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Global Sea Level Rise

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Published values for the long-term, global mean sea level rise determined from tide gauge records exhibit considerable scatter, from about 1 mm to 3 mm/yr. This disparity is not attributable to instrument error; long-term trends computed at adjacent sites often agree to within a few tenths of a millimeter per year. Instead, the differing estimates of global sea level rise appear to be in large part due to authors' using data from gauges located at convergent tectonic plate boundaries, where changes of land elevation give fictitious sea level trends. In addition, virtually all gauges undergo subsidence or uplift due to postglacial rebound (PGR) from the last deglaciation at a rate comparable to or greater than the secular rise of sea level. Modeling PGR by the ICE-3G model of Tushingham and Peltier (1991) and avoiding tide gauge records in areas of converging tectonic plates produces a highly consistent set of long sea level records. The value for mean sea level rise obtained from a global set of 21 such stations in nine oceanic regions with an average record length of 76 years during the period 1880–1980 is 1.8 mm/yr ± 0.1. This result provides confidence that carefully selected long tide gauge records measure the same underlying trend of sea level and that many old tide gauge records are of very high quality.

1. INTRODUCTION

Concern over the consequences of global warming has led to many determinations of the rate of sea level rise from historical tide gauge records. Excellent summaries on the sea level problem are available in *Sea Level Change* [*National Research Council* (*NRC*), 1990], and the Intergovernmental Panel on Climate Change (IPCC) report *Climate Change* [*Houghton et al.*, 1990].

Published values for global sea level rise for the last 50–100 years vary from about 1 to 3 mm/yr, with formal uncertainties ranging from 0.15 to 0.90 mm/yr. While there is not much doubt that sea level is rising, the scatter of results makes impossible a meaningful interpretation of the global balance of water in its various forms and locations.

The reason for the large scatter of results is, as was noted by Barnett [*NRC*, 1990, pp. 37–51], that authors analyze the data in different ways and select and group tide gauge stations according to different criteria. In this paper the stations are selected or rejected according to length and completeness of record, general agreement with other nearby stations over a common time interval, and freedom from obvious tectonic effects. Grouping of stations is done according to oceanic region. The station groups surviving this selection process form an extremely consistent set, particularly after correction for the effects of postglacial rebound (PGR) by the ICE-3G model of *Tushingham and Peltier* [1991]. In fact, the rms agreement of sea level rise for widely separated oceanic regions from long records exceeding 60–70 years, after correction for PGR, is so good (0.4 mm/yr) that one can simply aggregate them without regard to exact record length. This avoids the need for statistical methods such as empirical orthogonal function (EOF) analysis.

2. LOW-FREQUENCY VARIATIONS OF SEA LEVEL

Many hundreds of coastal and island tide gauges around the Earth regularly produce sea level data. However, this is a relatively recent development. The number of long (> 50 years) series is less than 100, and most of these series are unsuitable for determining global sea level rise for reasons shown below.

Short (a few decades) tide gauge records are of little use for determining the global trend of sea level because of very large local and regional interannual fluctuations of sea level. *Pugh* [1987, p. 320] gives a compelling graphical example of the problem for 10-year records, showing that 10-year trends at a site can have different signs, depending on the intervals chosen. *Sturges* [1987] has in addition pointed out the existence of interdecadal and longer fluctuations that can influence sea level trends. Finally, Roemmich [*NRC*, 1990, pp. 208–217], in his analysis of sea level records at Bermuda and Charleston, South Carolina, shows that coastal and relatively nearby mid-ocean sea level trends can differ markedly even over several decades, and states that 50-year records of sea level and dynamic height are needed to understand the interdecadal sea level fluctuations at a site.

It is difficult to visualize the low-frequency variations of sea level in a plot of monthly or annual means. Seasonal and annual signals are so large and variable that the smaller, longer-period signals are obscured. Appropriate filtering is needed for visualization of these signals. In this paper a multiyear sliding median filter on monthly means of sea level is used for plots of monthly mean sea level. This filter simultaneously edits and smoothes the record.

Figure 1 shows the sea level record for San Francisco from 1854 to 1986 after removal by least squares of semiannual and annual terms, median filtering, and detrending. For Figure 1 a median filter width of 5 years was used, reducing the amplitude of 10-year cycles about 20% and that of 20 year period about 3%.

The signal remaining for San Francisco after detrending is rich with long-wavelength components, which will obviously have a significant effect on the trend computed for any subportion of the total record. To show the effect on trends of the low-frequency variations of sea level at San Francisco, Figure 2 presents the trend of sea level computed from successive 30-year spans from the original unfiltered monthly mean data. The average value of the trend is 1.2

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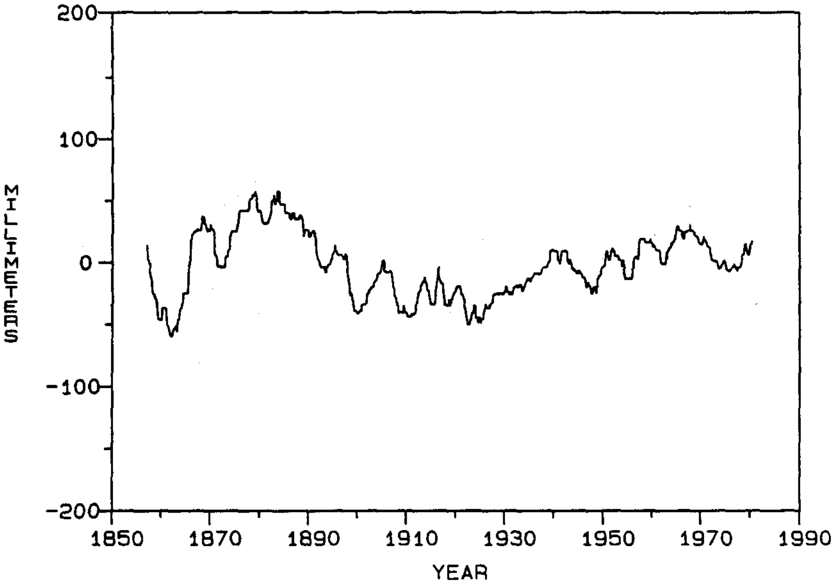


Fig. 1. Detrended and median filtered sea level record at San Francisco, 1854–1986. Note the large low-frequency variations of sea level.

mm/yr over the entire record, but the computed 30-year trends vary from about +5 to −2 mm/yr.

Low-frequency changes of sea level are the rule at other gauge sites as well. Figure 3 presents along with San Francisco four other filtered and detrended long records well distributed around the globe. In addition to long-period signals, correlations of sea level at low frequency between records of the type pointed out by *Sturges* [1987] are all too obvious. Any global trend analysis will be biased by this effect, and determination of acceleration of global sea level especially so.

