



Natural oscillations and trends in long-term tide gauge records from the Pacific

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Abstract. Recognition of climate patterns is needed to characterise and understand the various climate mechanisms that culminate in the behaviour of the atmosphere or the ocean. The analysis of the periodic patterns in the oscillating sea levels is an important step in determining the presence or absence of non-periodic accelerating behaviours due to global warming or other effects. This is true for periodic patterns with a multi-decadal scale. Fast periodic (sub-decadal) patterns would not matter much if one is looking at long range accelerations.

The analysis of high quality tide gauge records of the Pacific spanning more than 100 yr permits to evidence the multi-decadal oscillations of sea levels and their influence on the sea level rate of rise that may be computed by a linear fitting with different time windows. Without at least 65–70 yr of recorded data, the computed sea level rate of rise differs considerably from the actual long-term sea level rate of rise. These high quality long-term tide gauges show a non-accelerating oscillating behaviour with different periodicities in different locations. This result is consistent with a picture of locally and globally oscillating sea levels without any major sign of sharp positive accelerations at the present time.

1 Introduction

While nobody doubts the fact we humans are responsible for dramatic changes to our environment, it is still controversial which effect the traded anthropogenic carbon dioxide emission actually have on the climate in general and on rising temperatures and sea levels, in particular. For what concerns the sea levels, it is claimed (IPCC, 2012) that significant changes representing an integration of many aspects of climate change are presently occurring over a broad range of temporal and spatial scales, with primary contributors to global averaged sea level change the expansion/contraction of the ocean as it warms/cools and the transfer of water to/from the ocean/land particularly from glaciers and ice sheets.

The claim sea levels are accelerating are inferred from arbitrarily selecting the subset of measured data to be analysed (for example the less than 2 decades long tide gauges of the Pacific in AGBOM, 2012a or the less than 2 decades long tide gauges of Australia in AGBOM, 2012b), arbitrarily re-defining the subset of data to be analysed (for example ex-

tending and reconstructing the poor quality incomplete and short records of the Pacific in Becker et al., 2012), arbitrarily focusing the analysis on the small windows that are instrumental to the claim (for example, comparing the present 30 yr sea level rises of tide gauges along the North Atlantic coast of the US with the 1980 values, but not with the 1950 values in Sallenger Jr. et al., 2012) or by simply arguing that modelling the sea level as a function of the predicted temperature is superior to the standard approach of analysing the measured sea-level rise as a function of time (for example, Rahmstorf and Vermeer, 2011).

The paper is a contribution towards a better understanding of what is actually the rate of rise and the acceleration in the naturally oscillating sea level records, which are the requirements of the data to be analysed and which is the procedure to infer the pattern. The paper analyses the 10 century long sea level rate of rise records available for the Pacific Ocean and argues that these records present strong multi-decadal oscillating patterns. Even if disregarded by the most part of the present literature on sea levels that mostly ignores the importance of natural oscillations in geophysical climatic

systems, this pattern is not surprising because of the well-known multi-decadal ocean and temperature oscillations that present a major quasi 60-yr cycle and other shorter cycles.

It is found that only using records longer than 60–70 yr it is possible to bypass these natural multi-decadal oscillations and to determine how much and whether the sea level rate of rise presents a background long-range acceleration. In fact, if periods shorter than 60 yr are analysed (e.g., 30 yr), the severe risk is to mistake the bending of a natural multi-decadal oscillation as a long-range acceleration. This could yield a seriously erroneous forecast about future sea level rate of rise trending. Once records longer than 60–70 are used, no significant positive acceleration emerges in these records.

2 The long-term tide gauges of the Pacific

Recognition of climate patterns is needed to characterise and understand the various climate mechanisms that culminate in the behaviour of the atmosphere or the ocean. Climate indices based on several climate patterns known as modes of variability represents the status and timing of the climate factors and combine many details into a global description. If the climate indices are known to oscillate with different periodicities, the sea levels should also oscillate periodically. The analysis of the periodic patterns in the oscillating sea levels is an important step in determining the presence or absence of non-periodic accelerating behaviours due to global warming or other effects.

The Pacific Ocean is the largest of the Earth's oceanic divisions spanning from the Arctic in the north to Antarctica in the south, Asia and Australia in the west and the Americas in the east. At 165.25 million square kilometres the Pacific is the largest division of the World Ocean covering about 46 % of the Earth's water surface and about one-third of the Earth's total surface area. Understanding the sea level oscillations in the Pacific is of paramount importance to understand the global mean sea level evolution.

There are many multi-decadal periodicities of possible influence on the sea levels in the Pacific (NOAA, 2012). The Pacific Decadal Oscillation (PDO), the El Niño-Southern Oscillation (ENSO), the inter-decadal Pacific oscillation (IPO or ID), the quasi-decadal oscillation (QDO), the Southern Oscillation Index (SOI), the Pacific-North America (PNA) pattern, the Aleutian Low Pressure Index (ALPI) are only a few of the known indices that highlight the existence of possible natural oscillations in the climate system. Additional less-known indices with a minor impact on the global climate as the Victoria Pattern or the North Pacific Gyre Oscillation (NPGO) could also have effects on the sea levels in selected areas of the Pacific. Subtropical-gyre activity and the western-boundary dynamics may also be important, as both regional distribution of upper-ocean-heat content and geostrophic influences would impact sea-surface height. The matter is complex to attribute to any one oscil-

latory pattern centred in the region and interaction among oscillatory patterns may result in unexpected manifestations. These indices have influence in some areas of this large ocean while their influence in other areas is minimal. The influence of the multi-decadal oscillations on the sea levels and other climate parameters is discussed in Chambers et al. (2012); Jevrejava et al. (2008); Parker (2013a, b); Mazzarella et al. (2013); Scafetta (2012a, b, c); Mazzarella and Scafetta (2012). Scafetta (2012a) focuses mostly on solar physics. His paper does not explicitly discuss climate oscillations, but proposes a possible physical cause for the solar oscillations that may drive climate oscillations. More direct references related to the present paper explicitly addressing the climatic oscillations are Scafetta (2010) and (2012d). The above papers also discuss a PDO index since 1600, an AMO index since 1600 and the Indian summer monsoon index since 1830; these records present a major quasi 60-yr oscillation for centuries. A quasi 60 yr oscillation in the temperature is extensively discussed. Quasi-periodic fluctuations of sea levels with a period of about 60 yr are explicitly claimed by Chambers et al. (2012) and Jevrejava et al. (2008).

