Nat Hazards (2013) 65:1011–1021
DOI 10.1007/s11069-012-0400-5

SHORT COMMUNICATION

Sea level trends at locations of the United States with more than 100 years of recording

Albert Parker

Received: 17 August 2012 / Accepted: 11 September 2012 / Published online: 25 September 2012

Abstract The paper presents the sea level rises (SLR) computed for the United States tide gauges with more than 100 years of recording. It is shown that the monthly sea levels oscillate about an almost linear longer-term trend with important multidecadal periodicities. The SLR time history is computed by linear fitting of 20, 30 and 60 years of data up to a given time (SLR_{20}, SLR_{30} and SLR_{60}) and is compared to the value obtained by considering all the data. It is shown that SLR_{60} has smaller oscillations, while SLR_{20} and SLR_{30} have much larger and frequent fluctuations. While SLR_{60} may oscillate ±10–30 % about the latest longer-term value, SLR_{30} may fluctuate ±50–100 % and SLR_{20} ± 100–200 %. The values obtained by considering all the data with a minimum of 60 years (SLR_A) also fluctuate ±5–15 % about the latest longer-term value. This indicates the need to use the time history of SLR_{60} or SLR_A when the record is longer than 60 years to assess the accelerating trend. For all the stations, the sea levels regularly oscillate about the linear longer-term trend, and if acceleration has to be computed, this is eventually negative, that is, the SLR is reducing.

Keywords Sea level rise · Sea level acceleration · Climate change · Sea level oscillations · Teleconnections

1 Introduction

Deriving long-term (century scale) trends in sea level at a particular location is difficult due to other sea level oscillations of time scales of a few days to many decades. The shorter-time-scale oscillations can be averaged and effectively removed. However, oscillations over timescales of a few decades cannot be averaged because the averaging interval, which must be at least as long as the period of oscillation, becomes almost as long as the time series itself. In recent years, the scientific literature has many examples of recent sea level trends averaged over short periods even less than 20 years that are compared with past sea

A. Parker (✉)
Centre for Environmental Management, University of Ballarat, PO BOX 663, Ballarat, VIC, Australia
e-mail: albertparker@y7mail.com

level trends spanning the last century with different time windows in other locations (Australian Federal Government's Climate Commission 2011; Australian Government Bureau of Meteorology 2011) or 30 years SLR computed in a recent peak compared to the SLR of a prior valley of the periodic oscillations (Sallenger et al. 2012). In this paper, we analyze the periodicities in the long-term sea level data sets for the United States to assess what is the minimum averaging period which must be used to determine whether there are accelerating trends in SLR and if the comparison of just 2 values of a short-term distribution or of 1 value of a short-term and 1 value of a long-term distribution is meaningful. The least squares method is used to calculate a straight line that best fits the data. The equation for the line is $y = m \cdot x + b$ where the dependent y values, the monthly average sea levels, are a function of the independent x values, the time in years. The calculations for m, the SLR and b are based on the formulas:

$$m = \frac{\sum_{i=j}^{k} (x - x') \cdot (y - y')}{\sum_{i=j}^{k} (x - x')^2}$$

$$b = y' - m \cdot x'$$

where x′ and y′ are sample means and j and k are the indices of the first and last data of the measured distribution considered for the estimation of the SLR. At a certain time x_k, x_j is taken as x_k−20, −30 or −60 years, respectively, when computing the SLR_{20}, SLR_{30} and SLR_{60}, or as x_1 when computing the SLR_A over all the years. This way, from a measured distribution x_i,y_i for $i = 1$,N, it is possible to estimate the time histories of SLR_{20}, SLR_{30}, SLR_{60} and SLR_A.