Another effect of interdecadal and longer variations of sea level is to magnify the influence of gaps in sea level data records on derived trends. Data gaps that are significant relative to the data record length will bias the derived trend value because low-frequency variations are poorly sampled. In this paper, the requirement was enforced that data records must be at least about 80% complete.

Low-frequency fluctuations of sea level are not the only source of systematic signal in sea level records. Figure 4 presents a histogram of trends of the records 50 years and longer available from the Permanent Service for Mean Sea Level (PSMSL) [*Pugh et al.*, 1987] for which the ICE-3G value [*Tushingham and Peltier*, 1991] of the PGR correction is available but not applied. The smooth line is the best-fitting normal curve to the distribution. The large number of

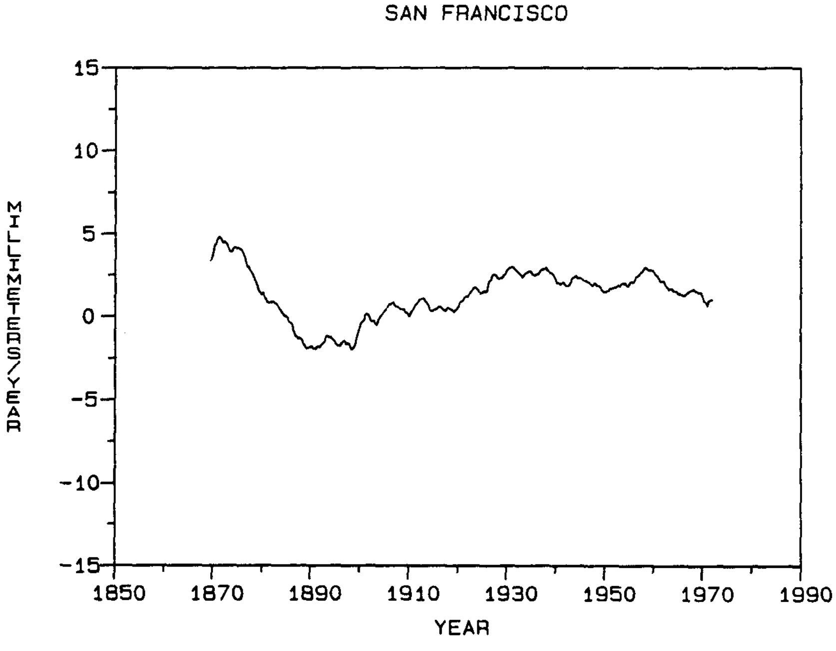


Fig. 2. Total sea level trend at San Francisco for a sliding 30-year window. The 30-year average value for sea level trend varies from +5 to −2 mm per year over the record span from 1854 to 1980.

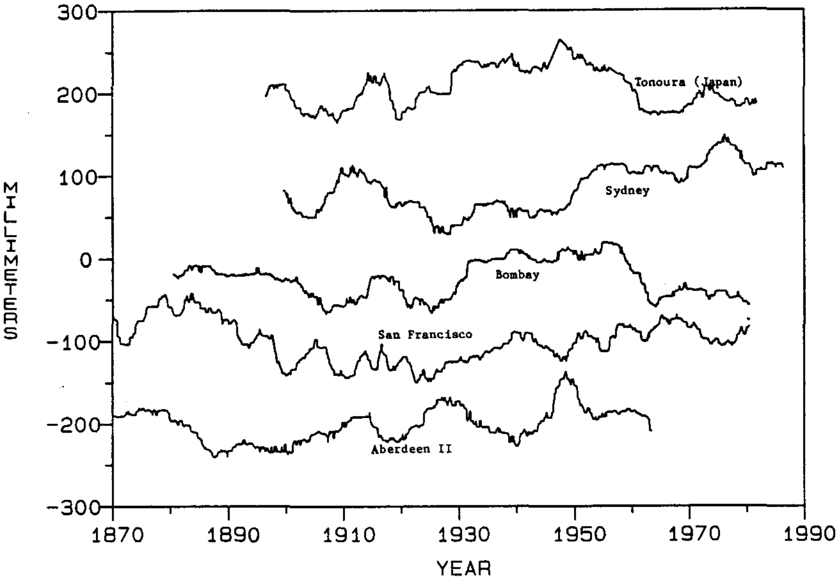


Fig. 3. Median filtered and detrended sea level records for five widely distributed tide gauge sites. Note the apparent correlations of the records at low frequencies.

sites with negative trends of sea level are of course mostly in the Baltic and northern Europe and are a consequence of postglacial rebound, as has been documented by Peltier and Tushingham (1989) and others.

Figure 5 is the same as Figure 4, but with ICE-3G values of PGR used to correct the sea level trends. The improvement in consistency of trends is striking, and the histogram is much more nearly normal, as the fitted curve illustrates. However, the variance is still too large and unexplained to stop here. It is necessary to conduct a region-by-region analysis of the data.

3. REGIONAL ANALYSES OF SEA LEVEL TRENDS

Barnett in the NRC report on Sea Level Change (NRC, 1990) shows regional trends to sea level and finds wide discrepancies between them. I present in this section a region-by-region analysis for a fixed time period (1930–1980) that indicates that regional discrepancies are mostly due to the location of many stations at convergent plate boundaries where changes of elevation are large, and to PGR. Only a few areas are really useful for global sea level trend analyses because of tectonic effects.

3.1. *East Coast of North America*

The east coast of North America is an especially valuable region for study of sea level trends. There are many long tide gauge records from Florida to New Brunswick, and data quality is very high. *Gornitz and Seeber* [1990] have conducted an extensive investigation of vertical crustal movements of the region from historic and late Holocene data and

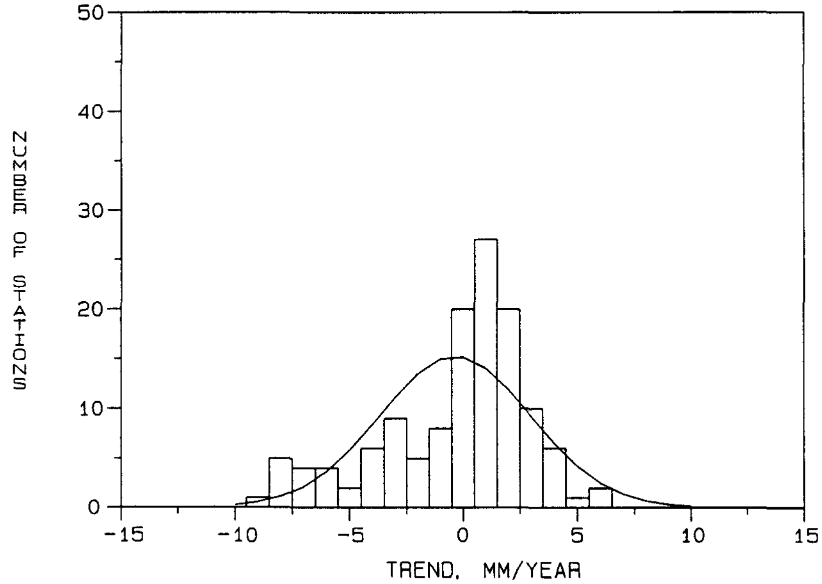


Fig. 4. Histogram of trends of all tide gauge records with length of 50 years or longer for which the ICE-3G PGR correction of *Tushingham and Peltier* [1991] is available but not applied.

