Gulf of Mexico and Atlantic Coast Sea Level Change

Bruce C. Douglas

Laboratory for Coastal Research, Florida International University

Twentieth-century relative sea level rise shows considerable variability along the U.S. East and Gulf coasts. Local rates of rise lie in the range of about 1.5 to more than 4 mm per year for records from Key West, Florida, to New York City. Rates of sea level rise in the Gulf of Mexico can be much higher. In Texas and Louisiana, long-term water levels are rising up to about 10 mm per year. This is having disastrous consequences in the form of wetlands loss in the region, estimated to be as much as 65 km^2 per year in the Mississippi Delta area of Louisiana alone. Beach erosion is also significant along both the Gulf and Atlantic coasts, resulting in ever-increasing exposure of fixed structures to the damaging impacts of storms. The especially high rates of sea level rise in Louisiana and Texas are a result of their particular geomorphology, and anthropogenic alterations in the form of sediment diversion and withdrawal of underground fluids. The average long-term local rate of sea level rise on the rest of the U.S. East and Gulf coasts when corrected for glacial isostatic adjustment is about 2 mm per year, in conformity with 20th century global sea level rise. U.S. East and Gulf coast tide gauge records also have regionally coherent low frequency (decadal and longer) variations that need to be understood because of their impact on wetlands loss, and to enable accurate determination of long-term trends of sea level rise.

1. INTRODUCTION

Sea level change is receiving considerable attention these days, and for good reasons. As a practical matter, about 100 million people live in the immediate severely flood-prone coastal zone within one meter elevation above mean sea level (Nicholls and Leatherman, 1995). It has been further estimated that about 450 million persons live within 10 meters elevation above MSL (Small and Nicholls, 2003). An increasing water level leads to more rapid beach erosion thereby increasing the exposure of coastal populations to the damaging effects of storms, and contaminates groundwater and raises water tables. In addition, coastal wetland flora do not have an unlimited ability to adjust to rising sea levels, so that increased rates of sea level rise in the 21st century will accelerate the present alarming rates of coastal wetland loss. Finally, sea level rise is an important indicator of climate change. Recent results (Miller and Douglas, 2004) indicate that ocean thermal expansion and melting of small glaciers cannot account for all of the observed global sea level rise in the 20th century; Greenland and/or Antarctica or some other source of fresh water must also be contributing an amount up to a sea level equivalent of about 1 mm per year.

On the U.S. East and Gulf coasts, beach erosion and wetland loss are ubiquitous. There are a few beach areas in the US that experience accretion of sand, e.g., the immediate area updrift of barrier island tidal inlets, but such are the exception. Galgano (1998) has estimated that about 86% of US East coast seaward barrier beaches are eroding. There are several reasons for this, including coastal development, changes of sediment supply, and rapidly rising sea levels (Boesch et al., 1994; Zhang, et al, 2004; Morton et al.,

Circulation in the Gulf of Mexico: Observations and Models
Geophysical Monograph Series 161

10.1029/161GM09

2004). Erosion and loss of low-lying coastal wetlands is especially severe in regions of the Gulf coast (the Mississippi Delta and Texas) where land subsidence gives an effective rate of long-term sea level rise of as much as five times the 20th century average global rate of nearly 2 mm per year (Douglas, 1991, 1997; Peltier, 2001) Wetlands loss in coastal Louisiana has in the second half of the 20th century occurred at a rate of about 65 km^2 per year (Boesch, et al., 1994) albeit with some evidence of a reduction in recent decades. This dramatic loss occurs because of the high rate of relative sea level rise, the small slope of the coastal plain (<1:1000), and lack of sediments to replace those that are compacting and producing the land subsidence. Under these conditions, the gently sloping land is inundated and plants are lost. Since Louisiana coastal wetlands amount to 40% of the national wetland area, the loss there is responsible for about 80% of the total U.S. annual wetland loss (see Boesch, et al., 1994, and S.J. Williams (no date) at http://marine.usgs.gov/fact-sheets/LAwetlands/lawetlands.html).

In this chapter, the primary attention will be given to the character of sea level rise, and its measurements. There is a good reason for this. It is that the measurement and impact of sea level change, rather like what has been asserted about politics, "is local." That is to say, local conditions can drastically alter the long term apparent sea level rise (SLR) at a site from the so-called eustatic or global mean value of about 2 mm per year. Indeed, in some areas (Fennoscandia and Hudson Bay), sea level is falling locally by up to a cm per year because of *uplift* of the land, whereas coastal Louisiana and Texas experience their rising sea levels of up to a cm per year from land *subsidence*. Sea level measurements made by tide gauges are thus referred to as relative, because they are made with respect to a nearby local land reference which may itself change in the vertical direction, rather than to an absolute reference such as the mass center of the earth. We shall see that untangling local land reference, regional, and global components of relative SLR is a complex task, but can yield important insights into geophysical and climate processes.

The best way to appreciate the nature of relative sea level change at a site is just to examine a sea level record. Since our interest here is primarily the Gulf of Mexico, we will consider a site there. Figure 1 shows a plot of annual means (the dots) of relative sea level (RSL) recorded by a tide gauge at Pensacola, Florida. Annual means are shown in order to suppress the seasonal cycle which has an amplitude of about 90 mm. In this paper we will not consider the familiar semi-daily or other ocean tides. A comprehensive presentation of the theory of tides can be found in Pugh (1987, 2004). These data were obtained from the Permanent Service for Mean Sea Level (see www.pol.ac.uk/psmsl) based at the Proudman Oceanographic Laboratory in the United Kingdom. The record is long, extending from 1924 to the present, and the location is an excellent one. It is geologically stable and not close to any significant river influence. In addition, the site is carefully maintained by the National Ocean Service (NOS) of NOAA, including annual surveys of the pier-mounted tide gauge relative to a stable benchmark on land. These surveys are done to determine if the gauge mount has settled, and if reinstallations for maintenance or technology upgrades have been done correctly. The PSMSL refers to gauge records for which such a complete geodetic history is available as Revised Local Reference (RLR) sites. The PSMSL states that with only a few exceptions, RLR sites are the ones that should be used for scientific applications.

Figure 1 shows that RSL is rising at Pensacola, in fact at 2.1 ± 0.2 mm per year, just a little more than the global mean value. We shall see later that this is not merely fortuitous. Any statistically significant acceleration of RSL is obscured by the large interannual variations in this and the other records in this study. Woodworth (1990) and Douglas (1992) in their large scale studies did not find evidence of an acceleration of GSL in the 20th century.

