LETTERS
PUBLISHED ONLINE: 6 JULY 2015 | DOI: 10.1038/NCLIMATE2702
nature climate change

Exposure of coastal built assets in the South Pacific to climate risks

Lalit Kumar* and Subhashni Taylor

Pacific island countries (PICs) are situated in a highly dynamic ocean–atmosphere interface, are dispersed over a large ocean area, and have highly populated urban centres located on the coastal margin[1]. The built infrastructure associated with urban centres is also located within close proximity to the coastlines, exposing such infrastructure to a variety of natural and climate change-related hazards. In this research we undertake a comprehensive analysis of the exposure of built infrastructure assets to climate risk for 12 PICs. We show that 57% of the assessed built infrastructure for the 12 PICs is located within 500 m of their coastlines, amounting to a total replacement value of US$21.9 billion. Eight of the 12 PICs have 50% or more of their built infrastructure located within 500 m of their coastlines. In particular, Kiribati, Marshall Islands and Tuvalu have over 95% of their built infrastructure located within 500 m of their coastlines. Coastal adaptation costs will require substantial financial resources, which may not be available in developing countries such as the PICs, leaving them to face very high impacts but lacking the adaptive capacity.

The Earth's climate is changing owing to human emissions of greenhouse gases and is expected to continue to change through the twenty-first century at rates projected to be unprecedented in recent human history[2]. Climate change is expected to bring about changes in air temperature and precipitation rates, sea levels, frequency and intensity of tropical cyclones, and wind and wave action patterns[3,4]. Impacts on coastal populations and infrastructure will be felt much more than inland regions owing to their increased exposure to climate processes[5,6].

The expected rise in the severity of climate change impacts through the twenty-first century will cause a number of physical changes to the world's coastal areas and hence have the potential to endanger coastal populations and infrastructure, as well as threaten many coastal ecosystems[7]. Land areas adjacent to the world's shorelines are associated with large and growing population centres, leading to increased socioeconomic activities and associated infrastructure around coastal regions[8]. Although a coastal location provides important benefits, it also exposes people and assets to a variety of natural and climate change-related hazards. Nowhere will these impacts be felt more than the small, low-lying islands in open oceans[9] such as the South Pacific.

The islands in the South Pacific are generally of coral/sandy formations, have a small land area, are low-lying, are spread out over a vast area of ocean and fall in a high tropical cyclone activity zone, making them profoundly vulnerable to natural and climate change-related hazards. The South Pacific region consists of 23 countries and territories, with thousands of islands and islets. The total land area, excluding Papua New Guinea, is 88,000 km^2 with a population of three million. The average area of these islands is 90 km^2, but the median is only 1.3 km^2, as island size is highly skewed towards smaller islands. Owing to the restricted land area, the population, major urban centres and critical infrastructure are generally located on the coast[10]. Hence, the climate risks are much more profound compared with larger islands or landlocked countries, because a much larger proportion of the land area is exposed to potential impacts.

A number of studies have reported potential climate impacts on built infrastructure in large coastal cities[11] and island regions such as the Caribbean[4]; however, similar investigations in the South Pacific have tended to focus on a single island within a PIC (refs 12,13). This area of research is critical given the high exposure to climate risks faced by PICs (refs 14–18). In this research, we undertake an analysis of exposure of built infrastructure to current and future climate risk for 12 PICs. We identify the proportion of built infrastructure 0–50 m, 50–100 m, 100–200 m and 200–500 m from the coastline and determine their replacement values as a proxy for their exposure to coastal hazards. We define coastal proximity according to ref. 18: the horizontal distance of a location to the nearest point on the coastline. The coastline is taken to be the continuous boundary between the subaerial and submarine fractions of the solid surface of the Earth[18].