2 Interannual and multidecadal oscillations

The monitoring of oceanic and atmospheric data shows the presence of teleconnections patterns, recurring and persistent, large-scale pattern of pressure and circulation anomalies that spans vast geographical areas (National Oceanic and Atmospheric Administration 2012). The teleconnections patterns are the preferred modes of low-frequency long-time-scale variability. Although these patterns typically last for several weeks to several months, they can sometimes be prominent for several consecutive years, thus reflecting an important part of both the interannual and interdecadal variability of the atmospheric circulation. Many of the teleconnections patterns are also planetary scale in nature and span entire ocean basins and continents. For example, some patterns span the entire North Pacific basin, while others extend from eastern North America to central Europe. These patters translate in interannual and multidecadal oscillations of sea levels. However, sea levels may also oscillate for other reasons. The multidecadal oscillations are covered in detail in the excellent papers by Scafetta (2010, 2012a, b), and the purpose of this paragraph is to recall the possible known periodicities that are likely to be found in the analysis of tide gauge records. That the sea level rise oscillates with a 60-year cycle is demonstrated by Jevrejeva et al. (2008). All the models proposed by the Intergovernmental Panel on Climate Change claim that see level rises by following the temperature rise. If the temperature index as well as all other climate indexes oscillates with multidecadal periodicities, the sea level rise must oscillate with the same harmonic.

The Atlantic Multi-decadal Oscillation (AMO) is a mode of natural variability occurring in the North Atlantic Ocean and which has its principle expression in the sea surface temperature (SST) field. The AMO is identified as a coherent pattern of variability in basin-wide North Atlantic SSTs with a period of 60–80 years. The AMO may certainly play a role in the sea levels recorded for both the North Atlantic coast (NC to MA) and for the Atlantic coast of Florida. There are two important tempos for the AMO: 20 and $\sim$60 year. The North Atlantic oscillation (NAO) is a climatic phenomenon in the North Atlantic Ocean of fluctuations in the difference of atmospheric pressure at sea level between the Icelandic low and the Azores high. Through east–west oscillation motions of the Icelandic low and the Azores high, it controls the strength and direction of westerly winds and storm tracks across the North Atlantic. It is part of the Arctic oscillation (AO) and varies over time with no particular periodicity. Unlike the El Niño–Southern Oscillation (ENSO) phenomenon in the Pacific Ocean, the NAO is a largely atmospheric mode. It is one of the most important manifestations of climate fluctuations in the North Atlantic and surrounding humid climates. Interannually, the NAO plays a role in both regions, although it, too, is modulated by the 60-year cycle. (Hurricane activity is influenced by phase of AMO, moderated by phase of ENSO.) The AO (aka NAM) is related to the NAO and has ties to a variety of other circulations. As these atmospheric patterns involve latitudinal exchange of air mass, the surrounding regions are affected by oscillatory patterns from subsurface ocean to stratosphere. The Gulf Stream and its extension may have some influence. For the Gulf of Mexico, possibly all the tropical circulations would come into play (and their interactions with one another). These might include the Atlantic Nino, the Atlantic Meridional Mode (AMM), which is roughly related to tropical expression of NAO, ENSO, which would remotely affect the region with teleconnected influence, to name a few.

The Pacific Decadal Oscillation (PDO) is a pattern of Pacific climate variability that shifts phases on at least interdecadal time scale, usually about 20–30 years. The PDO is detected as warm or cool surface waters in the Pacific Ocean, north of 20°N. During a "warm", or "positive", phase, the west Pacific becomes cool and part of the eastern ocean warms; during a "cool" or "negative" phase, the opposite pattern occurs. The prevailing hypothesis is that the PDO is caused by a "reddening" of the ENSO combined with stochastic atmospheric forcing. The interdecadal Pacific oscillation (IPO or ID) display similar sea surface temperature (SST) and sea level pressure (SLP) patterns, with a cycle of 15–30 years, but affects both the north and south Pacific. In the tropical Pacific, maximum SST anomalies are found away from the equator. This is quite different from the quasi-decadal oscillation (QDO) with a period of 8–12 years and maximum SST anomalies straddling the equator, thus resembling the ENSO. El Niño–Southern Oscillation (ENSO), or El Niño/La Niña–Southern Oscillation, is a quasiperiodic climate pattern that occurs across the tropical Pacific Ocean roughly every 5 years. The Southern Oscillation refers to variations in the temperature of the surface of the tropical eastern Pacific Ocean (warming and cooling known as El Niño and La Niña respectively) and in air surface pressure in the tropical western Pacific. The two variations are coupled: the warm oceanic phase, El Niño, accompanies high air surface pressure in the western Pacific, while the cold phase, La Niña, accompanies low air surface pressure in the eastern Pacific. Mechanisms that cause the oscillation remain under study. The Pacific Decadal Oscillation (PDO) is often described as a long-lived El Niño-like pattern of Pacific climate variability. The Pacific–North America (PNA) pattern is one of the most prominent modes of low-frequency variability in the Northern Hemisphere extra tropics, appearing in all months except June and July. The Aleutian Low Pressure Index (ALPI) measures the relative intensity of the Aleutian low pressure system of the north Pacific (December through March). For the Pacific Coast, CA to WA, the PDO (15–20 years and 50–70-year cycles) is the most significant. PNA (related to PDO on 50–70 year especially), ALPI (related to both the PDO and PNA) and NPO/WP patterns are also closely related to PDO and therefore to this region. A smaller and less-well-known oscillation is called the Victoria Pattern. It has been subsumed by the increasingly better known circulation called the North Pacific Gyre Oscillation (NPGO). Possibly the ENSO system is most likely to affect Hawaii (interannual with multidecadal modulation) while NPGO and PMM (Pacific meridional mode) might contribute.

