

Cost-Effective Methods for Accurate Determination of Sea Level Rise Vulnerability: A Solomon Islands Example

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ABSTRACT

For millions of people living along the coastal fringe, sea level rise is perhaps the greatest threat to livelihoods over the coming century. With the refinement and downscaling of global climate models and increasing availability of airborne-lidar-based inundation models, it is possible to predict and quantify these threats with reasonable accuracy where such information is available. For less developed countries, especially small island states, access to high-resolution digital elevation models (DEMs) derived from lidar is limited. The only freely available DEMs that could be used for inundation modeling by these nations are those based on data from the Shuttle Radar Topography Mission (SRTM). These data, with a horizontal resolution of ≈ 90 m and a vertical accuracy of ± 5 – 10 m, are generally unsuitable for local-scale planning and adaptation projects. To address this disparity, low-cost ground-based techniques were tested and applied to accurately determine coastal topography in the Solomon Islands. This method had a significantly improved vertical accuracy (± 2 cm) and was readily learned by local community members, who were able to independently map and determine the vulnerability of their coastal community to inundation from sea level rise. For areas where lidar is not economically viable, this method is intended to provide an important balance of cost, simplicity, accuracy, and local participation that can assist remote coastal communities with coastal planning decisions. The method can enhance local capacity and arguably promotes more meaningful local engagement in sea level rise planning and adaptation activities.

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1. Introduction

The risk of coastal inundation from climate change associated sea level rise is one of the more pressing concerns for coastal communities globally. This threat is of particular concern for communities in the less developed and small island states such as those in the Pacific, who are considered the most vulnerable to sea level rise

(Dasgupta et al. 2009; McClanahan and Cinner 2012). While variation is expected, the western Pacific region is likely to experience 0.1–0.9 m of sea level rise by 2100 (PCCSP 2011). In addition, it is widely predicted that increases in extreme wave events (McInnes et al. 2013) and coastal erosion will become the main driver of coastal vulnerability under future climate scenarios, and hence focusing on sea level rise vulnerability alone can be an oversimplification. Regardless, there is currently a large effort to support these small island states to reduce their vulnerability to sea level rise through community-based climate adaptation programs. One of the key components of understanding vulnerability is to first quantify exposure and sensitivity to a specific risk. While sea level rise predications (and hence exposure) are broadly similar across the Pacific region, there are large differences in sensitivity to this risk because of the highly variable coastal topography of the region. To date the only available coastal topography information for much of this region is based on mid-twentieth-century topographic maps (often in hard-copy form) or the more recent data collected by the Shuttle Radar Topography Mission (SRTM) in 2000. The SRTM data form the basis for most freely available digital elevation models (DEMs) in these regions. There are a number of online tools that model coastal inundation from sea level rise based on these SRTM topographic data and in some cases these have been recommended to Pacific governments in workshops discussing these issues (D. Yee, Solomon Islands government, 2011, personal communication).

A major limitation of SRTM-data-based methods for coastal vulnerability assessments is its horizontal resolution and vertical accuracy. Vertical accuracy of the data is between 5 and 10 m (Rodríguez et al. 2006), rendering it unsuitable for making assessments of sea level in the range of 20–100 cm. The horizontal grid size of SRTM data available globally is ≈ 90 m (3 s of arc data), effectively providing an average elevation over this area. In some areas of extensive flat homogenous topography, SRTM data have been successfully used to accurately map topography. However, in areas of highly variable topography in the coastal environment (e.g., near-shore limestone cliffs up to 40 m high), the averaging of elevation data over a 90-m grid renders the data useless for finescale topographic assessments. DEMs derived from 1 s of arc SRTM data (≈ 30 -m grid) are available in limited areas, although such data also suffer from the same averaging issues in sea level rise applications. Consequently, the online tools and software packages providing sea level inundation assessments based on SRTM data are not appropriate for sea level rise adaptation planning on low-lying Pacific islands.

