On the decadal rates of sea level change during the twentieth century

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[1]   Nine long and nearly continuous sea level records were chosen from around the world to explore rates of change in sea level for 1904–2003. These records were found to capture the variability found in a larger number of stations over the last half century studied previously. Extending the sea level record back over the entire century suggests that the high variability in the rates of sea level change observed over the past 20 years were not particularly unusual. The rate of sea level change was found to be larger in the early part of last century (2.03 ± 0.35 mm/yr 1904–1953), in comparison with the latter part (1.45 ± 0.34 mm/yr 1954–2003). The highest decadal rate of rise occurred in the decade centred on 1980 (5.31 mm/yr) with the lowest rate of rise occurring in the decade centred on 1964 (−1.49 mm/yr). Over the entire century the mean rate of change was 1.74 ± 0.16 mm/yr. **Citation:** Holgate, S. J. (2007), On the decadal rates of sea level change during the twentieth century, *Geophys. Res. Lett.*, *34*, L01602, doi:10.1029/2006GL028492.

1.   Introduction

[2]   In a previous paper, *Holgate and Woodworth* [2004] (hereinafter referred to as HW04), rates of mean "global" sea level change (i.e., global coastal sea level change) were calculated from a large number of tide gauge records (177) for the period 1955–1998. HW04 found that the highest and lowest rates of change in the 1955–1998 period occurred in the last 20 years of the record. In this paper it is examined whether a few high quality tide gauge records can replace the many used by HW04. On the basis of these high quality records the work of HW04 is then extended back to the early twentieth century to examine whether the rates of sea level change experienced in recent decades are unusual.

[3]   On a decadal timescale, the length scales of sea level change are very large (O(1000) km) though not necessarily global. As a result, many tide gauges in a given region are highly correlated with each other. This paper demonstrates that a few high quality records from around the world can be used to examine large spatial-scale decadal variability as well as many gauges from each region are able to.

2.   Method

[4]   When it comes to calculating long term global sea level means from tide gauge data, there are a number of problems. Firstly there is a bias in the distribution of tide gauges towards certain regions, notably Northern Europe and North America [*Douglas*, 1991]. Secondly there is the problem that not all tide gauge records are of equivalent quality. This can either be due to their location (being for example in an earthquake-prone region or an area of high glacial isostatic adjustment, GIA) or due to the quality of the instrumental record (being perhaps too discontinuous or lacking critical datum information to account for local vertical land movements).

[5]   As a result of these two problems, there are very few high quality, long tide gauge records in different regions suitable for calculating global mean sea level change. An alternative approach is to make use of regional composites of shorter records as in HW04.

[6]   In order to test whether a few high quality records could provide similar information to the composites, nine tide gauge records were carefully selected from the database of the Permanent Service for Mean Sea Level (PSMSL, available at http://www.pol.ac.uk/psmsl) [*Woodworth and Player*, 2003]: New York (1856–2003), Key West (1913–2003), San Diego (1906–2003), Balboa (1908–1996), Honolulu (1905–2003), Cascais (1882–1993), Newlyn (1915–2004), Trieste (1905–2004), and Auckland (1903–2000). The nine long records thus enable the study of HW04 into variability of decadal rates of sea level change to be extended over a much longer period. The locations of these tide gauge stations are shown in Figure 1.

[7]   These tide gauge stations are part of the Revised Local Reference (RLR) data set of the PSMSL in which each time series is recorded relative to a consistent reference level on the nearby land. Annual values in the RLR data set of the PSMSL are only calculated if there are at least 11 months of data and each month must have less than 15 missing days. Hence the tide gauge data presented here is of the very highest quality available. All these records are almost continuous and are far away from regions with high rates of vertical land movement due to GIA or tectonics.

[8]   Although most of these tide gauge records continue to the present, submissions of data to the PSMSL are often a year or two in arrears and hence most of these sea level records have data up until only 2003 or 2004. The current analysis begins in 1904 and ends in 2003 which ensures at least 70% completeness of the record in every decade.

[9]   Following the method described in HW04, consecutive, overlapping decadal mean rates were calculated for each sea level record. The advantage of calculating decadal rates in this way is that the tide gauge records can then be combined into a single mean sea level time series, despite the different gauges having different datums. Furthermore, decadal rates remove any minor data discontinuities and introduce an element of smoothing. The rates of change at each station are corrected for GIA using the ICE-4G model of *Peltier* [2001] and for inverse barometer effects using the HadSLP2 air pressure data set [*Allan and Ansell*, 2006].

