Vertical motion of Pacific Island tide gauges (2023)

Combined analysis from GNSS and levelling

GEOSCIENCE AUSTRALIA
RECORD 2024/09

N. J. Brown[1], A. Lal[2], S. Masoumi[1], S. McClusky[1], A.R. Riddell[1] and G. Hu[1]

1. Geoscience Australia.
2. Pacific Community (SPC).

Department of Industry, Science and Resources
Minister for Resources and Northern Australia: The Hon Madeleine King MP
Secretary: Ms Meghan Quinn PSM

Geoscience Australia
Chief Executive Officer: Dr James Johnson
This paper is published with the permission of the CEO, Geoscience Australia

Geoscience Australia acknowledges the traditional custodians of the country where this work was undertaken. We also acknowledge the support provided by individuals and communities to access the country, especially in remote and rural Australia.

ISSN 2201-702X (PDF)
ISBN 978-1-923084-05-6 (PDF)
eCat 148937

Bibliographic reference: Brown, N. J., Lal, A., Masoumi, S., McClusky, S., Riddell, A.R., and Hu, G, 2024. *Vertical motion of Pacific Island tide gauges (2023): combined analysis from GNSS and levelling*. Record 2024/09. Geoscience Australia, Canberra. https://doi.org/10.26186/148937

Version: 2001

Contents

1 Executive Summary

This Record provides an update on vertical motion of Pacific Island tide gauges results presented in Brown et al, 2020. Since 2020, staff from Geoscience Australia and the Pacific Community (SPC) have continued to observe and analyse Global Navigation Satellite System (GNSS) data and levelling data to extend the time series of land monitoring data.

- Australia has been supporting 13 Pacific Island countries (PICs) to measure, record and analyse long-term sea level and land motion for over 25 years. This is known as the Pacific Sea Level and Geodetic Monitoring (PSLGM) project which is funded by Australian Aid under the Climate and Oceans Support Program in the Pacific (COSPPac).
- The sea level data is collected continuously at one or two tide gauges in each of the 13 PICs. The land motion data is collected continuously at one or two Global Navigation Satellite System (GNSS) stations in each of the 13 PICs. The height difference between the tide gauges and GNSS stations is observed once every 18 months (approximately). The data is then analysed to produce sea level information-based products (e.g. tide calendars) and to inform about motion of the land (e.g. for coastal infrastructure planning).
- The PSLGM project involves Australian science agencies (Bureau of Meteorology (Bureau) and Geoscience Australia (GA)) working in partnership with regional organisations (Pacific Community (SPC)), and Pacific government ministries (meteorology and land and survey departments).
- This GA Record reports findings regarding the absolute vertical rate of movement (i.e. the rate at which the land is moving up or down with respect to the centre of the Earth) of 13 Pacific Island Countries tide gauges over the period 2003 – 2022 based on the analysis of Global Navigation Satellite System (GNSS) data and levelling data.
- The tide gauges of five (5) Pacific Island Countries (Papua New Guinea, Samoa, Solomon Islands, Tonga and Tuvalu) have a negative absolute vertical rate of movement (i.e. the tide gauges are moving closer to the centre of the Earth) (Figure 1).
- The tide gauges of Samoa and Tonga have experienced the largest negative absolute vertical rates of movement with the heights of the tide gauges decreasing by 7.8 mm/yr and 7.2 mm/yr respectively since 2010. The tide gauges of Papua New Guinea, Solomon Islands and Tuvalu have negative absolute vertical rates of movement between 1.3 mm/yr and 2.4 mm/yr.
- The tide gauges in Cook Islands, Federated States of Micronesia, Fiji, Kiribati, Nauru, Niue, and Republic of the Marshall Islands have a vertical rate of movement that is not greater than the uncertainty of the data. In these cases, either the absolute vertical rate of movement of the tide gauge is close to zero, or a longer time series of data is needed to better understand the absolute vertical rate of movement of the tide gauge.
- The tide gauge in Vanuatu has experienced a positive absolute vertical rate of movement (i.e. the tide gauge is moving away from the centre of the Earth) (Figure 1) by 3.5 mm/yr.

- The results presented in this report do not include information regarding changes in sea level. The Bureau is currently analysing and linking the land motion data from this report with tide gauge data to create an absolute sea level data set for PICs to improve their understanding of sea level changes.
- Relative sea level is what is experienced by people living on the islands. Changes in relative sea level are caused by changes in the height of the land and the water. At locations where the absolute vertical rate of movement of the tide gauge is negative, the impacts of sea level rise experienced may be compounded.
- The new analysis will be used to update the results of Pacific Sea Level and Geodetic Monitoring website (available at https://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/pacificsealevel).

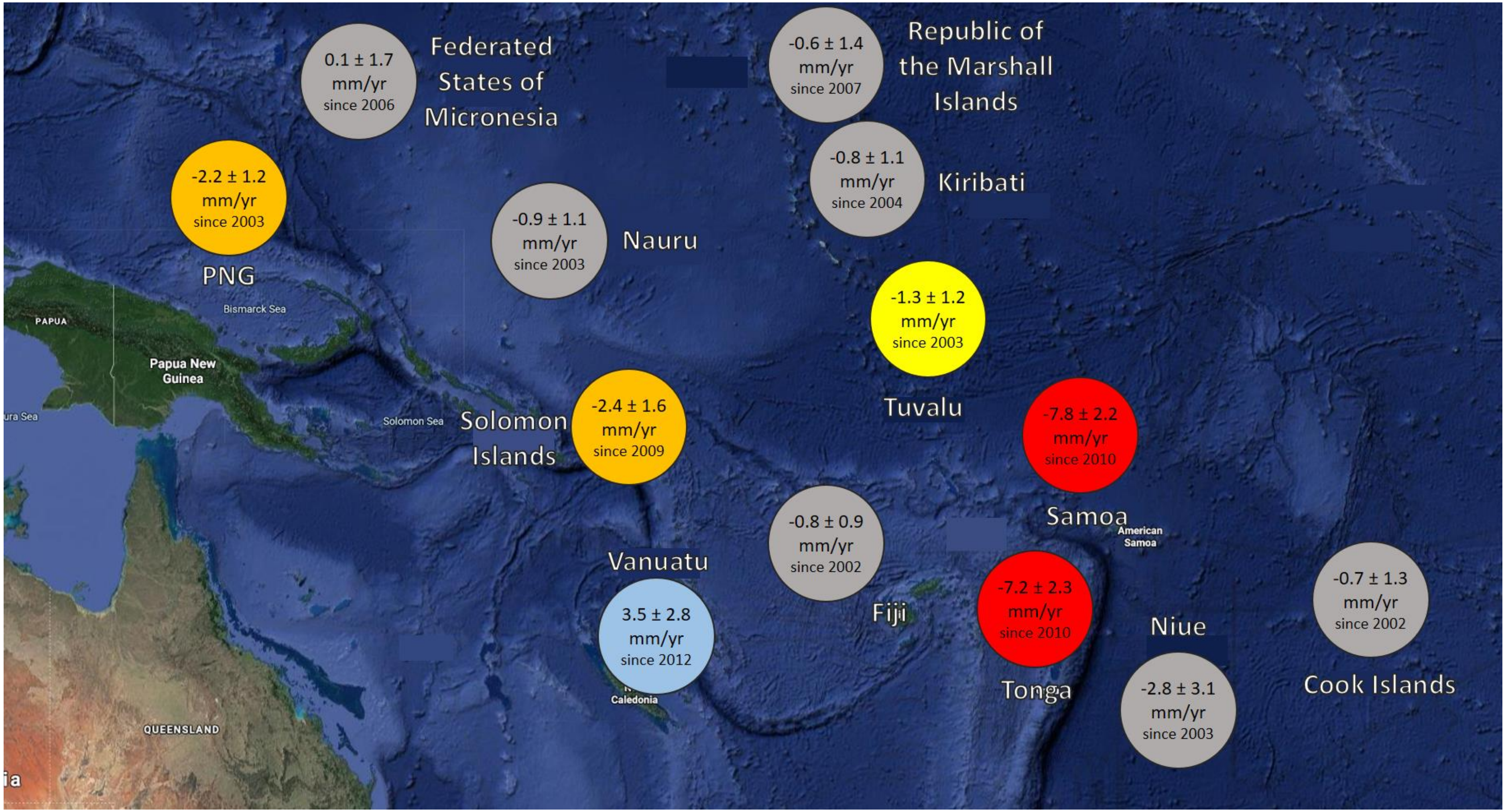


Figure 1: Absolute vertical rate of movement of the tide gauge in Pacific Island countries. For example, in Solomon Islands, -2.4 mm/yr represents the rate of movement of the tide gauge and ± 1.6 mm/yr represents the uncertainty in the rate of movement. Grey circles represent sites which have an absolute vertical rate of movement that is not greater than the uncertainty of the data. In these cases, either the absolute vertical rate of movement of the tide gauge is close to zero, or a longer time series of data is needed to better understand the absolute vertical rate of movement of the tide gauge.

2 Introduction

Operating under the Climate and Oceans Support Program in the Pacific (COSPPac), the Australian Aid funded Pacific Sea Level and Geodetic Monitoring (PSLGM) Project (the Project) is working towards generating an accurate record of the absolute and relative sea level in 13 countries throughout the Pacific (Figure 2).

The network of sea-level stations in the Pacific was established in the early 1990s. The Project is focused on determining the long-term variation in sea level through observation and analysis of sea level using tide gauges (managed and operated by the Bureau of Meteorology (Bureau)) and changes in the height of the land using Global Navigation Satellite System (GNSS) data (managed by Geoscience Australia (GA)) and levelling data (managed by Pacific Community (SPC)).

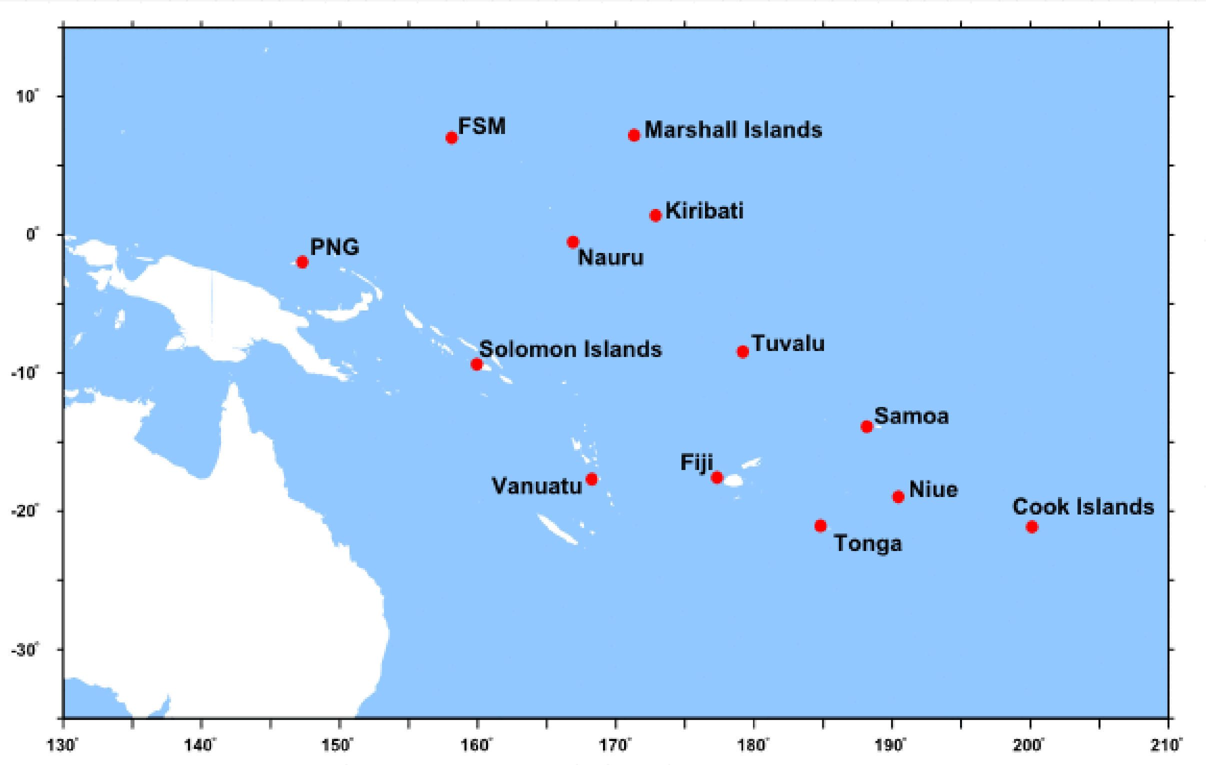


Figure 2: The 13 Pacific Island countries hosting both GNSS and tide gauge infrastructure are the Cook Islands, Federated States of Micronesia, Fiji, Kiribati, Nauru, Niue, Papua New Guinea, Republic of Marshall Islands, Samoa, Solomon Islands, Tonga, Tuvalu and Vanuatu.

2.1 Measuring absolute vertical motion of tide gauges

Absolute sea level height refers to the height of sea level with respect to the centre of the Earth. Tide gauges do not measure absolute sea level, instead they measure relative sea level variation. Relative sea level refers to the rise or fall of sea level with respect to a local reference point (e.g. the tide gauge sensor or a line etched into the pylon of a wharf). Relative sea level is what is experienced by people living on the islands and it will vary according to a combination of steric change (e.g. thermal expansion), eustatic change (e.g. ice melt) and changes to land height (e.g. subsidence, earthquake).

At locations where the absolute vertical rate of movement of the tide gauge is negative, the impacts of sea level rise experienced may be compounded.

