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# Sea-Level Acceleration: Analysis of the World's High-Quality Tide Gauges

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**ABSTRACT**

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Coastal sea-level acceleration is analyzed using all of the world's high-quality tide gauge recordings with lengths of at least 75 years that extend through 2017–19. Earlier studies have demonstrated that tide gauge recordings of at least 75 years in length are required to reduce the effects of multidecadal variations on acceleration. There are 149 tide gauge records that meet the criteria. Mean and median sea-level accelerations based on these gauges were 0.0128 ± 0.0064 mm/y$^2$ and 0.0126 ± 0.0080 mm/y$^2$, respectively, both at the statistically significant 95% confidence level. The mean acceleration is larger than that of earlier studies that analyzed fewer gauges or considered record lengths shorter than 75 years.

**ADDITIONAL INDEX WORDS:** *Global sea-level rise, tide gauges, decadal variations, climate change, decadal variations.*

## INTRODUCTION

Altimeter recordings show that from 1993–2018 the sea level rose a rate of 3.1 mm/y (University of Colorado, 2020). If this rise rate were to continue from 2020–2100, sea level would rise about 0.25 m by 2100. However, due to increasing global temperatures, the rate of sea-level rise is expected to increase. IPCC (2019) projected that the rate of sea-level rise for its Representative Concentration Pathways scenarios 2.6, 4.5, and 8.5 watts/m$^2$ would average 4, 7, and 15 mm/y, respectively, by 2100 with corresponding mean sea-level rises of 0.43, 0.55, and 0.84 m. Sea-level rise must accelerate to reach these greater levels. Great interest has been shown in determining whether sea-level acceleration has been detected to date in tide gauge recordings.

### Requirement for Records at Least 75 Years in Length

Multidecadal temporal variations in coastal sea-level obscure sea-level acceleration (Douglas, 1992; Woodworth, 1990). Wenzel and Schröter (2010) analyzed recordings of 56 tide gauges from around the world from 1900–2006 and found that coastal sea level was dominated by oscillations with periods of about 25 years and 50–75 years. Jevrejeva *et al*. (2006) found "substantial" 13–30 year periodicity in tide gauge records, and Holgate (2007) noted a 20-year cycle in the rate of sea-level rise. These multidecadal sea-level variations are caused in part by ocean response to natural climate variations in the patterns of wind stress and atmospheric pressure (Bromirski *et al*, 2011; Merrifield, 2011; Sturges and Douglas, 2011; Sturges and Hong, 2001). The impact of multidecadal variations in determining sealevel acceleration can be significantly reduced by increasing the record lengths of tide gauges that are analyzed (Douglas, 1992).

Douglas (1992) calculated accelerations for all worldwide tide gauge records with lengths of 10 years or more that were in the database of the Permanent Service for Mean Sea Level (PSMSL). Douglas found that the scatter of acceleration values increased rapidly with a decrease in record length, that accelerations were as likely to be negative as positive, and that the magnitude of the variations for 10-year record lengths ranged from about –1 mm/y$^2$ to +1 mm/y$^2$. Houston and Dean (2013) updated the analysis of Douglas (1992) with 20 years of additional data using the same approach. They determined acceleration *vs*. record length for PSMSL tide gauge records with lengths of 10–100 years (1123 records), as seen in Figure 1. A large number of records have been added since Douglas (1992), with record lengths of 10–20 years (Figure 1). For record lengths of 10 years, accelerations vary by a very large ±2 mm/y$^2$, which would change sea level by ±10 m if they persisted for 100 years. The range of scatter decreases almost two orders of magnitude from ±2 mm/y$^2$ for record lengths of 10 years to about ±0.03 mm/y$^2$ for record lengths of 75 years. The range of scatter at a record length of 60 years is about five times that of 75 years, an indication that Douglas (1992) followed the correct path in analyzing only tide gauge records that were 75 years or greater in length. Figure 1 shows that 100-year records have about the same degree of scatter as 75-year records.

The problem of using records less than 75 years in length to analyze sea-level acceleration is illustrated by Boon and Mitchell (2015), who used 40–60 year sections of longer records. For example, they analyzed 46 years from 1969–2014 of the San Diego, California, United States, tide gauge record, determined that it had a negative acceleration of –0.103 ± 0.144 mm/y$^2$, and used this to project a mean fall in sea level in

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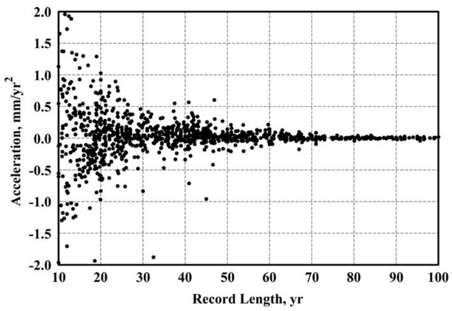


Figure 1. Accelerations *vs*. gauge record lengths using 1123 PSMSL tide gauges records with lengths of 10–100 years and illustrating the importance of analyzing only records with length 75 years or greater (from Houston and Dean [2013]).

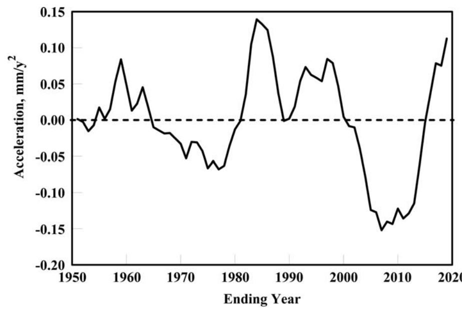


Figure 2. Sea-level acceleration at San Diego based on using 46-year analysis windows from 1906–2019. In a period of only 5 years, the acceleration changes from a large negative to positive value. It is clear that 46-year records cannot be used to project future sea-level rise.

