Relative sea-level rise and land subsidence in Oceania from tide gauge and satellite GPS

Abstract: The relative and absolute sea-level patterns in the five LTT tide gauge stations of Oceania, Fremantle, and Sydney in Australia, Auckland, and Dunedin in New Zealand, and Honolulu in the Hawaii Islands, United States of America, are analyzed first based on tide gauge and GPS time series. The average relative rate of rise is $+0.73 \text{ mm/yr.}$, the average acceleration is $+0.0 \text{ mm/yr}^2$, and the average absolute rate of rise is $+0.1 \text{ mm/yr}$. This result is consistent with the result for Japan and the West Coast of the Americas. All the LTT tide gauges of the Pacific consistently show a small sea-level rise, with a significant contribution by subsidence, and negligible acceleration. This result is well-matched by the land increase, rather than shrinking, of the Pacific atolls’ islands recently highlighted by other researchers. Two case studies for locations where there are no LTT tide gauges are then provided. In Tuvalu, over the short time window 1977 to present, the relative rate of rise is $+0.9 \text{ mm/yr}$, biased by low ESO water levels, and subsidence, but the absolute rate of rise is $+0.157 \text{ mm/yr}$. In Adelaide, the relative rate of rise of the sea level is less than $2.3 \text{ mm/yr}$ with an overwhelming contribution by subsidence of $2.1 \text{ mm/yr}$. The thermosteric effect is thus less than $0.2 \text{ mm/yr}$. The sea-level acceleration is also small negative in Adelaide, $−0.01936 \text{ mm/yr}^2$.

Keywords: tide gauges, GPS, sea level, subsidence, Oceania

1 Introduction

The sea levels are characterized by periodic oscillations, with different periodicities of hours, days, months [1], and decades [2] up to quasi-60 years. Along the coastline, these oscillations occur about a longer-term movement of rise or fall dictated by land and sea components. The land component is not limited to global glacial isostatic adjustment (GIA) [3, 4] or regional subsidence, for example for groundwater withdrawal [5, 6] or other reasons, as explained in [7]. The sea component is similarly not limited to the thermosteric effect [8] from the melting of ice on land and thermal expansion of ocean water as also explained in [7]. The relative sea level along the coast is well measured by tidal gauges, sometimes over periods of time often long enough to clear the longer-term trend of the sea levels periodic oscillations. Measurements of subsidence from satellite tracking of GPS domes nearby the tide gauges [9] permit to understand the sea component of the relative sea-level rise.

As relative sea-level trends oscillate with many periodicities, from hours to multi-decadal, up to quasi-60 years, only long-term-trend (LTT) tide gauges spanning more than 100 years without quality issues allow assessment of the rate of rise and the acceleration of the sea levels. The sea level oscillates with periodicities in the 60-year range, like other climate parameters [2, 10, 11]. Thus, more than 60 years of recording from the same tide gauge, without any major perturbation, are needed to compute a reliable rate of rise by linear fitting [12–14]. More than 100 years are otherwise needed to compute a reliable acceleration by parabolic fitting [15].

The measured monthly average mean sea levels (MSL) relative to the tide gauge instrument are given by the Permanent Service for Mean Seal Level (PSMSL, [16]). Different providers offer analyses of these data, (sealevel.info, [17]) and others.

The Global Positioning System (GPS) time series of antennas, originating from a constellation of satellites which is used for navigation and measurements of geodetic position, are given and analysed by different providers, such as Nevada Geodetic Lab (NGL, [18]), Jet Propulsion Laboratory (JPL, [19]), and Système d’Observation du Niveau des Eaux Littorales (SONEL, [20]). While the analysis of the sea level data is straightforward, the analysis of the GPS data is more troublesome, hence there is a need to use multiple providers, and compare the results of different analyses, to derive reliable values of the absolute vertical velocity of a
GPS antenna. The GPS analysis by NGL is described in [21]. The GPS analysis by JPL is described by [22].

In very few cases the GPS antenna is co-located with the tide gauge, and precise leveling is ensured between the tide gauge instrument and the GPS antenna. In other cases, the absolute vertical velocity of the tide gauge instrument may differ from the absolute vertical velocity of the GPS antenna.

It is fairly agreed that the correction of the relative rate of rise of the sea level by the absolute velocity of a GPS antenna near the tide gauge returns the absolute rate of rise of the sea level [9]. The GPS correction is more accurate than the correction by a global glacial isostatic adjustment (GIA) model such as [3, 4], that does not include any regional subidence, human-induced as well as natural, or crustal movements [23]. The GPS method is discussed in [13] and [24].

Aim of the present contribution is to use measurements of relative sea levels from tide gauges, and measurements of subidence from satellite tracking of GPS domes, to provide an up-to-date assessment of the relative and absolute sea-level rise, from actual observations, of Oceania, with cases study from Adelaide, South Australia, and Tuvalu.

2 Method

Two regressions are usually applied to the time series of the measured MSL to compute the relative sea-level rate of rise and acceleration. A linear regression:

\[ y(x) = A + v \cdot x \] (1)

returns the sea level rate of rise \( v \) as the slope. A quadratic regression:

\[ y(x) = A' + B' \cdot x + a \cdot x^2 \] (2)

returns the acceleration \( a \) as twice the second-order coefficient.

Linear regression is also applied to the time series of the absolute vertical position of a GPS antenna located near the tide gauge installations to compute the absolute velocity \( w \) as the slope:

\[ y'(x) = A + w \cdot x \] (3)

The absolute rate of rise of the sea level \( u \) is then computed [9] as their sum:

\[ u = v + w \] (4)

The analyses here proposed are from http://www.sealevel.info/, or originally developed in this manuscript by using MS Office Excel linear and 2nd order polynomial fittings of the raw data.

While the actual procedure used to compute trend and acceleration is described in http://www.sealevel.info/, it must be mentioned that the tide gauge signal from long term trend tide gauges does not need to be cleared of noise or seasonal terms to compute reliable trend and accelerations, as this only affects the confidence intervals or the \( R^2 \).

The pre-processing of http://www.sealevel.info/ is like the one adopted by NOAA [20]. If we apply MS Office Excel linear and 2nd order polynomial fittings to the raw data, we do not find any practical difference with the rate of rise and acceleration computed by http://www.sealevel.info/, that follows a slightly different procedure based on cleared data.

For a practical example, in the case of Brest, France, the slope in the analysis by http://www.sealevel.info/ is 0.997 mm/yr. vs. the 0.9984 mm/yr. of the simple linear fitting of the raw data, for a difference of 0.001 mm/yr. The acceleration in the analysis by http://www.sealevel.info/ is 0.01269 mm/yr2 vs. the 0.01264 mm/yr2 of the simple parabolic fitting of the raw data, for a difference of +0.00005 mm/yr2.

The only difference is the 95% confidence interval or the \( R^2 \) of the estimation, which, however, are parameters of minimal value, only supplying a measure of the statistical accuracy of the fitting. Both confidence interval and \( R^2 \) do not help with cases, unfortunately common, where the record is unreliable, as it is for example with segmented records, where records originating from different ride gauges, of different sea and land contributions, often also misaligned each other, and with gaps between them, are coupled together to form a single record. One example of a composite record is Aden [21].

If the goal of the assessment is to compute the sea level rise by 2100, by taking as the present (2018) sea level rate of rise and acceleration 0.9984 mm/yr. and 0.01264 mm/yr2, the constant acceleration sea level rise by 2100 is 124 mm. By taking as the present (2018) sea level rate of rise and acceleration 0.997 mm/yr. and 0.01269 mm/yr2, the constant acceleration sea level rise by 2100 is also 124 mm. These differences may be regarded as irrelevant.

