Comparing the role of absolute sea-level rise and vertical tectonic motions in coastal flooding, Torres Islands (Vanuatu)

Valérie Ballu[a,b,1], Marie-Noëlle Bouin[c], Patricia Siméoni[d], Wayne C. Crawford[a,b], Stephane Calmant[e], Jean-Michel Boré[f], Tony Kanas[g], and Bernard Pelletier[a,f]

[a]Géoazur, Unité Mixte de Recherche 6526, Institut de Recherche pour le Developpement, Port Vila, Vanuatu; [b]Institut de Physique du Globe—Sorbonne Paris Cité, Université Paris Diderot, Unité Mixte de Recherche, Centre National de la Recherche Scientifique 7154, 1 rue Cuvier, 75238 Paris Cedex 05, France; [c]Centre National de Recherches Météorologiques, Météo France. 13 rue du Chatellier CS 12804, 29228 Brest Cedex 2, France; [d]Géo-consulte, BP 946, Port Vila, Vanuatu; [e]Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, Unité Mixte de Recherche 5566, Observatoire Midi Pyrenées, Centre National de la Recherche Scientifique, Toulouse, France; [f]Géoazur, Unité Mixte de Recherche 6526, Institut de Recherche pour le Developpement, BP A5 Nouméa, New Caledonia; and [g]Land Survey Department, Luganville, Santo, Vanuatu

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Since the late 1990s, rising sea levels around the Torres Islands (north Vanuatu, southwest Pacific) have caused strong local and international concern. In 2002–2004, a village was displaced due to increasing sea incursions, and in 2005 a United Nations Environment Programme press release referred to the displaced village as perhaps the world's first climate change "refugees." We show here that vertical motions of the Torres Islands themselves dominate the apparent sea-level rise observed on the islands. From 1997 to 2009, the absolute sea level rose by 150 + / − 20 mm. But GPS data reveal that the islands subsided by 117 + / − 30 mm over the same time period, almost doubling the apparent gradual sea-level rise. Moreover, large earthquakes that occurred just before and after this period caused several hundreds of mm of sudden vertical motion, generating larger apparent sea-level changes than those observed during the entire intervening period. Our results show that vertical ground motions must be accounted for when evaluating sea-level change hazards in active tectonic regions. These data are needed to help communities and governments understand environmental changes and make the best decisions for their future.

geodesy | seismic cycle | island arcs | vertical motion

The Torres Islands are located at the northern end of the Vanuatu archipelago, just south of the eastern Solomon Islands in the southwest Pacific Ocean. Covering 45 km from south to north, the six remote inhabited islands of Toga, Loh, Linua, Tegua, Metoma, and Hiu (Fig. 1) have a total surface area of 111.8 km2 and a population of 685, according to a 2009 census. These islands belong to the Vanuatu arc, which results from the convergence between the Australian and Pacific plates. At the Torres Islands, the Australian plate subducts eastward beneath the Vanuatu arc at a 72 + / − 4.3 mm/yr relative convergence rate (1). While many of the Vanuatu islands are typical subaerial arc volcanoes related to present-day subduction, others, including the Torres group, appear to have emerged due to collision-driven uplift (2). The Torres Islands are located much closer to the plate boundary than the active volcanoes and have experienced particularly strong vertical motion over the past hundred thousand years, with long-term uplift rates close to 1 mm/yr (2). These islands are regularly struck by strong earthquakes (10 magnitude 7+ earthquakes less than 80 km from the islands since 1980), which can generate local tsunamis (3). They are also exposed to tele-tsunamis (caused by distant earthquakes) and cyclones.

Starting in the late 1990s, villagers became concerned that the sea was penetrating deeper and deeper inland during strong weather. Around the same time, part of a coconut plantation on Loh Island started gradually flooding with seawater (Fig. 2). In 2002–2004, the village of Lataw on Tegua Island was moved several hundred meters inland with the aid of the Vanuatu government and the Canadian International Development Agency in the framework of a climate change adaptation program. The issue exploded onto the international scene when a 2005 United Nations Environment Programme (UNEP) press release described the Lataw villagers as climate change "refugees," referring to them as possibly the world's first community to be "formally moved out of harm's way because of climate change" (see http://www.unep.org/Documents.Multilingual/Default.Print.asp?DocumentID=459&ArticleID=5066&I=en). Pictures of the flooded coconut plantation in Loh have circled the world as an example of the effect of climate change (see, for example, the Secretariat of the Pacific Community's 2009 flyer on Agriculture Forestry and Climate Change).