A tide gauge alone cannot differentiate between changes in the steric / eustatic sea level and movement of the land or wharf the tide gauge is attached to. For example, refer to Figure 3. If a tide gauge is observing 5 mm/yr rise in sea level, we are unable to distinguish whether the land to which the tide gauge is connected is subsiding by 5 mm/yr (Figure 3i), the sea level is rising by 5 mm/yr (Figure 3ii), or some combination of both.

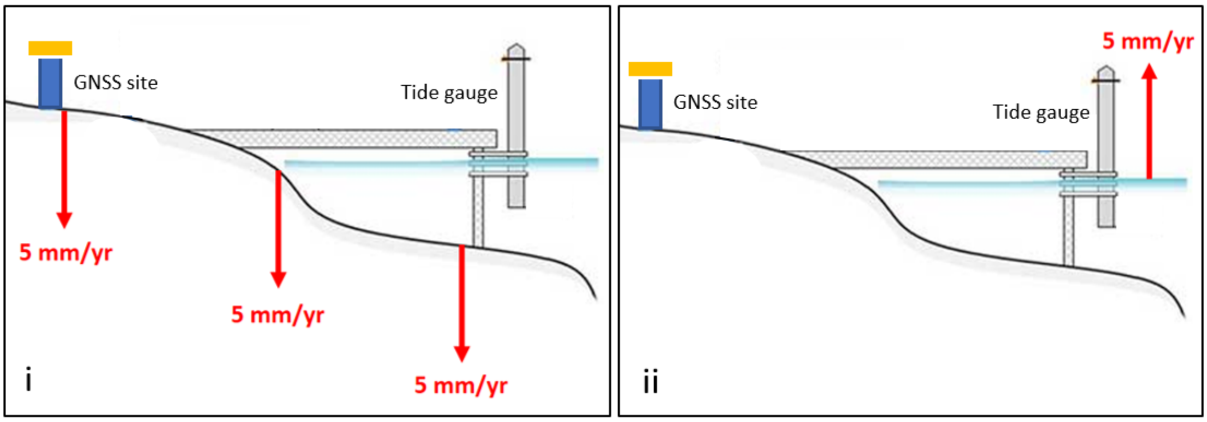


Figure 3: [i] land subsiding at a rate of 5 mm/yr with no change to absolute sea level; [ii] absolute sea level rising by 5 mm/yr and no movement of the land.

To distinguish between relative and absolute sea level variation from tide gauge data, it is necessary to know the movement of the tide gauge in an absolute frame of reference. The absolute frame of reference we use is the centre of the Earth. To measure the absolute movement of the tide gauge we use a combination of GNSS data and levelling data.

In the Pacific Island countries described in this report, a GNSS site is located within 1-5 km of the tide gauge. At these GNSS sites, it is possible to determine the absolute height of the GNSS site (Figure 4).

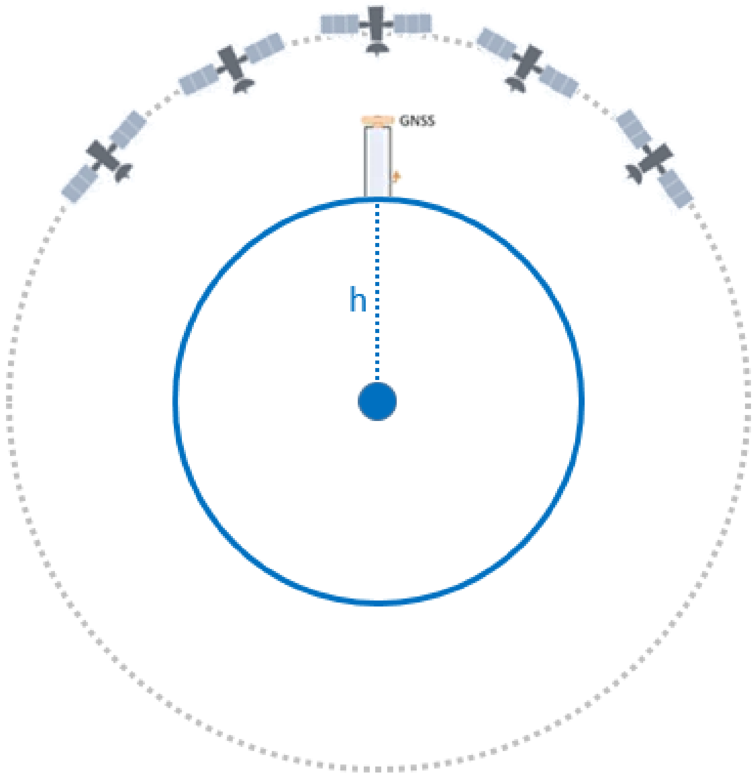


Figure 4: GNSS heights can be measured with respect to the centre of the Earth.

GNSS equipment is able to observe changes in the height of the land over time with precision of a few millimetres. For example, as shown in Figure 5, between 2002 and 2009 the GNSS site in Apia, Samoa observed very little vertical land motion. In 2009, Apia experienced an earthquake which caused the land to drop closer to the centre of the Earth by approximately 60 mm over 6 months and since that time the land has continued to move closer to the centre of the Earth by approximately 8 mm/yr.

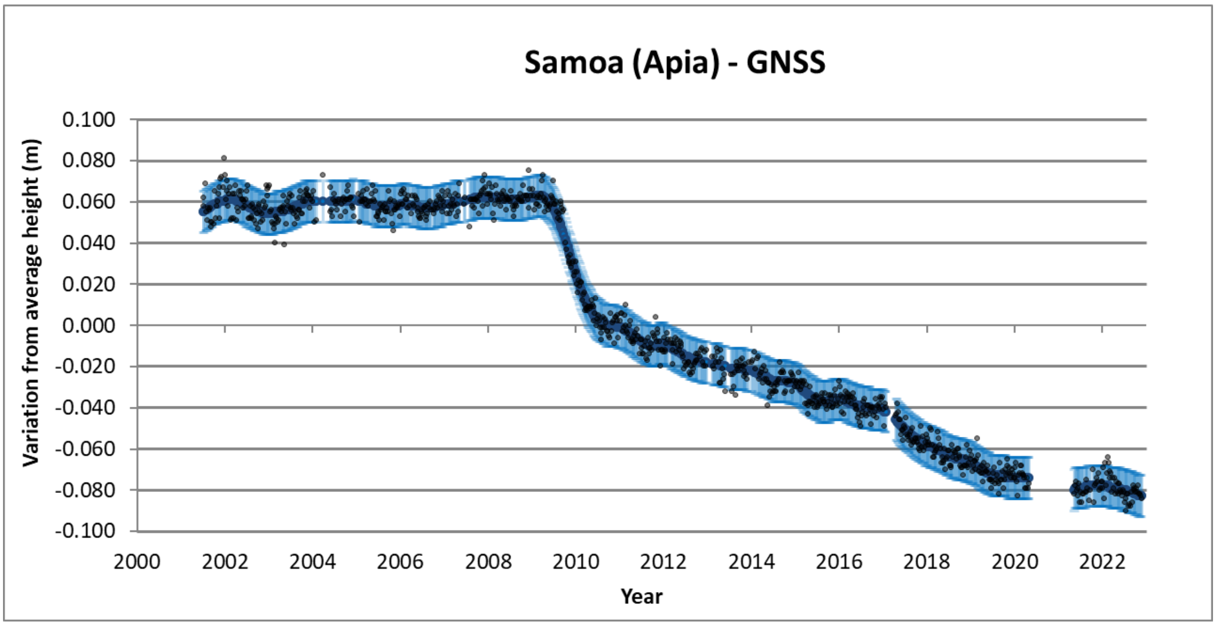


Figure 5: Change in the height of the Apia GNSS site with respect to the centre of the Earth. The grey dots are the height of the GNSS site every week with respect to the centre of the Earth. The dark blue line is a smoothed representation of the weekly data and the light blue error bars show the 95% Confidence Interval. See Section 3 for GNSS analysis methodology.

This downward motion of the land does not necessarily mean the tide gauge is experiencing the same motion, because in the case of Apia, the GNSS site is approximately 5 km from the tide gauge. To monitor the absolute height of the tide gauge, the height difference between the GNSS site and tide gauge is computed every 18 months in each country (Figure 6). This height difference is added to the GNSS height at the time of the levelling survey to compute the absolute height of the tide gauge (i.e. with respect to the centre of the Earth).

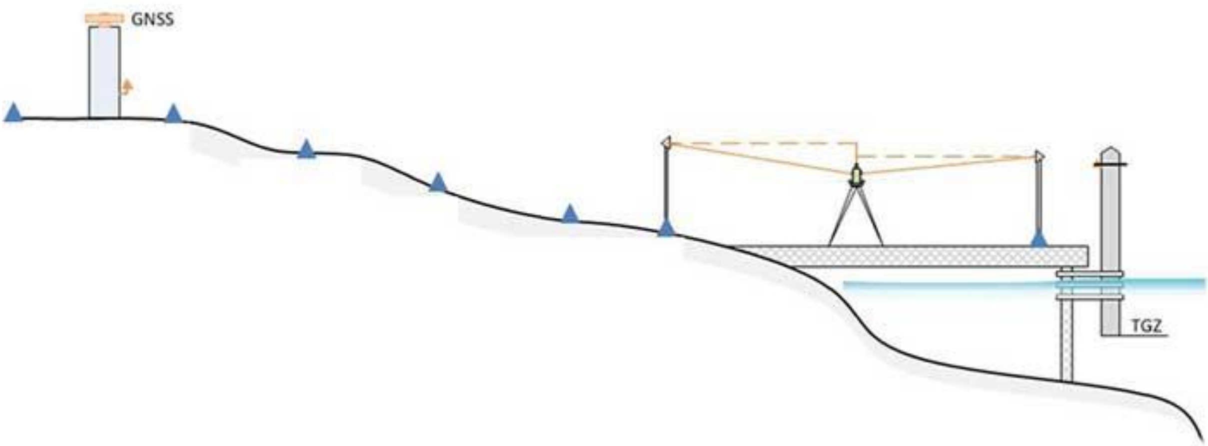


Figure 6: Levelling is undertaken every 18 months to compute the difference in height between the GNSS site and tide gauge. The blue triangles represent stable survey marks in the ground. Observations are made between each of the survey marks and added together to compute the difference in height between the GNSS site and tide gauge.

In the case of Apia, the absolute height of the tide gauge (Figure 7) is varying similarly to the GNSS site. Since 2010, the Samoa tide gauge has experienced a negative absolute vertical rate of movement of 8 mm/yr.

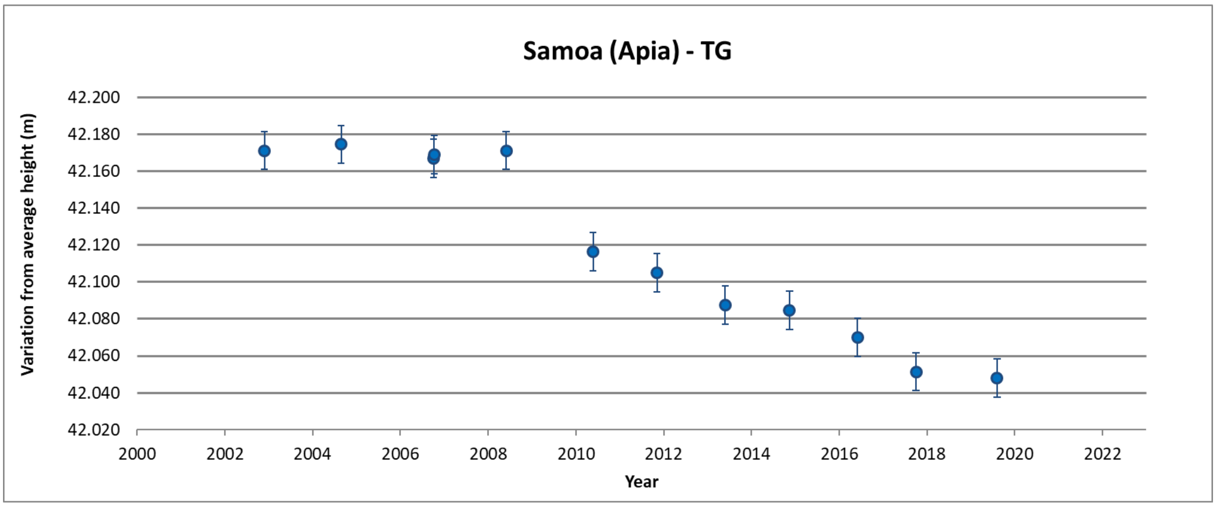


Figure 7: Change in the absolute height of the Apia tide gauge. The error bars show the 95% Confidence Interval.

3 Data and Analysis

3.1 GNSS analysis

The GNSS data is captured using infrastructure managed by GA and SPC in each of the 13 countries and transmitted back to GA for analysis. GA computes the three-dimensional position of the GNSS site every week with respect to the centre of the Earth. The weekly height component of the three-dimensional position varies predominantly due to a combination of land motion (e.g. subsidence, earthquake) and atmospheric noise.

Given that it is difficult to determine week-to-week whether the variability in the height is related to Earth movement or atmospheric noise (and other sources of error), a smoothing process is applied to the height measurements to provide a smoother trend of the site motion. The smoothed model (quadratic polynomial) is fitted to the weekly height measurements using a ‘locally weighted linear regression’ (Loess)[1].