For what concerns the absolute subsidence rates, we use here the results proposed by JPL. The results proposed by SONEL and NGL for the same domes are shown to give an idea of the uncertainty of the estimation, that, again, is not the statistical error of the fitting, either confidence interval or \( R^2 \), but depends on the length of the time series,
the reliability of the measurements, break-points, and re-alignments.

3 Long-term-trend tide stations of Oceania

There are five long-term-trend (LTT) tide stations with more than 90 years of data in Oceania, Fremantle, Sydney, Auckland, Dunedin, and Honolulu. However, there are many other tide gauges across the Pacific, along the east coast of Asia and the West coast of the Americas.

3.1 Pacific stations

Figure 1 presents the relative sea-level rise in the stations with enough data from 1900 to 2016 according to (PSMSL, www.psmsl.org). This image is modified after [16].

Across the Pacific, PSMSL only considers Sydney Fort Denison 2, in Australia, Honolulu, in the Hawaii, USA, Auckland 2, in New Zealand, Aburatsubo, Wajima and Hosojima in Japan, Ketchican, in AK, USA, Prince Rupert and Victoria, in Canada, Seattle, Astoria, San Francisco, Los Angeles, La Jolla, and San Diego, in the continental USA, AK excluded, and Balboa in Panama.

In the PSMSL RLR data set, Honolulu, Hawaii, US has data 1905 – 2018 and 100% completeness. The PSMSL trend is +1.89 mm/yr.
1. Sydney Fort Denison 2 has data 1914 – 2017 and 98% completeness. The PSMSL trend is +1.44 mm/yr.
2. Aburatsubo has data 1930 – 2017 and 98% completeness. The PSMSL trend is +1.04 mm/yr.
3. Wajima has data 1930 – 2017 and 98% completeness. The PSMSL trend is –0.03 mm/yr.
4. Hosojima has data 1930 – 2017 and 98% completeness. The PSMSL trend is –0.04 mm/yr.
5. Ketchican, US has data 1919 – 2018 and 99% completeness. The PSMSL trend is –0.33 mm/yr.
6. Prince Rupert, Canada has data 1909 – 2017 and 82% completeness. The PSMSL trend is +1.18 mm/yr.
7. Victoria, Canada has data 1909 – 2017 and 99% completeness. The PSMSL trend is +0.75 mm/yr.
8. Seattle, US has data 1899 – 2018 and 100% completeness. The PSMSL trend is +2.03 mm/yr.
9. Astoria, US has data 1925 – 2018 and 99% completeness. The PSMSL trend is –0.19 mm/yr.
10. San Francisco, US has data from 1854 to 2018 and 100% completeness. The PSMSL trend is +1.89 mm/yr.
11. Los Angeles, US has data 1923 – 2018 and 98% completeness. The PSMSL trend is +0.96 mm/yr.
12. La Jolla, US has data 1924 – 2018 and 96% completeness. The PSMSL trend is +2.20 mm/yr.
13. San Diego, US has data 1906 – 2018 and 98% completeness. The PSMSL trend is +2.14 mm/yr.
14. Balboa, Panama has data 1908 – 2017 and 99% completeness. The PSMSL trend is +1.45 mm/yr.

Across Oceania, PSMSL only considers the previously mentioned Sydney Fort Denison 2, in Australia, Honolulu, in Hawaii, USA, Auckland 2, in New Zealand, plus Fremantle, in Australia.

In the PSMSL RLR data set, Fremantle has data 1897 – 2017 and 92% completeness. The PSMSL trend is +1.71 mm/yr.

With reference to the above analysis by PSMSL, we prefer to use all the available data for every station to compute trends, and additionally, we compute accelerations. We also use stations neglected by PSMSL. Finally, we try to understand the subsidence contribution to the relative sea-level rise by looking at the subsidence rate of the nearby GPS domes.

Hence, we use for Fremantle, Australia all the data 1897 – 2017, and for Sydney, Australia we coupled together with the data of the collocated tide gauges of Fort Denison 1 and 2 to produce a time series covering the time window 1886 to 2017. For Honolulu, US, we consider the data 1905 – 2018. For New Zealand, in addition to Auckland 2, we also use the data of Dunedin, of time span 1900 – 2017 and 73% completeness.

Figure 2 presents the location of the GPS domes considered by JPL. This image is modified after [19]. JPL supplies the time rate of change of latitude, longitude, and elevation (height). The method is detailed in [22]. The data is obtained from eighty global GPS receivers. Precise GPS orbits and clocks are then computed in the NNR GPS reference frame. Transformation parameters are then computed from the NNR GPS frame to IGS14. Point positions for thousands of global GPS receivers are then computed in the NNR GPS reference frame. Phase ambiguities are resolved, and transformation parameters are applied to obtain the positions in IGS14. Finally, from the time series, after a search for breaks and removal of outliers, positions, velocities, breaks, and seasonal parameters are obtained.
3.2 Fremantle

Fremantle is the best tide gauge of the Indian Ocean. MSL and GPS data are shown in Figure 3.

From the MSL result at Fremantle, Australia, based on data from 1897/1 to 2016/12, it is $v = +1.694 \pm 0.246$ mm/yr, $a = +0.00571 \pm 0.01567$ mm/yr$^2$.

Based on the GPS time series, according to SONEL, in PERT $w = -2.09 \pm 0.38$ mm/yr. Even larger subsidence is found by SONEL for the inland GPS dome of HIL1 (Hillarys), $w = -2.78 \pm 0.31$ mm/yr.

According to JPL, in PERT $w = -2.883 \pm 0.612$ mm/yr., while JPL does not monitor HIL1.

Both PERT and HIL1 are far from the tide gauge.

PSMSL and SONEL reported until recently PERT as the nearby GPS dome to consider for Fremantle. While this GPS dome is certainly far from the tide gauge, it was, however, the resulting negative absolute rate of rise for the single long-term-trend tide gauge of the Indian Ocean that dictated the removal of the absolute sea-level information of Fremantle from the SONEL and PSMSL databases [27].

As shown in Figure 4, from one day to the other, SONEL decided to drop the single station of the Indian Ocean (and similarly the single station of Japan) with a long-term-trend tide gauge record and a near GPS dome, without any explanation.

While the Fremantle tide gauge may be subjected to reduced subsidence vs. the GPS domes of PERT (or HIL1), certainly all the Perth basin is subjected to subsidence [28–30], and the sea levels are rising here mostly because the land is sinking.

NGL has many more GPS antennas in the area. PERT has $w = -1.933 \pm 0.603$ mm/yr. HIL1 has $w = -2.821 \pm 0.603$ mm/yr. Moving closer to the tide gauge location, WLT1 has $w = -3.821 \pm 1.231$ mm/yr., CUTA has $w = -1.108 \pm 0.944$ mm/yr. and SPA8 has $w = -3.795 \pm 1.529$ mm/yr.

If we take the JPL estimation of the subsidence rate for PERT as a reasonable estimation of the subsidence rate of the Fremantle tide gauge, then in Fremantle the relative rate of rise is $v = +1.69$ mm/yr., the sea-level acceleration is $a = +0.00571$ mm/yr$^2$, and the absolute rate of rise is $u = -1.2$ mm/yr.

3.3 Sydney

Sydney is the best tide gauge of the South Pacific. MSL and GPS data are shown in Figure 5.