It is also obvious that there is a lot of year-to-year fluctuation of RSL at Pensacola. The standard deviation of the annual means around the upward trend is 35 mm, a little less than 1/2 of the seasonal cycle. Approximately this level of fluctuation is seen in all long tide gauge records of annual means, and is mostly due to local meteorological forcing (Tsimplis and Woodworth, 1994). But there is more to see in the Pensacola record than high-frequency noise; the smooth curve shown is the result of plotting a 5-year so-called boxcar filter (i.e., a running average that moves one year at a time) of the annual means of RSL, and shows that there are low-frequency variations of sea level as well. These interdecadal

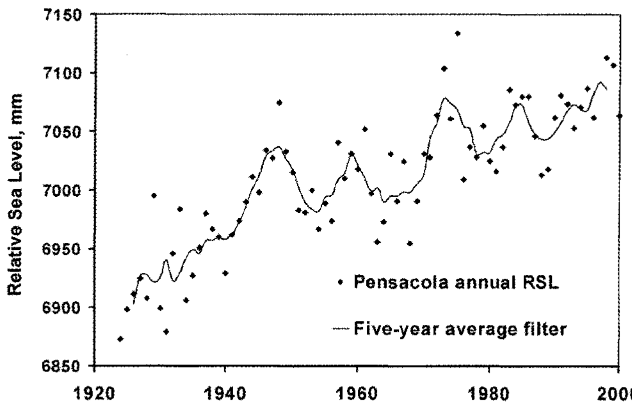

Figure 1. Annual means of Relative Sea Level at Pensacola, FL. Note the large low frequency fluctuations around the upward trend.

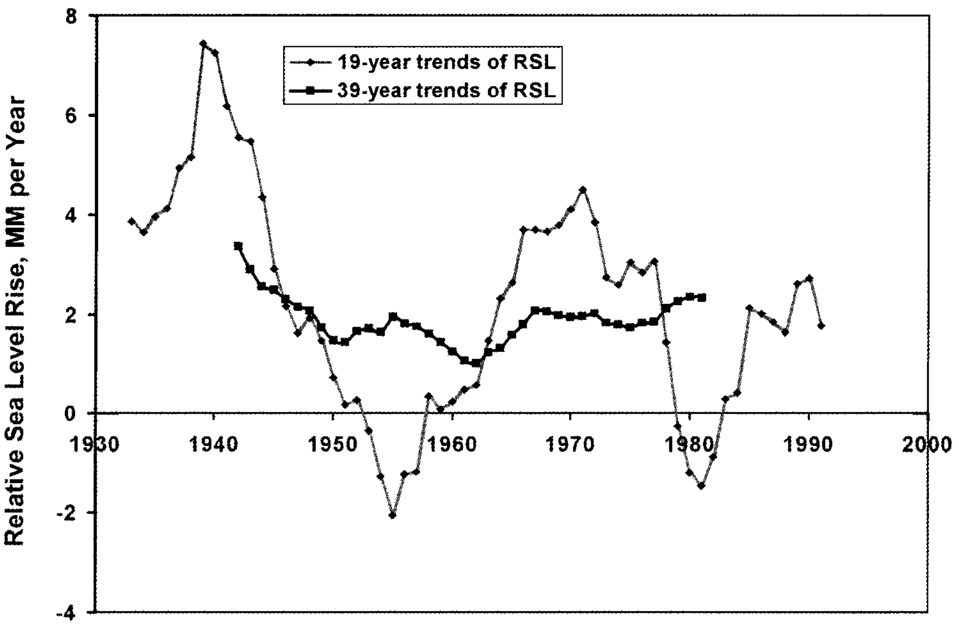

Figure 2. 19- and 39-year trends of relative sea level rise at Pensacola, Florida. The 19-year trends are highly variable, the 39-year trends much less so.

changes fluctuate from peak to trough up to 100 mm, and are the reason why long records are needed to determine the long-term trend of sea level rise at a site. Pugh (1987) noted that 10 year records of relative sea level have variable trends, with not even the sign of the long-term trend being determined. Records twice as long are also unreliable. To illustrate this, Figure 2 presents values for 19- and 39-year running trends of RSL at Pensacola. The values for each year in the figure are at the mid-points of the trend computation span. Note that an arbitrarily selected 19-year trend can vary from -2 to nearly 8 mm per year due to the influence of the low-frequency variations of sea level. Emery and Aubrey (1991) asserted that 20-year records of RSL rise are adequate to determine a long-term trend of sea level at a site, but this and numerous other counterexamples vitiate that notion. The 39-year trends shown in Figure 2 are more stable in value, having a smaller amount of variation. This sort of analysis was what convinced Douglas (1991) that about 50 years is required in most cases to determine a reasonably reliable value of the long-term trend of relative SLR. For some sites, such as Buenos Aires, Argentina which is affected by ENSO-associated rainfalls, much longer records are required (Douglas, 2001).

There are not many tide gauges on the Gulf coast with records longer than 50 years, so we will bend the rules somewhat and include records from 37 years on up for consideration. The example of Pensacola suggests that in this region, records of this length can give at least a good approximation to the actual long term trend of relative sea level. There are 11 tide gauges distributed around the Gulf of Mexico from Key West, Florida, to Vera Cruz, Mexico with data records 37 years or longer. In this study we shall also consider additional tide gauge records along the eastern Atlantic Coast of the United states from New York to south Florida (Table 1). The gauge locations in Table 1 are listed along the east coast from the north, southward to Key West, FL, and then counterclockwise around the Gulf of Mexico. This arrangement is especially useful in evaluating the impact of glacial isostatic adjust (GIA) on sea level trends, as will be seen below.

Figure 3 shows the locations of tide gauges used in this study. They are distributed over a very large area. What do these gauge sites have to do with one another, especially the gauge at Cristobal in Panama? The answer is to be found in the following figures, which sort out the effects of glacial isostatic adjustment (GIA), local land subsidence, and the everywhere-present and highly correlated low frequency variations of relative sea level. Figure 4 presents the rates of SLR for these sites. Obviously something very interesting is happening on both the mid-Atlantic, and Gulf Coasts.