The error bars shown in Figure 5 are a 95% Confidence Interval and are computed from a combination of the weekly analysis and the smoothing function. To compute 95% Confidence Interval, the one sigma uncertainty from the Loess smoothing process was multiplied by a coverage factor of two. This 95% Confidence Interval means that we are 95% confident the height of the GNSS site is within the height range reported.

A more detailed description of the GNSS analysis process is provided in Appendix A.

3.2 Levelling analysis

The differential levelling technique has been used for all surveys to compute the height difference between the GNSS site and tide gauge every 18 months in each country. This technique involves setting up a total station (surveying instrument) midway between two targets and computing the height difference between survey marks in the ground (see blue triangles in Figure 6). By summing the height differences between all the survey marks, we are able to compute the height difference between the GNSS site and tide gauge and thereby compute the absolute height of the tide gauge. By observing the height difference in both directions (from tide gauge to GNSS site and then reversed), we can confirm the quality of the results.

3.3 Combination analysis

To compute the absolute movement of the tide gauge, the analysis of the GNSS and levelling is combined together. This is done by:

1. Taking the smoothed GNSS height on the day the levelling survey is undertaken (e.g. on 2019.6, the height of the Apia GNSS pillar plate was 76.807 m);

[1] https://au.mathworks.com/help/curvefit/smoothing-data.html#bq_6zbc

2. Adding the levelled height difference between the GNSS pillar plate and tide gauge (-34.759 m) to the smoothed GNSS height (76.807 m) to compute the absolute height of the tide gauge (42.048 m).

3. Repeat this analysis for each set of levelling data (e.g. Table 1).

Table 1: Summary of height difference between the GNSS site and tide gauge for Apia. The date is shown in decimal years (e.g. 2012.58 = 1 July 2012).

Date	GNSS Height (m)	Height Difference (m)	Tide Gauge Height (m)	95%c CI (m)
2002.90	76.9229	-34.7517	42.1712	0.010
2004.65	76.9289	-34.7544	42.1745	0.010
2006.76	76.9259	-34.7588	42.1671	0.010
2006.77	76.9259	-34.7569	42.1690	0.010
2008.41	76.9299	-34.7587	42.1712	0.010
2010.39	76.8749	-34.7585	42.1164	0.010
2011.85	76.8589	-34.7537	42.1052	0.010
2013.40	76.8489	-34.7613	42.0876	0.010
2014.87	76.8409	-34.7562	42.0847	0.010
2016.42	76.8299	-34.7598	42.0701	0.010
2017.75	76.8139	-34.7624	42.0515	0.010
2019.60	76.8069	-34.7590	42.0479	0.010

4. Compute the 95% Confidence Interval of the combined GNSS and levelling analysis (e.g. Table 1). This means the uncertainty of the GNSS height is combined with the uncertainty of the levelling. In the case of the levelling undertaken on 2019.60, the combined uncertainty is 0.010 m.

5. Compute the absolute vertical rate of movement (and uncertainty) of each tide gauge (see Section 4).

The results presented in this report do not include information regarding the changes in sea level. The Bureau is currently analysing and linking the absolute land motion data from this report with tide gauge data to create an absolute sea level data set for PICs to improve their understanding of sea level changes.

4 Results

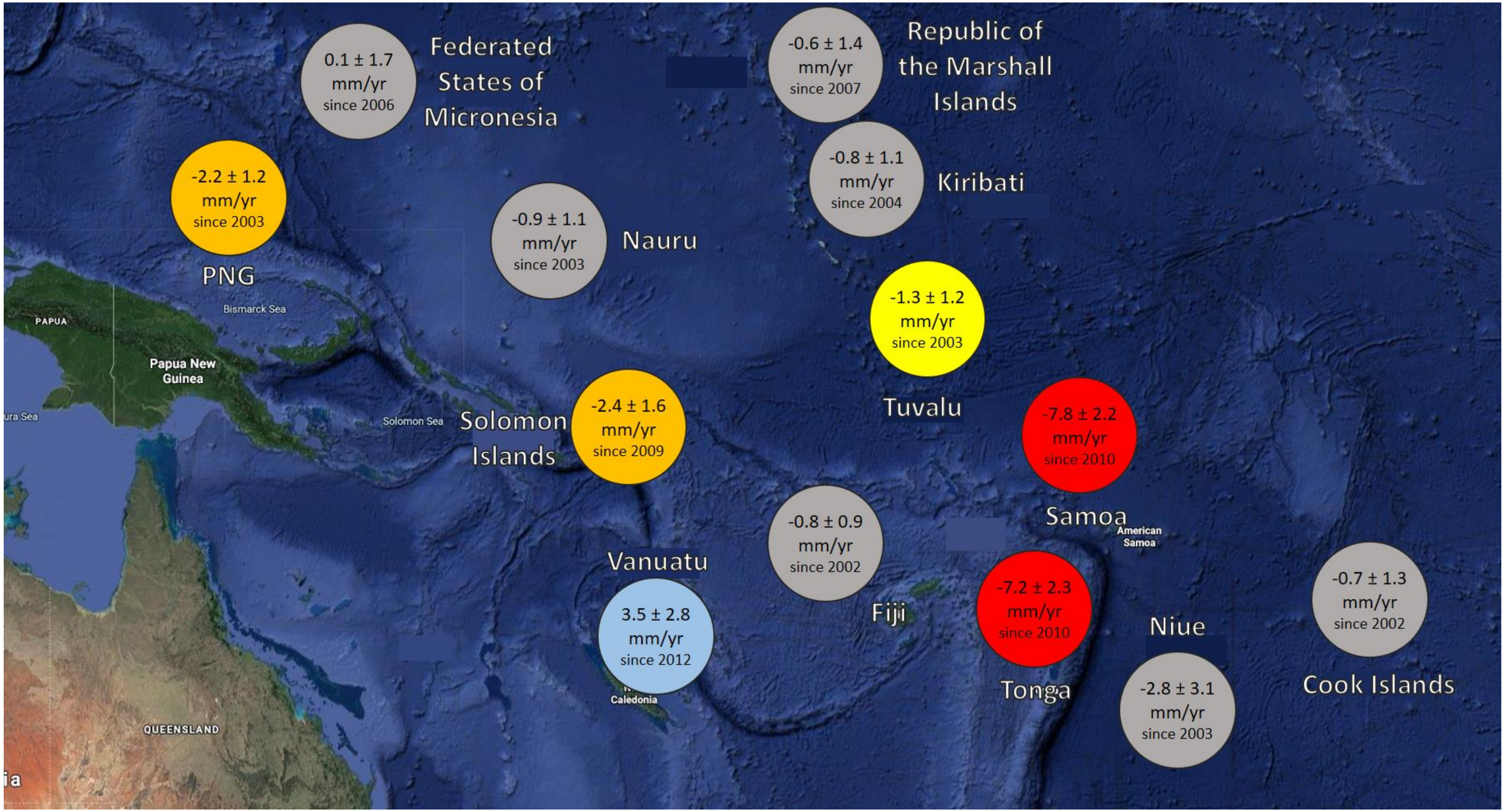


Figure 8: Absolute vertical rate of movement of the tide gauge in Pacific Island countries. For example, in Kiribati, -2.1 mm/yr represents the rate of movement of the tide gauge and ±1.5 mm/yr represents the uncertainty in the rate of movement. Grey circles represent sites which have an absolute vertical rate of movement that is not greater than the uncertainty of the data. In these cases, either the absolute vertical rate of movement of the tide gauge is close to zero, or a longer time series of data is needed to better understand the absolute vertical rate of movement of the tide gauge.

4.1 Preliminaries

- As shown in some of the GNSS height and tide gauge height time series figures below, short term variations in the height of the GNSS site and tide gauge mean a linear regression model is often too simplistic to accurately estimate the height at a particular point in time.
- A linear regression therefore should not be used for estimating sea level variation at a particular point in time. Linear regression has only been used to provide approximate long-term trends to guide discussion on the topic.
- There are often transient movements of land after a strong earthquake (e.g. Apia) than may stop or reverse after a few years. This should be considered when studying the short-term vertical land motion.
- In cases where the uncertainty of the trend in the data is greater than the trend, the tide gauge movement should be assumed to be negligible at 0 mm/yr. In these cases:
    - there is no statistically significant movement observable of the tide gauge over time;
    - the time series of the GNSS and levelling data needs to be extended;
    - the uncertainty in the GNSS data and / or levelling data needs to be reduced, and / or;
    - a more detailed site specific analysis of the data needs to be undertaken.

4.2 Cook Islands

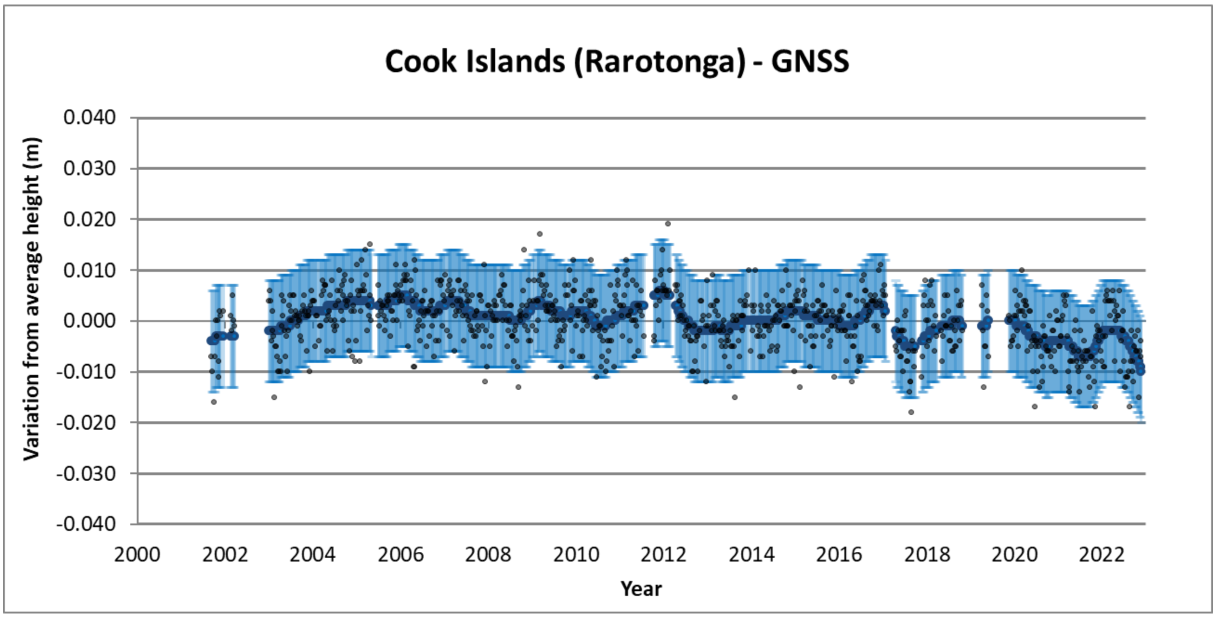


Figure 9: Change in the height of the GNSS site with respect to the centre of the Earth. The grey dots are the height of the GNSS site every week with respect to the centre of the Earth. The dark blue line is a smoothed representation of the weekly data and the light blue error bars show the 95% Confidence Interval.

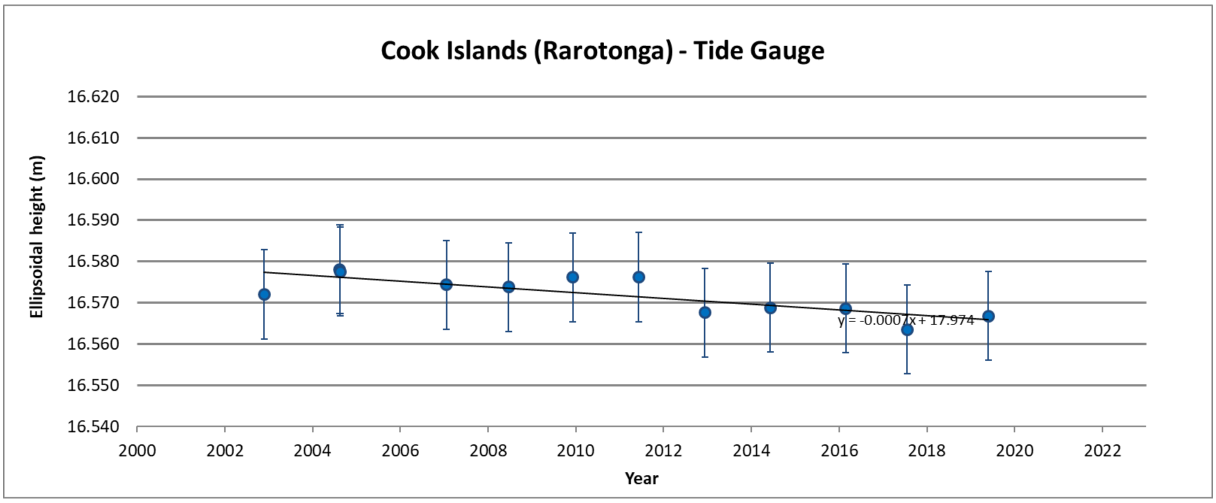


Figure 10: Change in the ITRF2020 ellipsoidal height of the tide gauge. The error bars show the 95% Confidence Interval.

NOTES:

- Linear regression of the tide gauge height data indicate the tide gauge movement is -0.7 ± 1.3 mm/yr at 95% Confidence Interval.
- This uncertainty is greater than the trend. This means the tide gauge movement is not certain.
- Tide gauge movement for absolute sea level analysis should be assumed to be 0 mm/yr until the time series is extended, the uncertainty in the GNSS data or levelling data is reduced, or both.

