Journal of Coastal Research	24	2B	218–227	West Palm Beach, Florida	March 2008

Concerning Evidence for Fingerprints of Glacial Melting

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ABSTRACT

DOUGLAS, B.C., 2008. Concerning evidence for fingerprints of glacial melting. *Journal of Coastal Research,* 24(2B), 218–227. West Palm Beach (Florida), ISSN 0749-0208.

Recent investigations of tide gauge and hydrographic data point to the conclusion that twentieth-century global sea-level rise was about 1.8 mm/y, with significant decadal and longer variability. Ocean thermal expansion can account for about 0.5 mm/y of the trend, leaving an additional ~1.3 mm/y water equivalent that must have come from other sources. Greenland, Antarctica, and small glaciers are obvious candidates, and "fingerprints" of their contributions must occur because additions of glacial ice or meltwater to the oceans will not cause a globally uniform rate of sea-level rise. As ice melts or is discharged, Earth will respond elastically, and the geoid will also adjust. The result is that large changes in relative sea level will occur near the area of melting or discharge, and significant (~20%) deviations from a uniform global rise will occur antipodal to the source. Thus, several authors have used trends of relative sea-level rise obtained from tide gauge data to investigate possible contributions from Greenland, Antarctica, and other sources of global sea-level rise. In this paper, we consider the fingerprint question morphologically by examining the regional variations of relative sea-level change for evidence of these fingerprints. Unambiguous evidence for fingerprints of glacial melting was not found, most likely due to the presence of other signals present in sea-level records that cannot easily be distinguished.

ADDITIONAL INDEX WORDS: *Sea-level rise, sea-level variability, sea-level pressure, glacial melting.*

INTRODUCTION

There is evidence that the twentieth-century average rate of global sea-level rise of about 1.8 mm/y (CHURCH and WHITE, 2006; CHURCH *et al.,* 2004; DOUGLAS, 1997; HOLGATE, 2007; HOLGATE and WOODWORTH, 2004; MILLER and DOUGLAS, 2004, 2006; PELTIER, 2001; WHITE *et al.,* 2005) is a recent phenomenon. The average trend value over the previous millennium was much less (DONNELLY *et al.,* 2004; FLEMMING, 1978, 1982; FLEMMING and WEBB, 1986; LEATHERMAN, 2001; SHENNAN and WOODWORTH, 1992; WOODWORTH, 1999). About half of the recent increase can be attributed to ocean thermal expansion and melting of small glaciers, but the remainder cannot be explained by available estimates of ice loss from Greenland and/or Antarctica. Although there are constraints on recent changes in the Greenland and Antarctic ice sheets, the ice mass balance for these great concentrations for the twentieth century is not known well enough to obtain an accurate estimate of their contribution to twentieth-century global sea-level rise (CHURCH *et al.,* 2001). However, to the extent that they are contributing, that contribution potentially can be observed indirectly by what are called "fingerprints" of ice-mass loss.

Earth adjusts both viscoelastically and elastically to the removal of a load. Concerning the former, the e-folding time for viscoelastic adjustment of Earth since the end of the last deglaciation is on the order of several thousand years. Thus, Earth is still responding to the last deglaciation event at a significant rate compared to the observed rate of sea-level change measured by tide gauges in the twentieth century (PELTIER, 2001). In contrast to the viscoelastic response, elastic adjustment of Earth to removal of a load is effectively instantaneous. Thus, glacial melt will cause an immediate adjustment of sea levels. CONRAD and HAGER (1997) and TAMISIEA *et al.* (2001) presented the elastic deviations of sea-level rise from uniformity over the globe for uniform contributions from Greenland and Antarctica, and from smaller glaciers. Their results show that relative sea level (RSL) will fall close to ice loads and increase in the hemisphere opposite from the source. The fall of RSL adjacent to the source can be as large as the global increase would be if it were uniform, and the distant increase can be 20% higher than that predicted by a uniform rise. Several authors (MITROVICA *et al.*, 2001; PLAG, 2006; TAMISIEA *et al.*, 2001) have estimated continental glacier contributions to sea-level rise based on regional differences in relative sea-level rise derived from tide gauge data. In this paper, selected tide gauge records are evaluated on a case-by-case basis to determine whether or

DOI: 10.2112/06-0748.1 received 24 August 2006; accepted in revision 21 November 2006.

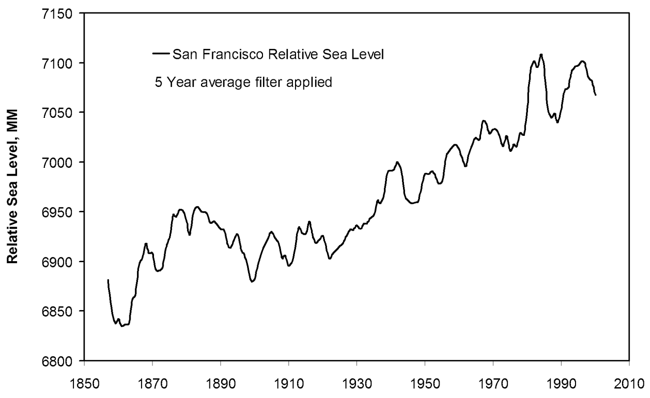

Figure 1. Relative sea level (RSL) at San Francisco. Note that the record is concave downward for the second half of the nineteenth century. The peak RSL reached in 1883 was not equaled until 1936. No adjustment has been made for the 1906 earthquake.

