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Sea-level trend analysis for coastal management

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ABSTRACT

A proper coastal management requires an accurate estimation of sea level trends locally and globally. It is claimed that the sea levels are rising following an exponential growth since the 1990s, and because of that coastal communities are facing huge challenges. Many local governments throughout Australia, including those on the coast, have responded to the various warnings about changes in climate and increases in sea levels by undertaking detailed climate change risk management exercises. These exercises, which use projections passed on by the relevant state bodies, are expensive, but still a fraction of the cost of the capital works that they recommend. Several councils have complained to an Australian Productivity Commission report on climate change adaptation they do not have the money for the capital works required. It is shown here that the exponential growth claim is not supported by any measurement of enough length and quality when properly analysed. The tide gauge results do not support the exponential growth theory. The projections by the relevant state bodies should therefore be revised by considering the measurements and not the models to compute the future sea level rises for the next 30 years following the same trend experienced over the last 30 years.

1. Introduction

It is claimed in the Intergovernmental panel on climate change reports (IPCC, 2001, 2007) that sea levels are rising faster than before because of the anthropogenic carbon dioxide emissions. According to the reports, sea surface temperature, sea level and storm intensity are all due to increase; the increased sea surface temperature will produce increased stratification/changed circulation, reduced incidence of sea ice at higher latitudes, increased coral bleaching and mortality, pole ward species migration and increased algal blooms; the increased sea level will produce inundation, flood and storm damage, erosion, saltwater intrusion, rising water tables/impeded drainage, wetland loss (and change); the increased storm intensity will produce increased extreme water levels and wave heights, increased episodic erosion, storm damage, risk of flooding and defence failure.

The sea-level scenarios of Ozcoasts (Australian Government/Geoscience Australia, 2012) translate into six greenhouse-gas emission 'marker' scenarios. Sea levels are supposed to follow over the period 1990–2100 an exponential curve:

$$y = y_0 + A \cdot e^{R_0 \cdot x} \qquad (1)$$

In this equation, x is the time, y the global mean sea level and y_0 and R_0 are constants. Starting from 1990, $y_0 = 0$ and R_0 is a constant dependent on the greenhouse-gas emission scenario. B1 produces the lowest emissions and A1FI produces the highest emissions. Accordingly, B1 produces the smaller R_0 and A1FI produces the larger R_0 resulting in lowest and highest sea level rises.

Because of these claims, ocean and coastal management has been forced to consider the opportunity to deal with increasingly higher and higher sea level rises by the end of the century with many studies suggesting values of sea level rise by the end of the century by 1 m, 2 m or even 5 m to be accounted for and proposing the necessary adaptation strategies in the planning for the future coastal communities. This contribution clarifies that contrary to the climate model predictions all the experimental results obtained so far when properly analysed do not show any positive acceleration of sea levels.

Sea level rise maps have been proposed for coastal management in Australia. With around 85% of Australia's population living in the coastal zone, rising sea levels and storm surges will have significant impacts on many of our coastal towns and cities. The Australian Government Australian Government/Geoscience Australia (2012) has developed a series of initial sea level rise maps to illustrate the potential impacts of climate change for key urban areas. The maps have been prepared by combining a sea level rise value with a high tide value. They illustrate an event that could be expected to

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occur at least once a year, but possibly more frequently, around the year 2100. Maps are available to show three sea level rise scenarios: low sea level rise (0.5 m), medium sea level rise (0.8 m) and high sea level rise (1.1 m). These sea level rise scenarios are for a 2100 period, relative to 1990.

The sea level rise values are based on IPCC projections B1 and A1FI scenarios (IPCC, 2007) and the three scenarios developed by CSIRO for sea level rise between 2030 and 2100 (relative to 1990) are presented in Table 1 from Australian Government/Geoscience Australia (2012). The low scenario (B1): considers sea-level rise in the context of a global agreement which brings about dramatic reductions in global emissions and represents the upper end of the range for sea-level rise by 2100 which is likely to be unavoidable. The medium scenario (A1FI): Represents the upper end of IPCC's 4th Assessment Report (AR4) A1FI projections (IPCC, 2007) according to CSIRO in line with recent global emissions and observations of sea-level rise (Australian Government/Geoscience Australia, 2012). The high-end scenario: considers the possible high end risk identified in the AR4 and more specifically in selected post IPCC AR4 research. This scenario factors in recent publications that explore the impacts of recent warming trends on ice sheet dynamics beyond those already included in the IPCC projections.

The claims of IPCC (2001, 2007) and the maps of Australian Government/Geoscience Australia (2012) are the result of the application of climate models assuming sea level rises are governed by anthropogenic carbon dioxide emissions. The most popular models used to estimate the impacts of climate-change are based on very simplistic assumption, as for example Rahmstorf (2007):

$$\frac{dSLR}{dt} = \frac{dCO_{2-a}}{dt} \tag{2}$$

In this equation, t is the time, SLR the sea level rise and CO_{2-a} the anthropogenic emission of carbon dioxide. Equation (2) (and more in general the assumption that the anthropogenic emissions of carbon dioxide are the only forcing of sea level rises) lack so far of validation.

All the measurements of sea levels indicate a smooth behaviour made up of shorter term oscillations about a longer term rise almost linear without any sign of the sharp departure postulated by the models (see Baart et al., 2012; Boretti, 2012a,b, 2012, in press-b, in press-c; 2013; Boretti and Watson, 2012; Daly, 2000; Donner, 2012; Gehrels et al., 2012; Gratiot et al., 2008; Gray, 2010; Houston and Dean, 2011; Jevrejeva et al., 2008; Morner, 2004, 2007, 2010a,b; 2011a,b,c; Parker, 2013a,b,c; Scafetta, 2010; Testut et al., 2010; Unnikrishan and Shankar, 2007; Watson, 2011) challenging the abrupt sea level acceleration theory).

The misunderstanding of the true sea level behaviour comes from the naturally oscillating pattern of the sea levels that require a significant number of years of continuous recording to understand the multi-decadal periodicity of individual tide gauge records, and the lack of coverage of the most part of the ocean surface, with for example large areas as the Pacific having only 5 tide gauges recording continuously since more than 100 years, Sydney, Honolulu, San Francisco, San Diego, Seattle, and therefore not enough data to properly assess a trend and a very uncertain past to compare with the recent measurements.

Table 1
Three global sea-level rise scenarios 2030–2100 (m) of Australian Government/Geoscience Australia, 2012.

Year	Scenario 1 (B1)	Scenario 2 (A1FI)	Scenario 3 (High end)
2030	0.13	0.15	0.2
2070	0.3	0.5	0.7
2100	0.5	0.8	1.1

2. Methods to analyse sea levels

Different methods are available to analyse the sea levels all based on very simple statistics. In the following subsections these methods are applied to the only tide gauges of Australia covering more than 100 years.

2.1. Linear fittings of tide gauge data

The claimed exponential growth of global sea level linked to the anthropogenic carbon dioxide emissions has brought more attention to the measurements collected by tide gauges and their analysis. Tide gauges have been recording sea levels in the best cases since the 19th century and in many cases since the first half of the 20th century (see databases PSMSL, 2012; NOAA, 2012a; AGBOM, 2012a) originally for other purposes and more recently with focus on the assessment of the impact of climate change.

It is very well known that sea levels oscillate with shorter term periodicities about a longer term trend. There are oscillations with different periods ranging from hours to multi-decades. The longer periodicity depends on the length of the record under consideration. The classic approach to analyse sea level data is to use a linear fit:

$$y = y_0 + a \cdot x \tag{3}$$

In this equation, y_0 and a are constants to compute the average sea level rise over the period of observation. The presence or absence of acceleration is then detected by observing the graph of the monthly or yearly average sea level data and/or the monthly or yearly deviations vs. the linear trend. This classic approach requires records of enough length to avoid computing as a longer term sea level rise the variation of sea level from a valley to a peak of a multi-decadal oscillation.

Fig. 1 presents the result of the fitting with a line of the monthly average sea levels and the monthly departures from this linear trend for Sydney and Fremantle. Data are from PSMSL (2012). Sydney and Fremantle are the only 2 records with length exceeding 100 years in Australia. The 12 months moving averages are also superimposed to clear out the data of the oscillations of periodicity less than 1 year. The oscillations since 1980 have been clearly previously measured by these two long recording tide gauges and there is no sign of any sharp positive acceleration 1980 to present that would have otherwise translated in much larger positive oscillations in the recent past vs. the remote past.

The results of Fig. 1 is consistent with all the other tide gauges of the world of enough length. If the length of the recording is not long enough, usually 60–70 years as clarified in a following paragraph, the computed sea level rises of individual tide gauges may change in time not because of positive (or negative) accelerations but simply because of the multi-decadal oscillations. However, compilations of tide gauge results not necessarily all exceeding the 60–70 years of recording do not show any significative increase of the average sea level rise.

The compilation of sea level rises for 193 global stations of NOAA (2012b) or 127 United States stations of NOAA (2012c) show sea level rises from linear fitting about constant on average, and the graphs of monthly average sea levels or their departure from the linear trend show regular oscillations with different interannual and multidecadal periodicities along the almost linear trend without any sign of departures over the last three decades.

2.2. Time histories of linear fittings of tide gauge data

If the least squares method is used to calculate a straight line that best fits the data, the equation for the line is (3) where the

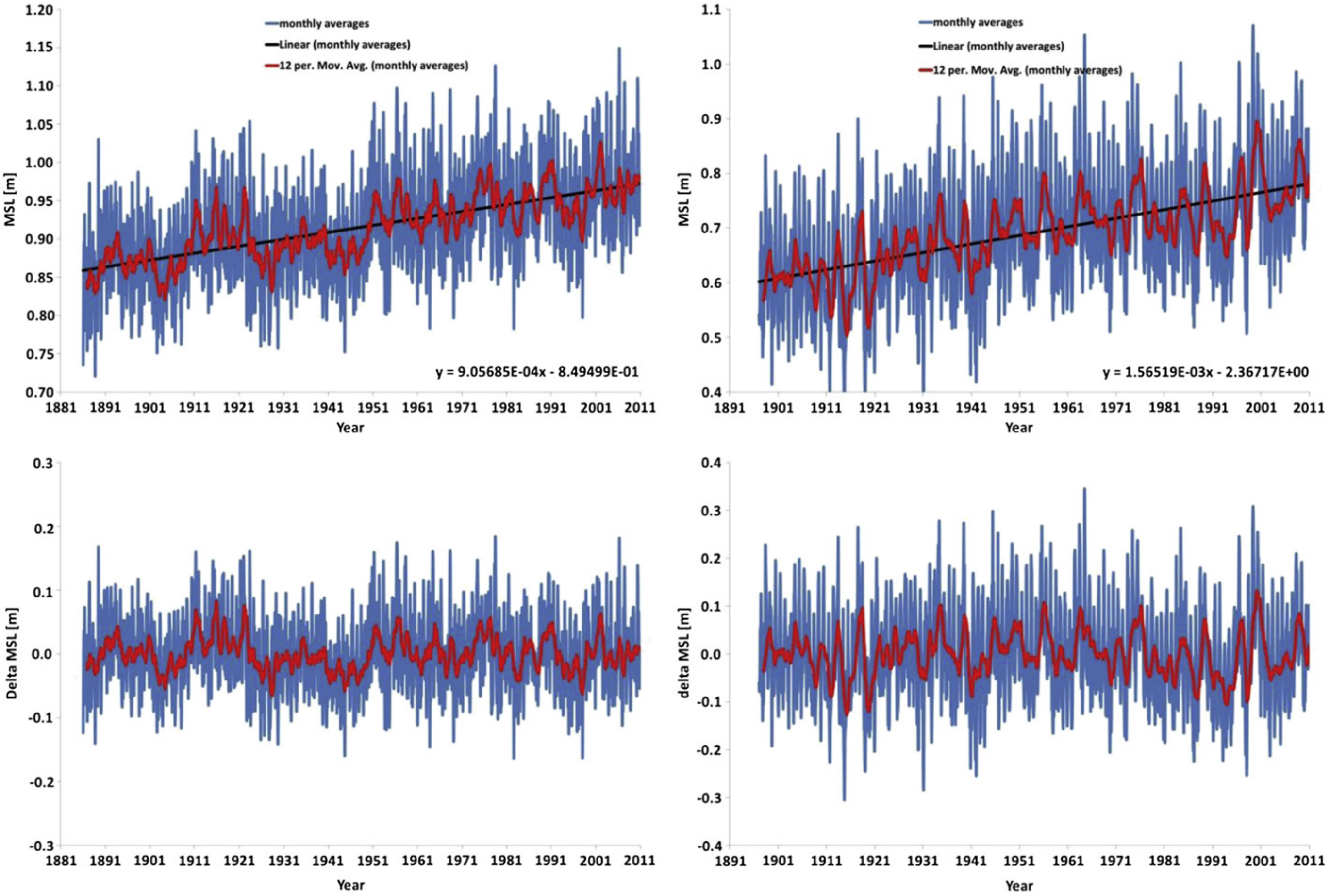


Fig. 1. Monthly average sea levels, linear fitting and monthly departures from the linear trend for Sydney (left) and Fremantle (right). Data are from PSMSL (2012). The 12 months moving averages are also superimposed to clear out the data of the oscillations of periodicity less than 1 year. The oscillations since 1980 have been clearly previously measured and there is no sign of any sharp positive acceleration 1980 to present that would have translated in much larger positive accelerations.