The analysis of the tide gauge records extending more than 100 yr determines the criteria to follow for a proper estimation of the sea level rate of rise trends deperated of the multi-decadal oscillations. The tide gauge records for the Pacific locations of interest are obtained from the Permanent Service for Mean Sea Level (PSMSL, 2012). PSMSL is the global data bank for long-term sea level change information from tide gauges and bottom pressure recorders.

3 The tide gauges analysed

The tide gauges analysed included all the 10 tide gauges of the Pacific with more than 100 yr of recording:

- Sydney NSW is the composite record of two tide gauges, SYDNEY, FORT DENISON of time span of data: 1886–1993 and completeness (%): 100 and SYDNEY, FORT DENISON 2 of time span of data: 1914–2010 and completeness (%): 98. The two records of Sydney are overlapping for almost 80 yr with only very minor differences and they can be used to produce a longer record of good quality.
- Auckland NZ (AUCKLAND II) has time span of data: 1903–2000 and completeness (%): 96.
- Honolulu HI (HONOLULU) has time span of data: 1905–2011 and completeness (%): 100.
- San Diego CA (SAN DIEGO QUARANTINE STATION) has time span of data: 1906–2011 and completeness (%): 98.
- San Francisco CA (SAN FRANCISCO) has time span of data: 1854–2011 and completeness (%): 100. This is

by far the best tide gauge of the area spanning without gaps more than 150 yr.

- Seattle WA (SEATTLE) has time span of data: 1899–2011 and completeness (%): 100.
- Victoria BC (VICTORIA) has time span of data: 1909–2011 and completeness (%): 99.

All these records are free of quality issues and their analysis may produce reliable results.

- Vancouver BC (VANCOUVER) has a quality issue, because many years of data are missed. The tide gauge has time span of data: 1910–2011 but completeness (%): 82.
- Tofino BC (TOFINO) also has a quality issue, because of the many years missed. The tide gauge has time span of data: 1909–2011 but completeness (%): 76.
- Similarly Prince Rupert BC (PRINCE RUPERT) has time span of data: 1909–2011 but completeness (%): 81.

These tide gauges have missed data but, however, more than 70–80 yr of recording.

4 Methods

The least squares method is used here to calculate a straight line that best fits the data within a time window and return the window's sea level rate of rise (SLR). The dependent y -values are the monthly average sea levels and the independent x -values are the time in years. The calculations for $SLR_{j,k}$ is based on the formula:

$$SLR_{j,k} = \frac{\sum_{i=j}^k (x_i - \bar{x}) \cdot (y_i - \bar{y})}{\sum_{i=j}^k (x_i - \bar{x})^2} \quad (1)$$

In this equation, \bar{x} and \bar{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 SLR estimation. At a certain time x_k , x_j is taken as $(x_k - 30)$ to compute the SLR_{30} , $(x_k - 60)$ when computing the SLR_{60} , or as x_1 when computing the SLR_A over all years of the record. This way, from a measured distribution x_i , y_i for $i = 1, N$, it is possible to estimate the time histories of SLR_{30} , SLR_{60} , and SLR_A .

Providing that more than 60–70 yr of continuously recorded data, without any quality issues, are available in a given location, the $SLR_{A,k}$ usually returns a reasonable estimation of the velocity of sea level change at the present time x_k and the acceleration may then be computed as

$$SLA_k = \frac{SLR_{A,k} - SLR_{A,k-1}}{x_k - x_{k-1}} \quad (2)$$

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

In the case with non-accelerating tide gauge records as the norm so far, $SLR_{1,N}$ returns the present sea level rate of rise, and the graphs of $SLR_{j,k}$ and SLA_k are only helpful in confirming the lack of any acceleration. In the case of accelerating tide gauge records as sometimes reconstructed, but so far never measured, this approach would confirm the presence of acceleration in the form of a constantly increasing $SLR_{j,k}$ and a constantly positive SLA_k rather than oscillating values about the longer term trend and the zero. At this stage, different mathematical methods would be needed to compute the present velocity and acceleration.

5 Discussion

Figure 1 presents the 12 months moving averages of sea levels, the periodogram of the monthly departures vs. the linear trend and the computed sea level rate of rises (SLR) with 20, 30, 60 yr or all the data for Sydney NSW; Honolulu HI; San Francisco, CA; San Diego, CA; Seattle, WA; Auckland, NZ; Victoria, BC; Vancouver, BC; Prince Rupert, BC and Tofino, BC. Sydney NSW; Honolulu HI; San Francisco, CA; San Diego, CA; Seattle, WA; Auckland, NZ and Victoria, BC are records almost fully complete without any problems. Unfortunately, no further data are available for Auckland, NZ since the year 2000, but the record is still very interesting. Vancouver, BC; Prince Rupert, BC and Tofino, BC have incomplete records and do need interpolation of data from neighbouring months and years to produce a continuous record. This procedure introduces uncertainty in assessing the present sea level trend, the time distributions of sea level rate of rises and the presence or absence of positive or negative accelerations at the present time. The SLR_A is computed only after 20 yr of recording. In general, the SLR_{20} and SLR_{30} have large oscillations while the SLR_{60} has these fluctuations significantly reduced. Over the last 60 yr, the SLR_{20} , SLR_{30} and SLR_{60} have been oscillating without a positive acceleration trend. The present values have been previously recorded and exceeded in all the stations. The 12 months moving averages oscillate about the linear trends. The SLR_A generally approaches the final long-term value after 65–70 yr as in Sydney and Honolulu, but sometimes it requires much more than the 65–70 yr as in San Francisco where the SLR_A is remarkably still changing significantly after 150 yr. In all the stations, the present SLR_{60} is not a maximum and the index is regularly oscillating over the last 6 decades.