Further investigation is certainly needed to see how these oscillations (and other processes) actually affect sea level measurements. Subtropical-gyre activity and the western-boundary dynamics would also be important things to consider, as both regional distribution of upper-ocean heat content and geostrophic influences would impact sea surface height. The matter seems far too complex to attribute to any one oscillatory pattern centered in these regions, and interaction between oscillatory patterns may result in unexpected manifestations.

3 Tide gauge data

Figure 1 presents the monthly sea levels (SL) and their linear trend, the periodogram of the monthly departures versus the linear trend δSL and the computed SLR_{20}, SLR_{30} and SLR_{60} for the locations of the United States with more than 100 years of data available at the present time. The 12-month moving average is also superimposed to the monthly sea levels. The spectral analysis of the δSL with output amplitude with Barlett kernel weighting of the periodogram is also provided in the figure as a preliminary evaluation of the relevant periodicities in the monthly fluctuations about the linear trend. The goal of the spectral analysis is to determine whether cycles characterize this activity by using spectral analysis, a method that is based on the Fourier transform (Anderson 1971). The periods of the peaks means that the sea levels oscillations vary with quite regular cycles of these periodicities. The period in the periodogram graph is months (the 60 years periodicity is 720 months, and the 20 years periodicity is 240 months). All the data are from Permanent Service Mean Seal Level (2012). The few missed points of the monthly averages are usually obtained by interpolation of the values in neighboring months if one month is missed, or from the values in same month of neighboring years if more months are missed. When the missed data are several years, a different procedure is used. In the two cases of significant gaps, the linear trend is obtained by using the data available in the previous and following years. In cases of decades of missed data, the missed data are obtained by enforcing a 60-year periodicity about the linear trend line.

The average SLR computed by linear fitting of all the data for 128 United States locations with update 2006 is 1.67 mm/year (National Oceanic and Atmospheric Administration 2009). The average SLR computed by linear fitting of all the data for 116 United States locations with update 1999 was 1.71 mm/year (National Oceanic and Atmospheric Administration 2003). For the same 116 stations, the data updated to 2006 give an SLR of 1.56 mm/year. As shown by Parker (2012a, b), these reducing SLR are consistent with a decelerating satellite radar altimeter reconstruction and the regular oscillations of the monthly departures from the linear trend to support a not positively accelerating trend.

Baltimore (STATION ID: 148 LAT: 39.266667 LON: −76.578333) has a time span of 1902–2011 and completeness of 99 %. The maximum SLR_{60} is 3.66 mm/year, and it was achieved in 1973. The present SLR_{60} is 3.00 mm/year. The latest SLR_A is 3.13 mm/year.