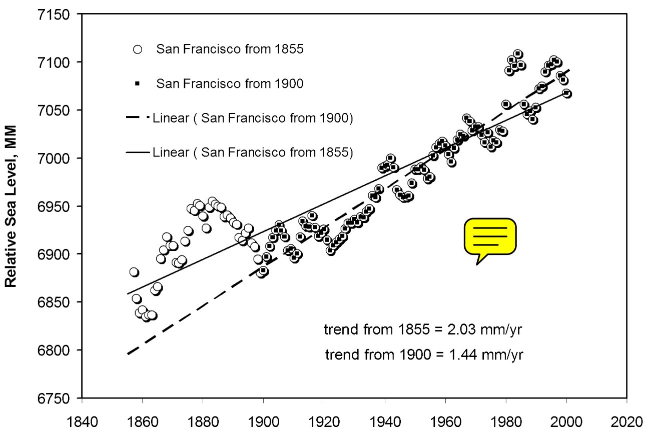

Figure 2. Trends of RSL computed from San Francisco tide gauge data. The twentieth-century trend is one-third greater than the trend for the entire record.

not long tide gauge records are actually providing clear evidence of fingerprints of glacial melting. Selected records suffice for this exercise because high regional correlations of tide gauge series are known to exist at decadal and longer periods; it is not necessary to test all records. See PAPADOPOULOS and TSIMPLIS (2006) for an extended discussion and review of regional correlations.

LONG TIDE GAUGE RECORDS IN WESTERN NORTH AMERICA

The longest continuous RSL record in North America is from San Francisco. It begins in 1854. Other records near a century in length on the U.S. west coast are available from San Diego and Seattle. Since these three records are spaced in a north-south direction over a considerable distance, they are good candidates for detection of fingerprints of glacial melting. In addition, the magnitude of the Glacial Isostatic Adjustment (GIA) correction, at least as given by PELTIER (2001), is very small at these sites, and it can be ignored for an initial examination of the records.

San Francisco RSL is notable for having radically different behavior in the nineteenth and twentieth centuries. Figure 1 presents this record. It was prepared from annual means of the data and was smoothed with a 5 y average (boxcar) filter. These and all data analyzed in this paper were obtained from the Permanent Service for Mean Sea Level (WOODWORTH and PLAYER, 2003; see www.pol.ac.uk for values).

The nineteenth-century portion of the record is concave downward, in sharp contrast to the pronounced twentieth-century upward rise, which is very apparent beginning about 1925. Obviously, the RSL trend for this record depends critically on the portion of the data used. Figure 2 illustrates the dependence of the RSL trend on record length.

The anomalous nineteenth-century record at San Francisco demands verification. Unfortunately it can not be confirmed by comparison to other nearby records, since none are long enough. But there is evidence that this behavior is an indirect result of atmospheric forcing. Figure 3 is a plot of detrended San Francisco RSL, and the inverted barometer (IB) correction (pressure data from JONES, 1987) at San Francisco scaled by the ratio of the Standard Deviation (SD) of RSL to the SD of the local IB correction.

This remarkable correlation was discovered by comparing normalized San Francisco RSL with the Southern Oscillation Index (SOI) (which is normalized), and various normalized sea-level-pressure records. The normalized Darwin sea-level pressure, a good proxy for the SOI, correlates well with San Francisco sea-level pressure (available only since 1875) at interannual frequencies but does not exhibit the nineteenth-century behavior seen in the San Francisco RSL record. The San Francisco sea-level-pressure record (also available only since 1875) in contrast does track the San Francisco sea-level record very well at all frequencies. No physical explanation for the correlation ($r = 0.72$) of RSL and the San Francisco sea-level pressure (or inverted barometer [IB] correction) is

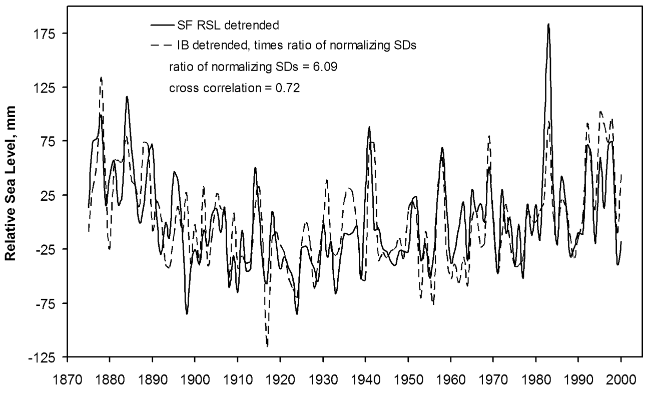

Figure 3. San Francisco RSL and scaled IB. The correlation is remarkable and indicates that the decadal and lower-frequency variations of RSL at San Francisco are in some way driven by basin-scale ocean/atmosphere phenomena. San Francisco sea-level pressure data are not available before 1875.

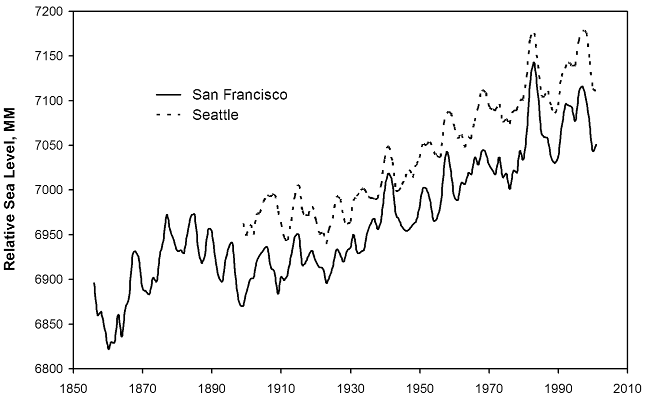

Figure 4. RSL at San Francisco and Seattle. The records closely resemble each other over their common time interval. Note that both records show only a small trend from 1900 to 1930.

