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Sea-Level Acceleration Based on U.S. Tide Gauges and Extensions of Previous Global-Gauge Analyses

J.R. Houston[†] **and R.G. Dean**[‡]

[†]Director Emeritus
Engineer Research and Development
Center, Corps of Engineers
3909 Halls Ferry Road
Vicksburg, MS 39180, U.S.A.
james.r.houston@usace.army.mil

[‡]Professor Emeritus
Department of Civil and Coastal Civil
Engineering
University of Florida
Gainesville, FL 32611, U.S.A.
dean@coastal.ufl.edu

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ABSTRACT

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Without sea-level acceleration, the 20th-century sea-level trend of 1.7 mm/y would produce a rise of only approximately 0.15 m from 2010 to 2100; therefore, sea-level acceleration is a critical component of projected sea-level rise. To determine this acceleration, we analyze monthly-averaged records for 57 U.S. tide gauges in the Permanent Service for Mean Sea Level (PSMSL) data base that have lengths of 60–156 years. Least-squares quadratic analysis of each of the 57 records are performed to quantify accelerations, and 25 gauge records having data spanning from 1930 to 2010 are analyzed. In both cases we obtain small average sea-level decelerations. To compare these results with worldwide data, we extend the analysis of Douglas (1992) by an additional 25 years and analyze revised data of Church and White (2006) from 1930 to 2007 and also obtain small sea-level decelerations similar to those we obtain from U.S. gauge records.

ADDITIONAL INDEX WORDS: *Global climate change, Sea level rise.*

INTRODUCTION

In the Fourth Assessment Report (4AR) of the Intergovernmental Panel on Climate Change (IPCC), Bindoff *et al.* (2007) project a global sea-level rise relative to 1990 of 18–59 cm by 2100 and add as much as 0.20 cm to the upper limit if melting of ice sheets increases in proportion to global average surface temperature increases (Meehl *et al.*, 2007). The current sea-level trend of about 1.7 mm/y will produce a rise of about 19 mm over 110 years from 1990 to 2100, but a rise to 79 cm will require an acceleration of about 0.10 mm/y^2. In the Copenhagen Synthesis report, Richardson *et al.* (2009) note that additional information, particularly on ice sheet dynamics, is available since 4AR. They also predict a rise of 1 m ± 0.5 m during the same period, requiring acceleration of about 0.05–0.22 mm/y^2; however, it is not clear that the acceleration necessary to achieve these comparatively large projected rises in mean sea level over the course of the 21st century is evident in tide-gauge records.

Determining the rate of rise and acceleration of global mean sea level is complicated by the small number of long-term tide-gauge records and their concentration in the northern hemisphere, strong worldwide spatial variations of sea-level rise, vertical land movements, and seasonal-to-decadal temporal variations that can be large compared to sea-level trends and accelerations. Following Sturges and Hong (2001), we use the term "decadal" to refer to low-frequency variations that are longer than a year and can extend beyond 10 years, and are caused in part by wind and atmospheric pressure variations and the Rossby and Kelvin waves they produce. Acceleration is a second-order effect and influenced by these complications. Vertical land movements such as glacial isostatic adjustment are considered approximately linear over the record length analyzed; therefore, they do not affect acceleration (Douglas, 1992). Short-term vertical tectonic movements such as those arising from earthquakes can affect both the apparent sea-level trend and acceleration, and tide-gauge records with these movements should be excluded from analyses of trend and acceleration.

Previous Sea-Level Acceleration Studies

There have been several studies focusing on the acceleration of sea level. Woodworth (1990) analyzed long records from European tide gauges and found an overall slight deceleration from 1870 to 1990, although he found accelerations in individual gauge records. He also analyzed the four oldest European gauge records from Brest, Sheerness, Amsterdam, and Stockholm in 1807, 1834, 1799, and 1774, respectively. Woodworth found a small acceleration on the order of 0.004 mm/y^2, which he indicated appeared typical of European Atlantic and Baltic coast mean sea-level acceleration over the last few centuries. He noted that this small acceleration was an order of magnitude less than anticipated from global warming.

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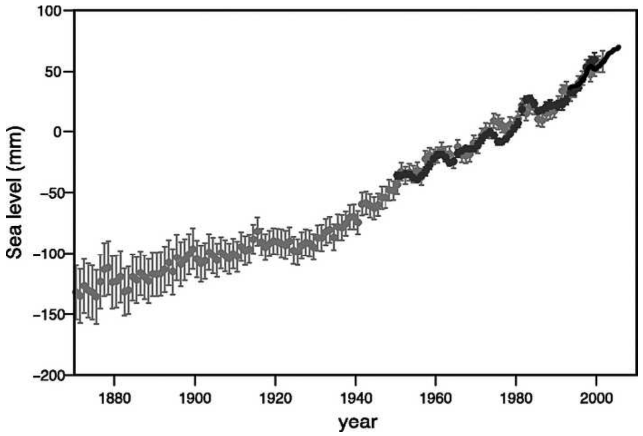

Figure 1. Annual mean sea-level data from Bindoff *et al.* (2007). Red data from Church and White (2006), blue from Holgate and Woodworth (2004), and black from altimeter measurements from Leuliette, Nerem, and Mitchum (2004). Ninety percent confidence error bars shown.