San Diego by the year 2050. However, San Diego has a tide gauge record starting in 1906. Using monthly sea-level data from PSMSL, Houston (2016) showed that by taking the entire San Diego record from 1906–2019, starting with a 46-year record from 1906–1951 and then moving the analysis a year to 1907–52 and so on until 1974–2019, Figure 2 was obtained. Figure 2 shows that acceleration depends strikingly on the 46-year period considered. The acceleration for 1974–2019 is 0.113 $\pm$ 0.077 mm/y$^2$ (95% = 95% confidence level). An additional five years of record results in a change from a large negative to a large positive acceleration. For the total record from 1906–2019, San Diego has an acceleration of 0.011 $\pm$ 0.007 mm/y$^2$ (95%), an order of magnitude less than the absolute values of the 1969–2014 and 1974–2019 accelerations. Houston and Dean (2013) showed that if one uses 40–60 year records, every long gauge record in the world has large variations in acceleration due to multidecadal variations that are similar to that of the San Diego record.

## Ground Motions at Tide Gauges

Tide gauges measure relative sea-level rise. If the vertical ground motion is constant, it affects sea-level trend, but not acceleration. However, if the motion is not constant, it affects determination of acceleration. For example, short-term vertical tectonic movements, such as those arising from earthquakes, can cause significant datum changes that, if uncorrected, lead to spurious accelerations when gauge recordings are analyzed. Similarly, there are cases where land development and groundwater extraction have changed the rate of local ground vertical motion at tide gauges, leading to spurious accelerations. Sea-level acceleration is not affected by relatively constant vertical ground motions such as glacial isostatic adjustment (Douglas, 1992; Woodworth, Menendez, and Gehrels, 2011). Tide gauges that are at locations with questionable vertical motions should be excluded in analyses of acceleration.

## Sea-Level Acceleration Studies

Several studies have analyzed sea-level acceleration, generally addressing multidecadal sea-level variations by considering only long tide gauge records and excluding questionable recordings.

Douglas (1992) analyzed 23 representative global tide gauge records that each had 80 years of data from 1905–85 and determined a sea-level acceleration of –0.011 $\pm$ 0.012 mm/y$^2$ (standard deviation [SD]). Houston and Dean (2011) extended Douglas's work into the 21st century by adding 25 years to his analysis to extend it to 1905–2010. They obtained a sea-level acceleration almost the same as Douglas at –0.012 $\pm$ 0.012 mm/y$^2$ (SD). Based on studies such as those of Woodworth (1990) and Douglas (1992), the Intergovernmental Panel on Climate Change (IPCC, 2001) concluded, "There is no evidence for any acceleration of sea level rise in data from the 20th century data alone."

Holgate (2007) analyzed nine long and representative worldwide tide-gauge records over a 100-year period from 1904–2003 and found the sea-level trend higher in the period 1904–53 than the period 1954–2003. The difference in trend he found was equivalent to an acceleration of –0.0012 mm/y$^2$.

Jevrejeva *et al*. (2008) developed synthetic "virtual stations" using all 1023 tide gauge records in the PSMSL data base regardless of record length. They had 385,324 individual monthly records for the 1023 gauges, resulting in an average record length of about 30 years. The gauges they considered had record lengths very similar to those in Figure 1, which has about 5 years of additional data. Records extended from as early as 1700 to 2000. They concluded that global sea-level acceleration up to the 2008 was about 0.01 mm/y$^2$ and appeared to have started at the end of the 18th century.

Wenzel and Schröter (2010) reconstructed mean sea level from 56 tide gauge recordings from 1950–2006 using neural networks and found that some ocean basins had small sea-level accelerations and others small decelerations. They found a global acceleration for all the gauge recordings of 0.0016 $\pm$ 0.0043 mm/y$^2$ (SD).

Church and White (2011) used TOPEX/Poseidon satellite altimeter data from 1993–2009 to estimate global empirical orthogonal functions (EOFs) that were then combined with historical tide gauge data to estimate global sea-level rise from 1880–2009 and 1900–2009. This enabled them to combine the benefits of the relatively short time but virtually complete global coverage produced by satellite altimetry with the relatively long time with spatially sparse coverage of world tide gauges. They combined records of nearby tide gauges, resulting in 290 records. Records lengths varied from about 12 to 202 years with an average record length of 55 years. They found considerable variability in sea-level acceleration during the 20th century and a global acceleration from 1880–2009 of 0.009 ± 0.003 mm/y$^2$ and from 1900–2009 of 0.009 ± 0.004 mm/y$^2$ (SD).

Ray and Douglas (2011) also used EOFs based on approximately 17 years (1993–2009) of satellite altimetry from the TOPEX/Poseidon, Jason-1, and Jason-2 satellite missions. Their approach attempted to address the problem of unknown tide-gauge datums in Church and White (2011), although they concluded their own approach also had problems. They used data at 89 tide gauges with at least 40 years of data and a median timespan of 64 years. They concluded that no statistically significant acceleration occurred in global mean sea level. They noted that there was no reason to assume that EOFs based on 17 years of altimetry were sufficient to describe sea level throughout the 20th century or before.

