mm.

Relative sea level change varies spatially due to deflections of the solid Earth and sea surfaces, computed here. On the longest wavelengths, groundwater depletion moves mass from continental sources, located mainly in the Northern Hemisphere, to the ocean basins, which are on average positioned in the Southern Hemisphere. Because this spherical harmonic degree 1 movement of water mass represents a change to the vector between Earth's center of mass and figure, the solid Earth shifts (by 8.89 mm away from 38°S, 133°W) and elevates relative sea level rise in the Pacific while depressing it southern Asia (Figure 1a). Because of this, central Pacific tide gauges (e.g., Honolulu and Wellington, Figure 2a) should measure rates of groundwater-induced sea level rise up to ~15% faster than the global average (Figure 1a).

Regional-scale variations in rates of relative sea level rise also result from more localized continental unloading. This occurs because rocks near regions of groundwater depletion uplift due to elastic expansion when

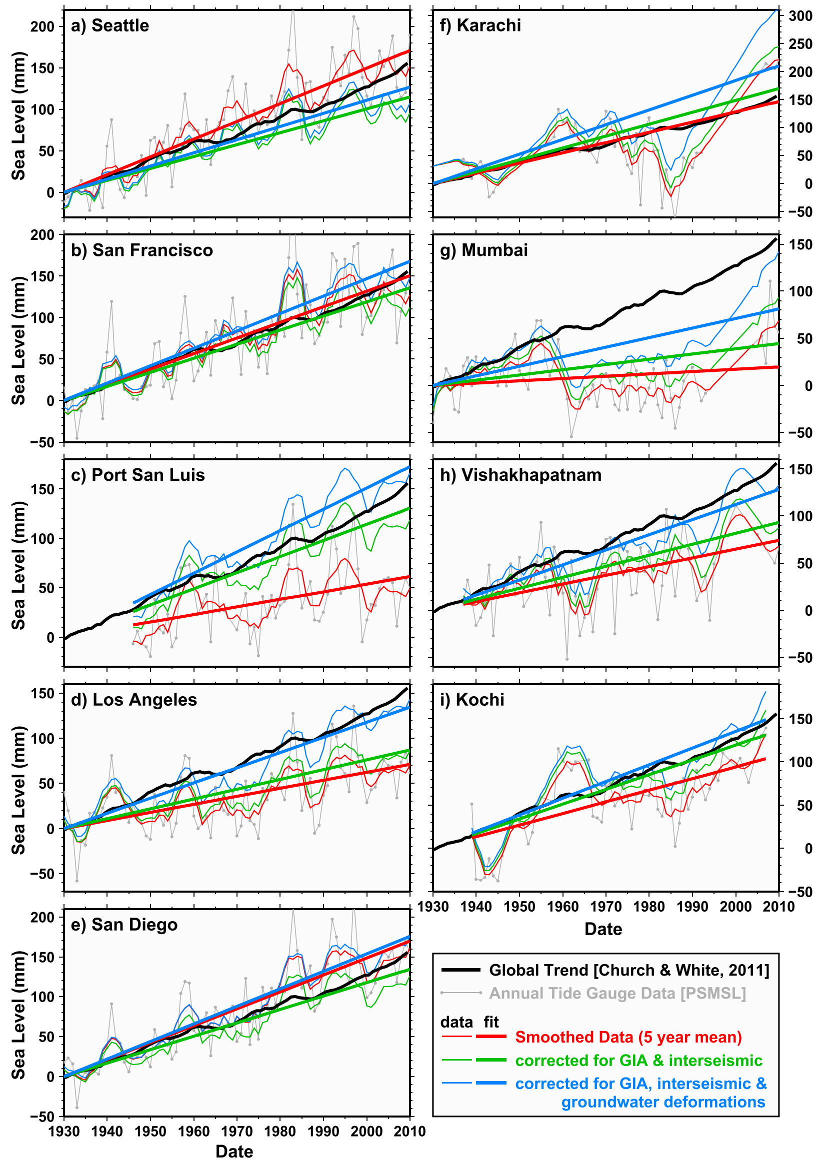

Figure 3. Comparison of selected tide gauge records (locations in Figure 1), both before and after the application of the successive corrections (colored lines), with *Church and White*'s [2011] global sea level reconstruction (black curve). Annual mean sea level data from the PSMSL (grey dots), with gaps filled by linear interpolation, are expressed here relative to their values in 1930 in raw form (grey lines), after application of a 5 year running mean (red lines), after correcting for GIA and interseismic deformations (green lines), and after additionally correcting for deformation due to groundwater depletion (blue lines). Estimates of long-term rates of sea level rise (Table 1) are computed from these curves using a linear fit (thick lines) to the sea level records (thin lines) between 1930 and 2010.

unloaded, while the mass loss also depresses the geoid locally, causing the sea surface to drop. Together, these effects cause large negative deviations in rates of sea level rise along coastlines nearest the largest groundwater depletion areas, particularly around California (Figure 1b), India, the western Yellow Sea, and eastern Mediterranean Sea (Figure 1c). Along portions of these coastlines, our model predicts that negative deviations can exceed the 25.8 mm global average rise, indicating that tide gauges should record a net drop in relative sea level due to groundwater depletion (Figures 2b and 2c).