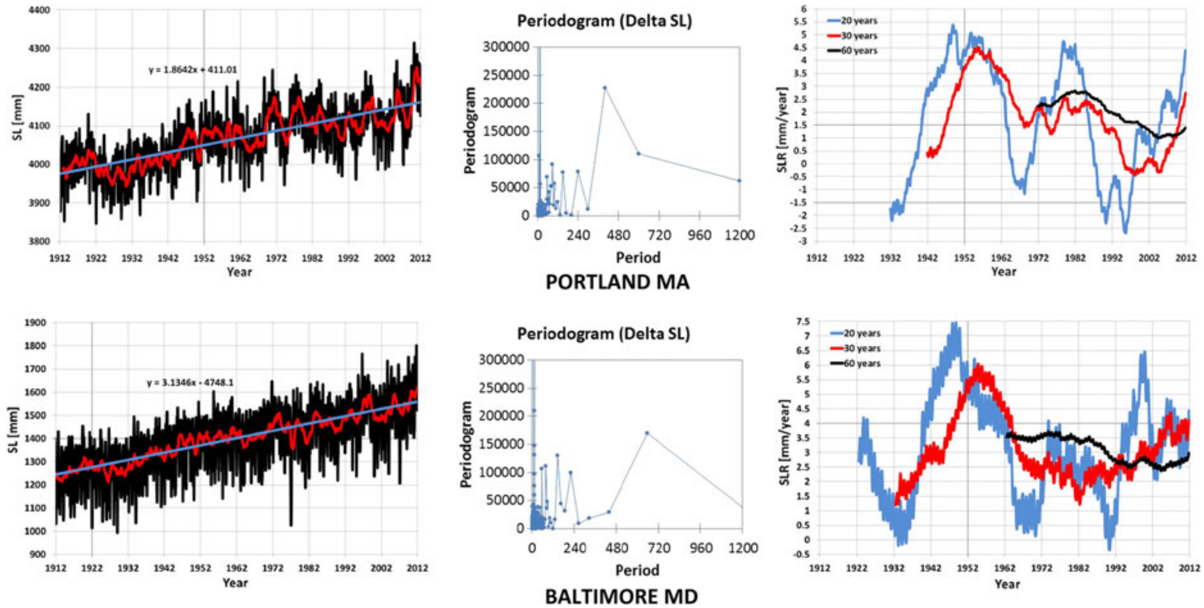

Fig. 1 Monthly sea levels and linear trend, periodogram of the monthly departures versus the linear trend and computed SLR_{20}, SLR_{30} and SLR_{60} for the locations of the United States with more than 100 years of data available at the present time