2. ANALYSIS OF EAST AND GULF COAST RELATIVE SEA LEVEL TRENDS.

In Figure 4, the solid black columns are the raw values of sea level trends in mm per year taken from the PSMSL web site. The gauges shown follow the coastline down the US East

Table 1. East and Gulf Coast Tide Gauge Locations Used in This Study..

	w. longitude	n. latitude	begin	end	span, years	trend, mm/yr		σ, mm/yr	st. dev., mm
New York City	74.0	40.7	1856	1999	143	2.76	±	0.06	29.3
Philadelphia	75.1	39.9	1901	1999	98	2.67	±	0.15	40.5
Atlantic City	74.4	39.4	1912	1998	86	4.03	±	0.15	32.4
Baltimore	76.6	39.3	1903	1999	96	3.17	±	0.11	28.9
Hampton Roads	76.3	36.9	1928	1999	71	4.41	±	0.2	35.5
Charleston	79.9	32.8	1922	1999	77	3.29	±	0.18	34.9
Fort Pulaski	80.9	32.0	1935	1999	64	3.09	±	0.22	32.9
Fernandina	81.5	30.7	1898	1999	101	2.00	±	0.14	36.9
Mayport	81.4	30.4	1929	1999	70	2.32	±	0.2	34.6
Daytona Beach	81.0	29.2	1925	1969	44	2.01	±	0.66	40.6
Miami Beach	80.1	25.8	1932	1980	48	2.29	±	0.26	24.6
Key West	81.8	24.5	1913	1999	86	2.25	±	0.11	25.5
St. Petersburg	82.6	27.8	1947	1999	52	2.42	±	0.21	23.3
Cedar Key	83.0	29.1	1939	1994	55	1.48	±	0.26	29.9
Pensacola	87.2	30.4	1924	1999	75	2.15	±	0.19	34.9
Grand Isle, LA	90.0	29.3	1947	1999	52	9.87	±	0.41	44.3
Galveston, TX	94.8	29.3	1909	1999	90	6.51	±	0.18	45.9
Freeport, TX	95.3	29.0	1955	1999	44	10.75	±	0.72	59.7
Rockport, TX	97.1	97.1	1948	1999	51	4.42	±	0.47	42.5
Port Isabel, TX	97.2	26.1	1945	1999	54	3.37	±	0.33	37.1
Veracruz	96.1	19.2	1953	1990	37	1.19	±	0.38	24.7
Cristobal	79.9	9.3	1909	1979	70	1.44	±	0.14	23.4

Values are from the Permanent Service for Mean Sea Level. Trend values are in mm per year. The standard deviations shown are the fluctuations of the annual means around a linear regression line, and the σ are the standard errors of the trends.

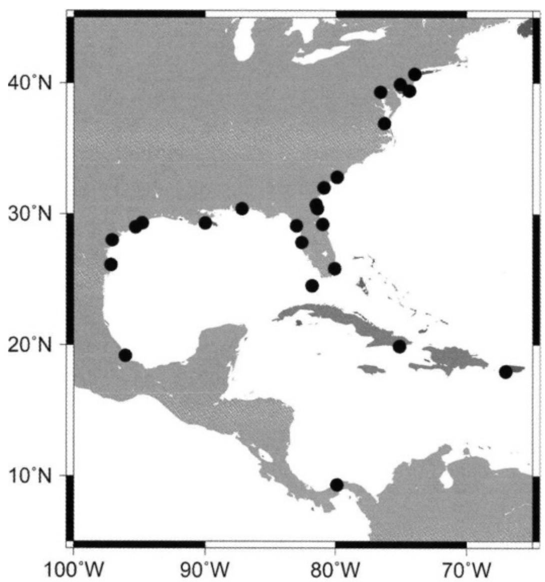

Figure 3. Locations with records > 37 years.

Coast from New York to Miami and Key West, and then on around the Florida Peninsula to the Gulf coast of the US and Mexico. Cristobal, Panama, is shown for reasons that will become clear below.

There are two obvious features of the raw sea level trends displayed in Figure 4. These are values up to about 4 mm per year or more at the Mid-Atlantic, with a fall-off to the south, and the cluster of values up to 10 mm per year in Louisiana and Texas. The Mid-Atlantic feature is due to glacial isostatic adjustment (GIA), the ongoing readjustment of the earth to the melting of the great glaciers that reached their maximum 21,000 years ago when global sea level was 125 meters lower than today. The very high rates in Louisiana and Texas are in contrast a result of local subsidence from sediment compaction, and withdrawal of subsurface fluids (Boesch, et al., 1994; Morton, et al., 2004).

Concerning the GIA effect, the enormous weight of the kilometers-thick ice sheets which covered all of Canada and a part of the northern U.S. caused the earth to deform viscously. Mantle material flowed from under the Laurentide ice

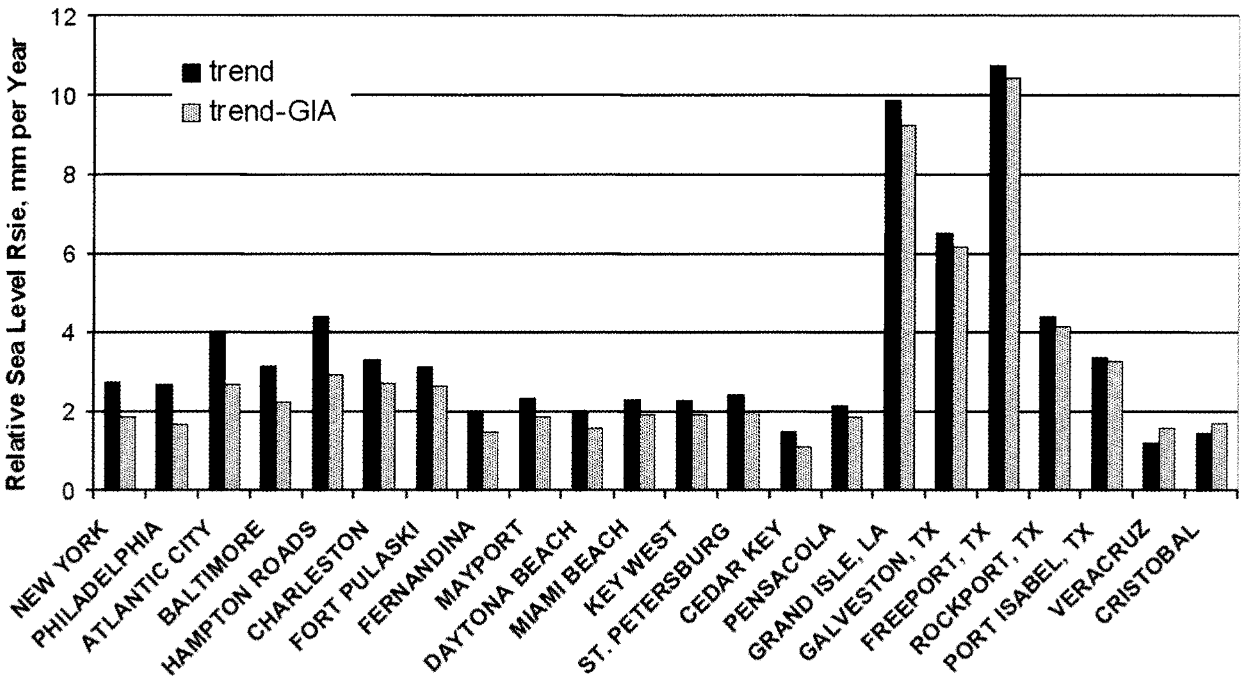

Figure 4. Atlantic and Gulf Coast relative sea level rise with and without the correction for glacial isostatic adjustment from Peltier (2001).

