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THE TSUNAMI OF MARCH 11, 2011 AS OBSERVED BY THE NETWORK OF TIDE GAUGES OF FRENCH POLYNESIA

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Key words: tsunami, Tōhoku earthquake, tide gauges, French Polynesia.

ABSTRACT

We present here the network of tide gauges spanning French Polynesia, and the set of records made by this network of the tsunami wave of March 11, 2011 (Tōhoku earthquake). We also outline the least-squares procedure used to separate the tsunami signal from the oceanic tides signal.

I. THE TOHOKU EARTHQUAKE AND TSUNAMI OF MARCH 11, 2011

The magnitude 9.0 (Mw) undersea megathrust "Tōhoku earthquake" that occurred off the coast of Japan at 14:46 Japan Standard Time (05:46 UTC) on Friday, 11 March 2011 was the most powerful known earthquake ever to have hit Japan, and one of the five most powerful earthquakes in the world overall since modern record-keeping began in 1900. Its epicenter was located approximately 70 kilometres east of the Oshika Peninsula of Tōhoku (Tōhoku Chiho Taiheiyo-oki, 38.322°N, 142.369°E) and the hypocenter at an underwater depth of approximately 32 km. The earthquake triggered powerful tsunami waves [11], which reached heights of up to 40.5 m in Miyako in Tōhoku's Iwate Prefecture, and which in the Sendai area travelled up to 10 km inland. Inundation affected 561 km^2 of land and caused 25 million tons of rubble and debris in Japan. In addition to loss of life and destruction of infrastructure (15,696 deaths in 18 prefectures, 5,715 injured, 4,666 missing, 190,000 buildings damaged and 45,700 destroyed, $309 bn in damages), the tsunami caused level 7 meltdowns at three reactors in the Fukushima I nuclear power plant ($7.4 bn in damages and losses), and the associated evacuation zones affecting hundreds of thousands of residents (115,433 residents were still living at evacuation shelters in August 2011 [8]).

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II. FRENCH POLYNESIA: AN OVERSEAS TERRITORY OF FRANCE

Spread over an area between 134 W – 155 W longitude and 7 S – 28 S latitude, French Polynesia better known as Tahiti and her islands, covers a vast (5,500,000 km^2) and remote (7,000 km from Los Angeles, 4,000 km from Australia) oceanic region located in the middle of the South Pacific Ocean (see Figs. 1 and 2). This French overseas collectivity, with a large political autonomy, is made up of 121 islands or islets, high volcanic islands (35) and low coral islands or atolls (86) which together represent a surface area of 3,668 km^2 of emerged land (half of Corsica) and 12,800 km^2 of lagoons.

These islands, lying on the Pacific lithospheric intraplate form five archipelagoes dispersed along a general North-West, South-East axis [6]:

- The Society Archipelago (1,590 km^2) composed of 14 islands (9 high volcanic islands and 5 atolls) divided into two groups: the Windward Islands with the principal island of Tahiti (itself a double island: Tahiti-Nui and Tahiti-Iti), and the Leeward Islands (including the very well known Bora-Bora Island);
- The Tuamotu Archipelago including 79 atolls spread over an area of 850 km^2 (three main atolls: Rangiroa, Hao and Makemo);
- The Gambier Archipelago (31 km^2), a half-drowned volcano, made up of 9 volcanic islets (main islet: Mangareva), remnants of the caldera, surrounded to the North and the East by a barrier reef;
- The Marquesas Archipelago (1,049 km^2) separated into the North Marquesas, (main island Nuku Hiva) and some coral banks, and the South Marquesas (main island Hiva Oa), including several shoals;