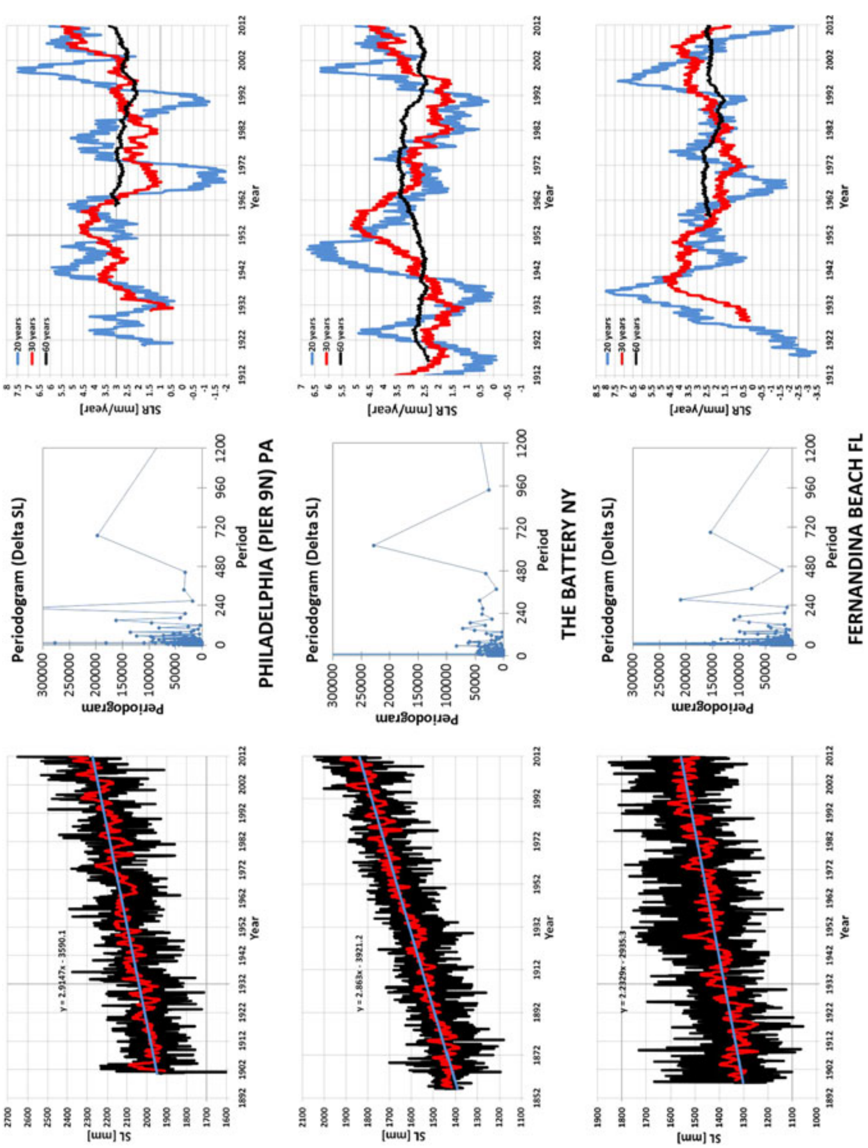

Fig. 1 continued

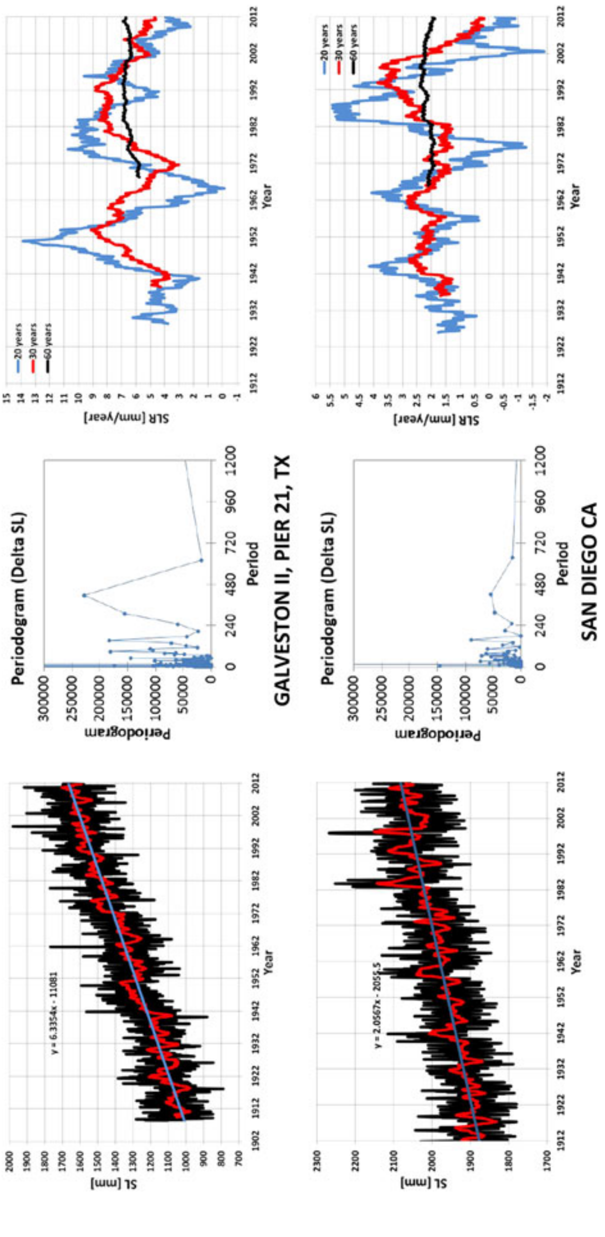

Fig. 1 continued

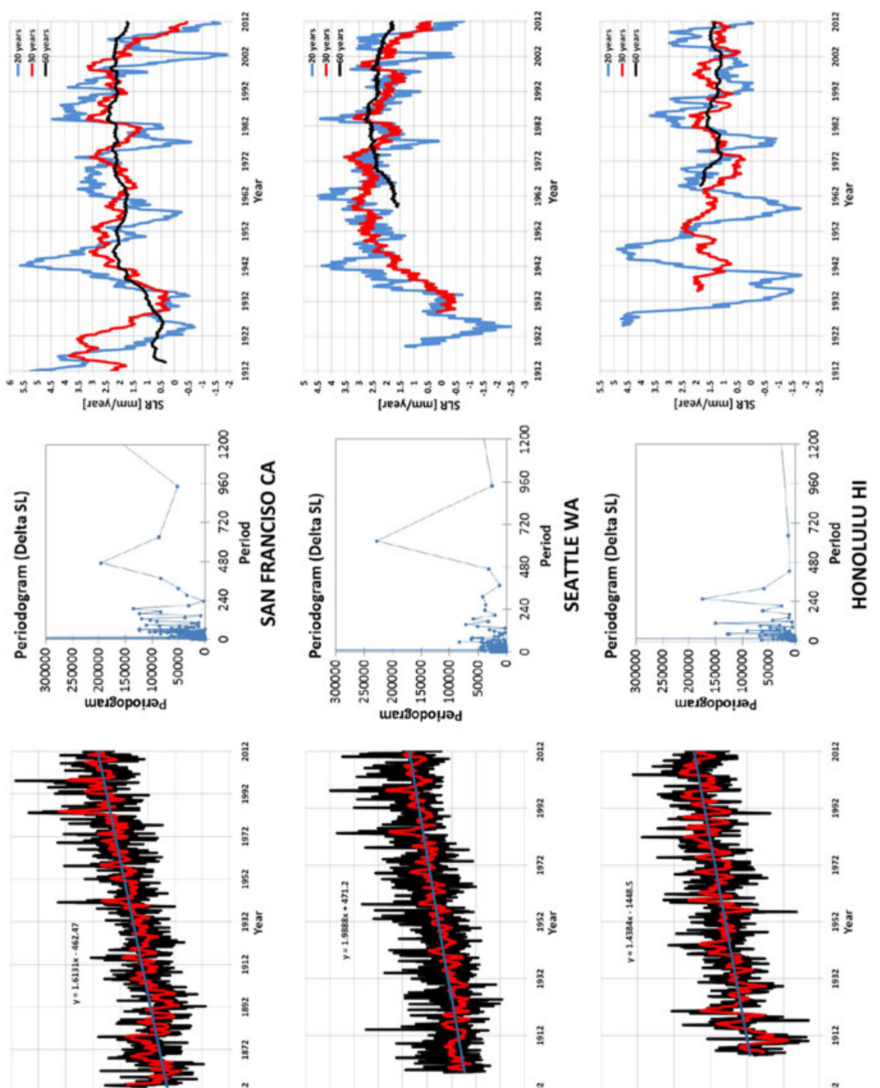

Fig. 1 continued

The SLR_{30} had a maximum in 1955 and minimums in 1932 and 1952. The SLR_{30} is poorly correlated with the latest SLR_A and suffers from large positive and negative oscillations. The SLR_{20} has a more complex behavior with oscillations increasing in number and in amplitude.

Portland (STATION ID: 183 LAT: 43.656667 LON: −70.246667) has a time span of 1912–2011 and completeness of 100 %. The maximum SLR_{60} is 2.78 mm/year, and it was achieved in 1982. The present SLR_{60} is 1.40 mm/year. The latest SLR_A is 1.86 mm/year. The SLR_{30} has a behavior different from the one of Baltimore, but still characterized by the poor correlation with the latest SLR_A and of large positive and negative oscillations.

Philadelphia (STATION ID: 135 LAT: 39.933333 LON: −75.141667) has a time span of 1900–2011 and completeness of 97 %. The maximum SLR_{60} is 3.15 mm/year recorded in 2011 versus a prior maximum of 3.14 mm/year recorded in 1963. The latest SLR_A is 2.91 mm/year. This is the only tide gauge with no deceleration at present versus the past. The SLR_{30} had a maximum in about 1952 and is having a maximum at present, while a minimum was achieved in 1982.