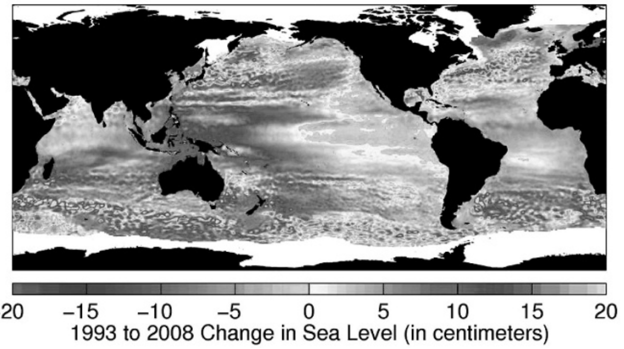

Figure 2. Satellite altimeter measurements from Willis (2010) of the change in sea level from 1993 to 2008.

Jevrejeva *et al.* (2008) performed a similar analysis based on long-term tide-gauge recordings at Amsterdam, Liverpool, and Stockholm. Jevrejeva *et al.* concluded that sea level has accelerated an average of approximately 0.01 mm/y² over the past 200 years, with the largest rise rate between 1920 and 1950.

Douglas (1992) analyzed 23 worldwide tide-gauge records of 75 years or greater and determined an average sea-level deceleration of -0.011 ± 0.012 mm/y² (standard deviation [SD]) for the 80-year period from 1905 to 1985. Douglas further analyzed 37 global records that had an average length of 92 years and determined that from 1850–1991 the average acceleration was 0.001 ± 0.008 mm/y² (SD). He noted that global climate models forecast acceleration over the next five to six decades in the range of 0.1–0.2 mm/y² and concluded there was no evidence of acceleration in the past 100 or more years that was statistically significant or consistent with values predicted by global warming models. Church *et al.* (2004) used nine years of Topography Experiment (TOPEX)/Poseidon satellite-altimeter data to estimate global empirical orthogonal functions (EOFs) that were then combined with historical tide-gauge data to estimate global sea-level rise from 1950–2000. The data led them to conclude, "… there is no detectable secular increase in the rate of sea-level rise over the period 1950–2000." Church and White (2006) used the same EOF method, 12 years of altimeter data, and extended the analysis back to 1870. They concluded that from January 1870 to December 2004 there was a sea-level acceleration of 0.013 ± 0.006 mm/y² (95% confidence interval = 95%) and a smaller acceleration of 0.008 ± 0.008 mm/y² (95%) in the 20th century.

A review paper on sea-level acceleration by Woodworth *et al.* (2009) notes that the analysis by Church and White (2006) shows a positive acceleration, or "inflexion" point, around 1920–30. They do not use the mathematical definition of an inflexion point as the point where the curvature (second derivative) changes, but instead define it as a change in sea-level trend. They say that the inflexion point around 1920–30 is the main contributor to acceleration from 1870 to 2004. Woodworth *et al.* (2009) concluded there was consensus among the authors that acceleration occurred from around 1870 to the end of the 20th century; however, with the major acceleration occurring prior to 1930, the sea-level rise (Figure 1) appears approximately linear from 1930 to 2004. Church and White (2006) did not separately analyze this specific period.

The TOPEX/Poseidon satellite altimeter recorded sea level from August 1992 to 2005, and the Joint Altimetry Satellite Oceanography Network (JASON-1) satellite altimeter recorded from late 2001 to the present. The satellites measured remarkable spatial variation of sea-level rise from 1993 to 2008 (Figure 2). Altimeter measurements are quite valuable because they measure elevations over the oceans from 66°N to 66°S rather than at the limited number of coastal-gauge locations. In addition, altimeter measurements are not unduly affected by fresh-water runoff and other processes that may distort shallow-water tide-gauge records. On the other hand, Ablain *et al.* (2009) note the many uncertainties and sources of error in satellite-altimeter measurements, including drift, subgrid-scale homogeneity and sea-state biases, wet and dry troposphere, inverse barometer, and orbit corrections.

From 1993–2010, these altimeters measured a global sea-level rise of 3.0 mm/y with the inverted barometer applied and the seasonal signal removed (University of Colorado, 2010). This rate is higher than the average 20th-century trend, but the trend fluctuated in the 20th century, and this rate is not uniquely high. Bindoff *et al.* (2007) note that sea-level trends similar to those measured by the altimeters have occurred in the past. Holgate (2007) calculated consecutive, overlapping 10-year-mean sea-level trends since 1910 for each of nine representative worldwide tide-gauge records. He found that the altimeters measured only the fourth highest of six peaks in rate since approximately 1910, with the highest rates of 5.31 mm/y centered on 1980 and 4.68 mm/y centered on 1939. Church *et al.* (2004) report that from 1950 to 2000 there have been periods with sea-level trends greater than those measured by the satellite altimeters. Similarly, White, Church, and Gregory (2005) note that sea-level trends varied from 0–4 mm/y from 1950–2000 with a maximum in the 1970s. Jevrejeva *et al.* (2006) analyzed 1023 gauge records over the 20th century and showed that the global sea-level trend measured by the satellite altimeters is similar to the trend from 1920–45.