In developed nations lidar has become the preferred method to provide high-resolution coastal topography

information with a level of accuracy suitable to develop sea level rise inundation models (Gesch 2009; Webster et al. 2006). Spatial resolution of lidar data is typically 50–100 data points per square meter. Although spatially there can be approximately 5 cm of error in the horizontal position of these data because of inherent location errors associated with the global positioning systems (GPS) used to record the location of the sensor. Vertical resolution of lidar data shows improvement when compared to SRTM-based data with error ranges of 20–60 cm often reported (Hodgson and Bresnahan 2004) depending on slope and vegetation (Bater and Coops 2009) and the level of ground-truth correction applied. In the Pacific island context, this vertical error is likely to be higher because of the lack of accurate geodetic controls, limited sea level data, and tectonically active nature of many islands. A further negative feature of lidar-derived sea level inundation models in the Pacific is the expense of acquiring data and the need for experienced specialists in geographic information systems (GIS) to process and map the data. Costs associated with the collection of lidar data for a typical rural community or small island in the Pacific (10–100 km²) is in the order of \$500K–\$1 million (Australian dollars). Furthermore, the processing and mapping of the data can often take several months and are often undertaken by external consultants with little or no opportunity for local involvement or capacity building.

An alternative to airborne systems such as SRTM and lidar are manual ground-based surveys using more traditional methods such as total stations, laser levels or optical levels. Of these, laser levels provide the best balance between accuracy and simplicity. Laser levels are typically used in the construction industry for setting levels across the building site or slope/grade of an incline. A rotating laser is mounted on a tripod, providing a 360° horizontally level beam. A small laser detector mounted on a staff is used to detect the signal and to indicate the point is level with other survey points. By moving the laser detector vertically on the staff, the laser level can be utilized in a similar fashion to an optical level to determine elevation differences between a range of points with a vertical error range of 1–2 cm.

In this study we tested the ability of laser levels to provide a useful sea level rise vulnerability assessment in a rural Pacific island setting.

2. Methods

a. Study site

Roviana and Marovo Lagoons in the western Solomon Islands (Fig. 1) were used to trial the application of the laser-level technique to a Pacific island setting. The

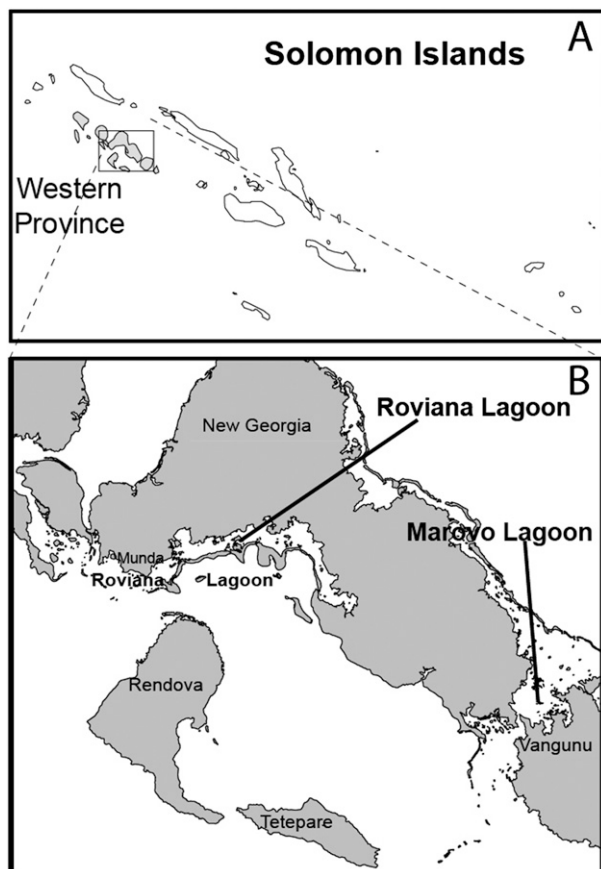


FIG. 1. Field sites in the (a) Solomon Islands and (b) Roviana and Marovo Lagoons.