The Battery (STATION ID: 158 LAT: 32.713333 LON: −117.173333) has a time span of 1906–2011 and completeness of 98 %. The maximum SLR_{60} is 3.41 mm/year, and it was recorded in 1971. The present SLR_{60} is 3.00. The SLR_{30} had a maximum in 1955 and minimums in 1932 and 1952, very closely resembling the behavior of Baltimore. The latest SLR_A is 2.86 mm/year.

Fernandina Beach (STATION ID: 112 LAT: 30.671667 LON: −81.465) has a time span of 1897–2011 but a completeness of only 85 %. The maximum SLR_{60} was about 2.66 mm/year, and it was recorded in 1975, 1993 and 2010. The latest SLR_A is 2.23 mm/year. Due to the significant reconstructed portion of the record, these results are less reliable than the others. The present SLR_{60} is 2.35 mm/year. The SLR_{30} has maximum in 1940 and in 2006 and a minimum in 1971. The SLR_{30} is poorly correlated with the latest SLR_A and suffers of large positive and negative oscillations. The SLR_{30} has a behavior not too far from those of the North Atlantic locations. The SLR_{20} has a more complex behavior with oscillations increasing in number and in amplitude.

Galveston (STATION ID: 161 LAT: 29.31 LON: −94.793333) has a time span of data 1908–2011 and completeness of 99 %. The maximum SLR_{60} is about 6.69 mm/year recorded in 1983, 1993 and 2010. The latest SLR_A is 6.34 mm/year. Galveston suffers from the large subsidy of the Texas coastline. The SLR_{30} has maximum values in 1992 and 1952, and a minimum in 1972.

San Diego (STATION ID: 158 LAT: 32.713333 LON: −117.173333) has a time span of 1906–2011 with completeness of 98 %. The maximum SLR_{60} is 2.30 mm/year, and it was recorded in 1997. The present SLR_{60} is 2.00 mm/year. The latest SLR_A is 2.06 mm/year. The SLR_{30} has a behavior completely different from those of the Atlantic, with smaller oscillations up to 1982, and larger oscillations after 1982, both in positive and negative about the long-term value. The SLR_{30} is poorly correlated with the latest SLR_A and suffers from large positive and negative oscillations. The SLR_{20} has a more complex behavior with oscillations increasing in number and in amplitude. The number of oscillations is larger than in the Atlantic signals.

San Francisco (STATION ID: 10 LAT: 37.806667 LON: −122.465) has a time span of 1854–2011 and completeness of 100 %. The maximum SLR_{60} is 2.35 mm/year, and it was recorded in 1983. The present SLR_{60} is 1.72 mm/year. The SLR_{20} and SLR_{30} are more similar to those of San Diego than the Atlantic stations; however, the longer record clearly show the highest peaks of the SLR_{20} and SLR_{30} distributions in the beginning of the 1900s. The latest SLR_A is 1.61 mm/year.

Seattle (STATION ID: 127 LAT: 47.601667 LON: −122.338333) has a time span of 1899–2011 and completeness of 100 %. The maximum SLR_{60} is 2.71 mm/year recorded in 1983. The present SLR_{60} is 1.74 mm/year. The latest SLR_A is 1.99 mm/year. The fluctuations of the SLR_{20} and SLR_{30} have a behavior different from San Francisco and San Diego while maintaining the Pacific signature of more frequent oscillations.

Honolulu (STATION ID: 155 LAT: 21.306667 LON: −157.866667) has a time span of 1905–2011 and completeness of 100 %. The maximum SLR_{60} was 1.63 mm/year, and it was recorded in 1963. The present SLR_{60} is 1.32 mm/year. The latest SLR_A is 1.44 mm/year. The oscillations of the SLR_{20} and SLR_{30} have the clear Pacific signature, with larger positive peaks in the first part of the 1900s rather than in the second part. The SLR_{20} and SLR_{30} are poorly correlated with the latest SLR_A and suffer from large positive and negative oscillations increasing in number and amplitude decreasing the time windows.

4 Discussion and conclusions

The sea levels oscillate with interannual and multidecadal periodicities. As a consequence, the SLR obtained by linear fittings of only 20 or 30 years of data are also oscillating significantly. The SLR_{20} and SLR_{30} are not particularly meaningful to indicate the long term trend, being the time windows too short, thus magnifying the influence of longer multidecadal oscillations.