Olivieri and Spada (2013) analyzed tide gauge records with the single criterion that record lengths be greater than 50 years. They did not eliminate tide gauge records for any reason, including gauges in Japan where nearby earthquakes had occurred. They used 315 tide gauge records that had record lengths greater than 50 years during the time period from 1810–2010. From figure 6a of Spada and Galassi (2012), about 60% of the tide gauges that Olivieri and Spada (2013) considered had record lengths between 50–75 years, so their analysis was dominated by gauges with records less than 75 years. As seen in Figure 1, this results in their sea-level acceleration being significantly affected by multidecadal variations. They calculated an acceleration of 0.0042 ± 0.0024 mm/y$^2$.

Hogarth (2014) analyzed sea-level acceleration, using up to 117 tide gauge records greater than 100 years in length and in most cases with at least 75% of data. The data were from PSMSL and extended through 2012. However, he noted that only 50 of the tide gauge recordings that he used from the PSMSL data set with lengths over 100 years were of revised local reference (RLR) quality. RLR-quality data are controlled tide gauge time series where a tide gauge datum history is provided by the supplying authority. Non-RLR gauge data are not strictly quality controlled, with benchmarks having been lost or time series having gaps. Hogarth (2014) carefully used a variety of other data sources to fill in data gaps or to extend data series, including use of historical documents and ancillary data. In addition, Hogarth developed composite time series using near-neighbor tide gauges. His figure 3 shows that about two-thirds of the gauges he analyzed had records with data that he added. Using this approach, he added 4800 years of synthetic record to the analysis. This is an average addition of more than 60 years per record for the two-thirds of the gauges he extended. He obtained an acceleration of 0.0105 ± 0.0081 mm/y$^2$ (90% confidence level).

## METHODS

This section describes the least-squares method that was used to determine sea-level acceleration, the source of the tide gauge data set, and the criteria used to winnow the set.

The analysis of sea-level acceleration uses a least-squares fit of the standard quadratic equation:

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

where, $y(t)$ is the measured tide level at time $t$ in years, $a_0$ is a constant, $a_1$ is the linear trend, and $a_2$ is the acceleration in mm/y$^2$.

Monthly gauge data that were used were from PSMSL (Holgate *et al*. 2013; PSMSL, 2020). Only tide-gauge records of length 75 years or greater that were RLR quality controlled and at least 75% complete were considered. Records were rejected if PSMSL had a warning. For records of 75 years or longer, there were warnings for Batumi, Georgia, on the Black Sea (PSMSL ID 51); Manila, Philippines (ID 145); Garden Reach, India (ID 438); Fort Phrachula Chomklao, Thailand (ID 444); and Valparaiso, Chile (ID 499). Hogarth (2014) included Batumi and Manila in his analysis. However, for example, PSMSL points out that Manila had a rapid increase in relative sea level starting in about 1965 due to sediment deposition from the river discharge and extensive land reclamation with subsidence a likely factor. From 1901 to 1965, relative sea level at the Manila tide gauge at a rose rate of about 1.5 mm/y, but from 1965 through 2018 it rose at a rate of 14.2 mm/y.

In addition to requiring records at least 75 years in length, only records continuing to 2018–20 (that is, through 2017–19) were considered. When the records were accessed in 2020, most gauges had records through 2018, but some records were through 2017 or 2019, with an average termination date for all records of 2018.3. Records terminating before 2017 were not considered because these records are missing part or all of the increase in the rate of sea-level rise that has been recorded since at least the end of 1992 by satellite altimeters (Church *et al*. 2008). For example, the Finland gauges at Lyokki (ID 16) and Lypyrtti (ID 17) were not considered because their records extend from 1858–1936. Similarly, the Aberdeen II (ID 21) gauge in the United Kingdom has records from 1862–1965. Hogarth (2014) used these records, employing a method to fill gaps, presumably by comparing to nearby gauges.

There are 149 tide gauge records that satisfy the criteria used.

## RESULTS

This section provides a brief summary of mean and median accelerations calculated using Equation (1) for each of the 149 tide gauge records. In addition, the change in mean and median values are given if records are shortened by 5 and 10 years.

Table 1 shows the 149 tide gauges considered, their PSMSL IDs, start (beginning of the year listed) and end times (end of the year listed), length of records, country locations, and $a_2$ values. These records have an average length of 106 years, with 110 records having positive accelerations and 39 negative accelerations.

The mean acceleration based on the 149 records is 0.0128 ± 0.0064 mm/y$^2$ (95%). As in Douglas (1992), the computed error of the mean is from the residuals about the mean, not from the error estimates of the individual gauge records. The acceleration based on the median is a similar 0.0126 ± 0.0080 mm/y$^2$ (95%). Shapoval *et al*. (2020) found an acceleration median larger than the mean and recommended that the median be

Table 1. *Accelerations determined for 149 worldwide gauges with records extending for 75 years or more through at least the years 2017–19.*