In case of SLR_A the window length is increasing while for the other curves SLR_{20} , SLR_{30} and SLR_{60} the window length is constant. The last point of the SLR_A curve corresponds to the linear fit of the entire record.

The periodicities of the fluctuations show significant differences. Longer periodicities are logically evidenced where there are more years of recording as in Sydney and San Francisco. Some differences are clear also in records of about the same length as, for example, in Seattle and Honolulu. San

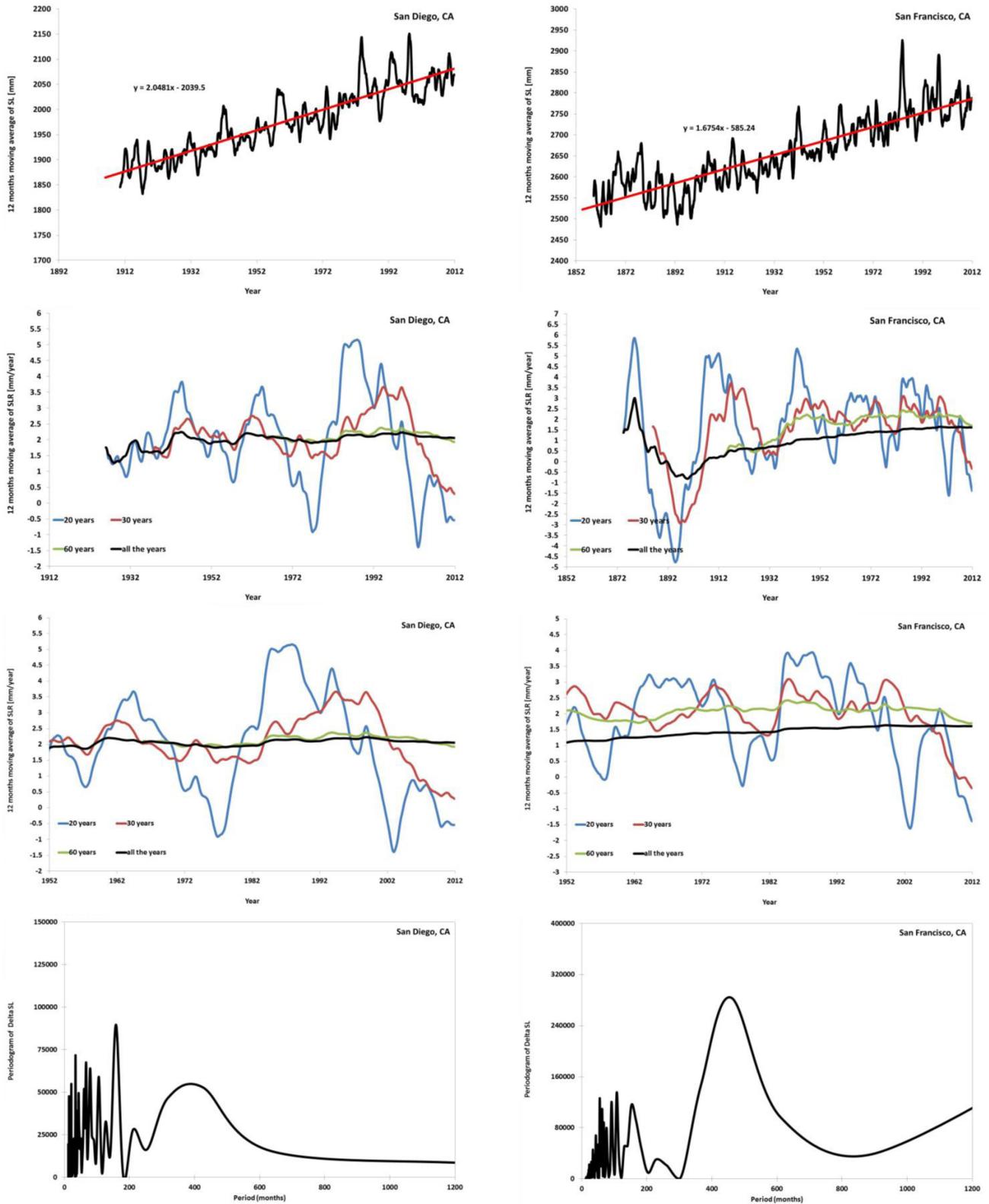


Figure 1a. 12 months moving averages of sea levels, periodogram of monthly departures vs. linear trend and sea level rises (SLR) with 20, 30, 60 yr or all the data for San Diego, CA and San Francisco, CA (data from PSMSL, 2012).