people of Roviana and Marovo inhabit small coastal communities with an average population of 100–1000 people per village. Houses are constructed of local timber and leaf materials and are often built adjacent to the coast in low-lying areas or small lagoon islands with limited potential for movement inland because of complex customary land tenure and governance systems. Individual families typically have ownership of higher-elevation lands on the mainland relocation to these areas, thus making whole community relocation difficult. Partial relocation would cause fracturing of the cohesive community unit that underpins life in the rural Solomon Islands.

b. Laser level

A Leica Rugby 100LR rotating laser level attached to an elevating tripod was used to survey coastal topography in the Roviana and Marovo Lagoons. Through consultation with the Roviana Conservation Foundation (RCF), a local community-based organization, and a trial of various approaches, a standardized method was developed. This method focused on mapping three contour lines [0 m (HAT), +0.5 m, +1 m] of relevance to sea

level rise rather than trying to determine the full coastal profile of an area.

c. Estimating highest astronomical tide

The referencing of coastal topography surveys to a known datum or reference point is important to ensure accuracy and repeatability of surveys. Ideally, these surveys would be referenced to the Highest Astronomical Tide (HAT) determined from surveying from known reference points or through tide gauge information. Unfortunately, neither of these options are available in Roviana (and most rural areas of the Pacific). Hence, traditional local knowledge was relied on to estimate HAT and to reference each survey to. At each survey site, several local residents were consulted for the location of estimated HAT. This information was combined with observation of coastal profile features such as location of sediment/rubble berm or terrestrial grasses. Once this estimated HAT mark was determined, a survey peg was installed to provide a reference point for the start of surveys.

d. Setting up tripod and laser level

The laser level and tripod were positioned approximately halfway between the HAT mark and expected 1-m contour. The tripod was positioned within line of sight of the first HAT reference point and as much of the survey area as possible. The laser-level height was typically 1.5–2 m. Three Leica digital Rod Eye Plus laser detectors were attached to either a 4-m survey staff or an improvised locally made staff with 1-cm increments ruled onto a 4-m length of 25 mm × 50 mm hardwood. Each of these laser detectors and staffs were allocated to a contour either 0, 0.5, or 1 m.

e. Recording contours with laser level

Each of the three staffs were positioned on top of the first HAT survey peg and laser detectors moved vertically until level with the laser beam (as indicated by audible/visual alarm). The 0-m contour staff and assistant would then proceed approximately 5–10 m along the shoreline and position the staff on the ground, moving it until the laser detector was in line with laser beam, and then the 0-m contour team would record the GPS position of this second 0-m point. The 0-m team continues along the shoreline every 5–10 m (depending on variability of the coastline), recording the 0-m contour, and approximately every tenth survey point (or every 50–100 m) would be marked with a survey peg.

The 0.5-m team would lower its laser detector exactly 0.5 m on the staff (after referencing it level with laser at first 0-m survey mark) and move inland, moving the staff position until the laser detector indicated it was level with the laser beam. The 0.5-m team would then record

the GPS position of this point (the first 0.5-m contour) and mark it with a survey peg. The 0.5-m team would then move 5–10 m along the coastline and move the staff until the detector indicated it was level with laser beam, again marking with this second 0.5-m point with the GPS. This process would continue marking the 0.5-m contour every 5–10 m along the coast, and approximately every tenth survey point (or every 50–100 m) would be marked with a survey peg. Likewise, the 1-m team would lower its laser detector exactly 100 cm on the staff (after referencing to laser) and mark GPS points and survey pegs for the 1-m contour as described above.