The present study includes 12 of the 23 PICs in the region, with the 12 selected on the basis of comprehensive data availability or where available data could be supplemented by satellite images or other ancillary sources. Note that in the context of this study PICs refers to individual countries, whether they are independent nations or states and territories governed by others. The selected countries are Cook Islands, Federated States of Micronesia (FSM), Kiribati, Marshall Islands, Nauru, Niue, Palau, Samoa, Solomon Islands, Tonga, Tuvalu and Vanuatu. The geographic spread of these countries is shown in Fig. 1; detailed information for each country is included in Table 1. The 12 PICs have a combined land area of 50,212 km^2, but the exclusive economic zone covers 13 million km^2, indicating the large spread of the islands. A total of 1,628 islands make up the 12 PICs, with a coastline of 19,841 km. The lithology of the islands is primarily volcanic, limestone, reef or a composite of these three; however, approximately 67% of the islands are of reef or sandy origin. The reef islands generally have a maximum elevation of less than 3 m but some of the volcanic islands have a maximum elevation of 2,400 m. The land area of individual islands ranges from 0.01 km^2 to 5,500 km^2, with the median being 0.9 km^2. The total population of the 12 countries is 1.4 million, with population varying from 1,480 to 547,540 inhabitants for individual countries.

The results of the analysis indicate that 57% of all assessed built infrastructure is within 500 m of the coast for the 12 PICs. Nine percent, 11%, 16% and 21% fall within the 0–50 m, 50–100 m, 100–200 m and 200–500 m intervals, respectively (Fig. 2). The total replacement value of all built infrastructure assessed was

University of New England School of Environmental and Rural Science Armidale, New South Wales 2351, Australia. *e-mail: lkumar@une.edu.au

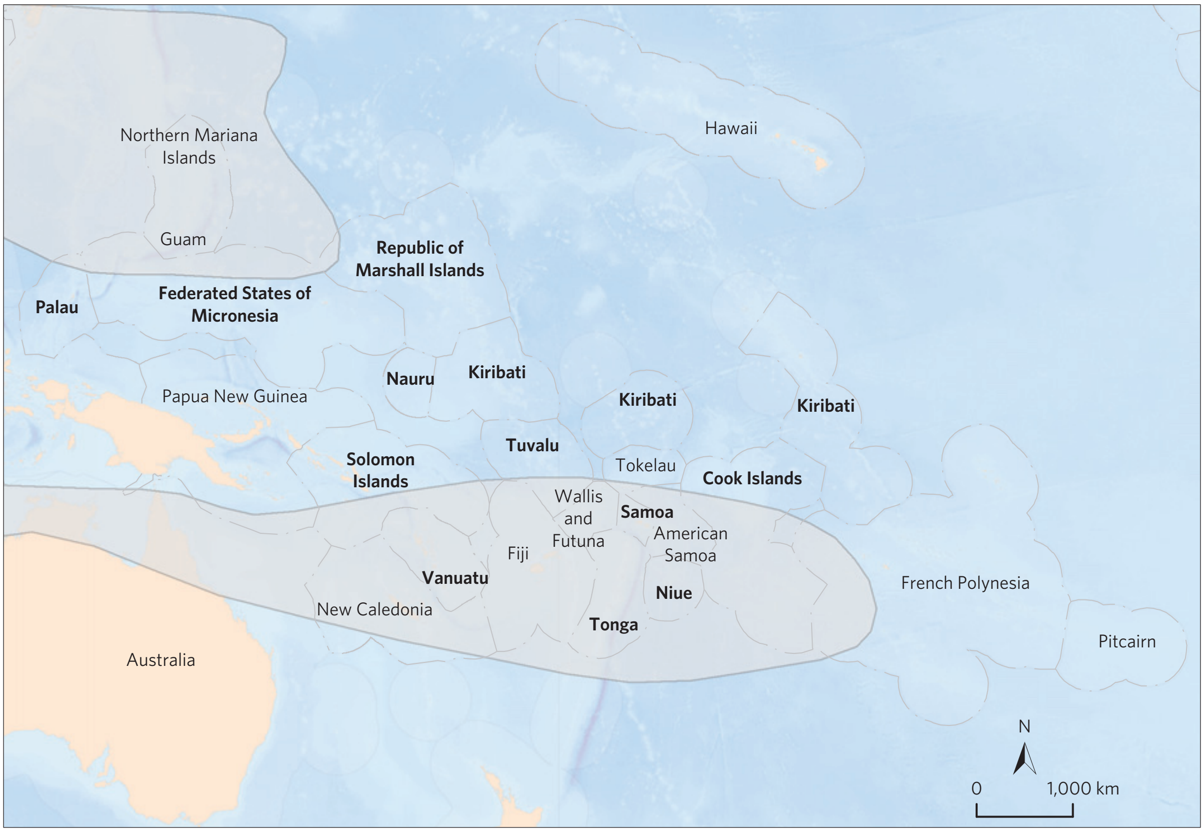

Figure 1 | Study region showing the locations of the 12 countries included in this study (in bold) and the other countries of the region for context. The grey shaded area shows the main tropical cyclone activity zones.