Table 2: ITRF2020 ellipsoidal height of the tide gauge sensor benchmark (SBM).

Date	TG SBM ellipsoidal height (m)
2002.90	16.5720
2004.62	16.5781
2004.63	16.5775
2007.05	16.5743
2008.47	16.5738
2009.93	16.5761
2011.43	16.5762
2012.94	16.5676
2014.43	16.5688
2016.15	16.5686
2017.55	16.5635
2019.40	16.5668

4.3 Federated States of Micronesia

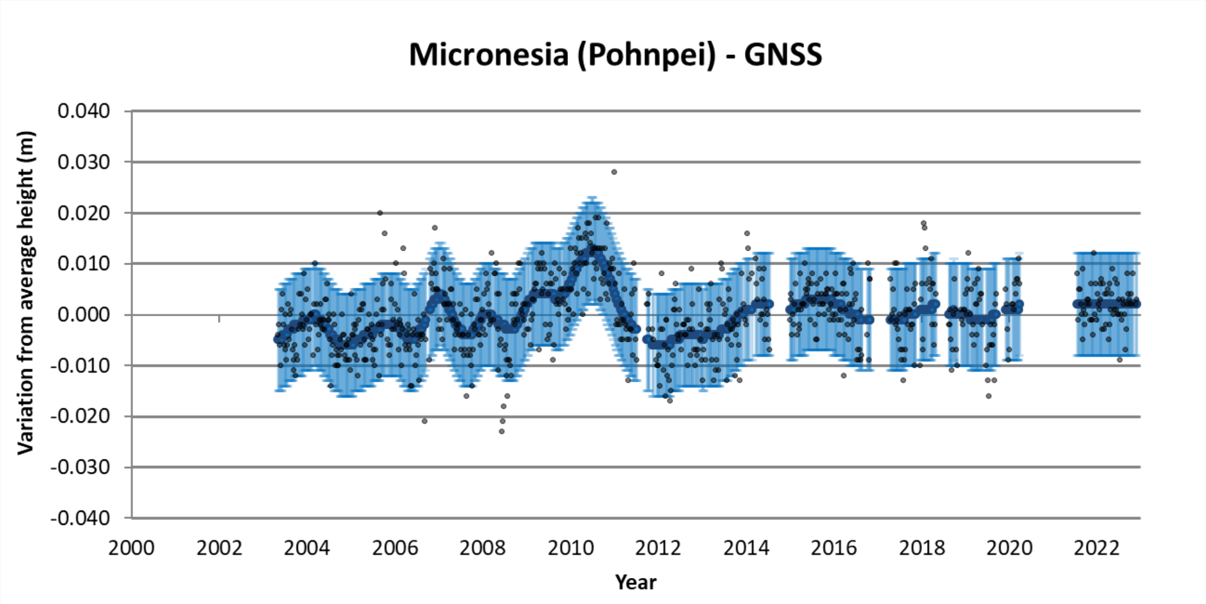


Figure 11: Change in the height of the GNSS site with respect to the centre of the Earth. The grey dots are the height of the GNSS site every week with respect to the centre of the Earth. The dark blue line is a smoothed representation of the weekly data and the light blue error bars show the 95% Confidence Interval.

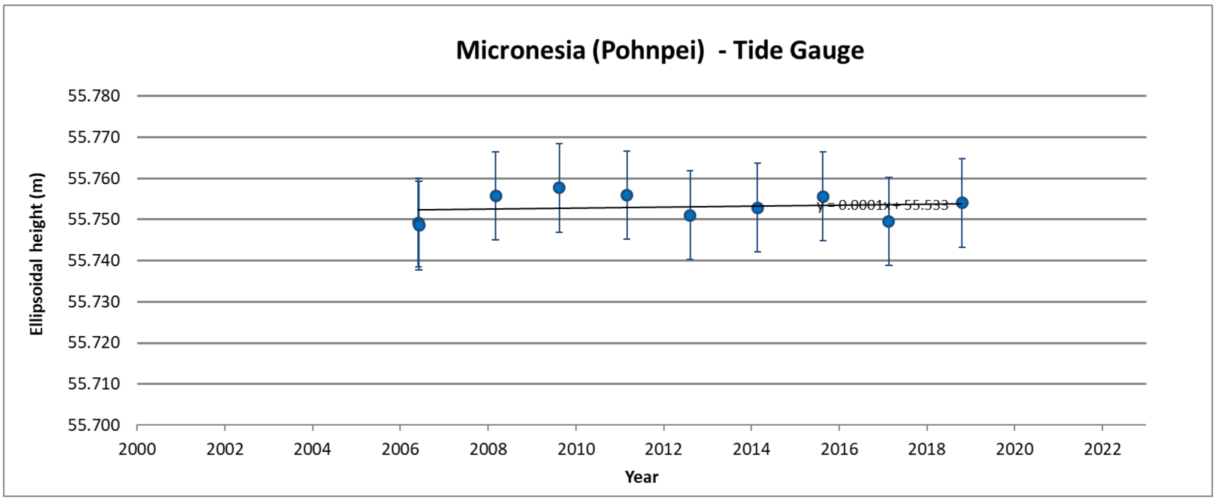


Figure 12: Change in the ITRF2020 ellipsoidal height of the tide gauge. The error bars show the 95% Confidence Interval.

NOTES:

- Linear regression of the tide gauge height data indicate the tide gauge movement is 0.1 ± 1.7 mm/yr at 95% Confidence Interval.
- This uncertainty is greater than the trend. This means the tide gauge movement is not certain.
- Tide gauge movement for absolute sea level analysis should be assumed to be 0 mm/yr until the time series is extended, the uncertainty in the GNSS data or levelling data is reduced, or both.

Table 3: ITRF2020 ellipsoidal height of the tide gauge sensor benchmark (SBM).

Date	TG SBM ellipsoidal height (m)
2006.41	55.7492
2006.42	55.7485
2008.17	55.7557
2009.62	55.7577
2011.16	55.7559
2012.60	55.7510
2014.14	55.7528
2015.63	55.7556
2017.13	55.7495
2018.80	55.7540

4.4 Fiji

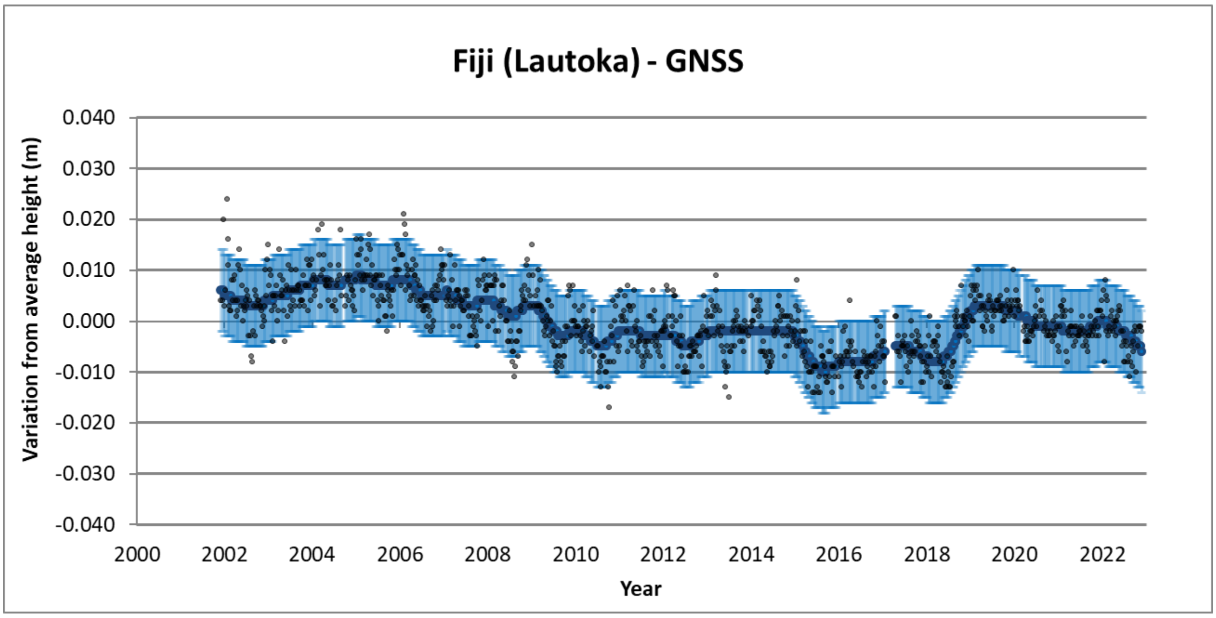


Figure 13: Change in the height of the GNSS site with respect to the centre of the Earth. The grey dots are the height of the GNSS site every week with respect to the centre of the Earth. The dark blue line is a smoothed representation of the weekly data and the light blue error bars show the 95% Confidence Interval.

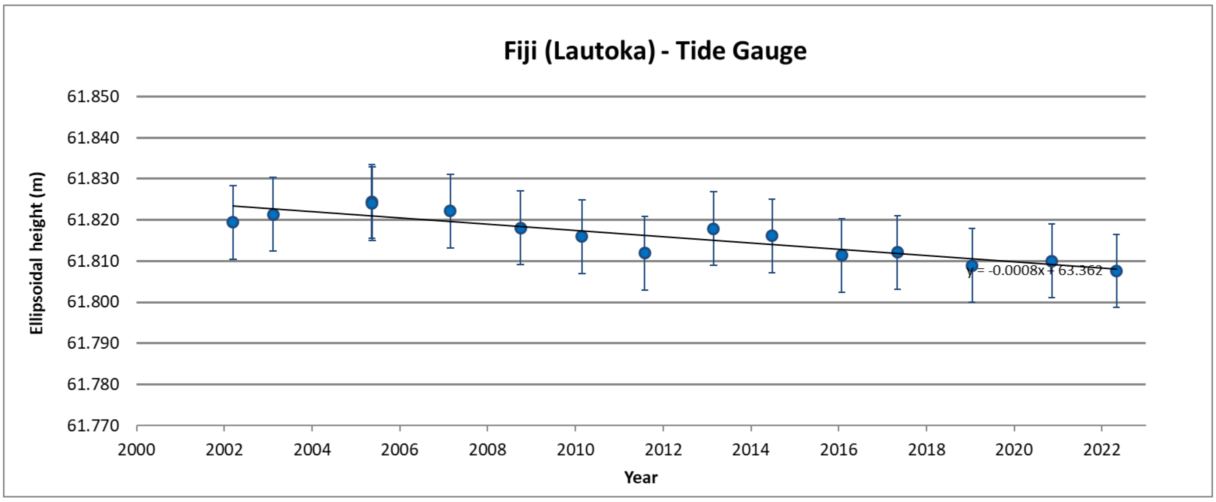


Figure 14: Change in the ITRF2020 ellipsoidal height of the tide gauge. The error bars show the 95% Confidence Interval.

NOTES:

- Linear regression of the tide gauge height data indicate the tide gauge movement is -0.8 ± 0.9 mm/yr at 95% Confidence Interval.
- This uncertainty is greater than the trend. This means the tide gauge movement is not certain.
- Tide gauge movement for absolute sea level analysis should be assumed to be 0 mm/yr until the time series is extended, the uncertainty in the GNSS data or levelling data is reduced, or both.

Table 4: ITRF2020 ellipsoidal height of the tide gauge sensor benchmark (SBM).

Date	TG SBM ellipsoidal height (m)
2002.20	61.8195
2003.11	61.8214
2005.36	61.8245
2005.37	61.8240
2007.15	61.8222
2008.75	61.8181
2010.15	61.8160
2011.58	61.8120
2013.15	61.8179
2014.48	61.8162
2016.07	61.8114
2017.34	61.8122
2019.04	61.8090
2020.86	61.8100
2022.33	61.8076

4.5 Kiribati

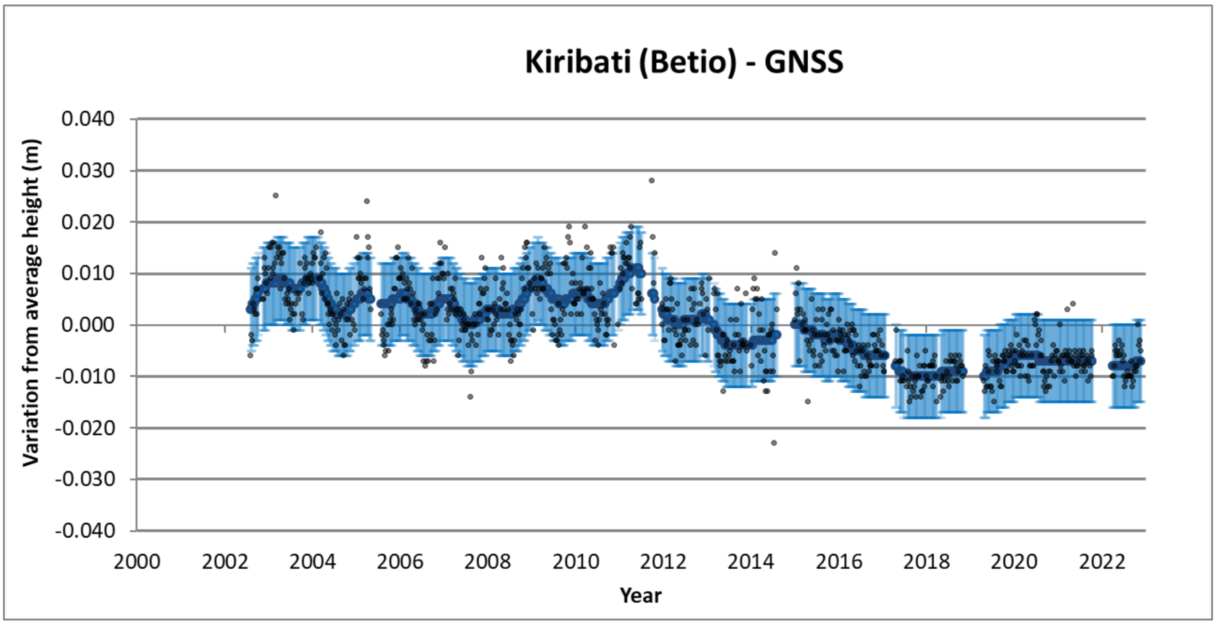


Figure 15: Change in the height of the GNSS site with respect to the centre of the Earth. The grey dots are the height of the GNSS site every week with respect to the centre of the Earth. The dark blue line is a smoothed representation of the weekly data and the light blue error bars show the 95% Confidence Interval.