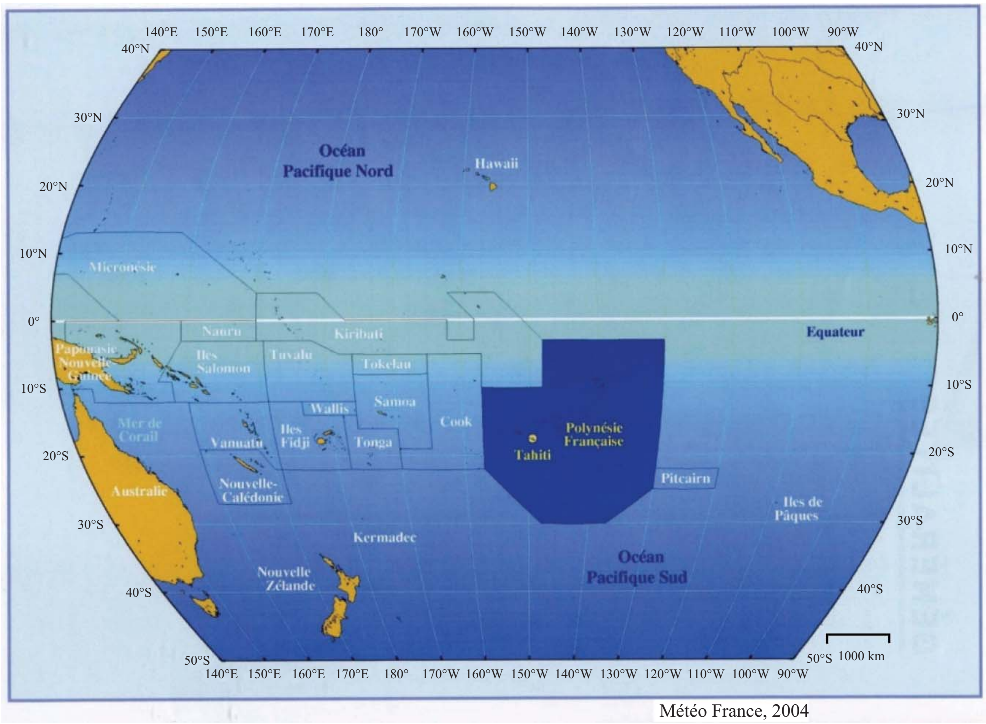

Fig. 1. The geographical zone of French Polynesia (source Météo-France).

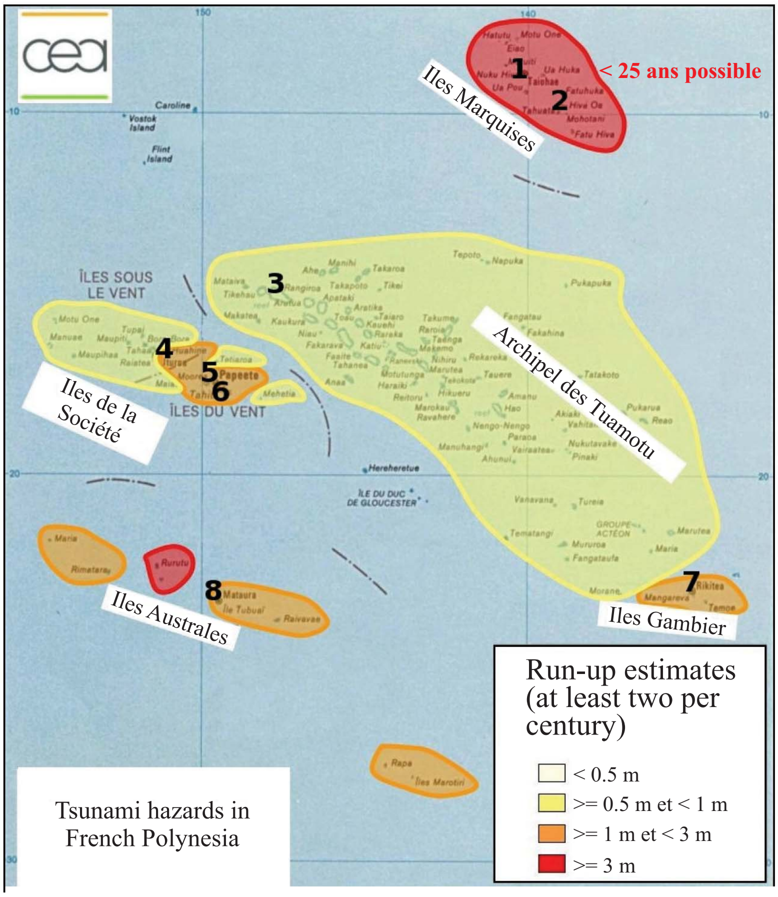

Fig. 2. The tsunami risk zones in French Polynesia (source: "Commissariat à l'Energie Atomique").

Table 1. The Tide Gauges Network of French Polynesia (March 2011).

