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# 1 Relative sea-level rise and the influence of vertical land motion at Tropical 2 Pacific Islands

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11

## 12 **Abstract**

13 This study investigates the relative sea-level changes and the influence of vertical land  
14 movements at South Western Tropical Pacific Islands. The dataset consists of tide gauge  
15 records, remote satellite altimetry observations and GPS records. After evaluating the  
16 uncertainties and the nature of vertical land movements, we focus on the present and future  
17 relative sea-level changes. The main source of uncertainty comes from the types of vertical  
18 land motion estimates. Results revealed that the relative sea level has increased more than the  
19 global mean sea level (from 0.8 to 4.2 mm yr<sup>-1</sup> higher) overall in the region during the last 4-6  
20 decades, especially at the islands located over the most tectonically active areas where future  
21 changes cannot be reliably projected. For most of the islands located outside tectonically  
22 active areas, relative sea-level projected changes by the end of the 21st century are of similar  
23 magnitude to the projected global mean sea-level (0.6 ± 0.2 m in the RCP 8.5 scenario), with  
24 the exception of Tahiti where major changes are projected (0.8 ± 0.2 m).

25

## 26 **1. Introduction**

27 Small Pacific island nations and in particular atoll nations have received much attention  
28 during the recent decades given their high exposure to sea-level rise (SLR) in the context of  
29 climate change (Nurse et al., 2014; Connell et al., 2015; Duvat et al., 2017). Despite the  
30 absence of scientific evidence of direct correlation between atoll island shoreline retreat and  
31 sea-level rise (McLean and Kench, 2015; Duvat, 2018), SLR superimposed with zonal  
32 extreme events (i.e. tropical cyclones) and distant-source wave intensification is expected to  
33 increase coastal erosion, marine flooding and soil and groundwater lens salinization. This will  
34 also be exacerbated by a decrease in the resilience of reef ecosystems (Keener et al., 2012;

35 Saunders et al., 2016; Shope et al., 2016 and references herein). In this region, sea-level  
36 changes are thus a key concern about the long-term adaptation to climate change issue.

37 The rate of global sea-level rise due to thermal expansion and melting ice sheets and glaciers  
38 has been significantly higher during the altimetry period (1993-2012) [ $3.2 \pm 0.1 \text{ mm yr}^{-1}$   
39 (Cazenave and Cozannet, 2014);  $3.2 \pm 0.4 \text{ mm yr}^{-1}$  (Masters et al., 2012)] than during the 20th  
40 century [ $1.7 \pm 0.2 \text{ mm yr}^{-1}$  (Church et al., 2011; Ray and Douglas, 2011);  $1.9 \pm 0.3 \text{ mm yr}^{-1}$   
41 (Jevrejeva et al., 2014);  $1.2 \pm 0.2 \text{ mm yr}^{-1}$  (Hay et al., 2015; Dangendorf et al., 2017)]. The  
42 dynamical response of the ocean and the atmosphere to climate variability as well as the  
43 glacier and ice-sheet water redistribution into the ocean and the terrestrial water storage,  
44 significantly contribute to sea level variability on interannual to longer time scales, and also to  
45 the spatial heterogeneity of sea-level rise (Church et al., 2013). In the Western Tropical  
46 Pacific, sea level has risen up to three times more than the global mean from the early 1990s  
47 (Cazenave and Cozannet, 2014). This rate ( $\sim 7 \text{ mm yr}^{-1}$ ) is more than twice the rate observed  
48 from 1950 over the same region ( $\sim 3 \text{ mm yr}^{-1}$ ) (Nerem et al., 2011; Becker et al. 2012). The  
49 opposite occurred in the Eastern Tropical Pacific, where sea level has increased at lower rates  
50 than the global mean from 1950 [ $\sim 1 \text{ mm/year}$  (Becker et al., 2012)] and declined during the  
51 1993-2008 period [ $\sim -3 \text{ mm yr}^{-1}$  (Moon et al., 2013)]. This longitudinal trend gradient has  
52 been attributed to the effect of global warming and the acceleration of the trade winds  
53 (Timmermann et al., 2010; Merrifield, 2011; Becker et al., 2012; McGregor et al., 2012;  
54 Palanisamy et al., 2015), which has been related to climate variability at interannual-to-  
55 decadal scales driven by El Niño Southern Oscillation (ENSO, Church et al., 2011; Becker et  
56 al., 2012; Barnard et al., 2015) and the Pacific Decadal Oscillation (PDO, Merrifield et al.,  
57 2012; Zhang and Church, 2012; Han et al., 2013; Hamlington et al., 2014; Han et al., 2017).  
58 The role of the Atlantic multidecadal variability in the intensification of the Pacific trade  
59 winds has also been recently demonstrated (McGregor et al., 2014; Li et al., 2016; Sun et al.,  
60 2017 and references herein), although it is difficult to robustly quantify the contribution of the  
61 low-frequency climate oscillations to the tropical Pacific sea level trends due to the absence of  
62 longer tide gauge records.

63 A crucial factor which has often been overlooked and can considerably exacerbate the sea-  
64 level change impact at the coast is the vertical land motion (VLM) (Wöppelmann and Marcos,  
65 2016). VLM, caused by natural processes, such as the Glacial Isostatic Adjustment (GIA),  
66 tectonics, volcanism and sediment compaction, or by human activities like, for instance,  
67 subsurface mineral and water extraction, can produce relative sea-level changes of the same  
68 order of magnitude as those caused by climate change and/or climate variability, and can

69 therefore give rise to major differences between local and regional sea-level rise  
70 (Wöppelmann and Marcos, 2016 and references herein). Here, we define the relative sea level  
71 (RSL) as the change in sea level relative to land, i.e. absolute (or geocentric) sea-level change  
72 minus local uplift or subsidence. Vertical land motion has been recognized, in many cases, as  
73 the main contributor to the RSL changes in the Southern Tropical Pacific, in particular the  
74 local vertical land motion caused by other processes than the GIA (Pfeffer et al., 2017 and  
75 references herein). Indeed, GIA only produces slight uplifts of about  $\sim 0.2$  mm/year over our  
76 region of interest (Peltier et al. 2015). Accounting for the contribution of vertical land motion  
77 is particularly relevant in the South Western Tropical Pacific, one of the most tectonically  
78 active regions of the globe. In the region, the convergence between the Australian and Pacific  
79 plates is accommodated by several subduction zones (mainly the Solomon and New Hebrides  
80 ones where the Australian plate subducts towards the East and the Tonga-Kermadec  
81 subduction zone where the Pacific Plate subducts towards the West) and a complex deforming  
82 system (the North Fiji Basin) between these subductions (e.g. Pelletier et al., 1998). Plates are  
83 mainly rigid and their relative motion is accommodated by elastic deformation near plate  
84 borders: vertical movements may be slow when induced by the stress accumulation between  
85 earthquakes and sudden when the stress is released through earthquakes. Vertical movements  
86 can be up or down with variable amplitude depending on the magnitude of the earthquake and  
87 the position with respect to the rupture plane. For example, in the Torres Islands (southwest  
88 Pacific Archipelago of Vanuatu) where the Australian plate subducts beneath the North Fiji  
89 Basin, a sudden earthquake-related subsidence followed by slow interseismic coastal  
90 subsidence over the 1997-2009 period ( $\sim 9$  mm/year) together with an absolute (geocentric)  
91 regional sea-level rise resulted in a very high rate of relative sea-level change ( $\sim 20$  mm/year)  
92 and subsequent coastal inundation of inhabited low-lying areas (Ballu et al., 2011). Other  
93 examples of sudden vertical land motion related to the same subduction context are, for  
94 instance, on Malakula Island (Vanuatu), where a 1965 event led to 120 cm of abrupt coastal  
95 uplift (Taylor et al., 1980), and in the Solomon Archipelago, where a major M8.1 earthquake  
96 in 2007 caused more than 2 m of uplift in Ranongga Island and 1 m of subsidence on Simbo  
97 Island (Taylor et al., 2008; Saunders et al., 2015). Away from tectonic plate boundaries, in the  
98 central part of the Southern Tropical Pacific, tectonic activity is not likely to contribute  
99 significantly to vertical motions. However, this region is characterized by a high volcanism  
100 concentration (McNutt and Fischer, 1987; Adam et al., 2014), with slower vertical land  
101 motion than that occurring near plate boundaries (Nunn, 2009; Becker et al., 2012). One

102 example is Tahiti Island (French Polynesia), where a subsidence of  $\sim 0.5$  mm/year is indicated  
103 by independent geodetic methods (Fadil et al., 2011; Becker et al., 2012).

104 Despite the high uncertainties of sea-level rise projections mainly associated with the  
105 unknowns of the processes driving the Antarctica and Greenland ice-sheets melting and  
106 shrinking (Church et al., 2013; Bamber and Aspinall, 2013; Ritz et al., 2015; DeConto and  
107 Pollard, 2016; Jevrejeva et al., 2016; Kopp et al., 2017), it is expected that global sea level  
108 rates continue increasing during the 21<sup>st</sup> century, especially at the Western Tropical Pacific  
109 where the highest sea-level rises are predicted (Church et al., 2013; Cazenave and Le  
110 Cozannet 2014; Kopp et al., 2014; Slangen et al., 2014; Carson et al., 2015; Jevrejeva et al.,  
111 2016). In such a context, coastal impacts assessment and adaptation planning critically need  
112 data on future sea level scenarios at the local scale (Church et al., 2013; Nicholls et al., 2014).  
113 Most of the previous studies, although they focused on relative sea level projections at the  
114 Southern Pacific, only included the VLM caused by the GIA (Church et al., 2013; Cazenave  
115 and Le Cozannet 2014; Kopp et al., 2014; Slangen et al., 2014; Carson et al., 2015; Jevrejeva  
116 et al., 2016). Considering the additional contribution of vertical land motion caused by other  
117 processes to relative sea level trends is therefore of high importance, as highlighted in The  
118 Fifth Assessment Report of the Intergovernmental Panel on Climate Change (AR5 IPCC)  
119 (Church et al., 2013). Some studies have investigated local vertical land motion at the small  
120 islands of the Southern Tropical Pacific (Nerem and Mitchum, 2002; Aung et al., 2009; Fadil  
121 et al., 2011; Becker et al., 2012; Ballu et al., 2014; Saunders et al., 2016; Pfeffer and  
122 Allemand, 2016; Pfeffer et al., 2017). However, these studies have one or more of the  
123 following limitations: i) the focus is on specific islands or archipelagos; ii) the uncertainty  
124 associated with the vertical land motion estimates obtained from different geodetic products is  
125 not explicitly estimated; iii) the quality of the data used to include VLM estimates into  
126 projections of future RSL is not properly assessed.

127 Here we present new estimates of relative sea-level changes at small islands of the South  
128 Western Tropical Pacific, and attempt to identify the contribution of local vertical land motion  
129 on these trends. This leads us to discuss the need, in the aim of establishing more robust  
130 future RSL projections, for a detailed analysis of the nature of the vertical land motion. We  
131 also attempt to overcome the above limitations by: i) using the most updated data available  
132 over the domain of interest from tide gauges, satellite radar altimetry and Global Positioning  
133 System (GPS) stations; ii) providing a measure of the vertical land motion uncertainty by  
134 including those associated with various satellite altimetry and GPS products; and iii) assessing  
135 the ability of the vertical land motion estimates to be projected into the future by examining

136 the time series in the past, especially paying attention to the tectonic context and the presence  
137 of earthquakes. Finally, we propose tentative future projections of relative sea level at a group  
138 of selected islands under three different greenhouse gases (GHG) emission scenarios  
139 (RCP2.6, RCP4.5 and RCP8.5) by combining the projected vertical land motion rates with the  
140 regionalized sea level projections presented in the AR5 IPCC (Church et al., 2013).