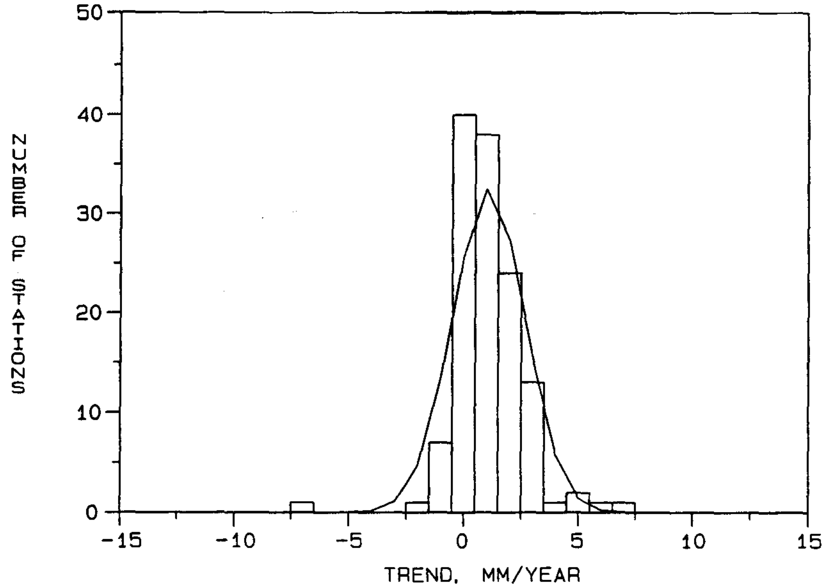


Fig. 5. As in Figure 4, but with PGR corrections from the ICE-3G model of *Tushingham and Peltier* [1991] applied.

conclude that about one half of the observed apparent sea level rise there comes from this source. The present paper in contrast concentrates on the sea level record over a fixed time period (1930–1980) for its analysis of this region and uses only sites with complete records (or nearly so) in that interval to obtain a very detailed view of the region and evaluate the precision of trends obtained from tide gauge data.

Table 1 presents sea level trends for the 19 stations on the east coast of North America for which sea level records were largely complete from 1930–1980. A common time period was selected for comparisons in order to prevent interdecadal signals from influencing the interpretation of the trend values.

TABLE 1. North American East Coast Sea Level Trends for 1930–1980 Without (TREND) and With (T-PGR) Correction for PGR

Station	Latitude, °N	Trend, mm/yr	PGR, mm/yr	T-PGR, mm/yr
Key West	24.5	2.0	−0.4	2.4
Miami	25.8	2.4	−0.4	2.8
Mayport	30.5	2.4	−0.2	2.6
Charleston 1	32.8	3.4	0.2	3.2
Portsmouth	36.8	3.7	1.2	2.5
Hampton Roads	37.0	4.1	1.2	2.9
Washington	38.8	3.2	1.3	1.9
Annapolis	39.0	3.9	1.4	2.5
Baltimore	39.2	3.5	1.3	2.2
Atlantic City	39.3	3.9	1.7	2.2
Philadelphia	40.0	2.8*	1.5	1.3*
New York	40.7	3.4	1.4	2.0
Willets Points	40.8	2.8	1.5	1.3
Newport	41.5	2.7	1.6	1.1
Boston	42.3	1.9*	1.3	0.6*
Portland	43.7	2.8	1.0	1.8
Halifax	44.4	3.8	2.3	1.5
Eastport	45.0	3.6	1.8	1.8
St. John	45.2	3.1	1.9	1.2
Average		3.2		2.1
rms		0.6		0.6

*Deviant values not used in calculations.

The "trend" column in Table 1 is the value of sea level rise in millimeters per year obtained from a linear regression on raw monthly mean sea level values. The column headed "PGR" is the effect of PGR on the sea level trend (i.e., minus the actual PGR) computed from the ICE-3G model by *Tushingham and Peltier* [1991]. The final column, headed "T-PGR," is the value of the sea level trend corrected for PGR. The rms values in Table 1 are the root-mean-square deviations of the columns of trends. The uncertainty of the mean has not been calculated, since the distribution of trends is so obviously nonrandom. Note in addition that

TABLE 2. Same as Table 1, but Separated at New York

Station	Latitude, °N	Trend, mm/yr	PGR, mm/yr	T-PGR, mm/yr
	SE North America			
Key West	24.5	2.0	−0.4	2.4
Miami	25.8	2.4	−0.4	2.8
Mayport	30.5	2.4	−0.2	2.6
Charleston 1	32.8	3.4	0.2	3.2
Hampton Roads	37.0	4.1	1.2	2.9
Washington	38.8	3.2	1.3	1.9
Annapolis	39.0	3.9	1.4	2.5
Baltimore	39.2	3.5	1.3	2.2
Atlantic City	39.3	3.9	1.7	2.2
Philadelphia	40.0	2.8*	1.5	1.3*
New York	40.7	3.4	1.4	2.0
Average		3.2		2.5
rms		0.7		0.4
	NE North America			
Willets Point	40.8	2.8	1.5	1.3
Newport	41.5	2.7	1.6	1.1
Boston	42.3	1.9*	1.3	0.6*
Portland	43.7	2.9	1.0	1.8
Halifax	44.4	3.8	2.3	1.5
Eastport	45.0	3.6	1.8	1.8
St. John	45.2	3.1	1.9	1.2
Average		3.1		1.5
rms		0.5		0.3

Note the rms agreement of PGR-corrected trends of a few tenths of a millimeter per year for the separate groups.

*Deviant values not used in calculations.