Number	Station name	Starting date	Coordinates	Sensors	Management	Sampling	Identification	
							GLOSS	PSMSL
1	NUKU HIVA	1982 upgraded 2007 and 2009	08° 54,9'S 140° 05,76'W	radar, pressure, GPS	U. of Hawaï Sea Level Center	1 min	142	1555
2	HIVA OA	Jan. 2003	09° 48,3'S 139° 02,04'W	pressure	LDG-CEA	1 min		1466
3	RANGIROA	Feb. 2009	14°56,75'S 147° 42,36'W	radar, pressure, GPS	UPF	2 min		
4	HUAHINE	May. 2010	16° 43,3'S 151° 01,92'W	pressure	UPF	2 min		
5	PAPEETE	1975	17° 32,0'S 149° 34,38'W	radar, pressure, GPS	U. of Hawaii Sea Level Center	1 min	140	1397
6	VAIRAO	Feb. 2011	17° 48,35'S 149° 17,7'W	radar, pressure, GPS	UPF	2 min		
7	RIKITEA	1969	23° 07,33'S 134° 58,02'W	radar, pressure	U. of Hawaï Sea Level Center	1 min	138	1253
8	TUBUAI	Dec. 2008	23° 20,51'S 149° 28,5'W	radar, pressure, GPS	UPF	2 min		

- The Austral Archipelago covering an area of 148 km^2 and including 6 high volcanic islands (principal island: Tubuai), one atoll and one quasi-island (Neilson reef).

III. THE NETWORK OF TIDE GAUGES OF FRENCH POLYNESIA

The network of tide gauges of French Polynesia was initiated by the University of Hawaii Sea Level Center and the Pacific Tsunami Warning Center, who built the tide gauges of the main harbor of Papeete (Tahiti, 1969) and Rikitea (King's fish pool of Mangareva, Gambier Islands, 1969) and Nuku Hiva (Marquesas archipelago, 1987, now with a permanent GPS receiver). Later the Laboratory of Geophysics of Pamatai (LDG) added a third tide gauge in Atuona (Island of Hiva Oa, Marquesas archipelago) in 2003. In 2006-2011, thanks to three consecutive grants from the "Contrat Etat-Pays" and "Fonds Pacifique" and additional funding from the hydrographic service of the French Navy (SHOM), three tide gauges (radar acquisition with collocated GPS permanent stations, hosted in secured concrete booths) were added by the Geodesy Observatory of Tahiti (OGT) in the islands of Tubuai, Rangiroa and in Tahiti-Iti (Vairao village). Two other similar tide gauges (secured housing) are under construction in Mangareva (Quai du Commerce) and in the Makemo atoll. Another tide gauge (pressure gauge w/o GPS) is operating in the Huahine Island, and a similar one will be in service in the Moorea Island (Cook's bay) by the end of 2012. All together, eight tide gauges are currently in service in French Polynesia (see Table 1), and eleven will operate by the end of 2012. A complete description of the current network can be found in [3, 4].

IV. THE TSUNAMI EVENT IN FRENCH POLYNESIA

All the eight tide gauges in service in March 11, 2011 recorded one-minute averaged sea levels during the tsunami event that reached French Polynesia 11h17mn (tides gauge of Huahine) after the main earthquake shock in Tōhoku (05h46 UTC). Run-ups up to 3 m were observed in Tahiti (Papenoo bay), but were less than one meter in average. In the Marquesas archipelago, classified as a high risk area (Fig. 2, submarine plateau), run-ups up to 4.5 m were observed in Nuku Hiva, (in Taipivai bay) with an average of 2.5 m. The Hiva Oa harbor was emptied and medium scale (100 m) vortices were observed near the coasts. Noticeable waves were observed by the population for about 2 hours, but the instruments recorded measurable signals for up to 48 hours. No casualties occurred during this tsunami event, thanks to the early warning system (sirens) maintained by the French Government and local authorities, and that was triggered at least 3 hours before the forecasted tsunami arrival time by the authorities from the information given by the LDG. In fact, an early seismic warning was triggered 13 minutes after the origin time of the main shock in Tahiti at the LDG that is equipped with its own seismic warning system.

In addition, the tsunami warning messages sent by the Pacific Tsunami Warning Center in Hawaii [5], are also received by both agents on duty at the LDG and in Civil Defense headquarters (the tsunami warning system is thus threefold for security reasons).