sheet to beyond its periphery, producing a subsidence of the land under the ice and a forebulge (uplift) adjacent. The greatest load concentration was over Hudson Bay in Canada, which today is still rising at about 1 cm per year as the land continues to recover from removal of the ice load many millennia after the glaciers retreated (Peltier, 2001). The forebulge, on the other hand, is collapsing, so the land in that area is subsiding. Figure 5 illustrates this effect of GIA in the Western Hemisphere by plotting the observed relative sea levels of gauges with long records as a function of their distance from Churchill in Hudson Bay. The mass of the Laurentide ice sheet was not concentrated at a point near Churchill, but as noted, this was the area of greatest ice load. The apparent peak of the forebulge collapse occurs at Hampton Roads, VA, and causes the local value of SLR (i.e., the relative SLR) to be more than 4 mm per year. The rate of collapse falls off with distance from the peak of the forebulge, and is only a few tenths of a mm per year by central and south Florida. This is why Pensacola has a value so near to the global average value.

Beyond the area of the forebulge collapse is the so-called "far field" of GIA. This region is one of emergence of about 0.3 mm per year due to draining of the far field water into the regions of subsidence, and readjustment of the geoid. So at great distances from Canada, such as for Cristobal and Balboa (on the Atlantic and Pacific sides of Panama, respectively), and Honolulu, the correction to the observed GIA must be increased by this amount to calculate the eustatic rise of sea level. The dashed line at 2 mm per year in Figure 5 thus is seen to be an asymptote to which far field rates of SLR approach if they are corrected for the emergence of about 0.3 mm per year.

The spotted columns in Figure 4 show the sea level trends adjusted for the GIA values of Peltier (2001). Correcting for GIA brings the rates of sea level rise into closer agreement for most of the sites, but has little effect on trends of SLR in Louisiana and Texas. Excluding the values of GIA-corrected relative SLR in Texas and Louisiana, the average of the rates shown in Figure 4 is 1.98 mm per year, a value close to recent global SLR estimates of other authors, including Douglas (1997), Peltier (1996, 2001), Church et al. (2004), and Miller and Douglas (2004).

It is reasonable to conjecture that the high rate of relative SLR at Grand Isle on coastal Louisiana might be a subsidence "hot spot", but there are many water level gauges in the Mississippi Delta that are not part of the PSMSL RLR data base, and these all confirm that the subsidence seen at Grand Isle is typical of the Delta region. Figure 6 (reprinted from Boesch et al, 1994, with permission) demonstrates the widespread nature of the high rate of relative sea level rise in coastal Louisiana. The many water level gauges in this area all show high and consistent long-term rates of increase, and also similar substantial decadal variations. Burkett et al. (2001) present a very detailed analysis of the hazards facing

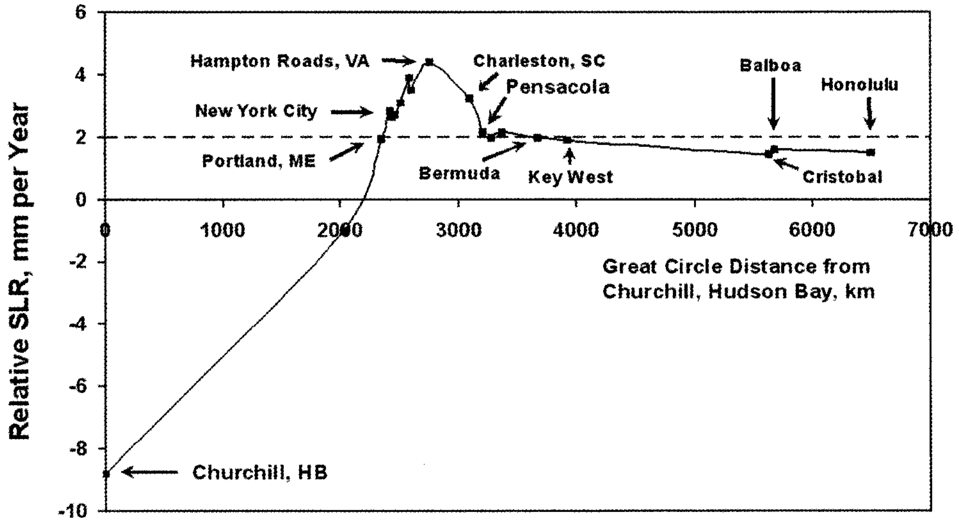

Figure 5. Observed relative sea level trends as a function of distance from Hudson Bay, Canada, the area of the greatest ice load at the peak of the last glacial maximum.

the city of New Orleans, Louisiana that exist because of the very high rate of subsidence-induced SLR that exists in this region. They analyzed a long sequence of repeated leveling surveys, and emphasize the severe threat to New Orleans from storm surges.

The Texas coast has a very wide range of rates of SLR ranging from about 3.4 to more than 10 mm per year. Freeport, TX is obviously a SLR "hot spot", since it has such a high rate of SLR compared to other nearby locations. But none of the high rates of SLR on the Texas coast are caused by GIA (which is small in this region). They reflect varying rates of local subsidence (Emery and Aubrey, 1991).

High rates of sea level rise are associated with rapid beach erosion because storm waves can reach farther up the beach as sea level increases. Figure 7 shows the consequences of the rapid sea level rise on the beach at Galveston, TX. This is a modern photo (courtesy of S.P. Leatherman) of the Galveston Island sea wall at high tide. The sea wall was constructed after the hurricane disaster of 1900, and originally had a wide beach in front of it. It has served the City well for a century, but the relentless increase of sea level has led to the virtual disappearance of the beach through a rapid erosion of the sand. Unlike The Mississippi Delta area of Louisiana, the Texas Gulf coast may be subsiding and eroding more from extraction of underground fluids than sediment compaction and starvation (Emery and Aubrey, 1991).