141

## 142 **2. Data sets**

### 143 **2.1 Tide gauges and reconstructed Global Mean Sea Level**

144 Tide gauge (TG) records are the main source of information on coastal sea-level changes  
145 since the mid-19<sup>th</sup> century. The TGs were engineered to measure the relative sea level, that is,  
146 the sea level relative to the land on which they are installed (Pugh, 1991). In this work, RSL  
147 records of an initial set of 35 TG stations located within the study domain (Fig. 1) and  
148 covering a minimum period of 4 years were obtained from the Permanent Service for Mean  
149 Sea Level (PSMSL; [www.psmsl.org/data/obtaining/](http://www.psmsl.org/data/obtaining/)) at monthly scale and from both the  
150 University of Hawaii Sea Level Center (UHSLC; [uhslc.soest.hawaii.edu](http://uhslc.soest.hawaii.edu)) and the Système  
151 d'Observation du Niveau des Eaux Littorales (SONEL; [www.sonel.org](http://www.sonel.org)) at a daily scale.  
152 Monthly averaged values were calculated from daily values following the procedure detailed  
153 by the PSMSL (only months containing more than 15 valid days were considered, Holgate et  
154 al. 2013). Gaps in daily data are not filled before averaging into monthly means. Comments  
155 on the data quality provided by the PSMSL were all taken into account and no suspicious  
156 records were found. Concatenated sea level time series were produced for TG records  
157 provided by the same database and located at a maximum distance of 4 km, namely Funafuti  
158 (A and B), Honiara (A and B) and Rarotonga (A and B) from the UHSLC and Nauru and  
159 Nauru B from the PSMSL. Concatenation between two series was done ensuring that the  
160 mean of the sea level records were equal after removing the datum offset (bias) calculated  
161 over their overlapping periods with at least 6-month of time span and a minimum correlation  
162 coefficient of 0.95. Variance consistency between concatenated time series was confirmed  
163 by visual inspection. We finally selected the longest and most updated monthly time series at  
164 each location from a set including both concatenated and original records leading to a final  
165 subset of 27 records of which 5 were concatenated (see Table 1). We have also used the 1880-  
166 2013 Global Mean Sea Level (GMSL) monthly time series from the Church and White (2011)  
167 global sea level reconstruction ([http://www.cmar.csiro.au/sealevel/sl\\_data\\_cmar.htm](http://www.cmar.csiro.au/sealevel/sl_data_cmar.htm))

168

169 **Table 1.** Tide gauge, database, country, location, period of operation and percentage of gaps.  
170 Concatenated tide gauge records (see text) are marked with an asterisk. Closest GPS station to  
171 the tide gauge, distance to the closest tide gauge, coordinates and covered period for each  
172 GPS record obtained from SONEL and Nevada Geodetic Laboratory (NGL) databases.  
173  
174

Name	Tide gauge						GPS					
	Database	Country	Lon (°E)	Lat (°N)	Total period	% Gaps	Closest GPS	Dist. (Km)	Lon (°E)	Lat (°N)	Period SONEL	Period NGL
Anewa Bay	UHSLC	Papua NG	155.88	-6.18	1968-1977	11	-	-	-	-	-	-
Honiara*	UHSLC	Solomon Is	159.95	-9.43	1974-2015	4	SOLO	0.5	159.96	-9.43	2008-2013	-
Noumea A	UHSLC	N Caledonia	166.44	-22.29	1967-2015	2	NOUM	3.8	166.41	-22.24	1997-2007	1997-2007
Ouinne	SONEL	N Caledonia	166.68	-21.98	1981-2015	85	YATE	33.8	166.94	-22.16	-	2008-2016
Nauru*	PSMSL	Nauru	166.9	-0.53	1974-2014	7	NAUR	3.7	166.93	-0.55	2003-2014	2003-2016
Lifou	SONEL	N Caledonia	167.28	-20.92	2011-2015	17	LPIL	1.7	167.26	-20.92	1996-2013	1996-2016
Norfolk Is	PSMSL	Australia	167.95	-29.07	1994-2014	4	NORF	2.2	167.94	-29.06	2008-2013	2008-2016
Port Vila VU A	UHSLC	Vanuatu	168.28	-17.75	1977-1982	6	-	-	-	-	-	-
Port Vila VU B	UHSLC	Vanuatu	168.28	-17.75	1993-2015	5	VANU	3.8	168.32	-17.76	2002-2013	2002-2013
Lautoka	PSMSL	Fiji	177.44	-17.6	1992-2014	0	LAUT	1	177.45	-17.61	2001-2013	2001-2016
Suva	PSMSL	Fiji	178.42	-18.14	1972-2015	6	SUVA	0.7	178.43	-18.14	1998-2002	1998-2002
"	"	"	"	"	"	"	FTNA	564.8	-178.12	-14.3	1998-2013	1998-2016
Funafuti*	UHSLC	Tuvalu	179.2	-8.53	1977-2015	3	TUVA	2.5	179.2	-8.5	2001-2013	2001-2016
Nukualofa	PSMSL	Tonga	-175.18	-21.14	1993-2014	1	TONG	0.3	-175.18	-21.14	2002-2013	-
Apia_A	UHSLC	Samoa	-171.75	-13.82	1954-1971	4	-	-	-	-	-	-
Apia_B	UHSLC	Samoa	-171.75	-13.82	1993-2015	3	SAMO	3.8	-171.74	-13.85	-	2001-2016
Kanton Is*	PSMSL	Kiribati	-171.72	-2.82	1949-2012	14	TUVA	1187.9	179.2	-8.5	2001-2013	2001-2016
Pago Pago	UHSLC	USA	-170.69	-14.28	1948-2014	3	ASPA	6.4	-170.72	-14.28	2001-2013	2001-2016
Rarotonga*	UHSLC	Cook Is	-159.78	-21.2	1977-2015	2	CKIS	1.9	-159.8	-21.2	2001-2013	2001-2016
Penrhyn	UHSLC	Cook Is	-158.07	-9.02	1977-2015	6	CKIS	1367.6	-159.8	-21.2	2001-2013	2001-2016
Papeete	UHSLC	F Polynesia	-149.57	-17.53	1969-2014	2	PAPE	0.4	-149.6	-17.5	2004-2013	2004-2016
"	"	"	"	"	"	"	THTI	3.9	-149.6	-17.5	1998-2013	-
Matavai	UHSLC	F Polynesia	-149.52	-17.52	1958-1967	32	-	-	-	-	-	-
Tubuai	SONEL	F Polynesia	-149.48	-23.34	2009-2013	13	TBTG	0.5	-149.48	-23.34	2009-2013	2009-2014
Rangiroa	SONEL	F Polynesia	-147.71	-14.95	2009-2014	31	-	-	-	-	-	-
Nuku Hiva	UHSLC	F Polynesia	-140.1	-8.92	1982-2015	34	-	-	-	-	-	-
Hiva Oa_A	UHSLC	F Polynesia	-139.03	-9.82	1977-1980	31	-	-	-	-	-	-
Hiva Oa_B	UHSLC	F Polynesia	-139.03	-9.82	2010-2015	25	-	-	-	-	-	-
Rikitea	UHSLC	F Polynesia	-134.97	-23.13	1969-2015	7	GAMB	0.9	-134.96	-23.12	2000-2010	2000-2016

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## 179 2.2 Satellite Altimetry

180 Gridded monthly Sea Level Anomaly (SLA) during 1993-2015 was obtained from two  
181 different sources, namely AVISO (Archiving, Validation and Interpretation of Satellite  
182 Oceanographic data, <http://www.aviso.altimetry.fr>.) and CSIRO (Commonwealth Scientific  
183 and Industrial Research Organization; [www.cmar.csiro.au/sealevel/sl\\_data\\_cmar.html](http://www.cmar.csiro.au/sealevel/sl_data_cmar.html)).  
184 These two Sea Level Anomaly products were selected with the concern of having an  
185 assessment of the uncertainty. This choice was based on results from a previous study in  
186 which the AVISO (CSIRO) product scored the best (worst) product in terms of statistical  
187 uncertainty to be used for the calculation of vertical land motion by combining altimetry with

188 TGs at a global scale (Wöppelmann and Marcos, 2016). The two Sea Level Anomaly datasets  
189 consist of merged multi-missions data (TOPEX/Poseidon, Jason-1, Jason-2) spanning the  
190 period 1993-2015. The spatial resolution for the CSIRO dataset is of  $1^\circ \times 1^\circ$  and for the  
191 AVISO it is of  $1/4^\circ \times 1/4^\circ$ . The higher resolution of AVISO product primarily stems from  
192 accounting for other complementary missions (ERS- 1, ERS-2, Envisat, Geosat Follow-On,  
193 CryoSat, SARAL/AltiKa and Sentinel-3A/B). We linearly interpolated the CSIRO data on the  
194  $1/4^\circ \times 1/4^\circ$  AVISO grid of higher resolution for comparison with tide gauge data. In addition,  
195 the effect of atmospheric pressure and wind on sea level is corrected for the AVISO dataset,  
196 whereas the TG records and CSIRO dataset includes these effects. For the sake of consistency  
197 in terms of signal contents across the sea level datasets, we added back the Dynamic  
198 Atmospheric Correction (DAC; Volkov et al., 2007), supplied by AVISO and containing  
199 these corrections, to the AVISO Sea Level Anomaly gridded product. A GMSL time series  
200 was computed by globally averaging the de-seasoned monthly Sea Level Anomaly from both  
201 data sets over 1993-2015.

202

### 203 **2.3 Sea level projections**

204 We used the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report  
205 (AR5) projected global sea-level rise by 2100, forced by different GHG emission scenarios  
206 (IPCC, 2013). Projected sea-level rise under each scenario is the sum of individual  
207 contributions from steric changes and melting of glaciers and ice caps, the Greenland Ice  
208 Sheet, the Antarctic Ice Sheet, and land water storage (CMIP5, Taylor et al. 2012). We  
209 considered three representative concentration pathways (RCP) scenarios ranging from drastic  
210 emission reductions (RCP 2.6) to moderate (RCP 4.5) and unmitigated growth of emissions  
211 (RCP 8.5). These data sets are obtained from the Integrated Climate data Center of the  
212 University of Hamburg (ICDC, <http://icdc.cen.uni-hamburg.de/1/daten/ocean/ar5-slr.html>).  
213 These datasets consist of gridded fields of projected sea-level change calculated as the 20-yr  
214 mean differences between the 2081-2100 and the 1986-2005 periods, with a spatial resolution  
215 of  $1^\circ \times 1^\circ$ , for 9 geophysical components driving long-term sea-level changes including the  
216 dynamic sea surface height, the thermosteric and the inverse barometer effect (see Fig. S1).  
217 We linearly interpolated the set of sea level projected fields to the  $1/4^\circ \times 1/4^\circ$  AVISO grid for  
218 comparison (see Fig. S1).

219

### 220 **2.4 GPS**



221 The linear trend estimates of vertical land motion derived from GPS data ( $VLM_{GPS}$ ) of 18  
222 stations located within the study domain were obtained from two different datasets produced  
223 by Système de l'Observation du Niveau des Eaux Littorales (SONEL, ULR6 velocity field,  
224 Santamaria-Gomez et al., 2017, <http://www.sonel.org/-GPS-.html>) and  
225 Nevada Geodetic Laboratory (NGL, IGS08-MIDAS velocity field, Blewitt et al., 2016,  
226 <http://geodesy.unr.edu/velocities/midas.IGS08.txt>) (see Table 1). These two data sets were  
227 selected because they use rather different methods and strategies to analyze the GPS  
228 measurements and estimate linear trends of the station positions.  $VLM_{GPS}$  trend estimates  
229 from SONEL are derived from daily station position time series obtained by using a  
230 combination of manual and automatized procedures to detect and remove offsets produced by  
231 natural processes (e.g., earthquakes) and/or instrumentation artefacts (changes or  
232 malfunctioning of GPS equipment) that can bias the estimation of the underlying linear trends  
233 of station positions (Gazeaux et al., 2013). The NGL linear trend estimates result from a  
234 different and automatized method which is claimed to be robust regarding offsets (Blewitt et  
235 al., 2016). Details are given on the websites of each dataset and can be found in the  
236 publications. These methodological differences have the potential to lead to significant  
237 differences in the  $VLM_{GPS}$  estimates and also in its uncertainties (Gazeaux et al., 2013;  
238 Reischung et al., 2016). But they represent the state-of-the art in GPS data analysis, and the  
239 differences in their estimates can provide a better appraisal of the real uncertainties beyond  
240 the statistical ones. Both  $VLM_{GPS}$  estimates and associated station position time series were  
241 obtained from SONEL (<http://www.sonel.org/-GPS-.html>) and NGL  
242 (<http://geodesy.unr.edu/NGLStationPages/GlobalStationList>) websites, respectively. These  
243 time series were examined to detect offsets or post-seismic deformation due to the occurrence  
244 of earthquakes. The nearest GPS station to each tide gauge station was searched and selected.  
245 When two or more GPS stations were similarly close to a TG station, the longest one (taking  
246 into account the gaps) was then selected, with the exception of the tide gauge of Papeete  
247 where the two closest GPS stations (PAPE and THTI) were finally selected (in spite of THTI  
248 being longer than PAPE) because they showed opposite VLM trends.

249

250

## 251 **2.5 GIA**

252 We used outputs of the GIA model ICE-6G (VM5a) (Peltier et al., 2015,  
253 <http://www.atmosph.physics.utoronto.ca/~peltier/data.php>) consisting of gridded fields with a  
254 spatial resolution of  $1/5^\circ \times 1/5^\circ$  of the two GIA components driving relative sea-level changes,

255 one accounting for its effect on the vertical crustal motion ( $VLM_{GIA}$ ) and another accounting  
256 for its effect on the sea surface height due to changes in gravity ( $GEOID_{GIA}$ ) (Tamisiea and  
257 Mitrovica, 2011). The net GIA effect on relative sea-level changes ( $NET_{GIA}$ ) is the  
258 combination of these two effects and it can be defined as  $NET_{GIA} = GEOID_{GIA} - VLM_{GIA}$ . We  
259 linearly interpolated the GIA dataset to the  $1/4^\circ \times 1/4^\circ$  AVISO grid for comparison.