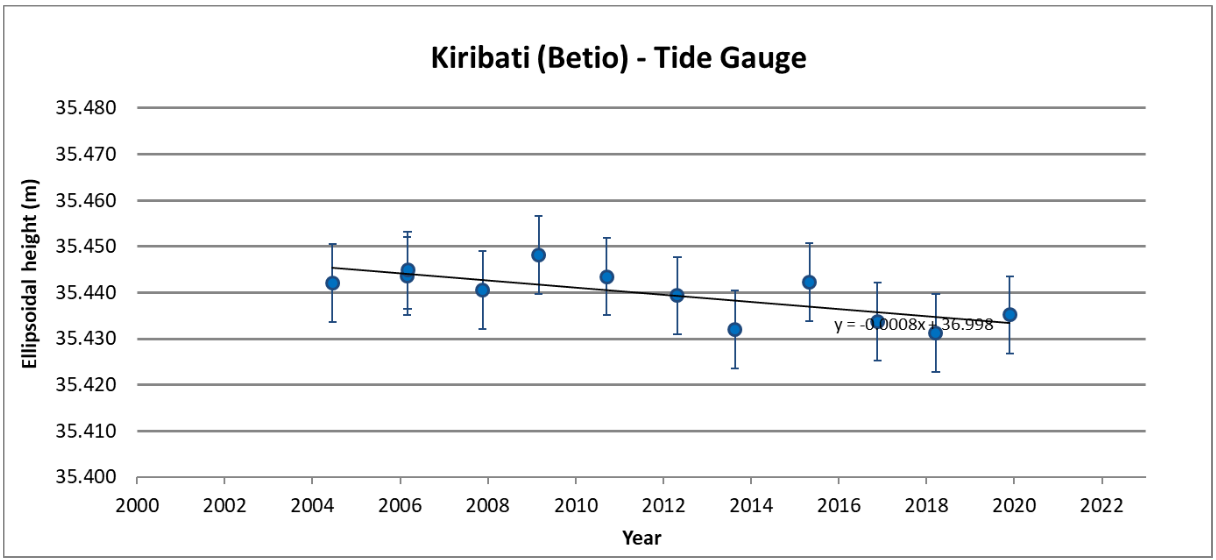


Figure 16: Change in the ITRF2020 ellipsoidal height of the tide gauge. The error bars show the 95% Confidence Interval.

NOTES:

- Linear regression of the tide gauge height data indicate the tide gauge movement is -0.8 ± 1.1 mm/yr at 95% Confidence Interval.
- This uncertainty is greater than the trend. This means the tide gauge movement is not certain.

- Tide gauge movement for absolute sea level analysis should be assumed to be 0 mm/yr until the time series is extended, the uncertainty in the GNSS data or levelling data is reduced, or both.

Table 5: ITRF2020 ellipsoidal height of the tide gauge sensor benchmark (SBM).

Date	TG SBM ellipsoidal height (m)
2004.46	35.4421
2006.16	35.4436
2006.17	35.4449
2007.88	35.4406
2009.16	35.4482
2010.71	35.4435
2012.32	35.4394
2013.63	35.4321
2015.33	35.4423
2016.88	35.4338
2018.21	35.4312
2019.90	35.4352

4.6 Papua New Guinea

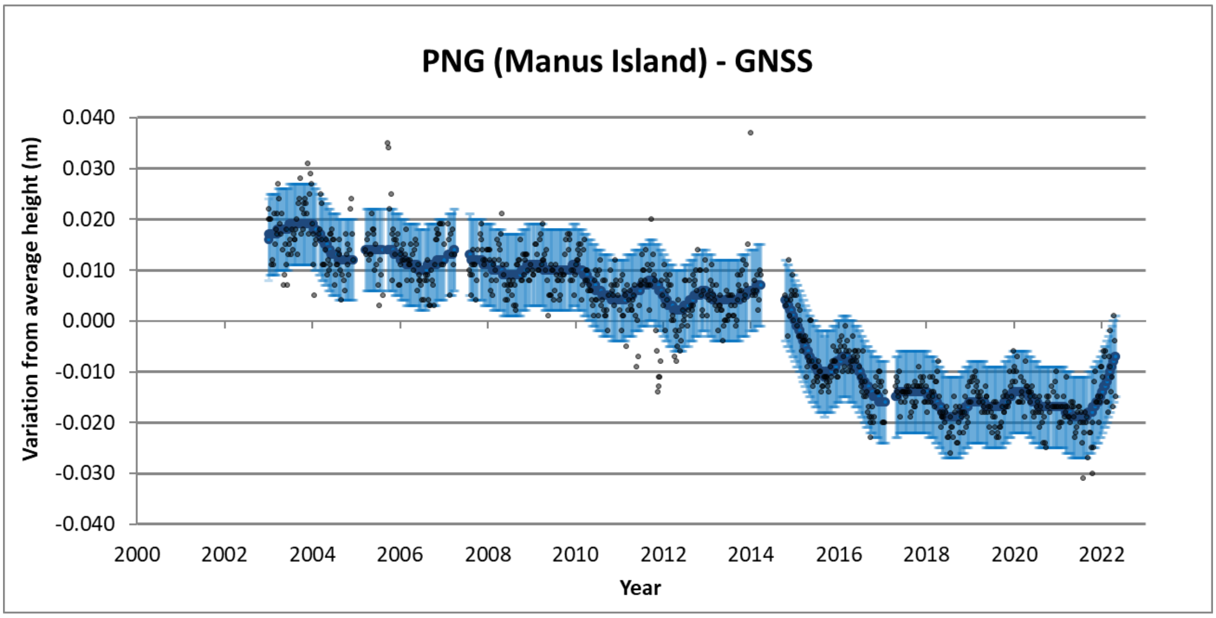


Figure 17: Change in the height of the GNSS site with respect to the centre of the Earth. The grey dots are the height of the GNSS site every week with respect to the centre of the Earth. The dark blue line is a smoothed representation of the weekly data and the light blue error bars show the 95% Confidence Interval.

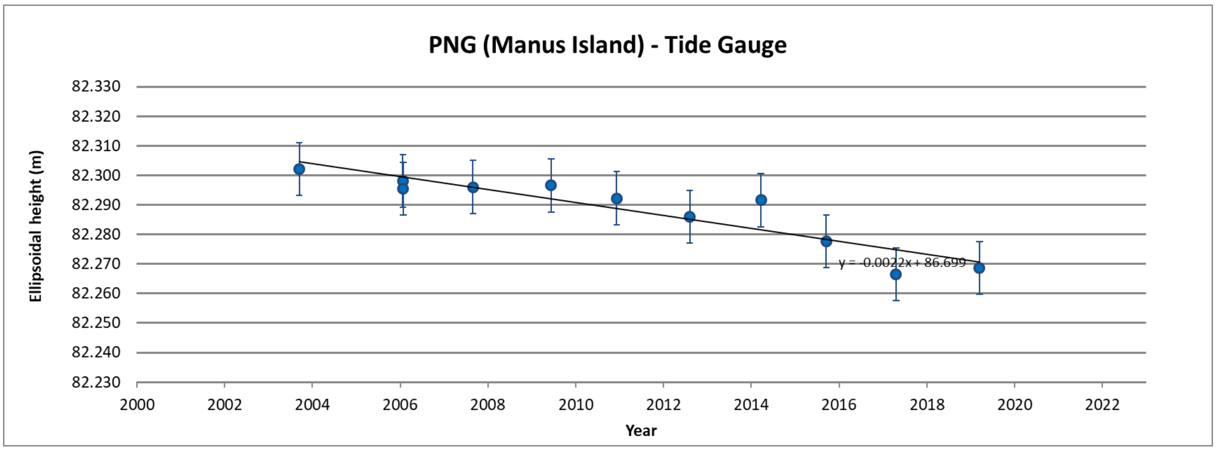


Figure 18: Change in the ITRF2020 ellipsoidal height of the tide gauge. The error bars show the 95% Confidence Interval.

NOTES:

- Linear regression of the tide gauge height data indicate the tide gauge movement is -2.2 ± 1.2 mm/yr at 95% Confidence Interval.

Table 6: ITRF2020 ellipsoidal height of the tide gauge sensor benchmark (SBM).

Date	TG SBM ellipsoidal height (m)
2003.70	82.3021
2006.06	82.2981
2006.07	82.2955
2007.66	82.2961
2009.44	82.2966
2010.93	82.2923
2012.60	82.2860
2014.22	82.2916
2015.71	82.2777
2017.30	82.2666
2019.20	82.2687

4.7 Samoa

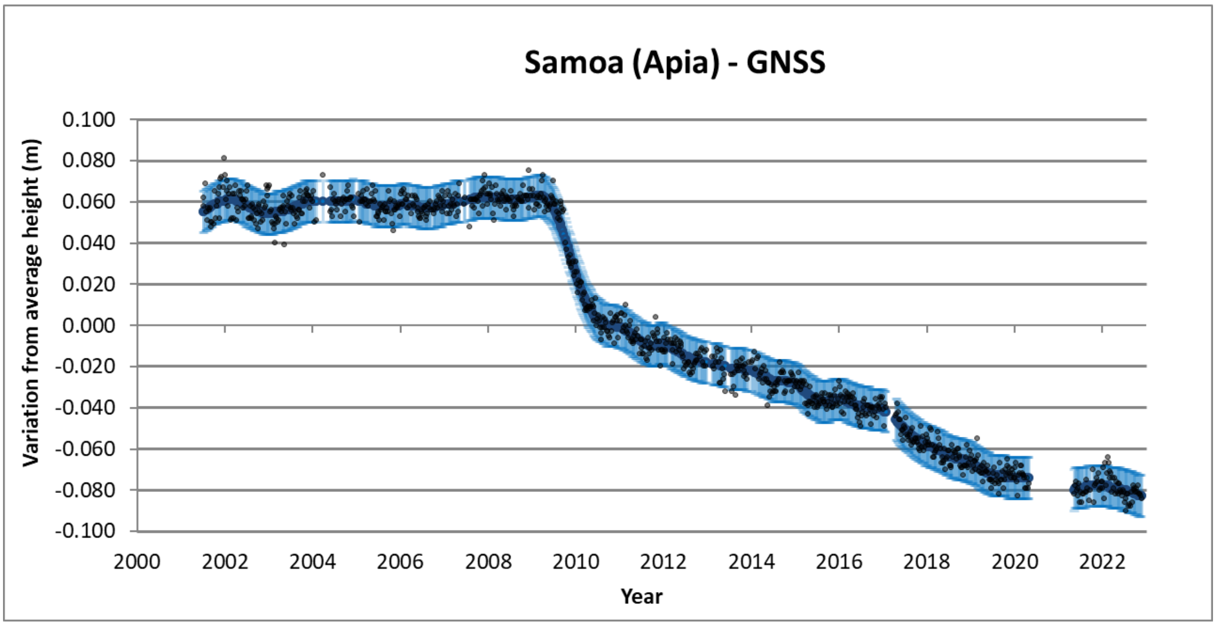


Figure 19: Change in the height of the GNSS site with respect to the centre of the Earth. The grey dots are the height of the GNSS site every week with respect to the centre of the Earth. The dark blue line is a smoothed representation of the weekly data and the light blue error bars show the 95% Confidence Interval.

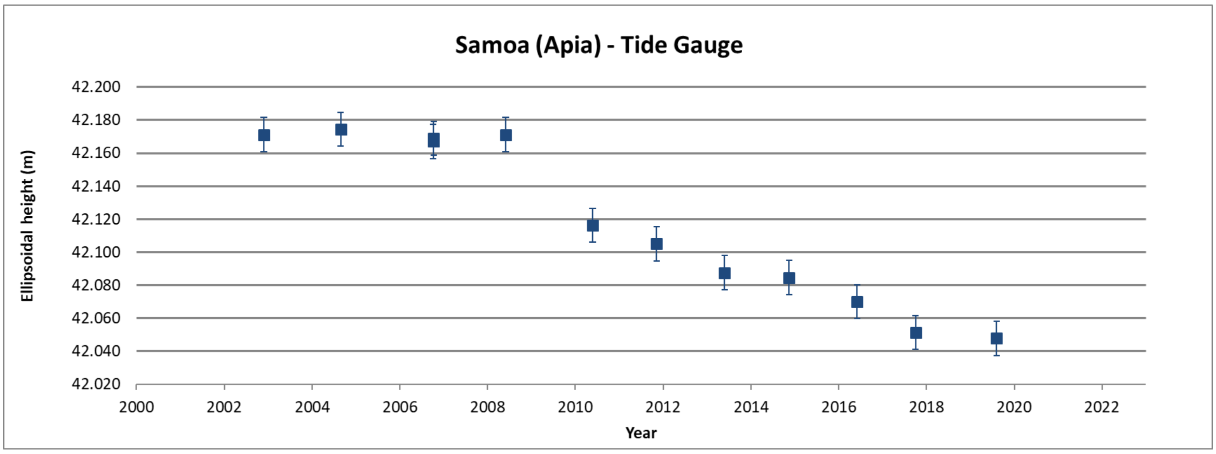


Figure 20: Change in the ITRF2020 ellipsoidal height of the tide gauge. The error bars show the 95% Confidence Interval.