dependent y-values, the monthly average sea levels, are a function of the independent x-values, the time in years. The calculations for a, the SLR, and y_0 are based on the formulae:

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

$$y_0 = y' - a\cdot x'$$

In these equations x' and y' are the sample means and j and k are the indices of the first and last record of the measured distribution considered for the estimation of the SLR. Sea level rises with windows 20, 30 or 60 years may be computed at any time. At a certain time x_k, x_j is taken as $(x_k - 20)$, $(x_k - 30)$ or $(x_k - 60)$ 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.

This analysis performed on long recording tide gauges is extremely helpful (Parker, 2013a,b). It shows that the 20 or 30 years SLR are oscillating significantly, and it does not make then any sense to focus on a specific value of their time histories. The 60 years SLR is a much more stable parameter suffering less of the multidecadal oscillations, but still fluctuating. The SLR computed with all the data approaches a reasonably accurate long term value only after 60–70 years. If a tide gauge is recording since only a few years, for example less than 20 years, the computed SLR is absolutely not a measure of the longer term SLR.

Fig. 2 presents the SLR_{20}, SLR_{30}, SLR_{60} and SLR_A computed for Sydney and Fremantle. The proposed values are 12 months averages for clarity of the graph. For Sydney, the SLR_{60} has been first increasing and it is now reducing over the last 40 years. The SLR_A is increasing since 1970, but is clearly reducing the rate of rise in the last few years. For Fremantle, the SLR_{60} and the SLR_A are both reducing since 1970. For both examples, the SLR_{20} and SLR_{30} in a particular year have absolutely no correlation with the longer term SLR.

The existence of multi-decadal oscillations along the coastline of Australia is discussed in AGBOM, 2003 where the 20 years El Niño – Southern Oscillation (ENSO) signal is shown to affect the measured sea level rise and a minimum 25 years of recording is introduced in the computation of the mean sea level rise by linear fitting in 33 locations.

The existence of the first multi-decadal oscillation of AGBOM, 2003 along the coastline of Australia is forgotten in AGBOM, 2012b,c and AFGCC, 2011 where the present sea level rise is evaluated by linear fitting of less than 20 years of data in only 14 stations completely neglecting the prior measurements in the same locations or the contemporary measurements in other stations. The average SLR from this short term subset of 14 stations is then compared with previously computed average SLR from other stations with different time windows to claim the existence of a present acceleration of sea levels in AGBOM, 2012c.

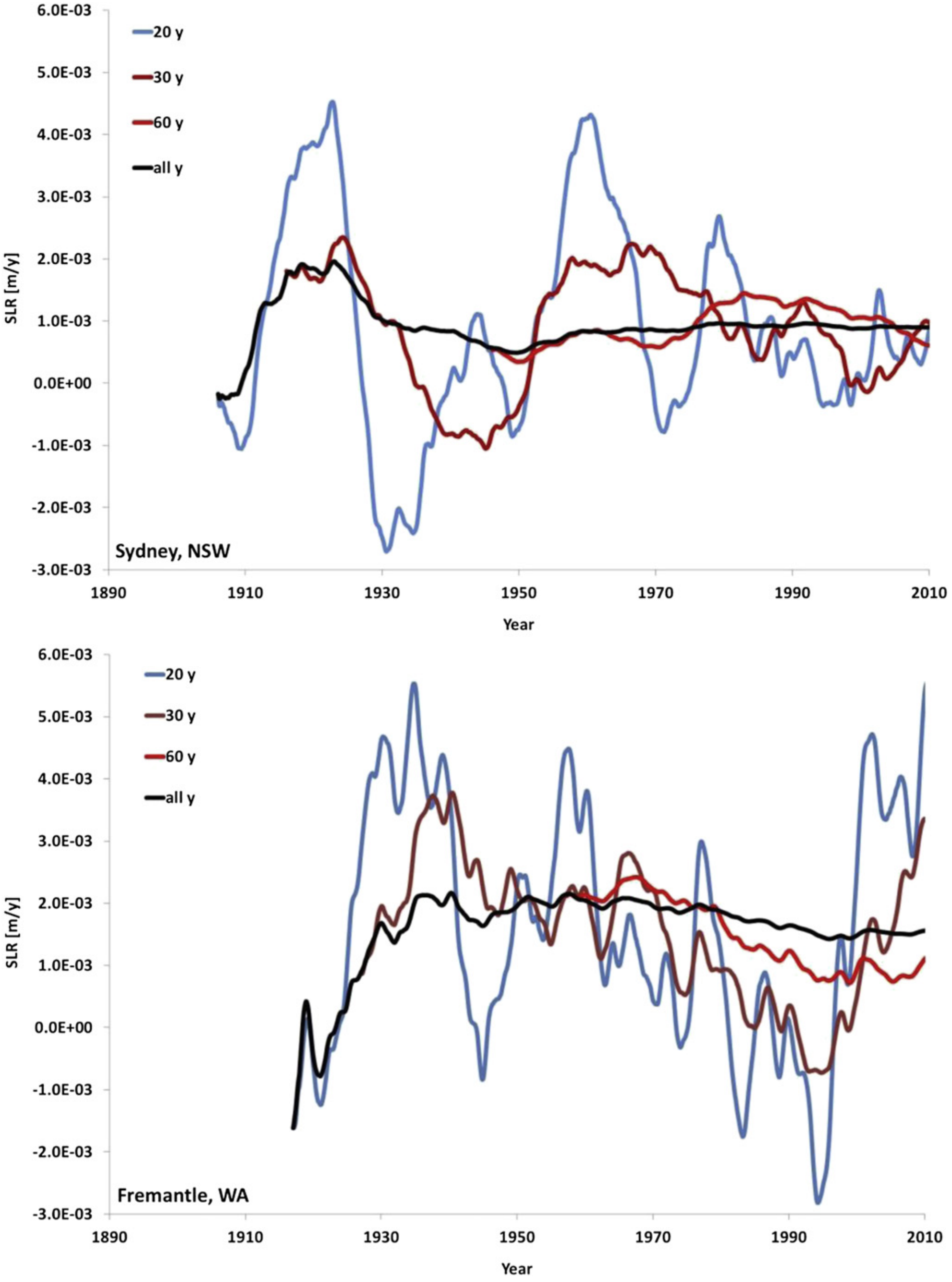


Fig. 2. SLR_{20}, SLR_{30}, SLR_{60} and SLR_A computed for Sydney (top) and Fremantle (bottom). Data are from PSMSL (2012). The SLR_{20} and SLR_{30} oscillate significantly because of the multidecadal periodicities. It does not make any sense to focus on an individual value of the distribution of SLR_{20} and SLR_{30} or compare 2 ad-hoc selected values of these distributions. Records of short length do not permit to assess any trend in sea level rise.

2.3. Parabolic fittings of tide gauge data

To support or negate presently accelerating trends, parabolic fittings have also been proposed.

$$y = y_0 + a \cdot x + b \cdot x^2 \tag{4}$$

In this equation, y_0, a and b are constants to compute the average sea level acceleration (or deceleration) over the period of observation.

The parabolic fittings have been proposed in Watson (2011) and Houston and Dean, 2011 to analyse the longer tide gauges of North American and Australia/New Zealand to conclude that there was no evidence of sea level acceleration in these records.

The parabolic fitting only permits to compute an average sea level rise over the period of observation, and therefore the 2nd order coefficient only is not of particular help to understand if the sea levels are presently accelerating or not. Without considering the monthly departures from the parabolic trend, the assessment of positive or negative present accelerations is impossible.

Fig. 3 presents the monthly average sea levels, the parabolic fitting and the monthly departures from the parabolic trend for Sydney (left) and Fremantle (right). The 12 months moving averages are also superimposed to clear out the data of the oscillations

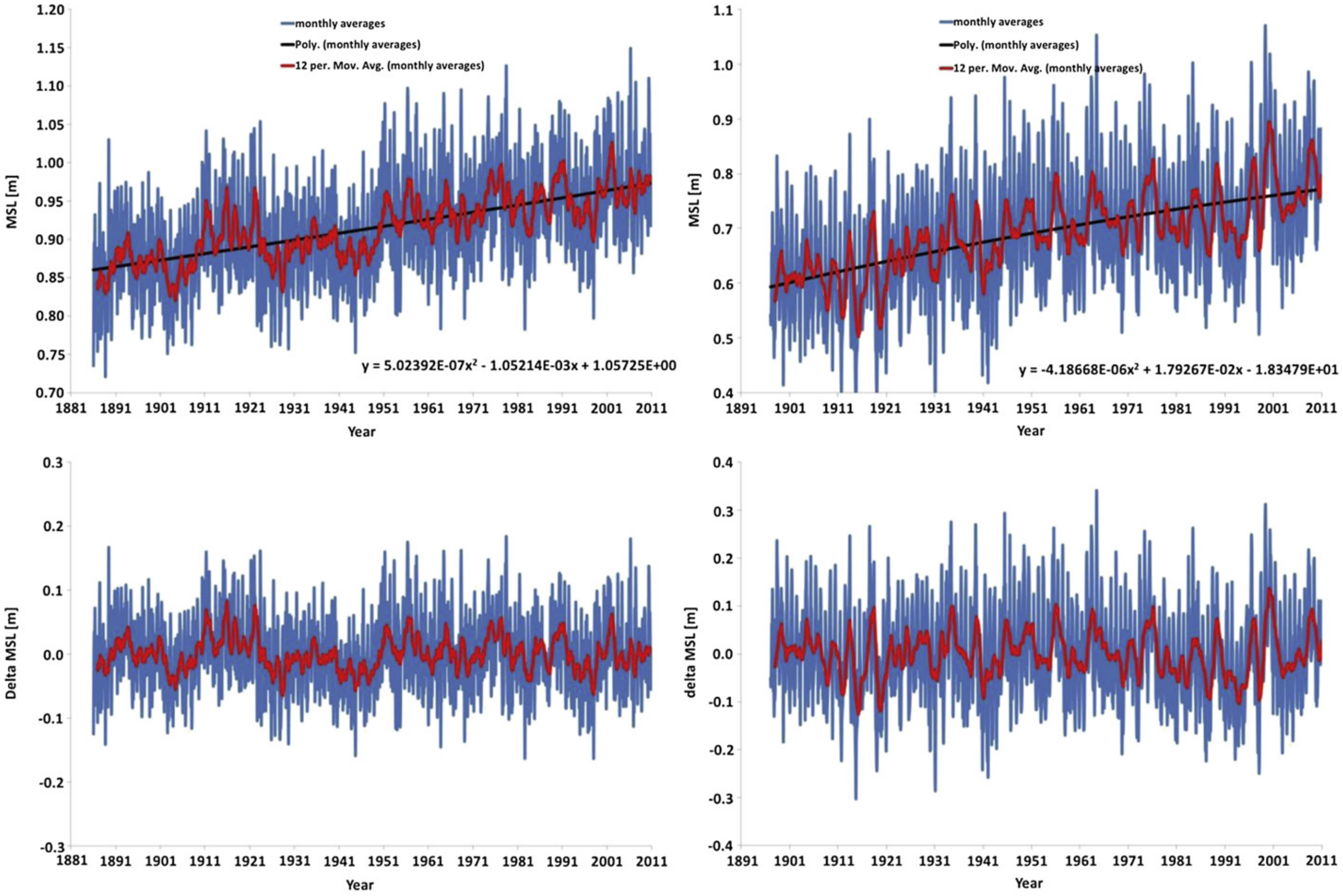


Fig. 3. Monthly average sea levels, parabolic fitting and monthly departures from the parabolic trend for Sydney (left) and Fremantle (right). Data are from PSMSL (2012). The 12 months moving averages are also superimposed to clear out the data of the oscillations of periodicity less than 1 year. The 2nd order coefficients are small. The oscillations since 1980 have been clearly previously measured and there is no sign of any sharp positive acceleration 1980 to present that would have translated in much larger positive accelerations.

of periodicity less than 1 year. The second order coefficients are very small positive for Sydney and negative for Fremantle and the monthly departures vs. the parabolic trend are regular oscillations since the beginning of the record.