[10]   The standard error of a sea level trend estimate, based on the assumption that each annual mean is inde-

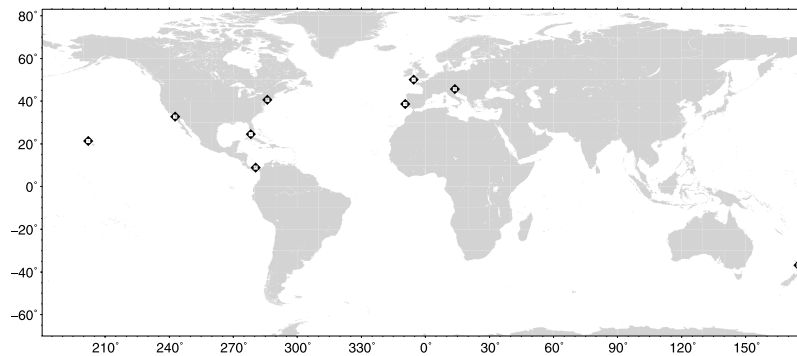[1]Proudman Oceanographic Laboratory, Liverpool, UK.

Figure 1. The distribution of the nine tide gauge records used in this study. Data are obtained from the Revised Local Reference data set of the Permanent Service for Mean Sea Level.

pendent, under-estimates the true error as the serial correlation is not accounted for [*Douglas*, 2001; *Nerem and Mitchum*, 2002]. Here serial correlation within each time-series is accommodated by reducing the number of degrees of freedom, using the lag-1 auto-correlation of the time-series [*World Meteorological Organization*, 1966; *Maul and Martin*, 1993]. The effect of calculating errors in this way increases one standard error for the trend over the 1904–2003 period from typically 0.02 mm/yr to 0.15 mm/yr.

3. Results

[11] Figure 2 compares the global decadal mean rates of change from the 177 stations of HW04 which were grouped into 13 regions (Figure 1 in HW04) with the global mean rates from the 9 long records. Although there are some differences between the two records, in particular the larger rate of rise in the 9 records during the 1950s, the two curves have overlapping error bars (based on one standard error). The global mean rates are similar for the second half of the 20th century (1953–97), 1.47 mm/yr and 1.41 mm/yr for the 177 and 9 stations respectively, with most of the disparity between the two due to differences in the 1950s. This comparison relies on using the HadSLP2 data set for pressure correction for both the 177 and 9 stations. HW04 used the NCEP pressure data set which gives a global mean rate for 177 stations of 1.64 mm/yr over the period 1953–97. Hence some uncertainty in the global mean rate of sea level rise is attributable to the commensurate uncertainty in the sea level pressure correction, which arises largely due to the difference in resolution between the two data sets (2.5° × 2.5° for NCEP and 5° × 5° for HadSLP2). Over the full 1904–2003 period, the mean global rate from the nine stations, corrected with HadSLP2, is 1.74 ± 0.16 mm/yr.

[12] Figure 3 shows that, not only is there considerable decadal variability in the individual sea level records, but there is generally little correlation between them. Stations which are in close proximity and which are affected by similar ocean and atmospheric processes show the greatest correlation. For example, Balboa and San Diego are both heavily influenced by the El Niño/Southern Oscillation (ENSO) and are similar (correlation of their decadal trends = 0.77), despite being over 4500 km apart. However, high correlation at a decadal scale does not imply that the long term trends are the same.

[13] The global mean sea level rates for the nine stations in Figure 2 show that the two highest decadal rates of change were recorded in the decades centred on 1980 (5.31 mm/yr) and 1939 (4.68 mm/yr) with the most negative decadal rates of change over the past 100 years during the decades centred on 1964 (−1.49 mm/yr) and 1987 (−1.33 mm/yr). There were also significant high decadal rates of change during the late 1910s, 1950s and 1990s. Negative decadal rates of change are seen in the early 1920s and early 1970s.

[14] Despite the high decadal rates of change in the latter part of the 20th century, it is found that the first half of the record (1904–1953) has a higher rate of rise overall (2.03 ± 0.35 mm/yr) than the 1954–2003 period which had a rate of 1.45 ± 0.34 mm/yr.