Merrifield and Merrifield (2009) argue that the increase in the rate of sea-level rise measured by the satellite altimeters is a sign of an acceleration that is distinct from decadal variations. They note that sea-level rise recorded by northern ocean (25°N to 65°N) gauges is trendless, being approximately constant since around 1925, but that southern (65°S to 25°S) and tropical (25°S to 25°N) ocean gauges have decadal variations that are typically 180° out of phase so that when one experiences an increase in the rate of sea-level rise the other experiences a decrease. Merrifield and Merrifield say that after the mid-1980s, the two became in phase, and their rise dominates the increase in sea-level trend measured by the satellite altimeters. Thus, they believe this recent increase in sea-level trend represents a long-term change rather than a cyclical variation and is caused by ice melt and a subduction of heat below the upper layers of the ocean; however, they note that few sea-level measurements from the tropical and southern oceans were made before approximately 1965. Merrifield and Merrifield (2009) show there have been only two cycles of decadal variations in sea-level trends since 1965 with the tropical and southern oceans' decadal oscillations being out of phase the first three half-cycles and in phase the latest half-cycle; therefore, it does not seem possible to discern from just two cycles whether the current half-cycle is a long-term change or a normal variation.

Recent papers such as those by Vermeer and Rahmsdorf (2009), Jevrejeva, Moore, and Grinsted (2010), and Grinsted, Moore, and Jevrejeva (2010) offer an alternative to the IPCC's approach of estimating future sea-level rise by modeling the major components of the sea-level budget. Their approach is based on statistical models that use semiempirical relationships between past and predicted future global temperature changes to predict sea-level rise. Using this approach, they predict a global mean sea-level rise between 0.6–1.9 m from 1990–2100. These levels would require accelerations of 0.07–0.28 mm/y^2 above the current trend over the 110-year period.

Studies of sea-level trend have converged on a rate of approximately 1.7–1.8 mm/y in the 20th century but there is disagreement on the rate of acceleration or even whether acceleration has or can be detected. As noted earlier, Woodworth *et al.* (2009), in a review article authored by six of the leading sea-level researchers and citing Church and White (2006), conclude that there is consensus among the authors that sea level accelerated from 1870 to 2004. However, they indicate much of the acceleration occurred prior to 1930, and they do not address the question of whether sea level has accelerated during the 80 years from 1930–2010. Indeed, they state, "… little evidence has been found in individual tide gauge records for an ongoing positive acceleration of the sort suggested for the 20th century by climate models" (Woodworth *et al.,* p. 778) They mention that most analyses have used essentially the same data set combined in different ways and there is a need to augment the data set.

DATA AND METHODOLOGY

Douglas (1992) notes that sea-level trends obtained from tide-gauge records with lengths less than 50–60 years are significantly "corrupted" by decadal variations; therefore, we analyzed U.S. tide-gauge records having at least 60, an average of 82, and as many as 156 years (San Francisco, California) of data recorded at single locations and without significant tectonic activity that has produced vertical-datum shifts. The 57 tide-gauge stations listed in Table 1 and shown in Figure 3 met these criteria; however, we eliminated two Alaska tide-gauge stations, Seward and Kodiak Island, Alaska, because the 1964 Alaskan earthquake significantly changed their datums. We did not modify the data by glacial-isostatic adjustment because glacial rebound is approximately linear over the lengths of the records and thus does not affect acceleration (Douglas, 1992). We also analyzed gauge records from 1930–2010 at 25 gauge locations shown in Table 1. Data were obtained from the PSMSL data base at http://www.psmsl.org/data/ (Permanent Service for Mean Sea Level, 2010a) as described by Woodworth and Player (2003).

For each of the 57 and 25 tide-gauge records, we determined the offset, a_0 in mm, slope, a_1 in mm/y, and quadratic-term acceleration, a_2 in mm/y^2, using a least-squares analysis that fit the data with the quadratic equation

$$y(t) = a_0 + a_1 t + \frac{a_2}{2} t^2 \tag{1}$$

where t = time in years and $y(t)$ is the measured tide at time t. Only the acceleration results are reported here.

RESULTS

Our first analysis determined the acceleration, a_2, for each of the 57 records with results tabulated in Table 1 and shown in Figure 4. There is almost a balance with 30 gauge records showing deceleration and 27 showing acceleration, clustering around 0.0 mm/y^2. The mean is a slight deceleration of $a_2 = -0.0014 \pm 0.0161$ mm/y^2 (95%). As in Douglas (1992), we computed the error of the mean from the residuals about the mean, not from the error estimates of the individual gauge records. There are six outliers (Figure 4) with absolute values of acceleration greater than approximately 0.01 mm/y^2. The record lengths of these outliers are relatively short, between 62 and 70 years. They are all in areas that have greater than average rises or falls in average mean sea level during the 15 years of altimeter measurements shown in Figure 2. Large changes in trends during the approximate final quarters of these records leads to large positive and negative accelerations. Figure 2 shows relatively large sea-level increases in the western Pacific, Guam, Midway, and Kwajalein, contributing to accelerations of 0.2546, 0.1382, and 0.1060 mm/y^2, respectively. Relatively large sea-level decreases are seen in Figure 2 along the coast of Alaska, Yakutat, Adak, and Skagway, contributing to decelerations of -0.1880, -0.1410, and -0.0994 mm/y^2, respectively. If these six gauge records are eliminated from the analysis the mean is -0.0027 ± 0.0085 mm/y^2 (95%), which is still a very small deceleration because of the balance of negative and positive accelerations, but has a reduced 95% confidence interval. The near balance of accelerations and decelerations is mirrored in worldwide-gauge records as shown in Miller and Douglas (2006) (their Figure 1).

