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The 2010 and 2011 Tsunamis in French Polynesia: Operational Aspects and Field Surveys

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Abstract—We present a detailed timeline of the warning procedures as they unfolded at the Laboratoire de Géophysique in Papeete, Tahiti, during the nights of 26–27 February 2010 (Maule, Chile tsunami) and 10–11 March 2011 (Tohoku tsunami). In particular, we discuss how the flow of information available to the warning center (including seismic evaluations obtained both locally and from other warning centers, as well as maregraph and DART buoy data) built up and eventually led to red alerts, which the local authorities used in both cases to impose an evacuation of low-lying areas on 68 islands. While the alerts were successful in Polynesia, a difficulty arose in 2011 when the alert had to be reinstated immediately as the all clear was being declared, since the maximum amplitude was carried by the fourth wave packet. We also present a complete dataset of 119 values of run-up and inundation surveyed in the aftermath of the two tsunamis, principally in the Marquesas Islands where their effects were maximal, and on Tahiti and Moorea for the 2011 event. The highest run-up (4.45 m) was observed in 2011 in the Bay of Taipivai on Nuku Hiva, where seven houses were flooded. We find no clear correlation between run-up values at the same locations in 2010 and 2011, suggesting that local responses are controlled by details specific to each tsunami. In 2010, in the village of Puamau on Hiva Oa (Marquesas), a delayed harbor response, probably due to resonance of the bay upon arrival of short-period components dispersed outside the shallow-water approximation, flung a launch onto a wharf, 7 h after the first arrivals, and 2.5 h after issuance of the all clear.

1. Introduction and Background

This paper summarizes the operational aspects of the alerts triggered in French Polynesia by the tsunamis of 27 February 2010 (Maule, Chile) and 11 March 2011 (Tohoku, Japan), and presents a complete dataset of inundation and run-up values surveyed in the aftermath of the events.

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French Polynesia constitutes an overseas territory of France in the southcentral Pacific, composed of 118 islands of which 68 are inhabited, with a total population of 260,000 (Fig. 1). While its total land mass covers only 4,167 km^2, it stretches over an area roughly the size of Europe with an EEZ of 5 million km^2. From the geological standpoint, the islands can be separated in three groups: (1) The Society Islands are the eroded remnants of Hawaiian-type shield volcanoes, presently fringed by coral reefs; their ages range from 0.5 Ma for the eastern edifice of Tahiti-Iti to 4.6 Ma for Maupiti (Duncan and McDougall, 1976; Uto *et al*., 2007). They host the overwhelming majority of the population (178,000 on Tahiti itself; 227,000 for the entire Society group). To the south, the Austral Islands share those structural properties despite more erratic ages (Turner and Jarrard, 1982; Chauvel *et al*., 1997); they host a total population of 6,300. (2) To the northeast, the nine Marquesas Islands make up another inactive hotspot chain aged 1.2 Ma (Fatu Hiva) to 6 Ma (Eiao), but lack coral reefs (Duncan and McDougall, 1974; Brousse *et al*., 1990; Desonie *et al*., 1993); only six are inhabited with a total population of 8,600. (3) In between, the Tuamotu Islands comprise 78 atolls, with a maximum altitude of 3 m above sea level, rising from a continuous plateau whose age, ranging from Late Cretaceous to Eocene, remains poorly constrained (Schlanger *et al*., 1984). Forty-one of them are inhabited, with a total population of 17,000.

In this context, the three island groups feature specifically different responses to tsunamis. Because of their low altitude, the atolls in the Tuamotu Islands offer no natural evacuation shelters, and they have historically suffered considerable damage and high death tolls during cyclones, most recently in 1982–1983. However, in the tsunami context, their steep slopes and small sizes (relative to transoceanic

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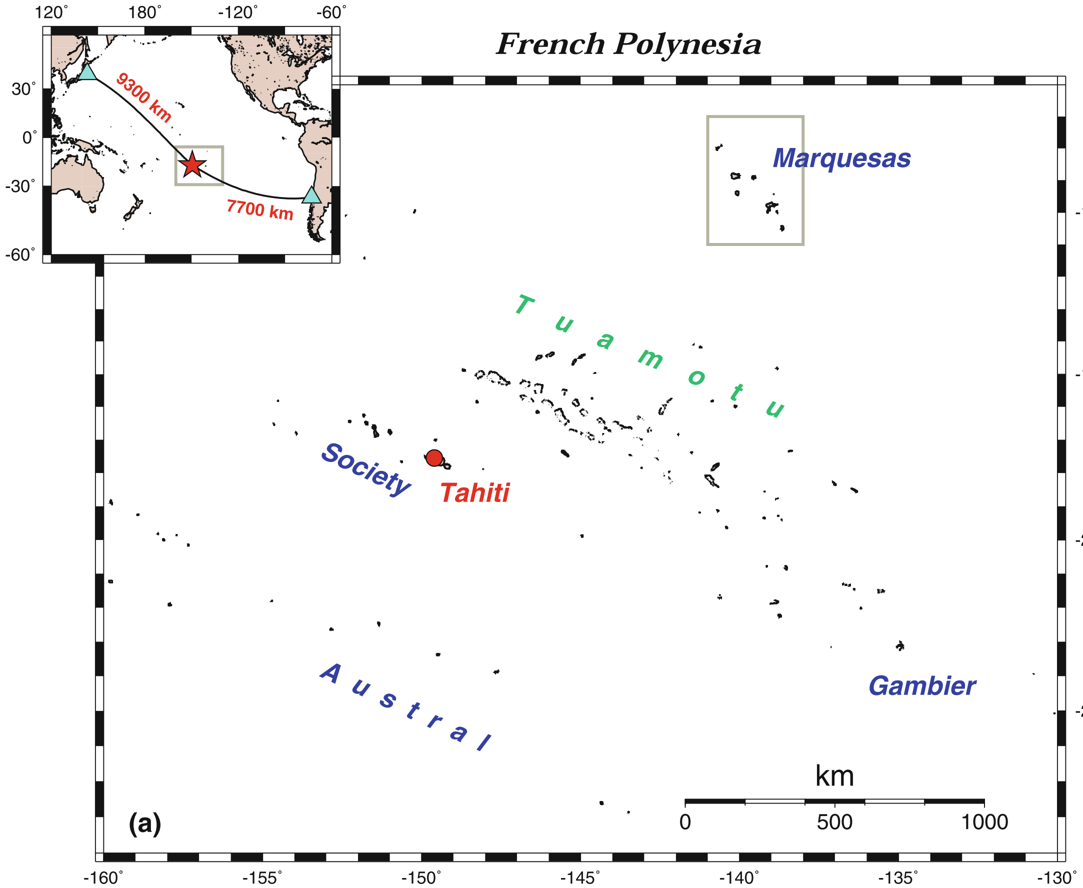
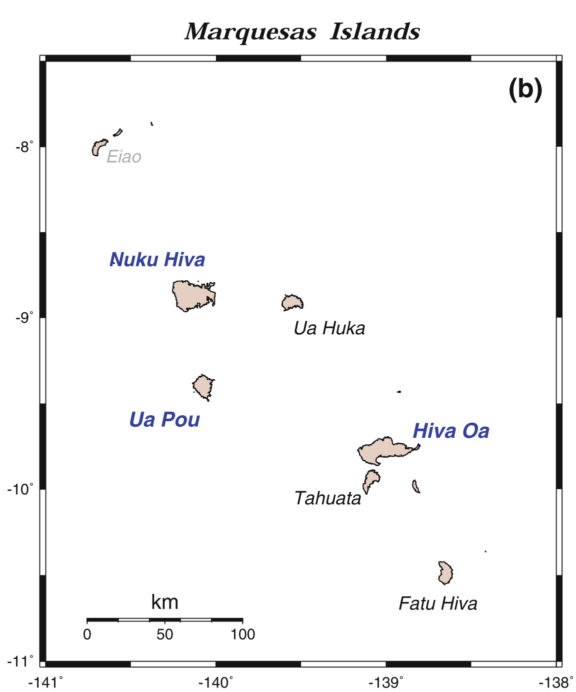
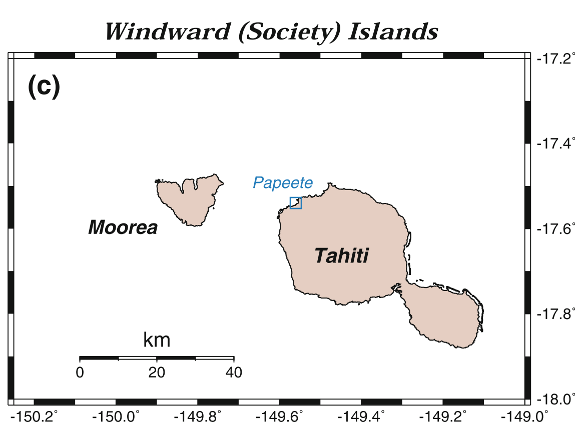