Results

Regional sea-level trend maps provided by various organizations (such as CLS/CNES/LEGOS and NASA) show that, from 1992–2010, the absolute sea level rises at a rate of nearly 8 mm/yr around the Torres Islands (Fig. 3). This trend, which is well above the global average of 3.2 + / − 0.4 mm/yr (4) over the same time period, is part of a decadal trend of high rise rates in the tropical zone of the western Pacific. The long-term stability of this trend is not yet confirmed due to the limited duration of the altimetry series. To look at absolute sea-level variations more closely during the studied period, we use multimission (SSALTO/DUACS) altimeter products around the Torres Islands, available from the AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data) web site of the French national space agency (http://opendap.aviso.oceanobs.com/thredds/dods) (Fig. 4). These data show that the sea-level rise rate is even higher from 1997–2009 (12 + / − 1.5 mm/yr) than from 1992–2010 (7.5 + /− 0.9 mm/yr).

Absolute sea-level rise is tied to a global reference, but the relative sea-level rise observed at a coast is a combination of this absolute rise and the vertical motion of the coastal lands. We show that the Torres Islands are subject to strong vertical motions during and in between earthquakes and that the observed sea-level rise on the Torres Islands is, in fact, dominated by these motions.

The Earth's crust is subject to large vertical and horizontal deformations. Some of the strongest movements come from post-

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[1]To whom correspondence should be addressed. E-mail: ballu@ipgp.fr.

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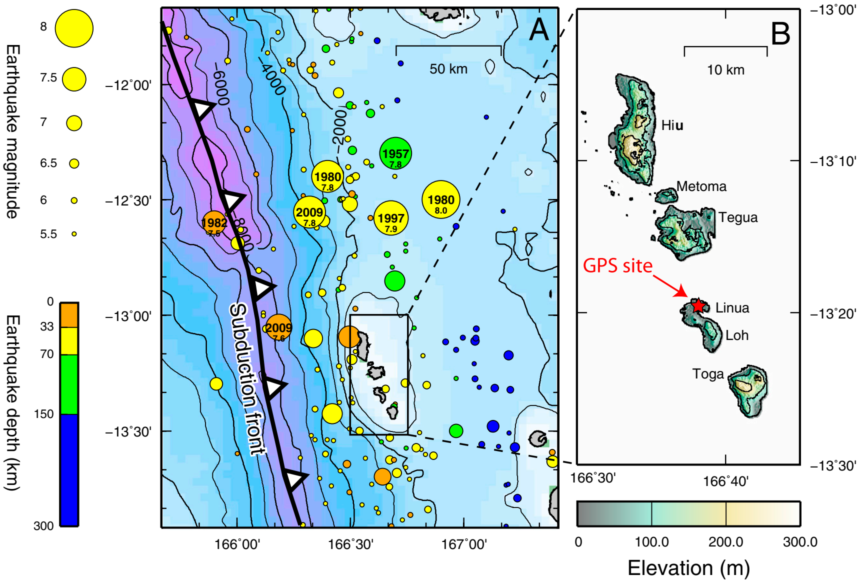

Fig. 1. Location of the study area. (*A*) Bathymetric map, overlain by magnitude 7.5 + earthquakes since 1900 and magnitude 5.5 + earthquakes since 1973 (USGS catalog). The earthquake circle sizes scale with their magnitude, and their color corresponds to their depth, using the USGS color code. The subduction front marks the boundary between the Australian plate to the west and the North Fiji Basin to the east. (*B*) Close-up of the Torres Islands. Altimetry data are from NASA ASTER global digital elevation map.

glacial rebound and from the seismic cycle. This latter is divided into three phases: interseismic motion, caused by strain accumulation during the loading phase; coseismic motion, which corresponds to strain release during the earthquake rupture; and postseismic motion, which results from adjustments after an earthquake. High rates of interseismic vertical motion have been documented in several subduction zones, including up to 4.5 mm/yr uplift in western Oregon (5), up to 8 mm/yr uplift in some parts of Japan (6, 7), and up to 14 mm/yr of subsidence in West Sumatra (8).