Table 1. *Accelerations for all 57 gauge records and 25 gauge records having data since 1930.*

Station	PSMSL ID	Record Length	Acceleration Entire Record	Acceleration since 1930
Adak Island, Alaska	487	1943–2009	−0.1410	
Alameda, California	437	1939–2009	−0.0050	
Annapolis, Maryland	311	1928–2009	−0.0272	−0.0218
Guam (Apra)	540	1948–2009	0.2546	
Astoria, Oregon	265	1925–2009	−0.0104	−0.0108
Atlantic City, New Jersey	180	1911–2009	0.0118	0.0254
Baltimore, Maryland	148	1902–2009	−0.0032	−0.0194
Bar Harbor, Maine	525	1947–2009	−0.0472	
Boston, Massachusetts	235	1921–2009	−0.0298	−0.0150
Cedar Key II, Florida	428	1938–2009	0.0104	
Charleston, South Carolina	234	1903–2009	−0.0252	−0.0286
Crescent City, California	378	1933–2009	−0.0138	
Eastport, Maine	332	1929–2009	−0.0512	−0.0504
Fernandina, Florida	112	1897–2009	0.0154	0.0086
Fort Pulaski, Georgia	395	1935–2009	0.0058	
Friday Harbor, Washington	384	1934–2009	−0.0100	
Galveston, Texas	161	1908–2009	0.0056	−0.0384
Hampton, Virginia	299	1927–2009	0.0076	0.0172
Hilo, Hawaii	300	1947–2009	−0.0632	
Honolulu, Hawaii	155	1911–2009	−0.0112	−0.0018
Juneau, Alaska	405	1936–2009	−0.0446	
Ketchikan, Alaska	225	1919–2009	−0.0114	0.0002
Key West, Florida	188	1913–2009	0.0004	0.0036
Kwajalein	513	1946–2009	0.1060	
La Jolla, California	256	1924–2009	−0.0026	−0.0096
Lewes, Delaware	224	1919–2009	0.0122	0.0118
Los Angeles, California	245	1924–2009	0.0044	0.0134
Mayport, Florida	316	1928–2000	0.0056	0.0066
Midway	523	1947–2009	0.1382	
Montauk, New York	519	1948–2009	0.0800	
Neah Bay, Washington	385	1934–2009	−0.0384	
New London, Connecticut	429	1938–2009	0.0286	
Newport, Rhode Island	351	1930–2009	−0.0052	
New York, New York	12	1856–2009	0.0076	−0.0096
Pago Pago	539	1948–2009	0.0548	
Pensacola, Florida	246	1925–2009	−0.0162	−0.0132
Philadelphia, Pennsylvania	135	1922–1994	0.0132	0.0290
Port Isabel, Texas	497	1944–2009	0.1008	
Portland, Maine	183	1912–2009	−0.0182	−0.0514
Port San Luis, California	508	1945–2009	−0.0344	
Providence, Rhode Island	430	1938–2009	0.0244	
San Diego, California	158	1906–2009	−0.0020	−0.0102
Sandy Hook, New Jersey	366	1932–2009	−0.0120	
San Francisco, California	10	1854–2009	0.0144	−0.0216
Santa Monica, California	377	1933–2009	−0.0380	
Seattle, Washington	127	1899–2009	0.0072	−0.0320
Seavey Island, Maine	288	1926–2001	−0.0926	−0.0886
Sitka, Alaska	426	1938–2009	0.0186	
Skagway, Alaska	495	1944–2009	−0.0994	
Solomons Is, Maryland	412	1938–2009	0.0166	
St Petersburg, Florida	520	1947–2009	0.0308	
Wake Island	595	1950–2009	0.0210	
Washington, DC	360	1931–2009	−0.0044	
Willets Point, New York	362	1931–2001	−0.0320	
Wilmington, North Carolina	396	1935–2009	0.0012	
Woods Hole, Massachusetts	367	1932–2009	−0.0020	
Yakutat, Alaska	445	1940–2009	−0.1880	

Since the worldwide data of Church and White (2006) from 1870–2001 (Figure 1) appear to have a linear rise since around 1930, we analyzed the period 1930 to 2010 for 25 of the 57 gauge records that had records during that period. As tabulated in Table 1 and seen in Figure 5, 16 records showed decelerations and 9 showed accelerations. None of the six outliers of the previous analysis have records extending back to 1930. We found a mean deceleration of -0.0123 ± 0.0104 mm/y^2 (95%). There is little regional dependence with 17 gauge records from Atlantic and Gulf coasts having an average deceleration of -0.0138 ± 0.0148 mm/y^2 (95%), and 8 gauge records from the Pacific coast having an average deceleration of -0.0091 ± 0.0096 mm/y^2 (95%). In addition, results did not depend greatly on data quality. We restricted the analysis to 18 gauge records

Figure 3. Locations of 57 tide gauges.

having no more than 5% missing data (with an average missing data of only 1%), and the mean deceleration was −0.00117 ± 0.0092 mm/y^2 (95%).

We also analyzed the worldwide data of Church and White (2006) for the period 1930–2001 and obtained a deceleration of −0.0066 mm/y^2. In 2009, Church and White posted a revised data set at http://www.psmsl.org/products/reconstructions/church.php that extended their original data set through 2007 and revised much of the early data. We analyzed the new data set from 1930–2007 and obtained a deceleration of −0.0130 mm/y^2. Therefore, the deceleration that we find in U.S. gauge records for 1930–2010 is consistent with worldwide-gauge data of Church and White (Permanent Service for Mean Sea Level, 2010b).