V. FILTERED TSUNAMI RECORDS

Separating the tsunami wave height from the lunisolar tide

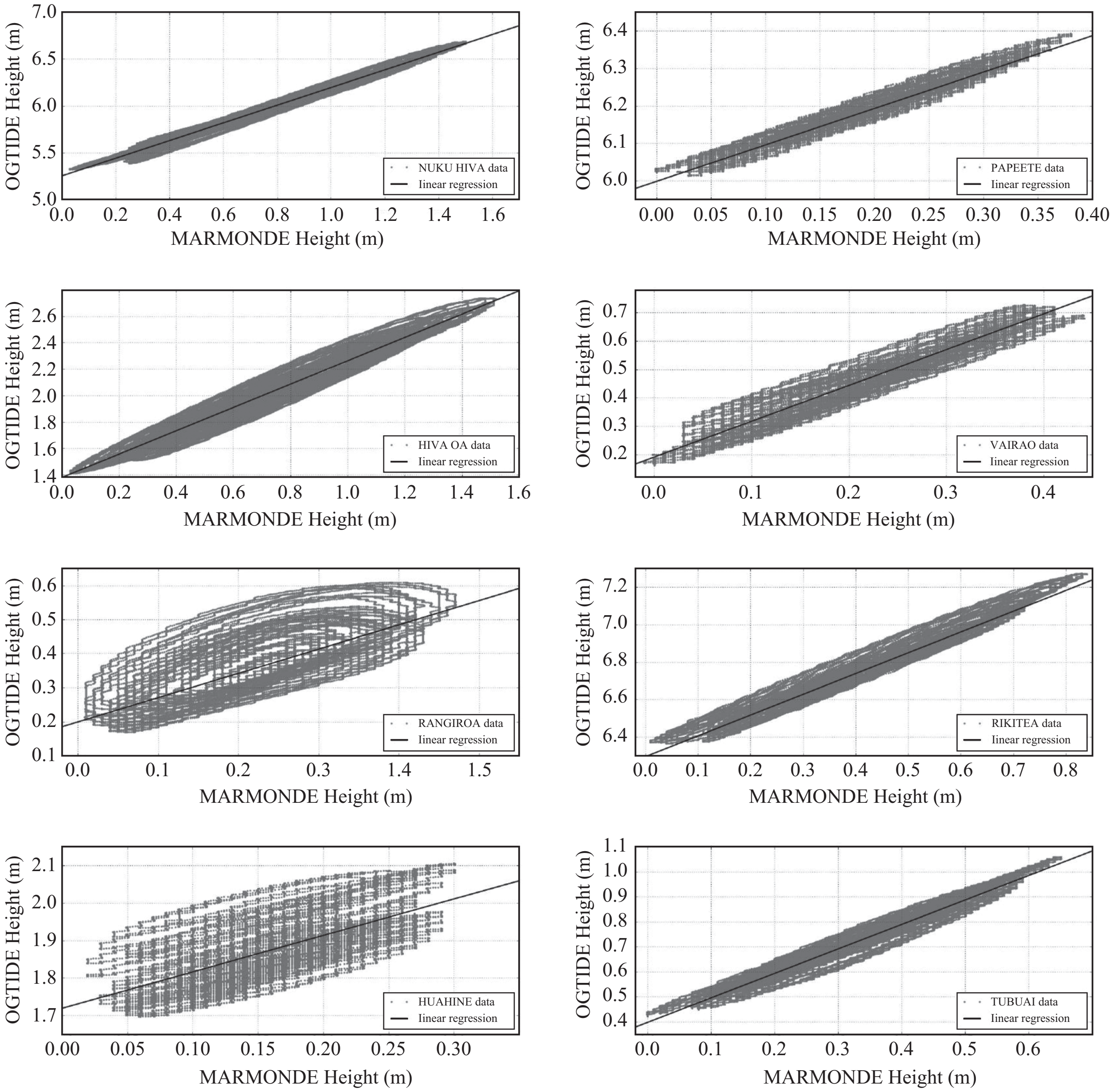

Fig. 3. Least-squares analysis of the tides computed by MARMONDE model (SHOM) with respect to the M4, MS4, S4, M6, M2, S2, N2, K2, O1, K1, P1, Q1, MF and MM harmonic constituents of the oceanic tides (see text). Notice the large phase delays for the tide gauges of Huahine and Rangiroa, and, to a lesser extent, Vairao.