French Polynesia
120° 180° -120° -60°
30° 0° -30° -60°
9300 km
7700 km
Marquesas
Tuamotu
Society
Tahiti
Austral
Gambier
km
0 500 1000
(a)
-10° -15° -20° -25°
-160° -155° -150° -145° -140° -135° -130°



Marquesas Islands
(b)
Eiao
Nuku Hiva
Ua Huka
Ua Pou
Hiva Oa
Tahuata
Fatu Hiva
km
0 50 100
-8° -9° -10° -11°
-141° -140° -139° -138°



Windward (Society) Islands
(c)
Papeete
Moorea
Tahiti
km
0 20 40
-17.2° -17.4° -17.6° -17.8° -18.0°
-150.2° -150.0° -149.8° -149.6° -149.4° -149.2° -149.0°

◀ Figure 1
a Map of French Polynesia identifying the various archipelagoes. The *grey box* around the Marquesas delineates Frame (**b**). The *inset* at *upper left* locates the region inside the Pacific in relation to the two earthquake epicenters, shown as triangles. **b** Close-up of the Marquesas islands. The unpopulated island of Eaio is labeled in half-tone. The three islands surveyed are labeled in *bold*. **c** Close-up of the Windward Islands (Society) showing the islands of Tahiti and Moorea, surveyed in 2011

tsunami wavelengths) result in minimal amplification upon shoaling, and those atolls have suffered only moderately from the great transpacific tsunamis, e.g., in 1946 and 1960. Such relative immunity to shoaling for atolls perched on small, steep structures was also documented in the Maldives during the 2004 Indian Ocean tsunami (Fritz *et al.*, 2006). The fringed high islands, such as Tahiti and the Austral Islands, are generally protected by their coral reefs, with a limited amplification of tsunami waves upon shoaling, leading to maximum run-up values of only 4 m during the great tsunamis of 1946 and 1960 (e.g., Okal and Hébert, 2007); a caveat of this pattern remains that most coastal communities tend to be established in front of "passes", i.e., gaps in the coral barrier, which reduce the restraining effect of the reef on shoaling, an observation also reported elsewhere, e.g., in Zanzibar and the Comoros during the 2004 Indian Ocean tsunami (Okal *et al.*, 2009). By contrast, the unfringed Marquesas Islands lend themselves to extreme amplification of tsunami waves, especially in the deeply eroded valleys and bays hosting most population centers, with run-up values of up to 20 m documented during the 1946 Aleutian tsunami (Okal *et al.*, 2002). In addition, local resonances inside unprotected ports have led to structural damage to boats and harbors in the Marquesas during more moderate tsunamis, such as the 1995 Antofagasta event (Guibourg *et al.*, 1997). Despite a miraculously low historical death toll (two deaths in 1946 and none in 1960), the Marquesan valleys are thus generally considered "tsunami traps", and warrant customized warning procedures during tsunami alerts.

2. Operational Aspects

The origin times of the 2010 Maule and 2011 Tohoku events (06:34 and 05:46 UTC, respectively), and their epicentral distances to Tahiti (7,700 and 9,300 km, respectively; see Fig. 1) resulted in essentially similar timelines for the warning procedures and tsunami alerts in French Polynesia. Most of the territory lies in the W time zone (UTC − 10) with only the easternmost Tuamotu and Gambier Islands in the V zone (UTC − 9); the Marquesas use an intermediate time (UTC − 9:30). In simple terms, both earthquakes occurred in the evening of the previous day in the Polynesian local times, with the first tsunami waves expected in Polynesia after sunrise in the morning, typically around 07:00–08:00 in local times. In this section, all times will use the main Polynesian W zone (UTC − 10). The response to the 2010 Maule event will be described in detail, and only substantial differences listed for the 2011 Tohoku event.

Because tsunami hazard in Polynesia is essentially far-field, and thus benefits from the luxury of time, the warning center at the Laboratoire de Géophysique (LDG) is not manned 24 h a day. Rather, the automated single-station TREMORS algorithm (Reymond *et al.*, 1991; Schindelé *et al.*, 1995) is used to summon a scientist-on-call. However, during the 2010 Maule alert, one of the authors (EAO), who was then on a research visit to the LDG, happened to be present in the laboratory at the time of the event.

2.1. The 2010 Timeline

We give below a detailed description of the timeline of the alert in Papeete, which is intended to analyze the flow of information and its impact on the decision-making process at the LDG, in particular regarding the estimation of tsunami hazard before the arrival of the waves.

The 2010 Maule, Chile event occurred at 20:34 (UTC − 10), and the alarm rang in the LDG at 20:47; the scientist-on-call arrived at 21:00, at which time the NEIC had revised *downwards* their initial magnitude from 8.5 to 8.3. By 21:15, the scientific staff of the LDG had assembled, and the NEIC *W*-phase solution had been released, with a moment of 2×10^{29} dyn cm ($M_w = 8.8$). By 21:20, 10 min after the arrival of the slowest mantle waves at the local station in Papeete (PPT), this moment was confirmed independently from the automated use of the M_m algorithm (Okal and Talandier, 1989) on the long-period sensors. It was then confirmed that the earthquake was the largest in the Pacific Basin in 46 years, with the potential for a damaging tsunami throughout the basin. Contact was established by telephone at 21:33 with the Headquarters of Civil Defense in the Office of the High Commissioner, where an Emergency Response Unit was activated at 22:30. However, the earliest estimated arrival times, 05:50 (UTC − 10; 06:50 local) for the easternmost islands (the Gambier chain), left ample time for the fine-tuning of the decision-making process, which could then benefit from later-arriving reports.

Around 22:20, a full moment tensor solution had been obtained from the application of the PDFM method (Reymond and Okal, 2000) to a group of a dozen worldwide stations, confirming the moment of the earthquake. By 22:45, the source had been quantified through the calculation of a number of robust estimates of its properties. These included mantle magnitudes up to 550 s of period, the calculation of a magnitude based on spectral amplitudes of W phases (Okal, 1993, 2008), the computation of the parameter $\Theta = -5.35$, characteristic of the energy-to-moment ratio (Newman and Okal, 1998), and the examination of the duration $\tau_{1/3} = 62$ s of high-frequency (2–4 Hz) P waves (Ni *et al.*, 2005; Okal, 2007). These estimates, taken over a very broad range of frequencies, established the stability of the source spectrum, in other words that it did not feature any anomalous slowness, and that it was therefore legitimate to use the available seismic moment (2×10^{29} dyn cm) in a simulation of the expectable far-field tsunami. Incidentally, the lack of a hidden low-frequency component to the source would be later confirmed by the quantification of the gravest free oscillations of the Earth (Okal *et al.*, 2012), which requires the processing of data windows lasting several weeks and is thus unavailable in real time in the context of tsunami warning.