The parabolic fitting is not particularly helpful when analysing long records, where the classic linear fitting and the study of the monthly departures already permits to assess the presence or absence of present accelerations, but may help with short records.

2.4. Multiple non linear fittings with sinusoids of tide gauge data

The linear fitting may be coupled to multiple non-linear fittings with periodic functions like sinus or sinus-squared to better detect the presence or absence of present accelerations. This user-defined fitting curve is:

$$y = (y_0 + a \cdot x) + \sum_{i=1}^{n} \left[y_{0,i} + A_i \cdot \sin^{b_j}\left(\pi \cdot \frac{x - x_{c,i}}{w_i} \right) \right] \quad (5)$$

In this equation, n is the number of sinus or sinus-squared functions and y_0, a, $y_{0,i}$, A_i, $x_{c,i}$, w_i, b_j are the fitting coefficients.

There is no need to use a particularly large number of sinusoidal functions, being the residual dropping significantly after the very first fittings and then not changing too much because some of the monthly departures are either not periodic or not represented by a sinus or a sinus-squared. The fitting for each periodicity is performed starting from the most relevant in order of power.

Fig. 4 presents the result of the fitting with a line and sinus-squared functions of the data for Sydney and Fremantle. If the sea level goes up and down following a sinusoidal law there is not too much to claim of positive or negative accelerations. The measured monthly mean sea levels have a more complex behaviour than the one described by equation (5). However, equation (5) may provide a better near future estimate of the monthly mean sea levels including the most relevant periodic oscillations.

Fig. 4 also presents a comparison of the sea level rises predicted for Sydney and Fremantle by CSIRO (Australian Government/Geoscience Australia, 2012) according to the 3 scenarios and the forecast by linear and sinusoidal fittings up to 2040. The difference in between what is guessed by considering the measurements up to date and the models is significant.

2.5. Time series analysis of tide gauges

The periodicities of the fluctuations detected for Sydney and Freemantle as well as for all the other stations of Australia with at least 25 years of recording are shown in the time analysis proposed in the Appendix 1. The maximum detectable multidecadal periodicity obviously depends on the length of the record. Sydney and Freemantle are the only records with more than 100 years in Australia and they permit to detect all the expected multi-decadal periodicities. Sydney has important multi-decadal oscillations about 18 and 56 years. Fremantle does not show these same multi-decadal oscillations. Fremantle, on the Indian Ocean, is not affected

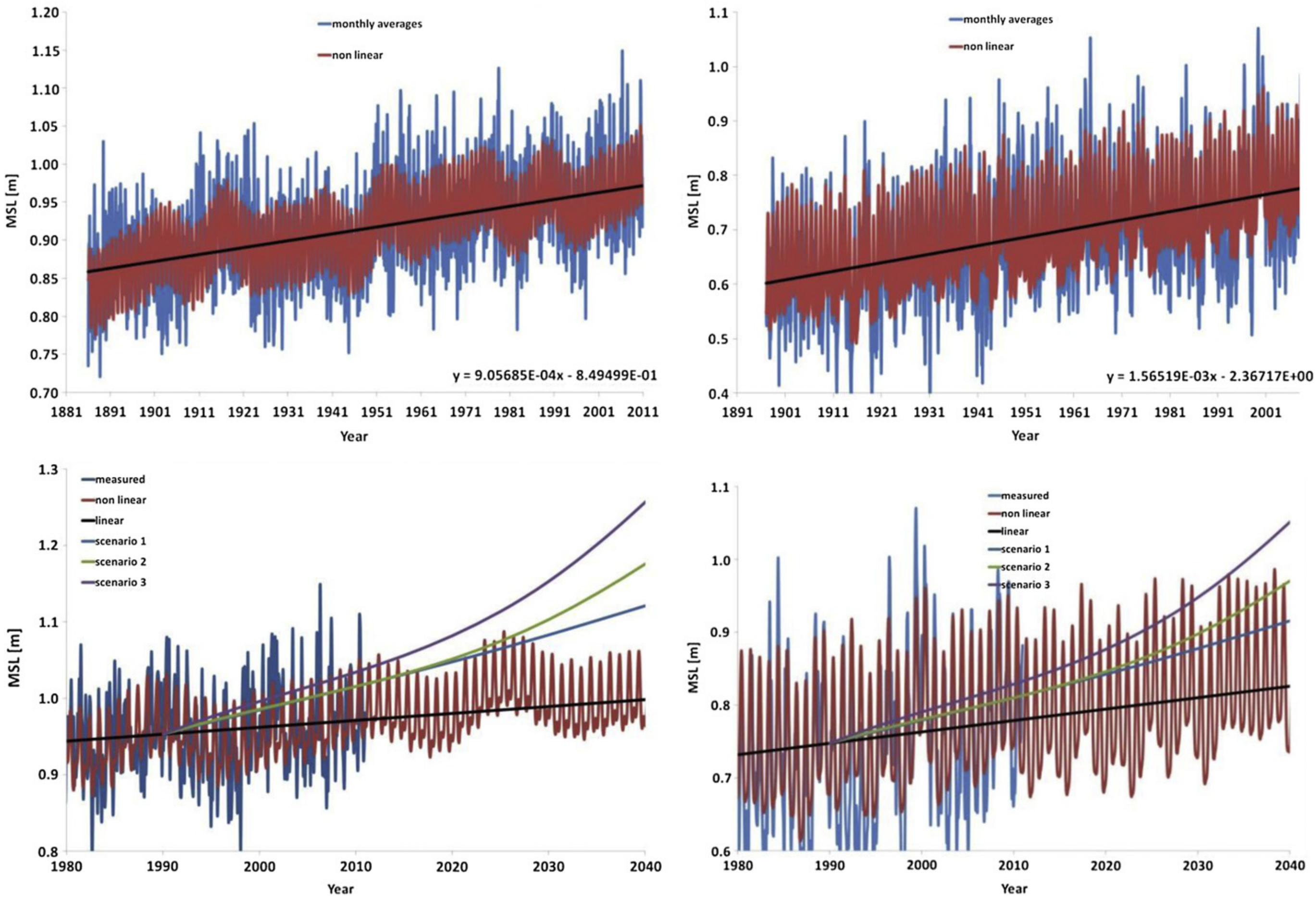


Fig. 4. Linear and non-linear fittings of the measured monthly averages plus 2040 forecast for Sydney (left) and Fremantle (right). Data are from PSMSL, 2012. The scenarios of Australian Government/Geoscience Australia, 2012 are not experimentally validated 1990–2010. The 2010–2040 trend is very likely the one experienced 1980–2010.

by the strong ENSO related signal of period about 18 years and contrary to Sydney, in the Pacific, also lack of the about 56 years periodicity.

2.6. Evaluation of present velocity and acceleration

Providing data of good quality and coverage are available, the sea level velocity at the present time x_k may be computed as

$$\mathrm{SLR}_{A,k} = \frac{\sum_{i=1}^{k}(x-x')\cdot(y-y')}{\sum_{i=1}^{k}(x-x')^2}$$

where x' and y' are the sample means and 1 and k are the indices of the first and last record of the measured distribution considered for the estimation of the $\mathrm{SLR}_{A,k}$. The acceleration may then be computed as

$$\mathrm{SLA}_k = \frac{\mathrm{SLR}_{A,k} - \mathrm{SLR}_{A,k-1}}{x_k - x_{k-1}}$$

This velocity and this acceleration may clearly oscillate, and their time history rather than a single value is of interest.

Fig. 5 presents the distribution of the acceleration SLA computed for Sydney and Fremantle over the last 3 decades. The velocity SLR_A computed for Sydney and Fremantle was given in Fig. 2. Over the last 3 decades, the velocity is about constant and the acceleration is about zero. The velocity weakly oscillates about the long term trend value. The acceleration weakly oscillates about the zero values both in positive and negative. This acceleration has to become constantly positive to make the sharp positive acceleration theory realistic.

3. Australian coastline sea level short term forecast

By using the techniques outlined in the previous paragraph, it is then possible to assess the sea level trends for Australia. The summary of the spectral and linear analysis of the Australian data is proposed in Table 2. This table provides a reliable estimation of the near future sea levels based on the data collected up to the present time.

Table 2 presents the sea level rises for all the tide gauges of Australia with more than 25 years of recorded data from the linear analysis. For Sydney, only the presently operated tide gauge is considered for a record length slightly less than 100 years. The table also presents the first two periodicities above 1 year in order of relevance.

The data quality and coverage does not permit to automatically detect all the important decadal and multi-decadal oscillations in all the measuring locations. The spectral analyses for all the stations are presented in the Appendix 1. This table gives the current sea level trend along the Australian coastline and the periodicities of the major oscillations within the limit of accuracy introduced by the record length. As shown in Fig. 2, with less than 60–70 years of recording, nor the long term sea level rise, nor the major periodicities of the fluctuations are expected to be accurately computed.