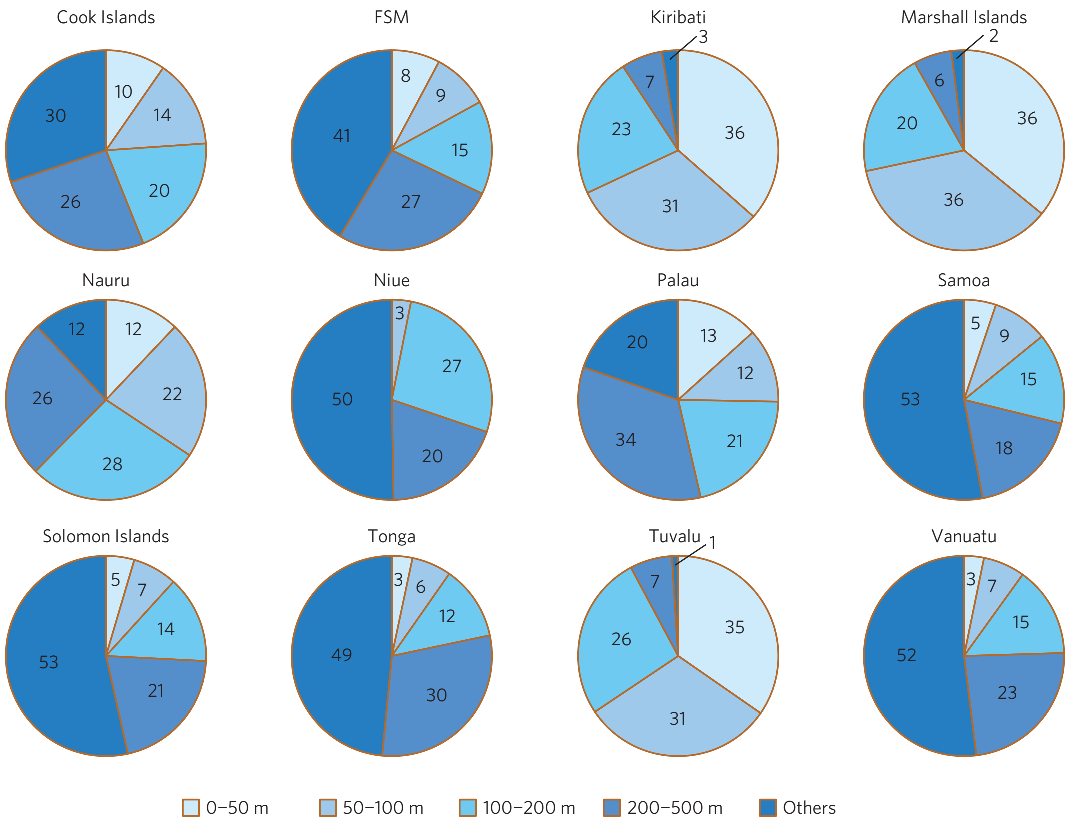

Figure 2 | Counts of built infrastructure (percentage of country total) within each interval from the coastline.

Table 1 | Characteristics of the 23 countries from the South Pacific.