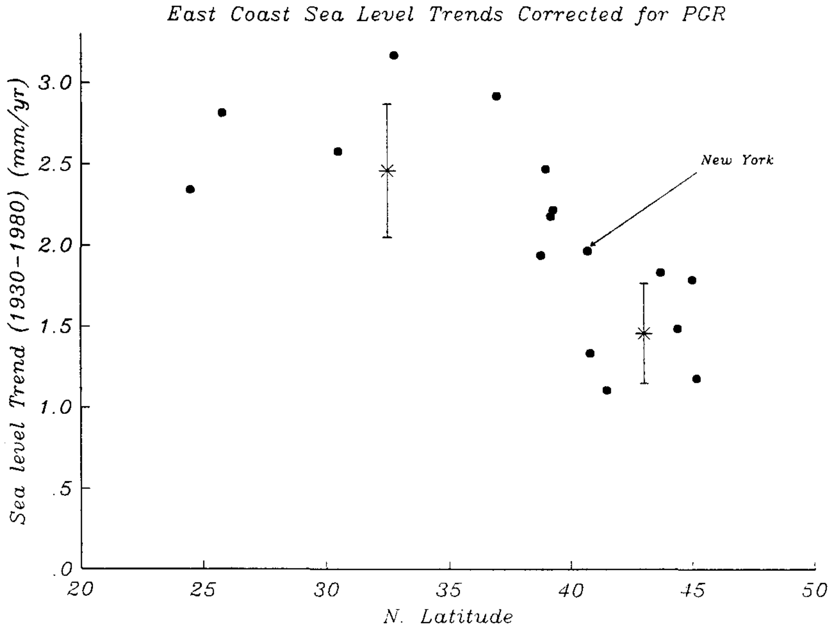
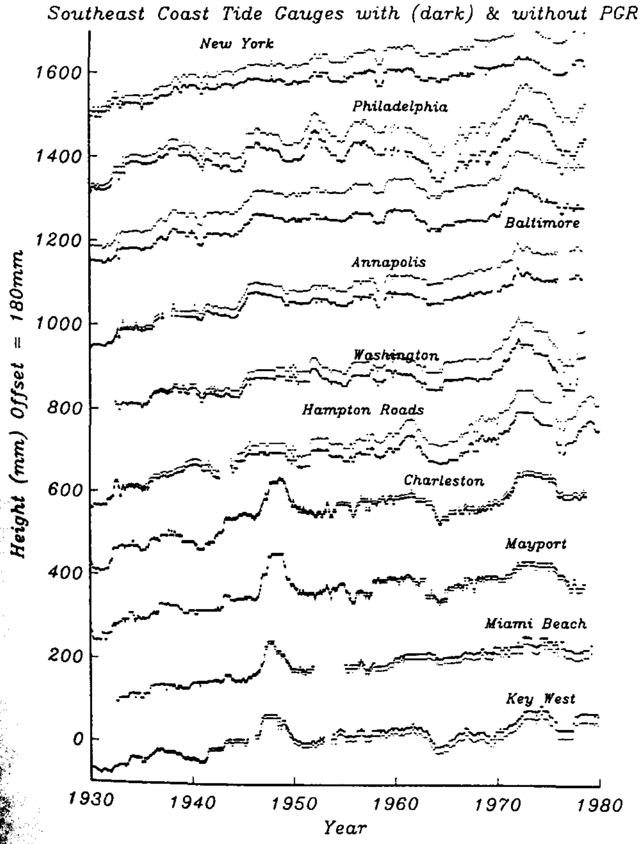


Fig. 6. PGR-corrected trends of sea level on the North American east coast plotted as a function of latitude. Note the sharp change near 38° latitude.

Philadelphia and Boston deviate significantly from trend values of nearby sites. (The reason for these unusual trends is unknown and is the subject of an ongoing investigation in the National Ocean Service of NOAA.) They are so far in value from neighboring sites that they are not used in any calculation in this paper.

The average value of sea level rise over the 17 stations remaining is reduced 1/3 by inclusion of the ICE-3G model



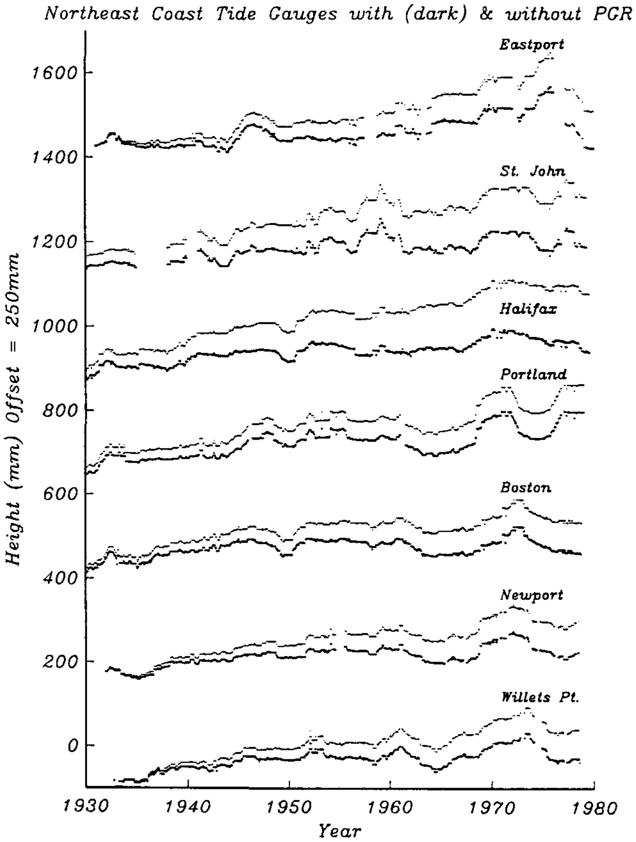


Fig. 7. Southeast coast median filtered sea level records with (heavy dots) and without correction for PGR. Note the change of sign of the PGR correction near Mayport, Georgia.

Fig. 8. Northeast coast median filtered sea level records with and without correction for PGR. The value of PGR at the northern sites is comparable to the sea level increase attributed to ocean rise.

TABLE 3. Southern California Sea Level Trends

Platform	Latitude	Longitude	Trend, mm/yr	PGR, mm/yr	T-PGR, mm/yr
		Total Record			
San Francisco	37°48'N	122°28'W	1.2	−0.4	1.6
San Diego	32°43'N	117°10'W	0.1	−0.6	0.7
Los Angeles	33°43'N	118°16'W	0.5	−0.6	1.1
La Jolla	32°52'N	117°15'W	1.7	−0.6	2.3
		Record 1930–1980			
San Francisco	37°48'N	122°28'W	1.8	−0.4	2.2
Los Angeles	33°43'N	118°16'W	0.2	−0.6	0.8
La Jolla	32°52'N	117°15'W	1.8	−0.6	2.4
San Diego	32°43'N	117°10'W	1.7	−0.6	2.3

The trends for 1930–1980 demonstrate that only by examining trends over the same time period can the gauge records be correctly compared and interpreted.

correction of *Tushingham and Peltier* [1991], but the scatter of results is apparently unchanged, remaining at 0.61 mm/yr. But if the trends are plotted as in Figure 6 as a function of latitude, a separation into two groups at about 38°–39°N is immediately apparent. Table 2 divides the east coast into two groups at New York, revealing an underlying internal consistency.