While tsunami warning in the far field has historically been based on an analysis of the properties of the parent earthquake, it benefits strongly from information relayed from intermediate locations, namely islands and, in recent years, deep-water observatories, located at shorter distances from the source along the path of the expected tsunami. In the geometry of the 2010 Chilean tsunami warning for Polynesia, the former include Juan Fernández and Easter Islands, the latter being the three DART observatories 32401, 32412, and 51406 (Fig. 2). In this context, around 22:45, a message was received

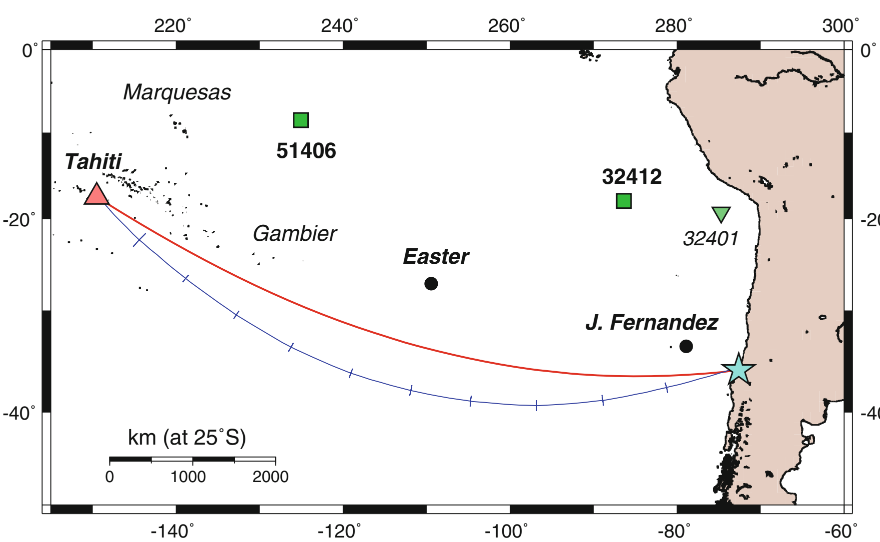


Figure 2
Map of the southeastern Pacific, showing the propagation path of the 2010 Maule tsunami to Tahiti. The large star is the epicenter, the *red path* is the *great circle* from the epicenter, and the *blue one* the refracted path obtained by ray-tracing through the correct bathymetry of the basin; *tick marks* are hours. The *solid dots* identify the islands of Juan Fernández and Easter. The two *squares* locate the reporting DART sensors (with ID number), the *inverted triangle*, the inoperative one

from the Pacific Tsunami Warning Center (PTWC), reporting an amplitude of 19 cm on the maregraph at Juan Fernández. This produced nothing short of bewilderment among the staff of the LDG, since such an onshore amplitude was obviously much too low in view of both the size of the seismic event, and the reports of local inundation along the coast of Chile which were starting to appear in the media as the sun was rising in the epicentral area. It later turned out that the Juan Fernández maregraph had been destroyed by the catastrophic onslaught of the tsunami on the island, where the International Survey Team later measured run-up reaching 18 m (Fritz *et al.*, 2011), and that the value of 19 cm was the last one transmitted by the maregraph before its annihilation. As fate would have it, the closest DART station (Number 32401 operated by the Chilean Servicio Hidrográfico y Oceanográfico de la Armada, 1,860 km from the source, and admittedly at an unfavorable azimuth from the source) was inoperative that day, and confirmation of the existence of a large tsunami on the high seas had to wait until the waves reached DART station 32412 (2,420 km from the source) at 23:45, where it registered an amplitude of 20 cm zero-to-peak, this value being, at the time and for the far field, the largest ever recorded on DART buoys since their inception. It was only then, after a stressful delay of one hour between the false report at Juan Fernández and the confirmation of the tsunami at 32412, that primary—as opposed to circumstantial—evidence became available, that a major tsunami was on its way across the Pacific Basin.

In the mean time, by 23:10, and despite the report from Juan Fernández, we had launched a numerical simulation using the MOST code (Titov and Synolakis, 1998) based on the PDFM moment tensor solution. While it started with a handicap of $\sim$2.5 h, the simulation propagated 8.5 times faster than the tsunami, and its accuracy was confirmed when it reached DART sensor 32412 at 23:55, only 10 min after the actual tsunami.

The next information came when the tsunami reached Easter Island at 01:15, where it was reported with an onshore amplitude of 1.50 m (run-up was later measured at 4.5 m [Fritz *et al.*, 2011]), this rather long delay simply illustrating the immensity of the expanses of the Pacific Basin, empty of both islands and instrumentation. By then, our simulation was indicating that the main lobe of the tsunami would be concentrated between Hawaii and Tahiti, and one hour later (around 02:40), the simulation ended showing that the tsunami would falter before reaching the coasts of Japan, where it would be observable but would not reach the destructive amplitudes observed in 1960. We were then expecting a significant tsunami throughout the Pacific Basin, and in particular in Polynesia, which would however remain smaller than the catastrophic events of 1946 or 1960.

At 23:25, a formal report of a "red alert", the highest level of warning, was issued by LDG for the entire territory of French Polynesia, and transmitted to Civil Defense authorities, whose responsibility it then became to order an evacuation of all low-lying areas in the 68 inhabited islands. While the emergency response unit, together with law enforcement, civil rescue, and paramedic personnel, had already started their preparations, the official order came only at 04:00 when, among other means of notification, 147 sirens wailed throughout the islands. This delay reflects the fact that a window of three hours (two in the small easternmost islands) was more than enough to evacuate people to high ground, and move boats out of harbors; it would have served no purpose to strand tens of thousands of residents for an additional three hours or more in the middle of the night when, once again, Polynesia enjoyed the luxury of time.

A special situation concerned the international airport at Faa'a, which is built on landfill inside the lagoon, 3 km west of the city of Papeete, at a maximum altitude of 2 m. On the night of the tsunami, two international flights were scheduled. Flight TN 77, an Airbus 340 from Tokyo, had an estimated arrival time of 08:00, basically coinciding with that of the tsunami waves; it was diverted at 03:30 to Honolulu, after consultation of the LDG by the Civil Aviation authority. Flight AF 674, a Boeing 777 from Los Angeles and Paris, landed on time at 04:30, with all passengers out of the airport by 05:45 when it was then closed to the public; the plane was refueled and took off empty at 07:20 (30 min before the arrival of the tsunami) flying to the north, presumably again to Honolulu. By contrast, it was observed that the local fleet of ten ATR regional aircraft remained at their home base at Faa'a, presumably because all airports within range of these aircraft are built at sea level, and thus provided no advantage over Faa'a. In the end, none of the airport infrastructures were reached by the waves.

The first waves reached the Gambier Islands at 05:50 (06:50 local) with the local maregraph registering 40 cm inside the lagoon. The Marquesas were reached at 07:00 (07:30 local) with reports of 2 m on Hiva Oa and 4 m on Nuku Hiva. As detailed below, final run-up values measured during the survey were 3.85 m on Hiva Oa and 3.79 m on Nuku Hiva. In Tahiti, the first waves arrived at 07:50, the maregraph recording 28 cm in the harbor. In the Papenoo district, 15 km east of the capital city of Papeete, where the ring road is built directly on the seawall, the water splashed over the road, to an altitude of 2.5 m, depositing debris on the pavement.

The evacuation was generally very successful and orderly, with the population taking the incident largely in stride. No injuries were reported directly related to the evacuation, and damage was reported only (at a moderate level; see below) in Hiva Oa (Marquesas).

The all clear was sounded at 09:14, except in the Marquesas where it was delayed ~2 h (11:50 local time).

2.2. *The 2011 Timeline*

As previously mentioned, the timeline of the Tohoku event is comparable to the 2010 one. The earthquake occurred at 19:46 (UTC—10), the alarm rang at 19:58 and the scientist-on-call arrived at 20:15. By 20:40, all LDG Staff had assembled. A preliminary statement was issued by the Governor's office at 23:15, a red alert declared by LDG at 01:00, and the evacuation ordered at 04:30. The first waves arrived in Maupiti at 06:30, in Papeete at 07:18, and in the Marquesas at 07:44 (08:14 local). With respect to the 2010 event, a number of similarities and differences will now be discussed.

1. The exact quantification of the earthquake remained a relatively slow process, with a severely deficient initial magnitude (7.9) derived by JMA, and reported by PTWC under international agreement. By 20:15, i.e., 1/2 h after the event, a local estimate of 8.7 was obtained at LDG, based on the SEISCOMP algorithm (Heinloo and Trabant, 2004), which had been implemented since 2010, to run in parallel with TREMORS. The first release of a *W*-phase solution by the NEIC (2.9×10^{29} dyn cm) was received at 20:45, and the final *W*-phase solution (4.0×10^{29} dyn cm) at 21:00. The exceptional size of the phenomenon was also clearly documented by the record deep-water amplitude of 1.7 m, registered on DART sensor Number 21418, located 500 km from the source, which was received in Papeete around 21:00.
2. The scope of the disaster was relayed in quasi-real time by media coverage, made possible by the daylight occurrence of the event in the epicentral area. The horrific scenes transmitted worldwide brought home the exceptional nature of the event, which probably contributed to the positive response of the population to the evacuation order.
3. Upon receipt of the *W*-phase moment, a full-scale basin-wide simulation was launched (around 21:00), using the algorithm of Hébert *et al.* (2001), which took about 1.5 h to run. However, and in parallel to the simulation, two estimates were obtained of the tsunami amplitude expectable in Papeete harbor, using methodologies currently under development at the LDG. Both algorithms are based on theoretical basin-wide simulations of tsunami amplitudes for a large number of sources covering all subduction zones over a wide range of seismic moments. The first one (Hébert *et al.*, 2009) attempts to model directivity effects (predictable in principle from the size (moment) of the earthquake) and the influence of propagation over an irregular bathymetry. In the second one, a simple interpolation is performed among a large number of pre-computed subduction scenarios (Reymond *et al.*, 2012). In both instances, a correction based on Green's (1838) law is performed, using a receiver depth of 20 m, representative of Papeete harbor. While this correction is largely ad hoc, some justification is provided by the absence of a deeply indented coastline in Papeete, and by the power 1/4 of

Green's law, which considerably reduces the influence of the selected harbor depth on the forecast tsunami amplitude; we note that HAYASHI *et al*. (2011) have successfully tested this approach in the case of the 1896 Meiji Sanriku tsunami. Both algorithms suggested amplitudes of 40 cm (zero-to-peak) in Papeete harbor. These results, available around 21:05, suggested a significant tsunami, generally larger than in 2010, but again, falling short of the truly catastrophic events of 1946 and 1960.