The average sea level rise for all the stations with more than 40 years of recorded data is 1.17 mm/year (21 stations, average record

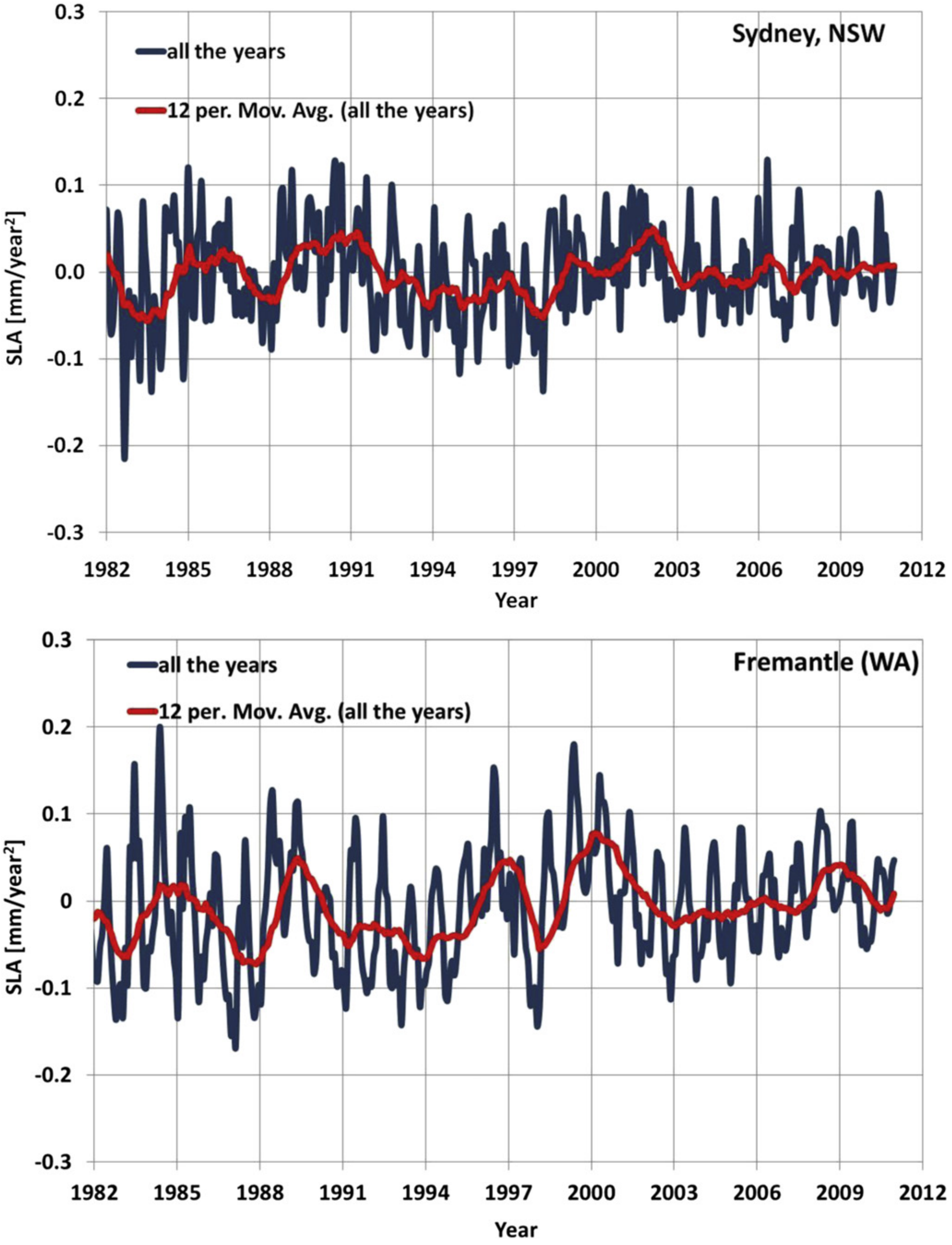


Fig. 5. Sea level acceleration over the last 3 decades for the long term Australian tide gauges of Sydney, and Fremantle (data from PSMSL (2012)). The acceleration weakly oscillates about the zero value in positive and negative.

length 52.5 years). This is in the opinion of the authors the most reliable estimation of the sea level rise along the Australian coastline at the present time because shorter tide gauges suffer too much from the short term oscillations. This average value may oscillates from one update to the other without representing an acceleration or a deceleration of the sea levels but simply because before 60–70 years of data are recorded in a station the long term trend is not cleared of important multidecadal oscillations. This value is very close to the estimation of AGBOM (2003) were the analysis of 29 of the 32 stations with more than 25 years of data (3 stations were removed due to unstable tide gauge datum) returned an average relative sea level rise around Australia of 1.2 mm/year.

Inclusion of stations with less than 25 years of records is not particularly meaningful, because it would just magnify the positive or negative multi-decadal oscillations of the El Niño – Southern Oscillation (ENSO) about the mean trend in the Pacific locations or other possible oscillations that the quality of data and the length of the records do not permit to detect. The most part of the records of Table 2 do not satisfy the minimum requirements for length. Therefore, the reliability of the values of Table 2 is linked to the length of the record. Significant changes may occur in between subsequent updates without representing acceleration or a deceleration.

4. Discussion

What is “acceleration” in a periodically oscillating time series does need some clarification. By definition, velocity is the first derivative of the position vs. time, and acceleration is the first derivative of the velocity vs. time or the second derivative of the

Table 2
Relative sea level trend estimates for all the tide gauges around Australia with more than 25 years of recorded data (data from AGBOM (2012a)).

Station	Years recorded	Years opened	Trend (mm/y)	1st harmonic > 1 y	2nd harmonic > 1 y
Fremantle	105.5	114	1.52	3.6	5.6
Fort Denison (Sydney)	95.42	97	0.87	18.4	55.2
Port Pirie	69.83	70	0.60	55.9	28.0
Port Adelaide (Outer Harbour)	68.83	71	2.21	4.1	56.0
Townsville	51.92	52	1.40	11.5	5.2
Darwin (ABSLMP since May 1990)	48.75	52	2.10	11.5	4.9
Point Lonsdale	48.08	49	−1.07	32.0	4.9
Port Lincoln	45.83	47	1.52	3.4	4.0
Geraldton	45.5	48	1.28	12.6	31.4
Newcastle	45.33	54	0.79	11.2	2.3
Albany	45	51	0.95	11.2	3.7
Williamstown	44.83	45	2.11	5.1	25.6
Victor Harbour	44.83	46	1.04	9.6	18.2
Thevenard (ABSLMP since Mar 1992)	44.75	45	1.16	5.0	9.4
Esperance (ABSLMP since Mar 1992)	44.75	46	0.91	9.0	30.0
Bundaberg	44.42	45	0.46	19.9	9.0
Bunbury	44.17	48	1.01	11.8	4.1
Port Hedland	43	51	1.57	33.7	11.9
Hobart	41.58	51	0.63	2.0	3.2
Wyndham	41	45	2.88	29.7	11.9
Brisbane	40.17	54	0.54	42.5	19.3
Burnie (ABSLMP since Sep 1992)	39.92	59	−0.98	10.6	21.2
Geelong	39.75	46	1.19	18.1	6.7
Carnarvon	38.58	46	1.94	12.9	9.5
Mackay	38.25	51	1.58	9.2	12.6
Broome (ABSLMP since Nov 1991)	38.17	45	3.02	5.2	6.6
Cairns	37.5	51	1.75	10.1	3.7
Howe Island	34.5	53	−2.04	3.4	9.0
Weipa	34.5	46	3.19	3.6	12.0
Port Kembla (ABSLMP since Jul 1991)	34.33	54	0.67	14.2	23.6
Stony Point (ABSLMP since Jan 1993)	31.83	48	−2.14	19.0	5.7
Gove Harbour	31	42	−1.98	3.5	9.7
Portland (ABSLMP since Jul 1991)	28.92	29	2.24	5.0	2.4
Booby Island	28.33	38	−7.31	31.1	11.1
King Bay	28.08	29	4.32	12.5	5.4
Wallaroo	28	35	−0.12	4.1	34.8
Botany Bay	27.25	30	0.68	16.9	5.2
Eden	26.75	45	2.05	5.1	3.1
Cape Ferguson (ABSLMP since Sep 1991)	26.67	32	3.00	10.4	3.8
Hay Point	26.08	42	2.56	8.7	2.5
Mourilyan Harbour	25.92	27	3.03	10.4	20.8
Spring Bay (ABSLMP since May 1991)	25.83	43	3.39	1.9	2.4
Lucinda	25.5	26	3.53	10.2	2.4
Onslow	25.42	26	5.47	11.3	5.6
Cape Lambert	25.08	39	−0.78	38.2	9.0
Port Alma	25	25	1.95	7.1	10.0
Mooloolaba	25	32	1.01	10.5	5.2

position vs. time. Now, if this concept is applied to a time series characterised by periodic oscillations, then this definition of first and second order derivatives vs. time does not help too much because if the time series is updated every hour, then every hour there is a very different value of the acceleration and the velocity to consider.

The paper suggests a logical approach to evaluate the "velocity" and the "acceleration" in a periodically oscillating time series as it is clearly the sea level recorded by tide gauges. It is suggested to evaluate the "velocity" (sea level rise) by linear fitting of more than 60–70 years of continuously recorded data up to a certain point. It is then suggested to evaluate the "acceleration" as the difference in between the velocities evaluated at different times divided by the delta time in between the two updates.

If less than 60–70 years of data are available, the computed sea level rise is very poorly correlated to the long term sea level rise. Proper evaluation of the long term sea level rises and then of the variation in between subsequent updates of this parameter requires tide gauges recording continuously over enough time the sea level. If this condition is not satisfied, there is no way to compute with accuracy the sea level rise and the sea level acceleration.

The length issue is also coupled to a quality issue. It is recommended to avoid inferring any trend from data sets of poor quality and not enough length because they cannot return the longer term sea level rise. If there are significant gaps and the record has not enough length, filing of the gaps, extension and reconstruction of the record are extremely dangerous. The presence of any biasing in the measurements or the occurrence of major perturbing events has to be assessed for all the records.

The claims of present sea level rises much higher than in the past along the Australian coastline (AGBOM, 2012b,c; AFGCC, 2011) is made by using present sea level rises computed by linear fitting with time windows shorter than 20 years in some locations to compare with past sea level rises computed in other locations by linear fittings with different time windows. This different analysis producing completely different results from the analysis of this paper is proposed in Appendix 2.

In some literature the present global mean sea level (GMSL) rise reconstructed from the satellite radar altimeters is compared with the past very rough estimations of GMSL based on a few tide gauge results. The satellite radar altimeter is the only method to properly compute the GMSL but it is only available since 1993 and it has to be

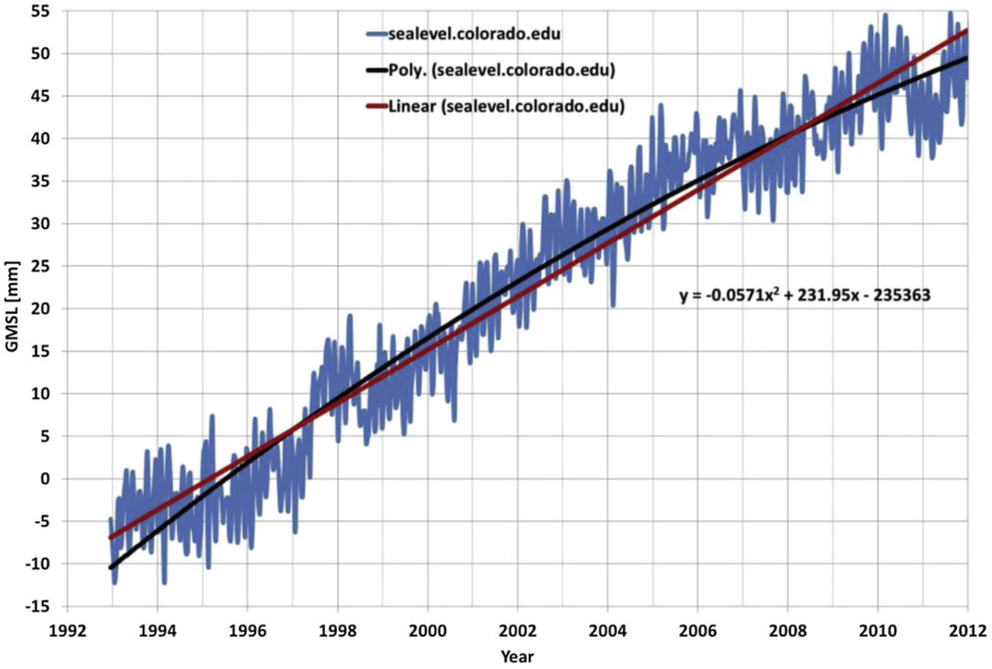


Fig. 6. Global mean sea level reconstruction based on satellite radar altimeters (data from CUSLRG (2012)). The GMSL is theoretically less affected by the oscillations, and within the limits of accuracy of the computation, this result does not support any positive acceleration claim having the parabolic fitting a negative 2nd order coefficient.

further refined with better computational algorithms and a better calibration/validation vs. tide gauge results. The very scattered tide gauge data of the past do not permit to compute any GMSL to compare with the latest satellite reconstruction. The past tide gauge measurements must be compared with the present tide gauge measurements and the GMSL datum must be analysed only over the covered time span taking care of the procedure still needing development.