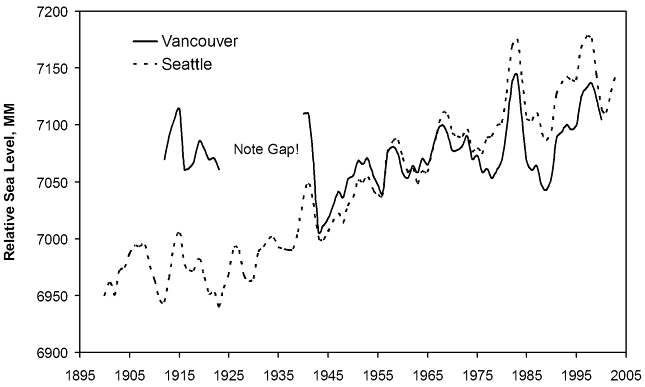

Figure 5. Seattle and Vancouver RSL. From 1943 to 1967, the records agree well, but after 1967, RSL at Vancouver always trends lower than Seattle. The gap in the record obviously indicates a datum problem. The RSL record at Victoria is similar.

known. It is plausible that this correlation indicates that an ocean-atmosphere basin-scale variation is occurring. The correlation does suggest that the behavior in the nineteenth century is real and is not an artifact in the data.

A RSL/IB scaling factor of about six gives excellent agreement for the amplitudes of the interannual and longer variations. However, the factor of six does not scale the trend of the inverted barometer, ~0.15 mm/y, to equal the twentieth-century trend of San Francisco RSL of 2 mm/y. More research is needed to obtain insight into the physical mechanisms involved in these atmospheric and sea-level records.

The other century-long records on the U.S. west coast are at San Diego and Seattle. The former is essentially identical to San Francisco over their common time interval beginning in 1906. The latter is usually ignored in discussions of sea-level rise (*e.g.,* DOUGLAS, 1991) because of its proximity to the colliding plate boundary in the Pacific Northwest. However, the results of LONG and SHENNAN (1998) and VERDONCK (2005) indicate that Seattle is far enough from the immediate compressive zone to have little if any uplift from the converging plates, so it is reasonable to compare the Seattle and San Francisco RSL records. Figure 4 shows Seattle and San Francisco together on the same plot. They obviously agree well as far as interannual variability is concerned. Most of that variation is caused by coastal Kelvin waves related to the El Niño–Southern Oscillation (ENSO) (CHELTON and DAVIS, 1982; PAPADOPOULOS and TSIMPLIS, 2006). The records are also parallel, so that the trends are the same over their common interval. Their trends (1.42 and 2.06 mm/y), reported by the Permanent Service for Mean Sea Level (PSMSL) web site (http://www.pol.ac.uk/psmsl/datainfo/rlr.trends), are caused by the different record lengths, not by geophysical or other phenomena. The PSMSL gives a warning about uncritical use of trends derived from tide gauge data.

Comparisons of the Seattle and San Francisco RSL records from 1900 to 1930 offer additional evidence that the behavior of San Francisco RSL record in the second half of the nineteenth century is real, beyond the scaled inverted barometer correction. The increase of RSL rise after 1930 is also consistent with the results of CHURCH and WHITE (2006), which showed a global increase of sea-level rise beginning ca. 1930.

There are other near-century-long tide gauge records in the Pacific Northwest. These are from Victoria and Vancouver, western Canada. However, these records have problems that are readily seen by a comparison with the Seattle record (Figure 5.) As noted in the PSMSL documentation for this site, there is a datum problem across the data gap for Vancouver. The first few years of data resumption are evidently in error also. But after 1943, the close agreement of the variability of the records suggests that Vancouver data are thereafter reliable. It is interesting that RSL at Vancouver appears to "level off" after about 1970, but not at Seattle. The Victoria RSL record is similar, including a large gap, and shows the same leveling phenomenon. Could this be a fingerprint of glacial melt? If so, it would have to be from Alaska, since Greenland and Antarctica are sufficiently distant that a sharp difference between Seattle and Vancouver/Victoria would not be observed (CONRAD and HAGER, 1997; TAMISIEA *et al.,* 2001). LARSEN *et al.* (2004) argued that an ongoing glacial melt in Alaska began in the eighteenth century. ARENDT *et al.* (2002) found a very large loss of ice (~0.3 mm/y global sea-level equivalent) in Alaska after 1950. However, the four permanent Alaska tide gauges at Skagway, Juneau, Sitka, and Yakutat, which cover the period from about 1940 to present, do not show any leveling off of RSL beginning in 1970. Thus, Alaskan glacial melt does not appear to be responsible for the leveling off of RSL observed at Vancouver and Victoria. Further investigation is needed. WOODWORTH (1987) noted a fall in the rate of sea-level rise in the U.K. and Europe also after about 1970. It will be shown later in this paper that a leveling off of RSL after about 1960–1970 was a widespread phenomenon that occurred in the northeastern part of North America and the Southern Hemisphere as well.

Other west coast tide gauge records that have been used for analysis of fingerprints of glacial melt include Santa Monica and Los Angeles. The Santa Monica record has several gaps and is obviously inaccurate—it flunks any comparison with records from nearby gauges. Los Angeles has a good

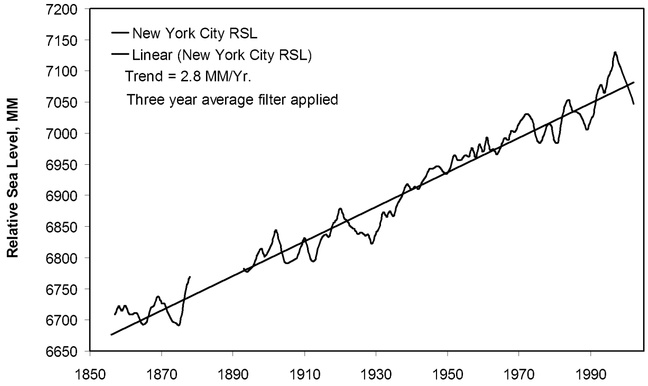

Figure 6. RSL rise at New York City. The trend value of about 2.8 mm/y is higher than the global sea-level rise value because of glacial isostatic adjustment.