4. By 21:45, and as in the case of the 2010 Maule event, the source characteristics had been evaluated. The parameter $\Theta = -5.65$ indicated no more than a trend towards slowness, and the high-frequency *P*-wave duration index $\tau_{1/3} = 77$ s, a source process relatively contained in time (OKAL, 2011). These values are generally compatible with source tomography studies indicating a bilateral rupture with high- and low-frequency energy released along patches of the fault plane separated by depth (e.g., KOPER *et al*., 2011).

   From the standpoint of tsunami excitation, we had by then obtained the important result that the source did not feature a hidden slow component, and that it was thus legitimate to use the available seismic moment (4×10^{29} dyn cm) for tsunami amplitude forecasting.

5. While the Faa'a airport was closed and evacuated along with the rest of the low-lying areas on Tahiti Island, this time the aircraft operating AF 674, which landed at 04:20, was kept on the ground at Faa'a during the alert, probably in view of the overly precautionary episode in 2010, and of the relatively contained values of the tsunami forecast. However, all airport fuel trucks were driven to high ground. The airport reopened at 10:00 and the return flight to Los Angeles, AF 673, left at 12:30, only four hours late, a remarkable achievement given the circumstances.

   Incidentally, this more restrained response in 2011 is reminiscent, on a much smaller scale, of the disruptions of airline operations during the volcanic crises in Iceland, also in 2010 and 2011. During the first one, and faced with a "new" form of emergency, authorities reacted with a fully cautionary approach, ordering the shutdown of the airspace over most of Europe and the North Atlantic. In 2011, under an admittedly different volcanic scenario, it was clear that the 2010 emergency had borne its lessons, and the response was more subdued, the airspace closures more focused, both in space and time, resulting in a more contained economic impact. Both stories clearly illustrate the simple idea that one learns a great deal from experience.

6. The first waves reached Papeete harbor at 07:18, with an amplitude of 18 cm (zero-to-peak) recorded on the harbor maregraph, this figure being only half that forecast. As shown on Fig. 3, the amplitude decreased during the next hour, suggesting the issuance of an all-clear signal. While the latter was being transmitted (at 08:32), the fourth wave reached the harbor, with a clearly rising amplitude which peaked at 39 cm at 08:44, when the alert was reinstated, until it was finally lifted at 09:30 (except in the Marquesas where it was prolonged three hours, to 13:07 local time) on account of the larger epicentral distance, and of the greater and more complex response of the unreefed bays. The pattern of the fourth wave carrying the largest amplitude of the initial group was repeated at all maregraphs in Polynesia, and thus cannot be attributed to site-specific resonances. The high tide, which came approximately 6 h later, occasionally resulted in the highest water level being reached as late as 13:00 local time, reaching 42 cm at Papeete.

   This episode was unfortunate, as the instructions given during an alert must be, first and foremost, clear and simple. It serves to illustrate the difficult trade-off between the legitimate desire of an obedient but displaced population eager to return to their homes and businesses, and our still imperfect understanding of the distribution of wave energy among the various packets. When combined with the possible delayed resonance of harbors under higher-frequency components of the tsunami traveling outside the shallow-water approximation (OKAL *et al*., 2006a, b; 2009), it emphasizes the need to instill in the populations at risk the simple concept that tsunami travel times, widely publicized during alerts, define only the arrival time of the *initial wave packet*, and that the

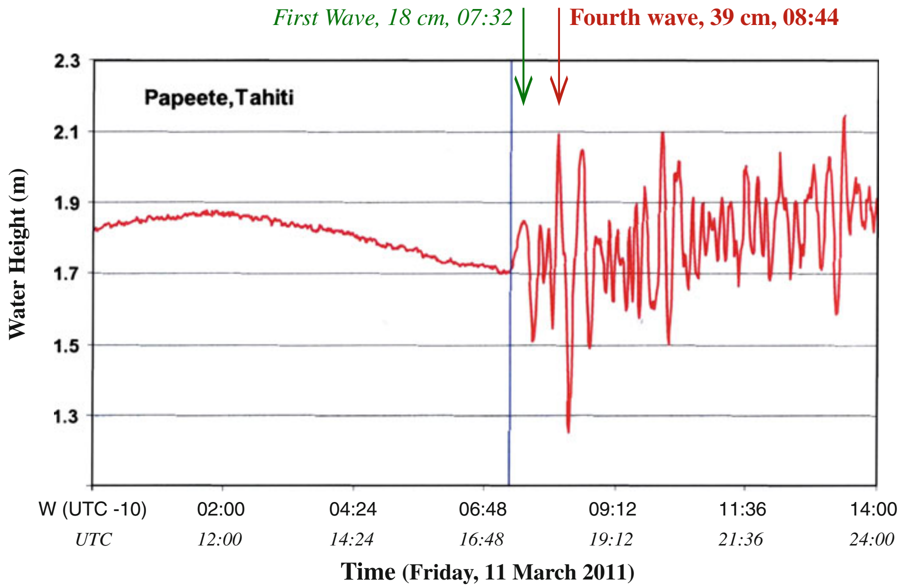


Figure 3

Maregram of the 2011 Tohoku tsunami recorded in Papeete harbor. The *blue line* (at 07:16 UTC − 10) is the theoretical arrival time. Note the contained first maximum, followed by two waves of smaller amplitude, and by a much stronger fourth wave cresting at 39 cm at 08:44, which motivated the last-minute reinstatement of the alert. The overall maximum occurs around 13:00, during the high tide

tsunami is in itself a prolonged phenomenon, whose duration still defies the understanding of the scientific community, even in the absence of delayed resonant effects.

7. In general, and expectably so given the larger size of the parent earthquake, the wave heights were higher than in 2010, and consequently, damage more substantial, with details given in the next sections. However, once again, the evacuation was successful and orderly, and no injuries were reported in the territory.

3. *Field Surveys*

3.1. Maule Tsunami, 2010

As the Maule tsunami produced substantial inundation only in the Marquesas Islands, the field survey was limited to that archipelago, located 1,300 km northeast of Tahiti (Fig. 1). A scientific party visited Hiva Oa and Ua Pou on 6–10 March 2010, while a second one performed a qualitative reconnaissance during an independently scheduled maintenance trip on Nuku Hiva. A follow-up trip to Nuku Hiva was conducted in November 2010 during which the sites identified in March were surveyed quantitatively.

The surveys used classical methods to measure the penetration of the waves (Synolakis and Okal, 2005). We recall that *Inundation* is defined as the maximum horizontal extent of penetration of the waves, *Flow Depth* as the thickness of the water column passing through a reference point (most often the shoreline), and *Run-up* as the altitude above sea level (corrected for tides) of the point of extreme penetration, where inundation is measured. A total of 48 points were obtained, with all data listed in Table 1, and presented on Fig. 4a–c.