First, note that the ICE-3G model for PGR significantly improves the agreement of sea level trend internal to each group. Table 2 makes it plausible that trends precise to a few tenths of a millimeter per year are obtainable from long records taken by float-type instruments. Old records of sea level thus can be a very precise source of information for studies of the response of the global distribution of water over long periods.

Table 2, like the analyses of *Peltier and Tushingham* [1989] and *Gornitz and Seeber* [1990], additionally shows that no reliable interpretation of sea level records can be made without considering PGR. But what remains unexplained is why grouping into northern and southern regions occurs. The reason may be inadequacy of the ICE-3G PGR model. The east coast PGR-corrected trend values divide at just about the latitude of the maximum southern extent of the last glaciation. At the margin of formerly ice-covered regions, the spatial scale of PGR is very short, and added complexity arises at the continental margin where oceanic and continental lithosphere are different. Alternatively, an oceanographic or meteorological effect may be responsible. Obviously, water masses north or south of Cape Hatteras, where the Gulf Stream turns sharply eastward, are very different, although the dividing line between the groups is about 3°–5° north of that location. Also arguing against an oceanographic/meteorological explanation is the fact shown later in this paper that the trend difference between the two groups is maintained on the scale of 100 years.

Figures 7 and 8 show the median (2.5-year filter width) filtered data for the North American east coast sites in Table 2. Plotted in Figure 7 are the sea level records from Key West to New York with and without corrections for PGR, and the same information is given in Figure 8 for Willets Point, New York, to Eastport, Maine.

Figures 7 and 8 show a striking interdecadal consistency of sea level. There was a rapid rise of sea level at many stations in the southeast United States during the 1940s, with a subsequent fall, and then leveling off until approximately 1970, when another large interannual anomaly occurred that was seen over the entire east coast. The extent of these phenomena shows that oceanographic and meteorological data over a very wide area will be needed to understand the underlying mechanisms.

Figures 7 and 8 also demonstrate the importance of corrections for PGR. PGR as given by the ICE-3G model is comparable to the rise of the water level at the northern sites and is responsible for roughly half of the total rise there.

For the purpose of the analysis presented in this paper, the east coast of North America is divided into two regions as shown in Table 2, and to minimize the effect of the decadal-scale fluctuations, only the very longest records are used.

3.2. *Southern California*

The next region to be considered is the southern half of California (Table 3). All records in this region were discarded by *Trupin and Wahr* [1990] because the region is tectonically active. However, this is a transform boundary with much less vertical motion than a convergent one, and an examination of the sea level records reveals a remarkable consistency.

TABLE 4. NW North American Sea Level Trends, 1930–1980

Platform	Latitude	Longitude	Trend, mm/yr	PGR, mm/yr	T-PGR, mm/yr
Victoria	48°25'N	123°22'W	0.8	−0.8	1.6
Neah Bay	48°22'N	124°37'W	−1.6	0.0	−1.5
Friday Harbor	48°33'N	123°00'W	0.6	−1.1	1.7
Settle	47°36'N	122°20'W	2.5	−0.7	3.2
Astoria	46°13'N	123°46'W	−0.4	0.7	−1.1
Crescent City	41°45'N	124°12'W	−0.9	0.1	−1.0

At this convergent plate boundary there is no agreement even of sign of sea level trend.

TABLE 5. Indian Subcontient Sea Level Trends, 1930–1980

Platform	Latitude	Longitude	Trend, mm/yr	PGR, mm/yr	T-PGR, mm/yr
		1930–1980			
Bombay	18°55′N	072°50′E	−0.3	−0.2	−0.1
Calcutta	22°33′N	088°18′E	5.9	−0.4	6.3
		1937–1980			
Cochin	09°58′N	076°15′E	2.2	−0.5	2.7
Vishakhapatnam	17°41′N	083°17′E	0.5	−.2	0.7
Saugor/Sagar	21°39′N	088°03′E	−4.4	−0.3	−4.1

The collision of the Indo-Australian and Eurasian plates leads to significant vertical changes that corrupt apparent sea level trend measured there.

The last column in Table 3, as before, shows the trend in millimeters per year after correction for PGR by the ICE-3G model. The trends are very disparate, but so are the record lengths, and an anomaly was obvious in a plot of the San Diego record in the late 1920s. Truncating all records for the period 1930–1980 gives an entirely different picture of the trends. San Francisco, La Jolla, and San Diego are in remarkably close agreement. The agreement of the last two is especially noteworthy. The sites are only about 20 km apart and provide an excellent test of the precision of the U.S. tide gauge measurement system over an extended period. Los Angeles, in contrast, is a clear outlier and will not be considered further. The reason for the discordant result for Los Angeles may be related to difficulties of maintaining geodetic control for the site in the presence of the very large subsidence that occurred in the area as a result of oil extraction. The excellent agreement of San Francisco with San Diego and La Jolla gives increased confidence in the precision of the very long San Francisco record.

3.3. *Northwest America*

Table 4 presents trend information for northwest America for the same time period as Table 3. This is a tectonically active area where the Juan De Fuca plate is subducting under the North American Plate, with resulting volcanic and seismic activity and vertical crustal movements. The disparity of both PGR-corrected trend values and raw sea level trends is very great, and the only reasonable conclusion is that data from these sites cannot be used in an evaluation of global sea level rise.

3.4. *Indian Subcontinent*

Trends for the Indian subcontinent are presented in Table 5. Evaluation of these sites is important because Bombay is one of a small number of stations with a record reaching well into the nineteenth century and is included in most analyses of global sea level trend. However, the Indian subcontinent is in an area of plate convergence. The collision of the