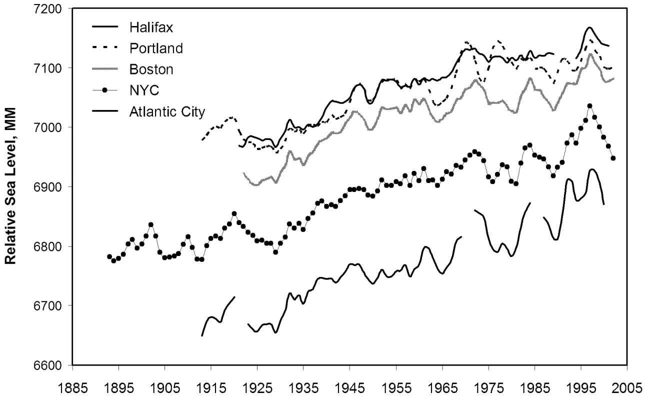

Figure 7. GIA-corrected RSLs from Atlantic City to Halifax. The decadal variations of RSL are obviously correlated at these locations. Note that RSL increases at a much lower rate for the three northern series after 1960 than before.

record with a sea-level rise of about 1 mm/y, but it is probably affected by uplift associated with earthquake faulting. In any case, a reduction of RSL trend of about 1 mm/y at Los Angeles compared to 2 mm/y for San Diego/San Francisco/Seattle is not a plausible fingerprint of either glacial melt or glacial isostatic adjustment.

LONG TIDE GAUGE RECORDS IN EASTERN NORTH AMERICA

The record of RSL on the east coast of North America has a very different morphology from the west coast. The two regions are on opposite sides of their respective ocean basins, and they are also subject to very different effects of glacial isostatic adjustment (GIA). As far as steric effects are concerned, MILLER and DOUGLAS (2004, 2006) showed that the twentieth-century trend is about 0.5 mm/y near the west coast and much less for the east coast. So, most of the GIA-corrected increase of sea-level rise on the east coast must have come from sources other than steric.

The longest RSL record on the east coast is from New York City, shown in Figure 6. It extends from 1856 to present, but data are missing from 1879 to 1892. However, this gap does not appear to be especially suspicious since the trend is the same to within 0.1 mm/y regardless of whether or not the early portion is included. The New York City record shows different variability than the west coast records because the sources of variation are entirely different on these eastern and western ocean boundaries.

The trend of RSL at New York City is 2.8 mm/y, of which 0.9 mm/y is due to GIA as given by the ICE 4G (VM2) model of PELTIER (2001). This GIA model is quoted here because it is very consistent with observed rates of RSL rise along the North American east coast.

Other long records on the North American east coast exist that can be examined along with New York City for evidence of fingerprints. Figure 7 presents a GIA-corrected RSL series for Atlantic City, Boston, Portland (Maine), and Halifax in addition to New York City. Figure 7 shows that the decadal variations in these sea-level time series are significantly correlated. What is different is the very low-frequency variation of sea level. Atlantic City and New York City show a nearly constant trend from 1930 onward, but Boston, Portland, and Halifax all show a leveling off of sea level after 1960, similar to what was seen in Figure 5 for Vancouver (Victoria also behaved this way). This can better be seen by referring the sea-level series to their means and then averaging them into two groups, as seen in Figure 8.

The significant reduction of sea-level rise after about 1960 is now readily apparent for the north group of tide gauges. The north group rate from 1913 to 1960 is 2.3 mm/y, and 1.2 mm/y thereafter. Is this a fingerprint of Greenland ice loss? The decrease in the trend is very great, and such a large loss of ice from Greenland would also have a large fingerprint easily visible at New York City and Atlantic City (CONRAD and HAGER, 1997, their Figure 3b) and further south along the U.S. east coast as well. Such a fingerprint is not observed, as Figure 8 shows. So this behavior is not plausibly due to glacial melt. A steric origin seems unlikely also, since MILLER and DOUGLAS

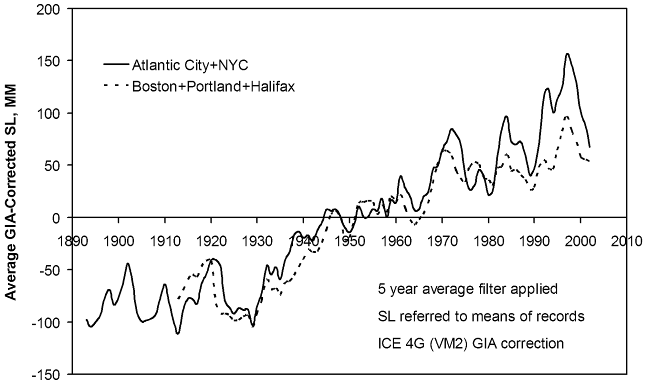

Figure 8. RSL of the series in Figure 7 referred to their means and averaged into northern and mid-Atlantic groups. The groups are parallel until about 1960.

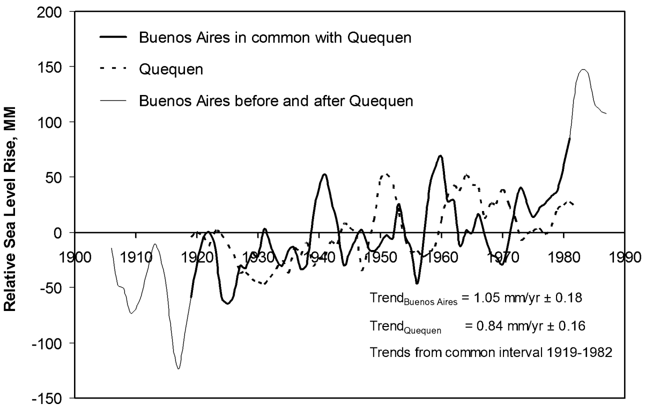

Figure 9. RSL series for Quequen and Buenos Aires. The trends over their common interval are not statistically significantly different. GIA correction has not been applied.