From the MSL result at Sydney, Fort Denison 1 and 2, Australia, based on data from 1897/1 to 2016/12, it is $v = +0.739 \pm 0.101$ mm/yr., $a = +0.01747 \pm 0.00585$ mm/yr$^2$. 

\[ v = +0.739 \pm 0.101 \text{ mm/yr.} \]
Based on the GPS time series, according to SONEL, in AUCK $w = -0.62 \pm 0.23$ mm/yr., while the domes of AUKT and TAKL have a signal not sufficiently robust to compute a trend.

For JPL, in AUCK $w = -0.512 \pm 0.321$ mm/yr., while in AUKT $w = -0.690 \pm 0.755$ mm/yr., and TAKL is not considered by JPL.

According to NGL, in AUCK $w = -0.939 \pm 0.582$ mm/yr., while in AUKT $w = -0.925 \pm 0.834$ mm/yr. and in TAKL $w = -0.030 \pm 1.659$ mm/yr.

If we take the JPL estimation of the subsidence rate for AUCK as a reasonable estimation of the subsidence rate of the Auckland tide gauge, then in Auckland $v = +1.29$ mm/yr., $a = -0.01106$ mm/yr$^2$, and $u = +0.78$ mm/yr.

### 3.5 Dunedin

Dunedin II is also one of “Mitrovica’s 23” tide stations with minimal vertical land motion. MSL and GPS data are shown in Figure 7.

From the MSL result at Dunedin II, New Zealand, based on data from 1900/1 to 2015/12, it is $v = +1.325 \pm 0.192$ mm/yr., $a = +0.01775 \pm 0.01170$ mm/yr$^2$.

Based on the GPS time series, according to SONEL, $w = -1.71 \pm 0.18$ for DUND and $w = -1.02 \pm 0.12$ in DUNT while the signal is considered not robust for OUS2.

According to JPL, in DUND $w = -1.452 \pm 0.366$ mm/yr. DUNT has $w = -0.432 \pm 0.569$ mm/yr., and OUS2 has $w = -1.056 \pm 0.494$ mm/yr.
3.6 Honolulu

Honolulu is also one of “Mitrovica’s 23” tide stations with minimal vertical land motion, as well as one of the “Holgate’s best 9” tide gauge records. MSL and GPS data are shown in Figure 8.

From the MSL result at Honolulu, HI, USA, based on data from 1905/1 to 2018/3, it is $v = +1.482 \pm 0.212$ mm/yr, $a = -0.00539 \pm 0.01450$ mm/yr$^2$.

Based on the GPS time series, according to SONEL, $w = -0.23 \pm 0.18$ in the dome of HNL, and $w = -0.62 \pm 0.30$ in the dome of ZHI.

According to JPL, $w = -0.518 \pm 0.139$ mm/yr. in HNL while ZHI is not considered.

According to NGL, in HNL $w = -0.704 \pm 0.806$ mm/yr and in ZHI $w = -0.242 \pm 0.0$ mm/yr.

If we take the JPL estimation of the subsidence rate for HNL as a reasonable estimation of the subsidence rate of the Honolulu tide gauge, then in Honolulu, $v = -1.48$ mm/yr, $a = -0.00539$ mm/yr$^2$, and $u = -0.96$ mm/yr.

4 Consistency of the result for Oceania with the global average

Table 1 and Figure 9 present a summary of the tide gauge and GPS results for the LTT stations of Oceania. $v$ is the relative rate of rise of the sea level, $a$ the acceleration of the
sea level, \( w \) the absolute vertical velocity of the tide gauge, \( u \) the absolute rate of rise of the sea level. The table also proposes as \( w \) the GIA vertical velocities VM2 from [4, 24].

Comparable results of stable sea levels have been recently found in the LTT stations of Japan not notably affected by crustal movement, namely Oshoro, Wajima, Hosojima and Tonoura [36].

Oshoro and Tonoura are neglected by PSMSL, which, however, includes Aburatsubo affected by considerable crustal movement.

The stable sea levels of Japan are also acknowledged by the Japanese Meteorological Office, [37], that openly states, “no clear long-term trend of rise is seen for the period from 1906 to 2017”.

The minimal sea level rise since the beginning of the 20th century shown by the Japanese Meteorological Office is the result of only the composite tide gauge record of Hamada, that is made of the long-term tide gauge of Tonoura, 1896 to 1984, of no sea-level rise, nor acceleration, plus the short-term tide gauge of Hamada II, 1984 to present, that is in an area of subsidence and experiences a large rate of rise [38].

In the 4 LTT tide stations of Japan not affected by significant subsidence, Hosojima (data 1894 to 2018), Oshoro (data 1905 to 2018), Wajima (data 1894 to 2018), and Tonoura (data 1894 to 1984), the average sea level rate of rise of negligible, \( v_{ave} = +0.08 \text{ mm/yr} \), and the average sea level acceleration is negative, \( a_{ave} = -0.0111 \text{ mm/yr}^2 \) [39].

The other LTT tide station of Japan, Aburatsubo (data 1894 to 2018), that is affected by subsidence, has a positive sea level rate of rise, \( v = +3.64 \text{ mm/yr} \), but still a negative acceleration, \( a = -0.0066 \text{ mm/yr}^2 \) [39].

The 20 LTT stations along the West Coast of North America, from the Panama canal to the western-most point of Alaska, namely Balboa, Panama, San Diego, CA, USA, La Jolla, CA, USA, Los Angeles, CA, USA, Santa Monica, CA, USA, San Francisco, CA, USA, Crescent City, CA, USA, Astoria, OR, USA, Neah Bay, WA, USA, Seattle, WA, USA, Friday Harbor, WA, USA, Tofino, Canada, Victoria, Canada, Vancouver, Canada, Point Atkinson, Canada, Prince Rupert, Canada, Unalaska, AK, USA, Juneau, AK, USA, Sitka, AK, USA and Ketchikan, AK, USA, the average sea level rate of rise is negative, \( v_{ave} = -0.47 \text{ mm/yr} \), and the average sea level acceleration is small, \( a_{ave} = +0.0012 \text{ mm/yr}^2 \) [40].

PSMSL neglect the stations of Santa Monica, CA, USA, Crescent City, CA, USA, Neah Bay, WA, USA, Friday Harbor, WA, USA, Tofino, Canada, Vancouver, Canada, Point Atkinson, Canada, Unalaska, AK, USA, Juneau, AK, USA, Sitka, AK, USA.
Table 1: Summary of sea-level rise and subsidence results for the LTT stations of Oceania

| tide gauge | time span         | v     | a     | GPS   | w     | w*    | u     |
|------------|-------------------|-------|-------|-------|-------|-------|-------|
| Fremantle  | 1897/1 to 2016/12 | 1.694 | 0.00571 | PERT  | -2.883 | 0.020 | -1.189 |
| Sydney     | 1886/12 to 2016/12| 0.739 | 0.01747 | SYDN  | -0.542 | 0.090 | 0.197 |
| Auckland   | 1903/11 to 2000/5 | 1.291 | -0.01106 | AUCK  | -0.512 | 0.330 | 0.779 |
| Dunedin    | 1900/1 to 2015/12 | 1.325 | 0.01775 | DUND  | -1.452 | 0.290 | -0.127 |
| Honolulu   | 1905/1 to 2018/3  | 1.482 | -0.00539 | HNLC  | -0.518 | 0.230 | 0.964 |
| averages   |                   | 1.306 | 0.00490 |       | -1.181 | 0.192 | 0.125 |

5 Case study of Tuvalu

The fact that the Pacific sea levels are rising very slowly and not accelerating is also proposed by [41] discussing the increasing, rather than shrinking, emerged land of Pacific and Indian Ocean atolls islands. The emerged land area of many atoll islands in the Pacific (and the Indian Ocean) is consistently increasing, rather than decreasing [42–44].