Country	No. of Islands[a]	Coastline[b] (km)	Total land area (km^2)	Population[c] (2014)	GDP[c] (US$M)	Max elevation (m)	Av. land area/island (km^2)	Dominant lithology
Cook Is[d,m]	**15**	**454**	**296**	**19,800**	**183**	**658**	**19.7**	**Reef**
FSM[e,l]	**607**	**1,036**	**702**	**111,560**	**331**	**791**	**1.2**	**Reef**
Kiribati[f,l]	**33**	**1,845**	**995**	**104,488**	**180**	**81**	**30.2**	**Reef**
Marshall Is[e,l]	**34**	**2,172**	**286**	**54,820**	**178**	**6**	**8.4**	**Reef**
Nauru[f,l]	**1**	**19**	**23**	**10,800**	**60**	**71**	**23.0**	**Limestone**
Niue[d,m]	**1**	**75**	**298**	**1,480**	**10**	**60**	**298.0**	**Limestone**
Palau[e,l]	**250**	**514**	**495**	**20,500**	**272**	**207**	**2.0**	**Limestone**
Samoa[f,l]	**7**	**482**	**3,046**	**182,900**	**995**	**1,858**	**435.1**	**Volcanic**
Solomon Is[f,l]	**413**	**8,848**	**29,672**	**547,540**	**1,046**	**2,449**	**71.8**	**Volcanic**
Tonga[f,l]	**176**	**929**	**847**	**103,350**	**523**	**1,033**	**4.8**	**Limestone**
Tuvalu[f,l]	**9**	**233**	**26**	**9,561**	**35**	**8**	**2.9**	**Reef**
Vanuatu[f,l]	**82**	**3,234**	**13,526**	**245,860**	**687**	**1,879**	**165.0**	**Volcanic**
American Samoa[g,n]	7	116	199	54,517	575	964	28.4	Volcanic
Fiji[f,l]	332	1,129	18,300	903,207	7,292	1,324	55.1	Volcanic
French Polynesia[h,n]	126	2,525	3,827	280,026	7,150	2,241	30.4	Reef
Guam[g,n]	1	125.5	544	161,001	4,600	406	544	Composite
Hawaii[i,l]	16	1,858	16,635	1,419,561	75,200	4,205	1,039.7	Volcanic
New Caledonia[h,n]	30	2,254	18,275	267,840	11,100	1,628	609.2	Limestone
Northern Mariana Islands[j,m]	16	1,482	464	51,483	733	965	29	Volcanic
Papua New Guinea[f,l]	440	5,152	452,860	6,552,730	18,110	4,509	1,029.2	Volcanic
Pitcairn[k,n]	4	51	47	48	n/a	347	11.8	Reef
Tokelau[d,n]	3	101	12	1,337	1.5	5	4	Reef
Wallis and Futuna[h,m]	14	129	142	15,561	60	765	10.1	Reef/Volcanic

The 12 countries used in this study are shown in bold. [a]As per literature. [b]Coastline lengths based on a scale of 1:20,000. [c]The World Factbook (https://www.cia.gov/library/publications/the-world-factbook/docs/profileguide.html). [d]Self-governing in free association with New Zealand; [e]Constitutional government in free association with the USA; [f]Independent nation; [g]Territory of the USA; [h]Territory of France; [i]US State; [j]Commonwealth in political union with the US; [k]Territory of the UK (https://www.cia.gov/library/publications/the-world-factbook/docs/profileguide.html). [l]United Nations (UN) Member State; [m]Non-UN Member State; [n]UN Non-Self-Governing Territory (http://www.un.org/en/members).

US$27.7 billion, of which 79% by value fall within 500 m of the coast. Eleven percent, 14%, 34%, and 20% fall in the 0–50 m, 50–100 m, 100–200 m and 200–500 m intervals, respectively (Fig. 3).