A simplified rule of thumb for the relation of beach erosion to sea level rise proposed decades ago by Bruun (1962) suggests that beaches that are not armored or near spits and inlets will erode shoreward about two orders of magnitude faster than the rate of rise of sea level. Zhang, et al. (2004) compared barrier island sandy beach erosion rates to local sea level rise on the U.S. East coast, and found evidence that supports the Bruun theory in at least a general way. Of course this simple rule cannot be used to predict the fate of the beach at an arbitrarily selected specific site, but it does demonstrate the huge leverage that sea level rise has in promoting beach erosion.

3. LOW-FREQUENCY VARIATIONS OF RELATIVE SEA LEVEL.

The example of Pensacola shows that the rate of SLR can depart from its long-term average value by a large factor for an extended time. Recall that 19-year trends of sea level at Pensacola ranged from -2 to nearly 8 mm per year (Figure 2.) These large and enduring variations, which on the Mississippi Delta and the Texas coastline can effectively double the already high rate of relative SLR from an average of about 10 mm per year, may play an important role in exacerbating the huge wetlands loss. Rapidly rising sea level can cause drowning of wetland plants if the high rate is sustained for an extended time. Boesch et al (1994) say that "...these episodes of rapid sea level rise could be a significant factor in wetlands loss,...and should be investigated further."

What causes the large low frequency variations of sea level? How extensive are they geographically? The answers to these questions are interesting indeed. Maul and Hanson (1991) have discussed the interdecadal variations of sea level in the southeast U.S. and noted the high correlation of sea level records there at low frequency. Their analysis used data from 1930–1986, while the present analysis has the luxury of 15 years more data and in addition adds several more records (Vera Cruz and Cristobal) to the analysis. We start by

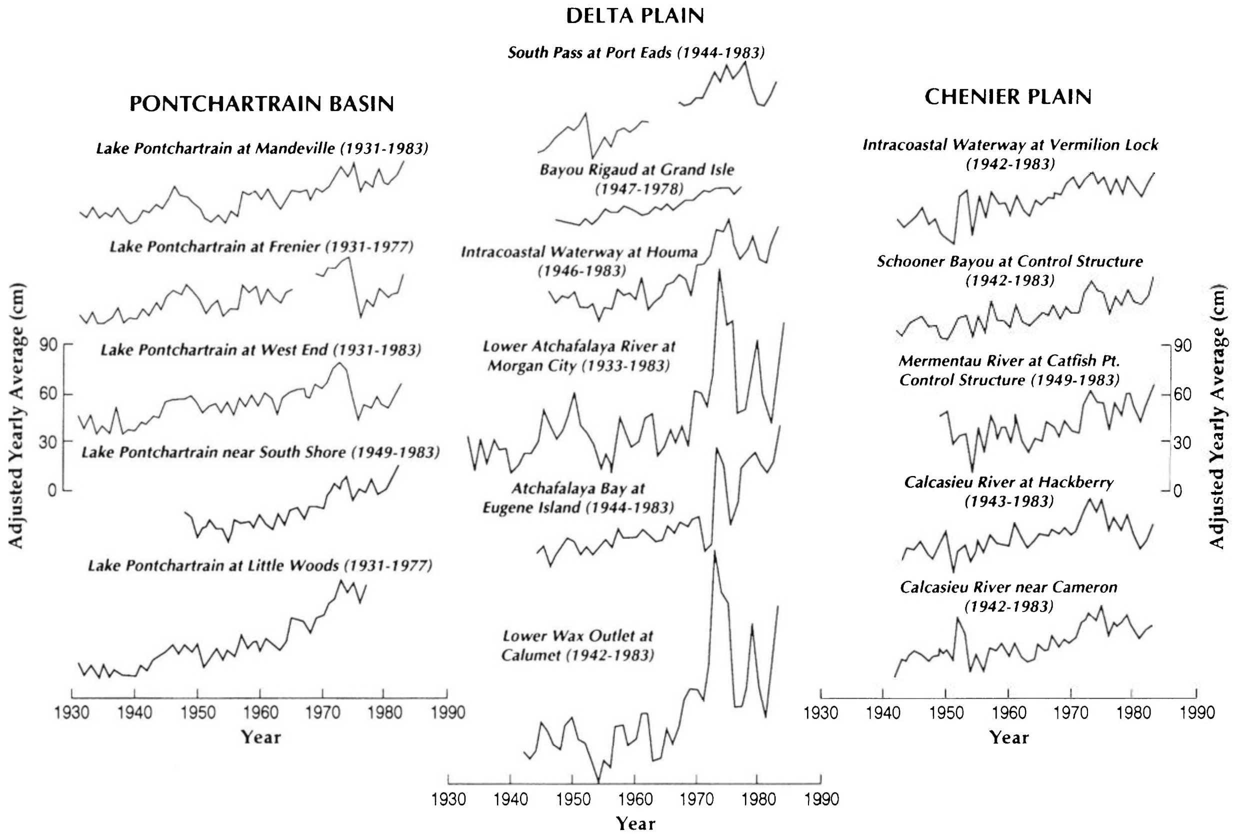

Figure 6. Mississippi Delta water level records. Note the widespread extent of rapidly increasing water levels over a broad area. The Delta Plain is south of the Pontchartrain Basin, and the Chenier Plain is in southwestern coastal Louisiana. From Boesch, et al. (2001).

examining in Plate 1 five-year smoothed (boxcar filter) and detrended tide gauge records for a representative sample of U.S. Southeast and Gulf Coast sites. Each record was detrended over its entire length to give a zero mean for the sake of clarity in the figure. These low-pass filtered sea level records have only about 2/3 of the variation of the annual means from which they were computed. The records are shown from Charleston southward to Key West, and then up and around the Gulf Mexico and on down to Cristobal, in Panama. They are all on the shoreward side of the Gulf Stream.

Low frequency variations of Gulf Coast sea level records are obviously similar in phase and amplitude to each other and those of the southeast coast, a result that is probably unexpected by most readers. It is necessary to go clear around to Cristobal, Panama for the low frequency correlation with Gulf and Atlantic coast gauge records to begin to disappear. The correlation of Cristobal and Charleston when detrended over their common length is only $R^2 = 0.18$ ($p < .001$). Equally as striking as the correlations are the big synoptic anomalies that occurred about 1920, 1950, and

Figure 7. Modern photo of the Galveston seawall by S.P. Leatherman. The once-wide beach has eroded away since its construction after the devastating hurricane of 1900.