260

### 261 **3. Methodology**

#### 262 **3.1 Relative sea level trends from tide gauges**

263 Relative sea level trends ( $RSL_{TG}$ ) were calculated by least squares linear fitting from the TG  
264 records over their total period and over the 1993-2015 period for comparison with the  
265 altimetric data (when both periods overlapped a minimum of 75% of the time) (see Table 1).  
266 The time series were previously deseasoned by removing the climatological monthly mean  
267 from the monthly values. Incomplete years were removed before computing the  
268 climatological monthly means. Uncertainties were defined as the Standard Error (SE) of the  
269 fit adjusted for lag-1 autocorrelation (Santer et al., 2000). One study found this method  
270 appropriate for annual RSL data but not recommendable for monthly data because the trend  
271 uncertainty may be underestimated (Bos et al., 2014). However, a recent global analysis of  
272 the PSMSL tide gauges (Pfeffer et al., 2016) found no significant differences in the SE  
273 adjusted by this method between monthly and annual data in agreement with a similar  
274 analysis that we performed with the TG records in this study (Table S1).

275

#### 276 **3.2 Vertical land movements**

277 In addition to VLM estimates from GPS, VLM can be obtained by subtracting TG data from  
278 satellite radar altimetry data ( $VLM_{ATG}$ ). Indeed, as sea levels from satellite altimetry are  
279 expressed relative to the Earth's centre of mass and those from TGs are relative to the land  
280 surface, the difference corresponds to a quantity similar to a geocentric vertical land surface  
281 motion, provided that the instrumental drifts are negligible and the oceanic signal content in  
282 both sea level measurements is identical (Cazenave et al., 1999). In this study, two sources of  
283 satellite altimetry data were considered (section 2), hence two different ATG monthly time  
284 series were produced at each TG location. Note that the satellite altimetry time series  
285 correspond to the spatially averaged Sea Level Anomaly time series over a region of 0.5  
286 degree of radius around the corresponding closest grid to each TG. Also note that a minimum  
287 of 70% of common sea level period was necessary to compute the above-mentioned  
288 differences between satellite and tide gauge data. Subsequently, two estimates of vertical land

289 motion were obtained by calculating the least squares linear trends ( $VLM_{ATG}$ ) from the ATG  
 290 monthly time series over the 1993-2015 period. SE of the fit were adjusted for lag-1  
 291 autocorrelation (Santer et al., 2000). A combined estimate of the  $VLM_{ATG}$  trends was  
 292 computed at TG locations by averaging the two  $VLM_{ATG}$  trend values obtained from each of  
 293 the altimetry datasets (AVISO and CSIRO) weighted by their respective inverse squared  
 294 uncertainty. Similarly, a combined estimate of the  $VLM_{GPS}$  trend was computed at each  
 295 location by averaging the two different  $VLM_{GPS}$  trend values obtained from SONEL and NGL  
 296 weighted by their respective inverse squared uncertainty. Uncertainties were estimated using  
 297 the standard error of a weighted mean.

298

299 The RSL variations at the TG locations were compared with GMSL, by estimating the linear  
 300 trend of the difference between the TG records to both the satellite altimetry Global Mean Sea  
 301 Level (1993-2015, Table 1 and Fig. 1a) and the reconstructed GMSL (1880-2013, Table 1 and  
 302 Fig. 1b, Church et al. 2013) during their overlapping period. Only differenced time series  
 303 covering at least five years were used to calculate the trends (Table 2).

304

### 305 **3.3 Estimation of future changes of relative sea level**

306 For the calculation of the projected RSL changes over the twenty-first century and their  
 307 corresponding uncertainties, we first obtained estimates of the projected absolute sea-level  
 308 (PSL) changes by combining all the geophysical components described in section 2.1.3 (see  
 309 Church et al., 2013b for more details). We then calculated projections of vertical land motion  
 310 due to GIA ( $VLM_{GIA}$ ), which is the only geophysical process for which there are reasonably  
 311 accurate models available, and due to any vertical land motion process ( $VLM_{TOTAL}$ ) as  
 312 observed by satellite techniques, provided there was no-evidence of past non-linearity in the  
 313 time series (e.g., due to earthquakes). Projections of RSL ( $PRSL_{GIA}$  and  $PRSL_{TOTAL}$ ) at these  
 314 selected locations were finally obtained by subtracting either  $VLM_{GIA}$  or  $VLM_{TOTAL}$   
 315 ( $VLM_{ATG}$  and  $VLM_{GPS}$ ) projections to the projected absolute sea-level projections at their  
 316 closest grid points and finally adding the  $GEOID_{GIA}$  projections to account for the geoid effect  
 317 of GIA.

318

$$319 \quad PRSL_{GIA} = PSL - VLM_{GIA} + GEOID_{GIA} = PSL + NET_{GIA} \quad (1)$$

$$320 \quad PRSL_{TOTAL} = PSL - VLM_{TOTAL} + GEOID_{GIA} \quad (2)$$

321

322 Standard errors for the projections were calculated as the root-sum-square of standard errors  
323 in PSL and vertical land motion projections.

324

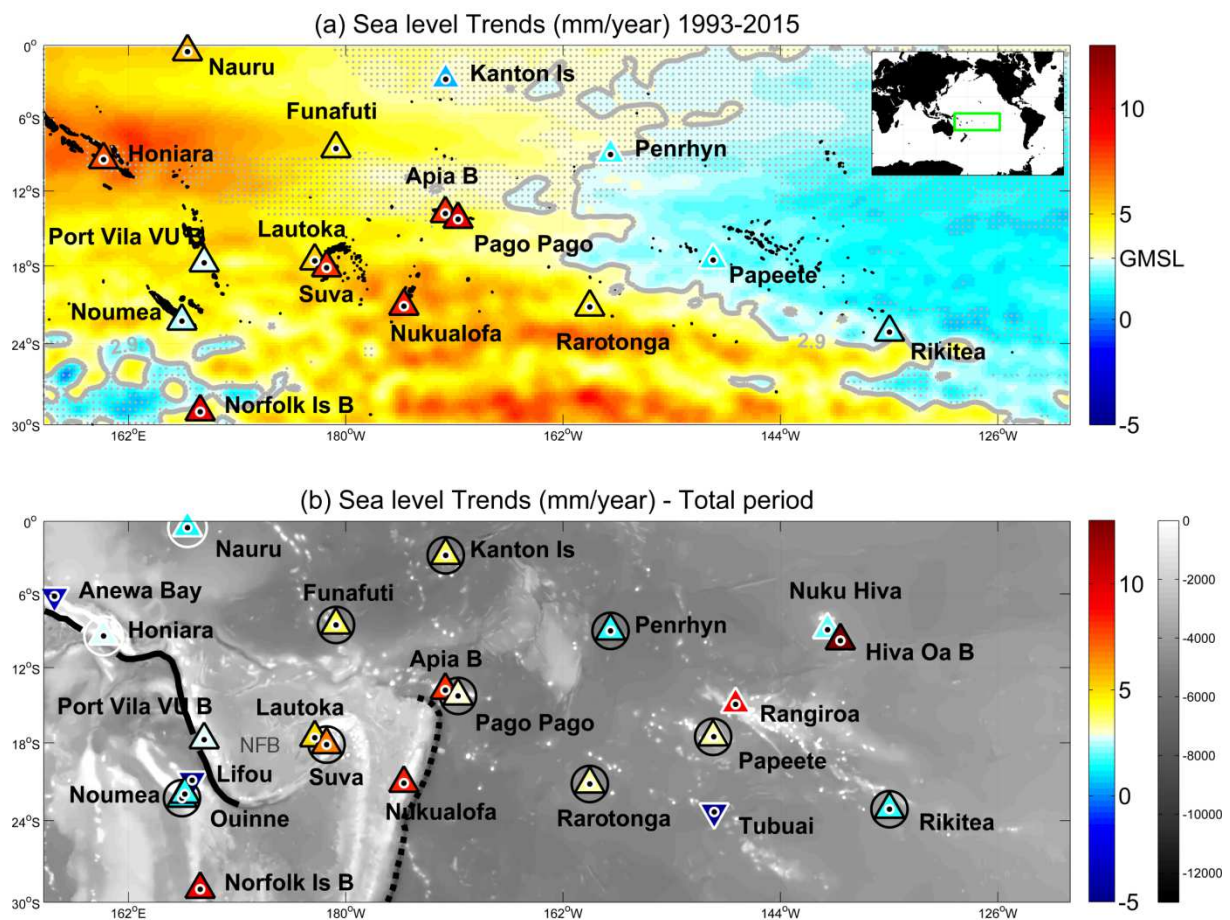
#### 325 4. Results

326

327 The spatial pattern of absolute sea level (ASL) trends from AVISO (1993-2015) is shown in  
328 Figure 1a. Significant trends were found overall in the study domain and higher values than  
329 the absolute Global Mean Sea Level rate ( $2.9 \pm 0.1 \text{ mm yr}^{-1}$ ) were found over the region  
330 covering the central and north western parts of the domain ( $\sim 5 \text{ mm yr}^{-1}$  on average and  
331 maximum values of  $9.0 \pm 1.3 \text{ mm yr}^{-1}$ ). Lower rates than global were found over the region  
332 covering the south western and eastern parts of the domain ( $\sim 2 \text{ mm yr}^{-1}$  on average and  
333 minimum values of  $1.0 \pm 0.5 \text{ mm yr}^{-1}$ ).

334

335



336

337

338 **Figure 1.** Relative Sea level trends (mm/year) at tide gauges (coloured triangles) and absolute  
339 sea level trends at AVISO altimetry grid points (coloured areas) calculated over the 1993-  
340 2015 period (a) and over the total period of each tide gauge (b). Grey contours mark global

341 mean sea level trend during 1993-2015. White-bordered triangles (a,b) and dot-shaded areas  
342 (a) denote no statistical significance at the  $2\sigma$  confidence level. Black circles denote tide  
343 gauges records longer than 40 years. Note that the colorbar is designed to emphasize the  
344 difference between sea level trends and the GMSL, but values are strictly sea level trends.  
345 GEBCO\_2014 (Weatherall et al. 2015) bathymetry (in meters) is also shown (b) to highlight  
346 tectonic features in the region. The Eastward dipping Solomon and New Hebrides subduction  
347 zones are evidenced by the elongated trench running long Anewa Bay, Honiara and Port-Vila  
348 (continuous black line) and the Westward dipping Tonga-Kermadec subduction zone runs  
349 East of Nukualofa (dashed black line). The North Fiji Basin (NFB on the map), North-West  
350 of Suva and Lautoka is shallower than the Pacific plate to the East and displays many tectonic  
351 features.

352

353 Even though RSLs from TGs can be expected to depart from the GMSL for various reasons,  
354 Figure 1b intentionally displays them to highlight these differences. Significant trends of RSL  
355 were found in most of the longest tide gauge records, with time spans ranging from 40 to 66  
356 years (Table 1 and Fig 1b). Trend values significantly higher than the absolute GMSL were  
357 found at most of the tide gauges located over the central part of the domain ( $-170^{\circ}\text{W}$  to  $170^{\circ}\text{E}$ )  
358 ranging from  $2.9 \pm 0.5 \text{ mm yr}^{-1}$  ( $0.8 \text{ mm yr}^{-1}$  higher than GMSL) at Pago Pago to  $6.6 \pm 0.7$   
359  $\text{mm yr}^{-1}$  ( $4.2 \text{ mm yr}^{-1}$  higher than GMSL) at Suva. Lower but still significant trends were  
360 found at most of the stations located at the western and eastern parts of the domain. Trends  
361 significantly lower than the GMSL were found at two stations, namely Noumea ( $0.9 \pm 0.4$   
362  $\text{mm yr}^{-1}$  [ $-1.4 \text{ mm yr}^{-1}$  lower than GMSL]) and Rikitea ( $1.7 \pm 0.3 \text{ mm yr}^{-1}$  [ $-0.6 \text{ mm yr}^{-1}$  lower  
363 than GMSL]) (Table 2 and Fig. 1b). Non-significant differences between TG and GMSL  
364 trends were found at two of the longest tide gauge records, namely Funafuti ( $3.8 \pm 1.3 \text{ mm yr}^{-1}$ )  
365 and Honiara ( $2.8 \pm 1.9 \text{ mm yr}^{-1}$ ), located in the region where sea level has a large  
366 interannual variability associated with ENSO resulting in large uncertainties in sea level  
367 trends (Church et al., 2006, Becker et al. 2012). The corresponding deviations of the ASL  
368 trends with respect to the global sea-level rise are thought to result from the climate  
369 variability driving regional sea-level changes from interannual to multidecadal scales, while  
370 differences between TG and GMSL trends are assumed to be due to climate variability, record  
371 length, VLM, instrumental errors or a combination of all. They will be discussed as  
372 appropriate later on.