(2004, 2006) calculated steric trends in this area for the latter half of the twentieth century and did not find a significant rate. The effect also cannot be a fingerprint of Antarctic ice loss because the amount is implausibly high, and the fingerprint of Antarctic loss is constant along the North American east coast (CONRAD and HAGER 1997, their Figure 2b). Some new source for this change of sea level must be found.

Finally, Figure 8 shows that New York City and Atlantic City show essentially no sea-level rise from late in the nineteenth century to 1930. Thereafter, the trend is steadily upward. This is consistent with the conclusion of CHURCH and WHITE (2006) concerning an inflection of their global sea-level curve in 1930. However, the RSL behavior of Boston, Portland, and Halifax after 1960 is not reflected in their global sea-level curve.

LONG SOUTHERN HEMISPHERE SEA-LEVEL RECORDS

There are not many long-term (>50 y) tide gauges far enough south for evaluation of Antarctic fingerprints of ice loss. Only a few tide gauges in Argentina, New Zealand, and Australia have records long enough to attempt to estimate trends of sea level rise.

DOUGLAS (2001) evaluated Quequen and Buenos Aires sea-level records and showed that the RSL trend at Buenos Aires is indirectly heavily contaminated by the 1982–83 ENSO. Quequen is not so affected. But Quequen and Buenos Aires do have a 64 y (1918–82) record in common that lacks any unusually large ENSO-related signals. If these sea-level series are truncated over their common interval that does not include the 1982–83 ENSO event, their records appear as in Figure 9. For this figure, both records have been smoothed with a three-year average (boxcar) filter and both series are referred to their respective means.

The rates of RSL rise for these two records over their common time interval are only about half of the global rate of about 2 mm/y obtained by many other authors. Of course, they must be corrected for GIA for interpretation. The ICE 4G (VM2) model of PELTIER (2001) gives −0.37 mm/y for Quequen and −0.99 mm/y for Buenos Aires. The GIA values are very different, much more than would ordinarily be expected for sites relatively far away from ice masses at the last deglaciation and only 4 degrees apart in latitude. In contrast to ICE 4G, the ICE 5G (VM2) (PELTIER, 2004; for values see http://www.pol.ac.uk/psmsl/peltier/index.html) model gives −0.74 mm/y for Quequen and −0.78 mm/y for Buenos Aires. When corrected using ICE 5G values, the rates are more nearly in line with the overall rate of global sea-level rise and do not indicate the presence of a fingerprint of Antarctic ice loss. Obviously there is some circularity to this argument because the rate of global sea-level rise was obtained using a GIA model, in fact ICE 4G in most cases. Finally, close examination of Figure 9 suggests that there may be a flattening of the RSL series after 1940–50. However, the records are too short and have too much decadal variability for a quantitative interpretation. The possibility of fingerprints in Argentine data must await improved analyses of contaminating signals in the data.

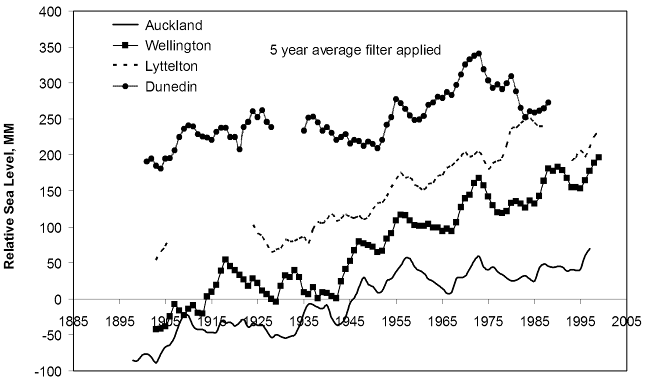

Figure 10. Long RSL records for New Zealand. Series offset for clarity. Auckland and Wellington have consistent decadal variability after 1940. Dunedin and Lyttelton have suspicious gaps. Data are from the PSMSL.

New Zealand RSL rise has been reported on by HANNAH (1990), BELL *et al.* (2000), and HANNAH (2004). There are two long records from the North Island (Auckland and Wellington) and two from the South Island (Lyttelton and Dunedin). HANNAH (2004) provided an analysis of recently improved and enlarged records from these sites. He averaged the data from the four tide gauges and concluded that RSL was rising at about 1.7 mm/y for the region during the twentieth century, a value that, after correction by a few tenths of a mm/y for GIA, is consistent with estimates of global sea-level rise of about 2 mm/y. BELL *et al.* (2000) made the observation that RSL at Auckland leveled off after about 1960 and attributed this to the preponderance of negative values of the SOI after that time. To gain insight into these issues, consider Figure 10.

HANNAH (2004) noted that the Dunedin record was of suspicious quality (note the gap) and gave it only 50% of the weight given to the others when he formed the New Zealand average. If left out entirely, the New Zealand average RSL rise is increased by a few tenths, so his overall conclusion about RSL rise in New Zealand is unaffected. What is more

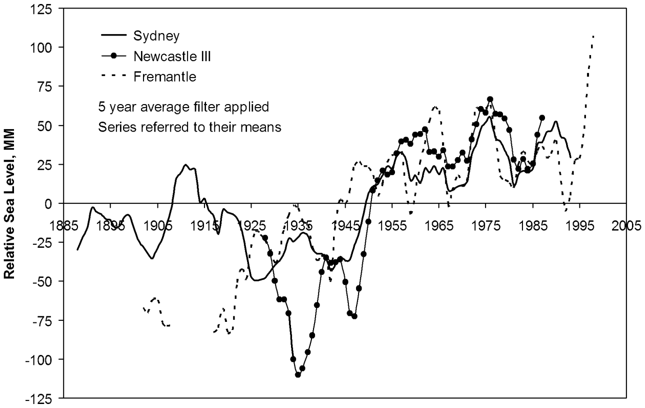

Figure 11. Long Australian RSL records. There is no correlation before 1950. The series level off thereafter.

interesting is the behavior of the series from Auckland and Wellington. The series are roughly parallel until about 1960, but after that, Auckland shows little or no increase, while Wellington RSL continues to increase at more than 2 mm/y. Since the decadal variations of Auckland and Wellington are consistent, it seems unlikely that ENSO is responsible for the flattening of the Auckland RSL curve as conjectured by Bell *et al.* (2000). Some other explanation must be found.