The seminal paper by Douglas (1992) analyzed representative worldwide gauges from 1905–85. His analysis showed a deceleration over the 80-year period of −0.011 ± 0.012 mm/y^2 (SD). We extended his analysis to 2010 by an additional 25 years of data in order to compare our results for U.S. gauge records with his for worldwide-gauge records and also to determine the effect of adding the years where satellite altimeters have recorded a sea-level trend greater than the 20th-century trend.

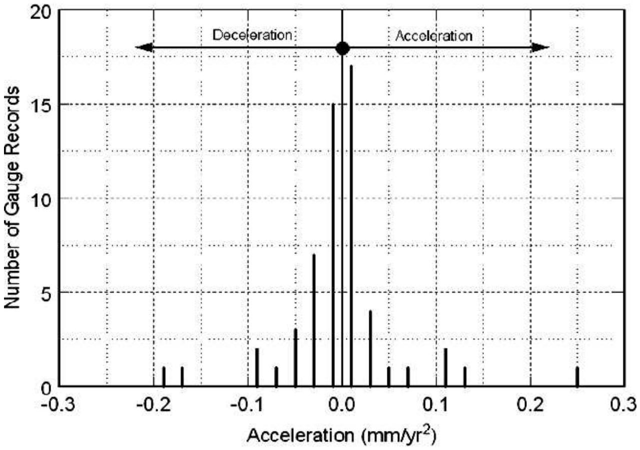

Figure 4. Number of gauge records in bins of acceleration, a_2, in mm/y^2.

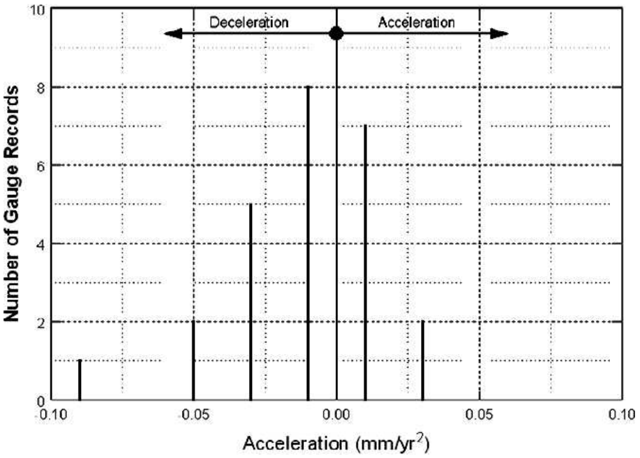

Figure 5. Acceleration from 1930 to 2010 in mm/y^2 for each of the 25 gauge records.

Table 2 compares the accelerations obtained by Douglas (1992) for 1905–85 to those that we obtained for 1905–2010. Douglas (1992) divides the world into 10 regions and determines mean accelerations for each region. He then averages the regional accelerations to determine a global-mean acceleration. Our addition of 25 years of data has little effect, producing a deceleration of −0.012 ± 0.012 mm/y^2 (SD), only slightly greater in magnitude than Douglas obtained. Furthermore, Holgate (2007) analyzed nine long worldwide tide-gauge records and found a decrease in the sea-level trend from the period 1904–53 to the period 1954–2003 that is equivalent to a deceleration of −0.012 mm/y^2, the same that we obtained by extending Douglas's analysis to the period 1905–2010. Holgate noted that the deceleration he obtained was consistent with "… a general deceleration of sea level rise during the 20th century" (pp. 243–244) that he said was suggested in analyses by Woodworth (1990), Douglas (1992), and Jevrejeva *et al.* (2006). We repeated the reanalysis of data presented in Douglas (1992) for the period 1930–2010 and obtained a deceleration of −0.015 ± 0.011 mm/y^2 (SD), which is somewhat greater than the deceleration from 1905–2010.

Douglas also selected 37 gauges that had a record length greater than 75 years during the years 1850–1991 and as a group had a mean record length of 92 years. He analyzed them using the same 10 regions and obtained a very small mean acceleration of 0.001 ± 0.008 (SD). We extended the records to 2010. Several European gauges and gauges in 3 of the 10 regions stopped recording prior to 1991, so we accepted the values determined by Douglas. For the same data set and using the same approach that he used to determine acceleration, we obtained a very small mean deceleration of −0.001 ± 0.007 mm/y^2 (SD). If the gauges without records beyond 1991 are eliminated from the analysis, we obtain 0.000 ± 0.006 mm/y^2 (SD).

Table 2. *Comparison of sea level accelerations (mm/y^2) obtained by Douglas (1992) for 1905–85 with accelerations we obtained for 1905–2010. The six locations marked with an * do not have records beyond 1985, so we used the results in Douglas (1992). If the six locations are eliminated from the analysis, the deceleration is 0.000 ± 0.006 mm/y^2 (SD).*