| Name | ID | Start | End | Years | Location | $a_2$ mm/y$^2$ |
|---|---|---|---|---|---|---|
| BREST | 1 | 1807 | 2018 | 212 | France | 0.0128 |
| SHEERNESS | 3 | 1832 | 2018 | 187 | Great Britain | 0.0172 |
| HOLYHEAD | 5 | 1938 | 2018 | 81 | Great Britain | 0.0244 |
| CUXHAVEN 2 | 7 | 1843 | 2018 | 176 | Germany | –0.0034 |
| WISMAR 2 | 8 | 1848 | 2018 | 171 | Germany | 0.0044 |
| MAASSLUIS | 9 | 1848 | 2018 | 171 | Netherlands | 0.0042 |
| SAN FRANCISCO | 10 | 1854 | 2019 | 166 | United States | 0.0146 |
| WARNEMUNDE 2 | 11 | 1855 | 2018 | 164 | Germany | 0.0066 |
| NEW YORK | 12 | 1856 | 2019 | 164 | United States | 0.0034 |
| TRAVEMUNDE | 13 | 1856 | 2018 | 163 | Germany | 0.0012 |
| HELSINKI | 14 | 1879 | 2018 | 140 | Finland | 0.0246 |
| VLISSINGEN | 20 | 1862 | 2018 | 157 | Netherlands | 0.0302 |
| HOEK VAN HOLLAND | 22 | 1864 | 2018 | 155 | Netherlands | –0.0016 |
| DEN HELDER | 23 | 1865 | 2018 | 154 | Netherlands | 0.0036 |
| DELFZIJL | 24 | 1865 | 2018 | 154 | Netherlands | 0.0144 |
| HARLINGEN | 25 | 1865 | 2018 | 154 | Netherlands | –0.0020 |
| IJMUIDEN | 32 | 1871 | 2018 | 148 | Netherlands | 0.0254 |
| POTI | 41 | 1874 | 2018 | 145 | Georgia | 0.0212 |
| STAVANGER | 47 | 1919 | 2019 | 101 | Norway | 0.0204 |
| VAASA / VASA | 57 | 1883 | 2018 | 136 | Finland | 0.0140 |
| BERGEN | 58 | 1915 | 2019 | 105 | Norway | 0.0184 |
| MARSEILLE | 61 | 1885 | 2018 | 134 | France | –0.0032 |
| OSLO | 62 | 1885 | 2019 | 135 | Norway | –0.0110 |
| OLANDS NORRA UDDE | 69 | 1887 | 2018 | 132 | Sweden | 0.0048 |
| KUNGSHOLMSFORT | 70 | 1887 | 2018 | 132 | Sweden | 0.0116 |
| HANKO / HANGO | 71 | 1887 | 2018 | 132 | Finland | 0.0184 |
| AARHUS | 76 | 1888 | 2017 | 130 | Denmark | 0.0100 |
| STOCKHOLM | 78 | 1889 | 2018 | 130 | Sweden | 0.0130 |
| OULU/ULEABORG | 79 | 1889 | 2018 | 130 | Finland | –0.0030 |
| ESBJERG | 80 | 1889 | 2017 | 129 | Denmark | 0.0110 |
| FREDERICIA | 81 | 1889 | 2017 | 129 | Denmark | 0.0058 |
| KOBENHAVN | 82 | 1889 | 2017 | 129 | Denmark | 0.0160 |
| RATAN | 88 | 1892 | 2018 | 127 | Sweden | 0.0080 |
| HIRTSHALS | 89 | 1892 | 2017 | 126 | Denmark | 0.0082 |
| FREDERIKSHAVN | 91 | 1894 | 2017 | 124 | Denmark | –0.0066 |
| NORTH SHIELDS | 95 | 1895 | 2018 | 124 | Great Britain | –0.0044 |
| SLIPSHAVN | 98 | 1896 | 2017 | 122 | Denmark | 0.0126 |
| FREMANTLE | 111 | 1897 | 2019 | 123 | Australia | 0.0058 |
| FERNANDINA BEACH | 112 | 1897 | 2019 | 123 | United States | 0.0190 |
| KORSOR | 113 | 1897 | 2017 | 121 | Denmark | 0.0086 |
| KLAIPEDA | 118 | 1898 | 2018 | 121 | Lithuania | 0.0436 |
| HORNBAEK | 119 | 1891 | 2017 | 127 | Denmark | 0.0210 |
| GEDSER | 120 | 1892 | 2017 | 126 | Denmark | 0.0058 |
| TROIS-RIVIERES | 126 | 1899 | 2018 | 120 | Canada | –0.0602 |
| SEATTLE | 127 | 1899 | 2019 | 121 | United States | 0.0098 |
| ABURATSUBO | 130 | 1930 | 2018 | 89 | Japan | 0.0142 |
| WAJIMA | 132 | 1930 | 2018 | 89 | Japan | 0.0704 |
| HOSOJIMA | 133 | 1930 | 2018 | 89 | Japan | 0.0228 |
| PHILADELPHIA | 135 | 1900 | 2019 | 120 | United States | 0.0216 |
| BATISCAN | 144 | 1901 | 2018 | 118 | Canada | –0.0246 |
| BALTIMORE | 148 | 1902 | 2019 | 118 | Unites States | 0.0074 |
| TRIESTE | 154 | 1875 | 2019 | 145 | Italy | 0.0046 |
| HONOLULU | 155 | 1905 | 2019 | 115 | United States | –0.0034 |
| SAN DIEGO | 158 | 1906 | 2019 | 114 | United States | 0.0108 |
| GALVESTON II | 161 | 1908 | 2019 | 112 | United States | 0.0182 |
| BALBOA | 163 | 1908 | 2019 | 112 | Panama | –0.0056 |
| TOFINO | 165 | 1909 | 2018 | 110 | Canada | 0.0206 |
| VICTORIA | 166 | 1909 | 2018 | 110 | Canada | 0.0074 |
| PRINCE RUPERT | 167 | 1909 | 2018 | 110 | Canada | 0.0124 |
| MANTYLUOTO | 172 | 1910 | 2018 | 109 | Finland | 0.0324 |
| KO LAK | 174 | 1940 | 2018 | 79 | Thailand | 0.1172 |
| VANCOUVER | 175 | 1909 | 2018 | 110 | Canada | 0.0266 |
| SMOGEN | 179 | 1911 | 2018 | 108 | Sweden | 0.0350 |
| ATLANTIC CITY | 180 | 1911 | 2019 | 109 | United States | 0.0154 |
| PORTLAND | 183 | 1912 | 2019 | 108 | United States | –0.0040 |
| KEY WEST | 188 | 1913 | 2019 | 107 | United States | 0.0168 |
| NEUVILLE | 192 | 1914 | 2018 | 105 | Canada | –0.0108 |
| POINT ATKINSON | 193 | 1914 | 2018 | 105 | Canada | –0.0040 |