At the country level, the results for Kiribati, Marshall Islands and Tuvalu are noteworthy. For Kiribati, 97% of all built infrastructure assessed falls within 500 m of the coast, with 67% falling within 100 m; making a large proportion of built infrastructure in Kiribati highly vulnerable to climate risks (Fig. 2). For Marshall Islands, 98% falls within 500 m of the coast, with 72% falling within 100 m. Similarly for Tuvalu, 99% falls within 500 m of the coast, with 66% within 100 m (Fig. 2). On the other hand, in Niue, Samoa, Solomon Islands and Vanuatu, 50% or more of the built infrastructure is beyond 500 m of the coast. This is to be expected, because these countries have some islands that are much larger in terms of land area than the largest islands in Kiribati, Marshall Islands and Tuvalu. The two largest islands by area in Kiribati, Marshall Islands and Tuvalu are 478 km^2 and 55 km^2, 29 km^2 and 24 km^2 and 10 km^2 and 8 km^2 respectively; but for Niue, Samoa, Solomon Islands and Vanuatu these are 298 km^2 (one island country), 1,823 km^2 and 1,215 km^2, 5,542 km^2 and 3,978 km^2, and 4,355 km^2 and 2,240 km^2 respectively. Supplementary Figs 1–4 show the most populous islands in FSM (Weno, Supplementary Fig. 1), Kiribati (Tarawa, Supplementary Fig. 2), Marshall Islands (Majuro, Supplementary Fig. 3) and Tuvalu (Funafuti, Supplementary Fig. 4) and how built infrastructure is concentrated around the coast for each.

In terms of replacement value at the country level, Kiribati, Marshall Islands and Tuvalu have 95%, 98% and 99%, respectively, of built infrastructure by value within 500 m of the coast (Fig. 3), indicating that almost the entire proportion of built infrastructure by value is located along the coast. For Vanuatu, although 52% of built infrastructure by count was beyond 500 m from the coastline, this represents only 10% by value, suggesting that the highest-value built infrastructure in Vanuatu is along the coast. This pattern is similar for most PICs and is expected, because high-value built infrastructure such as ports and refineries is always located close to the coast to facilitate transportation. Niue and Samoa are the only countries that have more than 50% of built infrastructure by value beyond 500 m of the coastline.

A higher proportion of commercial (71%), industrial (62%) and public (63%) built infrastructure is situated within 500 m of the coast compared with residential buildings (52%), because most of the urban centres in almost all PICs are located along the coastal fringe. Although transportation has traditionally been a key consideration in setting up commercial centres, most island economies in this region are predominantly dependent on tourism, as they possess pristine beaches, coral reef ecosystems, and other coastal amenities. Consequently, much of the infrastructure associated with this industry is located on the coast.

Of the built infrastructure within 500 m of the coast, 69% is situated on soft to firm soil (including sandy soil) and the remaining 31% is on soft to hard rock. Kiribati, Marshall Islands and Tuvalu have over 90% of the built infrastructure in this zone located on soft sandy soil.

These results have implications for damage under present climate extremes and geohazard events, such as tsunamis, as well as future climate change, posing considerable threats to economies in the highly concentrated coastal zone in the Pacific. Low-lying and exposed PICs will face major challenges from climate risks, such as sea level rise, storm surges and extreme weather events. The risks to infrastructure are considerable, because most of the population and urban centres are located along the coastline. Thus, vulnerability assessments, as undertaken in this study, together with other factors such as elevation, should play a