373

374 **Table 2.** Relative sea level trends at tide gauge stations calculated over both the total period  
375 and 1993-2015. Trends of the difference between the TG records to both the satellite altimetry  
376 GMSL (1993-2015, common period) and the reconstructed GMSL (total period) over their  
377 overlapping period (in parenthesis). Asterisks denote tide gauge records longer than 40 years.  
378 Absolute sea level trends at the closest grid points to the tide gauge locations and their  
379 differences with respect the Global Mean Sea Level. Trends of the differenced time series of

380 monthly satellite altimetry (AVISO and CSIRO products) minus tide gauge data, standard  
 381 errors and their weighted means of the trends.  $VLM_{GPS}$  trends and standard errors (SONEL,  
 382 NGL and their weighted means) at the closest GPS sites to the tide gauge stations. Non-robust  
 383 vertical land motion estimates at GPS sites as considered by the GPS centers are denoted with  
 384 the term *NR*. Total weighted means of vertical land motion trends and standard errors are also  
 385 listed. Black bold values indicate statistical significance at  $2\sigma$  level.  
 386  
 387

Tide gauge	Total period	Sea level Trends			Vertical land motion Trends									
		Total period	1993-2015 (common period)		VLM ATG (mm·yr <sup>-1</sup> )			Closest GPS	Period SONEL	Period NGL	VLM GPS (mm·yr <sup>-1</sup> )			
		RSL Trend (mm·yr <sup>-1</sup> )	RSL Trend (mm·yr <sup>-1</sup> )	ASL AVISO Trend (mm·yr <sup>-1</sup> )	AVISO	CSIRO	Weighted mean				SONEL	NGL	Weighted mean	
Anewa Bay	1968-1977	-3.6 ± 13.7 (-6.0 ± 13.7)	- (-)	- (-)	-	-	-	-	-	-	-	-	-	-
Honiara*	1974-2015	2.8 ± 1.9 (0.5 ± 2.1)	<b>7.6 ± 3.4</b> (4.8 ± 3.4)	<b>7.7 ± 3.5</b> (4.9 ± 3.5)	0.0 ± 0.3	<b>-1.3 ± 0.4</b>	-0.3 ± 0.2	SOLO	2008-2013	-	-	<i>NR</i>	-	-
Noumea A*	1967-2015	<b>0.9 ± 0.4</b> (-1.4 ± 0.4)	<b>2.4 ± 1.0</b> (-0.4 ± 1.0)	<b>4.2 ± 0.8</b> (1.4 ± 0.8)	<b>1.7 ± 0.3</b>	<b>1.6 ± 0.4</b>	<b>1.7 ± 0.2</b>	NOUM	1997-2007	1997-2007	-	<b>-1.4 ± 0.3</b>	-2.0 ± 1.2	<b>-1.4 ± 0.3</b>
Ouinne	1981-2015	<b>1.7 ± 0.3</b> (-1.4 ± 5.1)	- (-)	- (-)	-	-	-	YATE	-	2008-2016	-	-	1.7 ± 1.7	1.7 ± 1.7
Nauru*	1974-2014	1.4 ± 1.0 (-1.6 ± 0.9)	<b>5.5 ± 2.5</b> (2.7 ± 2.5)	<b>5.3 ± 2.1</b> (2.5 ± 2.1)	-0.2 ± 0.8	-1.1 ± 1.0	-0.6 ± 0.6	NAUR	2003-2014	2003-2016	-	<b>-1.0 ± 0.3</b>	-0.3 ± 1.0	<b>-0.9 ± 0.2</b>
Lifou	2011-2015	-5.0 ± 9.7 (-8.8 ± 9.7)	- (-)	- (-)	-	-	-	LPIL	1996-2013	1996-2016	-	0.2 ± 0.4	<b>-2.6 ± 1.2</b>	-0.2 ± 0.4
Norfolk Is	1994-2014	<b>9.3 ± 2.1</b> ( <b>6.5 ± 2.2</b> )	<b>9.3 ± 2.1</b> ( <b>6.5 ± 2.2</b> )	<b>2.6 ± 1.0</b> (-0.5 ± 1.0)	<b>-7.1 ± 2.2</b>	<b>-7.9 ± 1.9</b>	<b>-7.5 ± 1.4</b>	NORF	2008-2013	2008-2016	-	0.4 ± 0.4	-1.0 ± 0.8	0.1 ± 0.3
Port Vila VU A	1977-1982	13.6 ± 16.1 (-)	- (-)	- (-)	-	-	-	-	-	-	-	-	-	-
Port Vila VU B	1993-2015	<b>2.8 ± 1.3</b> (0.0 ± 1.4)	<b>2.8 ± 1.3</b> (0.0 ± 1.4)	<b>4.9 ± 1.0</b> (2.0 ± 1.0)	<b>1.8 ± 0.4</b>	<b>1.6 ± 0.5</b>	<b>1.7 ± 0.3</b>	VANU	2002-2013	2002-2013	-	<i>NR</i>	<i>NR</i>	-
Lautoka	1992-2014	<b>5.2 ± 1.5</b> (2.3 ± 1.5)	<b>5.2 ± 1.5</b> (2.3 ± 1.5)	<b>5.5 ± 1.3</b> (2.7 ± 1.3)	0.3 ± 0.3	0.3 ± 0.3	0.3 ± 0.2	LAUT	2001-2013	2001-2016	-	<b>-1.2 ± 0.3</b>	-0.6 ± 1.2	<b>-1.1 ± 0.3</b>
Suva*	1972-2015	<b>6.6 ± 0.7</b> ( <b>4.2 ± 0.7</b> )	<b>8.2 ± 1.6</b> ( <b>5.4 ± 1.7</b> )	<b>6.0 ± 1.3</b> (3.2 ± 1.3)	<b>-2.2 ± 0.5</b>	<b>-2.5 ± 0.6</b>	<b>-2.3 ± 0.4</b>	SUVA	1998-2002	1998-2002	-	<i>NR</i>	-4.0 ± 4.1	-4.0 ± 4.1
"	"	"	"	"	"	"	"	FTNA	1998-2013	1998-2016	-	-0.3 ± 0.3	-0.2 ± 2.3	-0.3 ± 0.3
Funafuti*	1977-2015	<b>3.8 ± 1.3</b> (1.0 ± 1.4)	<b>4.6 ± 2.1</b> (1.8 ± 2.1)	<b>4.9 ± 2.2</b> (2.1 ± 2.2)	<b>0.4 ± 0.2</b>	-0.4 ± 0.3	0.2 ± 0.2	TUVA	2001-2013	2001-2016	-	<b>-1.7 ± 0.2</b>	-1.7 ± 1.1	<b>-1.7 ± 0.2</b>
Nukualofa	1993-2014	<b>8.3 ± 1.1</b> ( <b>5.2 ± 1.2</b> )	<b>8.3 ± 1.1</b> ( <b>5.5 ± 1.2</b> )	<b>6.8 ± 1.1</b> ( <b>4.0 ± 1.1</b> )	<b>-1.5 ± 0.2</b>	<b>-2.1 ± 0.5</b>	<b>-1.6 ± 0.2</b>	TONG	2002-2013	-	-	<b>3.0 ± 0.4</b>	-	<b>3.0 ± 0.4</b>
Apia A	1954-1971	0.0 ± 1.6 (-1.1 ± 1.6)	- (-)	- (-)	-	-	-	-	-	-	-	-	-	-
Apia B	1993-2015	<b>8.2 ± 2.2</b> ( <b>5.3 ± 2.2</b> )	<b>8.2 ± 2.2</b> ( <b>5.3 ± 2.2</b> )	3.7 ± 2.2 (0.9 ± 2.2)	<b>-4.4 ± 0.7</b>	<b>-4.9 ± 0.7</b>	<b>-4.7 ± 0.5</b>	SAMO	-	2001-2016	-	-	<b>-5.0 ± 1.6</b>	<b>-5.0 ± 1.6</b>
Kanton Is*	1949-2012	<b>3.7 ± 0.5</b> ( <b>1.8 ± 0.6</b> )	0.4 ± 2.5 (-2.4 ± 2.5)	0.8 ± 2.9 (-2.0 ± 2.8)	0.2 ± 0.2	-0.1 ± 0.2	0.1 ± 0.1	TUVA	2001-2013	2001-2016	-	<b>-1.7 ± 0.2</b>	-1.7 ± 1.1	<b>-1.7 ± 0.2</b>
Pago Pago*	1948-2014	<b>2.9 ± 0.5</b> ( <b>0.8 ± 0.4</b> )	<b>9.5 ± 2.4</b> ( <b>6.7 ± 2.4</b> )	<b>4.0 ± 2.1</b> (1.2 ± 2.1)	<b>-5.5 ± 1.2</b>	<b>-6.4 ± 1.0</b>	<b>-6.1 ± 0.7</b>	ASPA	2001-2013	2001-2016	-	<i>NR</i>	<b>-5.4 ± 1.5</b>	<b>-5.4 ± 1.5</b>
Rarotonga*	1977-2015	<b>3.4 ± 0.5</b> (1.0 ± 0.6)	<b>4.6 ± 1.0</b> (1.8 ± 1.0)	<b>4.2 ± 1.0</b> (1.4 ± 1.0)	<b>-0.4 ± 0.2</b>	0.0 ± 0.6	-0.3 ± 0.2	CKIS	2001-2013	2001-2016	-	-0.5 ± 0.4	-0.1 ± 1.1	-0.5 ± 0.3
Penrhyn*	1977-2015	<b>1.7 ± 0.8</b> (-1.2 ± 0.9)	1.5 ± 1.7 (-1.3 ± 1.6)	2.4 ± 1.7 (0.4 ± 1.6)	<b>0.8 ± 0.2</b>	0.3 ± 0.4	<b>0.7 ± 0.2</b>	CKIS	2001-2013	2001-2016	-	-0.5 ± 0.4	-0.1 ± 1.1	-0.5 ± 0.3
Papeete*	1969-2014	<b>3.2 ± 0.4</b> (0.9 ± 0.5)	1.3 ± 1.0 (-1.4 ± 1.0)	<b>1.5 ± 0.9</b> (-1.3 ± 0.9)	0.1 ± 0.2	-0.2 ± 0.3	0.1 ± 0.1	PAPE	2004-2013	2004-2016	-	<b>-1.9 ± 0.2</b>	-1.5 ± 1.2	<b>-1.9 ± 0.2</b>
"	"	"	"	"	"	"	"	THTI	1998-2013	-	-	<b>-0.5 ± 0.2</b>	-	<b>-0.5 ± 0.2</b>
Matavai	1958-1967	2.1 ± 2.0 (2.2 ± 2.3)	- (-)	- (-)	-	-	-	-	-	-	-	-	-	-
Tubuai	2009-2013	-9.4 ± 15.1 (-12.7 ± 15.3)	- (-)	- (-)	-	-	-	TBTG	2009-2013	2009-2014	-	-0.3 ± 0.5	-1.6 ± 1.2	-0.5 ± 0.5
Rangiroa	2009-2014	9.1 ± 6.0 (6.0 ± 6.0)	- (-)	- (-)	-	-	-	-	-	-	-	-	-	-
Nuku Hiva	1982-2015	1.9 ± 1.3 (-1.4 ± 1.5)	- (-)	- (-)	-	-	-	-	-	-	-	-	-	-
Hiva Oa A	1977-1980	3.5 ± 8.9 (-)	- (-)	- (-)	-	-	-	-	-	-	-	-	-	-
Hiva Oa B	2010-2015	<b>39.8 ± 9.4</b> (-)	- (-)	- (-)	-	-	-	-	-	-	-	-	-	-
Rikitea*	1969-2015	<b>1.7 ± 0.3</b> ( <b>-0.6 ± 0.3</b> )	<b>1.8 ± 0.8</b> (-1.0 ± 0.8)	<b>1.7 ± 0.8</b> (-1.0 ± 0.8)	0.1 ± 0.2	-0.8 ± 0.5	-0.1 ± 0.2	GAMB	2000-2010	2000-2016	-	<b>-1.0 ± 0.4</b>	-0.9 ± 1.2	<b>-1.0 ± 0.4</b>