Table 1. *(continued).*

| Name | ID | Start | End | Years | Location | $a_2$ mm/y$^2$ |
|---|---|---|---|---|---|---|
| PIETARSAARI /JAKOBSTAD | 194 | 1914 | 2018 | 105 | Finland | 0.0378 |
| SAINT JOHN, N.B | 195 | 1896 | 2018 | 123 | Canada | –0.0068 |
| SYDNEY, FORT DENISON 2 | 196 | 1914 | 2019 | 106 | Australia | 0.0164 |
| DESCHAILLONS | 201 | 1915 | 2018 | 104 | Canada | –0.0320 |
| NEWLYN | 202 | 1915 | 2018 | 104 | Great Britain | 0.0100 |
| FURUOGRUND | 203 | 1916 | 2018 | 103 | Sweden | 0.0560 |
| TUAPSE | 215 | 1917 | 2018 | 102 | Russia | 0.0172 |
| PORT PIRIE | 216 | 1941 | 2018 | 78 | Australia | 0.0960 |
| WELLINGTON HARBOUR | 221 | 1944 | 2018 | 75 | Australia | 0.0476 |
| LEWES | 224 | 1924 | 2019 | 96 | United States | 0.0350 |
| KETCHIKAN | 225 | 1919 | 2019 | 101 | United States | –0.0220 |
| KEMI | 229 | 1920 | 2018 | 99 | Finland | 0.0350 |
| CHARLESTON I | 234 | 1921 | 2019 | 99 | United States | 0.0052 |
| BOSTON | 235 | 1921 | 2019 | 99 | United States | –0.0028 |
| WEST-TERSCHELLING | 236 | 1921 | 2018 | 98 | Netherlands | 0.0264 |
| TURKU/ABO | 239 | 1922 | 2018 | 97 | Netherlands | 0.0300 |
| RAAHE/BRAHESTAD | 240 | 1922 | 2018 | 97 | Finland | 0.0248 |
| LOS ANGELES | 245 | 1923 | 2019 | 97 | United States | 0.0204 |
| PENSACOLA | 246 | 1923 | 2019 | 97 | United States | 0.0214 |
| FOGLO/DEGERBY | 249 | 1923 | 2018 | 96 | Aland Islands | 0.0112 |
| LA JOLLA | 256 | 1924 | 2019 | 96 | United States | 0.0034 |
| ASTORIA | 265 | 1925 | 2019 | 95 | United States | 0.0134 |
| KASKINEN/KASKO | 285 | 1926 | 2018 | 93 | United States | 0.0382 |
| SEWELLS POINT | 299 | 1927 | 2019 | 93 | United States | 0.0258 |
| HILO, HAWAII ISLAND | 300 | 1927 | 2019 | 93 | United States | –0.0168 |
| TREGDE | 302 | 1927 | 2019 | 93 | Norway | 0.0152 |
| ANNAPOLIS | 311 | 1928 | 2019 | 92 | United States | 0.0098 |
| NARVIK | 312 | 1928 | 2019 | 92 | Norway | –0.0040 |
| HEIMSJO | 313 | 1928 | 2019 | 92 | Norway | 0.0302 |
| HAMINA | 315 | 1928 | 2018 | 91 | Finland | 0.0184 |
| KLAGSHAMN | 330 | 1929 | 2018 | 90 | Sweden | 0.0116 |
| EASTPORT | 332 | 1929 | 2019 | 91 | United States | –0.0130 |
| NEWPORT | 351 | 1930 | 2019 | 90 | Unites States | 0.0164 |
| MERA | 359 | 1931 | 2018 | 88 | Japan | 0.0108 |
| WASHINGTON DC | 360 | 1931 | 2019 | 89 | United States | 0.0258 |
| ABERDEEN I | 361 | 1931 | 2018 | 88 | Great Britain | 0.0270 |
| SANDY HOOK | 366 | 1932 | 2019 | 88 | United States | 0.0106 |
| WOODS HOLE | 367 | 1932 | 2019 | 88 | United States | 0.0240 |
| ST. GEORGES | 368 | 1932 | 2019 | 88 | Bermuda | 0.0024 |
| RAUMA / RAUMO | 376 | 1933 | 2018 | 86 | Finland | 0.0098 |
| SANTA MONICA | 377 | 1933 | 2019 | 87 | United States | –0.0042 |
| CRESCENT CITY | 378 | 1933 | 2019 | 87 | United States | –0.0054 |
| FRIDAY HARBOR | 384 | 1934 | 2019 | 86 | United States | 0.0120 |
| NEAH BAY | 385 | 1934 | 2019 | 86 | United States | –0.0160 |
| ST. JOHN'S, NFLD. | 393 | 1935 | 2018 | 84 | Canada | –0.0022 |
| CEBU | 394 | 1935 | 2018 | 84 | Philippines | 0.0558 |
| FORT PULASKI | 395 | 1935 | 2019 | 85 | United States | 0.0364 |
| WILMINGTON | 396 | 1935 | 2019 | 85 | United States | 0.0474 |
| SASSNITZ | 397 | 1935 | 2018 | 84 | Germany | 0.0118 |
| JUNEAU | 405 | 1936 | 2019 | 84 | United States | –0.0512 |
| UCHIURA | 407 | 1944 | 2018 | 75 | Japan | 0.0712 |
| SOLOMON'S ISLAND | 412 | 1937 | 2019 | 83 | United States | 0.0440 |
| OOSTENDE | 413 | 1937 | 2017 | 81 | Belgium | 0.0412 |
| ANDENES | 425 | 1938 | 2019 | 82 | Norway | –0.0028 |
| SITKA | 426 | 1938 | 2019 | 82 | United States | –0.0344 |
| CHARLOTTETOWN | 427 | 1911 | 2018 | 108 | Canada | –0.0006 |
| CEDAR KEY II | 428 | 1938 | 2019 | 82 | United States | 0.0704 |
| NEW LONDON | 429 | 1938 | 2019 | 82 | United States | 0.0460 |
| PROVIDENCE | 430 | 1938 | 2019 | 82 | United States | 0.0418 |
| MONTEVIDEO | 431 | 1938 | 2018 | 81 | Uruguay | –0.0006 |
| ALAMEDA | 437 | 1939 | 2019 | 81 | United States | 0.0208 |
| YAKUTAT | 445 | 1940 | 2019 | 80 | United States | –0.2390 |
| KO TAPHAO NOI | 446 | 1940 | 2018 | 79 | Thailand | 0.2192 |
| CHURCHILL | 447 | 1940 | 2018 | 79 | Canada | –0.0220 |
| PORT ADELAIDE | 448 | 1940 | 2018 | 79 | Australia | –0.0156 |
| LE HAVRE | 453 | 1938 | 2018 | 81 | France | 0.0432 |
| DUNKERQUE | 468 | 1942 | 2018 | 77 | France | –0.0462 |
| ST JEAN DE LUZ | 469 | 1942 | 2017 | 76 | France | –0.0122 |