3. Comparison to Tide Gauge Records of Sea Level

To explore the importance of groundwater-induced lateral variations in sea level within the tide gauge record, we examined groundwater corrections for tide gauges near primary groundwater depletion areas with

Table 1. Linear Sea Level Trends (mm/yr, 1930–2010, Compute as in Figure 3) for Tide Gauges in Western North America and Southern Asia[a]

		Applied Corrections					
		GIA		Interseismic		Groundwater	
Station Name	Linear Fit to Tide Gauge Data	Correction	Applied	Correction	Applied	Correction	Applied
		Western USA					
Seattle	2.14	−0.70	1.44	0.00	1.44	0.15	1.59
San Francisco	1.88	−0.42	1.46	0.23	1.69	0.40	2.10
Alameda	0.69	−0.40	0.29	0.31	0.60	0.46	1.07
Port San Luis	0.77	−0.33	0.44	1.20	1.64	0.52	2.16
Santa Monica	1.43	−0.20	1.23	0.35	1.58	0.66	2.24
Los Angeles	0.89	−0.22	0.67	0.42	1.09	0.59	1.68
La Jolla	2.19	−0.23	1.96	−0.12	1.84	0.53	2.38
San Diego	2.12	−0.24	1.88	−0.20	1.68	0.51	2.19
Mean	**1.51**	−0.34	**1.17**	0.27	**1.45**	0.48	**1.93**
Standard Deviation	**0.65**	0.17	**0.64**	0.44	**0.41**	0.16	**0.44**
		Southern Asia					
Alexandria	1.85	0.03	1.88			0.24	2.12
Aden	1.38	0.13	1.51			0.16	1.67
Karachi	1.83	0.29	2.12			0.51	2.63
Mumbai	0.25	0.31	0.56			0.46	1.02
Kochi	1.35	0.36	1.71			0.22	1.93
Chennai	0.61	0.28	0.89			0.28	1.17
Vishakhapatnam	0.93	0.24	1.17			0.43	1.60
Mean	**1.17**	0.23	**1.41**			0.33	**1.73**
Standard Deviation	**0.60**	0.12	**0.56**			0.13	**0.55**

[a]Fits to the annual mean tide gauge data (left column) are corrected for glacial isostatic adjustment (GIA) using *Peltier*'s [2004] ICE-5G model, interseismic tectonic deformations using *Smith-Konter et al.*'s [2014] reference model (based on an earthquake cycle model of the San Andreas Fault system employing a 70 km thick elastic plate above 10^{19} Pa s half-space viscosity), and groundwater depletion (this study), successively. These local estimates of sea level trends compare to the 1.8 ± 0.3 mm/yr global trend estimated by *Church and White* [2011]. The bold values are for the mean and standard deviation.