	Douglas (1992)		This Study	
Location	Acceleration	Group Acceleration	Acceleration to 2010	Group Acceleration
Group 1				
Varberg*	−0.028		−0.0280	
Ystad*	−0.017		−0.0170	
Kungholmsfort*	0.031		0.0310	
Landsort	0.009		0.0334	
Stockholm	−0.001		0.0282	
Ratan	−0.019		0.0204	
Oulu/Uleaborg	−0.006		0.0204	
Vaasa/Vasa	−0.008		0.0254	
Helsinki	0.034		0.0380	
		0.000		0.0169
Group 2				
North Shields	−0.027		−0.0102	
Cascais	−0.021		−0.0286	
		−0.024		−0.0194
Group 3				
Trieste	−0.011		−0.0050	
		−0.011		−0.0050
Group 4				
Bombay*	−0.084		−0.0840	
		−0.084		−0.0840
Group 5				
Tonoura*	−0.064		−0.0640	
		−0.064		−0.0640
Group 6				
Sydney	0.047		0.0346	
Auckland	−0.009		−0.0100	
		0.019		0.0123
Group 7				
Honolulu, Hawaii	−0.013			
		−0.013	−0.0112	−0.0112
Group 8				
Seattle, Washington	0.044		0.0036	
San Francisco, California	0.029		−0.0028	
San Diego, California	0.019		−0.0020	
		0.031		−0.0004
Group 9				
Buenos Aires*	0.041			
		0.041	0.0410	0.0410
Group 10				
Baltimore, Maryland	−0.011		−0.0084	
New York, New York	−0.015		−0.0054	
		−0.013		−0.0069
Mean		−0.011		−0.012
Standard Error		0.012		0.012

DISCUSSION

We analyzed the complete records of 57 U.S. tide gauges that had average record lengths of 82 years and records from 1930 to 2010 for 25 gauges, and we obtained small decelerations of −0.0014 and −0.0123 mm/y^2, respectively. We obtained similar decelerations using worldwide-gauge records in the original data set of Church and White (2006) and a 2009 revision (for the periods of 1930–2001 and 1930–2007) and by extending Douglas's (1992) analyses of worldwide gauges by 25 years.

The extension of the Douglas (1992) data from 1905 to 1985 for 25 years to 2010 included the period from 1993 to 2010 when satellite altimeters recorded a sea-level trend greater than that of the 20th century, yet the addition of the 25 years resulted in a slightly greater deceleration. The explanation may be, as noted by Domingues *et al.* (2008), that altimeter and tide-gauge

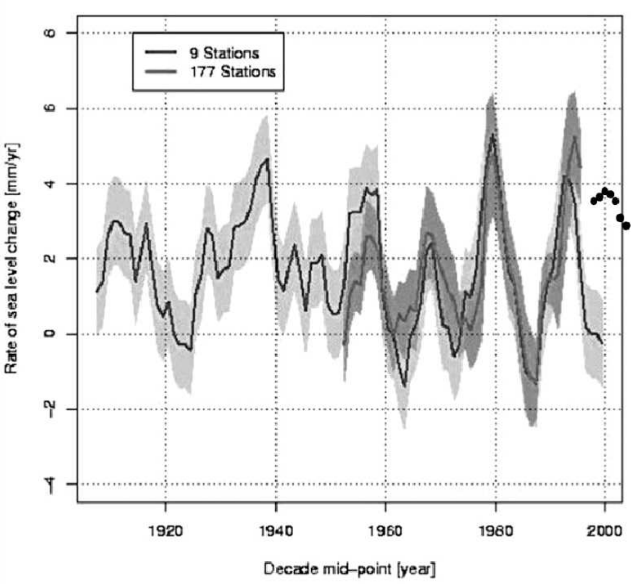

Figure 6. Altimeter data (black dots) plotted on figure from Holgate (2007).

measurements were in good agreement up until 1999 and then began to diverge with the altimeters recording a significantly higher sea-level trend than worldwide-tide gauge records. Domingues *et al.* say that an explanation for the divergence is “urgently needed” (p. 1092) This divergence adds significant uncertainty to the altimeter measurements because tide-gauge records are used to calibrate the altimeter and correct for drift (Bindoff *et al.*, 2007). Moreover, Ablain *et al.* (2009) show that 3- and 5-year moving averages of the trend measured by the altimeters have shown a continual decline in trend with the 3-year average having recently dropped as low as 1 mm/y and the 5-year average approaching 2 mm/y. We analyzed the altimeter data from November 1992 to April 2010 and found a deceleration of -0.06 mm/y^2. Furthermore, Holgate (2007) showed decadal oscillations from 1904 to 2003 by plotting 10-year moving averages of trends for tide-gauge data. We performed the same analysis using data from the University of Colorado (2010). Figure 6 shows 10-year moving averages of trends measured by the altimeters (represented by black dots) plotted *vs.* Holgate’s data. The trend from 1993 to 2003 is represented by a dot at 1998, the trend from 1994 to 2004 by another dot at 1999, and so on with the final dot at 2005, representing the trend from 2000 to 2010. When viewed in this historical perspective, the altimeter measurements appear similar to several decadal oscillations over the past 100 years, and it is not possible to determine if the increased trend measured by the altimeters is the leading edge of acceleration or merely a typical decadal oscillation; however, the decreasing average suggests an oscillation.

Chao, Wu, and Lee (2008) analyzed the effect of water impoundment by reservoirs and determined that the impoundment reduced sea-level rise by an average of approximately 0.55 mm/y for the past half-century. They showed (in their Figure 4) that if the data of Church and White (2006) were modified to include the impoundment, the trend of sea level since 1930 would be almost linear rather than the deceleration that we have noted. Water impoundment is a possible explanation for the deceleration we found from 1930–2010 in U.S. and worldwide-gauge records. However, in the IPCC, Bindoff *et al.* (2007) note that the reservoir impoundment is largely offset by other anthropogenic activities that accelerated since 1930, such as groundwater extraction, shrinkage of large lakes, wetland loss, and deforestation. Sahagian (2000) indicated that the net land–water interchange that includes all of these factors was on the order of 0.05 mm y^{-1} of sea-level rise over the past 50 years, with an uncertainty several times as large. This net contribution to sea level is an order of magnitude less than the contribution that Chao, Wu, and Lee (2008) determined by considering only impoundment. Huntington (2008) showed ranges of the contribution of each term of the land–water interchange determined in several studies and concluded that the net effect of all the contributions was to increase the sea-level trend. Therefore, the conclusions of Sahagian (2000) and Huntington (2008) do not support the land–water interchange as an explanation for the deceleration of sea level in the 20th century. However, there are large uncertainties in the magnitudes of the terms in the land–water interchange and disagreements among investigators as to the net effect of the interchange. For example, Gornitz (2001) determined that the net was a reduction of 0.9 ± 0.5 mm/y (SD) in sea-level rise.