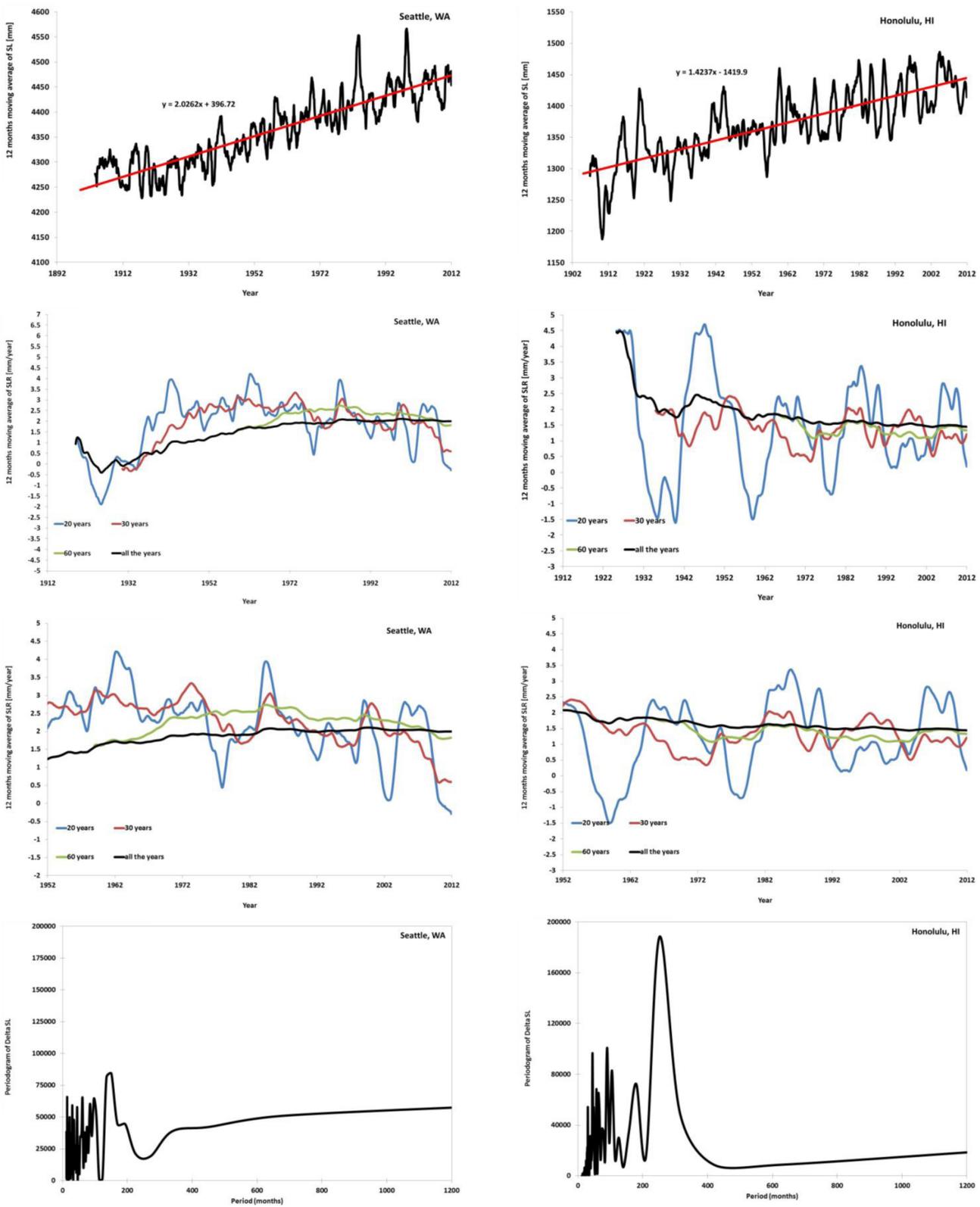


Figure 1b. 12 months moving averages of sea levels, periodogram of monthly departures vs. linear trend and sea level rises (SLR) with 20, 30, 60 yr or all the data for Seattle, WA and Honolulu, HI (data from PSM SL, 2012).