observations spanning at least 60 years [*Douglas*, 2001], In North America, the largest groundwater impact occurs along the western United States, where stations with a sufficiently long tide gauge record from the Permanent Service for Mean Sea Level (PSMSL, http://www.psmsl.org, retrieved November 2015) [*Holgate et al.*, 2013] include Seattle, San Francisco, Alameda, Port San Luis, Santa Monica, Los Angeles, La Jolla, and San Diego (Figure 1b). We exclude several long-duration records for stations north of San Francisco because they are significantly affected by poorly constrained tectonic motions associated with Cascadia subduction [*Komar et al.*, 2011]. We include Seattle because its inland location is thought to be relatively stable [*Burgette et al.*, 2009]. In Eurasia, the largest groundwater impacts are in the Arabian Sea, where we consider records from Mumbai, Kochi, Karachi, and Aden. We excluded a long-duration record from Kandla that is likely affected by localized tectonic activity [*Unnikrishnan and Shankar*, 2007]. In the Bay of Bengal, we considered records at Vishakhapatnam and Chennai but excluded Diamond Harbor, which experiences rapid subsidence of the Ganga River Delta, and Ko Taphao Noi, which measures variable discharge from the River Irrawady [*Unnikrishnan and Shankar*, 2007]. We included Alexandria, which is the only tide gauge station in the eastern Mediterranean with a record longer than 50 years. A long-duration Black Sea record is available at Poti but is affected by subsidence along the Georgian coast. Our models predict significant sea level impacts in the Yellow Sea (Figure 1c), mostly after the year 2000 (e.g., Tianjin, Figure 2c). Unfortunately, tide gauges in this area (Yantai, Qinhuangda, and Tanggu) stopped recording in the mid-1990s, so we excluded them.

We linearly interpolated to fill gaps in annual mean sea level data from the PSMSL to obtain long-term records of sea level change relative a 1930 baseline (grey curves, Figure 3). From these, we computed 5 year running means and measured a linear fit to the resulting sea level trends (red curves, Figure 3). We then applied corrections (Table 1) for glacial isostatic adjustment (GIA) [*Peltier*, 2004] and in California for vertical crustal motions associated with interseismic tectonic deformation (green curves, Figure 3) [*Smith-Konter et al.*, 2014]. Such estimates of tectonic vertical motion are not readily available for stations outside of California for the ~80 year timescale we considered. Finally, we applied a correction for groundwater depletion (Table 1), estimated here