To explain the increasing emerged land of the Pacific Ocean atolls islands, the case of Funafuti, Tuvalu is considered in detail. Since the average height of the islands is less than 2 m above sea level, Tuvalu is indeed particularly vulnerable to sea-level rise.

As previously mentioned, sea level may rise because the volume of water in the ocean is increasing (melting of ice on land and thermal expansion), as well as because the land is subsiding. It is well accepted that Pacific Atolls may be subjected to subsidence. Darwin’s theory of Pacific atolls formation [45, 46], assumes a subsiding volcano fringed by an upwards growing coral reef. While this theory may need extensions [47], land subsidence and growth of corals are key aspects to consider studying sea-level rise in the Pacific atolls.

Tuvalu has two tide gauges, the historical tide gauge of FUNAFUTI and the recent tide gauge of FUNAFUTI B, part of the Australian Government Pacific Sea Level Monitoring (PSLM) Project [48].

The University of Hawaii managed the discontinued, historical tide gauge of FUNAFUTI. Same of all the historical tide gauges of the Pacific Forum Stations on the Joint Archive for Sea Level Data Holdings, it is analyzed in the report [49].

The presently operational tide gauge of FUNAFUTI B, part of the latest PSLM Project, has reports periodically provided in [50]. Despite the data are still updated regularly, there is no consolidated report since 2011 [51].

Sea level data has been recorded in Funafuti by one subsiding tide gauge from November 1977 to December 1999, and from another tide gauge from May 1993 to the present. The two tide gauge records are both too short to infer any proper trend for the rate of rise and acceleration. These two short tide gauge records cannot be coupled together because of the different sea and land contributions to the relative sea-level signal. The two nearest long-term tide gauges are Honolulu, at East, and Auckland, at West.

According to [44], the rate of rise of the sea level at the Funafuti tide gauge is +3.9 mm/yr., a value that they also claim is twice the global average. However, [44] also measured a significant increment in land size that is difficult to reconcile with an intense sea level rise.

Similarly, [44] and [52] have shown that the land area of Tuvalu is increasing, rather than reducing. The increment of the land area is the effect of the coral growth outpacing the sea-level rise of a weakly subsiding atoll.

The subsidence rate in Tuvalu may be assessed by using tide gauges and Global Positioning System (GPS) data. Three GPS antennas are in Funafuti, Tuvalu, close to the tide gauge. The time-series of monthly average mean sea level (MSL) relative to the tide gauge instrument are provided by PSMSL or the Australian Government Bureau of Meteorology (BOM, [53]). The time-series of GPS positions of antennas, together with their analyses, are provided by NGL, JPL, or SONEL.

Figure 10a presents the location of the GPS antennas of TUVT, TUVA, and TUV1 in Funafuti. This image is modified after NGL.

Figure 10b presents the location of the FUNAFUTI B tide gauge (SEAFRAME SENSOR) and of the benchmarks used for the leveling of the tide gauge. This image is modified after [54].

The GPS antenna of TUVA, at the airport, has the best coverage. This antenna is 2,544 m from the FUNAFUTI B tide gauge. The tide gauge is much closer to the TUVT GPS antenna which does not have enough coverage in the data sets considered. The principal benchmark is located close to the airport, where also the TUVA GPS antenna is located. The relative MSL of FUNAFUTI and FUNAFUTI B are compared over the period of overlapping to discover differential subsidence. Linear fitting of the difference in MSL re-
turns the difference in subsidence rate. The precise leveling information of the FUNAFUTI B tide gauge referred to the datum at the airport is then used to determine the subsidence rates of both tide gauges versus the datum.

5.1 Relative sea level

The tide gauges of Tuvalu have been recently analyzed in [55].

As acknowledged by the PSMSL, “Documentation added 2018-06-14. Data for 2000 and 2001 removed - this data was recorded by Australian National Tidal Centre’s gauge (ID 1839) and was incorrectly attached to this site” the data of FUNAFUTI ends in Dec. 1999.

The linear and parabolic fittings of the data Nov. 1977 to Dec. 1999 suggest a rate of rise of +0.43 mm/yr. and an apparent acceleration of +0.0354 mm/yr². The time window is too short to infer proper trends and accelerations [15, 56].

John Daly first pointed out in 2001 the lack of any sea-level-rise in the just discontinued FUNAFUTI tide gauge, [57]. In the following year, [58], The National Tidal Facility, Australia, now part of the Bureau of Meteorology, came to the same conclusion in their 2006 news release on Tuvalu, [59], now a broken link. It was written “The historical record from 1978 through 1999 indicated a sea-level rise of 0.07 mm per year” and “The historical record (from Tuvalu) shows no visual evidence of any acceleration in sea level trends.”

The lack of any sea-level-rise in Funafuti was also commented by [60].

As shown in [55], the small rate of rise of the historical tide gauge of FUNAFUTI was perfectly aligned with the historical results proposed for the Pacific Forum Stations on the Joint Archive for Sea Level Data Holdings as at March 2006 [49].

The mean trend for all the tide gauge records that span more than 25 years, a minimum requirement to compute a trend, was +1.14 mm/yr.

The historical data is forgotten since that year, with the observations from the new monitoring project started in 1993 replacing the observation from the historical stations. Figure 11b presents the MSL recorded in FUNAFUTI B. This tide gauge started recording in 1993, about the time of a low El Nino/Southern Oscillation (ENSO) water levels.

The linear and parabolic fittings of the data from May 1993 to Dec. 2017 suggest a rate of rise of +3.65 mm/yr. and an apparent acceleration of –0.2258 mm/yr². The time window is too short to infer proper trends and accelerations. As first noticed by [61], after the recovery from the low ENSO waters of 1998, since 1999, there is no sea-level rise at all.

Figure 11c presents the analysis of the FUNAFUTI B tide gauge record with the starting date Jan. 1999, after the end of the low ENSO waters. The linear and parabolic fit-
tings suggest a rate of rise of $+1.32 \text{ mm/yr.}$ and an apparent acceleration of $+0.1190 \text{ mm/yr}^2$. The time window is too short to infer proper trends and accelerations.

Figure 11d presents the delta MSL in between FUNAFUTI and FUNAFUTI B. Apart from the initial data collected in the FUNAFUTI B tide gauge during the years 1993 and 1994, with sometimes also missing months, to show some initial trouble in the operation of the new tide gauge, since 1995 the difference is increasing.

Figure 12a presents the monthly maximum, mean and minimum sea level in FUNAFUTI. This graph was included in the 2006 news release on Tuvalu by The National Tidal Facility, Australia, [59], a link now broken. The figure shows the periodic drops in sea level during the ENSO events, but no rise.

Figure 12b presents the monthly maximum, mean and minimum sea level in FUNAFUTI B. Apart from the initial troublesome measurements of 1993, the sea level is rising only because of the low ENSO waters of 1998. The monthly maximum mean and minimum sea-level are all characterized by a very weak rising trend. FUNAFUTI and FUNAFUTI B are two different tide gauges, suffering different land and sea contributions to the relative sea-level signal recorded by the tide gauges. They should not be coupled together to infer any trend.

As suggested by [62], FUNAFUTI had initial site-specific subsidence larger than FUNAFUTI B responsible for a larger than the real apparent rate of rise in this tide gauge. The stable sea level of Tuvalu is also confirmed by [63].