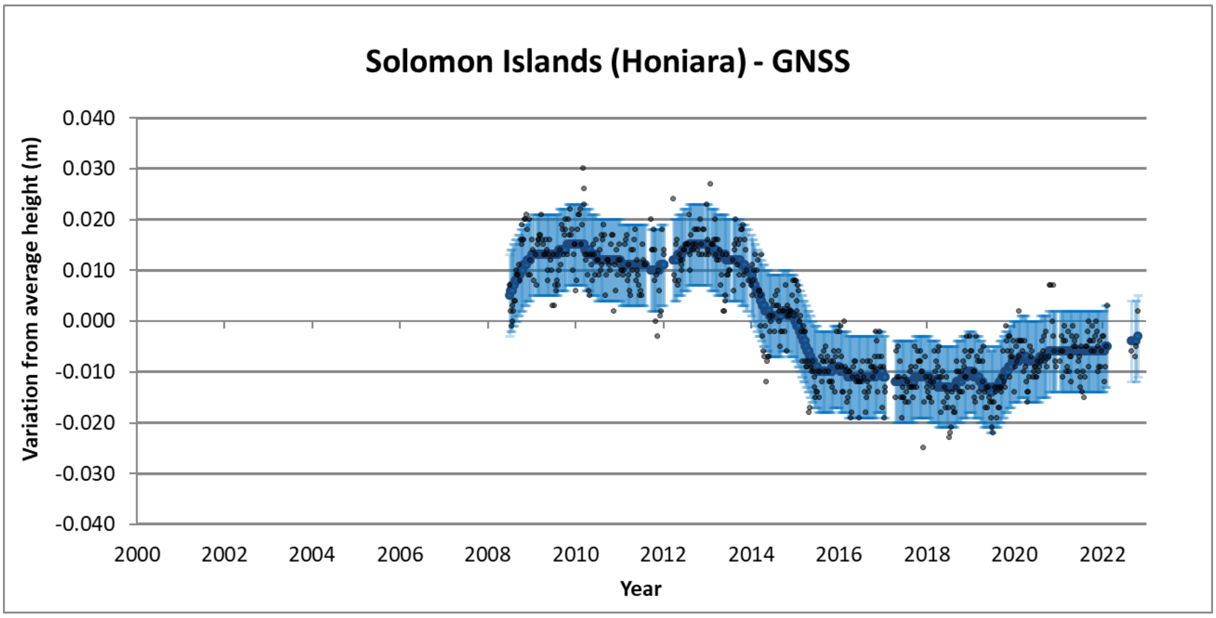
NOTES:

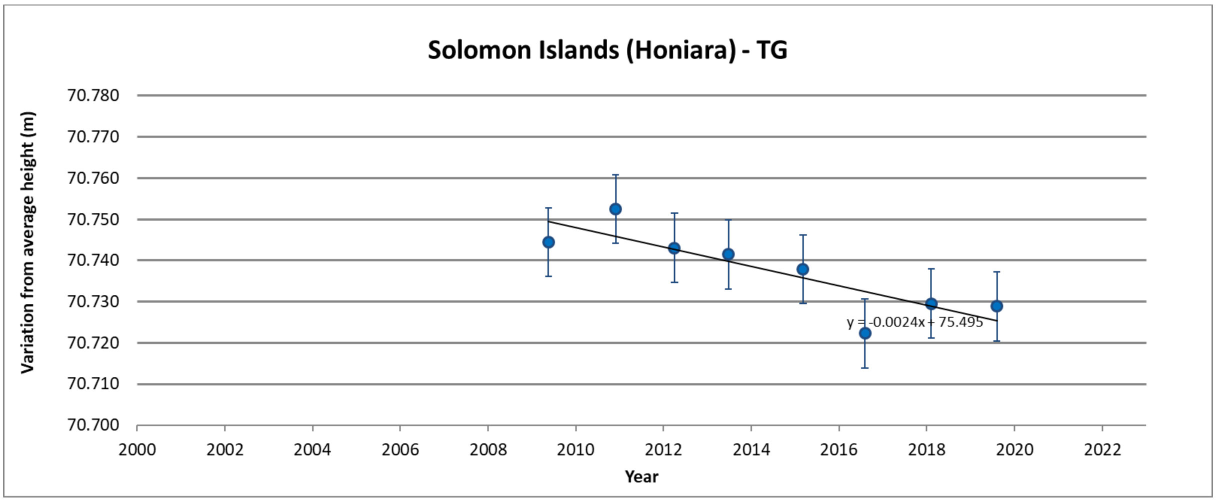
- Linear regression of the tide gauge height data indicate the tide gauge movement is -7.8 ± 2.2 mm/yr at 95% Confidence Interval between 2010 and 2019.

Table 7: ITRF2020 ellipsoidal height of the tide gauge sensor benchmark (SBM).

Date	TG SBM ellipsoidal height (m)
2002.90	42.1712
2004.65	42.1745
2006.76	42.1671
2006.77	42.1690
2008.41	42.1712
2010.39	42.1164
2011.85	42.1052
2013.40	42.0876
2014.87	42.0847
2016.42	42.0701
2017.75	42.0515
2019.60	42.0479

4.8 Solomon Islands





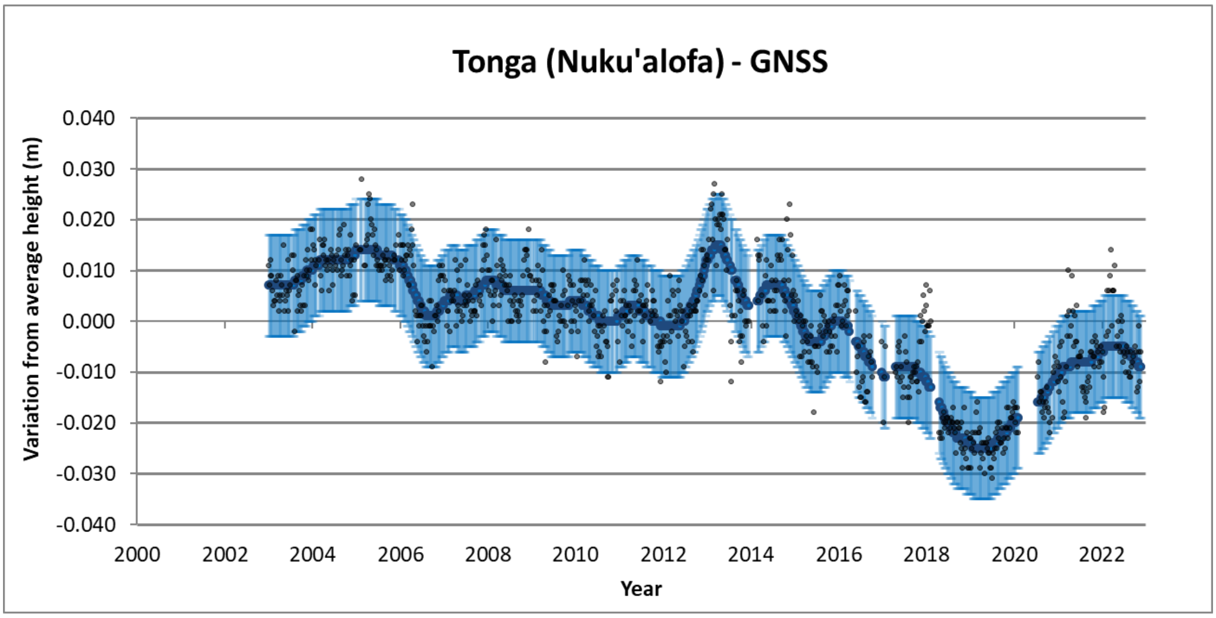
NOTES:

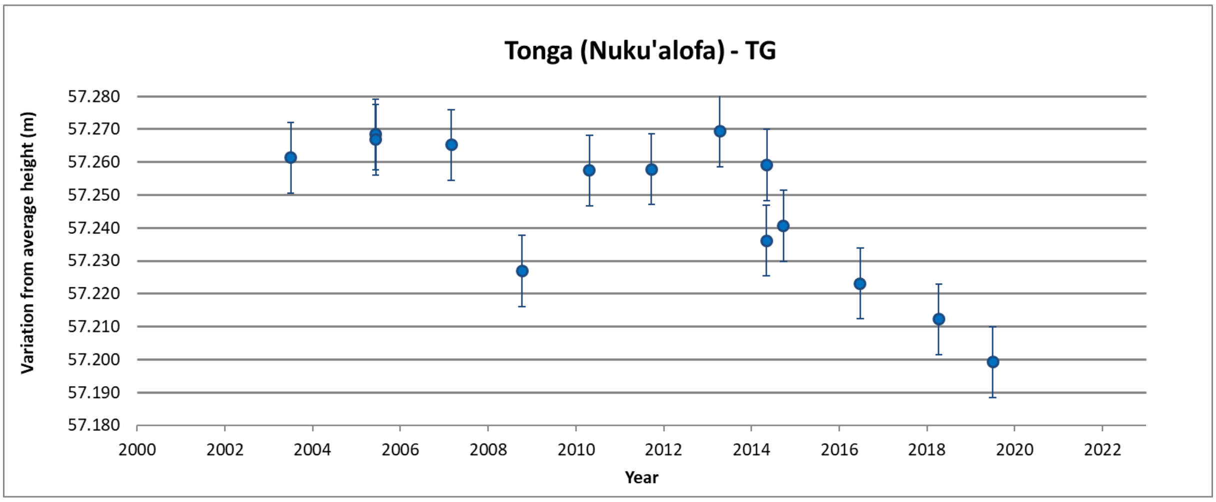
- Tide gauge movement for absolute sea level analysis is -2.4 ± 1.6 mm/yr at 95% Confidence Interval between 2009 and 2019.

Table 8: ITRF2020 ellipsoidal height of the tide gauge sensor benchmark (SBM).

Date	TG SBM ellipsoidal height (m)
2009.38	70.7445
2010.91	70.7525
2012.25	70.7431
2013.48	70.7415
2015.18	70.7379
2016.59	70.7223
2018.10	70.7296
2019.60	70.7289

4.9 Tonga





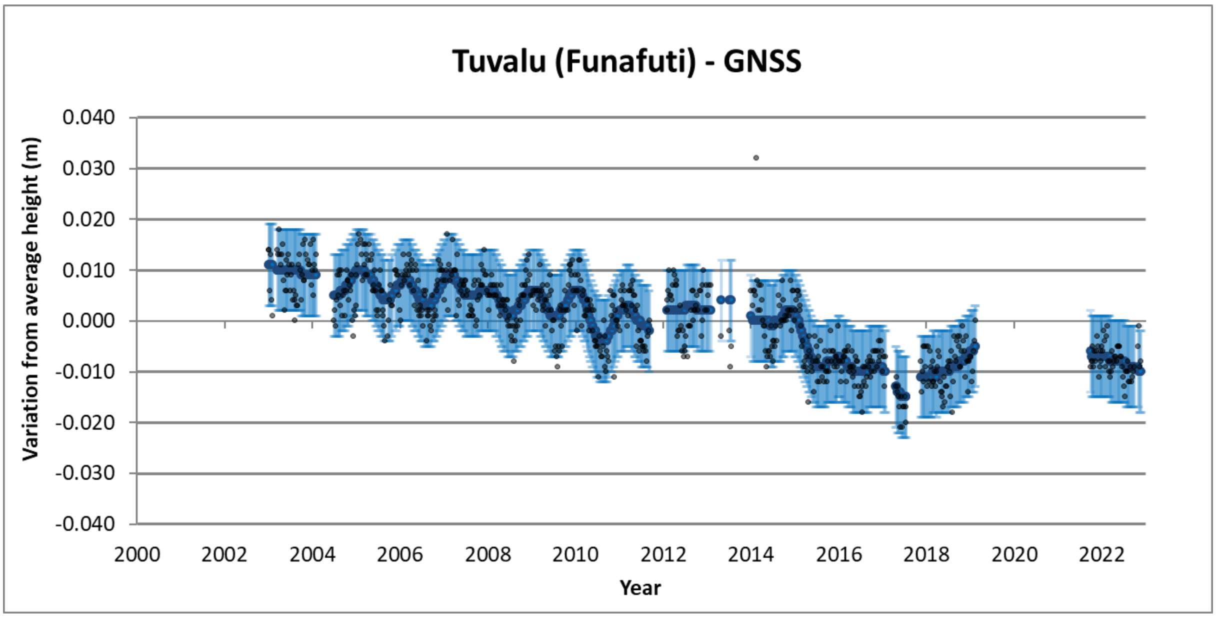
NOTES:

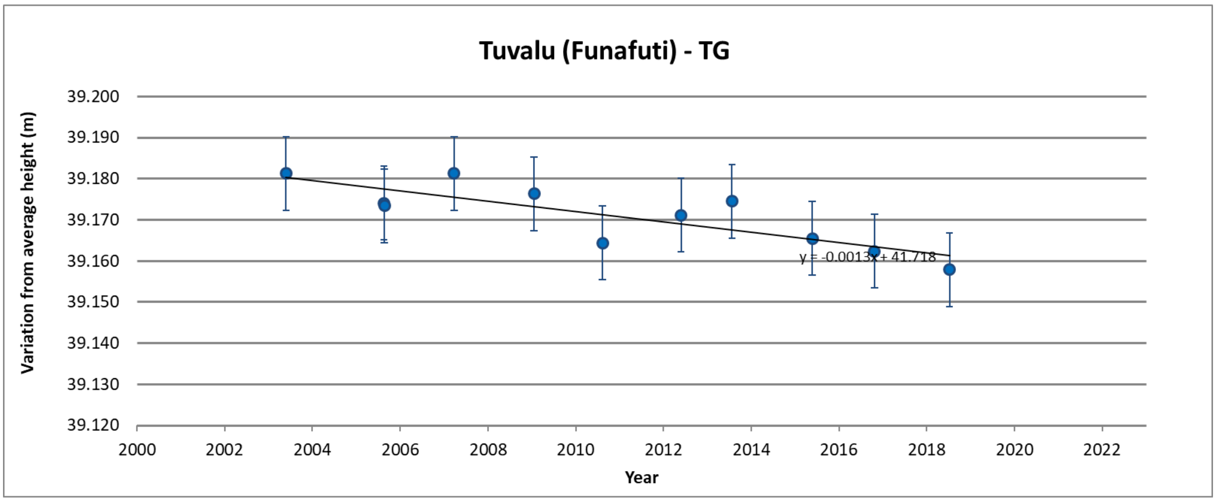
- Levelling data observed in 2008.77 was removed from the trend analysis because the tide gauge was in the incorrect position after being hit by a boat.
- Tide gauge movement for absolute sea level analysis since the tide gauge was re-established following the boat strike is -7.2 ± 2.3 mm/yr at 95% Confidence Interval between 2010 and 2019.
- No levelling has been undertaken between 2020 and 2022 in which time the GNSS site has risen by approximately 2 cm.