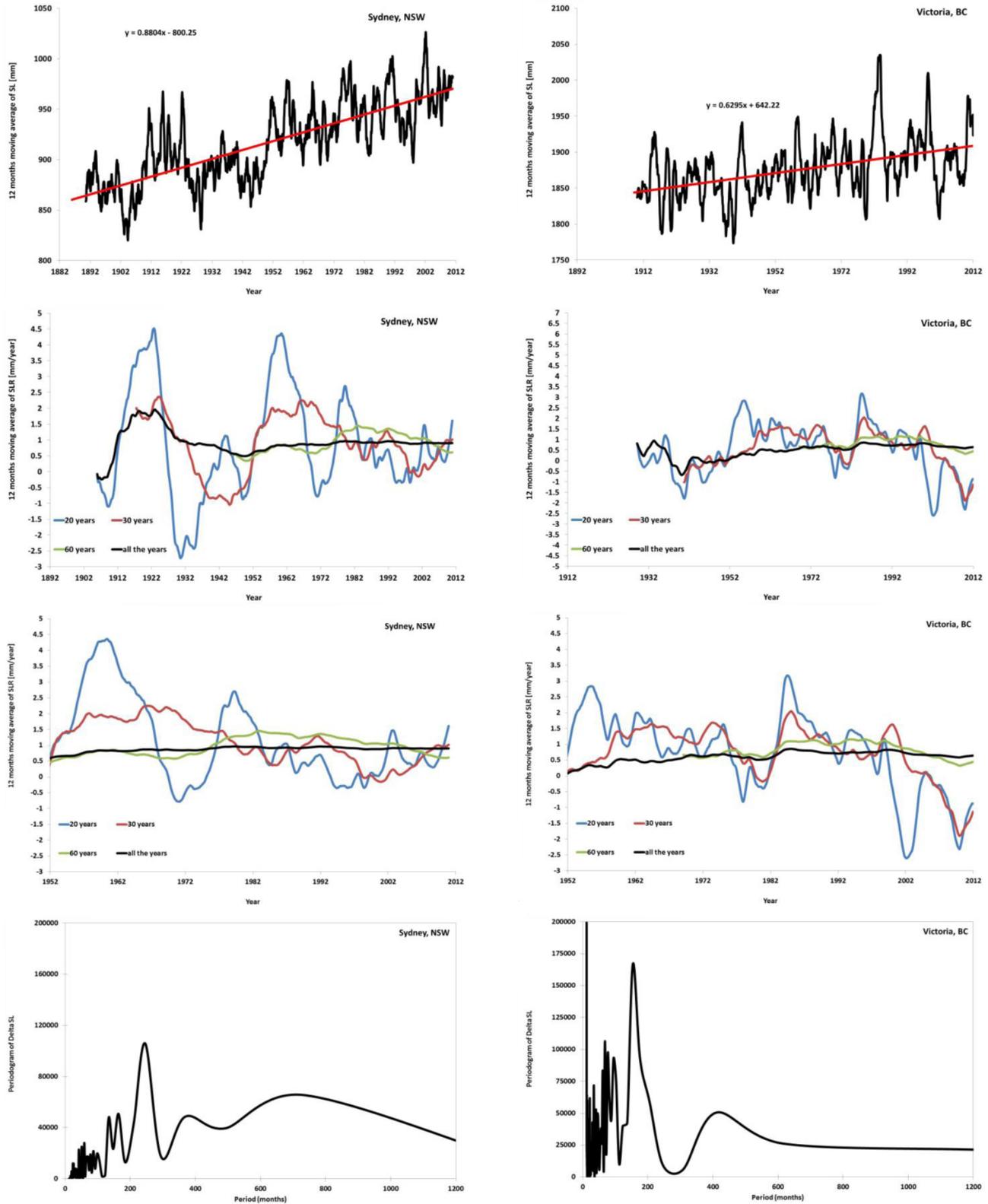


Figure 1c. 12 months moving averages of sea levels, periodogram of monthly departures vs. linear trend and sea level rises (SLR) with 20, 30, 60 yr or all the data for Sydney, NSW and Victoria, BC (data from PSMSL, 2012).

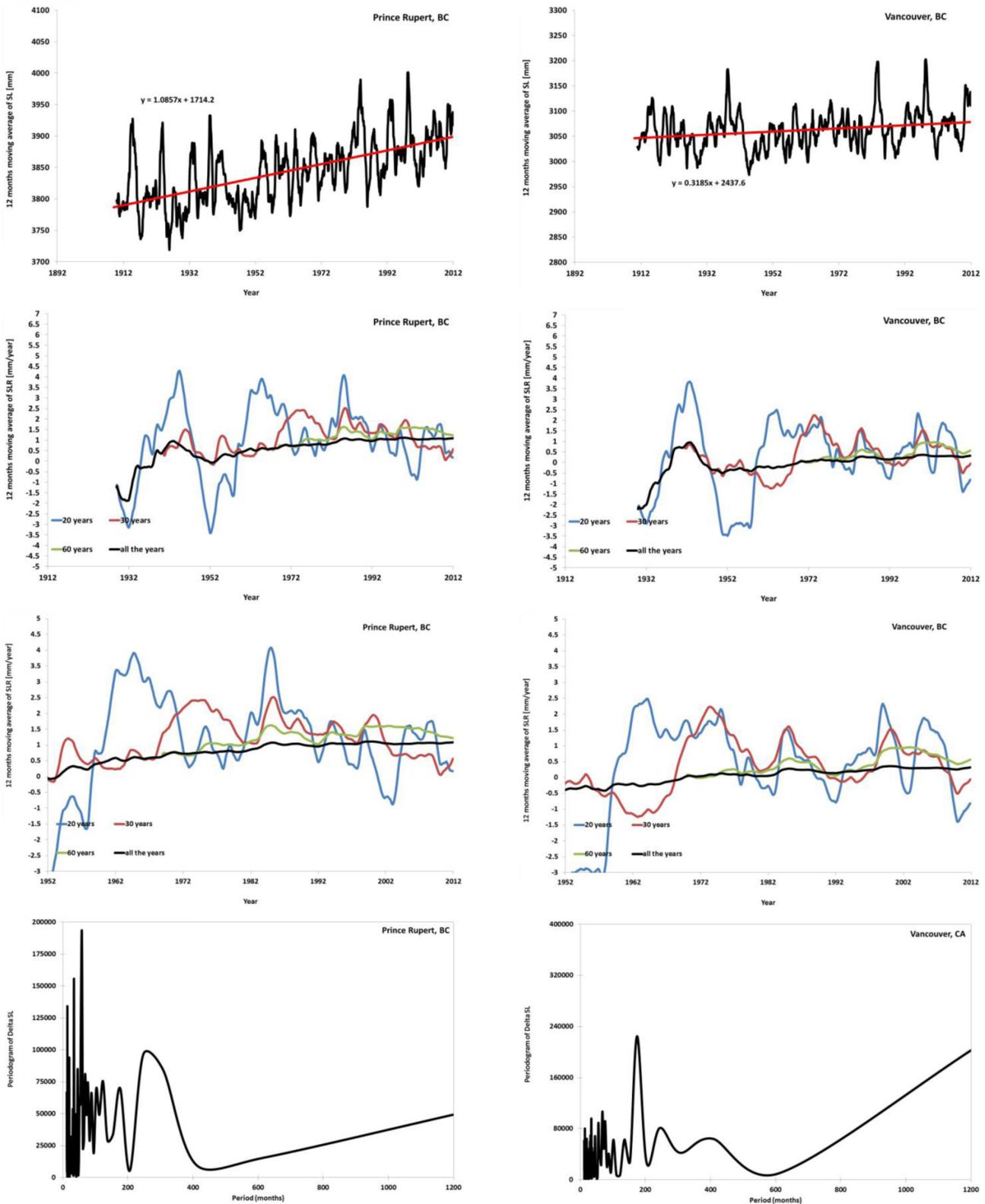


Figure 1d. 12 months moving averages of sea levels, periodogram of monthly departures vs. linear trend and sea level rises (SLR) with 20, 30, 60 yr or all the data for Prince Rupert, BC and Vancouver, BC (data from PSMSL, 2012).