Since 1995 the MSL of FUNAFUTI has been growing at a rate of $3.016 \text{ mm/yr.}$ faster than the MSL of FUNAFUTI B. We may assume the FUNAFUTI tide gauge had an extra subsidence of $3.016 \text{ mm/yr.}$ vs. the FUNAFUTI B tide gauge.

From the latest report of the PSLMP [51], we also know the FUNAFUTI B tide gauge is subsiding $0.1 \text{ mm/yr.}$ vs. the primary benchmark close to the airport.

What is clear from Figures 11 and 12, is that sea levels have been rising in Tuvalu, as recorded by the tide gauges of FUNAFUTI and FUNAFUTI B, at an everything but dramatic rate, of the order of $1 \text{ mm/yr.}$ or less. The FUNAFUTI tide gauge was subjected to extra subsidence vs. the FUNAFUTI B tide gauge, and this tide gauge is subjected to minimal subsidence vs. the primary benchmark. How much of the mm/yr. of relative sea-level rise is due to subsidence that may be determined by GPS positioning.

The data of Figures 11 and 12 do not supply any proper estimation of the rate of rise of the sea level, and even less of the sea-level acceleration, as the records, are too short. From the data of Figures 11 and 12, it may be only concluded that the sea levels have been rising truly little since 1979. There are however long-term trend tide gauges elsewhere in the Pacific. They are in Auckland and Honolulu. On average, the acceleration is small across the Pacific. There is no reason to expect anything different in Tuvalu.

5.2 Subsidence

We may understand the contribution of land subsidence to the relative sea-level rise from the tide gauge signal by considering the time series of the GPS position of nearby antennas [9]. These data are, however, only recent.

According to NGL, the vertical velocity of the GPS antennas nearby the tide gauge of FUNAFUTI B, namely TUV1 and TUVA, are $-5.924 \pm 25.594 \text{ mm/yr.}$ and $-1.645 \pm 1.041 \text{ mm/yr.}$ respectively. The result for TUV1 is unreliable, based on very few data points. Opposite, the result for TUVA, Figure 13a, is based on 16 years of data. NGL has also the data for another station, TUVT, also suffering the lack of enough data.

For TUVA, even slightly larger subsidence of $-1.71 \pm 0.17 \text{ mm/yr.}$ is computed by SONEL, based on a slightly different analysis of the same data over a shorter time window, Figure 13b, while slightly smaller subsidence, $-0.919 \pm 0.715 \text{ mm/yr.}$ is computed by JPL, also because of slightly different analyses, Figure 13c.

The sea-level rise of Tuvalu is due to subsidence rather than the increasing volume of the ocean waters.

The relative sea level of Tuvalu is characterized by a mild rising, non-accelerating trend, mostly due to subsidence.

5.3 Absolute sea level

The results shown in the prior sections may be used to compute a time series of absolute and relative sea-level since 1977. The FUNAFUTI tide gauge was subsiding at an extra rate of $3 \text{ mm/yr.}$ The FUNAFUTI tide gauge result may thus be coupled to the FUNAFUTI B tide gauge result by shifting the FUNAFUTI MSL for the same value in December 1999, and then tilting the MSL for FUNAFUTI of $3.02 \text{ mm/yr.}$, Figure 14a is the time window 1993 to 2000. There is a perfect agreement between the FUNAFUTI B and the FUNAFUTI shifted and tilted result apart from the very first measurements collected in FUNAFUTI B that are unreliable. Figure 14b shows the composite record obtained by coupling the FUNAFUTI shifted and tilted result from 1977 to 2000 and the FUNAFUTI B result 2000 to 2018. The time window is from 1977 to 2018. The rate of relative sea-level rise is $1.90 \text{ mm/yr.}$ Figure 14c presents the abso-
lute sea-level record, obtained by considering the subsidence of FUNAFUTI B vs. the datum TUVABM, 0.1 mm/yr., plus the absolute subsidence of the TUVA GPS antenna, 1.645 mm/yr. from NGL.

From the subsidence rates of Figures 12, 13 and 14, we may conclude that the thermosteric (absolute) sea level rate of rise may be less than 0.5 mm/yr. also in Tuvalu, +/0.16 mm/yr. to be precise.

The short FUNAFUTI tide gauge, which was subsiding at a rate of 3.1 mm/yr. vs the primary benchmark, suggests an apparent relative rate of rise of sea level of 0.43 mm/yr. The similarly short FUNAFUTI B tide gauge, that is minimally subsiding at a rate of 0.1 mm/yr. vs. the primary benchmark, suggests an apparent relative rate of rise of sea level of +3.65 mm/yr. This latter result is biased by the extremely low ENSO waters of 1998. Since January 1999, the apparent rate of rise reduces to +1.32 mm/yr. All the tide gauge records are too short to infer any proper trend. The composite tide gauge record of Funafuti shows a relative rate of rise of the sea level of 1.91 mm/yr. The TUVA GPS dome remarkably close to the primary benchmark shows a clear subsidence of 0.92 to 1.71 mm/yr. over the longer time window. The thermosteric (absolute) sea level rate of rise may thus be less than 0.5 mm/yr. also in Tuvalu. Tuvalu is growing in the area because the sea level is rising much less than what is thought. There are no signs in Tuvalu and nearby long-term tide gauges of significant sea-level rise exceeding the subsidence rate.

6 Case study of Adelaide

The historic tide gauge records of Port Adelaide Inner and Outer Harbor have been previously analyzed by [65]. Geological evidence shows that most of the significant rate of local sea-level rise is due to the localized, significant subsidence of the land, attributed to human activities associated with port development, reclamation of Holocene wetlands and groundwater extraction from deeper Tertiary aquifers. Three-quarters of the relative rate of rise of the sea level estimated at +2.5 to +2.9 mm/yr. is attributed by [65] to land subsidence. Authors of [65] computed an absolute rate of rise of the sea levels of +0.7 mm/yr.

According to [66], “On the evidence, the Board is satisfied that sea level is presently rising at a rate of approximately 1.5 mm/yr. at most parts of the SA coast - the rate differs at a few locations because of local land subsidence or uplift.”
Port Pirie sea levels were previously analyzed by [67]. They found a long-term rate of sea-level fall attributed to isostatic up-warp of the coast. At Port Pirie, they found a relative sea-level trend of $-0.02$ mm/yr. with neotectonics masking an absolute sea-level rise of $+0.31$ mm/yr.

The sea level data are obtained from the PSMSL [16], as well as the National Tidal Centre, NTC, [68].

While the data should be the same, as discussed later, there are few remarkable differences between the PSMSL and the NTC data sets.

The result of JPL is usually more reliable, but NGL covers a much larger number of GPS antennas, and usually more years of data, albeit sometimes also proposing subsidence rates computed by 1 year of data or even less that are everything but reliable.

Figure 15 presents a picture with the location of the longest tide gauges of South Australia presently considered by PSMSL. The time window is from 1957 to 2016. The relative rate of rise of the sea level ranges from the $+1.17$ mm/yr. of Victor Harbour, to the $+2.12$ mm/yr. of Port Adelaide Outer Harbor.

Figure 16 presents a picture of the location of the GPS antennas of South Australia presently considered by JPL. In Adelaide, JPL has ADE1 and ADE2, of vertical velocity $-2.10$ and $-2.65$ mm/yr. respectively. Then, the only other GPS antenna of South Australia is CEDU, in Ceduna, North West of Adelaide, of vertical velocity $-1.05$ mm/yr. The GPS antenna of MOBS, in Melbourne, Victoria is South East, with vertical velocity $-1.48$ mm/yr.