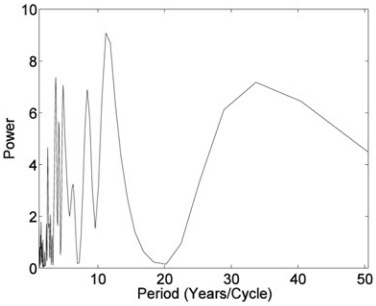
The parabolic and linear fittings of the satellite radar altimeter reconstruction of the GMSL are proposed in Fig. 6 (data from CUSLRG, 2012). If the satellite reconstruction of the GMSL presented in Fig. 6 reproduces the actual variation of the ocean volume or not is an open discussion, being the raw satellite data mostly flat before adjustments (Goddard, 2012; Mörner, 2004; Nova, 2012; Watts, 2012). Being this GMSL theoretically less affected by oscillations, and within the limits of accuracy of the computation, this result does not support any positive acceleration claim having the parabolic fitting a negative 2nd order coefficient. The GMSL is actually drastically decelerating since the 2006.

The proposed approach is based on the analysis of high quality tide gauge measured data with a procedure that returns the present sea level rise and acceleration accounting for the multidecadal oscillations. The procedure may suggest a different behaviour of sea levels vs. what is provided by the analysis of short and incomplete tide gauges reconstructed and extended with different short time windows. Appendix 3 presents the analysis of the Pacific tide gauges with the present method and with other approaches.

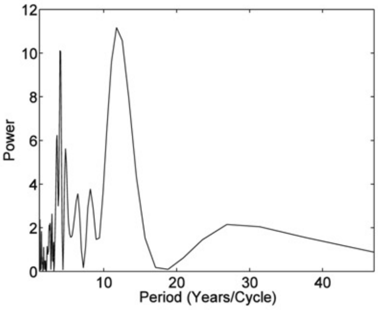
5. Conclusions

- What is important to note in the tide gauge records is the presence (or absence) of a sharp positive acceleration at the present time. This acceleration should be evidenced by a sharp departure from the regular behaviour. Without this departure, there is no sharp positive acceleration.
- The regular behaviour is made of oscillations of inter-annual and multi-decadal periodicities well repeated in time. Without more than 60–70 years of recording, there is not enough information to compute the longer term trend cleared of the shorter term oscillations and the analysis may be misleading.
- Without a record long enough it is very likely that any fitting would overestimate or underestimate the sea level rise starting from a peak or a valley of a decadal or multi-decadal oscillation. Short term estimations of sea level rise by linear fittings should not be used.
- In addition to the length of the records, worth of mention is also the quality of the records. Missed data are difficult to be replaced, and changes of the measuring technique, relocation of the tide gauge and every possible disturbance should be accounted for to ensure the consistency of the measurement results over the full record length. Subsidence or uplift of the tide gauge relative to a datum is also of concern to address quality issues. Poor quality data should not be used.
- Coastal management should consider sea level rises much smaller than those based on modelling activities presently considered in Australia as well as in the other parts of the world at least for the next 30 years. The projections by the relevant state bodies should therefore be revised considering lower bounds to future sea level scenarios the continuation of the trend measured up to the present point.
- A study of long-term tide gauge records is not necessarily a good indicator of future circumstances. However, this result is good indicator of the present and recent past conditions. The claim that the sea levels are accelerating since the 1990 is not supported by any measurement of proper length and quality.
- Considering a scenario for the 21st century similar to the one of the past century is certainly imprudent to adopt for coastal planners, but to plan mass relocation of millions of peoples because of positively accelerating sea levels still far from being detected in any measurement properly made and analysed is certainly even much less reasonable.

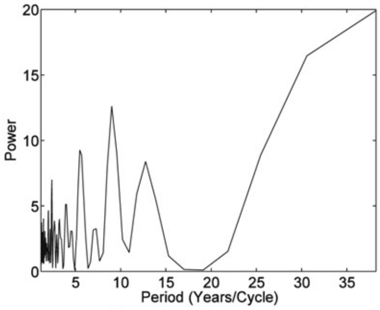
Appendix 1. Spectral analysis of Australian tide gauges with more than 25 years of recorded data



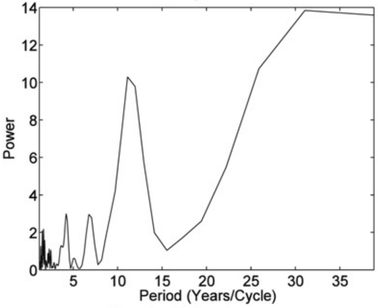
Albany



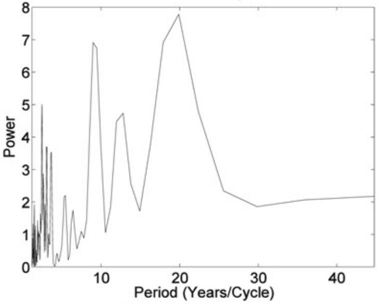
Bunbury



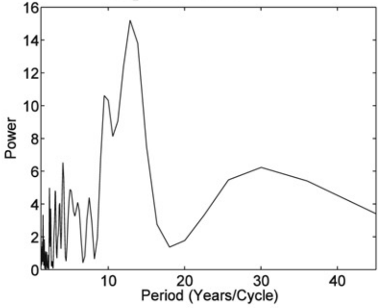
Cape Lambert



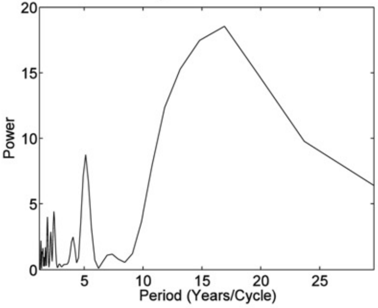
Booby Island



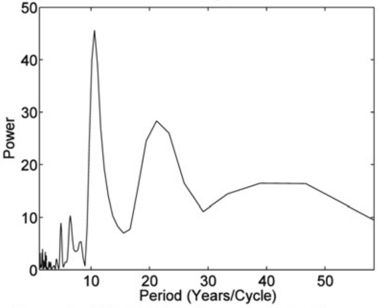
Bundaberg



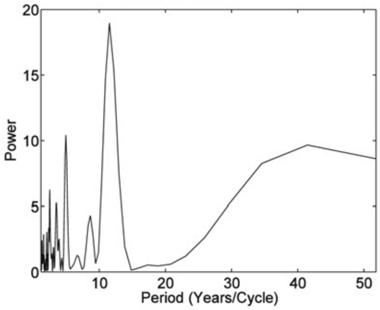
Carnarvon



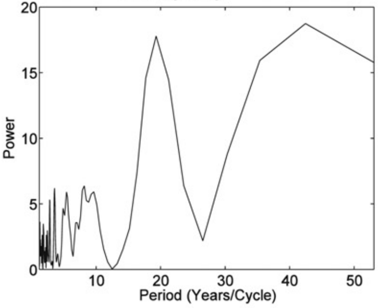
Botany Bay



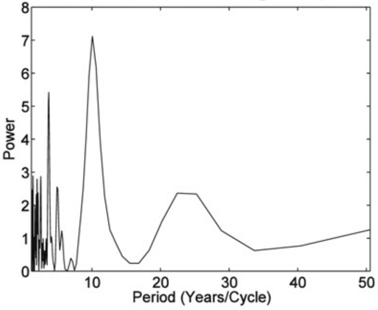
Burnie (ABSLMP since Sep 1992)



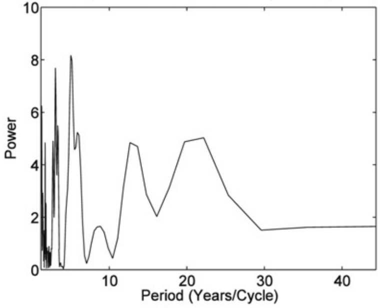
Darwin (ABSLMP since May 1990)



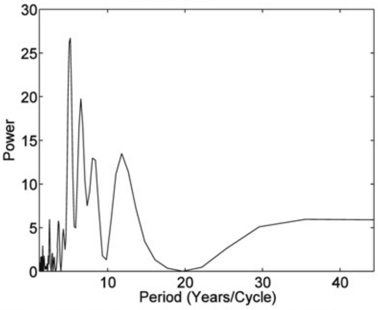
Brisbane



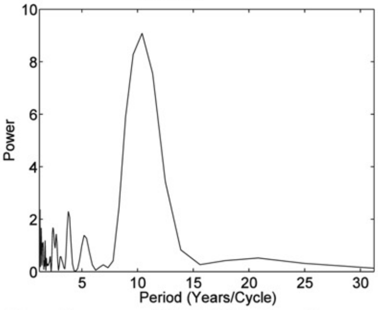
Cairns



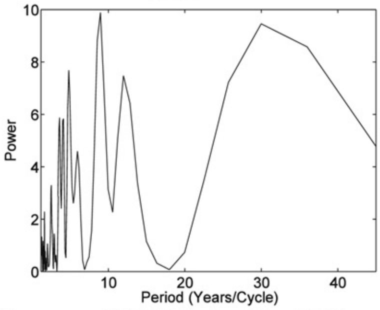
Eden



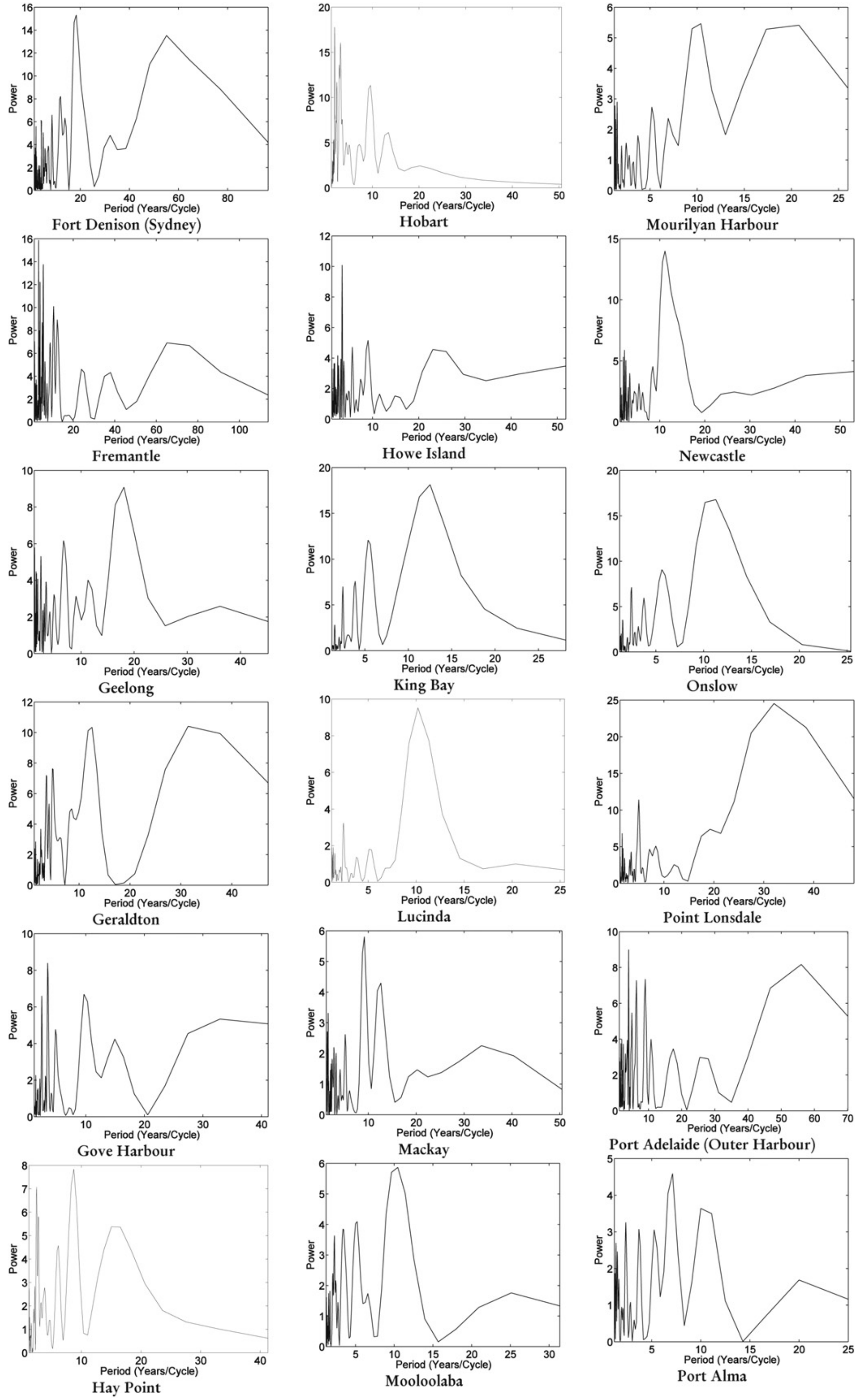
Broome (ABSLMP since Nov 1991)