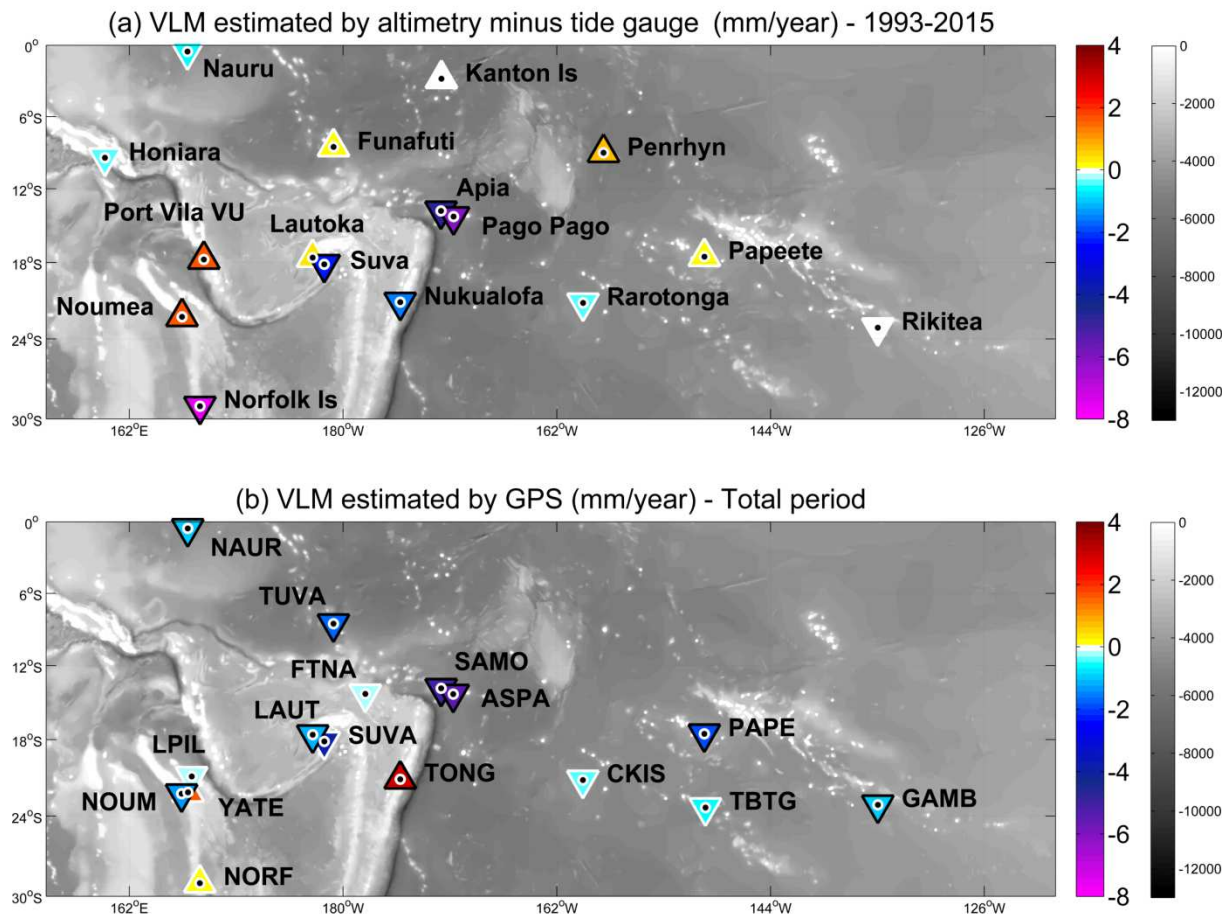
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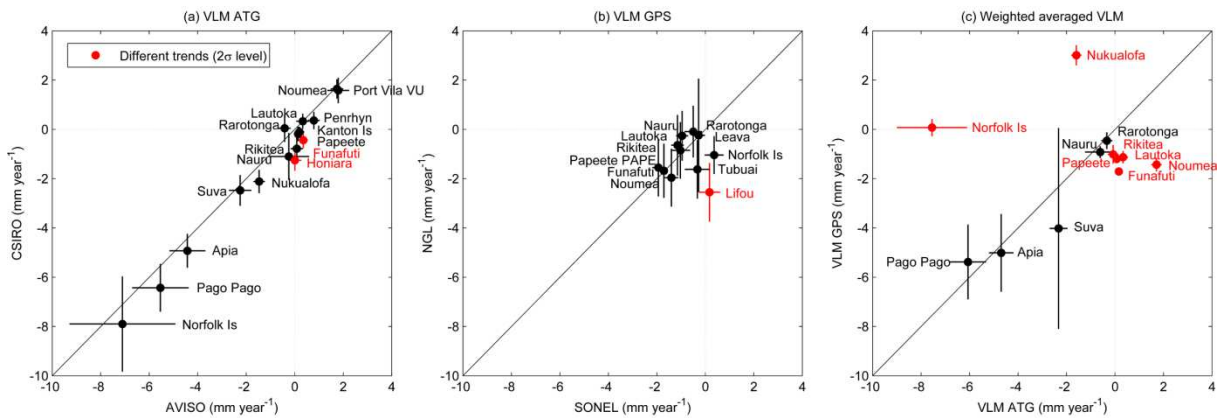
395 **Figure 2.**  $VLM_{ATG}$  weighted means (AVISO and CSIRO) calculated over 1993-2015 at the  
396 tide gauge locations (a) and  $VLM_{GPS}$  weighted means (SONEL and NGL) calculated at their  
397 closest GPS stations (b). Upward (downward) triangles denote positive (negative) VLM  
398 values. White-bordered triangles denote no statistical significance at  $2\sigma$  level. GEBCO  
399 bathymetry (in meters) is also shown.

400  
401

402 A comparison of ASL and RSL trends at each TG station over the altimetry period is shown  
403 in Figure 1a and listed in Table 2. The spatial pattern of the RSL trends obtained from tide  
404 gauge records was overall found very similar to that of the ASL trends from altimetry, with  
405 positive trends over all the domain and maximum values at the stations located at central and  
406 north western parts of the domain, namely Pago Pago ( $9.5 \pm 2.4 \text{ mm yr}^{-1}$  [ $6.7 \text{ mm yr}^{-1}$  higher  
407 than GMSL]) and Honiara ( $7.6 \pm 3.4 \text{ mm yr}^{-1}$  [ $4.8 \text{ mm yr}^{-1}$  higher than GMSL]) and minimum  
408 values at the tide gauges located at the south western and eastern parts, namely Rikitea ( $1.8 \pm$   
409  $0.8 \text{ mm yr}^{-1}$  [ $-1.0 \text{ mm yr}^{-1}$  lower than GMSL]) and Noumea A ( $2.4 \pm 1.0 \text{ mm yr}^{-1}$  [ $-0.4 \text{ mm}$   
410  $\text{yr}^{-1}$  lower than GMSL]) (Table 2 and Figs. 1a, b).

411 However, locally significant differences between ASL and RSL trends were found at 8 out of  
 412 the 27 tide gauge locations (Table 2). These differences can be due to VLM. For instance,  
 413 significant subsidences were found in the central part of the domain at Pago Pago ( $-6.1 \pm 0.7$   
 414  $\text{mm yr}^{-1}$ ), Apia B ( $-4.7 \pm 0.5 \text{ mm yr}^{-1}$ ), Suva ( $-2.3 \pm 0.4 \text{ mm yr}^{-1}$ ) and Nukualofa ( $-1.6 \pm 0.2$   
 415  $\text{mm yr}^{-1}$ ), and the highest subsidence was found at Norfolk Island, which is located in the  
 416 south western part ( $-7.5 \pm 1.4 \text{ mm yr}^{-1}$ ) (Fig. 2a and Table 2). Significant uplift was found at  
 417 three tide gauges: Port Vila B ( $1.7 \pm 0.3 \text{ mm yr}^{-1}$ ), Noumea A ( $1.7 \pm 0.2 \text{ mm yr}^{-1}$ ), and  
 418 Penrhyn ( $0.7 \pm 0.2 \text{ mm yr}^{-1}$ ). Note that the uplift obtained for the Port-Vila tide gauge  
 419 ( $\text{VLM}_{\text{ATG}}$ ) may be overestimated due to the fact that a  $\sim 11\text{cm}$  offset related to an earthquake  
 420 in 2002 (Level, 2009) has been corrected in the tide gauge series available from the UHSLC  
 421 website . Discrepancies between  $\text{VLM}_{\text{ATG}}$  from AVISO and CSIRO were found at two  
 422 stations: first, at Honiara, where no significant vertical land motion was found with AVISO  
 423 dataset, whereas a significant subsidence ( $-1.3 \pm 0.4 \text{ mm yr}^{-1}$ ) was found with CSIRO; second,  
 424 at Funafuti, where significant trends (at  $2\sigma$  level) with opposite sign were found with AVISO  
 425 ( $0.4 \pm 0.2 \text{ mm yr}^{-1}$ ) and CSIRO ( $-0.4 \pm 0.3 \text{ mm yr}^{-1}$ ) (Table 2 and Fig. 3a).

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430 **Figure 3.** Scatterplot between trends of vertical land motion from (a) satellite radar altimetry  
 431 minus tide gauge ( $\text{VLM}_{\text{ATG}}$ ) data from AVISO and CSIRO, (b) GPS data from SONEL and  
 432 NGL, and (c) weighted means of  $\text{VLM}_{\text{ATG}}$  and  $\text{VLM}_{\text{GPS}}$  trends (see section 3). Error bars  
 433 denote one  $\sigma$  standard error. In red colour denotes that trends are different at the  $2\sigma$   
 434 significance level (T-test).  
 435

436 A question now arises as to whether VLM trend estimates obtained by using different  
 437 approaches are consistent with each other. To answer this question, we first compared the  
 438  $\text{VLM}_{\text{ATG}}$  with the  $\text{VLM}_{\text{GPS}}$  obtained from the GPS data centers. Significant subsidence  
 439 (weighted averaged  $\text{VLM}_{\text{GPS}}$ ) was found at 11 out of the 19 GPS stations, with the highest



440 values at those stations located over the central part of the domain: Pago Pago (ASPA,  $-5.4 \pm$   
441  $1.5 \text{ mm yr}^{-1}$ ) and Apia B (SAMO,  $-5.0 \pm 1.6 \text{ mm yr}^{-1}$ ), which are affected by a major  
442 earthquake (Fig. 2b and Table 2), the 2009 M8.1 Samoa earthquake which occurred on the  
443 outer rise of the Tonga-Kermadec subduction zone. This earthquake is responsible for a  
444 significant sudden offset in the timeseries, but also a longer-term change in the ground motion  
445 due to post-seismic deformation. Such major seismic events are a real issue in terms of sea-  
446 level monitoring using tide gauges since their long-term impact (due to the post-earthquake  
447 viscoelastic deformation occurring in the lower crust and upper mantle (i.e. Johnson and  
448 Tebo, 2018)) cannot easily be modeled and accounted for. Lower but still significant  
449 subsidence was found at most of the remaining stations with values ranging from  $-0.9 \pm 0.2$   
450  $\text{mm yr}^{-1}$  at Nauru (NAUR) to  $-1.9 \pm 0.2 \text{ mm yr}^{-1}$  at Papeete (PAPE). Nukulaofa (TONG) is the  
451 only location where a significant  $\text{VLM}_{\text{GPS}}$  uplift ( $3.0 \pm 0.4 \text{ mm yr}^{-1}$ ) was found. Note that  
452  $\text{VLM}_{\text{GPS}}$  estimates shown for ASPA, SAMO and TONG are not weighted averages because  
453 they were considered non-robust by SONEL. Discrepancies between SONEL and NGL  
454  $\text{VLM}_{\text{GPS}}$  were found only at Lifou (LPIL) where a high subsidence was found only for  
455 SONEL (Table 2 and Fig. 3b). Major discrepancies were found between  $\text{VLM}_{\text{GPS}}$  and  
456  $\text{VLM}_{\text{ATG}}$  at 7 out of the 12 locations when weighted averaged trends were compared. In  
457 particular, significant  $\text{VLM}_{\text{GPS}}$  subsidence was found at five locations where the  $\text{VLM}_{\text{ATG}}$   
458 were found either non-significant (Lautoka, Funafuti, Papeete and Rikitea), or positive, as in  
459 Noumea A in agreement with the  $\text{VLM}_{\text{ATG}}$  uplift of  $2.5 \pm 1.5 \text{ mm/yr}$  found by Nerem and  
460 Mitchum (2002) (Table 2 and Fig. 3c). Significant  $\text{VLM}_{\text{ATG}}$  subsidence was found at two  
461 locations, namely Norfolk Island and Nukulaofa, where  $\text{VLM}_{\text{GPS}}$  were found non-significant  
462 and positive, respectively. These discrepancies were not present at 5 of these 7 stations  
463 (Lautoka, Funafuti, Nukulaofa, Papeete and Rikitea) when  $\text{VLM}_{\text{ATG}}$  estimates were directly  
464 compared with  $\text{VLM}_{\text{GPS}}$  estimates from NGL, mainly due to much higher uncertainties. Note  
465 that significant  $\text{VLM}_{\text{GPS}}$  subsidence was found at Papeete at two different GPS stations for  
466 SONEL, namely PAPE ( $-1.9 \pm 0.2$ ) and THTI ( $-0.5 \pm 0.2$ ), located very close to each other (1  
467 and 3900 m from the tide gauge, respectively), indicating the high spatial variability of the  
468  $\text{VLM}_{\text{GPS}}$  trend estimates at this island.