6.1 Relative and absolute sea level of Adelaide

PSMSL includes 3 tide gauge records for Adelaide, Port Adelaide Inner Harbor, Port Adelaide Inner II, and Port Adelaide Outer Harbor. NTC included in the past a shorter record of Port Adelaide Inner Harbor, plus the Port Adelaide Outer Harbor. Presently, they only have Port Adelaide Outer Harbor. The data of Port Adelaide Inner II and Port Adelaide Inner Harbor in the PSMSL data set have exactly the same values, with only a constant difference of 271 mm, in the exact same months of measurements, and exactly the same months of no data. This suggests that one
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Figure 14: Absolute and relative sea level in Funafuti 1977 to present; (a) relative sea level from the two tide gauges over the time window 1993 to 2000; (b) the relative sea level of the composite tide gauge record over the time window 1977 to 2018; (c) absolute sea level of the composite tide gauge record over the time window 1977 to 2018.

There are two long tide gauge records in Adelaide, the Port Adelaide Inner Harbor tide gauge record of a time span of data 1882 – 2012 and completeness 50%, and the Port Adelaide Outer Harbor tide gauge record, of a time span of data 1940 – 2016 and completeness 96%. The two tide gauges are remarkably close to each other. Additionally, there is the Port Adelaide Inner II tide gauge record, nearby the two other tide gauges, of a time span of data 1933 – 1990 and completeness 61%.

While the datum information is considered by PSMSL, only for the Port Adelaide Outer Harbor tide gauge record, it is otherwise interesting to consider the data for all the stations.

Figure 15: Tide gauges of South Australia with at least 70% of data over the time window 1957 to 2016. Image modified after PSMSL.

Figure 16: GPS antennas of South Australia from JPL. Image modified after JPL.

Figure 17a presents all the metric data. The Port Adelaide Inner Harbor data suggest a rate of rise of 0.82 mm/yr. 1882 to 2012, but the alignment of the data collected in the 1800s may be suspicious. The Port Adelaide Outer Harbor data suggest a larger rate of rise +2.35 mm/yr. 1940 to 2016, but this result may be an artifact of an initially larger subsidence rate. Figure 17b shows all the metric data from January 1940 to December 1990. The relative rate of rise is +2.22 and +2.18 mm/yr. for the perfectly consistent Port Adelaide Inner Harbor and Port Adelaide Inner II tide gauges, and it is a larger +2.75 mm/yr. for the Port Adelaide Outer Harbor tide gauge. Hence, the Port Adelaide Outer Harbor tide gauge had at least initially extra subsidence for compaction or other causes. In Figure 17c there is the previous data all shifted for zero MSL December 1990. January 1941 to December 1945, the difference between the
Inner and Outer Harbor tide gauges reduces from 110 to 40 mm. Figure 17d shows the difference between the MSL of the Inner and Outer Harbor tide gauges. The difference is suspiciously high in the early-to-mid 1940s, as well as low in the late 1960s and early 1970s, to show datum issues in the two tide gauges.

While it appears to be difficult to couple together the two tide gauge records of Adelaide Inner and Outer Harbor to form a single tide gauge record as done in Sydney, where the nearby Fort Denison 1 and 2 tide gauge records have a very successful overlapping of 80 years (Sydney Fort Denison 1 has data 1886 – 1993, Sydney Fort Denison 2 has data 1914 – 2016), it is worth considering only the data since January 1943.

- With data since January 1940, for Adelaide, the relative sea-level rise is +2.3 mm/yr., and the acceleration is −0.01936 mm/yr² (Figure 18a). The image is from http://www.sealevel.info.
- With data since January 1943, for Adelaide, the relative sea-level rise is +2.1 mm/yr., and the acceleration is +0.00924 mm/yr² (Figure 18b). Also, this image is from http://www.sealevel.info.
- The subsidence (ADE1 GPS dome as analyzed by JPL) is −2.1 mm/yr. (Figure 18c).

Again, other GPS antennas of the area with less coverage, and therefore reduced reliability, that is even closer to the tide gauge location show smaller or larger subsidence. We use here JPL, rather than NGL, as the provider of the GPS data, because JPL has for this location a time series with more years of data. NGL has a shorter record of S021 suggesting a subsidence rate of −1.93 mm/yr. based on data from 2000 to 2008.
- In Adelaide, the absolute rate of rise is about +0.2 mm/yr., i.e. the effect of global warming is small.

Authors of [65] computed an absolute rate of rise of the sea levels of 0.7 mm/yr. Figures 17 and 18 suggest the relative sea-level rate of rise is small, the subsidence contribution is large, and the absolute rate of rise of the sea levels is smaller.

### 6.2 Relative sea levels of other medium-length tide gauges of South Australia

South Australia has other 3 tide gauges of about 60 years record length. The MSL data is from the NTC. As shown in Figure 19, the relative rate of rise is less than in Adelaide.

- In Port Pirie, north of Adelaide, of 80 years length, the relative rate of rise of the sea levels is about 1 mm/yr.
- In Port Lincoln, also North of Adelaide, of less than 60 years length, the relative rate of rise of the sea levels is about 1.9 mm/yr.
In Victor Harbor, South of Adelaide, also of less than 60 years, the relative rate of rise of the sea levels is about 1.4 mm/yr.

This is the result of reduced subsidence.

The Port Pirie tide gauge record shows a jump about 1997 that is not reproduced by the other tide gauges of Port Lincoln, Port Adelaide Inner and Outer Harbour, and Victor Harbour. This may be an artifact of a localized crustal movement or a movement of the tide gauge instrument.

**Figure 18:** Relative sea level rise (a, b) and land subsidence (c, d, e) for Adelaide. Images modified (a,b) after http://www.sealevel.info, (c) after NGL (S021 GPS antenna), (d) and (e) after JPL (ADE1 and ADE2 GPS antennas).

**Figure 19:** Relative sea-level rise around Adelaide. MSL data from NTC.
7 Discussion

The proposed pattern is coherent with the other long-term-trend tide stations of the world. The global pattern is consistent with a small thermo-steric sea level rise with negligible acceleration, explained as a gentle recovery from the low temperatures of the Little Ice Age, that was caused by the record low solar activity of the Maunder and Spörer Minima [70] as well as volcanic activity and internal oscillations in the climate system [71]. The onset of the Little Ice Age occurred after the Medieval Warm Period, about 1350 [71]. It was the cause of the Vikings’ decolonizing of the once green Greenland [72]. This cooling period ended about 1850 [73]. Since then, the sea levels are rising without any significant acceleration component. The effect of global warming on the rate of rise of the sea level is thus much smaller than thought.

The lack of any acceleration in the long-term-trend tide gauges is well known, claimed for example in [7, 17, 27, 28, 31] to [35, 39] to [41, 62, 74–108].

8 Conclusions

The relative sea-level measurements at the tide gauges, when collected over time windows long enough to clear a trend of the multidecadal oscillations, are the unsurpassed way to understand sea-level changes. The GPS positioning time series further help, understanding the contribution of subsidence to the relative sea-level signal. This latter result is less reliable.

The tide gauge and GPS measurements show a stable pattern across Oceania, of mild rising sea levels, with negligible accelerations, mostly explained by the sinking of the tide gauge instrument. In Fremantle, Sydney, Auckland, Dunedin, and Honolulu, the average relative rate of rise is +1.306 mm/yr., the average acceleration is +0.00490 mm/yr., and the average absolute rate of rise is +0.125 mm/yr. This pattern is consistent with the other long-term-trend tide stations of the Pacific.