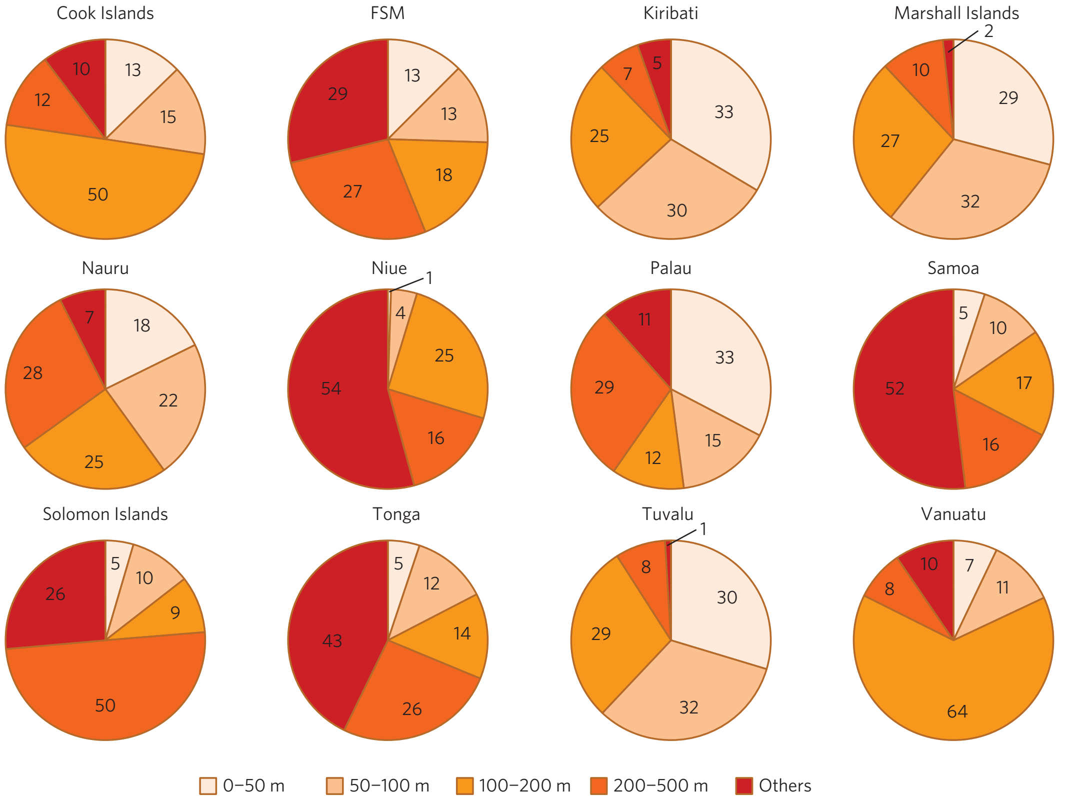

Figure 3 | Replacement value of built infrastructure (percentage of country total) within each interval from the coastline.

major role in formulation of adaptation measures. However, such assessments have been hampered in the South Pacific owing to a lack of comprehensive data. To undertake a comprehensive coastal vulnerability assessment, detailed knowledge of the location of built infrastructure is paramount. Previous studies on climate risks to coastal regions have investigated the impacts of specific risks such as sea level rise on coastal ecosystems, infrastructure and human populations in Europe[19], America[5], Australia[20] and the Caribbean[21], and risks to food production and agriculture in the Pacific Islands[22] and India[23]. Other studies have investigated adaptation strategies in terms of hurricane preparedness in the Cayman Islands[3]. Climate risks to infrastructure have been less studied[11], even though they have been identified as major impediments to adaptation planning, particularly in low-lying island states[4]. Investigations into climate risks to infrastructure in the South Pacific have generally focused on a single island within a PIC (refs 12,13). This study, to the best of our knowledge, is the first to present a comprehensive assessment of the proximity of built infrastructure to coastlines at the whole-country scale for 12 PICs in the region.

The trends identified have serious implications for the coastal infrastructure of the low-lying islands included in the study. A combination of characteristics, such as small land area and widespread low elevations, makes the built infrastructure assets in these countries acutely vulnerable to climate risks. With climate change and projected sea level rise, a larger percentage of the built infrastructure assets will be in closer proximity to the coast, increasing their risk to coastal hazards. Therefore, these results could be used in the context of sea level rise, wave action or coastal erosion to assess how much built infrastructure would be impacted by different climate change risks, either at present or in the future.

Exposure to climate risks will vary for the different PICs across the region and thus the impacts on the islands and built infrastructure will be different. For example, tropical cyclone activity in this region is highly dependent on El Niño/Southern Oscillation cycles[24] and is quite variable across the Pacific (Fig. 1). Furthermore, changes in sea level and tidal ranges are also projected to be variable for different PICs (ref. 25), thus adding to the complexities of adaptation planning.

This study would have benefited from the inclusion of elevation data; however, vertical accuracy for elevation needs to be at the centimetre scale to have any meaning in climate change discussions, because sea level rise in the region could range from 26 to 55 cm or 45 to 82 cm by 2081–2100, relative to 1986–2005 under the Representative Concentration Pathway (RCP)2.6 and RCP8.5 emissions scenarios respectively[25]. Elevation data at this accuracy are not available for most of the Pacific and are unlikely to be collected in the foreseeable future owing to remoteness and the costs involved. Perhaps there is a need for a concerted effort to target such data collection for areas that have been identified as having the highest exposure. There should also be a greater effort on systematic collection of data on extreme events and related infrastructure damage in the region; such data can enhance the findings of similar studies as undertaken here.