Table 9: ITRF2020 ellipsoidal height of the tide gauge sensor benchmark (SBM).

Date	TG SBM ellipsoidal height (m)
2003.50	57.2613
2005.43	57.2684
2005.44	57.2668
2007.16	57.2652
2008.77	57.2269
2010.31	57.2574
2011.72	57.2578
2013.28	57.2694
2014.34	57.2361
2014.35	57.2591
2014.73	57.2406
2016.48	57.2231
2018.27	57.2122
2019.51	57.1992

4.10 Tuvalu





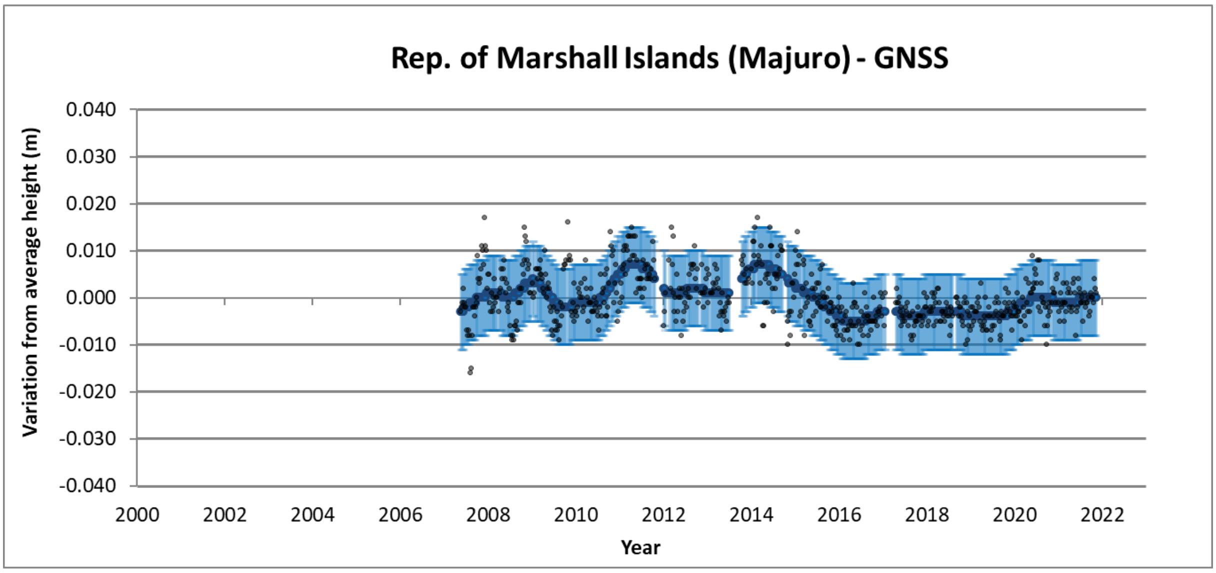
NOTES:

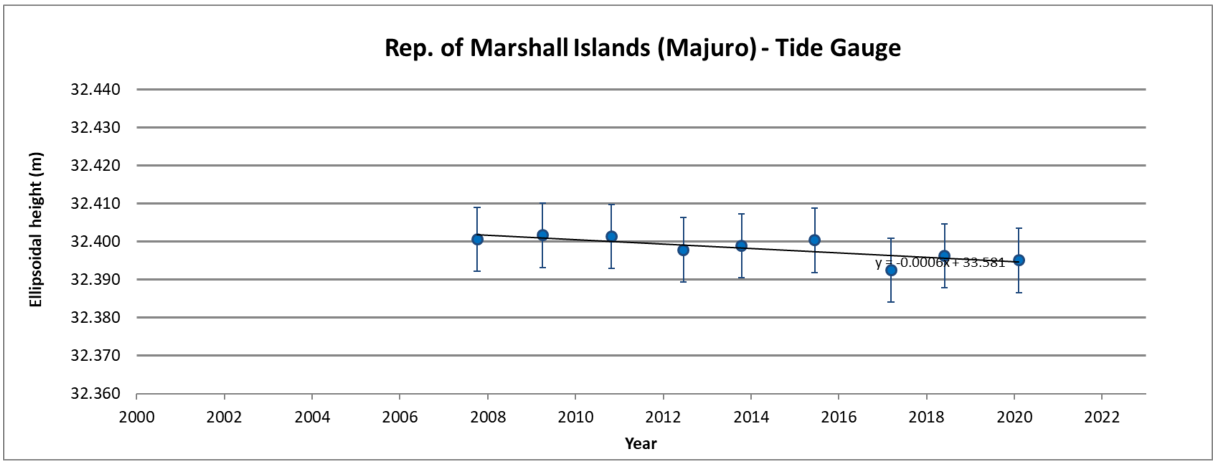
- Tide gauge movement for absolute sea level analysis is -1.3 ± 1.2 mm/yr at 95% Confidence Interval between 2003 and 2018.
- No GNSS data was available at the time the 2019 levelling survey was undertaken.

Table 10: ITRF2020 ellipsoidal height of the tide gauge sensor benchmark (SBM).

Date	TG SBM ellipsoidal height (m)
2003.40	39.1813
2005.63	39.1741
2005.64	39.1735
2007.23	39.1813
2009.05	39.1764
2010.61	39.1644
2012.40	39.1712
2013.56	39.1746
2015.39	39.1655
2016.81	39.1625
2018.52	39.1579

4.11 Republic of the Marshall Islands





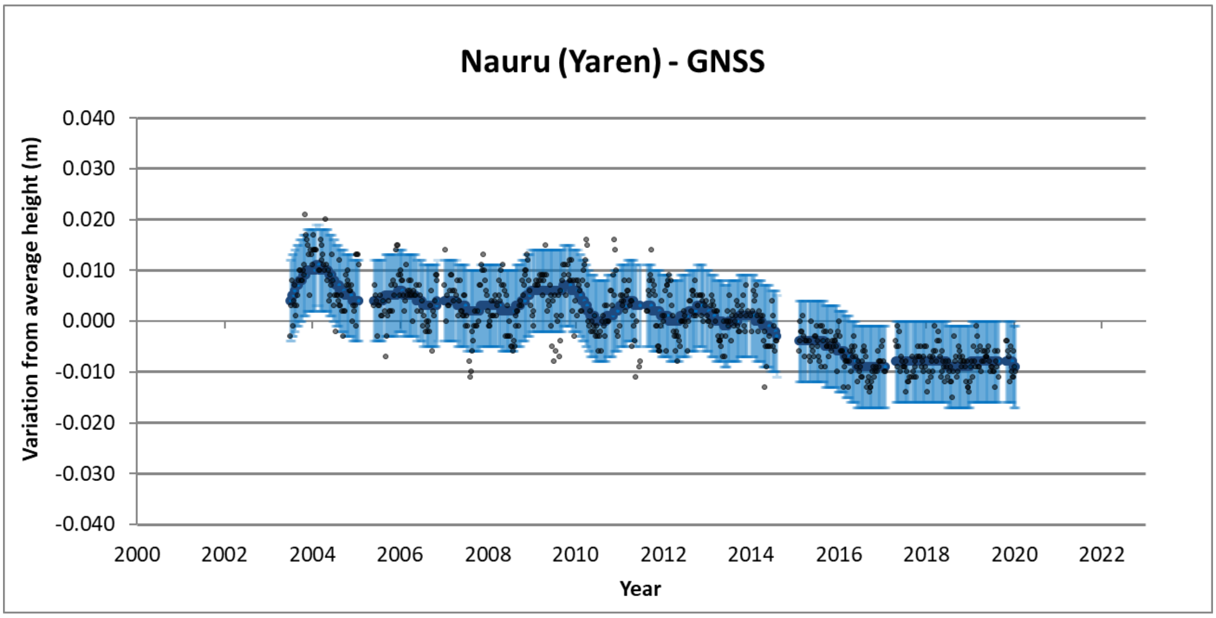
NOTES:

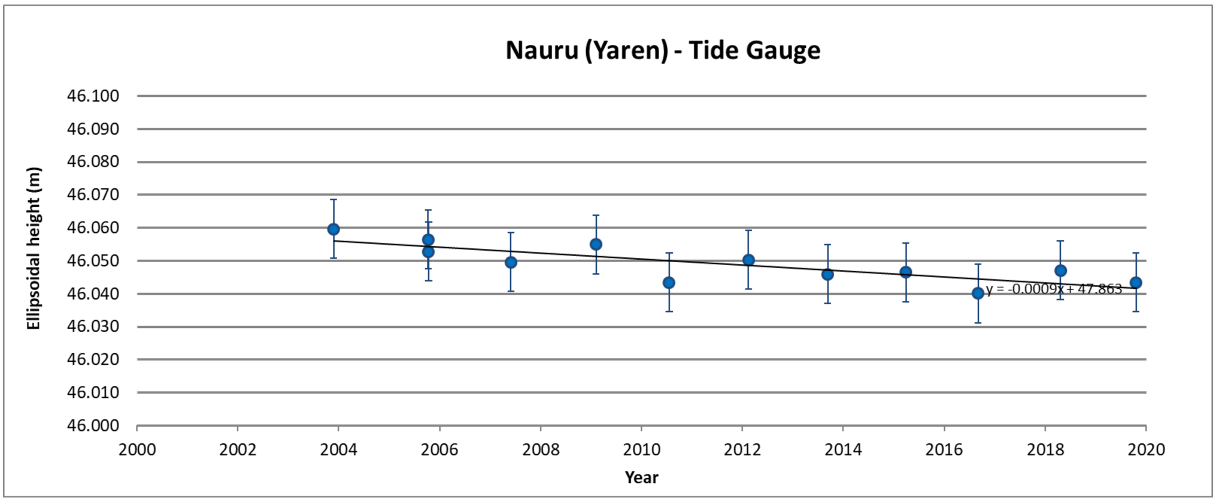
- Combined analysis from GNSS and levelling show the tide gauge movement -0.6 ± 1.4 mm/yr at 95% Confidence Interval.
- This uncertainty is greater than the trend. This means the tide gauge movement is not certain.
- Tide gauge movement for absolute sea level analysis should be assumed to be 0 mm/yr until the time series is extended, the uncertainty in the GNSS data or levelling data is reduced, or both.

Table 11: ITRF2020 ellipsoidal height of the tide gauge sensor benchmark (SBM).