f. Mapping

After the complete coastline (typically 500–1000 m for a typical village in Roviana/Marovo) of an island has been surveyed and GPS positions recorded for 0-, 0.5-, and 1-m contours every 5–10 m across the survey area, a map was developed. First, 0-m contour marks are imported into the Google Earth platform (version 6.2.2, Google Inc.). A polygon is then drawn around these points. The area of this polygon can be calculated using Google Earth Pro or the freely available GE-Path software. The 0.5-m contour points are then imported and a polygon drawn and area calculated. Last, the 1-m contour points are imported and a polygon drawn and area calculated. The difference between the areas of these polygons indicates the area of inundation under the 0.5- or 1-m sea level rise scenario. It should be noted that the freely available software systems were used in this case, as they are likely to be the first systems used in less developed countries; however, the same results can also be readily achieved using commercially available GIS software.

g. Local participation

The implementation of this method at a cluster of rural villages in Solomon Islands first required purchase of the equipment (laser level, GPS, tripod, measuring staff) for approximately \$2000 (U.S. dollars). After a one-day training session was conducted with a few local facilitators and nongovernment organization (NGO) staffs, these individuals were able to independently implement the method in the surrounding villages. Typically, this would involve incorporating the inundation mapping into village awareness sessions, whereby general climate change awareness and information was discussed with the community in the evening and the following day interested community members would participate in surveying the 0-, 0.5-, and 1-m contours using the laser level. During these mapping exercises, several members of the community would join in the process and it provided an opportunity for discussing sea level rise and coastal

TABLE 1. Vulnerability of study communities in Roviana and Marovo Lagoons to sea level rise.

	Village area (m ²)	Land under 0.5 m (%)	Land under 1 m (%)
Kida	70 485	5	9
Madou	148 396	10	19
Olive	185 261	12	18
Kindu	202 165	13	19
Nusa Banga	75 156	16	31
Egholo	12 020	22	29
Bareho	86 024	49	77
Nusa Hope	12 483	52	61
Tusu Ngoete	21 704	82	96

erosion issues for that specific village. A typical coastal village with 500–1000 m of coastline was mapped in one or two days, with map development then taking an additional day.

3. Results

a. Laser-level survey

Results from the nine study villages in the Solomon Islands vary significantly. In the worst-case scenario, Tusu Ngoete village would lose 82% of village area with a 0.5-m sea level rise scenario. Kida village, however, was the least sensitive with only 5% of village area being lost with a 0.5-m sea level rise (Table 1). Across all nine villages surveyed, an average of 29% of village area would be lost with a 0.5-m sea level rise scenario and 40% lost with a 1.0-m sea level rise scenario. In some cases such as Nusa Banga, the area lost was not particularly high but projected inundation from sea level rise indicates significant changes in village layout with the splitting of one island into two, thus separating the village (Fig. 2).

b. Limitation of method

The inundation percentages under various sea level rise scenarios are intended to provide an approximate assessment of the relative vulnerability of a range of sites. It should also be noted that while the elevations measured using this laser-level method are vertically accurate to 10–20 mm, because of inherent 3–5-m horizontal error in handheld GPS units, the maps produced have a potential 3–5-m positional inaccuracy. Hence, the actual ground-based surveys and positioning of the survey pegs are what should be relied upon by communities in making sea level rise adaptation decisions. A further limitation of this method is determining mean sea level or highest astronomical tide in the absence of data. As Roviana Lagoon is an enclosed lagoon with limited wave action, we were able to confidently use anecdotal information and coastal features; however, in areas of high