We identified the penetration of the wave from a combination of physical evidence deposited by the tsunami, such as debris and sedimentary deposits, chemical evidence (as the wave's saltwater led to death and discoloration of vegetation), and testimony from witnesses present during the arrival of the tsunami. In addition to the geometrical parameters described above, we interviewed witnesses to collect data on the kinematics of the waves (number, relative size, temporal separation, polarity of the first wave). Measurements of run-up, flow depth and inundation were taken using conventional leveling instruments

Table 1

Surveyed dataset for the 2010 Maule tsunami

Number	Location		Date and time		Run-up		Inundation (m)	Remarks
	(°N)	(°E)	Year-month-day	GMT	Raw (m)	Corrected (m)		
Hiva Oa								
1	−9.80115	−139.03035	2010-03-07	02:20	3.23	3.54	181	Tahauku—end of bay
2	−9.80387	−139.03035	2010-03-07	02:40	2.86	3.24	45	Tahauku— wharf
3	−9.80618	−139.03140	2010-03-07	02:55	2.78	3.21	36	Tahauku— breakwater
4	−9.83570	−139.06225	2010-03-07	03:55	3.23	3.85	31	Taaoa
5	−9.71672	−139.01265	2010-03-07	17:15	1.52	2.19	19.5	Hanaiapa
6	−9.76445	−138.87723	2010-03-07	19:05	1.20	0.91		Puamau— wharf. Boat moved at 23:30 GMT
7	−9.76388	−138.88407	2010-03-07	19:15	<1.30	2.13		Puamau—along road
8	−9.73975	−138.92292	2010-03-07	19:50	1.80	2.62	12	Naohe—wall along meeting hall
9	−9.73965	−138.92218	2010-03-07	19:50	1.38	2.21		Naohe, across road at east end of village
10	−9.74012	−138.96027	2010-03-07	21:00	<1.30	2.02		Hanapaaoa—coprah stand
Ua Pou								
11	−9.43618	−140.04545	2010-03-08	21:05	1.98	2.79	15.6	Hohoi—south
12	−9.43382	−140.04578	2010-03-08	21:15	2.09	2.89	26.8	Hohoi—north
13	−9.45042	−140.08578	2010-03-08	23:00	<1.60	2.16		Hakatao—boat launch
14	−9.38522	−140.03653	2010-03-09	00:40	2.91	3.18	35	Hakamoui—far South on abutting berm
15	−9.38478	−140.03692	2010-03-09	00:50	2.44	2.69	41.8	Hakamoui—at trees on beach—2nd line only 34 m
16	−9.38452	−140.03702	2010-03-09	01:10	2.65	2.85	50	Hakamoui—max. inundation on flat beach
17	−9.38380	−140.03720	2010-03-09	01:20	2.90	3.09	79	Hakamoui—max. inundation on berm near estuary
18	−9.38287	−140.03750	2010-03-09	01:35	2.50	2.68		Hakamoui—at bungalows
19	−9.36118	−140.04628	2010-03-09	03:05	1.35	1.50		Hakahau—wharf in harbor
20	−9.34458	−140.08422	2010-03-09	17:55	2.55	2.98	16.8	Aneou—close to runway
21	−9.34490	−140.08512	2010-03-09	18:05	2.38	2.84	17.0	Aneou—western end of beach
22	−9.34545	−140.09232	2010-03-09	18:15	2.57	3.06	15.8	Baie des Requins
23	−9.41603	−140.11412	2010-03-09	19:30	1.45	2.16	6	Hakamaii—next to launch
24	−9.41608	−140.11530	2010-03-09	19:45	−2.50	−1.76	−20	Hakamaii—channel exposed at down-draw
25	−9.35920	−140.10397	2010-03-09	21:00	1.72	2.57	6	Hakahetau—berm near boat launch
26	−9.36138	−140.03975	2010-03-10	02:55	2.5	2.62	31	Anahoa—east end of bay
27	−9.36075	−140.04033	2010-03-10	03:05	3.68	3.79	39.9	Anahoa—west end of bay—abutting on mound
28	−9.35972	−140.04093	2010-03-10	03:15	2.40	2.52	17.7	Anahoa—cove at western end of bay
Nuku Hiva								
29	−8.877229	−140.053632	2010-11-22	23:40	2.55	3.26	30	Taipivai—hangar on beach
30	−8.875372	−140.051939	2010-11-22	23:54	1.55	2.31	26	Taipivai—beach parking and outrigger stand
31	−8.873435	−140.060822	2010-11-23	00:25	0.45	1.28	1050	Taipivai—bridge on river
32	−8.889334	−140.027917	2010-11-23	01:10	1.70	2.61	20	Hooumi—berm on beach (Flow depth)
33	−8.887655	−140.029523	2010-11-23	01:15	0.95	1.86	350	Hooumi—bridge on river
34	−8.942441	−140.161274	2010-11-23	19:00	2.05	2.22	11	Hakatea—eastern end of beach
35	−8.941867	−140.161692	2010-11-23	19:10	2.80	2.95	53	Hakatea—profile by house

Table 1 *continued*

Number	Location		Date and time		Run-up		Inundation (m)	Remarks
	(°N)	(°E)	Year-month-day	GMT	Raw (m)	Corrected (m)		
36	−8.942004	−140.161296	2010-11-23	19:10	2.60	2.75		Hakatea—watermark on house
37	−8.941600	−140.162113	2010-11-23	19:25	1.20	1.42	60	Hakatea—center of beach
38	−8.940964	−140.162734	2010-11-23	19:35	0.95	1.19	67	Hakatea—western end of beach
39	−8.941326	−140.162838	2010-03-11	22:30	1.20	2.10	0	Hakatea—watermark on tree at beach line
40	−8.941803	−140.168274	2010-11-23	20:00	2.90	2.95	17	Hakaui—Michel's house at western end of beach
41	−8.942452	−140.167808	2010-11-23	20:10	2.70	2.75	18	Hakaui—berm at western beach (Flow depth)
42	−8.940884	−140.168906	2010-11-23	20:15	1.10	1.16	168	Hakaui—bridge on river
43	−8.940333	−140.167771	2010-11-23	20:40	0.65	0.71	200	Hakaui—riv er bed at Ms. Fougerousse's house
44	−8.941117	−140.167323	2010-11-23	20:40	1.10	1.16	180	Hakaui—pig sty on side of river bed
45	−8.914499	−140.095670	2010-11-23	23:15	2.05	2.86	11	Taiohae east—fare at harbor
46	−8.911334	−140.104159	2010-11-23	23:35	1.65	2.41	157	Taiohae Center—river bed at Celine's shop
47	−8.917359	−140.108848	2010-11-23	23:45	2.75	3.49	31	Taiohae west—roundabout at end of road
48	−8.916671	−140.108979	2010-11-23	23:50	3.05	3.78	35	Taiohae west—on road along beach