This result is consistent with the land increase, rather than shrinking, of the Pacific atolls’ islands recently highlighted by other researchers, here explained for the specific case study of Tuvalu, where over the short time window 1977 to present, the relative rate of rise is +1.902 mm/yr., biased by low ESO water levels and subsidence, but the average absolute rate of rise is +0.157 mm/yr.

The relative rate of rise of the sea level is less than 2.3 mm/yr. in Adelaide, with an overwhelming contribution by subsidence. The thermosteric effect is estimated to be around +0.2 mm/yr. This result is perfectly aligned with the result for Sydney, and Fremantle. The sea-level acceleration is also negative in Adelaide.

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References

[1] Provis D.G., Radok R., Sea-level oscillations along the Australian coast, Marine Freshwat. Res., 1979, 30(3), 295-301.
[2] Chambers D., Merrifield M.A., Nerem R.S., Is there a 60-year oscillation in global mean sea level? Geophys. Res. Lett., 2012, 39(18), GL052885.
[3] Peltier W.R., Postglacial Variations in the Level of the Sea: Implications for Climate Dynamics and Solid-Earth Geophysics, Rev. Geophys, 1998, 36(4), 603-689.
[4] Peltier W.R., Global Glacial Isostasy and the Surface of the Ice-Age Earth: The ICE-5G(VM2) model and GRACE, Ann. Rev. Earth. Planet. Sci., 2004, 32, 111-149.
[5] Erban L.E., Gorelick, S.M. and Zebker, H.A., Groundwater extraction, land subsidence, and sea-level rise in the Mekong Delta, Vietnam. Environmental Research Letters, 2014, 9(8), 084010.
[6] Minderhoud P.S.J., Erkens G., Pham V.H., Bui V.T., Erban L., Kooi H., Sluhatmer E., Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta, Vietnam, Environ. Research Lett., 2017, 12(6), 064006.
[7] Mörner N.-A., Rates of Sea Level Changes — A Clarifying Note, Int. J. Geosci., 2016, 7(11), 1318-1322.
[8] Antonov J.I., Levitus S., Boyer T.P., Thermometric sea level rise, 1955-2003, Geophys. Res. Lett., 2005, 32(12), GLO23112.
[9] Wöppelmann G., Leetletl C., Santamaria A., Bouin M.-N., Collilieux X., Altamimi Z., Williams S.D.P., Martin Miguez B., Rates of sea level change over the past century in a geocentric reference frame, Geophys. Res. Lett., 2009, 36, GLO38720.
[10] Iyengar R.N., Monsoon rainfall cycles as depicted in ancient Sanskrit texts, Current Sci., 2009, 97(3), 444-447.
[11] Schlesinger M., Ramankutty N., An oscillation in the global climate system of period 65-70 years, Nature, 1994, 367, 723-726.
[12] Parker A., Natural oscillations and trends in long-term tide gauge records from the Pacific, Pattern Recogn. Phys., 2013, 1, 1-13.
[13] Parker A., Accuracy and Reliability Issues in the Use of Global Positioning System and Satellite Altimetry to Infer the Absolute Sea Level Rise, J. Satell. Oceanogr. Meteor., 2015, 1(1), 13-23.
[14] Parker A., Minimum 60 years of recording are needed to compute the sea level rate of rise in the Western South Pacific, Nonlin. Eng., 2014, 3(1), 1-10.
[15] Parker A., There is no Indication That the Extreme Water Levels in Rhode Island have Strongly Accelerated Since the Start of the 20th Century, Amer. J. Environ. Sust. Develop., 2017, 2(4), 37-42.
[16] www.psmsl.org , visited December 1, 2019.
[17] www.sealevel.info , visited December 1, 2019.
[18] geodesy.unr.edu , visited December 1, 2019.
[19] sideshow.jpl.nasa.gov/post/series.html , visited December 1, 2019.
[20] www.sonei.org , visited December 1, 2019.
[21] Blewitt G., Kremer C., Hammond W.C., Gazeaux J., MIDAS robust trend estimator for accurate GPS station velocities without step detection, J. Geophys. Res. Solid Earth, 2016, 121, 2054-2068.
[22] Heflin M. et al., Introduction to JPL’s, GPS Time Series, 2018, NASA.
[23] Mörner N.A., Glacial Isostasy: Regional-Not Global, Int. J. Geosci., 2015, 6(06), 577.
[24] Parker A., Ollier C.D., A Critique of Satellite Global Mean Sea Levels, Journal of Earth and Atmosph. Sci., 2016, 1(2), 36-43.
[25] Zervas, R., Sea Level Variations of the United States 1854-2006, NOAA Technical Report NOS CO-OPS 053, 15-24, 2009.
[26] Parker A., Ollier C.D., Is the sea level stable at Aden, Yemen?, Earth Syst. Environ. 2017, 1, 18.
[27] Parker A., Tide gauge of absolute sea level rise negative removed from data base, New Concepts Glob. Tecton. J., 2018, 6(2), 314-316.
[28] Parker A., The Sea Level Rate of Rise and the Subsidence Rate Are Constant in Fremantle, Amer. J. Geophys., Geochem. Geosyst., 2016, 2(4), 43-50.
[29] Featherstone W.E., Penna N.T., Filmer M.S., Williams S.D.P., Nonlinear subsidence at Fremantle, a long-recording tide gauge in the Southern Hemisphere. J. Geophys. Res.: Oceans, 2015, 120(10), 7004-7014.
[30] Featherstone W., Filmer M., Penna N., Morgan L., Schenk A., Anthropogenic land subsidence in the Perth Basin: Challenges for its retrospective geodetic detection, J. Royal Soc. West. Australia, 2012, 95(1), 53-62.
[31] Houston J.R., Dean R.G., Sea-Level Acceleration Based on U.S. Tide Gauges and Extensions of Previous Global-Gauge Analyses, J. Coast. Res., 2011, 27, 609-417.
[32] Boretti A., Is there any support in the long term tide gauge data to the claims that parts of Sydney will be swamped by rising sea levels? Coast. Eng., 2012, 64, 161-167.
[33] Parker A., Sea level trends at locations of the United States with more than 100 years of recording, Natural Hazards, 2013, 65(1), 1011-1021.
[34] Parker A., Ollier C.D., California sea level rise: evidence based forecasts vs. model predictions, Ocean Coast. Manag., 2017, 149, 198-209.
[35] Parker A., Ollier C.D., Short-Term Tide Gauge Records from One Location are Inadequate to Infer Global Sea-Level Acceleration, Earth Syst. Environ., 2017, 1(2), 17.
[36] Parker A., Sea level oscillations in Japan and China since the start of the 20th century and consequences for coastal management-Part 1: Japan, Ocean Coast. Manag., 2019, 169, 225-238.
[37] www.data.jma.go.jp/gmd/kaiyou/english/sl_trend/sea_level_around_japan.html , visited December 1, 2019.
[38] Okunaka Y., Hirahara T., Long-term trend of sea level on coast of Japan - Recent research review and correction using ground variation by GPS observation , Sokkou-jiho, 2016, 83, 521-5.
[39] Parker A., Sea level oscillations in Japan and China since the start of the 20th century and consequences for coastal management - Part 2: China pearl river delta region, Ocean Coast. Manag., 2018, 163(1), 456-465.
[40] Parker A., Absolute rates of sea level rise based on Tide Gauges and Global Navigation Satellite System along the West Coast of North America, Nonlin. Eng., in press.
[41] Parker A., Ollier C.D., Pacific sea levels rising very slowly and not accelerating, Quaestiones Geographicae, 2019, 38(1), 179-184.
[42] Duvat V.K.E., A global assessment of atoll island planform changes over the past decades. Wiley Interdisc. Rev.s: Climate Change, 2018, 10, e557.
[43] Kench P.S., Thompson D., Ford M.R., Ogawa H., McLean R.F., Coral islands defy sea-level rise over the past century: Records from a central Pacific atoll, Geology, 2015, 43(6), 515-518.
[44] Kench P.S., Ford M.R., Owen S.D., Patterns of island change and persistence offer alternate adaptation pathways for atoll nations, Nature Comm., 2018, 9(1), 605.
[45] Darwin C., Journal of Researches into the Geology and Natural History of the Various Countries Visited by H.M.S. Beagle, 1839, London, Henry Colbourn.
[46] Darwin C., The Structure and Distribution of Coral Reefs, 1842, London, Smith, Elder and Co.
[47] Terry J.P., Goff J., One hundred and thirty years since Darwin: ‘Reshaping’ the theory of atoll formation, The Holocene, 2013, 23(4), 615-619.
[48] www.bom.gov.au/pacific/projects/pslim/ , visited December 1, 2019.
[49] Australian Government Bureau of Meteorology, Pacific Country Report Sea Level and Climate: Their Present State, Tuvalu, 2006, www.bom.gov.au/ntc/IDO60033/IDO60033.2006.pdf
[50] www.bom.gov.au/pacific/tuvalu/index.shtml , visited December 1, 2019.
[51] Australian Government Bureau of Meteorology, The South Pacific Sea Level and Climate Monitoring Project Sea Level Data Summary Report July 2010 - June 2011, 2011, www.bom.gov.au/ntc/IDO60102/IDO60102.2011_1.pdf
[52] Hisabayashi M., Rogan J., Elmes A., Quantifying shoreline change in Funafuti Atoll, Tuvalu using a time series of Quickbird, Worldview and Landsat data, GI Sci. Remote Sensing, 2018, 55(3), 307-330.
[53] www.bom.gov.au , visited December 1, 2019.
[54] Australian Government Geoscience Australia, South Pacific Sea Level and Climate Monitoring Project (SPSLCMP) Survey Report EHM Height Traversing Levelling Survey, Tuvalu, 2007, ftp.ga.gov.au/geodesy-outgoing/gnss/pub/SPSLCMP/PreviousLevellingSurveyReports/TUVALU%20LEVEL%20SVY%202007.pdf
[55] Parker A., Tuvalu Sea Level Rise, Land Change, Mismanagement and Overpopulation, New Concepts Glob. Tecton. J., 2018, 6(1), 107-123.
[56] Parker A., Persisting problems affecting the reliability of the satellite altimeter based Global Mean Sea Level computation, Pattern Recogn. Phys., 2014, 2(2), 65-74.
[57] www.john-daly.com/press/press-01b.htm#tuvalu , visited December 1, 2019.
[58] www.john-daly.com/press/press-02a.htm#funafuti , visited December 1, 2019.
[59] www.ntf.fliinders.edu.au/TEXT/NEWS/tuvalu.pdf, visited December 1, 2006.
Eschenbach W., Tuvalu not experiencing increased sea level rise, Energy Environ., 2004, 15(3), 527-543.