Several different types of motions can be superimposed at different time scales. For instance, in the region of the 1964 Great Alaska Earthquake in Prince William Sound, vertical motions vary from strong subsidence (more than 8 mm/yr) to strong uplift (more than 15 mm/yr) due to a combination of long-term postglacial rebound and interseismic and postseismic deformations; the uplift rate locally exceeds 30 mm/yr in the southeast due to extreme postglacial rebound (9). Global studies indicate that vertical deformations must be accounted for when estimating global sea-level rise from tide-gauge data, even after correcting for postglacial rebound (10, 11). In addition, large subduction zone earthquakes can cause nearly instantaneous vertical movements of up to several meters (see, for example refs. 12–15).

The Torres Islands, which are located very near the plate interface, are likely to be affected by both sudden and slow vertical motions over different time scales. By dating uplifted coral platforms, Taylor et al. (2) determined that the islands have uplifted by more than 100 m in the last 125,000 yr (0.7 to 0.9 mm/yr). This long-term uplift is probably caused by the subduction of a large topographic feature on the Australian plate (the West Torres Plateau) beneath the Vanuatu arc in front of the Torres Islands. In the short term, the islands can experience strong vertical motions due to interseismic, postseismic, and coseismic deformations.

Fig. 2. Photo, taken in April 2009, of the flooded coconut plantation on Loh Island, with many dead coconut trees. The flooding extends along about 400 m of land that was dry before 1997.

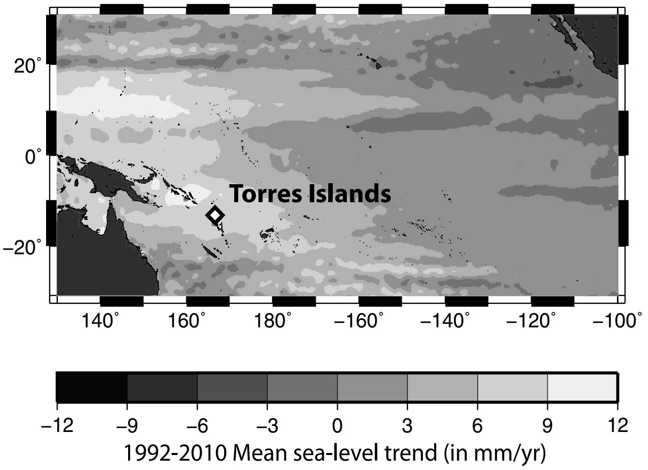

Fig. 3. Map of regional mean sea-level trends compiled from multisatellite altimetric mission data (product MSL_Map_MERGED_Global_IB_RWT_NoGIA_Adjust.nc available from www.aviso.oceanobs.com/en/news/ocean-indicators/mean-sea-level). Data used in this compilation cover the period 1992–2009. The mean sea-level rise trend is significantly lower over the entire period than during the 1997–2009 period that we use in this paper (see Fig. 4), due to especially low sea levels during the major El Niño period around year 1998.

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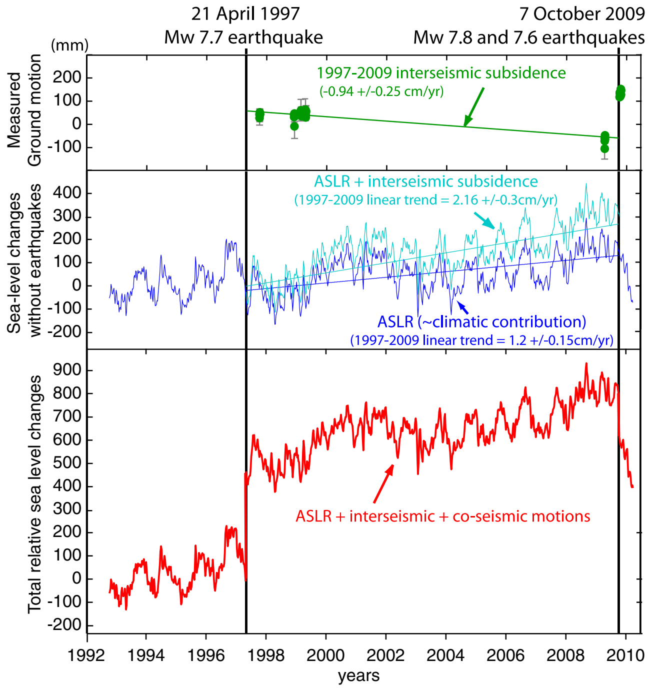

Fig. 4. The role of ground motion in relative sea-level rise. (*Upper*) Ground motion measured by GPS on Linua Island (Torres). (*Middle*) Sea-level variations on the Torres Islands between major earthquakes. Blue curve: absolute sea-level rise (ASLR) observed by satellite altimetry (extracted from file dt_upd_global_merged_msla_h available on AVISO server: http//opendap.aviso.oceanobs.com/thredds/dods/). Cyan curve: relative sea-level rise: ASLR plus interseismic ground motion from the upper panel. (*Lower*) Total relative sea-level change: ASLR plus interseismic and coseismic (earthquake) ground motions.