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## 471 **5. Discussion**

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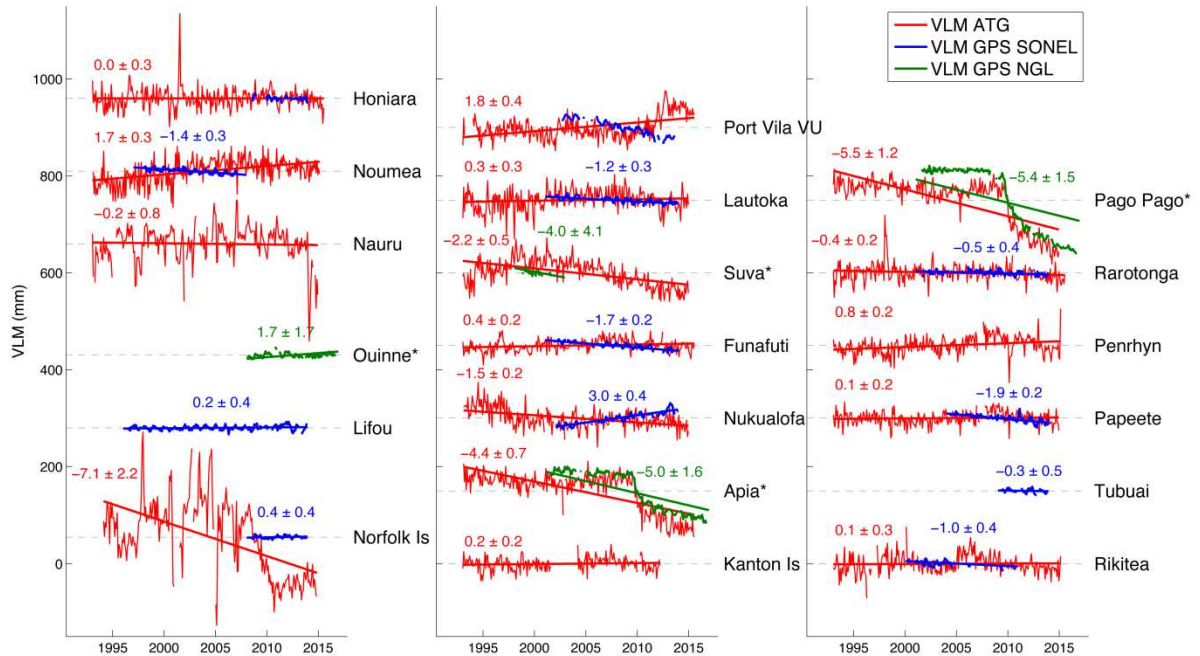
473 We have investigated sea level trends at the islands located over the South Western Tropical  
474 Pacific region, both through their variation with respect to the land surface and through their  
475 geocentric variation. This has allowed us to identify (Fig. 1) and quantify (Fig. 2) the  
476 contribution of ground vertical movements to sea level trends observed at the coast using  
477 independent geodetic methods and assuming a linear rate of change. We have found that RSL  
478 rose at higher rates than the GMSL over the last 4-6 decades, especially where the highest  
479 land subsidence occurred, coinciding with the region where the Pacific and Australian  
480 tectonic Plates converge. Differences and similarities between local RSL trends and the  
481 GMSL rise (Fig. 1) can be at least partially accounted for by the presence or absence of VLM,  
482 as at Honiara, Noumea and Penrhyn, where the vertical displacements of the tide gauge with  
483 respect to the centre of mass of the Earth significantly accounted for these differences (Table  
484 2 and Fig. S4).

485

486

487 At Noumea and Penrhyn, however,  $VLM_{ATG}$  and  $VLM_{GPS}$  estimates are not consistent,  
488 indicating probably that the TG is subject to non-linear processes, such as earthquakes,  
489 superimposed on the long-term motion detected at the GPS station. However, no evidence of  
490 earthquakes has been found at Penrhyn. At Nauru, Suva, Pago Pago and Rarotonga, we did  
491 not find discrepancies between  $VLM_{ATG}$  and  $VLM_{GPS}$  estimates although they cannot totally  
492 account for the long-term local sea level deviations with respect the GMSL trend. It might  
493 have been due either to the presence of non-linear VLM, or to the impact of multidecadal  
494 climate variability, which can produce at Pago Pago deviations of similar magnitude to the  
495 observed (Becker et al., 2012), or to a combination of both. TGs did not subside over the  
496 altimetry period at Funafuti, Kanton Island and Papeete, but they recorded a high sea-level  
497 rise over the long-term, in agreement with subsidence found at the GPS data. A possible  
498 explanation for this can be that non-linear uplifts occurred at the start of the altimetry period,  
499 which could not be registered at the GPS records. No evidence of earthquakes was found at  
500 Kanton Island and Papeete, which carries the implication of other processes, for instance  
501 related to the stability of the volcanic edifice or to the influence of multi-decadal regional  
502 variability which may be especially important at Funafuti and Papeete (Becker et al., 2012). It  
503 is worth mentioning that the complex behavior of the volcanic edifice at Tahiti may cause  
504 different rates of vertical land motion depending on the location (S. Calmant, personal  
505 communication). At Rikitea, RSL rose at a lower rate than globally on the long term, and it  
506 cannot be accounted for by any of the VLM estimates and neither by regional multidecadal

507 variability, which has an opposite effect on sea level trends at this location (Becker et al.,  
 508 2012). We have no explanation for this discrepancy.  
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511  
 512 **Figure 4.** VLM<sub>ATG</sub> time-series at tide gauge locations from the AVISO satellite altimetry  
 513 database (red lines). VLM<sub>GPS</sub> time-series from SONEL (blue lines) and from NGL (green  
 514 lines). Units are millimetres. VLM<sub>ATG</sub>, VLM<sub>GPS</sub> and standard error values are shown together  
 515 with their corresponding linear trend lines (units in mm/year). Asterisks denote the locations  
 516 where robust VLM<sub>GPS</sub> trends from SONEL are not available and VLM<sub>GPS</sub> time-series, in this  
 517 case the trends from NGL are plotted. VLM<sub>GPS</sub> values are absent at the locations where robust  
 518 VLM<sub>GPS</sub> estimates are not available for both SONEL and NGL.  
 519

520 We have explored the uncertainty associated with VLM at three different levels: (1)  
 521 differences between types of VLM estimates: (i) VLM<sub>GPS</sub> mainly assuming linear processes,  
 522 (ii) VLM<sub>ATG</sub> including all processes, linear and non-linear and (iii) VLM<sub>GIA</sub> that obviously  
 523 include only the GIA, which is linear over the time periods considered here; (2) differences  
 524 between GPS products: SONEL and NGL; and (3) differences between altimetry products:  
 525 AVISO and CSIRO. Not surprisingly, the largest discrepancies were found at the first level,  
 526 i.e. when the different types of VLM were compared, not only when VLM<sub>GIA</sub> estimates were  
 527 compared to the two others, but also when VLM<sub>GPS</sub> and VLM<sub>ATG</sub> (both including GIA and  
 528 non-GIA VLM) estimates were compared (see Fig. 3c). In addition, the GIA model is not  
 529 intended to account for any process different than GIA, which in turn has a weak impact  
 530 (mainly uplift) over the study domain.  
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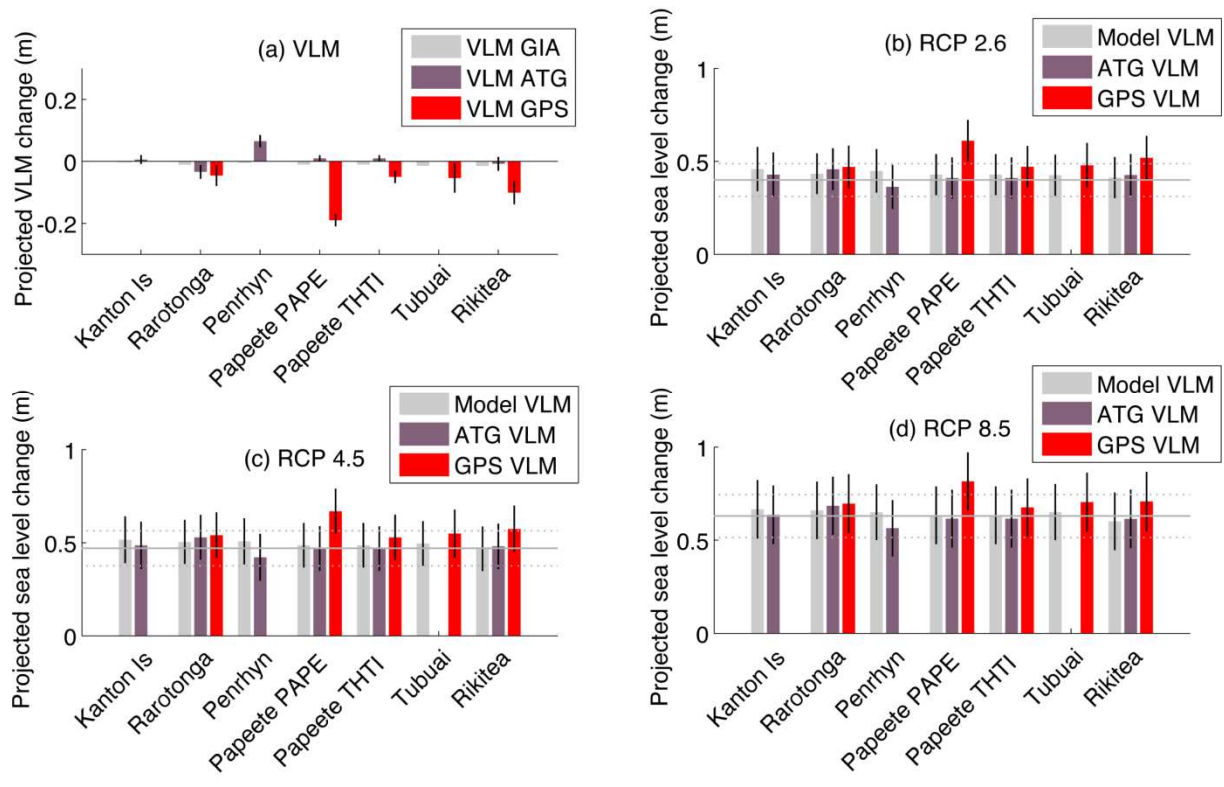
532 Figure 4 shows a comparison of the VLM time series obtained from the difference between  
533 altimetry and TG data and those obtained from the GPS analysis centres. It can be seen that  
534 ATG time series, at those stations where discrepancies between weighted averaged  $VLM_{ATG}$   
535 and  $VLM_{GPS}$  are important (Lautoka, Funafuti, Papeete, Rikitea, Noumea A, Norfolk Island  
536 and Nukulaofa), present non-linear oscillations that do not appear in the GPS time series.  
537 Another example is Port Vila B (Vanuatu), where SONEL and NGL did not provide robust  
538 VLM trend estimates, and where we found that the tide gauge uplift over the altimetry period  
539 ( $1.7 \pm 0.2$  mm/y) may have been mainly produced by the effect of earthquakes that can impact  
540 the land motion in the area (Ballu et al., 2011). At the stations where VLM linear trends from  
541 SONEL were not assessed as robust (Suva, Apia B and Pago Pago), both  $VLM_{GPS}$  time series  
542 from NGL were more similar to that for  $VLM_{ATG}$ , which is not surprising given that the GPS  
543 position time series provided by NGL include the offsets. It is especially evident at Apia B  
544 and Pago Pago, where  $VLM_{ATG}$  and  $VLM_{GPS}$  time series present the impact (co-seismic and  
545 post-seismic signal) of a large earthquake which occurred in 2009 (Okal et al., 2010) due to  
546 the bending of the plate entering the Tonga-Kermadec subduction zone.

547

548 We explored the impact of the uncertainty associated with the different VLM estimates to  
549 explain the RSL trends by comparing the RSL trends estimated from the TG records over the  
550 1993-2015 period with those calculated from differenced (satellite altimetry minus VLM)  
551 trends.  $VLM_{GPS}$  (SONEL, NGL and their weighted mean) and  $VLM_{GIA}$  trends were used here  
552 (see Fig. S5). RSL trends obtained from satellite altimetry minus weighted averaged  $VLM_{GPS}$   
553 were similar to the tide gauge RSL trends in most of the cases except at some locations where  
554 tide gauge RSL trends were either overestimated, as at Noumea A and Papeete (PAPE), or  
555 underestimated, as at Norfolk Island and Nukulaofa. Similar results were found when  
556  $VLM_{GPS}$  from SONEL and NGL were used separately, except for Papeete (PAPE), where the  
557 observed RSL trend was not significantly overestimated for NGL. RSL trends obtained from  
558  $VLM_{GIA}$  were similar to the tide gauge trends at most of the cases, except for some stations,  
559 namely Norfolk Island, Pago Pago and Apia B, where observed RSL trends were highly  
560 underestimated which is not surprising given that the GIA model is not intended to account  
561 for the strong subsidence of tectonic origin observed in these stations.