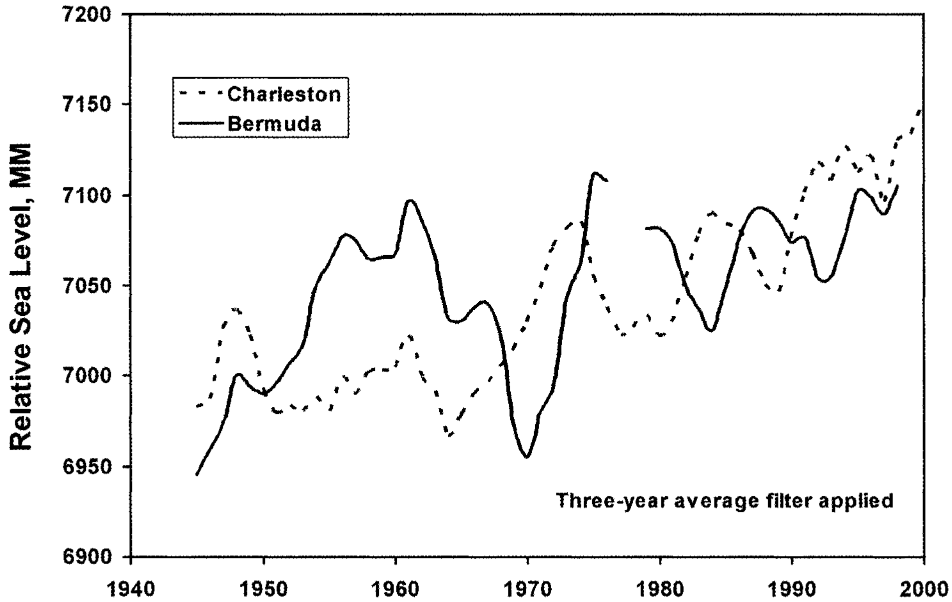

Figure 8. Low-pass filtered relative sea levels at Charleston and Bermuda.

1975; apparently there is a dominant energetic time scale of roughly 25 years in the 20th century, but this appearance is not conclusive evidence of any periodicity of that duration, as can be seen by the lack of another major event at the end of the 20th century. Maul and Hanson (1991) found a large spectral peak at 13.3 years, but the longer records used here indicate even higher energy near 25 years for this data record.

What is the source of these low-frequency variations of sea level? It is not an inverted barometer effect (i.e., not due to loading by atmospheric pressure at the tide gauge sites) as Maul and Hanson (1991) demonstrated. They instead found that a significant positive correlation exists between U.S. southeast and Gulf coast sea level variations and the Bermuda/Azores sea level pressure (SLP) anomaly. This high correlation of mid-ocean SLP and sea level variation suggests that wind forcing on the broad ocean is involved in producing the interdecadal signal seen in the tide gauge records.

An elegant and straightforward analysis of this problem has been given by Sturges and Hong (2001) and Hong, et al. (2002) in their analysis of a Rossby Wave model forced only by open ocean winds. The westward-propagating Rossby waves were shown to be directly producing the offshore low-frequency variations seen in tide gauge data at Bermuda. But on the inshore side of the Gulf Stream, the sea level variations come from wind-forced gyre-scale variations, that is, fluctuations of transport integrated from low latitudes to the point of interest on the coast. Figure 8 shows that Bermuda and Charleston sea level records are dissimilar in their low frequency variations, although they have a similar overall upward trend.

This origin of low frequency variations of coastal tide gauge records has another important implication for mixed tide gauge/satellite altimetry analyses. Some authors have used coastal tide gauge records and satellite altimetry together to infer information about sea level variations in the broader ocean. But Figure 8 shows that western boundary tide gauge data does not provide direct quantitative information about the offshore ocean. Such information requires a wind-forced model for its computation. This means that purely statistical analyses attempting to extend backward in time open ocean observations from satellite altimeters by using western boundary coastal tide gauge data can be expected to have limitations. In addition, the regional correlations of coastal tide gauge records at low frequencies clearly implies that little is gained by using a very large number of gauges in a region to determine regional long-term trends of sea level rise. It also seems likely that that the presently available satellite altimeter record of about 13 years is not long enough to determine low frequency regional variations of sea level.

Further evidence of the gyre-scale origin of the low frequency variations of southeast and Gulf coast sea level potentially can be found by comparing Caribbean sea level records to those on the Gulf coast. Unfortunately, the PSMSL RLR database does not contain any long records from Caribbean islands. Most are short and/or fragmentary. However, it is possible to construct a composite sea level record from the