height is straightforward if we have at our disposal a good tide model. This is the case for long-time chartered tide gauges, like the ones in the coasts of Europe or America. In French Polynesia, we used the MARMONDE model, a commercial software under SHOM license [7], which is considered as one of the best available models in the French speaking countries. Tahiti is close to an amphidromic point, therefore the tides are small and mainly semi-diurnal [1]. In order to assess the accuracy of the MARMONDE model in our area, we performed a least-squares harmonic fit of its prediction by our in-house tide model (OGTIDE) for the months of January and February 2011 for the eight tide gauges that observed the tsunami signals, with respect to the M4 (06h13mn), MS4 (06h06mn), S4 (06h00mn), M6 (04h08mn), M2 (12h25mn), S2 (12h00mn), N2 (12h40mn), K2 (11h58mn), O1 (01d01h49mn), K1 (23h56mn), P1 (01d00h04mn), Q1 (01d02h52mn), MF (13d15h50mn) and MM (27d13h12mn) harmonic components that are usually taken into account for short term predictions. Fig. 3 and Table 2 summarize the results. Clearly the tides are well modeled for the tide gauges already established for a long time (Hiva Oa, Nuku Hiva, Papeete and Rikitea), but there are discrepancies for the recently established ones (Huahine, Rangiroa and Vairao), with the notable exception of the Tubuai tide gauge. Phase delays

Table 2. Linear fits between the MARMONDE estimates X and the OGTIDE estimates Y (see Fig. 3).

Tide Gauges	R^2	Linear fit
NUKU HIVA	0.99	Y = 0.9425 X + 5.2527
HIVA OA	0.96	Y = 0.8839 X + 1.3794
RANGIROA	0.58	Y = 0.7123 X + 0.1993
HUAHINE	0.49	Y = 0.9727 X + 1.7189
PAPEETE	0.94	Y = 0.9708 X + 5.9988
VAIRAO	0.91	Y = 1.2598 X + 0.1917
RIKITEA	0.96	Y = 1.1084 X + 6.2953
TUBUAI	0.96	Y = 0.9793 X + 0.3975