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**Figure 5.** (a) Vertical land motion change (m) over the twenty-first century (2081-2100 mean minus the 1986-2005 mean) obtained from the GIA model (light grey bars), weighted averaged  $VLM_{ATG}$  (purple bars) and  $VLM_{GPS}$  (red bars) at the locations with no-evidence of earthquakes. Error bars (vertical black lines) denote standard errors. Projected relative sea-level changes over the twenty-first century under (b) the RCP 2.6, (c) RCP 4.5 and (d) RCP 8.5 including VLM projected changes. Horizontal lines denote the global mean sea-level changes over the twenty-first century and their standard errors.

575 We illustrated that VLM linear trend estimates from both GPS data and the GIA model may  
576 underestimate the observed RSL changes at locations where non-linear VLM occur. However,  
577 when it comes to obtaining future projections of RSL, VLM estimates including non-GIA  
578 effects are needed. The question arises how projectable into the future are VLM estimates, in  
579 particular in the presence of non-linear processes. One can assume that only linear processes  
580 are reasonably projectable into the future, however it is very difficult to assess that estimated  
581  $VLM_{GPS}$  result from a combination of only linear processes. Given that earthquakes are not  
582 predictable, it is not suitable to use any observed VLM estimates to obtain RSL projections at  
583 locations where there is evidence of earthquakes of any magnitude. That does not, however,  
584 prevent that where there is no observational evidence of earthquakes, other unpredictable non-  
585 linear processes could arise. In spite of the necessary caution of the outcome, we projected the  
586 linear estimates of our VLM to obtain RSL changes by the end of the 21<sup>st</sup> Century under three

587 different GHG emission scenarios at a subset of 7 selected locations where no evidence of  
588 non-linear processes, especially earthquakes, was found in both GPS data centres. These sites  
589 are located far from active tectonic boundaries. We implicitly assumed that observed VLM,  
590 when they are linear, will continue along the 21<sup>st</sup> Century (see Fig. 5a). Results at this region  
591 revealed no significant differences between projected RSL that accounted for all vertical  
592 movements (including both GIA and non-GIA) and projected RSL that only account for GIA  
593 motions, with the exception of Papeete, where projected sea-level changes accounting for  
594  $VLM_{GPS}$  ( $0.8 \pm 0.2$  m under RCP 8.5) were significantly higher than those obtained with  
595  $VLM_{GIA}$  ( $0.6 \pm 0.2$  m) and  $VLM_{ATG}$  ( $0.6 \pm 0.2$  m) under the three GHG scenarios (see Fig.  
596 5b-c). The Tahiti case requires more research to elucidate the high discrepancies in the VLM  
597 estimates between the two GPS stations located there, which could be revealing the strong  
598 local differences of VLM that can be found even within the same island. RSL at the  
599 remaining locations is expected to rise in a similar way than the global sea level rise along the  
600 21<sup>st</sup> century with values of  $0.4 \pm 0.2$  m,  $0.5 \pm 0.2$  m and  $0.6 \pm 0.2$  m for the RCP2.6, RCP4.5  
601 and RCP8.5 scenarios, respectively.

602

## 603 **6. Conclusion**

604 Previous studies on the impact of vertical land motion (VLM) on sea-level changes over the  
605 South Western Tropical Pacific Islands predominantly focused on specific islands or  
606 archipelagos and/or lacked deep analysis of the uncertainties associated. Moreover, they have  
607 not assessed whether reliable future relative sea level projections can be obtained on the basis  
608 of the vertical land motion estimates.

609 We have investigated present and future relative sea level (RSL) changes at as many islands  
610 as possible over the region and for this, we have quantitatively analyzed the uncertainties and  
611 nature of the vertical land movements. We found that, on the long term (last 4-6 decades), the  
612 relative sea level has increased more than globally over this region, confirming the results of  
613 Becker et al., 2012. Moreover, we found the highest increases at the islands located over the  
614 central part of the South Western Tropical Pacific, mainly due to the vertical land movements  
615 produced by the high tectonic activity in this area, which limits our ability to obtain reliable  
616 future RSL projections, but highlights the importance for the populations in earthquake prone  
617 areas to be aware of the potential contribution of vertical land motion to future RSL changes.  
618 We also found that the eastern islands, located in the tectonically inactive areas, experienced  
619 vertical land movements of higher magnitude than those produced by the GIA. However,  
620 although RSL projections obtained there are better constrained, they generally show a similar

621 rise than globally over the 21st century ( $0.6 \pm 0.2$  m under RCP8.5 scenario), with the  
622 exception of Papeete (Tahiti), where future relative sea level projections obtained by  
623 considering the subsidence registered at a GPS station (PAPE) show much larger rises ( $0.8 \pm$   
624  $0.2$ ). Strong differences between these two types of vertical land motion estimates were also  
625 observed for most of the islands located over the region indicating that future work should  
626 show if these differences can be linked to the high spatial variability of vertical land  
627 movements at local scale or due to the data processing.

628 From a more policy perspective, two benefits are to be expected from better including vertical  
629 land motion (sources, rates, and uncertainty) in projections on future sea-level rise, i.e. move  
630 towards more reliable future RSL projections. First, this would help refining the projections.  
631 While projections of global mean sea-level rise are critical to raise the issue worldwide,  
632 refined information is needed locally to estimate context-specific vulnerability to sea-level  
633 rise and design robust adaptation strategies. This is especially true for the South Western  
634 Tropical Pacific that is at the frontline of climate change. Second, this would help improving  
635 confidence in projections. Including vertical land motion into projections of future sea level  
636 will not be a straightforward exercise, as suggested in this study, and more local scale  
637 projections will still be accompanied with uncertainty, for instance related to the occurrence  
638 of earthquakes that are important contributors to vertical land motion in some areas. However,  
639 better capturing the contribution of vertical land motion to future relative sea-level rise would  
640 help providing levels of confidence on future sea level rise projections, from moderate  
641 confidence in areas that are highly affected by vertical land motion mainly due to earthquakes,  
642 to higher confidence in areas where vertical land motion are dominated by more gradual and  
643 predictable drivers.

644

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 658 would also like to acknowledge comments received from the anonymous reviewers, which led  
 659 to significant improvements of the paper.

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662 **Supplementary material**

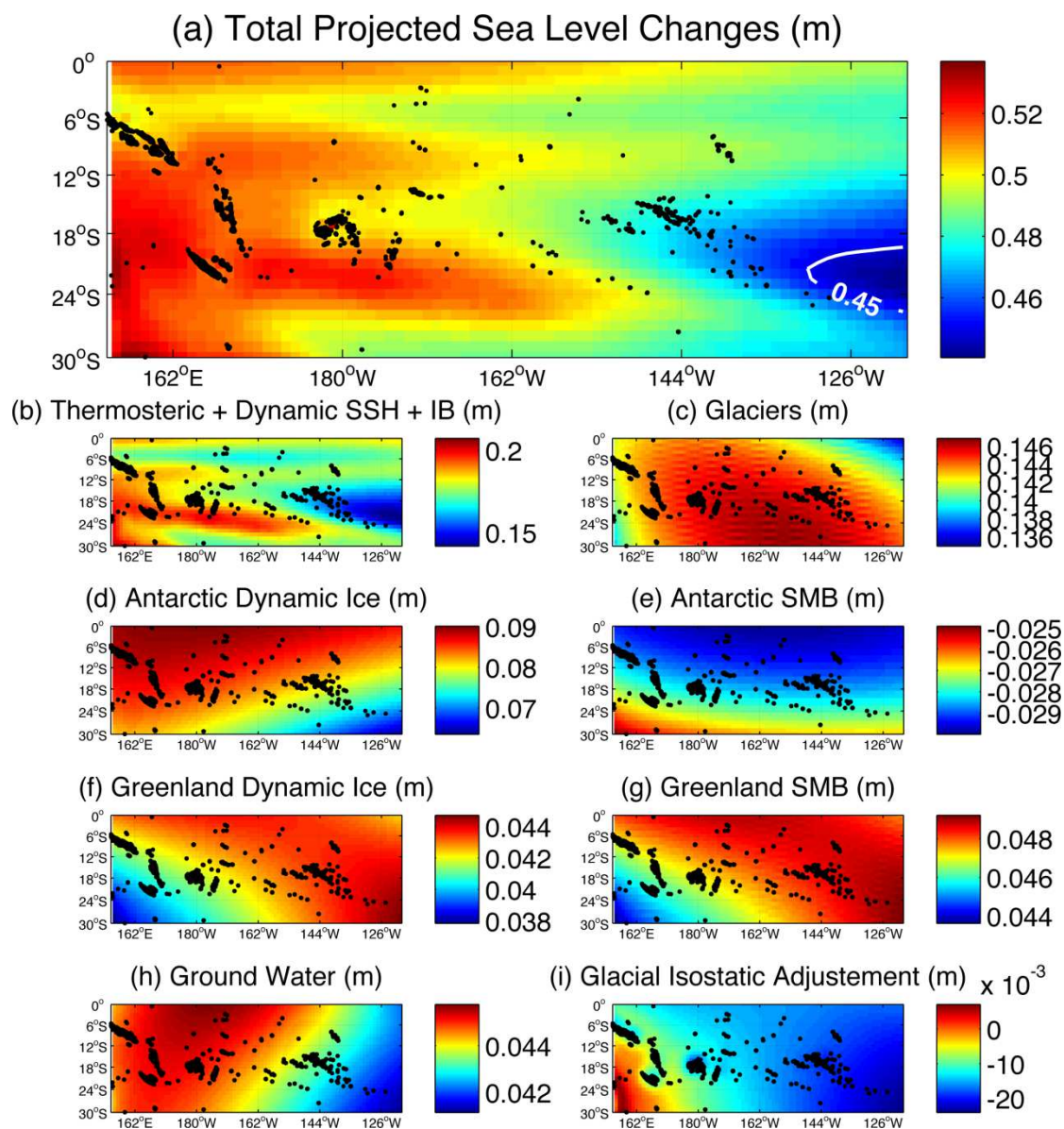
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**Table S1.** RSL trend uncertainties defined as the SE of the fit adjusted for lag-1 autocorrelation for monthly and annually averaged time series at each tide gauge location. Only years containing more than 10 valid months were considered.

Tide gauge	Total period	SE adjusted (mm/year)	
		Monthly data	Annual data
Anewa Bay	1968-1977	13.7	7.1
Honiara	1974-2015	1.9	1.5
Noumea A	1967-2015	0.4	0.6
Ouinne	1981-2015	0.3	0.3
Nauru	1974-2014	1.0	1.0
Lifou	2011-2015	9.7	7.2
Norfolk Is	1994-2014	2.1	3.4
Port Vila VU A	1977-1982	16.1	-
Port Vila VU B	1993-2015	1.3	2.2
Lautoka	1992-2014	1.5	1.4
Suva	1972-2015	0.7	1.1
Funafuti	1977-2015	1.3	0.9
Nukualofa	1993-2014	1.1	1.6
Apia A	1954-1971	1.6	1.7
Apia B	1993-2015	2.2	1.6
Kanton Is	1949-2012	0.5	0.7
Pago Pago	1948-2014	0.5	0.5
Rarotonga	1977-2015	0.5	0.6
Penrhyn	1977-2015	0.8	1.0
Papeete	1969-2014	0.4	0.5
Matavai	1958-1967	2.0	0.8
Tubuai	2009-2013	15.1	9.1
Rangiroa	2009-2014	6.0	23.4
Nuku Hiva	1982-2015	1.3	0.8
Hiva Oa A	1977-1980	8.9	-
Hiva Oa B	2010-2015	9.4	3.3
Rikitea	1969-2015	0.3	0.3
MEAN		3.7	2.9

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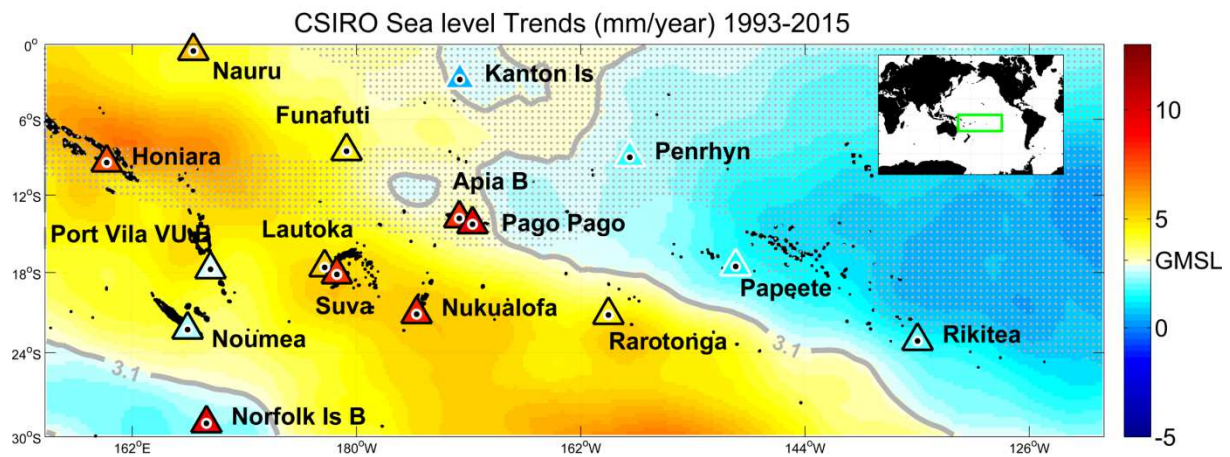




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673 **Figure S1.** Regional sea-level changes of the different sea level contributions from RCP8.5  
 674 over the period from 1986–2005 to 2081–2100 (in meters). Total projected regional sea-level  
 675 changes resulting from the sum of all the contributions (a). The CMIP5-RCP8.5 ensemble  
 676 mean of the sum of the thermosteric, dynamic and atmospheric (b), glacier (c), ice sheet (d-g),  
 677 groundwater (h) and GIA (i) contributions.