[15] The highest rates of sea level change over the common period for all gauges (1918–1996), occurred in New York (mean rate = 2.64 ± 0.44 mm/yr), San Diego (2.02 ± 0.31 mm/yr), Key West (2.00 ± 0.36 mm/yr) and
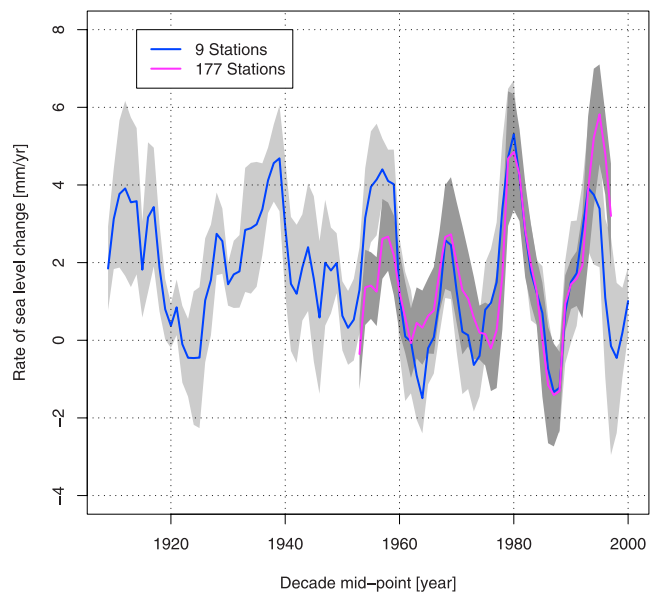

Figure 2. Comparison of the global mean decadal rates of sea level change based on the nine records with the rates from the 177 stations used in HW04. All rates are corrected for glacial isostatic adjustment and inverse barometer effects. The shaded region indicates ±1 standard error.
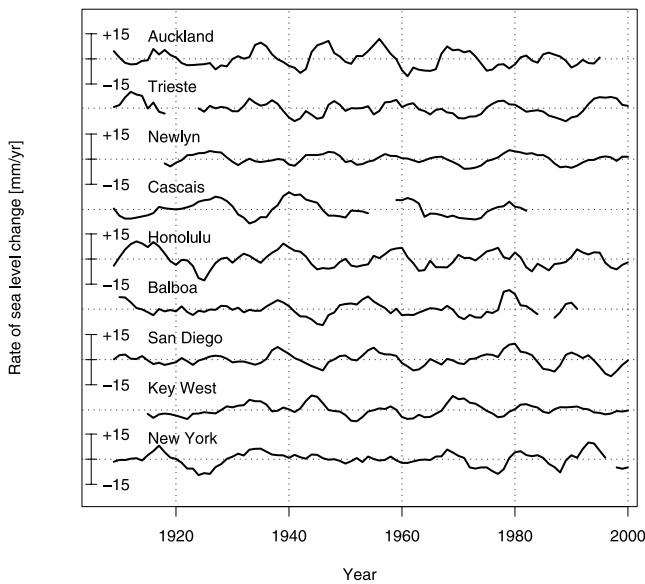
Figure 3. Comparison of the decadal rates of sea level change for each of the nine records. All rates are corrected for glacial isostatic adjustment and inverse barometer effects.

Cascais (1.85 ± 0.37 mm/yr). The smallest changes in sea level are seen in Trieste (1.25 ± 0.23 mm/yr) and Newlyn (1.46 ± 0.30 mm/yr).

[16] San Diego has the highest correlation with the global mean rates (r = 0.62) over the 1904–2003 period, followed by Honolulu (r = 0.58), New York (r = 0.56), Balboa (r = 0.55) and Trieste (r = 0.42). Cascais and Auckland have insignificant correlations at the 95% confidence level while the correlations with Newlyn (r = 0.29) and Key West (r = 0.25) are significant but low.

4. Discussion

[17] The nine stations selected here as high quality records capture the mean decadal rates of change described by the larger set of stations used in HW04 and also have a similar global mean rate over the common period of the two analyses (1953–1997). This provides confidence that the nine station set can be used to study decadal rates of global mean sea level change throughout the twentieth century.

[18] All the stations in this study show a significant increase in sea level over the period 1904–2003 with an average increase of 174 mm during that time (Figure 4). This mean rate of 1.74 mm/yr is at the upper end of the range of estimates for the 20th century in the Intergovernmental Panel on Climate Change, Third Assessment Report (IPCC TAR) [*Church et al.*, 2001], and consistent with other recent estimates [*Holgate and Woodworth*, 2004; *Church and White*, 2006].