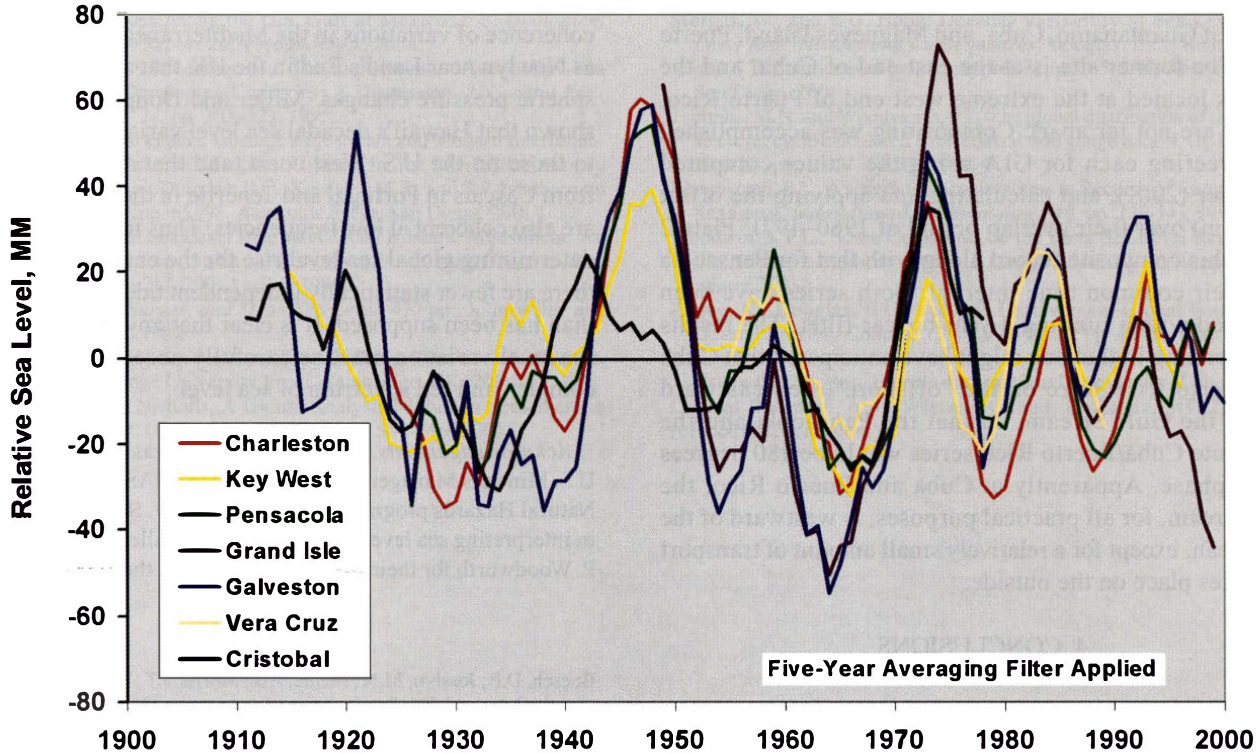

Plate 1. Smoothed (5 year boxcar) and detrended sea level records from East Coast and Gulf of Mexico tide gauges. Note that a weak correlation exists even between Charleston, SC (red curve), and Cristobal, Panama (black curve).

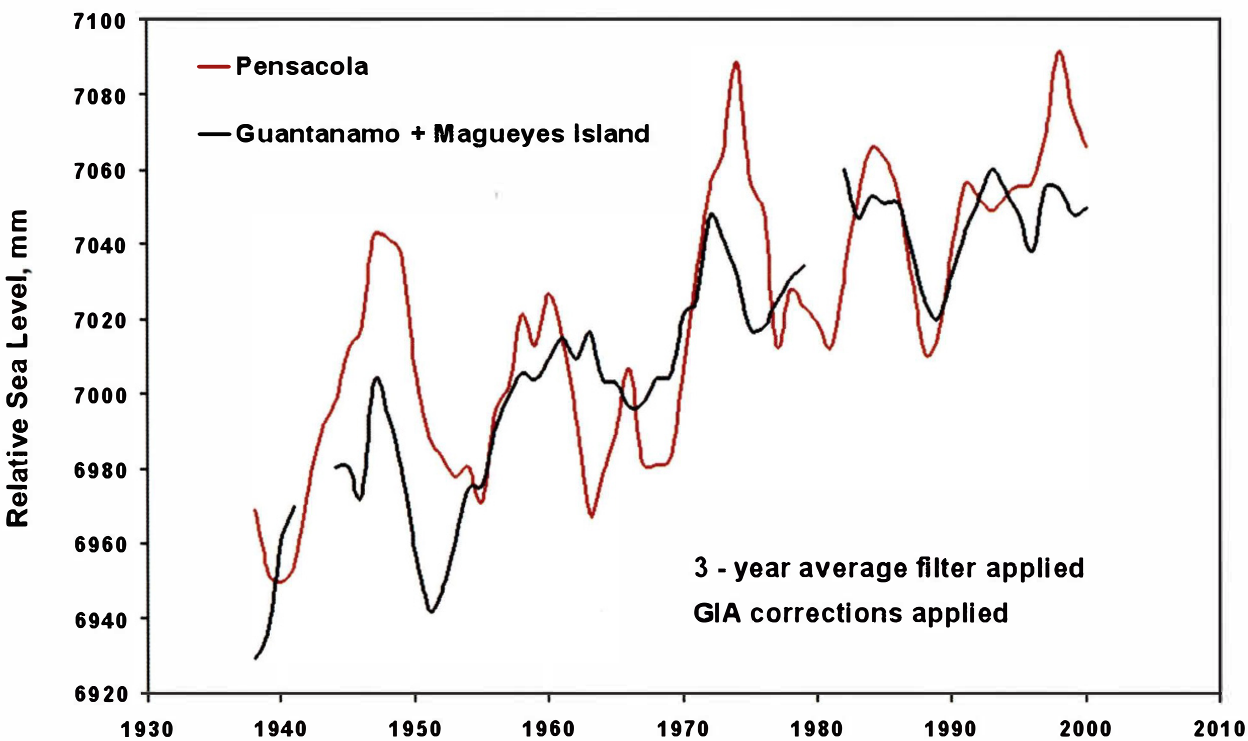

Plate 2. Relative sea levels for Pensacola, FL, and a composite of Guantanamo, Cuba, and Magueyes Island, Puerto Rico. Note that the records are in phase.

gauges at Guantanamo, Cuba, and Magueyes Island, Puerto Rico. The former site is at the east end of Cuba, and the latter is located at the extreme west end of Puerto Rico, so they are not far apart. Compositing was accomplished by correcting each for GIA using the values computed by Peltier (2001), and calculating and applying the offset (10.1 mm) over their overlap period of 1960–1971. Plate 2 shows this composite record along with that for Pensacola over their common time interval. Both series have been smoothed with a running 3 year boxcar filter. The results are surprising in that one might have anticipated that Cuba and Puerto Rico were on the "offshore", i.e., eastward side of the Gulf Stream, so that the Pensacola and the composite Cuba/Puerto Rico series would be 180 degrees out-of-phase. Apparently at Cuba and Puerto Rico, the Gulf Stream, for all practical purposes, is westward of the Caribbean, except for a relatively small amount of transport that takes place on the outside.

4. CONCLUSIONS

The rapid rates of long-term sea level rise in Louisiana and Texas are due to local conditions including interference with sediment supplies (especially in Louisiana) and by withdrawal of underground fluids in both places. The consequences of the high rates are well documented (Boesch et al., 1994; Morton, et al., 2004), and mitigation is necessary to avoid severe social and ecological consequences. Long-term sea level rise on the rest of the Gulf coast and the south U.S. East Coast is remarkably consistent when corrected for glacial isostatic adjustment, and is in good agreement with more geographically extensive analyses that give a global rate of sea level rise of about 2 mm per year for the 20^{th} century. The Gulf of Mexico and U.S. Atlantic coast also experience decadal and longer variations of up to about 100 mm peak-to-trough which may endure long enough to exacerbate wetland damage. These low-frequency variations appear to have their origin in wind forcing on the Atlantic Ocean. A common interdecadal signal is seen even as far around as Vera Cruz, Mexico, fading away but still detectible at Panama.