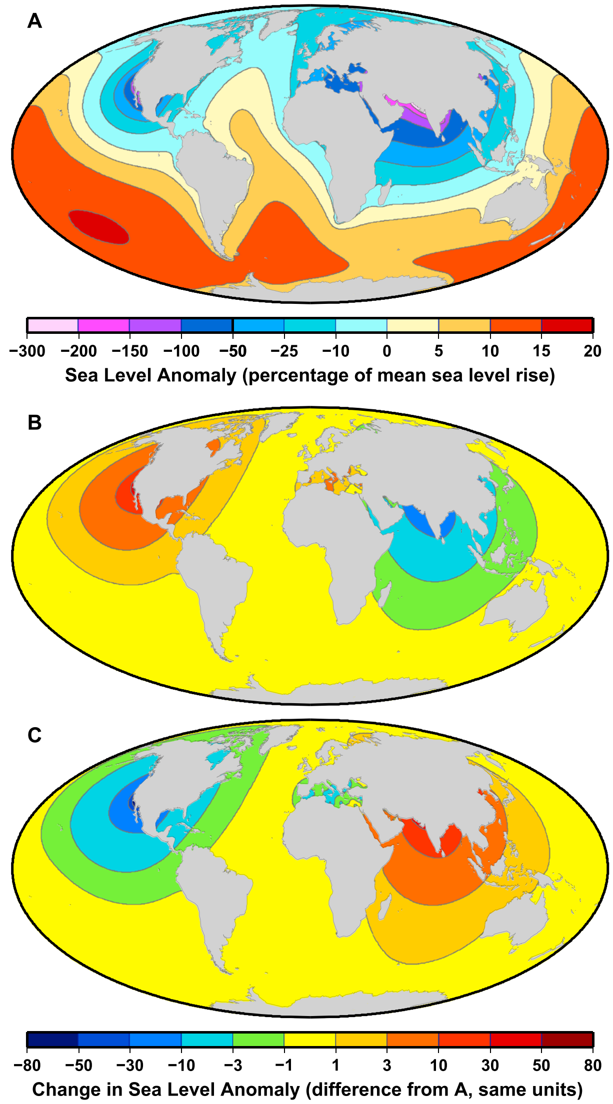

Figure 4. Spatial variations in relative sea level change for different models of groundwater depletion in the year 2000. (a) Deviations from mean sea level, shown as a percentage of the global average rise of 0.57 mm caused by *Wada et al.*'s [2010] estimate of 204 km^3 of groundwater loss. Changes to this pattern result from different distributions of continental groundwater loss, as shown here relative to Figure 4a for models in which the ~20% uncertainty range estimated by *Wada et al.* [2010] is either (b) maximized in Asia and minimized in North America or (c) maximized in North America and minimized in Asia.

as the difference between the global average sea level rise associated with groundwater transfer to the oceans (black curves, Figure 2) and the relative sea level change due to groundwater depletion at each station (colored curves, Figure 2). We then recomputed the linear sea level trend of the resulting curves (blue curves, Figure 3).

The inclusion of a correction for groundwater depletion on average improves the match between the long-term trend of sea level change (thick blue lines, Figure 3; rates are shown in Table 1) and *Church and White*'s [2011] global average sea level rise trend of 1.8 ± 0.3 mm/yr (black curves, Figure 3). Without any corrections (red lines, Figure 3), the mean sea level trend for these stations presents an average rise rate that is smaller (1.17 and 1.51 mm/yr for Asian and North American stations, respectively, Table 1) than the global trend (1.8 mm/yr). The GIA correction moves the southern Asia regional average (1.41 mm/yr) toward the global trend and the western North America regional average (1.17 mm/yr) away from it. The latter is opposed by interseismic corrections, which, when included, yield a regional average (1.45 mm/yr) similar to that for southern Asia (green lines, Figure 3). Finally, including the correction for groundwater depletion (blue lines, Figure 3) moves the average for both southern Asia (1.73 mm/yr) and western North America (1.93 mm/yr) closer to the global trend of 1.8 mm/yr (Table 1). Indeed, both sets of observations (Table 1) are consistent with sampling from a normal distribution about 1.8 ± 0.3 mm/yr (Anderson-Darling statistic with 95% confidence [*Press et al.*, 1992]), but only if the groundwater correction is applied. This match to the global trend is only useful if western North America and southern Asia represent useful measures of global average sea level and are not subject to additional regional corrections. Furthermore, recent studies have suggested slower rates of twentieth century sea level rise [*Hay et al.*, 2015], although these reconstructions are mostly slower only prior to 1960, which is before groundwater depletion became important (Figure 2).

4. Discussion

Rates of groundwater depletion are difficult to constrain and therefore subject to significant uncertainty, especially on the continental length scales and decadal timescales employed for this study. For example, satellite [*Jensen et al*., 2013] and sea level mass balance [*Dieng et al*., 2015] constraints on total land water storage loss (from groundwater, impoundment, and natural aquifer mass changes) suggest significantly slower sea level rise during the past decade (0.2 and 0.3 mm/yr, respectively) than does *Wada et al*.'s [2012] groundwater model (~0.7 mm/yr). Much of this discrepancy can be attributed to an offsetting contribution from reservoir impoundment [*Wada et al*., 2012], which exhibits a different sea level fingerprint [*Fiedler and Conrad*, 2010]. Furthermore, *Wada et al*. [2010] estimated model uncertainties for the year 2000 of ±20–30% for several different regions, and *Wada et al*. [2012] estimated a global uncertainty in the groundwater contribution to sea level rise of ±15%. If ±15% uncertainty is applied uniformly across the globe, then the pattern of sea level variations (Figure 4a) remains unchanged, but amplitudes become ~15% higher or lower. Since negative anomalies near California and India exhibit amplitudes up to 200% and 300% of the average global rise (Figure 4a), then ±15% uncertainty in the 25.8 mm of groundwater-induced sea level rise corresponds to sea level deflections of up to 51.6 ± 7.7 and 77.4 ± 11.6 mm for California and India, respectively.