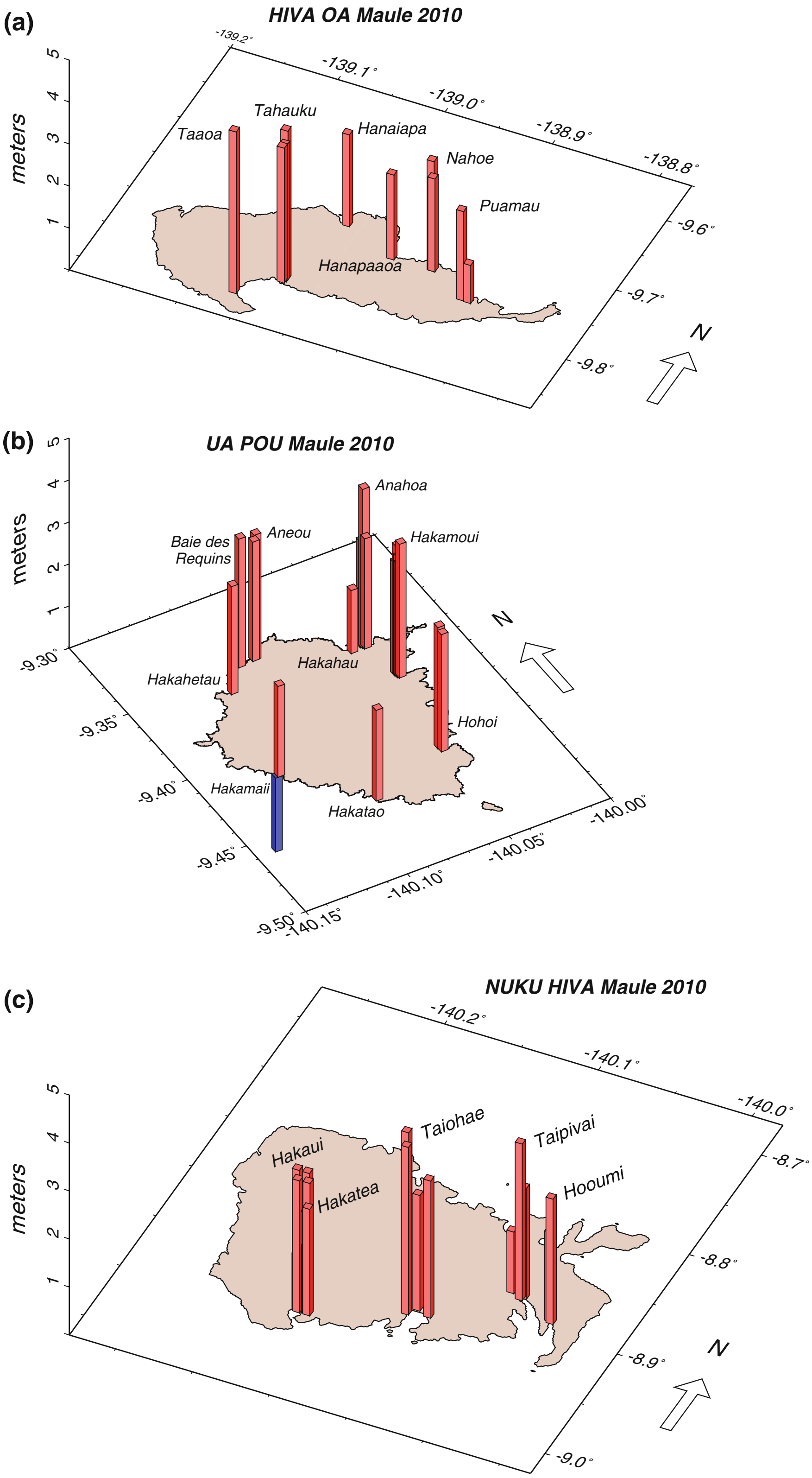
Figure 4 ▶

a Run-up values measured on Hiva Oa following the 2010 Maule tsunami. Note the large values on the southern shore at Taaoa and in Tahauku Bay. **b** Same as Fig. 4a for Ua Pou. The *blue bar* identifies the measurement of a down draw during the ebbing phase (Data point 24 in Table 1). **c** Same as **a** for Nuku Hiva

(survey rod and eye-visor level), complemented by laser ranging. Raw values of run-up were subjected to a tidal correction using the tidal heights computed for Taihoae, Nuku Hiva by the French Service Hydrographique et Océanographique de la Marine (http://www.shom.fr). The negative run-up and inundation values for Site 24 (Hakamaii, Ua Pou) correspond to the depth of a channel exposed during down-draw, which linked a small rocky islet to the shoreline, 20 m away.

Maximum run-up values reached nearly identical values (3.8 ± 0.05 m) on all three islands surveyed. While no substantial damage was reported, one boat was sunk in Tahauku harbor, Hiva Oa, its owner having refused to take it out of the harbor. The most important effects resulted from harbor responses, primarily in the form of eddies induced by strong currents (Fig. 5). In Tahauku, the latter resulted in structural damage being inflicted to the extremity of the jetty. Note that the development of strong eddies is not necessarily correlated with high values of inundation and run-up: in Hakahau (Fig. 5b), run-up reached only 1.5 m, the lowest value measured on the island of Ua Pou, but powerful eddies took place, including during the flooding phases. As a result, the harbor, which was undergoing a dredging project, was filled with mud, and had to be closed to large vessels.

The most interesting episode was narrated to us by the Mayor of Puamau, on the island of Hiva Oa (Fig. 6). This locality is built in a crescent-shaped bay approximately 1 km across, where run-up was contained to <2.13 m in the center of the village (the water was reported not reaching the road). On the day of the tsunami, the supply ship *Ara Nui 3* was visiting Puamau as part of its scheduled rotations to the islands. In the absence of a deep anchorage, the ship stays at anchor ~500 m offshore, and a launch is used to offload passengers and light cargo. The operation was delayed during the alert, but resumed after the all clear was given at 11:50 local time (21:20


(a)
HIVA OA Maule 2010
meters
Taaoa
Tahauku
Hanaiapa
Nahoe
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Hanapaaoa
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(b)
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meters
Anahoa
Baie des Requins
Aneou
Hakamoui
Hakahetau
Hakahau
Hohoi
Hakamaii
Hakatao
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(c)
NUKU HIVA Maule 2010
meters
Taiohae
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Hakaui
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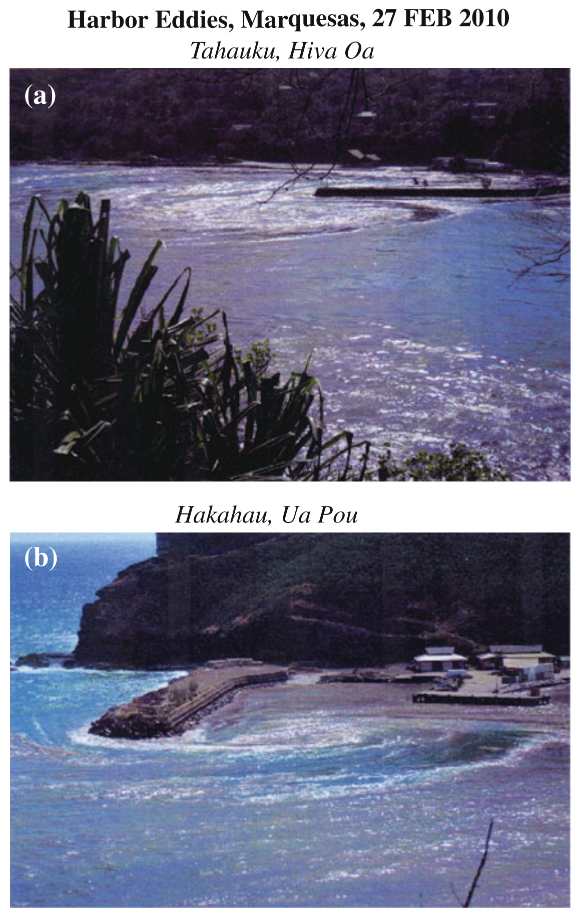

Figure 5
Examples of spectacular eddies during ebbing phases of the 2010 Maule tsunami in the Marquesas. **a** Tahauku Bay, Hiva Oa (Site 3 in Table 1). The extremity of the jetty was destroyed during the tsunami. Photograph courtesy of Eric Olivier. **b** Hakahau, Ua Pou (Site 19 in Table 1). Note the empty harbor basin during the downdraw. Photograph courtesy of Jacques Vitellini

UTC). At "around 14:00", i.e., a little more than 2 h later and 7 h after the arrival of the first waves, the launch was flung onto the wharf, at a height of ~ 1 m above sea level. Based on available bathymetry, it is found that Puamau Bay possesses a resonant mode at $T = 120$ s (Hébert and Allgeyer, personal communication, 2010). Using an average depth of 3,600 m along the path from Maule to Hiva Oa (as suggested by the arrival time of the non-dispersed low-frequency waves), we compute from classical full wave theory a dispersed group velocity of 112 m/s at $T = 120$ s, leading to a travel time of 18 h for a path of 7,250 km, suggesting an arrival time of 15:00 (UTC − 9:30), which is in acceptable agreement with the testimony of the witness, based on his non-scientific recollection, two weeks after the fact. This resonance of the bay is fully comparable to similar episodes described in the aftermath of the 2004 Sumatra earthquake in Le Port, Réunion, Toamasina, Madagascar and Dar-es-Salaam, Tanzania, and at Crescent City, California during the 2006 Kuril tsunami (Okal *et al.*, 2006a, b, 2009; Dengler *et al.*, 2009). It emphasizes once again the hazard presented by later arriving wavetrains, and the importance of maintaining alerts active well beyond time windows suggested by simple applications of the shallow water approximation.

3.2. Tohoku Tsunami, 2011

The three main islands of the Marquesas were similarly surveyed in the weeks following the 2011 tsunami. An effort was made to survey the same locales as in 2010, in order to allow for a meaningful comparison of the effects of the two tsunamis. In addition, surveying was carried out in the Windward Islands (Tahiti and Moorea) of the Society archipelago. A total of 71 points were surveyed and are listed in Table 2 and presented on Fig. 7a–e.

In general, the run-up heights in the Marquesas were comparable to 2010, being actually less on Hiva Oa (maximum 3.0 m), and Ua Pou (maximum 3.2 m). However, run-up reached significantly higher values than in 2010 in the bay of Taipivai, on the island of Nuku Hiva, where a maximum of 4.45 m was recorded. This extremely indented and flat bay repeatedly leads to extreme inundation, reaching 820 m in 2011, and as much as 1,250 m in 1946 (Okal *et al.*, 2002). Even though the bay was located in the lee of the arriving waves, it generated the largest amplitudes recorded in Polynesia, which were also larger than in 2010, when the bay directly faced the azimuth of the incoming tsunami. Severe damage was inflicted (by the third arriving wave) on a hangar used to dry coprah and to shelter outrigger canoes (Fig. 8), and seven houses were flooded, to a variable, but lesser, degree.