What about New Zealand RSL as a fingerprint of glacial melting? The fingerprint calculations of Conrad and Hager (1997) and Tamisiea *et al.* (2001) showed only a very small fingerprint effect for New Zealand from any source. Given the disparate and unexplained differences in the series shown in Figure 10, it is probably best to average the rates of sea-level rise for the four series and regard them as indicating a single rate of relative sea-level rise far from ice masses. The combined rate is 1.6 ± 0.3 mm/y. GIA values are about −0.3 mm/y for ICE 4G (VM2) and as much as twice this number for ICE 5G (VM2). So a reasonable estimate for the GIA-corrected rate is about 2 mm/y, with an uncertainty of perhaps 0.5, consistent with most estimates of global sea-level rise.

Sea-level rise at the Australian coast is as complex as that for New Zealand. There are three long tide gauge records, Sydney, Newcastle, and Fremantle. The first two are a few degrees apart on the SE coast, and the other is on the SW coast near Perth. Figure 11 presents smoothed RSL data for the three sites, each referred to its mean value. These series have not been corrected for GIA in Figure 11.

A trend can be calculated for each of these series or their average, but what meaning will it have? A single trend value cannot characterize any of these series in a manner that has any meaning. What is interesting is that the three records level off after about 1960. The sudden sharp increase at Fremantle starting in 1996 suggests that this behavior may have ended, but there is no confirmation available from the other two records.

The behavior after 1960 reminds one of the Auckland sea-level record. However improbable it may seem, there is a definite cross-correlation ($r = 0.76$), as Figure 12 shows. It is obvious that the Southern Hemisphere RSL records are much harder to characterize and explain than those of the Northern Hemisphere. As in the case of New Zealand, there is not anything apparent here that will contribute to the issue of fingerprints of glacial melting. It is even unclear whether or not these three long Australian tide gauge records can tell anything at all about twentieth-century global sea-level rise.

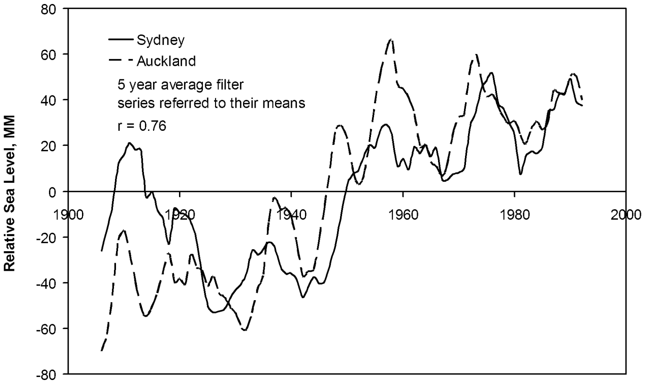

Figure 12. Auckland and Sydney RSL rise. The correlation is 0.76.

LONG RECORDS OF SEA-LEVEL RISE IN EUROPE

Europe contains a large number of long sea-level records. Some of the longest records are unfortunately in areas of Fennoscandia that have very large values of GIA. See Miller and Douglas (2006) for an overview of sea-level rise in Europe and its relation to GIA. Errors in the GIA correction for many of these locations can be comparable (a significant fraction of a mm/y) to anticipated fingerprints (Douglas, 1991), so it is best to stay away from sites with large GIA corrections. However, there are several long RSL time series in Europe for which GIA is moderate, and these have been widely used in determinations of global sea-level rise. They are the obvious candidates for examination for fingerprints.

One of the longest and most nearly continuous records in Europe is the series for Brest, France. There is some evidence that data prior to 1860 is offset from later values, so data prior to that time are not considered. Figure 13 shows the Brest RSL record and that of Newlyn, U.K.; the latter was chosen because it is nearby, continuous, and of high quality (Woodworth, 1987). It is clear that the decadal variability at Brest and Newlyn is very similar and that there is a possibility of a previously unrecognized offset between the series prior to about 1945. The average difference between Newlyn and Brest from 1918 to 1945 is −23 mm. This difference yields the result shown in Figure 14. It is obvious that application of this simple offset has brought the records into agreement. Figure 14 also shows that these series have virtually the same trend over their common interval after correction for the offset of 23 mm. Woodworth (1987) previously noted that Newlyn and Brest had significantly different trends over their common time interval, which was difficult to understand given the close proximity of the sites. He speculated that local land movements could be responsible.

Brest is well known for the "bump" centered at 1915. This

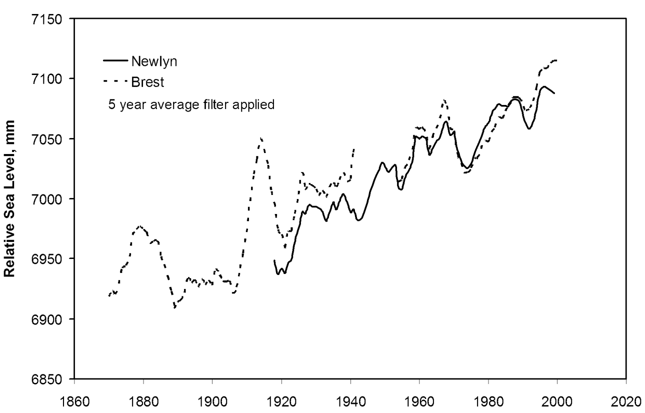

Figure 13. Brest and Newlyn RSL. Note the apparent offset of Brest and Newlyn during their common interval 1918–45.