Methods

Methods and any associated references are available in the online version of the paper.

Received 17 December 2014; accepted 2 June 2015; published online 6 July 2015

References

1. Barnett, J. Adapting to climate change in Pacific Island countries: The problem of uncertainty. *World Dev.* **29,** 977–993 (2001).
2. IPCC *Climate Change: The Physical Science Basis* (eds Stocker, T. F. *et al.*) (Cambridge Univ. Press, 2013).
3. Tompkins, E. L. Planning for climate change in small islands: Insights from national hurricane preparedness in the Cayman Islands. *Glob. Environ. Change* **15,** 139–149 (2004).

4. Lewsey, C. *et al.* Assessing climate change impacts on coastal infrastructure in the Eastern Caribbean. *Mar. Policy* **28,** 393–409 (2004).
5. Arkema, K. K. *et al.* Coastal habitats shield people and property from sea-level rise and storms. *Nature Clim. Change* **3,** 913–918 (2013).
6. Hallegatte, S. *et al.* Future flood losses in major coastal cities. *Nature Clim. Change* **3,** 802–806 (2013).
7. McLean, R. F. *et al.* in *Climate Change 2001: Impacts, Adaptation and Vulnerability* (eds McCarthy, J. J. *et al.*) 343–380 (IPCC, Cambridge Univ. Press, 2001).
8. Small, C. & Nicholls, R. J. A global analysis of human settlement in coastal zones. *J. Coast. Res.* **19,** 584–599 (2003).
9. Woodruff, J. D. *et al.* Coastal flooding by tropical cyclones and sea-level rise. *Nature* **504,** 44–52 (2013).
10. Mimura, N. Vulnerability of island countries in the South Pacific to sea level rise and climate change. *Clim. Res.* **12,** 137–143 (1999).
11. Hunt, A. & Watkiss, P. Climate change impacts and adaptation in cities: A review of the literature. *Climatic Change* **104,** 13–49 (2011).
12. Forbes, D. L. & Solomon, S. L. *Approaches to Vulnerability Assessment on Pacific Island Coasts: Examples from Southeast Viti Levu* (*Fiji*) *and South Tarawa* (*Kiribati*) (South Pacific Applied Geoscience Commission (SOPAC), 1998).
13. World Bank *Cities, Seas and Storms: Managing Change in Pacific Island Economies. Vol. IV: Adapting to Climate Change* (World Bank, 2000).
14. Nurse, L. *et al.* in *The Regional Impacts of Climate Change: An Assessment of Vulnerability* (eds Watson, T. *et al.*) 333–354 (IPCC, Cambridge Univ. Press, 1998).
15. Nunn, P. D. & Mimura, N. Vulnerability of South Pacific island nations to sea-level rise. *J. Coast. Res.* **24,** 133–151 (1997).
16. Brookfield, H. Global change and the Pacific: Problems for the coming half-century. *Contemp. Pacific* **1,** 1–17 (1989).
17. Hay, J. & Mimura, N. Supporting climate change vulnerability and adaptation assessments in the Asia-Pacific region: An example of sustainability science. *Sustain. Sci.* **1,** 23–35 (2006).
18. Small, C. & Nicholls, R. J. A global analysis of human settlement in coastal zones. *J. Coast. Res.* **19,** 584–599 (2003).
19. Nicholls, R. & Klein, R. T. in *Managing European Coasts* (eds Vermaat, J. *et al.*) 199–226 (Springer, 2005).
20. Department of Climate Change and Energy Efficiency *Climate Change Risks to Coastal Buildings and Infrastructure: A Supplement to The First Pass National Assessment* (Australian Government, 2011).
21. Lorde, T. *et al. An Assessment of the Economic and Social Impacts of Climate Change on the Coastal and Marine Sector in the Caribbean* (United Nations, 2013).
22. Barnett, J. Dangerous climate change in the Pacific Islands: Food production and food security. *Reg. Environ. Change* **11,** 229–237 (2011).
23. O'Brien, K. *et al.* Mapping vulnerability to multiple stressors: Climate change and globalization in India. *Glob. Environ. Change* **14,** 303–313 (2004).
24. Henderson-Sellers, A. *et al.* Tropical cyclones and global climate change: A post-IPCC assessment. *Bull. Am. Meteorol. Soc.* **79,** 19–38 (1998).
25. Australian Bureau of Meteorology and CSIRO *Climate Change in the Pacific: Scientific Assessment and New Research. Volume 1: Regional Overview. Volume 2: Country Reports* (Australian Government, 2011).