Mörner N.-A., Chapter 12 - Sea Level Changes as Observed in Nature, in Evidence-Based Climate Science (Second Edition). Data Opposing CO2 Emissions as the Primary Source of Global Warming, Ed: Easterbrook D., 2016, 215-229.

Mörner N.-A., There Is No Alarming Sea Level Rise! 21st Century Science and Technology, Fall, 2010, 7-17.

Ollier C., Sea Level in the Southwest Pacific is stable, Energy Environ., 2010, 21(7), 833-839.

www.john-daily.com/press/press-02a.htm , visited December 1, 2019.

Belperio A.P., Land subsidence and sea level rise in the Port Adelaide estuary: implications for monitoring the greenhouse effect, Austral. J. Earth Sci., 1993, 40(4), 359-368.

South Australia Coast Protection Board, Policy Document, 2016, www.environment.sa.gov.au/files/sharedassets/public/coasts/coast-protection-board-policy-document.pdf.

Harvey N., Barnett E.J., Bourman R.P., Belperio A.P., Holocene sea-level change at Port Pirie, South Australia: a contribution to global sea-level rise estimates from tide gauges, J. Coast. Res., 1999, 15(3), 607-617.

www.bom.gov.au/oceanography/projects/ntc/monthly/index.shtml#sa, visited December 1, 2019.

Australian Government Bureau of Meteorology, Australian Mean Sea Level Survey 2009, 2009. www.conscious.com.au/docs/new/128.21_AustMSLSurvey2009%28%29.pdf

Eddy J.A., The Maudmer minimum, Science, 1976, 192(4245), 1189-1202.

Miller G.H., Geirsdóttir Á., Zhong Y., Larsen D.J., Otto-Bliesner B.L., Holland M.M., Bailey D.A., Refsnider K.A., Lehman S.J., Southon J.R., Anderson C., A abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks, Geophys. Res. Lett., 2012, 39(2), GL050168.

Grove J., The place of Greenland in medieval Icelandic saga narrative, J. North Atlantic, 2009, 2, 30-51.

Matthews J.A., Briffa K.R., The 'Little Ice Age': re-evaluation of an evolving concept. Geografska Annaler: Series A, Phys. Geogr., 2005, 87(1), 17-36.

Beeston M., Reingewertz Y., Paldor N., Polynomial cointegration tests of anthropogenic impact on global warming, Earth Syst. Dynam., 2012, 3(2), 173-188.

Beeston M., Felsenstein D., Frank E., Reingewertz Y., Tide gauge location and the measurement of global sea level rise, Environ. Ecolog. Stat., 2015, 22(1), 179-206.

Boretti A., Short Term Comparison of Climate Model Predictions and Satellite Altimeter Measurements of Sea Levels, Coastal Eng., 2012, 60, 319-322.

Boretti A., Watson T., The inconvenient truth: Ocean Levels are not accelerating in Australia. Energy Environ., 2012, 23(5), 801-817.

Chen X., Feng Y., Huang N.E., Global sea level trend during 1993-2012, Glob. Planet. Change, 2014, 112, 26-32.

Curry J., Sea Level and Climate Change, 2018, curryja.files.wordpress.com/2018/11/special-report-sea-level-rise3.pdf

Dean R.G., Houston J.R., Recent sea level trends and accelerations: comparison of tide gauge and satellite results. Coastal Engineering, 2013, 75, 4-9.
[103] Parker A., The actual measurements at the tide gauges do not support strongly accelerating twentieth-century sea-level rise reconstructions, Nonlin. Eng., 2016, 5(1), 45-71.

[104] Parker A., Ollier C.D., Coastal planning should be based on proven sea level data, Ocean Coast. Manag., 2015, 124, 1-9.

[105] Scafetta N., Multi-scale dynamical analysis (MSDA) of sea level records versus PDO, AMO, and NAO indexes, Climate Dyn., 2014, 43, 175-192.

[106] Schmith T., Johansen S., Thejll P., Statistical analysis of global surface temperature and sea level using cointegration methods, J. Climate, 2012, 25(22), 7822-7833.

[107] Wenzel M., Schröter J., Reconstruction of regional mean sea level anomalies from tide gauges using neural networks, J. Geophys. Res. - Oceans, 2010, 115, C08013.

[108] Wunsch R., Ponte R., Heimbach P., Decadal trends in sea level patterns: 1993-2004, J. Climatol., 2007, 20(24), 5889-5911.