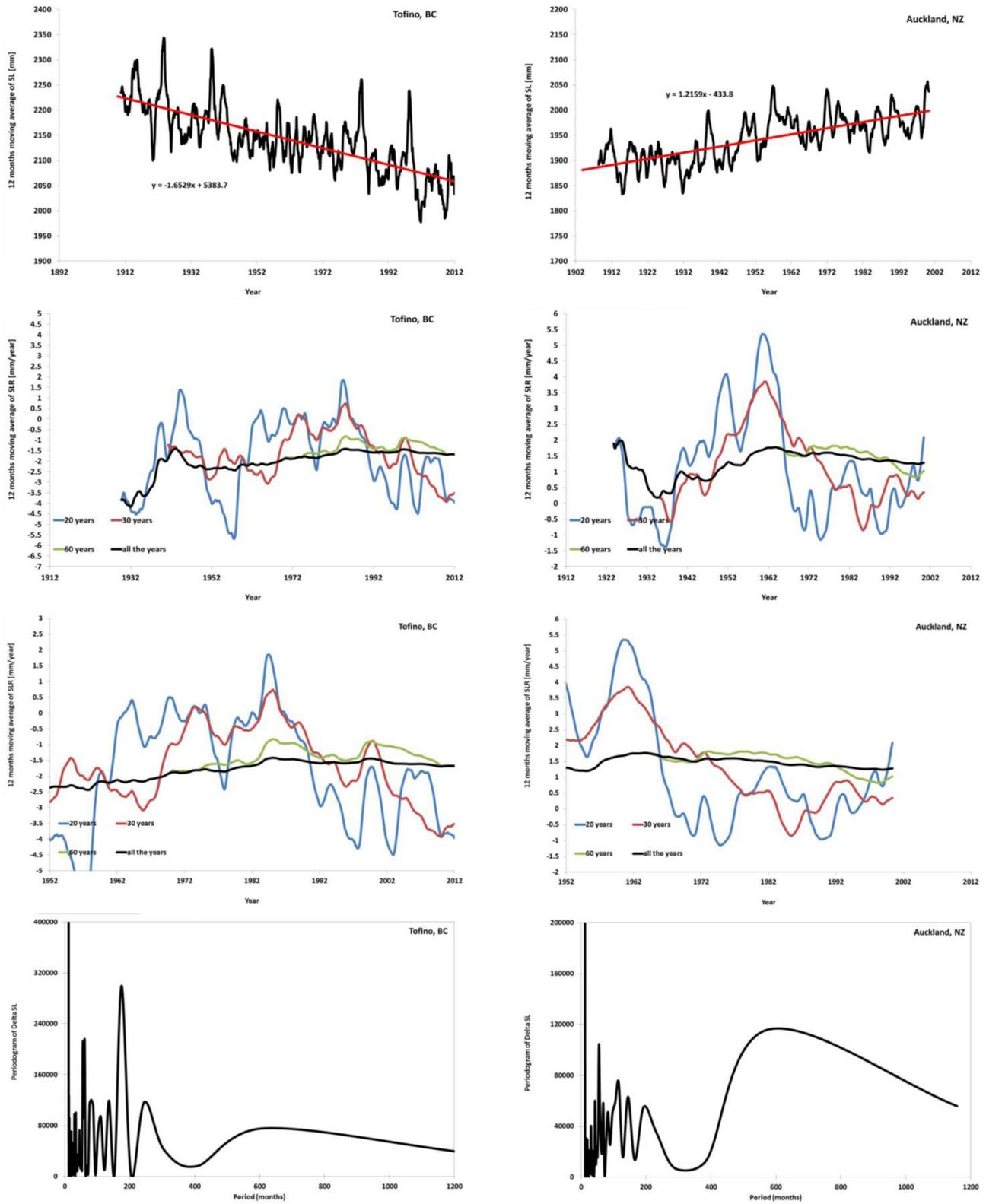


Figure 1e. 12 months moving averages of sea levels, periodogram of monthly departures vs. linear trend and sea level rises (SLR) with 20, 30, 60 yr or all the data for Tofino, BC and Auckland, NZ (data from PSMSL, 2012).