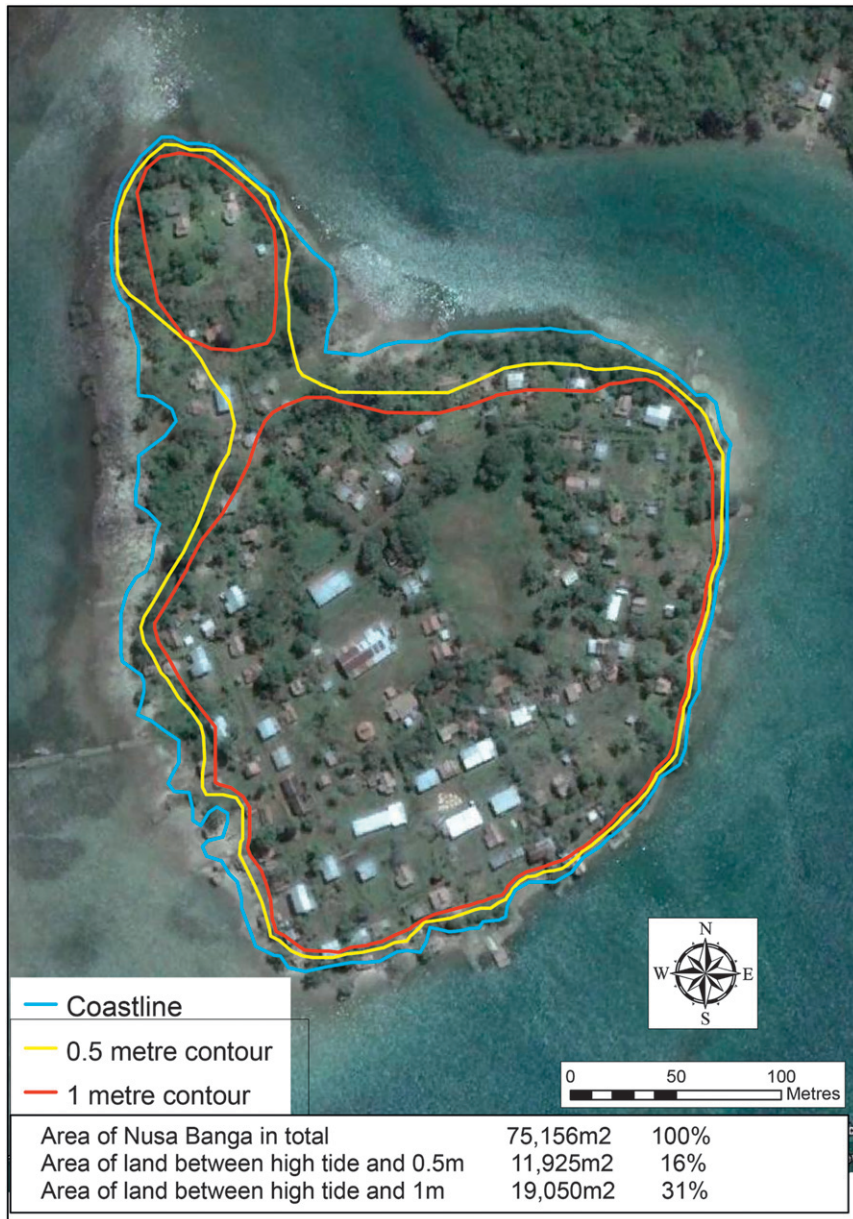


FIG. 2. Sea level rise inundation map of Nusa Banga village in Roviana Lagoon using manual laser-level surveys.

seasonal variability and wave energy, this estimation will be more difficult. Last, like all “bathtub”-style inundation models, this vulnerability assessment focusses only on the increase in mean sea level and not the influences of extreme events driven by ENSO and cyclones.

4. Discussion

Small island developing states (SIDS), such as the Solomon Islands, are among the most vulnerable countries in the world to climate change, and sea level

rise is one of the most pressing climate change challenges facing SIDS (Mimura et al. 2007). However, accurate topographical data required for predicting differential exposures to sea level rise at local scales are only available using lidar-based data, which can be prohibitively expensive and technical. This study sought to test simple, low-cost methods for determining coastal topography in the Pacific context, and that could also be readily used by communities, government, and nongovernment organizations to assess sea level rise vulnerability.