If deviations from *Wada et al*.'s [2012] groundwater depletion model are not uniformly distributed, then additional uncertainty is introduced by regional deflections, and by degree 1 motion of the solid Earth toward regions of extra groundwater depletion. To examine this effect, we ran our model for the year 2000 for two other groundwater depletion patterns that also fall within *Wada et al*.'s [2010] range of uncertainties: one that maximizes depletion in Asia and minimizes it in North America (Figure 4b) and another that reverses this pattern (Figure 4c). Although these models do not involve a significant change in net groundwater loss to the oceans, they do regionally introduce additional relative sea level changes of about ±50% of the average global sea level rise (Figures 4b and 4c), with negative anomalies occurring close to regions with excess groundwater depletion. This increases the uncertainty in the groundwater-induced sea level change since 1930 to as much as ±13 mm for both California and India, although anomalies this large on opposite sides of the globe would need to be oppositely signed. Such variations correspond to an additional ±25% and ±17% uncertainty in the ~52 and ~77 mm sea level deflections occurring regionally near California and India, respectively.

Mass movements on Earth's surface affect its moment of inertia, which can perturb Earth's rotation axis and move the equatorial bulge relative to continental shorelines, elevating sea level in some regions and depressing it in others [*Milne and Mitrovica*, 1998]. Using *Rietbroek et al*.'s [2012] method to relate changes in moment of inertia to changes in gravitational potential, we estimate that the global pattern of groundwater depletion (Figure 1) should lead to rotation-induced sea level changes that are ~24% larger than those that result from the same water loss from the West Antarctic Ice Sheet, which *Gomez et al*. [2010] associated with sea level deviations of ~15% of the global sea level rise. This suggests that rotation-induced sea level deviations, which are not included in our model, may have amplitudes of 18.6% of the associated sea level rise, or about ±5 mm for the 25.8 mm of sea level change since 1930. The (degree 2, order 1) harmonic pattern of sea level rise and fall is oriented in longitude by the geographic position of net mass loss from the continents [*Milne and Mitrovica*, 1998]. This position is uncertain for groundwater depletion because the ±20% uncertainty in mass loss from both California and India [*Wada et al*., 2010] permits the locus of net mass loss, and thus the associated sea level change, to lie within a range of areas between California and India.

5. Conclusions

Groundwater depletion has elevated sea level during the past century and is currently contributing to sea level rise [*Wada et al*., 2012]. The rise rate is not uniform across the oceans, however, because deflections of the solid Earth and sea surfaces result in slower rates of sea level rise close to regions of groundwater depletion. We estimated these sea level deflections using a model of the solid Earth's response to groundwater depletion during the past century [*Wada et al*., 2012] and find that groundwater depletion in western North America and southern Asia significantly depresses sea level in these regions. Indeed, tide gauges in both regions have recorded slower sea level rise (average of ~1.4 mm/yr rise, Table 1) compared to global sea level reconstructions (1.8 mm/yr) [*Church and White*, 2011]. Introducing a correction for the regional influence of groundwater depletion, which in these two areas is greater than the GIA or interseismic deformation corrections (Table 1), diminishes these differences.

Our work suggests (Figure 2) that relative sea level is currently as much as 30 mm lower in California and 50 mm lower in India than it would be in the absence of global groundwater depletion. Indeed, given that groundwater depletion has elevated GMSL by ~25 mm since 1930, the spatial variations associated with this groundwater loss have lowered sea level in California and India by up to ~55 and 75 mm, respectively. Such variations should accelerate into the next century, along with faster rates of groundwater depletion [*Wada et al.*, 2012], affecting global estimates of the average rate of sea level change [e.g., *Church and White*, 2011] and impacting coastal communities.

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