Gravity Recovery and Climate Experiment (GRACE) twin satellites launched in March 2002 are making detailed measurements of Earth’s gravity field and have the potential to reduce the uncertainty of the contribution of the land–water interchange to sea-level change. Ramillien *et al.* (2008) analyzed GRACE measurements for a 3-year period from 2003–06 and determined that the net contribution of the land–water interchange was to increase the trend of sea level by 0.19 ± 0.06 mm/y. Llovel *et al.* (2010) performed a similar analysis for the 7-year period from August 2002 to July 2009 and determined the opposite, *i.e.,* that the interchange decreased the trend of sea level by 0.22 ± 0.05 mm/y. They noted that during the period of analysis the cycle of dry and wet conditions in the Amazon basin dominated the total land–water interchange signal and stated, “The fact that the land-water component oscillates from positive to negative values depending on the time span strongly suggests the dominance of interannual variability for this component” (pp. 186–187). Interannual variability that is sufficiently large enough to change the sign of the net land–water interchange suggests that the net contribution of reservoir impoundment, groundwater extraction, shrinkage of large lakes, wetland loss, and deforestation must be close to zero and, therefore, the net contribution of these terms does not explain the deceleration of sea level from 1930–2010. Llovel *et al.* (2010) concluded that year-to-year variability so dominated the value they estimated that it could not be considered as representative of a long-term trend. Several additional years of GRACE measurements will be necessary to accurately determine the contribution of the land–water interchange to sea level.

CONCLUSIONS

Our analyses do not indicate acceleration in sea level in U.S. tide gauge records during the 20th century. Instead, for each time period we consider, the records show small decelerations that are consistent with a number of earlier studies of worldwide-gauge records. The decelerations that we obtain are opposite in sign and one to two orders of magnitude less than the +0.07 to +0.28 mm/y^2 accelerations that are required to reach sea levels predicted for 2100 by Vermeer and Rahmsdorf (2009), Jevrejeva, Moore, and Grinsted (2010), and Grinsted, Moore, and Jevrejeva (2010). Bindoff *et al.* (2007) note an increase in worldwide temperature from 1906 to 2005 of 0.74°C. It is essential that investigations continue to address why this worldwide-temperature increase has not produced acceleration of global sea level over the past 100 years, and indeed why global sea level has possibly decelerated for at least the last 80 years.

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REFERENCES

Ablain, M.; Cazenave, A.; Valladeau, G., and Guinehut, S., 2009. A new assessment of the error budget of global sea level rate estimated by satellite altimetry over 1993–2008. *Ocean Science*, 5, 193–201.

Bindoff, N.L.; Willebrand, J.; Artale, V.; Cazenave, A.; Gregory, J.; Gulev, S.; Hanawa, K.; Le Quéré, C.; Levitus, S.; Noijiri, Y.; Shum, C.K.; Talley, L.D.; and Unnikrishnan, A., 2007. Observations: oceanic climate change and sea level. *In:* Solomon, S., et al. (eds.), *Climate Change 2007: The Physical Science Basis, Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, pp. 385–432.

Chao, B.F.; Wu, Y.H., and Lee, Y.S., 2008. Impact of artificial reservoir water impoundment on Global Sea Level. *Science*, 320, 212, doi:10.1126/science.1154580.

Church, J.A.; White, N.J.; Coleman, R.; Lambeck, K., and Mitrovica, J.X., 2004. Estimates of the regional distribution of sea-level rise over the 1950 to 2000 period. *Journal of Climate*, 17(13), 2609–2625.

Church, J.A. and White, N.J., 2006. 20th century acceleration in global sea-level rise. *Geophysical Research Letters*, 33, L01602, doi:10.1029/2005GL024826.

Domingues, C.M.; Church, J.A.; White, N.J.; Gleckler, P.J.; Wiffels, S.E.; Barker, P.M., and Dunn, J.R., 2008. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. *Nature*, 453, 1090–1094, doi:10, 1038/nature07080.

Douglas, B.C., 1992. Global sea level acceleration. *Journal of Geophysical Research*, 97(C8), 12699–12706.

Gornitz, V., 2001. Impoundment, groundwater mining, and other hydrologic transformations: impacts on global sea level. *In:* Douglas, B.C., Kearney, M.S., and Leatherman, S.D. (eds.), *Sea Level Rise*. San Diego, California and London: Academic Press, pp. 97–116

Grinsted, A.; Moore, J.C., and Jevrejeva, S., 2010. Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. *Climate Dynamics*, 34, 461–472, doi:10.1007/s00382-008-0507-2.

Holgate, J.R. and Woodworth, P.L., 2004. Evidence for enhanced coastal sea level rise during the 1990's. *Geophysical Research Letters*, 31, L07305, doi:10, 1029/2004GL019626.