Table 1. *(continued).*

| Name | ID | Start | End | Years | Location | $a_2$ mm/y$^2$ |
|---|---|---|---|---|---|---|
| ZEEBRUGGE | 470 | 1942 | 2017 | 76 | Belgium | 0.0294 |
| VIGO | 483 | 1943 | 2018 | 76 | Spain | –0.0610 |
| LA CORUNA I | 484 | 1943 | 2018 | 76 | Spain | 0.0054 |
| SANTANDER I | 485 | 1943 | 2018 | 76 | Spain | 0.0180 |
| MALOY | 486 | 1943 | 2019 | 77 | Norway | 0.0568 |
| ADAK SWEEPER COVE | 487 | 1943 | 2019 | 77 | United States | –0.0778 |
| TARIFA | 488 | 1943 | 2018 | 76 | Spain | 0.0990 |
| NIEUWPOORT | 489 | 1943 | 2017 | 75 | Belgium | 0.0142 |
| SKAGWAY | 495 | 1944 | 2019 | 76 | United States | –0.1222 |
| PORT ISABEL | 497 | 1944 | 2019 | 76 | United States | 0.0856 |
| CEUTA | 498 | 1944 | 2018 | 75 | Spain | 0.0206 |
| PORT SAN LUIS | 508 | 1945 | 2019 | 75 | United States | 0.0168 |
| ALESUND | 509 | 1945 | 2019 | 75 | Norway | 0.0224 |

used; however, they analyzed only 32 gauge records, a subset of the 149 gauge records used in this analysis, and they used 40–60 year windows.

To see how the acceleration varies with record length, means and medians were also calculated for records reduced in lengths by 5 and 10 years. Keeping all gauge records, means and medians were 0.0073 ± 0.0066 mm/y$^2$ (95%) and 0.0112 ± 0.0082 mm/y$^2$ (95%), respectively, for reductions of 5 years and 0.0054 ± 0.0067 mm/y$^2$ (95%) and 0.0072 ± 0.0084 mm/y$^2$ (95%), respectively, for reductions of 10 years. If gauge records less than 75 years in length are eliminated from the analysis of reducing record lengths by 5 and 10 years, means and medians are 0.0059 ± 0.0055 mm/y$^2$ (95%) and 0.0104 ± 0.0069 mm/y$^2$ (95%), respectively, for reductions of 5 years and 0.0062 ± 0.0048 mm/y$^2$ (95%) and 0.0072 ± 0.0060 mm/y$^2$ (95%), respectively, for reductions of 10 years. Medians exceed means for the reduced periods as Shapoval *et al*. (2020) found in their analysis. The value of means and medians decrease when records are decreased by 5 and 10 years. If only record lengths of 75 or greater are retained, accelerations are still at the 95% confidence level.

## DISCUSSION

This section shows that sea-level accelerations vary little when records with "outlier" values are excluded from the analysis; notes results are consistent with IPCC (2019) conclusions and compares accelerations with those determined in other studies.

Four gauge records are outliers, with absolute values of acceleration greater than 0.1 mm/y$^2$: Ko Lak (ID 174), Yakutat (ID 445), Ko Taphao Noi (ID 446), and Skagway (ID 495). The tide gauges at Ko Lak and Ko Taphao Noi in Thailand are near rapidly developing tourist towns (Phuket and Hua Hin) where groundwater has been increasing withdrawn, and this has likely caused accelerated ground subsidences and, therefore, large positive relative sea-level rise accelerations. Yakutat and Skagway are in areas where the ground has been rebounding from the age of glaciation, and an increasing melting of glaciers due to climate warming has occurred that may be increasing ground upward movement, causing large negative relative sea-level rise accelerations. The PSMSL did not have warnings for these four gauges. If these four gauges are eliminated from the analysis, leaving 145 gauge records, the mean and median accelerations are 0.0133 ± 0.0042 and 0.0126 ± 0.0053 mm/y$^2$ (95%), respectively. If the 17 gauges with an absolute value greater than 0.05 mm/y$^2$ are eliminated, the mean and median accelerations are 0.0115 ± 0.0029 and 0.0119 ± 0.0037 mm/y$^2$ (95%), respectively. For all of these cases, positive accelerations occur at the statistically significant 95% confidence level. Elimination of outliers did not have a significant effect on mean and median values.