Over the past decade, several advances have been made in utilizing lidar-based data to improve understanding of coastal exposure and vulnerability to sea level rise. These datasets can yield high-resolution digital elevation and bathymetric models that are able to accurately map inundation under a range of sea level rise and extreme event scenarios (Gesch 2009). For large areas of coastline with major infrastructure, a lidar-based approach with high vertical and horizontal accuracy is essential and is likely to be cost effective. However, for many developing country governments seeking to understand and predict the vulnerability of the people in remote coastal areas to sea level rise, the high cost and technical capacity required to process and map lidar data is prohibitive. In addition, seismically active areas such as the Solomon Islands can have major topography changes after seismic events, where tectonic shifts can change coastal elevations on the order of 2 m (Albert et al. 2007). Such events would negate any previous lidar surveys and require resurvey and greatly increased costs depending on seismic event frequency. Global DEMs based on SRTM have been the only feasible option for vulnerability assessments in these rural areas. However, SRTM data are too coarse in resolution, and the averaged elevation for coastline is inaccurate for determining exposure to sea level rise for comparisons of different communities and localized areas. The laser-level survey methods described here provide an alternative solution. While labor intensive and slow (one day for a small team to map 500–1000 m of coastline), these manual methods have proven accurate and informative for rural communities in the Solomon Islands. Like all sea level rise inundation predications based on topographic data alone (known as a bathtub model), the inundation maps generated by this laser-level method are excluding the variability in inundation caused by changes in coastal geomorphology (Webb and Kench 2010). However, without further detailed studies of coastal sediment dynamics and erosion processes at a local scale, this assumption of bathtub inundation is required.

Global estimates indicate 0.31% of land surface would be inundated from 1 m of sea level rise (Dasgupta et al. 2009). In comparison, results from mapping coastal topography using laser-level survey methods show the scale of inundation in the Solomon Islands is relatively high, with four of the nine villages surveyed likely to experience $\geq 0.31\%$ loss of land. In the Solomon Islands, as in the wider Pacific (Mimura 1999), occupation of low-lying coastal areas (within the 0.5-m contour) is a relatively recent occurrence, resulting from rapid population growth, and a trend toward more centralized communities around churches. Our results for the Solomon Islands have also demonstrated the high variability

in exposure to sea level inundation within the region. With some particularly vulnerable communities such as Tusu Ngoete expected to lose 82% of their inhabitable area under a 0.5-m rise scenario, others such as Kida are expected to lose less than 5% of village area under the same scenario. For remote coastal communities such as those in the Solomon Islands, the provision of this accurate measure of exposure to sea level rise is invaluable for identifying the most vulnerable areas, prioritizing resource allocation, guiding possible adaptations to reduce exposure, and preventing maladaptation in nonvulnerable areas.

In the Solomon Islands, broad assessments of vulnerability to climate change and variability in coastal areas have been made at national and provincial levels (Narsey Lal et al. 2009; MECDM 2008; MECDM/MFMR 2010). Sparse climatic trend data and coarse geographical elevation data within provinces and at the community level have meant climate change vulnerability assessments at finer scales have not been possible. Yet, there is emphasis on community-based adaptation (lead by the community and driven by community needs) as a national strategy to improve food security and well-being, and to build adaptive capacity to climate change in the context of other pressures (MECDM 2008; MECDM/MFMR 2010). The Solomon Islands' government looks to community-based solutions while improved linkages between national-, provincial-, and community-level governance are being developed. Furthermore, there is strong evidence that community-based activities are effective in the Solomon Islands to enhance resilience and reduce vulnerability (Schwarz et al. 2011). Given the weight placed on community measures to adapt to climate changes, accurate information on the predicted impacts of sea level rise for communities to make decisions is required.