A geodetic benchmark (a stainless steel rod driven deep into a flat coral outcrop) was installed on Linua Island in the Torres group in 1997 to monitor the islands' motion following a magnitude Mw 7.8 earthquake that occurred on April 21, 1997 (3). The benchmark sits about 1 km away from the now-flooded coconut plantation on Loh Island. Its position was measured by GPS in October 1997 (6 d), November 1998 (8 d), and February and April 1999 (7 and 8 d). We remeasured the benchmark position in May 2009 (6 d) and then several times (16 d) after a seismic crisis (magnitude Mw 7.6, 7.8, and 7.4 earthquakes within 70 min) that took place in October 2009. GPS data were collected using constant height masts to reduce measurement errors. Daily data were first processed in a global network with modern standard procedures (see *Materials and Methods*) and then combined to derive interseismic and coseismic deformations.

Our data show that the Torres GPS station subsided by 117 + / − 30 mm (9.4 + / − 2.5 mm/yr) from 1997 to early 2009. This is one of the highest measured interseismic subsidence rates on Earth [along with northwest Malekula Island (1) and West Sumatra (8)]. Interseismic subsidence usually occurs only on islands that are close enough to the subduction plate boundary to be well over the locked part of the interplate fault (16). Adding this interseismic subsidence rate to the absolute sea-level rise rate from 1997–2009 gives a relative sea-level rise rate of more than 20 mm/yr around the Torres Islands.

Large earthquakes that significantly change the relative sea level also strike the Torres Islands. After a magnitude Mw 7.8 earthquake in April 1997, villagers reported an important rise in sea level, which actually corresponds to a subsidence of the island. A series of interviews with villagers corroborated by dives on the fringing coral platforms in October 1997 constrain the subsidence to between 500 and 1,000 mm. Because there was no GPS benchmark before the earthquake, we use the lower value of 500 mm in this paper.

On October 7, 2009, a seismic crisis consisting of three major earthquakes (magnitudes Mw 7.6, 7.8, and 7.4) lifted the islands by approximately 200 mm, bringing the relative sea level back down to about its 1998 level. Fig. 4 summarizes the relative sea-level variations resulting from the combination of absolute sea-level rise and the vertical motion of the islands.

The 1997 earthquake is probably the main reason for the sea incursions and flooding in the Torres Islands. Although the islanders noticed changes soon after this earthquake, such as the deepening of a submarine cave and the beginning of the plantation flooding; the increase in the flooding over the course of several years contributed to the idea that global climate change was responsible for the problems. However, sudden relative sea-level rise can also lead to gradual effects by modifying local hydrodynamics or coastal erosion patterns. One possible explanation for the gradual flooding of the plantation is that the relative sea-level rise caused by the 1997 earthquake led to a progressive erosion of natural barriers. The tsunami that followed the 1997 event may also have affected the barriers and the shallow seafloor. Finally, postseismic deformation may have further lowered the islands over several months following the 1997 earthquake. We do not believe that the subsidence observed from 1997 to 2009 is due to postseismic deformation, for two reasons: (*i*) GPS measurements started more than 5 mo after the earthquake, when the postseismic signal had probably decreased significantly, and (*ii*) the measured horizontal and vertical velocities fit those calculated using a simple back-slip model (16) (parameters: 120 mm/yr convergence rate between the Australian and Pacific plates and a locked zone 76 km wide with 20° dip).

Discussion

Island nations such as Vanuatu are concerned about natural hazards and ways to reduce or mitigate risks. In recent years, many of the risk mitigation plans have been carried under the general umbrella of "climate change adaptation." However, in the case of the Torres Islands, interseismic and 1997 coseismic subsidence is much larger than the climate-induced sea-level rise.