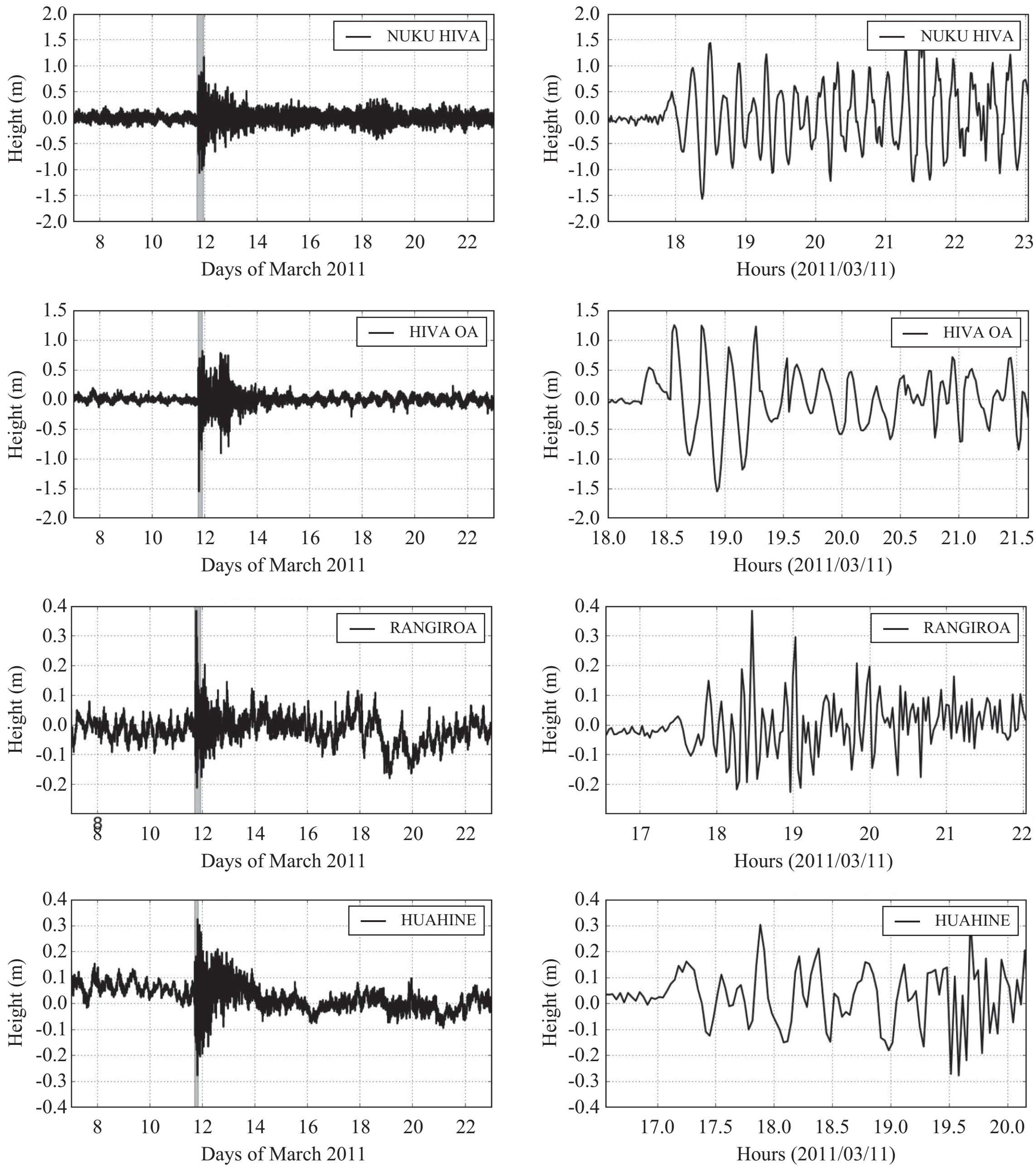

Fig. 4-a. Filtered tsunami signals (left) for the March 11, 2011 tsunami event for the tide gauges of Nuku Hiva, Hiva Oa, Rangiroa and Huahine. Enlargments of the greyed areas are shown in the right figures (a few hours window after the arrival of the first wave).