TABLE 6. Northern European Sea Level Trends, 1930–1980

Platform	Latitude	Longitude	Trend, mm/yr	PGR, mm/yr	T-PGR, mm/yr
Narvik	68°26′N	017°25′E	−4.0	−3.3	−0.7
Bergen	60°24′N	005°18′E	−1.1	−0.9	−0.2
Stavanger	58°58′N	005°44′E	−0.3	−0.1	−0.2
Oslo	59°54′N	010°45′E	−4.2	−4.6	0.4
Smögen	58°22′N	011°13′E	−2.3	−2.6	0.3
Varberg	57°06′N	012°13′E	−1.3	−1.1	−0.2
Klagshamn	55°31′N	012°54′E	0.1	0.4	−0.3
Ystad	55°25′N	013°49′E	0.3	0.4	−0.1
Kungholmsfort	56°06′N	015°35′E	0.0	0.0	0.0
Landsort	58°45′N	017°52′E	−3.2	−2.9	−0.3
Stockholm	59°19′N	018°05′E	−4.1	−4.1	−0.0
Ratan	64°00′N	020°55′E	−8.2	−9.3	1.1
Furuogrund	64°55′N	021°14′E	−8.8	−9.6	0.8
Kemi	65°44′N	024°33′E	−6.7	−10.0	3.3
Oulu/Uleåborg	65°02′N	025°26′E	−6.5	−10.0	3.6
Vaasa/Vasa	63°06′N	021°34′E	−7.6	−8.6	1.0
Kaskinen/Kaskö	62°23′N	021°13′E	−7.0	−7.4	0.5
Mäntyluoto	61°36′N	021°29′E	−6.1	−6.1	0.0
Turku/Abo	60°25′N	022°06′E	−4.1	−3.7	−0.5
Degerby	60°02′N	020°23′E	−3.6	−4.4	0.8
Hanko/Hangö	59°49′N	022°58′E	−3.2	−2.3	−0.9
Helsinki	60°09′N	024°58′E	−2.0	−2.5	0.5

Relative sea level rise is dominated in this region by PGR. The ICE-3G model, which did not use these data, accounts for these motions very well, but the trends are still not usable for global sea level analysis.

TABLE 7. Japanese Sea Level Trends, 1930–1980

Platform	Latitude	Longitude	Trend, mm/yr	PGR, mm/yr	T-PGR, mm/yr
Mera	34°55′N	139°50′E	0.8	−0.4	1.2
Aburatsubo	35°09′N	139°37′E	3.5	−0.4	3.9
Hosojima	32°26′N	131°40′E	0.0	−0.4	0.4
Tonoura	34°54′N	132°04′E	−1.1	−0.5	−0.6
Wajima	37°24′N	136°54′E	−1.2	−0.3	−0.9

This convergent plate boundary region, like the others, cannot be used for sea level analyses because of land elevation changes.

Indo-Australian and Eurasian plates causes significant vertical changes, which are reflected in the highly varying rates of sea level rise for the region. The buckling of the Indo-Australian plate at the Indian subcontinent has also been vividly displayed by *McAdoo and Sandwell* [1985], who used Seasat altimeter data to observe folds in the oceanic geoid immediately to the south of India. Tide gauges from this region must also be excluded from analyses of global sea level rise, since they lie within the diffuse compressional plate boundary.

3.5. *Northern Europe*

The situation for Norway, Sweden, and Finland is presented in Table 6. As is well known, observed trends and PGR values in this region are as much as a centimeter per year, and even corrected trends are not usable for sea level trend analysis. Table 6 does show that the ICE-3G model removes most (but not enough for this paper) of the trend signal even though the spatial scale of the trends in the region is small. What Table 6 underscores is the high accuracy of the ICE-3G model, which did not include any tide gauge data in its derivation.

3.6. *Japan*

Trends of sea level for Japan are given in Table 7. Japan is, of course, a very tectonically active area. As in the case of India, consideration of the effects on elevation at or near a convergent plate boundary is important because a widely used very long sea level record (Tonoura) is available. The comparison of Japanese sea level trends over the time period presented in Table 7 clearly shows that Tonoura and other records there are not usable for long-term trend analysis, probably because of vertical crustal movements.

3.7. *Australia*

Complete and long southern hemisphere records in the data set obtainable from the PSMSL are in Australia, as is shown in Table 8. Unfortunately, the trend values for the sites there differ by a factor of 2 over the common time period 1930–1980. Figure 9 presents median-filtered (but not detrended) plots of the monthly mean data, which are in fair agreement from 1950 to 1980. However, from about 1930 to the late 1940s the data are 180° out of phase. Since is was not possible to determine which is correct, both sites were excluded from further consideration.

There are other stations with long records (> 60 years) used elsewhere in analyses of global sea level rise that are excluded here. These are Port Tuapse (Black Sea), Takoradi (Ghana), Manila, Aden, and Lagos (Portugal). The first was excluded because of its tenuous connection with the open oceans. The second and third were excluded because of their peculiar values of sea level rise of −2 mm/yr (Takoradi), and +5 mm/yr (Manila). The high rate at Manila may be due to tectonic activity in the area, the location of the deepest ocean trench, or harbor development (P. Woodworth, private communication, 1990). The reason for a fall of sea level at Takoradi is unclear, although possibly due to data problems after 1966 (P. Woodworth, private communication, 1990). Finally, the records at Aden and Lagos are only about 70% complete owing to gaps in their records, and so were also excluded.

4. GLOBAL SEA LEVEL ANALYSIS

In accordance with the results presented in the preceding section, the selection of gauges for this paper excludes all sites at convergent tectonic plate boundaries. In addition, those sites whose records are less than about 80% complete are also excluded. Finally, sites very near each other and sampling the same oceanic region should, over a common time period, give results for sea level trend that are in reasonable agreement. Table 9 presents 21 tide gauge sites in nine oceanic regions that meet these selection criteria. The average record length is 76 years (with a minimum record of 60 years). The average record length understates the true temporal coverage because the U.S. east coast sites are mostly only about 60 years in length. A better view of the temporal coverage is given in Figure 10. This figure shows the temporal coverage of the groups. The time 1900–1980 is very well covered by these groups, and 1880–1980 nearly as well. Figure

TABLE 8. Australian Sea Level Trends, 1930–1980

Platform	Latitude	Longitude	Trend, mm/yr	PGR, mm/yr	T-PGR, mm/yr
Newcastle	32°55′S	151°48′E	3.5	−0.6	4.1
Sydney	33°51′S	151°14′E	1.7	−0.6	2.3

The disagreement of these sites makes it impossible to decide which one to use.