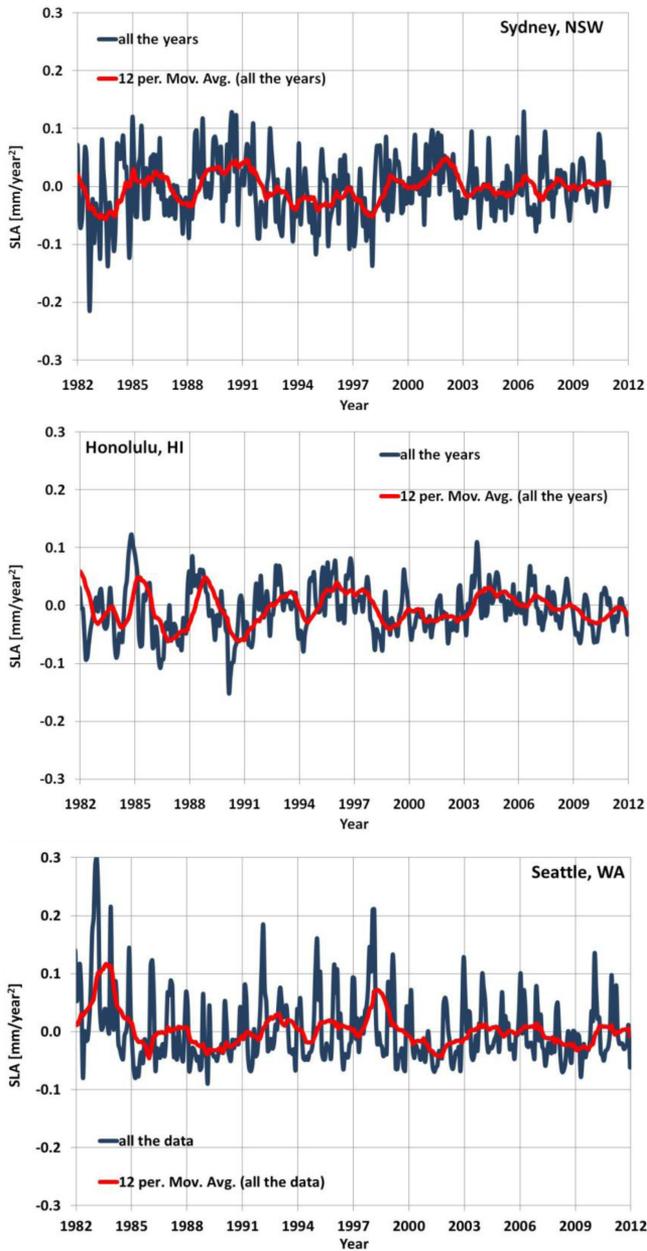


Figure 2. Sea level acceleration over the last 3 decades for the long-term Pacific tide gauges of Sydney, NSW, Honolulu, HI and Seattle, WA.

Diego, CA and San Francisco, CA have a multi-decadal periodicity of about 400 months and many oscillations of period below 200 months. Victoria, BC has a behaviour similar to San Diego, CA and San Francisco, CA. Seattle, WA has a not that different behaviour, but the about 400 months periodicity is not clearly evidenced. Honolulu, HI has a very clear multi-decadal oscillation of period about 240 months and lack of the about 400 months periodicity. Sydney, NSW has the same very clear multi-decadal oscillation of period about 240 months, but also oscillations of period about 400

Table 1. SLR_A averaged over different time windows (values in $mm\ yr^{-1}$).

	10 yr average	20 yr average	30 yr average
Sydney, NSW	0.905	0.912	0.918
Auckland, NZ	1.295	1.354	1.425
Honolulu, HI	1.472	1.489	1.518
San Diego, CA	2.082	2.133	2.125
San Francisco, CA	1.618	1.611	1.584
Seattle, WA	2.026	2.037	2.035
Tofino, BC	-1.633	-1.582	-1.555
Vancouver, BC	0.296	0.281	0.255
Victoria, BC	0.643	0.705	0.727
Prince Rupert, BC	1.058	1.058	1.040

Table 2. SLA averaged over different time windows (values in $mm\ yr^{-2}$).

	10 yr average	20 yr average	30 yr average
Sydney, NSW	0.004	-0.004	-0.003
Auckland, NZ	-0.007	-0.012	-0.007
Honolulu, HI	-0.002	-0.002	-0.007
San Diego, CA	-0.008	-0.003	0.003
San Francisco, CA	-0.001	0.004	0.006
Seattle, WA	-0.006	0.001	0.002
Tofino, BC	-0.012	-0.004	-0.001
Vancouver, BC	0.002	0.009	0.009
Victoria, BC	-0.007	-0.003	0.001
Prince Rupert, BC	0.004	0.007	0.007

and above 600 months. Auckland, NZ has similarly multi-decadal oscillations of period about 200 and 600 months. These results clearly show a complex oscillating pattern certainly deserving further studies.

The sea level rate of rise indexes (Eq. 1) are oscillating around an apparent average value which suggests the existence of natural oscillations. To determine the presence or absence of a present acceleration, a linear fit of the rate curve functions of Fig. 1 does not help too much because similarly to the fitting of the original sea level data with a second order polynomial this approach would return an average acceleration over the time of observation and not the present acceleration. As proposed in Fig. 2 for Sydney, NSW, Honolulu, HI and Seattle, WA, it is graph of the SLA (Eq. 2) that may show the presence or the absence of acceleration. If the SLA oscillates about zero over the last few decades, then the positive accelerating theory is wrong.

Tables 1 and 2 below present the sea level rate of rise SLR_A (Eq. 1) and the sea level acceleration (SLA Eq. 2) computed in the different locations considered. The SLR_A is in $mm/year$ and the SLA in $mm\ yr^{-2}$. Because of the naturally oscillating behaviour of the seas, if the data are updated

month by month, the SLR and the SLA then oscillates month by month. Averaged values over 10, 20 and 30 yr are considered. The computed accelerations are negligible in all the stations, with small positive and small negative values alternating depending on the window adopted. The differences in between the SLR_A and the magnitudes of the acceleration are well below the limit of accuracy of the measurement and are not discussed here.

It is worth mentioning that only the SLR_A and the SLA graphs in Figs. 1 and 2 and the averaged values of these parameters of Tables 1 and 2 permit to assess the presence of a positive acceleration at the present time. Houston and Dean (2011) and Watson (2011) both adopted a polynomial fitting of the monthly average mean sea levels to compute the average acceleration of sea levels over the length of the tide gauges as twice the second order coefficient. It has been argued by Donoghue and Parkinson (2011), Rahmstorf and Vermeer (2011) and many others that this average acceleration over the length of the tide gauge record does not tell us if the sea levels are presently accelerating or not. The subject is also covered by Parker et al. (2013) that agree with Donoghue and Parkinson (2011) and Rahmstorf and Vermeer (2011) there are better indicators of the presence or absence of present accelerating patterns. The procedure proposed here is certainly the best option provided so far in the literature to clarify if there is or not a present acceleration.

The 2nd order polynomial fitting of the monthly sea levels in all the long-term Pacific stations is presented in Appendix Fig. A1 as a reference. The average acceleration over the period of observation is twice the second order coefficients. Five of the ten stations have small positive average accelerations and five of the ten stations have small negative accelerations of magnitudes of the order of 0.01 mm yr^{-2} . Worth mentioning, especially the longer record of San Francisco seems to indicate a change of slope about the year 1900.