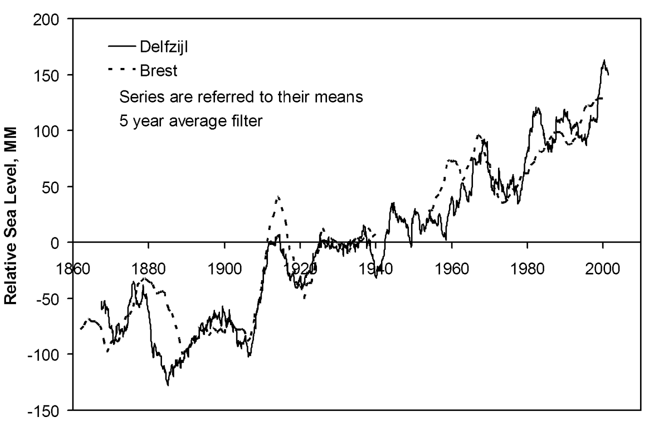

Figure 15. RSL for Brest (FR) and Delfzijl (NL). The correlation of decadal and longer variability is obvious, including the "bump" at about 1915.

improbable-appearing feature is in fact real. Figure 15 shows Brest RSL and that for Delfzijl in the Netherlands. The decadal and longer variability is highly correlated, and the 1915 "bump" is in both series.

Earlier in this paper, RSL was compared to the inverted barometer (IB) at San Francisco, and there was a striking agreement between them if the IB was scaled by a factor of about six. Since the Brest record has very different nineteenth- and twentieth-century behavior, a similar analysis is appropriate for it. Figure 16 shows that the correlation of scaled IB and RSL is very high for Brest also.

The Brest IB and RSL series in Figure 16 have been detrended and normalized by their respective standard deviations, which is why the normalized values lie between ±3. The scale factor for the IB that gives the agreement shown in Figure 16 is 3.6, somewhat more than half of the scale factor for the San Francisco IB. Again, there is no obvious physical explanation for this value, but it is interesting. Note also that the bump in Brest RSL at 1915 mirrors a bump in normalized IB, further demonstrating that the 1915 feature in Brest RSL is real.

Brest and San Francisco, both at eastern ocean boundaries, have anomalous behavior in the nineteenth and twentieth centuries. It is interesting to put these two series on the same plot, as in Figure 17. The decadal variability of the RSL series is not correlated, nor should such be anticipated, but these two ocean eastern boundary sea-level records both show much reduced rate of rise in the nineteenth century compared to the twentieth. That facet of the signals can be plausibly related somehow to atmospheric forcing.

Do the Brest and Newlyn records provide evidence of fingerprints of glacial melt? As seen in Figure 14, Newlyn and Brest have trends of RSL rise of about 1.6–1.7 mm/y over their common interval. The ICE 4G (VM2) and ICE 5G (VM2) models of PELTIER (2001, 2004) both a GIA correction at Newlyn or Brest of about 0.3 mm/y. This gives corrected sea-level trends of about 1.4 mm/y, significantly lower than the GIA-corrected U.S. west coast and the east coast from New

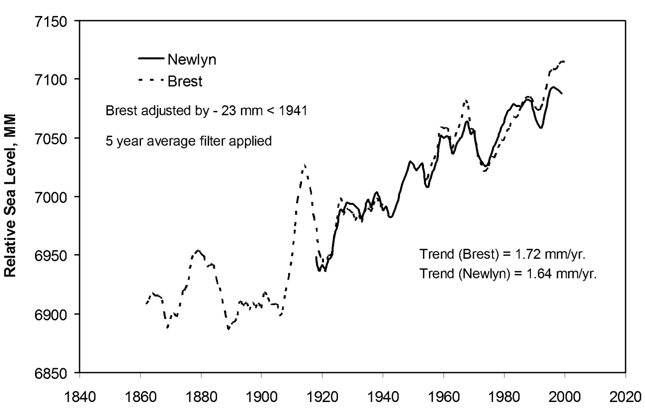

Figure 14. Newlyn and Brest RSL after adjusting Brest by −23 mm. The agreement is striking, and the two records have essentially the same trend from 1916 onward.

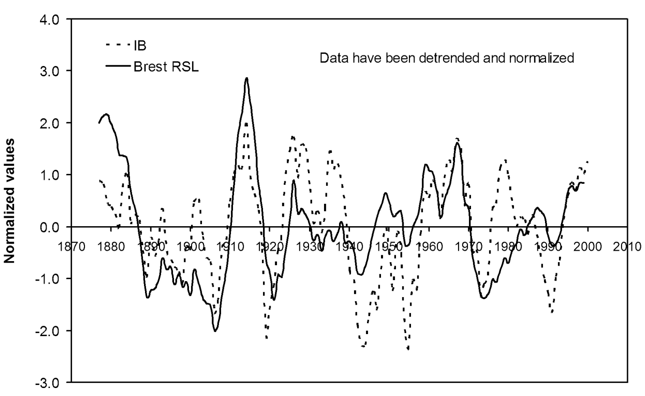

Figure 16. RSL and scaled IB correction for Brest. The data are detrended and normalized. The 1915 bump at Brest is apparently indirectly related to atmospheric forcing.

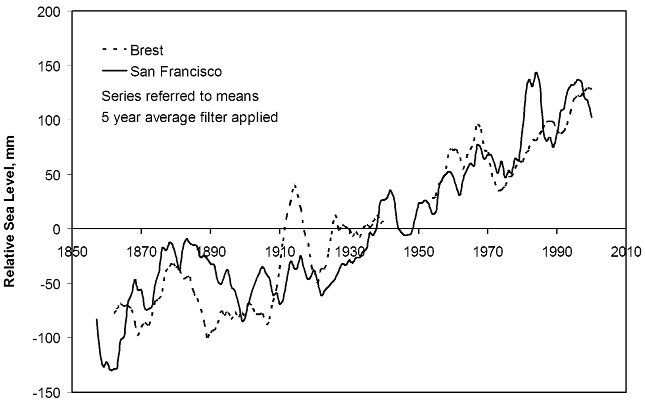

Figure 17. Brest and San Francisco RSL records. Decadal variability is not correlated, but nineteenth-century behavior is similar and in both cases is probably related somehow to atmospheric forcing.