Cape Ferguson (ABSLMP since Sep 1991)

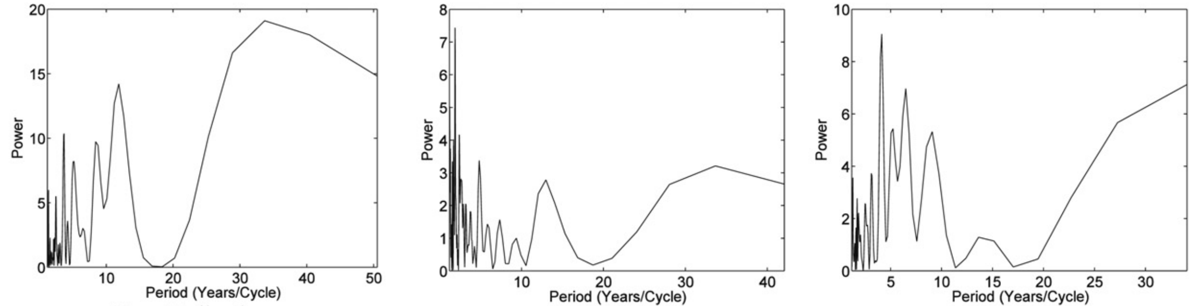


Esperance (ABSLMP since Mar 1992)

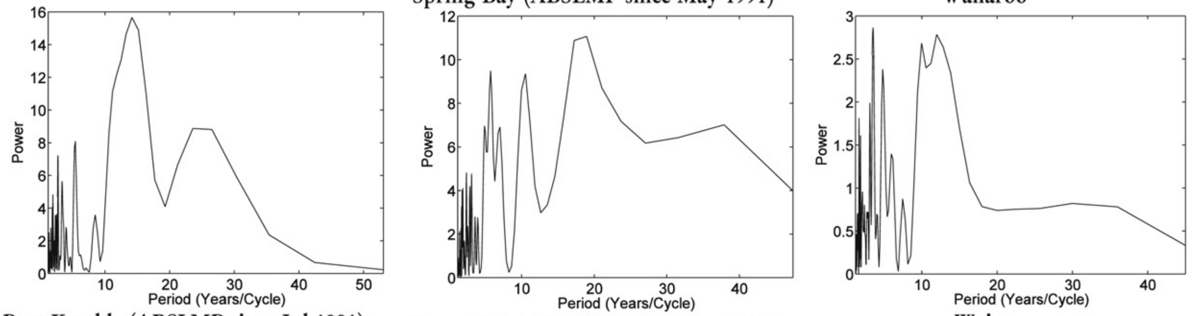


Fort Denison (Sydney)
Hobart
Mourilyan Harbour
Fremantle
Howe Island
Newcastle
Geelong
King Bay
Onslow
Geraldton
Lucinda
Point Lonsdale
Gove Harbour
Mackay
Port Adelaide (Outer Harbour)
Hay Point
Mooloolaba
Port Alma

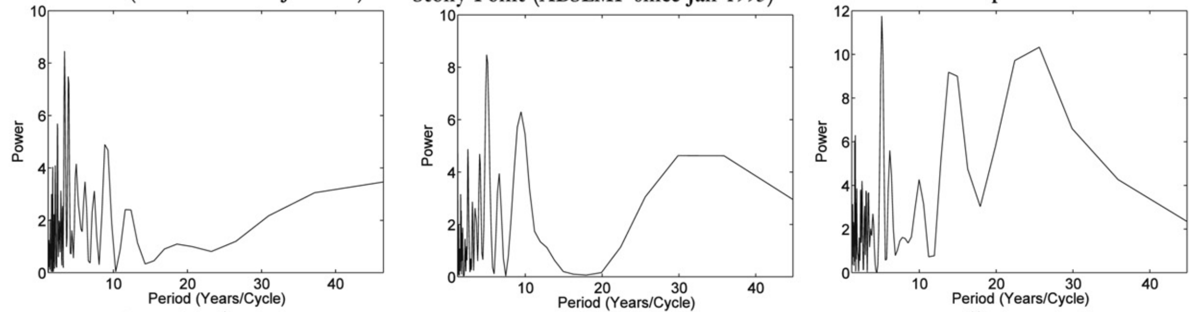
(*continued*).



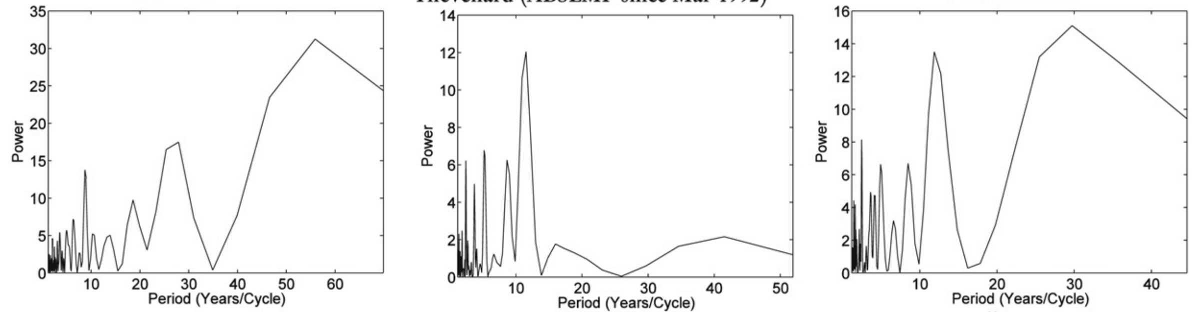
Port Hedland **Spring Bay (ABSLMP since May 1991)** **Wallaroo**



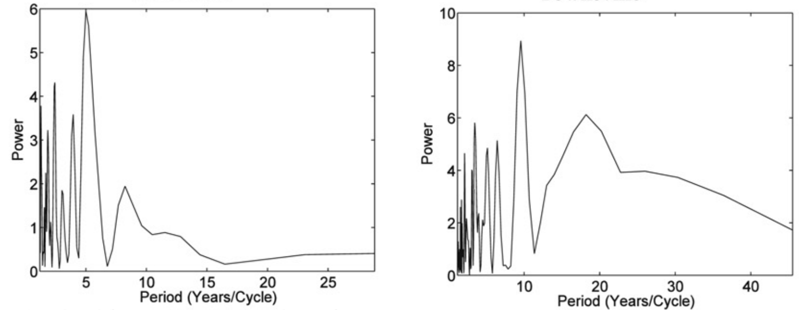
Port Kembla (ABSLMP since Jul 1991) **Stony Point (ABSLMP since Jan 1993)** **Weipa**



Port Lincoln **Thevenard (ABSLMP since Mar 1992)** **Williamstown**



Port Pirie **Townsville** **Wyndham**



Portland (ABSLMP since Jul 1991) **Victor Harbour**

(*continued*).

Appendix 2. Different Australian data sets and analyses

The papers has proposed a method to compute the longer term sea level rise cleared of the shorter term interannual and multi-decadal oscillations requiring records of sufficient length and quality to infer a reasonable trend. The result for Australia is a sea level rise about 1 mm/year (Table 2 of the manuscript) without major signs of a positive or a negative acceleration in the stations where the data may permit to assess the accelerating trend (Figs. 1–4 in the manuscript). The other claims made about the present sea level rise and acceleration by AGBOM, 2012b,c and AFGCC, 2011 have been made focussing on less than 20 years of data collected with a novel equipment in only 14 locations and disregarding what was measured in these same locations prior of the establishment of this later monitoring project and what is available in other locations. The latest sea level rise computed for the selected short term tide gauges is proposed in Table A.2.1. The average 5.375 mm/year of Table A.2.1 is very far from the about 1 mm/year Table 2 of the manuscript. It is mostly the result of being very selective in filtering the information. However, considering the data recorded in the same locations before and after the start of the Australian Baseline Sea Level Monitoring Project, it is very clear the abrupt change of slope of the sea level rise curve exactly at the time the novel measurement were introduced. Fig. A.2.1 proposes the data for Darwin, where all the data collected before May 1990 follow a smooth linear trend of slope 0.49 mm/year, and the data collected after May 1990 follow a much sharper curve of slope 8.19 mm/year. Worth of note, the most part of the sea level rise of the period May 1990 to Dec 2010 is produced before Dec 2000, and the sea level is more oscillating afterwards.

Table A.2.1
Relative sea level trend estimates for the tide gauges of the Australian Baseline Sea Level Monitoring Project (from AGBOM (2012b)).

Location	Installation date	Trend (mm/y)	Change in trend from June 2010 (mm/year)
Cocos Islands	Sep 1992	8.1	−0.6
Groote Eylandt	Sep 1993	9.0	1.9
Darwin	May 1990	8.6	1.4
Broome	Nov 1991	9.1	1.3
Hillarys	Nov 1991	9.1	1.5
Esperance	Mar 1992	6.0	0.7
Thevenard	Mar 1992	4.5	0.3
Port Stanvac*	Jun 1992	4.7	−0.3
Portland	Jul 1991	3.2	0.2
Lorne	Jan 1993	2.7	1.4
Stony Point	Jan 1993	2.6	1.3
Burnie	Sep 1992	3.1	0.2
Spring Bay	May 1991	3.5	0.1
Port Kembla	Jul 1991	3.2	0.2
Rosslyn Bay	Jun 1992	3.8	1.5
Cape Ferguson	Sep 1991	4.8	1.4

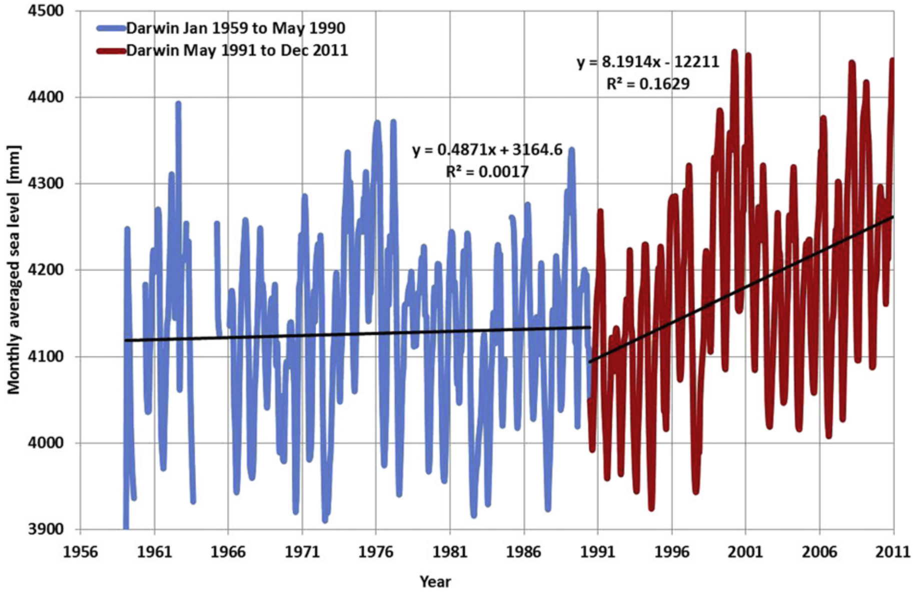


Fig. A.2. (1) Monthly averaged sea levels recorded in Darwin before and after the start of the Australian Baseline Sea Level Monitoring Project (data from AGBOM (2012a)).