The IPCC (2019) concluded with "high confidence" that global mean sea level was accelerating and had a "very high confidence" that the sum of ice sheet and peripheral glacier contributions from Greenland and Antarctica had become the dominant source of global mean sea-level rise. The IMBIE Team (2018, 2020) showed that Greenland and Antarctica were contributing an increasing 435 gigatons/y of ice melt from 2007–12 to 463 gigatons/y from 2010–17. They also noted that there was substantial evidence for the existence of a "sustained increase in the rate of sea level rise over the 20th century and early part of the 21st century." This study shows an increasing acceleration in mean sea level when only gauges with record lengths of at least 75 years are retained with an acceleration of 0.0059 ± 0.0055 mm/y$^2$ (95%) to 2007–09, 0.0062 ± 0.0048 mm/y$^2$ (95%) to 2012–14, and 0.0128 ± 0.0064 mm/y$^2$ (95%) to 2017–19.

Table 2 compares results of this study with earlier ones. The mean acceleration determined in this study of 0.0128 ± 0.0064 mm/y$^2$ (95%) is similar to but larger than mean accelerations determined in the earlier studies. These studies have typically determined mean accelerations from about –0.01 to 0.01 mm/y$^2$. Only Douglas (1992), Holgate (2007), Houston and Dean (2011), and Hogarth (2014) used tide gauge data with record lengths of 75 years or greater. However, except for Hogarth, who analyzed 117 gauge records, these studies analyzed fewer than 24 gauges. Of the 117 gauge records analyzed by Hogarth (2014), 67 used non-RLR data that are not strictly quality controlled. About half of the gauge records considered in this paper have lengths 75–99 years and are not in Hogarth's data set. Moreover, for about half of the records with lengths of 100 years or greater that were analyzed in this paper, Hogarth filled gaps or extended records by adding on average of over 60 years of data. Therefore, only about 25% of tide gauge measured data in the two studies are in common. In addition, his records extended through 2012, whereas records in this

Table 2. *Comparisons of results in earlier studies with those of this study.*

| Study | Number of Gages | Based Completely on Measurements | Record Lengths Years | Period Years | $a_2$ mm/y$^2$ |
|---|---|---|---|---|---|
| Douglas (1992) | 23 | Yes | 80 | 1905–85 | –0.011 ± 0.012 |
| Holgate (2007) | 9 | Yes | 100 | 1904–2003 | –0.0012 |
| Jevrejeva *et al*. (2008) | 1023 | No | Average 30 | 1700–2000 | 0.01 |
| Wenzel and Schröter (2010) | 56 | No | 56 | 1950–2006 | 0.0016 ± 0.0043 |
| Houston and Dean (2011) | 23 | Yes | 105 | 1905–2010 | –0.012 ± 0.012 |
| Church and White (2011) | 290 | No | Average 55 | 1880–2009 | 0.009 ± 0.003 |
| Ray and Douglas (2011) | 89 | No | >40 | 1807–2009 | 0.00 |
| Olivieri and Spada (2013) | 315 | Yes | >50 | 1810–2010 | 0.0042 ± 0.0024 |
| Hogarth (2014) | 117 | No | >100 | 1807–2012 | 0.0105 ± 0.0081 |
| This study | 149 | Yes | >75 | 1807–2019 | 0.0128 ± 0.0064 |

analysis extend through 2017–19. Despite these significant differences, both analyses show similar and statistically significant accelerations.

Watson (2011, 2016, 2017) showed in analyses of tide gauge records in Australia, the United States, and Europe that recent accelerations in these records were not abnormal or higher than short-term rates measured at these locations in the historical record. Watson (2017) concluded in his analysis of records in Europe through 2014 that another 15–20 years of records would be necessary to determine an acceleration that was statistically significant above similar accelerations in the historical record. However, Haigh *et al*. (2014) noted that rates significantly higher than the past are "likely to become detectable later this decade, or early next decade." This study matches the time frame of "later this decade," and the results are statistically significant at the 95% level.

## CONCLUSIONS

An analysis of 149 tide gauge records with lengths at least 75 years (average of 106 years) that extend through 2017–19 show that sea level has accelerated at a mean rate of 0.0128 ± 0.0064 mm/y$^2$ that is statistically significant at the 95% confidence level. This mean rate is higher than determined in earlier studies that considered records less than 75 years in length, analyzed fewer gauge records, or extended records significantly and used non-RLR data.

## LITERATURE CITED


Boon, J.D. and Mitchell, M., 2015. Nonlinear change in sea level observed at North American tide stations. *Journal of Coastal Research*, 31(6), 1295–1305.

Bromirski, P.D.; Miller, A.J.; Flick, R.E., and Auad, G., 2011. Dynamical suppression of sea level rise along the Pacific Coast of North America: Indications for imminent acceleration. *Journal of Geophysical Research: Oceans*, 116, C7.

Church, J.A. and White, N.J., 2011. Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophysics*, 32(4), 585–602.

Church, J.A.; White, N.J.; Aarup, T.; Wilson, W.S.; Woodworth, P.L.; Domingues, C.M.; Hunter, J.R., and Lambeck, K., 2008. Understanding global sea levels: Past, present and future. *Sustainability Science*, 3, 9–22.