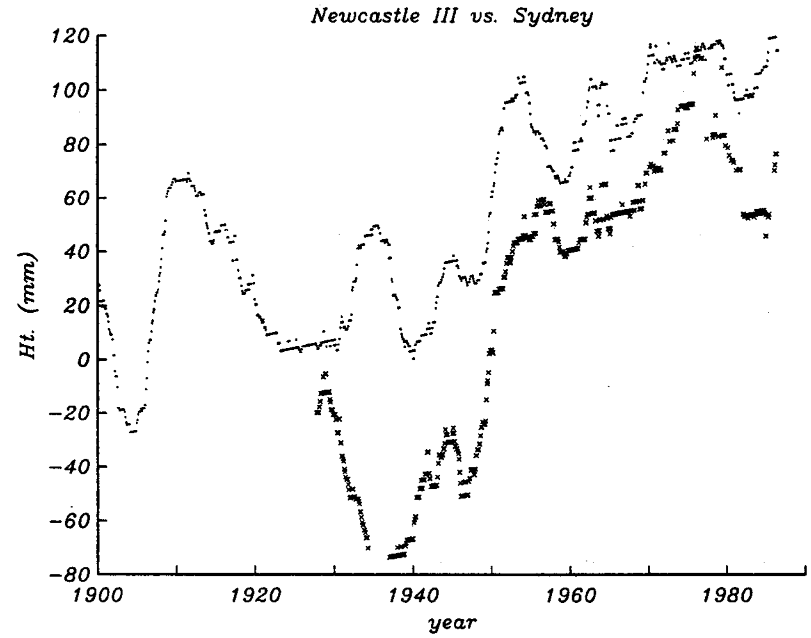


Fig. 9. Median filtered sea level records for Newcastle (crosses) and Sydney (dots) tide gauges. Agreement is good for 1950–1980, but the sea level record is 180° out of phase from 1930 to 1950.

TABLE 9. Sea Level Trends (From 1880 Onward) for Tide Gauges Selected for Global Analysis With Minimum Record Length of 60 Years

Site	Start	End	Latitude	Longitude	Trend, mm/yr	PGR	T-PGR
			North Sea				
Aberdeen II	1880	1966	57°09′N	022°05′W	1.0	−0.6	1.6
North Shields	1895	1986	55°00′N	001°27′W	1.9	−0.5	2.4
			English Channel				
Newlyn	1915	1986	50°06′N	005°33′W	1.7	−0.1	1.8
Brest	1880	1988	48°23′N	004°30′W	1.3	−0.1	1.4
			Atlantic				
Cascais	1882	1988	38°41′N	009°25′W	1.2	−0.5	1.7
Tenerife	1927	1988	28°29′N	016°14′W	1.8	0.0	1.8
			Mediterranean				
Marseille	1885	1964	43°18′N	005°21′E	1.7	−0.2	1.9
Genova	1884	1986	44°24′N	008°54′E	1.3	−0.2	1.5
Trieste	1905	1989	45°39′N	013°45′E	1.3	−0.3	1.6
			Pacific				
Honolulu	1905	1981	21°19′N	157°52′W	1.6	−0.4	2.0
			North American West Coast				
San Francisco	1880	1987	37°48′N	122°28′W	1.3	−0.4	1.7
			Central America				
Balboa	1908	1970	08°58′N	079°34′W	1.6	−0.3	1.9
Cristobal	1909	1970	09°21′N	079°55′W	1.1	−0.3	1.4
			SE North America				
Key West	1926	1987	24°33′N	081°48′W	2.3	−0.4	2.7
Charleston I	1933	1980	32°47′N	079°56′W	3.4	0.2	3.2
Hampton Roads	1928	1987	36°57′N	076°20′W	4.3	1.2	3.1
Baltimore	1902	1980	39°16′N	076°35′W	3.3	1.3	2.0
Atlantic City	1912	1976	39°21′N	074°25′W	4.0	1.7	2.3
New York	1920	1980	40°42′N	074°01′W	3.3	1.4	1.9
			NE North America				
Portland	1912	1987	43°40′N	070°15′W	2.2	1.0	1.2
Eastport	1930	1987	44°54′N	066°59′W	3.2	1.8	1.4

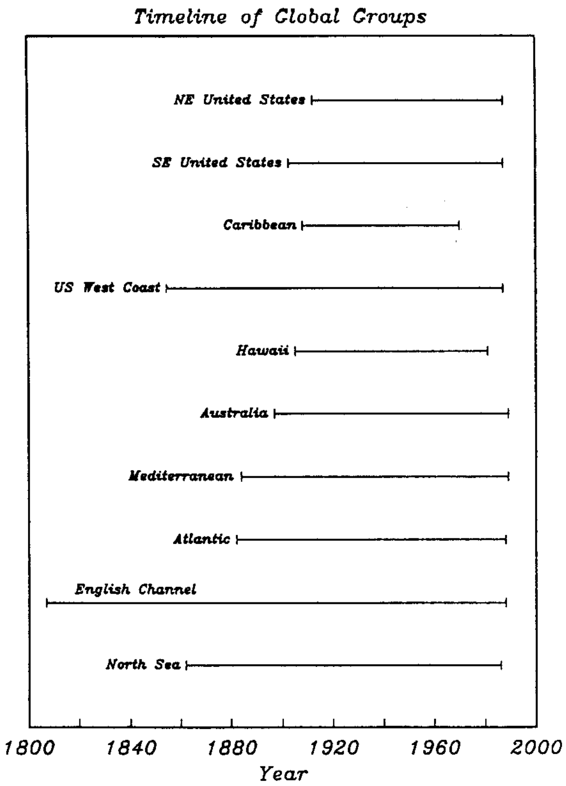


Fig. 10. Temporal coverage of the longest record for each sea level group used in this paper. The period 1900–1980 is represented very well, and 1880–1980 is represented nearly as well.

11 gives plots of the filtered data for one station in each group for 1880–1980 with (heavy dots) and without correction for PGR. The consistency of the corrected records and necessity of applying the PGR correction is very apparent.

To calculate global sea level rise, the mean rise in each group was determined, and the average of all groups was taken giving each equal weight. Giving weights according to some other criterion did not seem justified, since the sea level records contain so much systematic signal. Table 10 gives the results for each group, the overall global means, and the formal standard error of the means. Note that although the global mean value is unchanged at 1.8 mm/yr after correction for PGR, the rms scatter of the groups and the precision of the global mean are reduced by one half. The PGR has a wavelike character over the sphere and tends to average out for the selected set of stations, so that the consistency of trends is improved without having a significant effect on the mean value.

An estimate based on all stations with records of 70 years or longer has also been prepared. Extension of the requirement to 70 years eliminates the Balboa and Cristobal sites and most of the east coast of North America, as can be seen in Table 11, but raises the average record length to 86 years. The result for global mean sea level rise for the 70 year and longer records is changed slightly to 1.7 mm/yr. The standard error of the result has also dropped slightly because only one site (Baltimore) has remained on the southeast North America list and its trend value is significantly closer to the mean. The two global values are well within their formal errors, but the value based on the longer records is possibly slightly freer of systematic error effects arising from low-frequency fluctuations of sea level and therefore may be preferred.