Appendix 3. Different Pacific data sets and analyses

The paper has proposed a new analysis to compute the longer term sea level rise and to evaluate the present acceleration. This method requires tide gauge results of sufficient quality and length to produce accurate results. It is shown in this appendix how the proposed approach returns different understanding of the sea level accelerating trends for the specific of the Pacific Ocean as compared to the analysis by Becker et al. (2012). By definition, velocity is the first derivative of the position vs. time, and acceleration is the first derivative of the velocity vs. time or the second derivative of the position vs. time. If this concept is applied to a time series characterised by periodic oscillations, then this definition of first and second order derivatives vs. time does not help too much because if the time series is updated every hour, then every hour there is a very different value of the acceleration and the velocity to consider. It is suggested in this paper to evaluate the "velocity" (sea level rise) by linear fitting of more than 60–70 years of continuously recorded data up to a certain point, and it is then proposed to evaluate the "acceleration" as the difference in between the velocities evaluated at different times divided by the delta time in between the two updates. The "extension" and "reconstruction" of a Pacific subset of tide gauges of poor quality and length and the analysis of the reconstructed records by using different short time windows done in Becker et al. (2012) produces the results of the Table A.3.1 below. The acceleration is assessed by comparing the reconstructed sea level rise (RESL) 1993–2009 and 1950–2009. The conclusion of Becker et al. (2012) is that the Pacific Seas are positively accelerating. The Pacific has many other tide gauges, many of them of good quality and length, as for example those of Australia, New Zealand, Japan, The North Pacific Coast of the United States and Canada, The Hawaii islands or the US atolls of the Pacific.

Fig. A.3.1 presents the sea level data for the long term Pacific tide gauges of Sydney, NSW, Honolulu, San Francisco, San Diego, and Seattle, WA. Left hand column: Monthly average sea levels (black), linear trend (blue line). Centre column: departures of monthly average sea level from the linear trend. Right hand column: computed rate of SLR with 20, 30 and 60 years of data and all the data. The effect of the multi-decadal oscillations is clear. Less than 60–70 years of data do not permit the inference of a reasonably accurate trend. No detectable sign of positive acceleration is evidenced in the records. The proposed analysis does not support any acceleration.

Fig. A.3.2 presents the monthly average sea levels and linear trend for the other Pacific tide gauges covering more than 70 years with good quality and completeness, and without any major disturbing event. Similarly, there is no detectable sign of positive acceleration also in these records.

Fig. A.3.3 presents the monthly average sea levels and their linear trend in the Hawaii, Johnson and Midway atolls and Wake Island all not included in Table A.3.1. The oscillations about this trend are regular and no sign of any departure is evidenced in the last 20 years also in these records.

Fig. A.3.4 finally presents the monthly average sea levels and their linear trend in Chuuk, Caroline Is.; Pago Pago, American Samoa; Kwajalein, Marshall Is.; Guam, Marianas Is.; Majuro, Marshall Is. and Rikitea, France that are all included in Table A.3.1. Guam had a major event affecting the quality of the record and the data should not be used to infer any trend. The sea level rises for Guam in Table A.3.1 are however not supported by the recorded data. Pago Pago had another major event affecting the quality of the record in 2009. The record should not be used to infer any further trend, but the computed sea level rise 1950 to 2009 of 2.07 mm/year is reliable. Table A.3.1 proposes values of sea level rises of 2.5, 2.5 and 2.5 mm/year. For Chuck, the measured data available up to 1995 suggest a sea level rise of 0.8 mm/year. Table A.3.1 proposes values of sea level rises of 0.6, 0.1 and 1.1 mm/year. Kwajalein is the only record showing a departure from the usual trend about 2005 that probably need further investigation. The computed sea level rise from the picture is 1.43 mm/year. Table A.3.1 proposes values of sea level rises of 2.2, 1.2 and 1.2 mm/year. For Majuro, the recording from two different tide gauges is consistent. The long term sea level rise is 3.11 mm/year. Table A.3.1 proposes values of sea level rises of 3.7, 1.8 and 1.4 mm/year. Finally, for Rikitea, the record up to 2003 provides a sea level rise of 1.72 mm/year. Table A.3.1 proposes values of sea level rises of 2.1, 2.5 and 2.5 mm/year. The proposed method based on the high quality data set and the use of a procedure that accounts for the decadal and multidecadal oscillations suggests that the Pacific seas are oscillating and not positively accelerating at the present point. The sea level rises are shown to be about constant over the last 2 decades, and the sea level accelerations are therefore assessed to be zero. Figs. A.3.1–A.3.4 all present what is actually measured by tide gauges. The method of Becker et al. (2012) produces records of 60 years in stations with scattered measurements of poor quality and length by using a method for extension and reconstruction that has no validation vs. the true measurements of the high quality data set. Furthermore, the method of Becker et al. (2012) assesses the presence of an acceleration comparing sea levels computed with different, short time windows, in particular of only 16 years for what concerns the present sea level rise that is below two important multidecadal periodicities.

Table A.3.1
Sea level rises in 27 Pacific locations computed by considering incomplete data sets completed by extension and reconstruction for the period 1950–2009 (from Becker et al. (2012)).

Station	Start	End (extended by altimetry)		Span (yr)	% of gap	Trend (mm/y)	RESL (tide gauge time span)	RESL (1950–2009)
							Trend (mm/y)	Trend (mm/y)
Saipan	1979	(2004)	2009	31	16 (24)	3.1	3.6	1.5
Guam	1950		2009	60	6 (14)	1.9	1.4	1.4
Yap	1970	(2005)	2009	40	8 (28)	1.3	1.3	0.7
Malakal	1970		2009	40	5(5)	2	−0.4	−0.1
Chuuk Is.	1950		1995	46	11 (23)	0.6	0.1	1.1
Pohnpei	1974	(2004)	2009	36	0 (0)	3.0	1.6	1.4
Kwajalein	1950		2009	60	1 (2)	2.2	1.2	1.2
Enewetok	1951		1972	22	0 (0)	0.5	−1.0	1.4
Majuro	1969	(2001)	2009	41	8 (16)	3.7	1.8	1.4
Lombrum	1995		2009	15	6 (10)	5.9	5.4	1.4
Nauru	1974		1994	21	7 (3)	−0.1	1.7	2.3
Tarawa	1988	(1997)	2009	22	24 (7)	3.4	1.7	2.2
Kapingamarangi	1979	(2008)	2009	31	7 (7)	3.1	2.5	1.9
Rabaul	1966	(1997)	2009	44	17 (45)	1.5	1.8	1.7
Honiara	1974		2009	36	2 (4)	2.1	3.4	3.2
Funafuti	1978	(2001)	2009	32	4 (3)	4.4	4.1	4.7
Penrhyn	1978		2009	32	5 (7)	2.5	1.1	3.5
Pago Pago	1950		2009	60	7 (24)	2.4	2.5	2.5
Kanton	1950	(2007)	2009	60	17 (31)	0.9	2.1	2.1
Fanning	1973		1987	15	7 (3)	1.4	0.5	1.5
Christmas Is.	1974	(2003)	2009	36	5 (5)	1.1	1.0	1.8
Papeete	1976		2009	34	3 (7)	2.7	2.8	2.9
Suva	1990		2009	20	7 (6)	6.0	3.6	1.2
Nuku'alofa	1990		2009	20	1 (1)	5.8	5.3	1.2
Noumea	1967		2003	37	7 (12)	0.5	0.7	0.5
Rikitea	1970	(2003)	2009	40	10 (7)	2.1	2.5	2.5
Rarotonga	1977	(2001)	2009	33	3 (2)	3.7	3.4	1.8

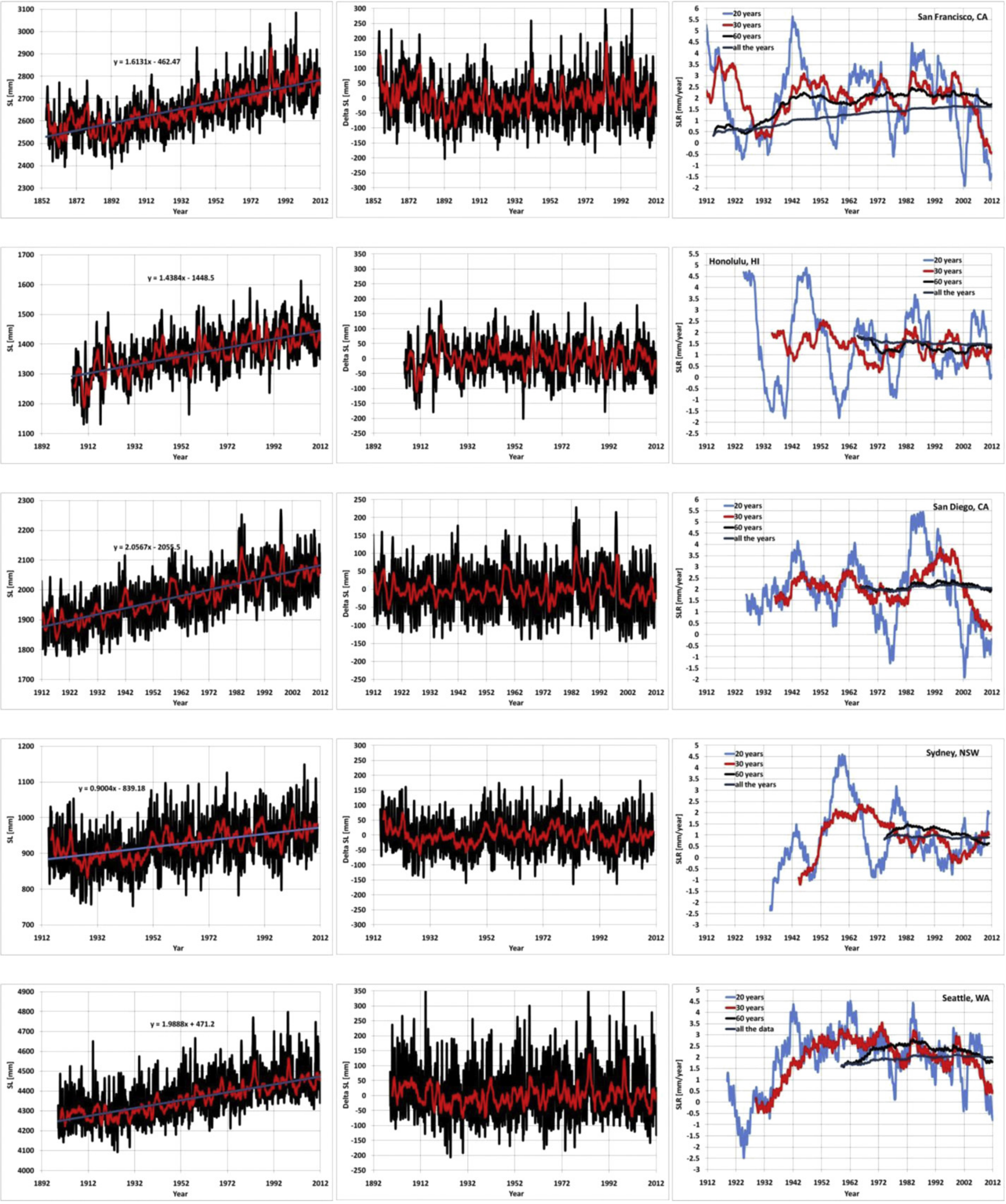


Fig. A3. (1). Sea level data for the long term Pacific tide gauges of Sydney, NSW, Honolulu, San Francisco, San Diego, and Seattle, WA (data from PSMSL (2012)). (2). Monthly average sea levels and linear trend for the other Pacific tide gauges covering more than 70 years with good quality and completeness, and without any major disturbing event (from NOAA (2012a)). (3). Monthly average sea levels and their linear trend in the Hawaii, Johnson and Midway atolls and Wake Island all not included in Table A.3.1 (from NOAA (2012a)). (4) Monthly average sea levels and their linear trend in Chuuk, Caroline Is.; Pago Pago, American Samoa; Kwajalein, Marshall Is.; Guam, Marianas Is.; Majuro, Marshall Is. and Rikitea, France that are included in Table A.3.1 (from NOAA (2012a)).