The 2011 tsunami featured significant amplitudes on the northern coast of Tahiti, where run-up reached 3.1 m on the Papenoo straightaway of the coastal ring road, ~ 0.5 m higher than in 2010. This additional

Puamau, Hiva Oa, 27 FEB 2011

Figure 6

Top Google Earth view of the bay of Puamau, Hiva Oa, which went into resonance 7 h after the arrival of the tsunami. The asterisk shows the estimated anchorage of *Ara Nui 3*. The launch was flung onto the wharf at the location of the arrow (Site 7 in Table 1). Also shown is Site 6 (Table 1) where the tsunami did not reach the road. *Bottom* File photograph from a previous rotation of *Ara Nui 3* documenting the process of transfer by launch (http://www.aranui.com)

amplitude was enough to bring debris and cause minor flooding but no damage, to the houses built on the mountain side of the roadway, at a distance of 15 m from the coastline, the first such occurrence since the great Chilean tsunami of 1960, which had reached an estimated 4 m at the same location (Talandier, personal communication, 1985).

4. Conclusion

Both the 2010 and 2011 tsunamis triggered red-level alerts, leading to full-scale evacuation of low-lying islands in all inhabited islands of French Polynesia. The documented, if clearly minor, damage wrought by the 2011 event, notably at Taipivai, Nuku

Table 2

Surveyed dataset for the 2011 Tohoku tsunami

Number	Location		Date and Time		Run-up		Inundation (m)	Remarks
	(°N)	(°E)	Year-month-day	GMT	Raw (m)	Corrected (m)		
Marquesas								
Hiva Oa								
1	−9.71767	−139.01312	2011-03-29	21:30	1.30	2.60	7.6	Hanaiapa
2	−9.74067	−138.95860	2011-03-29	23:10	1.65	2.70	8.0	Hanapaaoa
3	−9.74067	−138.95860	2011-03-29	23:10	1.55	2.60	7.2	Hanapaaoa
4	−9.74067	−138.93729	2011-03-29	23:35	2.00	3.00	13.2	Hanahi
5	−9.74112	−138.92873	2011-03-30	00:10	1.40	2.20	10.1	Motuua
6	−9.73968	−138.92213	2011-03-30	00:30	1.25	2.00	10.7	Nahoe
7	−9.76165	−138.88542	2011-03-30	03:10	2.00	2.40	16.0	Puamau
8	−9.76865	−139.14095	2011-03-30	19:15	1.70	2.60	68.3	Hanamenu—river valley
9	−9.76787	−139.14102	2011-03-30	19:20	1.00	1.90	21.0	Hanamenu—mouth of east river
10	−9.76753	−139.13908	2011-03-30	19:35	1.05	2.00	50.0	Hanamenu—east river
11	−9.80475	−139.03070	2011-03-30	23:40	1.60	2.70		Tahauku—wharf
12	−9.80625	−139.03148	2011-03-30	23:50	1.40	2.50	5.0	Tahauku—base of dyke
13	−9.80077	−139.02943	2011-03-31	00:25	1.80	2.80	90.0	Tahauku—toe of Bay
14	−9.80077	−139.03043	2011-03-31	02:55	1.80	2.40	51.9	Tahauku—Bay Canoe shack
15	−9.83575	−139.06226	2011-03-31	01:20	2.20	3.00	17.0	Taaoa
Ua Pou								
16	−9.36097	−140.04057	2011-04-01	02:45	1.90	2.49	28.7	Anahoa
17	−9.35975	−140.04103	2011-04-01	03:00	2.10	2.64	12.0	Anahoa
18	−9.35975	−140.04103	2011-04-01	03:10	2.10	2.61	12.0	Anahoa
19	−9.43317	−140.04572	2011-04-01	17:30	2.65	2.99	19.3	Hohoi
20	−9.43438	−140.04585	2011-04-01	17:45	2.00	2.36	21.5	Hohoi
21	−9.43442	−140.04584	2011-04-01	17:55	2.60	2.97	11.5	Hohoi
22	−9.43643	−140.04553	2011-04-01	18:10	1.75	2.15	12.9	Hohoi—south
23	−9.45130	−140.08563	2011-04-01	19:20	1.90	2.53	9.1	Hakatao
24	−9.38463	−140.04073	2011-04-01	20:45	1.00	1.99	40.0	Hakamoui
25	−9.38522	−140.03705	2011-04-01	21:05	1.50	2.57	34.0	Hakamoui—south
26	−9.38247	−140.03809	2011-04-01	21:45	1.30	1.78	54.0	Hakamoui—north
27	−9.34497	−140.08521	2011-04-01	22:45	1.90	2.60	10.0	Aneou
28	−9.34492	−140.09264	2011-04-01	23:15	1.90	2.71	14.5	Baie des Requins
29	−9.35968	−140.10687	2011-04-02	01:40	1.60	2.89	7.0	Hakaetau
30	−9.35935	−140.10387	2011-04-02	01:55	1.40	2.71		Hakaetau—wharf
31	−9.35960	−140.04964	2011-04-02	02:40	1.80	3.12		Hakahau—river mouth
32	−9.35782	−140.04637	2011-04-02	02:48	1.90	3.22		Hakahau—wharf
Nuku Hiva								
33	−8.81433	−140.13077	2011-03-26	02:06	2.25	2.65	28.0	Aakapa
34	−8.82953	−140.08447	2011-03-26	01:05	3.15	3.53	48.0	Hatiheu

Table 2 *continued*

Number	Location		Date and Time		Run-up		Inundation (m)	Remarks
	(°N)	(°E)	Year-month-day	GMT	Raw (m)	Corrected (m)		
35	−8.82935	−140.08447	2011-03-26	01:22	2.40	2.77	78.0	Hatiheu
36	−8.82443	−140.06723	2011-03-25	22:03	2.35	3.26	33.0	Anaho
37	−8.82293	−140.06789	2011-03-25	21:55	1.55	2.46	70.0	Anaho
38	−8.82055	−140.06863	2011-03-25	21:26	1.45	2.45	182.0	Anaho
39	−8.82010	−140.06702	2011-03-25	21:35	2.15	3.13	16.0	Anaho
40	−8.91528	−140.10887	2011-03-26	17:55	1.65	2.56	15.0	Taiohae
41	−8.91690	−140.10873	2011-03-26	17:48	1.80	2.68	21.0	Taiohae
42	−8.94193	−140.16946	2011-03-24	20:10	2.10	3.16	44.0	Hakaui
43	−8.94270	−140.16748	2011-03-24	20:25	2.70	3.71		Hakaui
44	−8.94230	−140.16121	2011-03-24	18:45	2.25	3.51	22.0	Hakatea
45	−8.94162	−140.16121	2011-03-24	18:55	1.95	3.20	70.0	Hakatea
46	−8.94108	−140.16193	2011-03-24	19:08	1.70	2.93	73.0	Hakatea
47	−8.94092	−140.16255	2011-03-24	19:35	2.25	3.42	73.0	Hakatea
48	−8.88940	−140.02823	2011-03-24	01:28	2.00	2.58	17.0	Hooumi
49	−8.88865	−140.02673	2011-03-24	01:40	1.90	2.53	20.0	Hooumi
50	−8.87327	−140.05405	2011-03-24	02:00	2.70	3.43	330.0	Taipivai
51	−8.87358	−140.05653	2011-03-24	02:23	2.40	3.24	600.0	Taipivai
52	−8.87322	−140.05862	2011-03-24	02:43	3.25	4.18	820.0	Taipivai
53	−8.87722	−140.05405	2011-03-24	00:00	4.15	4.45	60.0	Taipivai
54	−8.87562	−140.05287	2011-03-24	00:30	3.94	4.31	47.0	Taipivai
55	−8.87600	−140.05534	2011-03-24	01:00	3.70	4.17	260.0	Taipivai
Society (Windward)								
Tahiti								
56	−17.52405	−149.52049	2011-03-18	01:00	0.55	0.99	13.0	Arue—Vaipoopoo
57	−17.52405	−149.51857	2011-03-18	01:10	1.00	1.43	7.0	Arue—town hall
58	−17.49533	−149.49567	2011-03-15	21:30	0.80	1.35	22.0	Pointe Venus
59	−17.49990	−149.48000	2011-03-15	17:50	0.50	0.93	16.0	Mahina—Motu Martin
60	−17.50083	−149.47929	2011-03-15	17:50	1.30	1.73	6.0	Mahina—communication center
61	−17.50687	−149.46793	2011-03-15	18:20	1.80	2.25	8.0	Mahina—Ahonu
62	−17.50758	−149.46516	2011-03-15	18:30	1.80	2.26	11.2	Mahina—Ahonu Beach
63	−17.50832	−149.43900	2011-03-12	03:00	2.60	3.07	15.0	Papenoo—road straightaway
64	−17.50872	−149.42998	2011-03-15	19:00	1.85	2.32	10.0	Papenoo—Bay
65	−17.51172	−149.41980	2011-03-15	19:30	1.30	1.80	23.0	Papenoo—river mouth
66	−17.56302	−149.32513	2011-03-15	19:55	1.10	1.62	22.0	Mahaena—river mouth
Moorea								
67	−17.50368	−149.81845	2011-03-21	20:30	0.55	1.06		Baie Cook
68	−17.50618	−149.81927	2011-03-21	20:45	0.58	1.11		Baie Cook—Wharf
69	−17.48660	−149.82739	2011-03-21	21:40	−0.90	−0.31		North Coast Down-draw in Lagoon
70	−17.51197	−149.84962	2011-03-21	22:55	0.40	1.04		Opunohu
71	−17.51645	−149.84966	2011-03-21	23:00	1.10	1.74		Opunohu—toe of Bay