Date	TG SBM ellipsoidal height (m)
2007.76	32.4007
2009.25	32.4017
2010.82	32.4014
2012.46	32.3979
2013.78	32.3989
2015.45	32.4004
2017.19	32.3926
2018.41	32.3963
2020.10	32.3951

4.12 Nauru





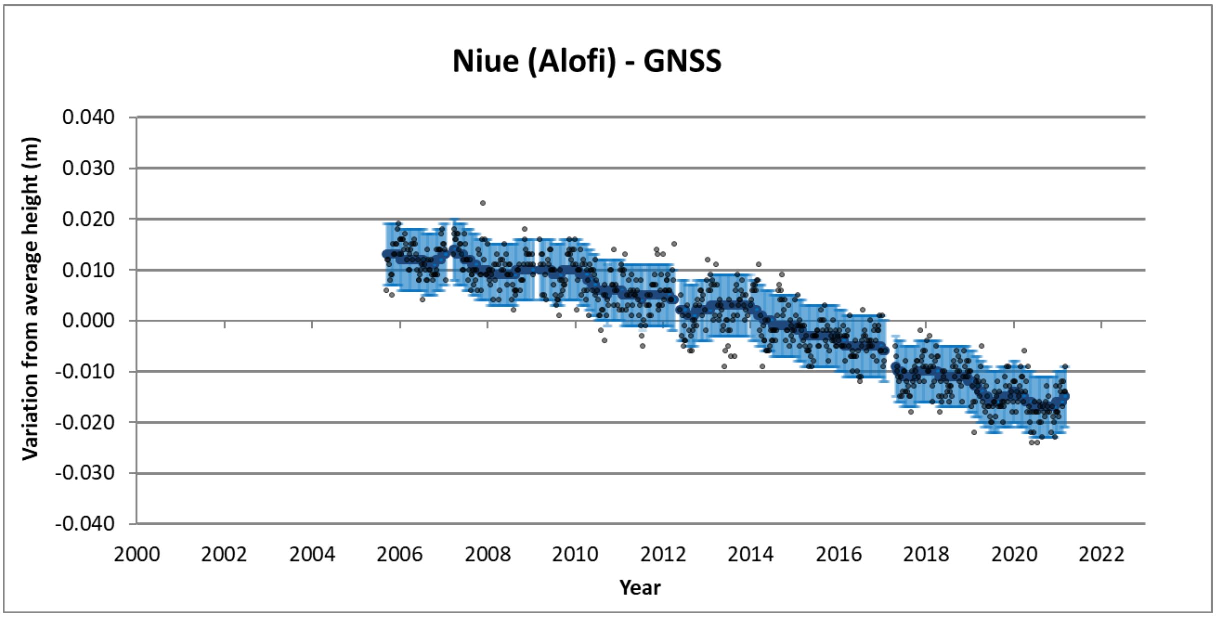
NOTES:

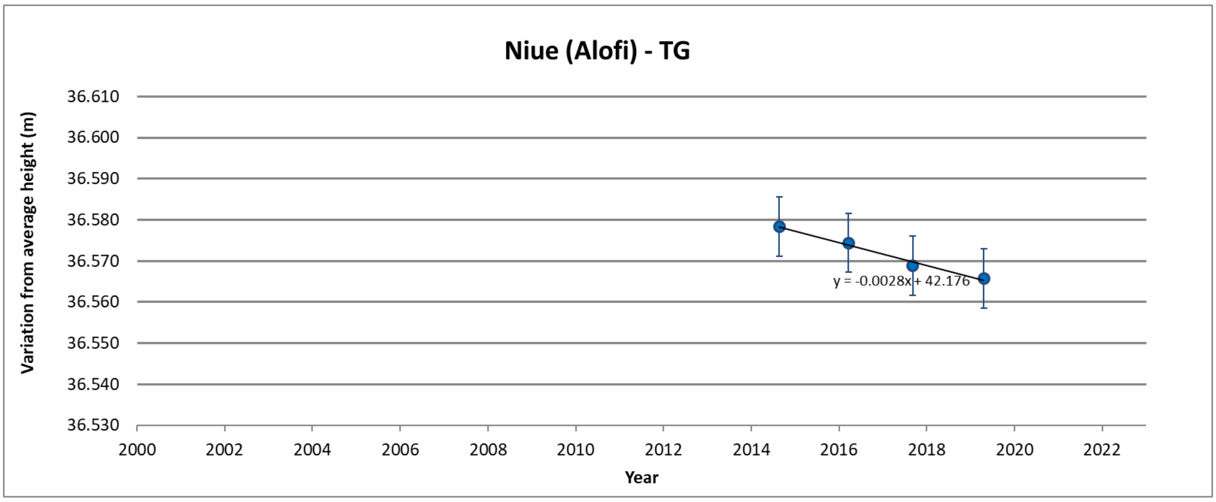
- Combined analysis from GNSS and levelling show the tide gauge movement -0.9 ± 1.1 mm/yr at 95% Confidence Interval.
- This uncertainty is greater than the trend. This means the tide gauge movement is not certain.
- Tide gauge movement for absolute sea level analysis should be assumed to be 0 mm/yr until the time series is extended, the uncertainty in the GNSS data or levelling data is reduced, or both.
- In the 2020 Record (Brown et al., 2020), the ellipsoidal height of a benchmark at the base of the tide gauge (NAURU14) was provided instead of the ellipsoidal height of the sensor benchmark on the tide gauge (NAURU15). For this reason, the ellipsoidal heights shown here are approximately 2.1 m different to those shown in the 2020 Record. This does not impact the reported vertical rate of movement of the tide gauge.

Table 12: ITRF2020 ellipsoidal height of the tide gauge sensor benchmark (SBM).

Date	TG SBM ellipsoidal height (m)
2003.90	46.0597
2005.77	46.0565
2005.78	46.0528
2007.41	46.0496
2009.10	46.0550
2010.55	46.0435
2012.12	46.0503
2013.69	46.0460
2015.24	46.0465
2016.67	46.0401
2018.32	46.0471
2019.82	46.0435

4.14 Niue





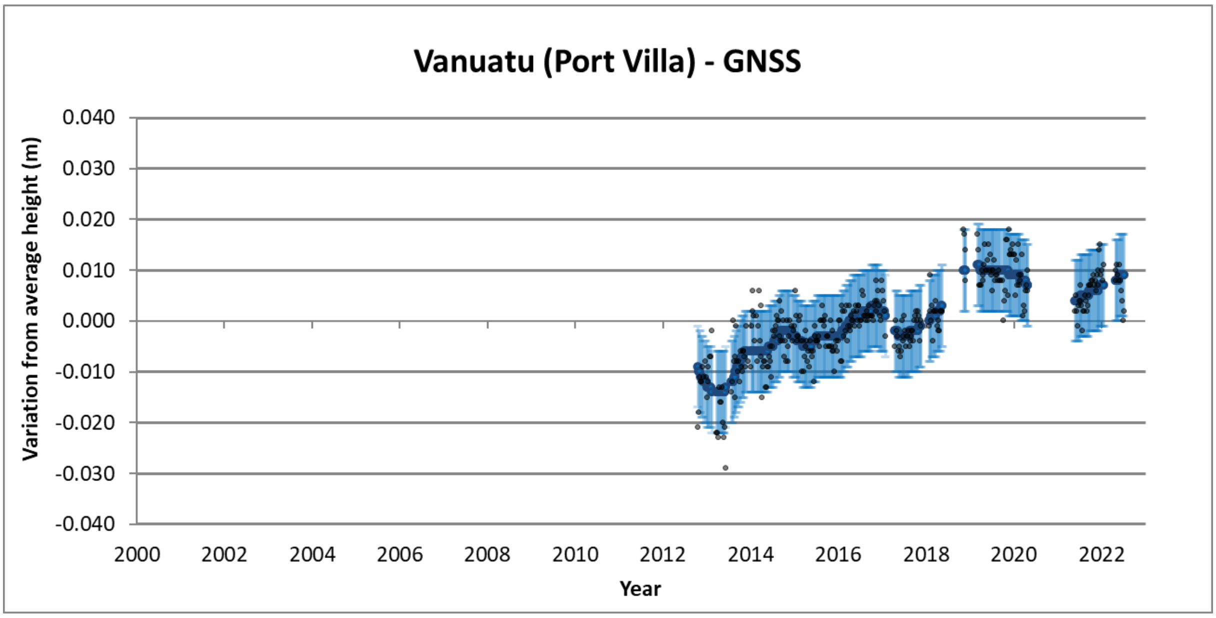
NOTES:

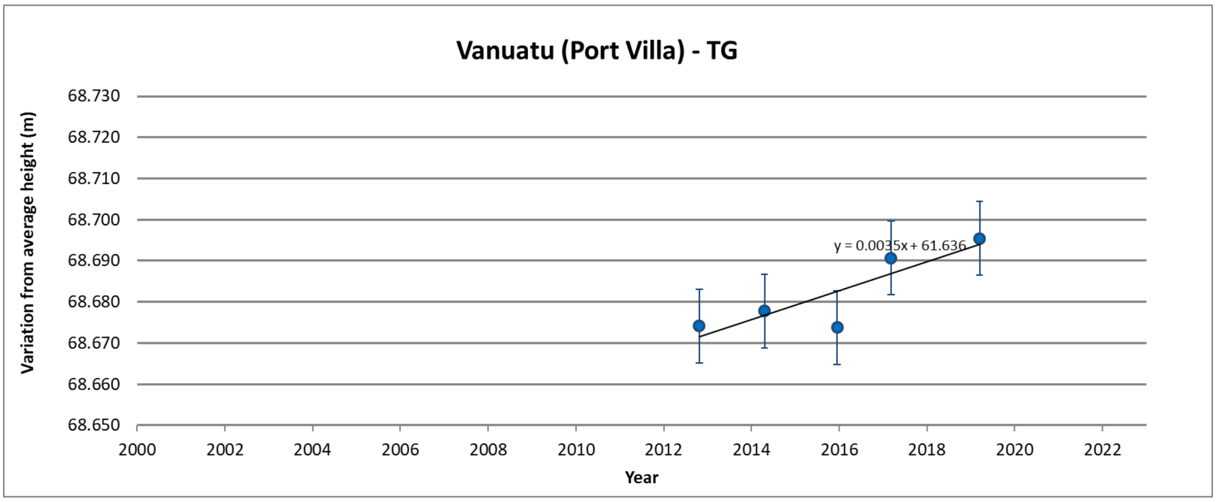
- Combined analysis from GNSS and levelling show the tide gauge movement -2.8 ± 3.1 mm/yr at 95% Confidence Interval.
- This uncertainty is greater than the trend. This means the tide gauge movement is not certain.
- Tide gauge movement for absolute sea level analysis should be assumed to be 0 mm/yr until the time series is extended, the uncertainty in the GNSS data or levelling data is reduced, or both.

Table 13: ITRF2020 ellipsoidal height of the tide gauge sensor benchmark (SBM).

Date	TG SBM ellipsoidal height (m)
2014.64	36.5783
2016.22	36.5744
2017.68	36.5689
2019.30	36.5658

4.15 Vanuatu





NOTES:

- Tide gauge movement for absolute sea level analysis is 3.5 ± 2.8 mm/yr at 95% Confidence Interval between 2009 and 2019.

Table 14: ITRF2020 ellipsoidal height of the tide gauge sensor benchmark (SBM).

Date	TG SBM ellipsoidal height (m)
2012.81	68.6742
2014.30	68.6778
2015.95	68.6738
2017.18	68.6907
2019.20	68.6955

References

Brown, N. J., Lal, A., Thomas, B., McClusky, S., Dawson, J., Hu, G., and Jia, M. 2020. Vertical motion of Pacific Island tide gauges: combined analysis from GNSS and levelling. Record 2020/03. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/Record.2020.003

Dach, R., S. Lutz, P. Walser, P. Fridez (Eds); 2015. Bernese GNSS Software Version 5.2. User manual, Astronomical Institute, University of Bern, Bern Open Publishing. DOI: 10.7892/boris.72297; ISBN: 978-3-906813-05-9.

Altamimi, Z., Rebischung, P., Collilieux, X. *et al.* ITRF2020: an augmented reference frame refining the modeling of nonlinear station motions. *J Geod* 97, 47 (2023). https://doi.org/10.1007/s00190-023-01738-w

Appendix A

The previous analysis of the GNSS time-series for the PSLGM was performed in 2019 (Brown et al, 2020), with the time-series in the IGS14 terrestrial reference frame (which is aligned to the International Terrestrial Reference Frame, ITRF2014). Since then, more GNSS data has become available, a new reference frame (IGS20 aligned to ITRF2020) has been released, and station metadata has been updated. A new set of analysis of the PSLGM GNSS time-series was performed in February 2023 to update the height time-series using the latest data/metadata available as well as results in the IGS20 reference frame.

GNSS data and processing methodology

The Asia-Pacific Reference Frame (APREF) weekly position solutions from January 2001 until November 2022 were used for estimating the position time-series of the 15 stations included in the PSLGM project. The weekly solutions were estimated at Geoscience Australia from the raw GPS observations of the APREF stations, using Bernese (Dach et al, 2015) GNSS processing software (v5.2), using a network approach. The weekly solutions were then combined into a cumulative solution using CATREF software (e.g Altamimi et al., 2023), aligning the solutions to the IGS20 reference frame and taking into account the station position discontinuities (due to equipment changes, earthquake or other events), from the latest IGS20 discontinuity list, adding the non-IGS station discontinuities from station metadata, and using the latest post-seismic deformation model provided by the National Institute of Geographic and Forest Information, France (IGN) to be used by CATREF with ITRF2020.

The magnitude of the offsets at the discontinuity epochs were initially estimated by CATREF. The modelled residuals were independently inspected by two analysts to ensure there were no obvious discontinuities missed in the analysis. The offsets were also estimated using the TSVIEW software by taking shorter windows (2 to 10 weeks) of data around the offset dates to confirm the validity of the offsets estimated by CATREF. After removing the outlier station solutions from the weekly solutions, and aligning them to the IGS20 reference frame, the estimated offsets were applied to the position time-series only for instrumental discontinuities. Therefore, the position time-series include only geophysical signals and not ‘systematic’ impacts caused by equipment changes/failure or other non-geophysical events.

The estimated time-series were then smoothed using a LOESS algorithm and fitting the appropriate models to the time-series using the TSVIEW software.

Comparison to 2019 solution

The majority of the time-series are within the uncertainty bounds of the previous 2019 solutions. Differences are observed from the previous analysis for a number of stations, which are mainly due to the previously missed or differently estimated position discontinuities, with many discontinuities added more recently to the IGS20 station discontinuity list or the station metadata. For example, the total number of listed discontinuities for the stations in this project increased from 21 in the IGb14 discontinuity list to 57 in the IGS20 discontinuity list over the same time period until mid-2019, with the discontinuities due to equipment change or unknown sources increasing from 14 to 34.