The comparison of 2 ad-hoc selected values of the SLR_{30} distribution in a valley and a peak, for example the comparison of the SLR_{30} measured in 1979 and 2009 along the Atlantic coast of North America by Sallenger et al. (2012), is not a proof that the sea levels are accelerating in the area. Similarly, the comparison of the latest less-than-20-year SLR with past values of SLR computed in other locations over different time scales by the Australian Federal Government's Climate Commission (2011) and Australian Government Bureau of Meteorology (2011) is not a proof that the sea levels are accelerating in the area.

Over the last 30 years, the SLR_{60} is clearly generally decreasing and the only reasonable claim that can be made of present acceleration is that it is eventually negative for all the 10 long-term tide gauges considered in the Atlantic and the Pacific. The sea levels oscillate with periodicities linked to those of the major indices for the Pacific and the Atlantic climates but also showing remarkable differences. A better focus on the understanding the natural or other man-made forcing on sea levels is certainly needed, while the claim of sea levels accelerating because of the anthropogenic carbon dioxide emissions does not find any support in the proposed data.

References

Anderson TW (1971) The statistical analysis of time series. Wiley, New York

Australian Federal Government's Climate Commission (2011) The critical decade. climatecommission.gov.au/wp-content/uploads/4108-CC-Science-WEB_3-June.pdf. Accessed 2012 August 16

Australian Government Bureau of Meteorology (2011) The australian baseline sea level monitoring project annual sea level data summary report July 2010–June 2011.www.bom.gov.au/ntc/IDO60202/IDO60202.2011.pdf. Accessed 2012 August 16

Jevrejeva S, Moore JC, Grinsted A, Woodworth P (2008) Recent global sea level acceleration started over 200 years ago?. Geophys Res Lett 35: L08715. www.agu.org/pubs/crossref/2008/2008GL033611.shtml. Accessed 2012 August 16

National Oceanic and Atmospheric Administration (2003) Sea level variations of the united states 1854–1999. NOAA technical report NOS CO-OPS 36. tidesandcurrents.noaa.gov/publications/techrpt36doc.pdf. Accessed 2012 August 16

National Oceanic and Atmospheric Administration (2009) Sea level variations of the united states 1854–2006. NOAA technical report NOS CO-OPS 53. tidesandcurrents.noaa.gov/publications/Tech_rpt_53.pdf. Accessed 2012 August 16

National Oceanic and Atmospheric Administration (2012) Teleconnections. www.ncdc.noaa.gov/teleconnections/. Accessed 2012 August 16

Parker A (2012a) Comment to Shepard, C.C., Agostini, V.N., Gilmer, B., Allen, T., Stone, J., Brooks, W., Beck, M.W., assessing future risk: quantifying the effects of sea level rise on storm surge risk for the southern shores of Long Island, New York. Nat Hazards 60(2):727–745. doi:10.1007/s11069-012-0314-2

Parker A (2012b) Oscillations of sea level rise along the Atlantic coast of North America north of Cape Hatteras. Nat Hazards, doi:10.1007/s11069-012-0354-7

Permanent Service Mean Seal Level (2012) Obtaining tide gauge data. www.psmsl.org/data/obtaining/. Accessed 2012 August 16

Sallenger AH, Doran KS, Howd PA (2012) Hotspot of accelerated sea-level rise on the Atlantic coast of North America. Nat Clim Chang. www.nature.com/nclimate/journal/vaop/ncurrent/full/nclimate1597.html. Accessed 2012 August 16

Scafetta N (2010) Empirical evidence for a celestial origin of the climate oscillations and its implications. J Atmos Sol Terr Phys 72:951–970

Scafetta N (2012a) Testing an astronomically based decadal-scale empirical harmonic climate model versus the IPCC (2007) general circulation climate models. J Atmos Sol Terr Phys 80:124–137

Scafetta N (2012b) A shared frequency set between the historical mid-Lat aurora records and the global surface temperature. J Atmos Sol Terr Phys 74:145–163