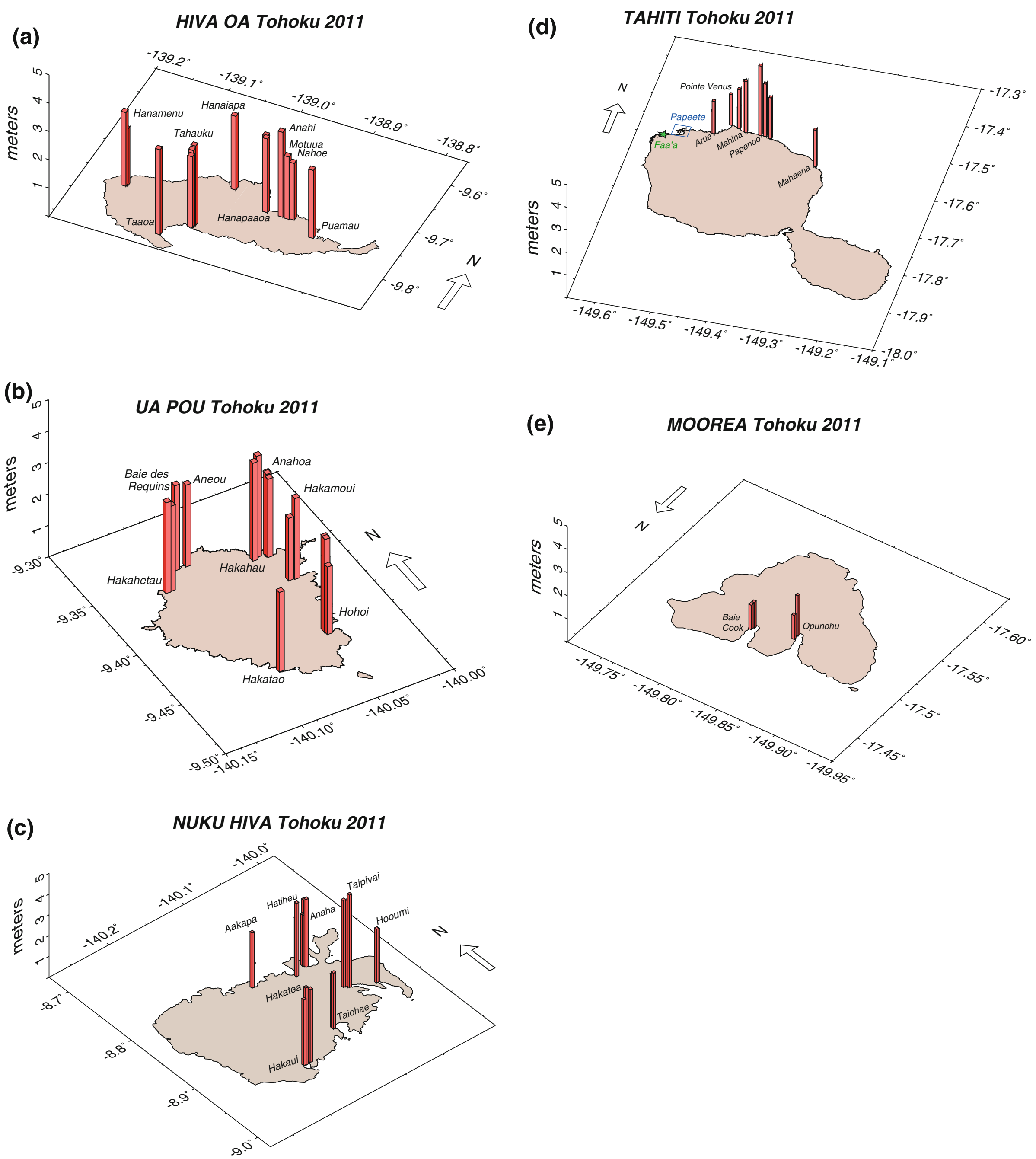

Figure 7

a Same as Fig. 4a for the 2011 Tohoku tsunami. **b** Same as Fig. 7a for the island of Ua Pou. **c** Same as Fig. 7a for the island of Nuku Hiva. Note the large values at Taipivai. **d** Same as Fig. 7a for the island of Tahiti. The *square* locates Papeete harbor (where the maregram shown on Fig. 3 was recorded), and the *star* the international airport at Faa'a. **e** Same as Fig. 7d for the island of Moorea

Hiva, serves to emphasize the very serious hazard posed by far-field tsunamis in French Polynesia. Yet, it is a sobering thought that no personal injury or death was reported in the territory. Indeed, this trend was repeated uniformly throughout the Pacific basin, with, to our best knowledge, only two deaths reported

Tsunami Onslaught, 11 MAR 2011

Bay of Taipivai, Nuku Hiva

Figure 8
Destruction of a beach hangar on the shoreline of the Bay of Taipivai (Site 29 in Table 1 and 53 in Table 2). *Top* The second wave attacks the front of the structure. *Bottom* The third wave destroys the ocean-side façade. From video, courtesy of M. Vohi

in the far field (one in Crescent City and one in Jayapura, Indonesia, both of them avoidable in the sense that they took place inside the zone designated for evacuation).

For this reason, the tsunami alerts of 2010 and 2011 in Polynesia, can be regarded as clear successes. Over and beyond the general accuracy of the forecasts, both in terms of timings and amplitudes, such success is due primarily to the efficiency of the evacuation plans drawn and implemented by the Civil Defense authorities. But there could be no success if the population was not well-prepared to evacuate responsibly, which stresses once again the value of education in tsunami mitigation. In this respect, it is remarkable that in the past three years, three tsunami alerts have taken place in French Polynesia (Samoa, 29 September 2009; Chile, 27 February 2011, and Japan, 11 March 2011), with the size of the earthquake, and consequently the amplitude of the observable effects, increasing each time; it is certain that this rapid sequence played the useful role of maintaining the population's awareness for tsunami hazard, as well as allowed to fine-tune operational and logistical aspects of the evacuation procedures. In addition, and most remarkably, a tsunami drill had taken place a few days before the 2011 tsunami in several townships of the island of Tahiti, with the population having an exceptionally fresh memory of "what to do" and "where to go". Finally, in both instances, the timing of the evacuation (in the early morning hours, about the time when many residents get up) certainly contributed to its success.

Despite this generally satisfactory situation, the 2010 and 2011 tsunamis clearly raise the need for a better control of the duration of evacuation before an all clear can be sounded, and life return to normalcy. While the episode at Puamau in 2010 could conceivably be forecast based on systematic modeling of the resonance of bays and harbors, the premature all-clear in 2011 points out to a present lack of firm understanding of the parameters controlling the repartition of energy among the individual waves, even in the absence of non-linear phenomena attributable to the response of individual sites. Before theoretical progress is achieved in this respect, a precautionary approach suggests a minimum waiting time of at least two hours after arrival of the first waves before lifting an alert, even if this may seem excessive to the lay population.

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