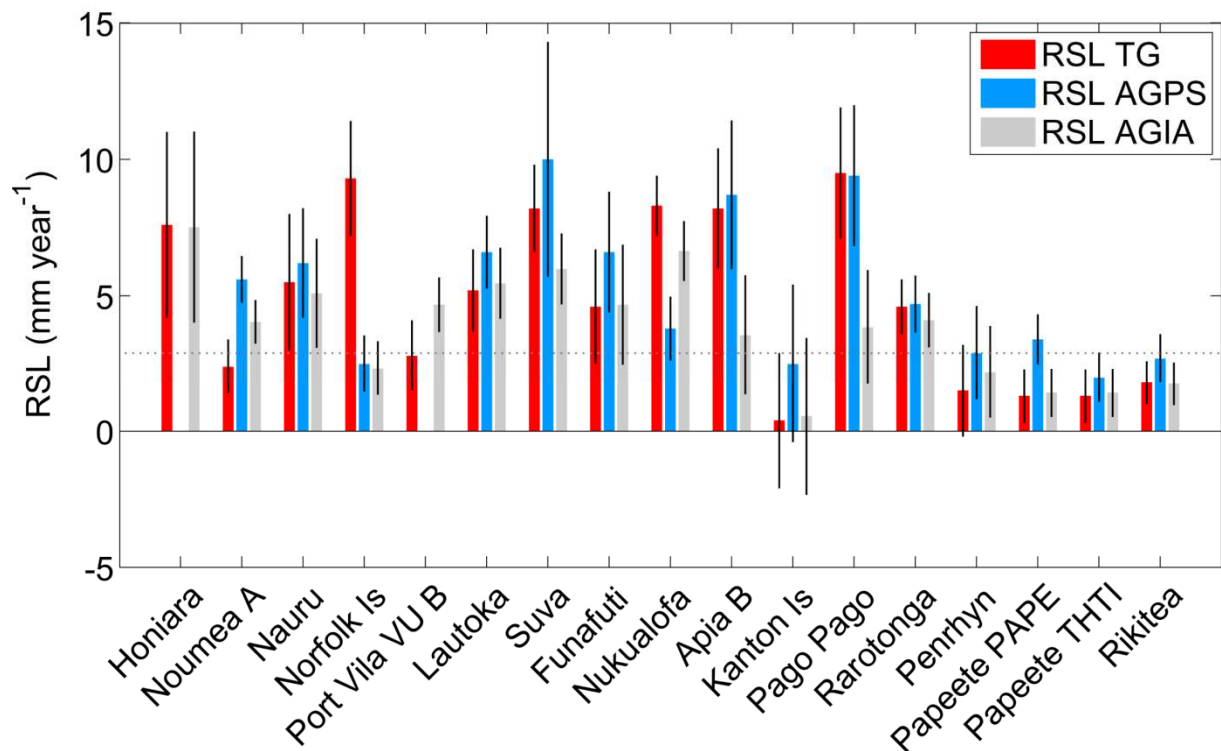
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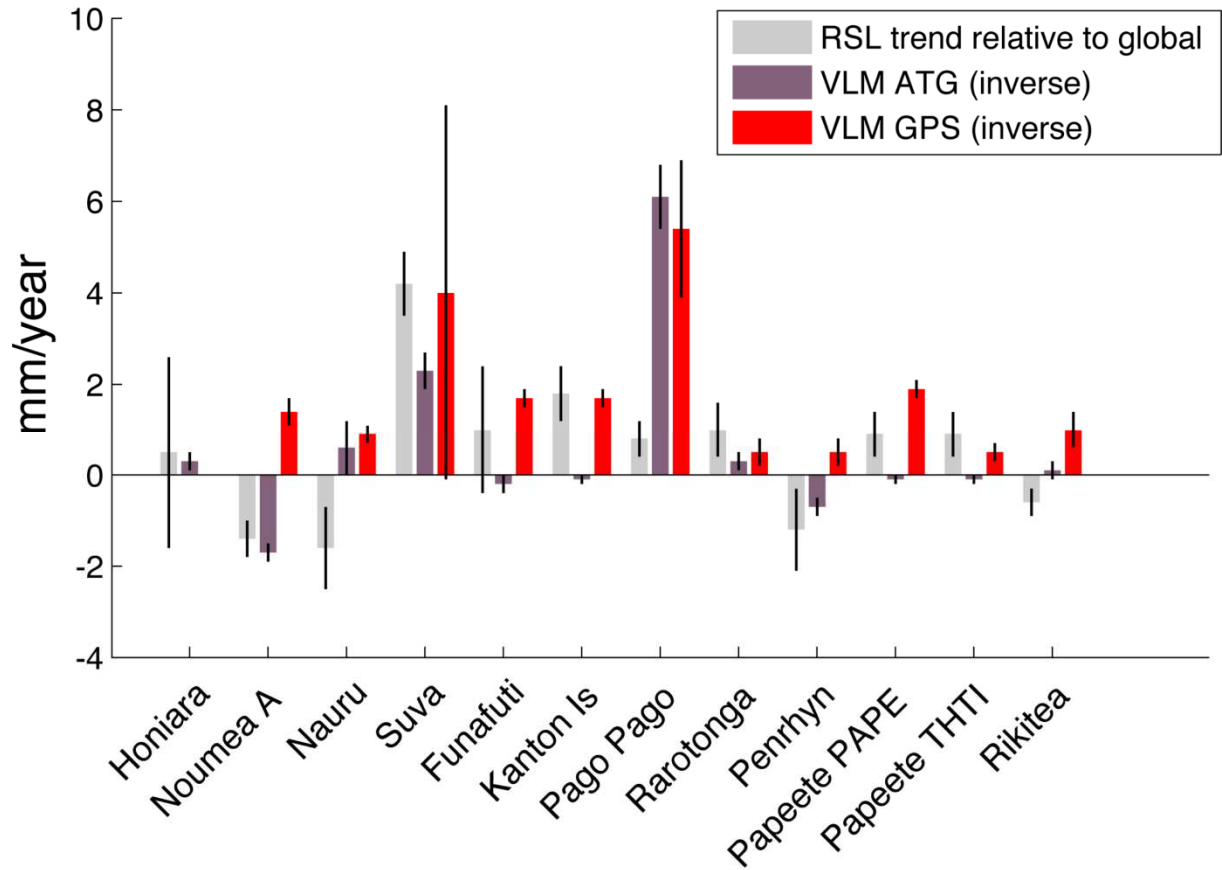
683 **Figure S2.** Sea level trends (mm/year) at tide gauges (coloured triangles) and CSIRO  
684 altimetry grid points (coloured areas) calculated over 1993-2015. Grey contours mark global  
685 mean sea level trend during 1993-2015. White-bordered triangles and dot-shaded areas denote  
686 no statistical significance at  $2\sigma$  level.

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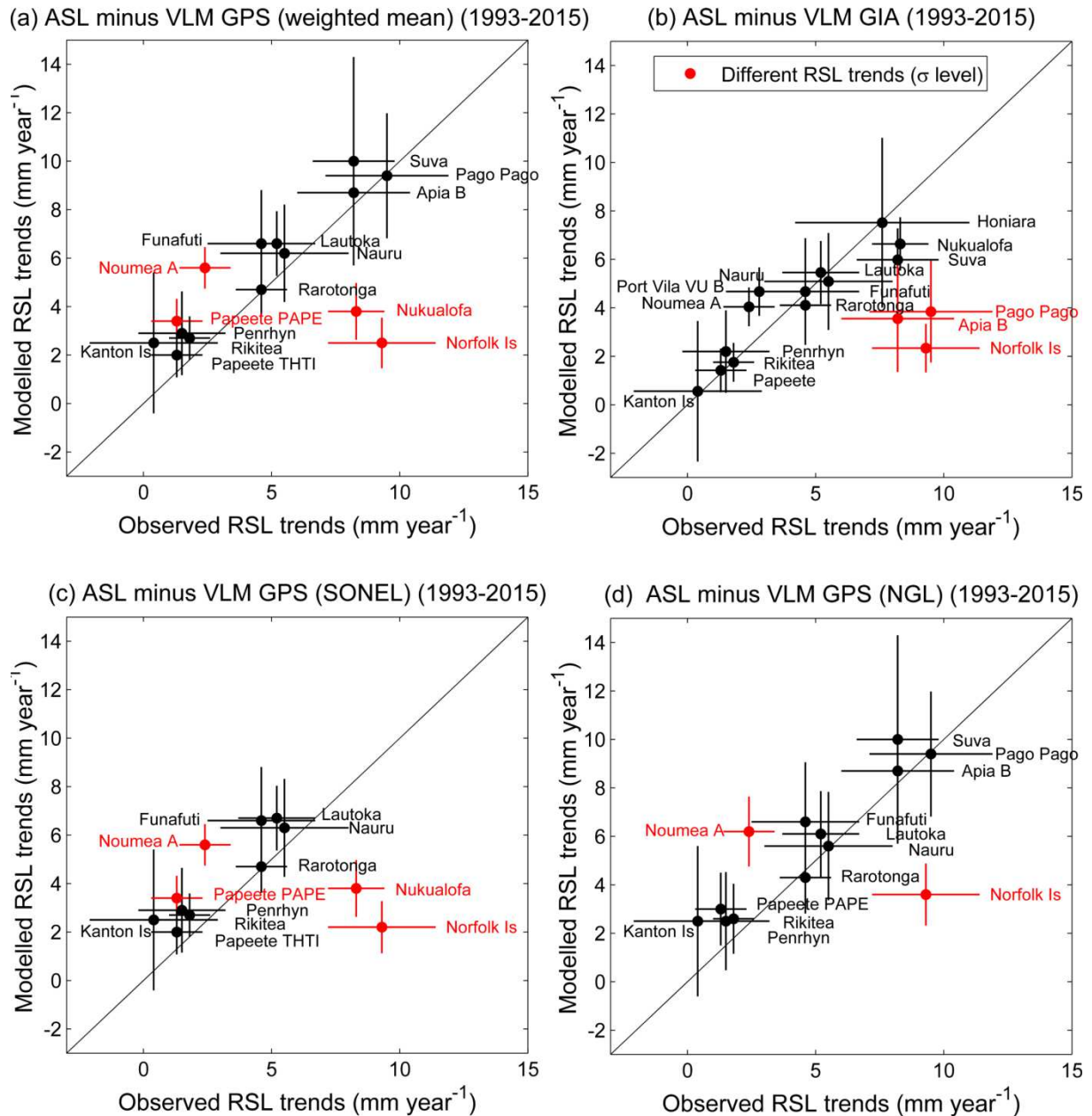
691 **Figure S3.** RSL TG: Trends of relative sea level from tide gauges records (red bars), satellite  
692 radar altimetry (AVISO) minus weighted averaged  $VLM_{GPS}$  trends (blue bars) and satellite  
693 radar altimetry (AVISO) minus modelled  $VLM_{GIA}$  (grey bars). Error bars denote one standard  
694 error of the trends.



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698 **Figure S4.** Difference between local RSL trends and global mean sea-level rise (mm/year) at  
 699 the longest tide gauges (light grey bars). Inverse of the vertical land motion rate (mm/year)  
 700 obtained from weighted averaged  $VLM_{ATG}$  (purple bars) and  $VLM_{GPS}$  (red bars). Error bars  
 701 (vertical black lines) denote standard errors.

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706 **Figure S5.** Scatterplot between observed and modelled RSL trends obtained from ASL trends  
707 (AVISO) minus vertical land motion trends from weighted mean  $VLM_{GPS}$  trends (a),  $VLM_{GIA}$   
708 trends (b) and  $VLM_{GPS}$  trends from SONEL (c) and NGL (d). Error bars denote one  $\sigma$   
709 standard error of the trends. Red dots and bars denote different trends at  $\sigma$  significance level  
710 (T-test).

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