[19] The rates for individual stations are consistent with those published by other authors [*Douglas*, 2001; *Peltier*, 2001; *Hannah*, 1990]. As has been noted previously [*Woodworth*, 1990], the rates for northern European tide gauges are consistently lower than the global mean. Trieste, along with other Mediterranean tide gauge stations, has shown a much lower rate of increase since 1960 [*Douglas*, 1997; *Tsimplis and Baker*, 2000]. However, the difference

between the global mean and Trieste is 0.49 in comparison with the difference between the global mean and New York (the highest individual rate) which is 0.62. It would therefore seem that Trieste no more biases the mean low than New York biases the mean high. Nevertheless, excluding Trieste from the results would slightly increase the global mean from 1.74 to 1.80 mm/yr.

[20] Although the mean rate of change of global mean sea level is found to be greater in the first half of the twentieth century, the two rates are consistent with being the same at the 95% confidence level, given their individual standard errors. However, a greater rate of rise in the early part of the record is consistent with previous analyses of tide gauge records which suggested a general deceleration in sea level rise during the 20th century [*Woodworth*, 1990; *Douglas*, 1992; *Jevrejeva et al.*, 2006]. A twentieth century deceleration is consistent with the work of *Church and White* [2006] who, although finding evidence for a post-1870 acceleration based on an EOF reconstruction of global sea level, found that much of the overall acceleration occurred in the first half of the 20th century. *Church and White* [2006] suggested that the greater rate of sea level rise observed in the first half of last century was due to reduced volcanic emissions (and hence also lower variability in sea level) during the 1930s to 1960s. This idea is supported by results from the HadCM3 model which suggest that the simulated global mean sea level did not accelerate through the twentieth century due to the offsetting of anthropogenic warming by reduced natural forcing [*Gregory et al.*, 2006].

[21] The decadal rates of sea level change shown in Figure 2 are qualitatively similar to the corresponding rates in Figure 2 of *Church and White* [2006], with the exception of the period 1930–1940 which shows lower variability in the work of *Church and White* [2006]. The variability in the second half of the century is also similar to that found by
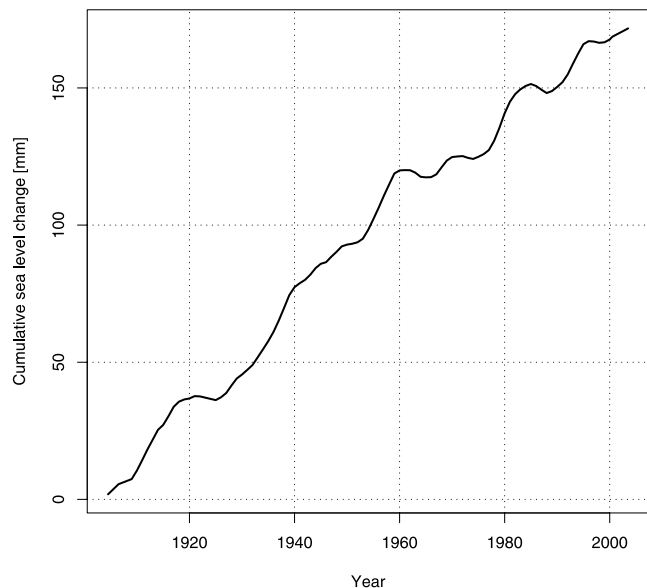

Figure 4. The mean sea level record from the nine tide gauges over the period 1904–2003 based on the decadal trend values for 1907–1999. The sea level curve here is the integral of the rates presented in Figure 2.

Chambers et al. [2002] though the lower number of gauges in the present study results in a greater level of variance.

5. Summary and Conclusions

[22] Based on a selection of nine long, high quality tide gauge records, the mean rate of sea level rise over the period 1904–2003 was found to be 1.74 ± 0.16 mm/yr after correction for GIA using the ICE-4G model [*Peltier*, 2001] and for inverse barometer effects using HadSLP2 [*Allan and Ansell*, 2006]. The mean rate of rise was greater in the first half of this period than the latter half, though the difference in rates was not found to be significant. The use of a reduced number of high quality sea level records was found to be as suitable in this type of analysis as using a larger number of regionally averaged gauges.

[23] Finally, in extending the work of HW04 to cover the whole century, it is found that the high decadal rates of change in global mean sea level observed during the last 20 years of the record were not particularly unusual in the longer term context.

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