TABLE 10. Group and Global Mean Trends for the Stations in Table 9

	Trend, mm/yr	
	Raw	PGR Corrected
North Sea	1.5	2.0
English Channel	1.5	1.6
Atlantic	1.5	1.7
Mediterranean	1.4	1.6
Pacific	1.6	2.0
North American West Coast	1.3	1.7
Central America	1.3	1.6
SE North America	3.4	2.5
NE North America	2.7	1.3
Global mean	1.8	1.8
rms	0.8	0.4
SE of mean	0.2	0.1

PGR does not change significantly the value of global sea level rise derived from these stations, but reduces the rms scatter and standard error of the mean by 50%.

5. DISCUSSION

This paper has produced another estimate of global sea level rise in a field crowded with estimates. What is significant about the present paper is that its strict selection of tide gauge records based on regional tectonics, completeness of record, agreement of trends for nearby sites, and emphasis on only the longest records has produced a list of sites (Table

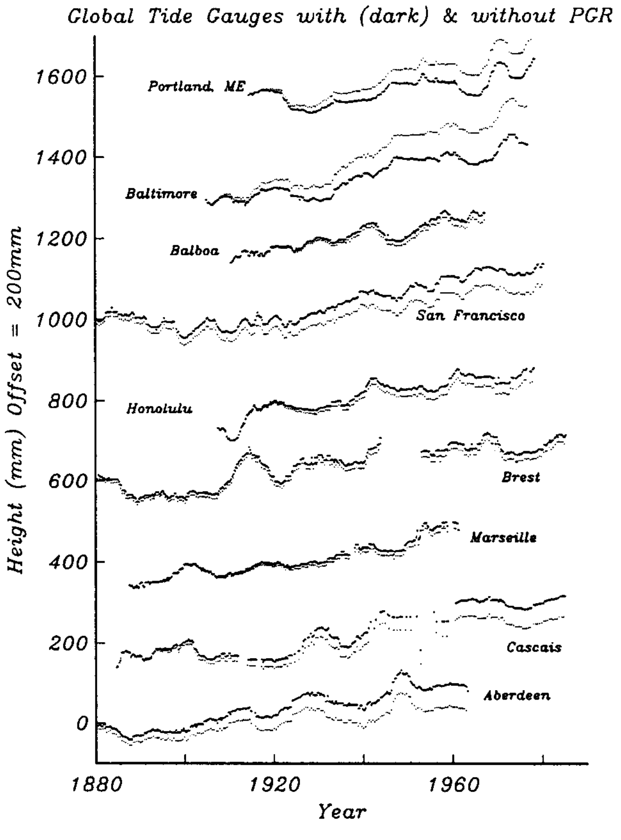


Fig. 11. Median filtered sea level records with (heavy dots) and without PGR correction for one member of each sea level group.

TABLE 11. PGR-Corrected Trends and Global Mean for the Groups With Minimum Record Length of 70 Years

Region	PGR-Corrected Trend, mm/yr
North Sea	2.0
Aberdenn II	
North Shields	
English Channel	1.6
Newlyn	
Brest	
Atlantic	1.7
Cascai	
Mediterranean	1.6
Marseille	
Genova	
Trieste	
Pacific	1.9
Honolulu	
North American West Coast	1.7
San Francisco	
SE North America	2.0
Baltimore	
NE North America	1.2
Portland	
Global trend	1.7 ± 0.3
SE of mean	±0.1

Although there are fewer stations with longer records, the standard error of the mean is slightly smaller.

9) that yield very highly consistent measurements of sea level trend. The paper has also confirmed the importance of correcting for postglacial rebound and the high quality of the ICE-3G model of *Tushingham and Peltier* [1991]. A facet of these results that must be emphasized is that the ICE-3G model did not use any contemporary values of sea level rise in its derivation. It is a model that fully respects the physics of the deglaciation and isostatic readjustment process and is based on global sea level change data of the order of 100 m over the last 20,000 years.

It will not go unnoticed that *Peltier and Tushingham* [1989] obtained the value 2.4 mm/yr with an uncertainty of 0.9 for global sea level rise employing the same ICE-3G model values of PGR used for this paper. However, their analysis used many sites, including Tonoura, Bombay, and others, explicitly rejected in the present paper because of contamination by tectonic effects. Significantly, the analysis of Peltier and Tushingham gave an uncertainty that is less than 1 standard deviation away from the present result and so was true to its data set.

Another recent estimate of global sea level rise has been made by *Trupin and Wahr* [1990]. Using 84 stations with a minimum record length of 37 years, they obtained for the global trend the value 1.75 mm/yr ± 0.13, essentially identical to the results obtained here. What is interesting is that using 84 stations gave no improvement in uncertainty over the nine groups used here. In fact, an uncertainty of 0.13 mm/yr in the trend for 84 stations implies an rms scatter of trends of 1.2 mm/yr, about 3 times the rms scatter of the much longer records used in this paper. The reason for this situation almost certainly lies in their use of series as short as 37 years. As was noted earlier, interdecadal fluctuations of sea level have a very large effect on the trend even for records many decades in length, that being the reason 60 years was chosen as the minimum record length for this investigation and an estimate made for records longer than 70 years.

The consistency of trends (0.4 mm/yr rms) of the sites selected according to the criteria of this paper has another significant implication. There is little evidence of other than a secular increase of sea level over the last 100 years. The filtered records plotted in Figure 11 do not, as a whole suggest any recent changes. San Francisco does have an apparent curvature concave upward, but this is lacking in other records and so may be simply part of a very low frequency change there. The existence of individual sites with an apparent acceleration of sea level, but no evidence of acceleration of overall global sea level, has previously been documented by *Woodworth* [1990].

Finally, a few comments are in order concerning the implication of these results on future investigations of sea level change. Port Tuapse, earlier rejected in this study because of its tenuous connection with the ocean basins, has a PGR-corrected trend of 2.2 mm/yr over its 71-year record. This fact, and the agreement of trends of the other sites in both the Pacific and Atlantic oceans, confirms that on a 100-year time scale a global rise of sea level is accurately detectable everywhere that is tectonically quiet, something that is definitely not true on time scales of a few decades for which regional fluctuations dominate. It is noteworthy that tide gauge measurements over the last 100 years taken for rather different purposes than global change are accurate enough to reveal this balance. Additional confirmation is supplied by a recent paper by *Hannah* [1990] that gives for the average of four sites in New Zealand the value (uncorrected for PGR) of 1.7 mm per year, within the range of values found for the northern hemisphere sites. Unfortunately, the fact that the ocean basins are in balance with each other as far as sea level rise is concerned over 100 years or so is of little comfort for those who seek to evaluate global change on a much shorter time scale. A vigorous program of research and observation must be undertaken to understand and model the interdecadal fluctuations of sea level and remaining uncertainties of PGR and other crustal movements [*Carter et al.*, 1989] so that the time required to determine significant changes of sea level is drastically reduced.

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