Holgate, S.J., 2007. On the decadal rates of sea level change during the twentieth century. *Geophysical Research Letters*, 34, L01602, doi:1029/2006GL028492.

Huntington, T.G., 2008. Can we dismiss the effect of changes in land-based water storage on sea-level rise? *Hydrological Processes*, 22, 717–723.

Jevrejeva, S.; Grinsted, A.; Moore, J.C., and Holgate, S., 2006. Nonlinear trends and multiyear cycles in sea level records. *Journal of Geophysical Research*, 111, C09012, doi:10.1029/2005JC003229.

Jevrejeva, S.; Moore, J.C.; Grinsted, A., and Woodworth, P.L., 2008. Recent global sea level acceleration started over 200 years ago? *Geophysical Research Letters*, 35, L08715, doi:10, 1029, 2008 GL033611.

Jevrejeva, S.; Moore, J.C., and Grinsted, A., 2010. How will sea level respond to changes in natural and anthropogenic forcings by 2100? *Geophysical Research Letters*, 37, L07703, doi:10.1029/2010GL042947 (accessed May 4, 2010).

Leuliette, E.W.; Nerem, R.S., and Mitchum, G.T., 2004. Calibration of TOPEX/Poseidon and Jason altimeter data to construct a continuous record of mean sea level change. *Marine Geodesy* 27(1–2), 79–94.

Llovel, W.; Becker, M.; Cazenave, A.; Cretaux, J-F., and Ramillien, G., 2010. Global land water storage change from GRACE over 2002–2009; inference on sea level. *Geoscience* 342, 179–188.

Meehl, G.A.; Stocker, T.F.; Collins, W.; Friedlingstein, P.; Gaye, A.; Gregory, J.; Kitoh, a.; Knutti, R.; Murphy, J.; Noda, A.; Raper, S.; Watterson, I.; Weaver, A., and Zhao, Zong, Ci., 2007. Global climate change projections. *In:* Solomon, S., et al. (eds.), *Climate Change 2007: The Physical Science Basis, Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, pp. 749–844.

Merrifield, M.A. and Merrifield, S.T., 2009. An anomalous recent acceleration of global sea level rise. *Journal of Climate*, 22, 5772–5781.

Miller, L. and Douglas, B.C., 2006. On the rate and causes of twentieth century sea-level rise. *Philosophical Transactions of the Royal Society*, 364, 805–820, doi:10,1098/rsta.2006.1738 (accessed March 21, 2010).

Permanent Service for Mean Sea Level, 2010a. Obtaining Tide Gauge Data. http://www.psmsl.org/data/obtaining/ (Accessed December 2010).

Permanent Service for Mean Sea Level, 2010b. Church and White Global Mean Sea Level Reconstruction. http://www.psmsl.org/products/reconstructions/church.php (Accessed: December 2010).

Ramillien, G.; Bouhours, S.; Lombard, A.; Cazenave, A.; Flechtner, F., and Schmidt, R., 2008. Land water storage contribution to sea level from GRACE geoid data over 2003–2006. *Global and Planetary Change*, 60, 381–392.

Richardson, K.; Steffen, W.; Schellnhuber, H.J.; Alcamo, J.; Barker, T.; Kammen, D.M.; Leemans, R.; Liverman, D.; Munasinghe, M.; Osman-Elasha, B.; Stern, N., and Wæver, O., 2009. Synthesis Report, Climate Change—Global Risks, Challenges and Decisions. Copenhagen, Denmark, March 10–12, http://climatecongress.ku.dk/pdf/synthesisreport (accessed May 3, 2010).

Sahagian, D.L., 2000. Global physical effects of anthropogenic hydrological alterations: sea level and water redistribution. *Global Planet Change* 25, 39–48.

Sturges, W. and Hong, B.G., 2001. Decadal variability of sea level. *In:* Douglas, B.C.; Kearney, M.S., and Leatherman, S.P. (eds.), *Sea Level Rise*, San Diego, California and London: Academic Press, pp. 165–179.

University of Colorado, 2010. Sea level change. http://sealevel.colorado.edu/current/sl_ib_ns_global.pdf (accessed May 10, 2010).

Vermeer, M. and Rahmsdorf, S., 2009 Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences*, 106, No. 51, 21527–21532 doi:_10.1073_pnas.0907765106.

White, N.J.; Church, J.A., and Gregory, J.M., 2005. Coastal and global averaged sea level rise for 1950 to 2000. *Geophysical Research Letters*, 32, L01601, doi:10.1029/2004GL021391.

Willis, J., 2010. Waves in the bathtub—why sea level rise isn't level at all, NASA. http://climate.nasa.gov/blogs/index.cfm?FuseAction=ShowBlog&NewsID=239 (accessed April 21, 2010).

Woodworth, P.L., 1990. A search for accelerations in records of

European mean sea level. *International Journal of Climatology*, 10, 129–143.

Woodworth, P.L. and Player, R., 2003. The permanent service for mean sea level: an update to the 21st century. *Journal of Coastal Research*, 19, 287–295.

Woodworth, P.L.; White, N.J.; Jevrejeva, S.; Holgate, S.J.; Church, J.A., and Gehrels, W.R., 2009. Evidence for the accelerations of sea level rise on multi-decade and century timescales. *International Journal of Climatology*, 29, 777–789, doi:10.1002/joc.1771.