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

Haigh, I.D.; Wahl, T.; Rohling, E.J.; Price, R.M.; Pattiaratchi, C.B.; Calafat, F.M., and Dangendorf, S., 2014. Timescales for detecting a significant acceleration in sea level rise. *Nature Communications*, 5, 3635.

Hogarth, P., 2014. Preliminary analysis of acceleration of sea-level rise through the twentieth century using extended tide gauge data sets. *Journal of Geophysical Research*: *Oceans*, 119(11), 7645–7659.

Holgate, S.J., 2007. On the decadal rates of sea level change during the twentieth century. *Geophysical Research Letters*, 34, L01602.

Holgate, S.J.; Matthews, A.; Woodworth, P.L.; Rickards, L.J.; Tamisiea, M.E.; Bradshaw, E.; Foden, P.R.; Gordon, K.M.; Jevrejeva, S., and Pugh, J., 2013. New data systems and products at the permanent service for mean sea level. *Journal of Coastal Research,* 29(3), 493–504.

Houston, J.R., 2016. Discussion of: Boon, J.D. and Mitchell, M., 2015. Nonlinear change in sea level observed at North American tide stations. *Journal of Coastal Research,* 31(6), 1295–1305; *Journal of Coastal Research,* 32(4), 983–987.

Houston, J.R. and Dean, R.G., 2013. Effects of sea-level decadal variability on acceleration and trend difference. *Journal of Coastal Research*, 29(5), 1062–1072.

Houston, J.R. and Dean, R.G., 2011. Sea-level acceleration based on U.S. tide gage and extensions of previous global-gage analysis. *Journal of Coastal Research*, 23(3), 409–417.

Ice Sheet Mass Balance Inter-Comparison Exercise (IMBIE) Team, 2018. Mass balance of the Antarctic Ice Sheet from 1992–2017. *Nature*, 558, 219–236.

IMBIE Team, 2020. Mass balance of the Greenland Ice Sheet from 1992–2018. *Nature*, 579, 233–254.

Intergovernmental Panel on Climate Change (IPCC), 2001. Climate change 2001: The scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. *In:* Houghton, J.T.; Ding, Y.; Griggs, D.J.; Noguer, M.; van der Linden, P.J.; Dai, X.; Maskell, K., and Johnson, C.A. (eds.). Cambridge, United Kingdom, and New York, New York, USA: Cambridge University Press, 881p.

IPCC, 2019. Summary for policymakers. *In:* Pörtner, H.-O.; Roberts, D.C.; Masson-Delmotte, V.; Zhai, P.; Tignor, M.; Poloczanska, E.; Mintenbeck, K.; Nicolai, M.; Okem, A.; Petzold, J.; Rama, B., and Weyer, N. (eds.), *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. In press.

Jevrejeva, S.; Grinsted, A.; Moore, J.C., and S. Holgate, 2006. Nonlinear trends and multiyear cycles in sea level records. *Journal of Geophysical Research*, 111(C9), C09012.

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(8), L08715.

Merrifield, M.A., 2011. A shift in western tropical pacific sea level trends during the 1990s. *Journal of Climate*, 24(15), 4126–4138.

Olivieri, M. and Spada, G., 2013. Intermittent sea-level acceleration. *Global and Planetary Change*, 109, 64–72.

Permanent Service for Mean Sea Level (PSMSL), 2020. *Obtaining tide gauge data*. http://www.psmsl.org/data/obtaining/

Ray, O.D. and Douglas, B.C., 2011. Experiments in reconstructing twentieth-century sea levels. *Progress in Oceanography*, 91(4), 496–515.

Shapoval, A.; Mouël, J.-L.; Courtillot, V., and Shnirman, M., 2020. Influence of very large spatial heterogeneity on estimates of sea-level trends. *Applied Mathematics and Computation*, 386, 125485.

Spada, G. and Galassi, G., 2012. New estimates of secular sea level rise from tide gauge data and GIA modelling. *Geophysical International*, 191(3), 1067–1094.

Sturges, W. and Douglas, B. C., 2011. Wind effects on estimates of sea level rise. *Journal of Geophysical Research: Oceans*, 116(C6), C06008.

Sturges, W. and Hong, B.G., 2001. Decadal variability of sea level. *In:* Douglas, B.C.; Kearney, W.S., and Leatherman, S.P., (eds.), *Sea Level Rise*, Chapter 7. San Diego, California: Academic Press, 165–180.

University of Colorado, 2020. *Sea Level Research Group*. https://sealevel.colorado.edu/data/2020rel1-global-mean-sea-level-seasonal-signals-retained

Watson, P.J., 2017. Acceleration in European mean sea level? A new insight using improved tools. *Journal of Coastal Research*, 33(1), 23–38.

Watson, P.J., 2016. Acceleration in U.S. mean sea level? A new insight using improved tools. *Journal of Coastal Research*, 32(6), 1247–1261.

Watson, P.J., 2011. Is there evidence yet of acceleration in mean sea level rise around mainland Australia? *Journal of Coastal Research*, 27(2), 368–377.

Wenzel, M. and Schröter, J., 2010. Reconstruction of regional mean sea level anomalies from 595 tide gauges using neural networks. *Journal of Geophysical Research*, 115(C8), C08013.

Woodworth, P.L., 1990. A search for accelerations in records of European mean sea level. *International Journal of Climatology*, 10(2), 129–143.

Woodworth, P.L.; Menendez, M., and Gehrels W.R., 2011. Evidence for century-timescale acceleration in mean sea levels and for recent changes in extreme sea levels. *Surveys in Geophysics*, 32(4–5), 603–618.