It is also with some urgency that accurate sea level rise information is provided to communities. In the Solomon Islands, the impacts of sea level rise are already being felt by vulnerable communities, with houses being inundated during spring high tides (personal observation). In a vulnerability assessment conducted in 2010 across a number of hamlets in Roviana Lagoon and a few hamlets in Marovo Lagoon ($N = 156$), 88% of the surveyed households said there had been shore erosion in their community, of which 48% attested that this was caused by increasingly high winds, currents, and tides; 25% explained that this was caused by sea level rise; and 16% suggested that the 2007 earthquake and tsunami had caused erosion. A large majority of respondents (78%) agreed that all the observed changes began after the year 2000 (S. Aswani 2011, unpublished data). In 2011, sea level rise and the transformation that would be required by communities that would need to relocate were cited by experts in the region as the climate change

prediction of most concern (Albert et al. 2012). In communities, there is a sense of uncertainty about the causes and implications of sea level rise, and what will happen to communities in the future, and in some cases this has distorted into fear of future sea level rise under climate change scenarios.

While undertaking the laser-level surveys, we observed many cases where there was a general sense of concern and paranoia regarding predicted sea level rise, triggered by media reports of the Pacific islands' extreme vulnerability, and predictions that many islands would "sink into the ocean," resulting in forced migration and irreversible changes in islanders "way of life." While we have shown in some cases it is likely sea level rise may require people to move from their current location, but for many people of the Pacific inhabiting high volcanic islands, sea level rise will cause the loss of relatively small proportions of land. In many of the study locations in Roviana, less than 20% of village area was lower than the 1-m contour. Having tangible and specific results of sea level rise prediction for their own community provided reassurance to community members that their island will not disappear and that they have time to develop simple measures and plans to adapt. This heightened level of confidence in village-specific vulnerability has led to a sense of empowerment, which is essential for communities to adapt, as there is a danger if climate changes are overstated and internalized (uncorrected) by people, it can lead to practices where communities respond to the idea of climate change rather than the actual changes (Barnett and Adger 2003). Furthermore, discourses of vulnerability such as those read and listened to in the media can downplay the resilience of communities, when in fact they have a high capacity to adapt (Campbell 1997). For example, in the last few generations in Roviana, communities have been exposed to tectonic subsidence and uplift, tsunamis, an influx of foreign logging companies, a shift to Christianity, and a world war—all of which have changed coastal village life and people have adapted. The Solomon Islands also have experienced high climatic variability over time and its people have methods to cope (Rasmussen et al. 2009). It is our belief that using methods such as the laser-level surveys, which clearly demonstrate locally specific and accurate information to communities, may help to counter the potentially destabilizing or debilitating effects that sensationalism of climate change impacts can have for community-based adaptation action.

Another important aspect of the laser-level survey method is its participatory nature. Lidar-based approaches utilize aircraft and offshore data processing, while laser-level surveys require people on the ground to work in teams to take measurements. In areas of the Pacific where lidar

has been applied, there has been little involvement of the local community and they have been simply provided with a map showing the area of inundation. In contrast, the laser-level methods outlined here are conducted by community members from the local area and the physical participation process itself has been observed to be an effective means of communicating the impact of sea level rise predicted by climate change. The old adage "seeing is believing" proved to be true in this study, and the survey activities provided a forum to discuss the issues surrounding vulnerability to coastal inundation. These methods were also incorporated by the local communities of Roviana Lagoon into an existing climate change education and awareness campaign. The local team that was trained in the laser-level surveys held village meetings in the evening about climate change and then the next morning would take interested community members out to map their vulnerability to sea level rise. Now, without external support and minimal equipment, this process that emphasized a locally led and participatory approach has helped to build the capacity of Roviana communities in understanding the general threats climate change pose as well as their specific vulnerability to sea level rise. Participatory approaches that are rooted in locally derived knowledge and coping strategies, in collaborative learning, and in communities that are empowered to take their own decisions, are widely accepted to be more successful for adaptation to climate change in developing nations than top-down initiatives (Reid et al. 2009). It has been our experience in this study that in order to have climate change resonate at the community level and to foster change required for adaptation in places that need to think about transformation, it is important to provide experiences that people trust, and in a way that connects with the community's own experience.

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In Albert et al. (2013), the current affiliation of the final coauthor was not given on the title page. The affiliations of the authors should have appeared as it does here.

The staff of *Weather, Climate, and Society* regrets any inconvenience this may have caused.

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