Acknowledgements
This rapid assessment is based partially on data drawn from the Pacific Risk Information System (PacRIS) and made available through the Secretariat of the Pacific Community Applied Geoscience and Technology Division (SOPAC). The funding for this project was provided by the Australian Government Department of Environment under the Pacific-Australia Climate Change Science and Adaptation Planning (PACCSAP).

Author contributions
L.K. and S.T. contributed to data analysis and writing the paper. The financial support for the project and data used were acquired by L.K.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. A copy of the raw data used in this study is deposited with the South Pacific Applied Geoscience Commission (SOPAC), a part of the South Pacific Commission (SPC), in Suva, Fiji. Correspondence and requests for materials should be addressed to L.K.

Competing financial interests
The authors declare no competing financial interests.

Methods

Raw data used in this study were drawn from the Pacific Risk Information System[26] (PacRIS), one of the largest collections of geospatial risk data for PICs. PacRIS was established through the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI), a joint initiative of the Secretariat of the Pacific Community, World Bank and the Asian Development Bank. Data covering 15 PICs (the above 12 plus Fiji, Papua New Guinea and Timor Leste) were collected as part of this initiative[26]; however, data from only 12 PICs were included in this analysis, as they were sufficiently comprehensive. No data were collected or available for the other 8 PICs (see Table 1). The 12 countries selected are representative of the small island states in the South Pacific in terms of their lithology, range of maximum elevations, remoteness, demography and economic status (Table 1). It should be noted that this analysis is based on exact geographic coordinates of each built infrastructure asset and such data are rarely available at the country scale for multiple countries in any region.

The database provides a comprehensive inventory of buildings, such as residential, commercial, public and industrial, and other built infrastructure, such as airports, communications infrastructure, power generation, docks and ports, bridges, storage facilities, and water infrastructure such as storage tanks. The database includes information on the location, occupancy, construction type and the replacement value of the assets. Although analysis was undertaken at the detailed infrastructure type, they were grouped together as built infrastructure for reporting in this study.

The information was collected from a variety of data sources, including field visits, manual inspection of high-resolution satellite imagery, GIS (geographic information system) databases, data provided by the Australian Government, reports and publications, public databases and disaster reconnaissance reports. Of the 12 countries assessed here, built infrastructure data were complete for three countries, with others having a coverage ranging from 22 to 97%, with the average being 73%.

For quality control, all point data were overlain against a georeferenced background in a GIS package and points that were not aligned or that fell outside island coastlines owing to recording errors were removed. The number of points removed through this exercise ranged from 0 to 2% for individual countries; hence, overall a low number of points were lost. After error corrections, there were 451,726 built infrastructure points left in the database.

Coastline data were obtained from individual countries where accurate data were available or digitized from high-resolution imagery and topographic maps at a scale of 1:20,000. As the purpose of this assessment was to determine the exposure of built infrastructure to coastal hazards, four intervals from the coast were used in the analysis: 0–50 m, 50–100 m, 100–200 m and 200–500 m. We selected a maximum distance of 500 m from the coastline because most islands in the South Pacific are small in area, and for some countries (notably Marshall Islands and Tuvalu) around 99% of the land area of the entire country falls in this zone. We note that the authors of ref. 4 have used a distance of 2 km for the Eastern Caribbean region; however, this distance would be inappropriate for the small island states of the South Pacific. For each of these intervals, the number and replacement value of built infrastructure was extracted. Furthermore, the built infrastructure point data were overlain on a soil layer for each country and the soil type was determined for the location of each asset. The soil type was regrouped into two categories: soft to hard rock; and soft to firm soil, including sandy soil.

References

26. *Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI) Component 2* (AIR Worldwide, 2011).