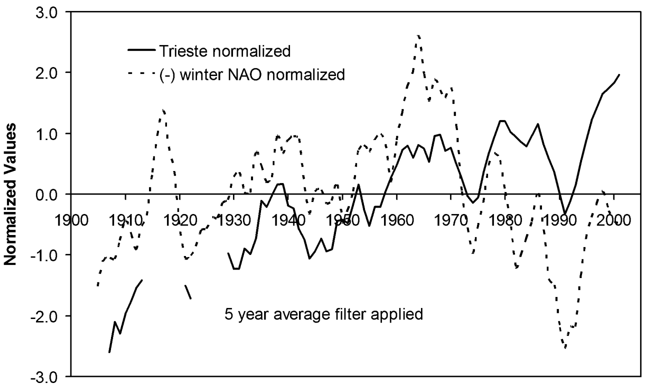

Figure 18. Normalized RSL at Trieste and the negative of the normalized winter NAO. The negative values of the NAO and Trieste RSL are parallel until 1960. The stabilizing of Trieste RSL after 1960 appears to be associated with a precipitous increase of the winter NAO.

York City southward. According to the figures in Conrad and Hager (1997) and Tamisiea *et al.* (2001), an Antarctic ice-mass loss causes practically the same effect on RSL for either the U.S. east coast or western Europe, and not the generally lower values for Europe that are actually observed. In contrast, a loss of ice from Greenland would cause a lower increase of RSL in Europe than along the U.S. east coast. However, the discussion of Figure 8 for the U.S. east coast shows that the behavior of the sea-level trends is inconsistent with glacial melt from Greenland. Of course the possibility of compensating signals from multiple sources cannot be absolutely excluded.

Other long European RSL records with low GIA corrections can be found in the Mediterranean at Marseille, Genova, and Trieste. However, these long records have their own peculiarities apparently related to atmospheric forcing. The records level off after about 1960, as noted by Douglas (1997) and investigated by Tsimplis and Baker (2000) and Tsimplis and Josey (2001).

It is interesting to plot normalized values of the winter NAO and Trieste RSL together, as in Figure 18. Marseille or Genova would give the same result, since their records are very similar to that of Trieste, so Trieste is a good proxy for RSL for western Mediterranean RSL.

The records are parallel until about 1960, and they also show some agreement of decadal variability. After 1960, RSL rise ceases, while the trend of winter NAO increases rapidly (the negative of the NAO is what is plotted in Figure 18). Once again, a meteorological origin for decadal- to centennial-scale variations in RSL is suggested. However, the rapid fall of the winter NAO from 1905 to 1960 was not associated with unusual behavior of the Trieste RSL record, so the atmospheric forcing situation for Mediterranean RSL rise is probably more complicated than it appears. A falling winter NAO is apparently associated with rising RSL at Trieste (and in the western Mediterranean in general), but a more rapidly rising winter NAO produces only a cessation of RSL rise. Given this unexplained physical situation, one should be should be hesitant in using Mediterranean SL records for fingerprint solutions to glacial melting.

DISCUSSION

The goal of this investigation was to determine if long records of RSL showed clear evidence of fingerprints of glacial melting. The calculations of Conrad and Hager (1997) and Tamisiea *et al.* (2001), who assumed that Greenland and Antarctic glaciers were contributing ice uniformly over their areas, have been followed. To the extent that this model is correct, conclusive evidence of fingerprints was found in any of the very long tide gauge records that have been used by most previous authors in their determinations of global sea-level rise. Instead, what became apparent were centennial-scale variations of RSL apparently associated with atmospheric forcing of some type, further complicating an already complex problem. The spectrum of RSL is red at many sites, and progress in analyzing sea-level data requires explanations and models of the low-frequency variations so that they may be cleared from the sea-level histories, particularly the large effects that appear to be related to atmospheric forcing. Woodworth (1987) carried out such an analysis for the U.K. and some European tide gauge records using regressions of sea-level and atmospheric series, and the results show that the uncertainties in sea-level trends can in some cases be reduced considerably by the elimination of interannual to decadal variability. Ponte (2006) extended the analysis to a global set of tide gauge and atmospheric pressure data for 1958–2000, but the results of this paper indicate that corrections on a centennial scale are required.

Given the additional requirement to correct for steric, tectonic, and GIA effects, the difficulty of using the fingerprint method for determining the source of water associated with the twentieth-century rate of global sea-level rise is very great. Plag (2006) attempted to overcome these difficulties by using a large quantity of tide gauges, including those with much shorter record lengths than those evaluated in this paper. He used a least-squares adjustment for the mass contributions that included steric corrections (to 500 m depth) on a global scale and concluded that the rate of global sea-level rise for the second half of the twentieth century was 1.05 ± 0.75 mm/y. The large uncertainty he obtained for global sea-level rise underscores the difficulty of the problem. The desirability of continuing the GRACE satellite approach (*e.g.,* CHEN *et al.*, 2006) of measuring ice masses by their gravitational attraction is obvious. However, if our goal is to understand the twentieth-century contributions of continental ice to global sea-level rise, then new sources of RSL data such as colonial land records and proxy sea-level records from salt marshes are needed along with new attention to clearing the sea-level series of atmospheric, steric, tectonic, and GIA effects.

ACKNOWLEDGMENTS

I am indebted to W. Sturges and P. Woodworth for reviews and comments on this paper. W.R. Peltier, R. Ray, and J. Sauber also offered useful suggestions. This investigation was supported by the National Aeronautics and Space Administration, Interdisciplinary Science, and Solid Earth and Natural Hazards programs.

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