6 Conclusions

The extension of discontinued tide gauges up to present time and the reconstruction of tide gauges in the past are dangerous procedures that may produce unrealistic sea level trends. The interpolation of the missed data in a record is also risky for the prediction of sea level rate of rise trends. Still, the following conclusions seem justified.

- The strong variability in the periodicities of 20 and 30 yr implies that meaningful sea level trends cannot be deduced from such short segments. This is important because many future sea level scenario are, in fact, based on records confined to one or two decades (e.g., the official Australian analysis).
- The multi-decadal periodicities recorded in the Pacific tide gauges analysed imply that the search for meaningful long-term trends must, at least, cover a period of 60–70 yr. This may have far reaching consequences as the 12 selected global master-curves of tide gauge records chosen by IPCC do only cover periods of 40 yr or less (IPCC, 2012).
- None of the ten long-term tide gauge records analyses show any increase in sea level rise over the last two decades. This is in conflict with many papers claiming the occurrence of a significant recent acceleration in the sea level rate of rise (e.g., Church and White, 2011). It is consistent, however, with many other analyses indicating an absence of any signs of acceleration (e.g., Boretti and Watson, 2012; Boretti, 2012a, b, c, d, e; Holgate, 2007; Houston and Dean, 2011; Mörner, 2004, 2007, 2010a, b; Parker, 2012, 2013a, b, c; Unnikrishnan and Shankar, 2007; Watson, 2011; Wenzel and Schröter, 2010; Wunsch et al., 2007).
- The variations recorded in the ten tide gauges records differ in time and amplitude; i.e., they exhibit an oscillating pattern across the Pacific. This seems originate from an irregular redistribution of ocean water masses as proposed by Mörner (e.g., 1995, 1996). Further studies are certainly needed in order to reconstruct this oscillating pattern across the Pacific as well as the other oceans.

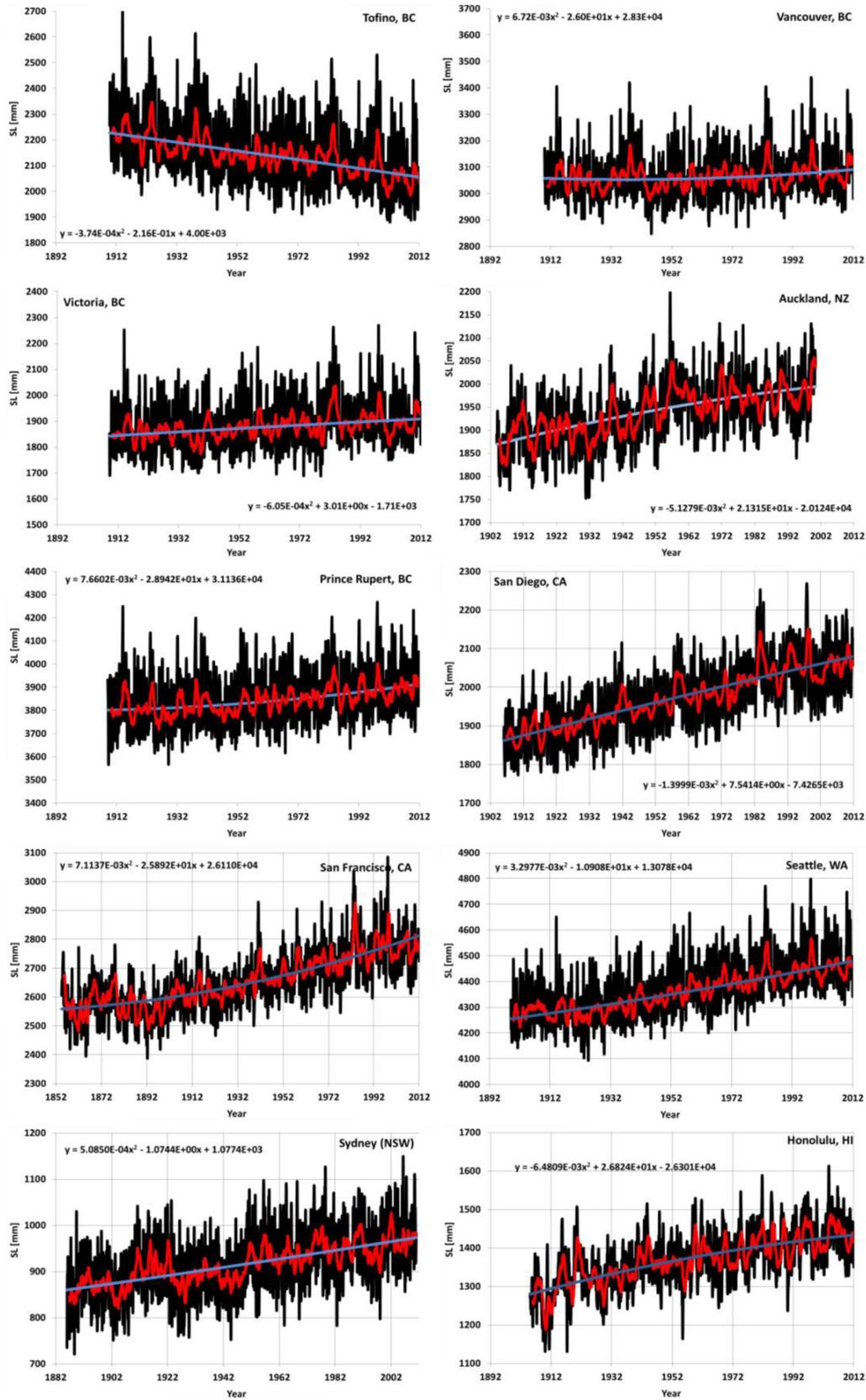


Figure A1. 2nd order polynomial fittings of the monthly sea levels in the long-term Pacific locations.

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