On a scale of thousands of years and more, the Torres Islands are less threatened by climate-induced sea-level rise than are many other islands. Most of the Torres Islands are more than a hundred meters high and in no immediate risk of disappearing. Currently, however, the islands are subsiding and villages located close to the ocean may be strongly affected by catastrophic events such as cyclones or tsunamis. In 2010, we conducted a survey of oral traditions, which indicated that there is ancestral knowledge of danger from the ocean and that villages were formerly located on a 100+ meter high coral platform (the villagers' gardens are still located on this platform). Archeological work confirms the presence of abandoned settlements on the platform (17) and early Christian mission papers refer to the villages' location there (18). The oral traditions state that disasters, such as tsunamis, were created by black magic and the migration toward the coast coincides with the evangelization of the islands and the rejection of black magic (black magic oral traditions were reported to us mainly by Chief Richmond Selwyn of Liraq village on Tegua island and Chief Pita Watego and field worker William Collins from Lounaragi on Loh Island). More generally, Mondragon (19) reports on the rejection or loss of oral traditions and magic practices in the Torres Islands. In rejecting black magic, the villagers appear to have lost their concern about dangers coming from the ocean. Foster and Kokko (20) consider superstitions as an inevitable feature of adaptive behavior, and similar cases where the rejection of black magic or folk science has lead to a higher vulnerability to natural disaster have been invoked in other contexts such as lake explosions in Cameroon (21) and the hantavirus

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outbreak in the Four Corners region of the United States of America (22).

A new understanding of the environment and of the causes of danger from the ocean is slowly arising in these remote islands. With the help of the Vanuatu Meteorological Office, villagers are becoming more aware of ocean-related risks and of the interest of moving back away from the coast in some areas. The Lataw villagers were helped to move by an aid program related to climate change adaptation, and this action was indeed prudent. However, although the village was moved several hundred meters, it sits on the same coral platform as before, and we estimate that the altitude of the village was not substantially increased. A full analysis of the causes of the problem would probably have led to a bigger move because the relative sea level could rise much faster than absolute sea-level rise rates predict. Furthermore, tsunamis could penetrate into the village's current location almost as easily as they could into the previous location.

Evaluating the sources and impact of sea-level rise on islands is crucial to risk mitigation for coastal communities, especially on islands that are low-lying or sinking in the long term. The vertical motion of islands must be evaluated in order to predict and mitigate coastal risks in tectonically active areas. Such data are needed to help local communities to understand environmental changes and make the best decisions for their future.

Materials and Methods

GPS data for 1997–1999 were collected using ASHTECH Z-XII dual frequency receivers and choke-ring antennas. GPS data for 2009–2010 were collected using GB1000 Topcon dual frequency receivers and Topcon PG_A1 antennas with ground-planes. In order to reduce antenna height uncertainties, we use constant height geodetic masts (manufactured by Tech2000).

We calculated daily GPS positions in 24 h sessions from 30 sec double-differenced ionosphere-free carrier phase data, with phase cycle ambiguity resolution and 10° cutoff angle, using GAMIT software version 10.34 (23) and standard modern procedures, including the global mapping function (24) for tropospheric delay estimates. We use tables provided by IGS for absolute antenna phase center models igs05_1597_plus.atx (25). Daily position data were processed in a globally distributed network to ensure a homogeneous reference frame, using a network of 44 stations from the International GNSS Service (IGS) (26), complemented by regional and local stations. The regional stations were TONG, VANU, KIRI, NAUR (Geosciences Australia), and KOUC (DITTT, New Caledonia).

To express our solutions in a unique and well-defined reference frame, allowing us to compare GPS data collected at different periods, we combined our daily coordinate sets into the ITRF2005 reference frame, using the CATREF software and the minimum constraints approach (27). We assume linear motion of stations in between earthquakes (constant interseismic velocity); this does not account for postseismic signals. The CATREF software allows us to jointly estimate the interseismic velocity and the coseismic displacement at a specific site.

The formal uncertainty for this velocity vertical estimate is 0.47 mm/yr. As has been shown by many studies (28), formal uncertainty estimates are unrealistic and should be reweighted by a factor of approximately 5; this gives an uncertainty of about 2.5 mm/yr.

To check the solution quality, we calculated the daily position residuals at each station. Mean weighted RMS on global stations are 1.4, 1.1, and 2.5 mm, respectively, on the north, east, and vertical components.

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