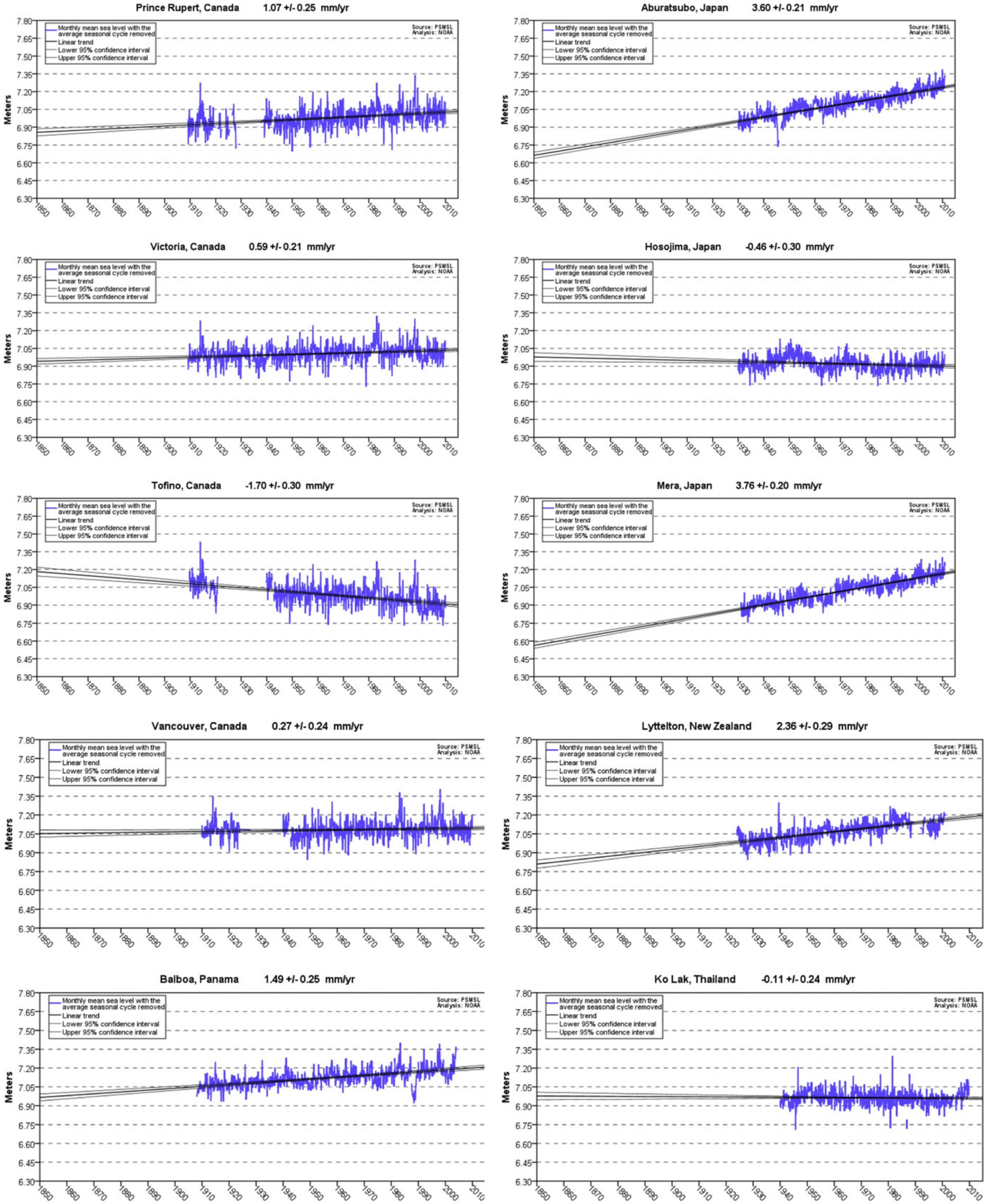


Fig. A3. (*continued*).

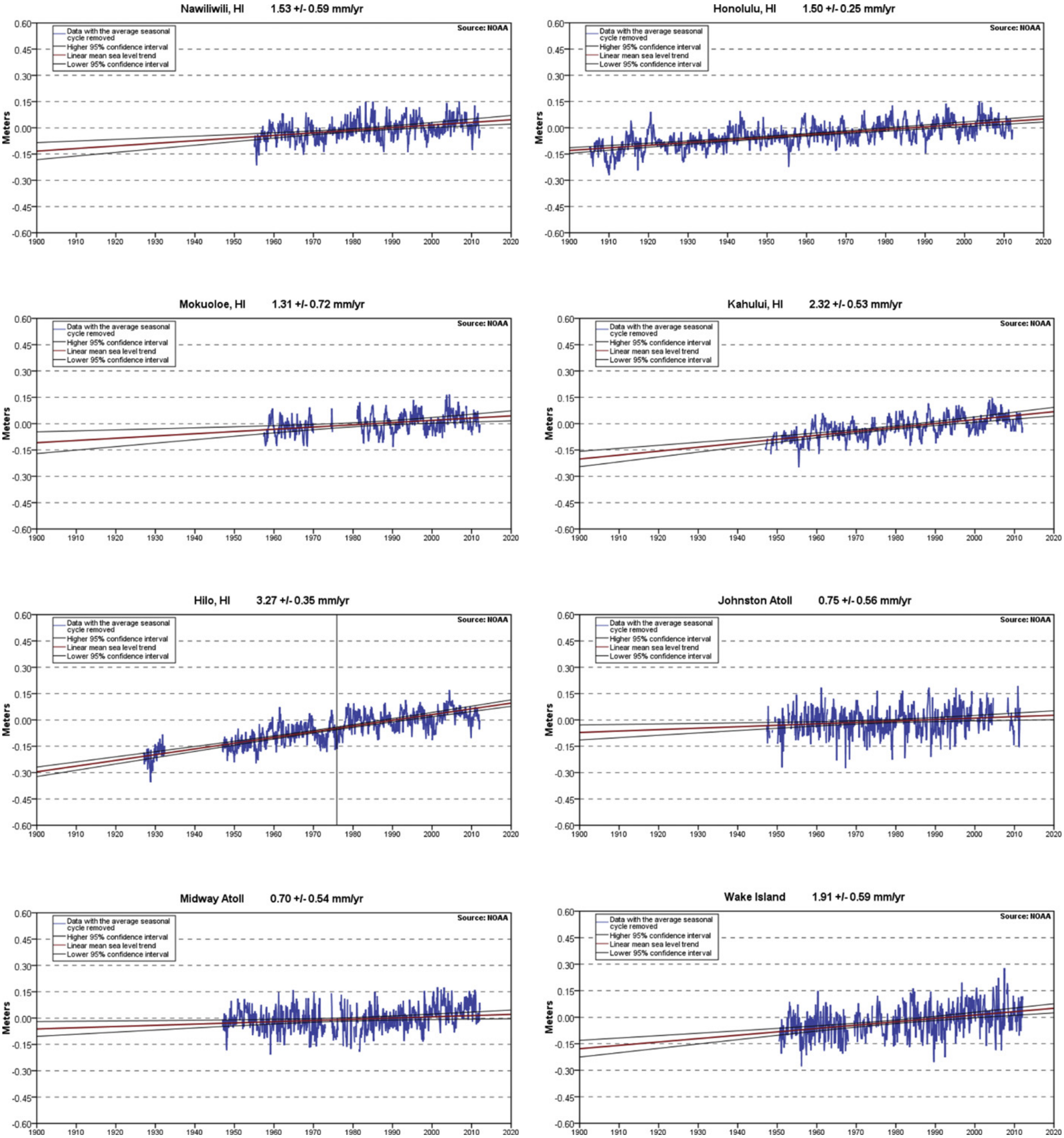
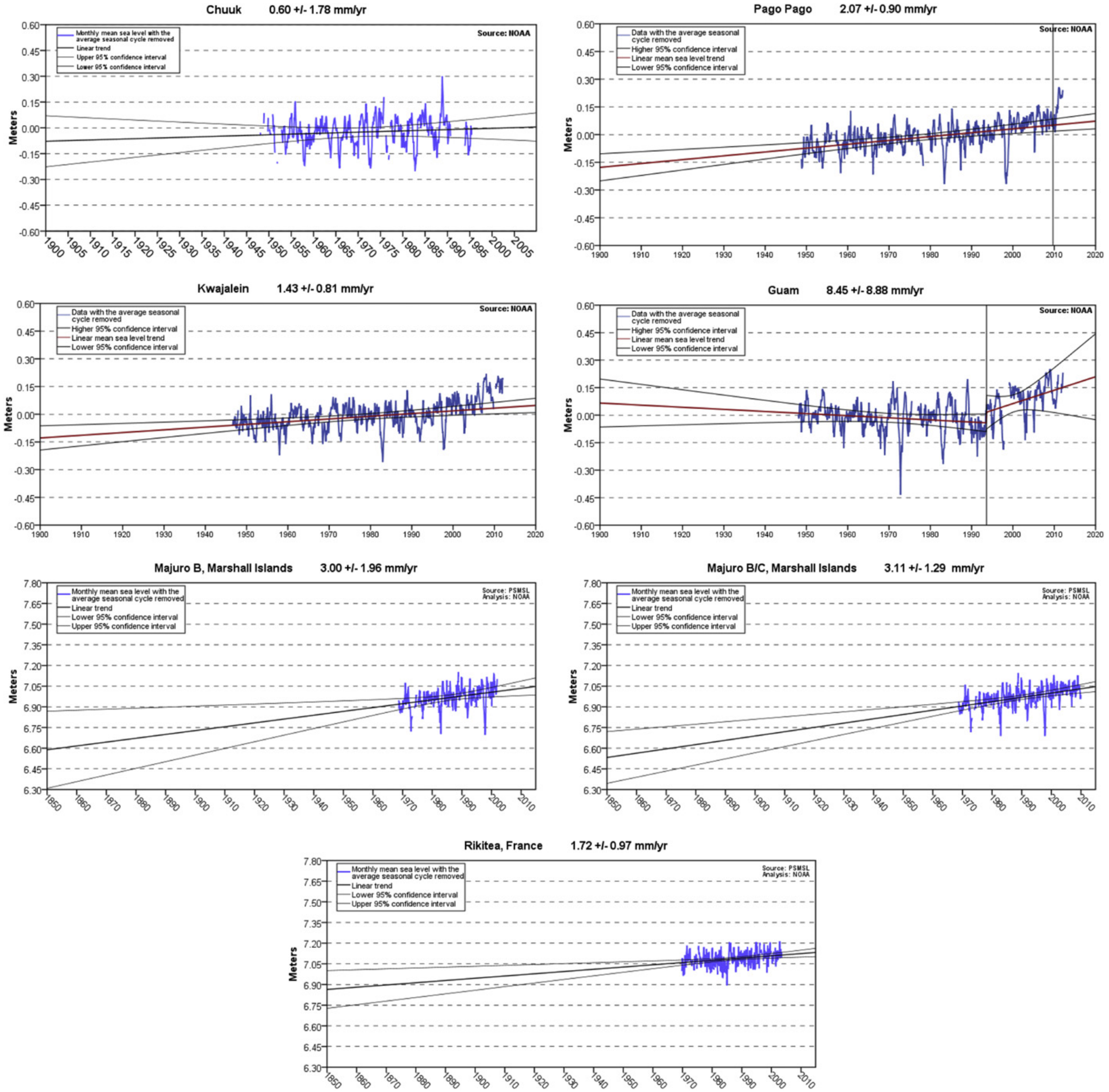


Fig. A3. (*continued*).


Chuuk 0.60 +/- 1.78 mm/yr

Pago Pago 2.07 +/- 0.90 mm/yr

Kwajalein 1.43 +/- 0.81 mm/yr

Guam 8.45 +/- 8.88 mm/yr

Majuro B, Marshall Islands 3.00 +/- 1.96 mm/yr

Majuro B/C, Marshall Islands 3.11 +/- 1.29 mm/yr

Rikitea, France 1.72 +/- 0.97 mm/yr

Fig. A3. (*continued*).

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