Such regionally coherent low-frequency variations of sea level are seen everywhere there are enough tide gauges to show it. These variations have a character that depends on whether they are on eastern or western ocean boundaries. Chelton and Davis (1982) demonstrated the effect on the West Coast of the North America due to ENSO events. Douglas (1991, 1997, 2001) grouped a global set of long tide gauge records into regions based on the coherence of their low-frequency signal components and then averaged the regional rates to avoid overweighting areas with many sites. More recently Woodworth (2003) has discussed the coherence of variations in the Mediterranean to as far away as Newlyn near Land's End in the UK that arise from atmospheric pressure changes. Miller and Douglas (2004) have shown that Hawaii's decadal sea level variations are similar to those on the U.S. West coast, and that sea level records from Cascais in Portugal and Tenerife in the Canary Islands are also coherent at low frequencies. Thus for the purpose of determining global sea level rise for the entire 20^{th} century, there are fewer statistically independent tide gauge locations than has been supposed. It is clear that any issue involving sea level variation must be carefully posed because of the complex and red spectrum of sea level.

Acknowledgements. This investigation was supported by the U.S. Minerals Management Service and the NASA Solid Earth and Natural Hazards program. I am grateful to W. Sturges for his help in interpreting sea level records, and to L. Miller, R. Nicholls, and P. Woodworth for their helpful comments on the manuscript.

REFERENCES

Boesch, D.F., Josslyn, M.N., Mehta, A.J., Morris, J.T., Nuttle, W.K., Simestad, C.A., and D.j. Swift, Scientific Assessment of Coastal Wetland Loss, Restoration and Management in Louisiana, *J. Coastal Res., Special Issue no. 20,*. 103 pp., May, 1994.

Bruun, P., Sea-Level Rise as a Cause of Shore Erosion, *American Society of Civil Engineers Proceedings, Journal of Waterways and Harbors Division 88*, pp. 117–130, 1962.

Burkett, D.R., Zilkoski, D.B., and D.A. Hart, Sea Level Rise and Subsidence: Implications for Flooding in New Orleans, Louisiana, *USGS Open File Report 03-308*, pp.63–70, 2001.

Chelton, D.B., and R.E. Davis, Monthly Mean Sea-Level Variability along the West Coast of North America, *J. Phys. Oceanog. 12*, August 1982.

Church, J.A., White, N.J., Coleman, R., Lambeck, K., and J.X. Mitrovica, Estimates of the Regional Distribution of Sea Level Rose over the 1050–2000 Period, *J. Climate 17*, pp. 2609–2624, July, 2004

Douglas, B.C., Global Sea Level Rise, *J. Geophys. Res. 96*, no. c4, April 15, 1991.

Douglas, B.C., Global Sea Level Acceleration, *J. Geophys. Res. 97*, no. c8, August 15, 1992.

Douglas, B.C., Global Sea Rise: A Redetermination, *Surveys in Geophys. 18*, pp. 279–292, 1997.

Douglas, B.C., 2001, Sea Level Change in the Era of the Recording Tide Gauge, Chapter 3 in *Sea Level Rise: History and Consequences*, Douglas, B.C., Kearney, M.S., and S.P. Leatherman (eds.), chapter 4, pp. 65–93, Academic Press, San Diego, 2001.

Emery, K.O., And D.G. Aubrey, *Sea Levels, Land Levels, and Tide Gauges*, Springer Verlag,, New York, 237 pp., 1991.

Galgano, F., *Geomorphic Analysis of Modes of Shoreline Behavior and the Influence of Tidal Inlets on Coastal Configuration*, Ph.D. dissertation, Dept. of Geography, University of Maryland, College Park, MD, 484 pp., 1998.

Hong, B.G., Sturges, W. and A. J. Clarke, Sea level on the U.S. east coast: decadal variability caused by open-ocean wind-curl forcing. *J. Phys. Oceanogr., 30,* pp. 2008–2098, 2000

Maul, G.A., and K. Hanson, Interannual coherence Between North Atlantic Atmospheric Surface Pressure and Composite Southern U.S.A. Sea Level, *Geophys. Res. Letters, 18,* no. 4, pp 653–656, April 1991.

Miller, L, and B.C. Douglas, Mass and Volume Contributions to 20^{th}-Century Global Sea Level Rise, *Nature, 428*, pp. 406–409, March 25, 2004.

Morton, R.A., Miller, T.A., and L.J. Moore, National Assessment of Shoreline Change: Part 1: Historical Shoreline Changes and Associated

Coastal Land Loss Along the U.S. Gulf of Mexico. *U.S. Geological Survey Open-file Report 2004–1043*, 45pp., 2004.

Nicholls, R.J., and S.P. Leatherman, The Implication of Accelerated Sea Level Rise for Developing Countries: A Discussion, *J. Coastal Res., Special Issue no. 14*, pp. 303–323, 1995.

Peltier, W.R., Global Glacial Isostatic Adjustment and Modern Instrumental Records of Relative Sea Level History, in *Sea Level Rise: History and Consequences*, Douglas, B.C., Kearney, M.S., and S.P. Leatherman (eds.), chapter 4, pp. 65–93, Academic Press, San Diego, 2001.

Peltier, W.R., Global Sea Level Rise and Glacial Isostatic Adjustment: An Analysis of Data from the East Coast of North America, *Geophys. Res. Lett., 23*, no.7, pp 717–200, April 1, 1996.

Pugh, D.T., *Tides, Surges, and Mean Sea Level*, 472 pp., John Wiley and Sons, New York, 1987.

Pugh, D.T., *Changing Sea Levels: Effects of Tides, Weather, and Climate*, 280 pp., Cambridge University Press, Cambridge, UK, 2004

Small, C., and R.J. Nicholls, A Global Analysis of Human Settlement in Coastal Zones, *J. Coastal Res. 19*, no. 3, pp. 584–599, 2003

Sturges, W., and B.G. Hong, Decadal Variability of Sea Level, in *Sea Level Rise: History and Consequences*, Douglas, B.C., Kearney, M.S., and S.P. Leatherman (eds.), chapter 7, pp. 165–180, Academic Press, San Diego, 2001.

Tsimplis, M.N. and Woodworth, P.L. The global distribution of the seasonal sea level cycle calculated from coastal tide gauge data. J. *Geophys. Res., 99* (C8), pp. 16031–16039, 1994.

Woodworth, P.L., A search for Accelerations in Records of European Mean Sea Level, *International J. Climatology, 10*, pp. 129-143, 1990.

Woodworth, P.L., Some Comments on the Long Sea Level Records from the Northern Mediterranean, *J. Coastal Res. 19*, no. 1, pp. 212–217, winter 2003.

Zhang, K., Douglas, B.C., and S.P. Leatherman, Global Warming and Coastal Erosion, *Climatic Change 64* (1–2), pp. 41–58, May 2004.

Bruce C. Douglas, Florida International University, Laboratory for Coastal Research, 6544 Wiscasset Road, Bethesda, MD 20816-2113 (bruced7082@aol.com)