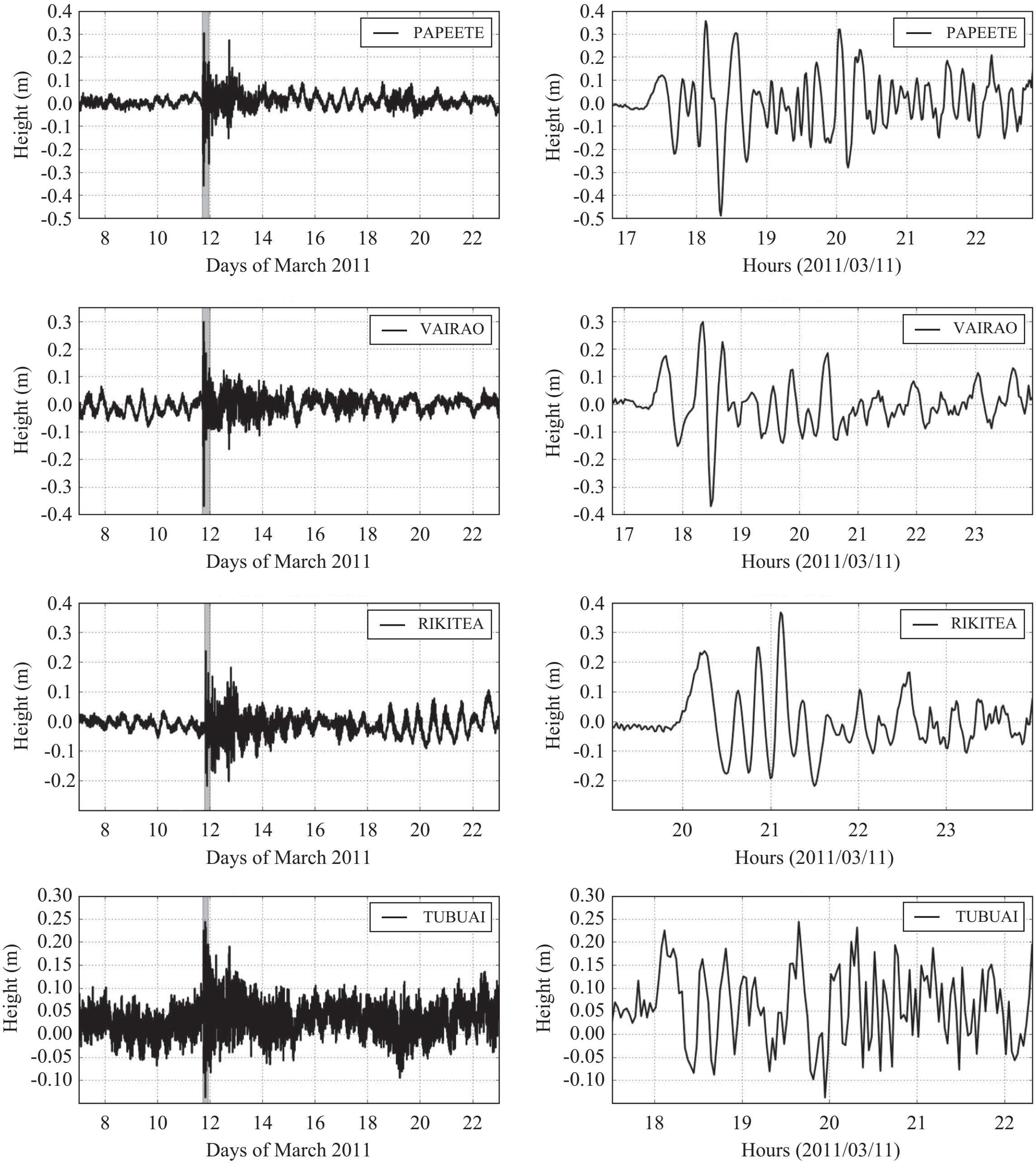

Fig. 4-b. Filtered tsunami signals (left) for the March 11, 2011 tsunami event for the tide gauges of Papeete, Vairao, Rikitea and Tubuai. Enlargments of the greyed areas are shown in the right figures (a few hours window after the arrival of the first wave).

show up as elliptic motions for these three stations when we compare the OGTIDES estimates with the MARMONDE estimates (Fig. 3). This may be due to the fact that the Huahine, Rangiroa and Vairao stations are installed in a wide lagoon well protected by an efficient fringing reef barrier, with a narrow path. Thus, the response of the lagoon, probably integrated in the MARMONDE model, has probably an important effect on phase delay between the theoretical tide and the observed one inside the lagoon. The islands of Rikitea and Tubuai are also surrounded by a wide lagoon, but the fundamental difference is that the coral reef barrier is not fringing, but submerged: consequently the lagoon is able to empty easily and rapidly without delay on the tide of the sea.

The biases between the MARMONDE zeros and the OGTIDE zeros are summarized in Table 2. As we lacked sufficient information about the exact flow of computations and local adjustments performed by the MARMONDE model (access to the source code is restricted), we therefore choose to use our in-house least-squares tide analysis program (OGTIDE) to perform the filtering of the observed tsunami signals, with the same harmonic frequencies as above. A window of 3 months (February to April) was chosen, with the exclusion of a 48 hours period centered around the tsunami event. The obtained tsunami filtered signals are shown in Figs. 4a and 4b. Significant low frequency fluctuations with a half-period of ~15 days, close to the MM period, still show up at the Huahine, Rikitea and Tubuai tide gauges. We think that these fluctuations are linked to the trade winds or other meteorological processes and clearly need further investigations, but fortunately these remaining low frequency signals are outside the tsunami frequency band. All the signals show a leading peak, albeit these peaks are sometimes difficult to identify on the time series. It has been shown that the number and height of the tsunami waves hitting the shoreline depends critically on the shape of the initial surface wave in deep water [2].

Without surprise, the highest amplitudes are observed on the stations of Marquesas islands, with a maximum of 1.5 m and 1.3 m in Nuku Hiva and Hiva Oa respectively. For the other islands, the amplitudes are in the 0.2-0.4 m range. Notice the important fact that the amplitudes measured with the instruments, does not represent the run-up measured in the sites of the same islands: for example in Tahiti, the maximum read on the tsunami record in Papeete harbour is only 0.45 m, while the maximum run-up on the North shore in Papenoo (that is not protected by coral barrier) is 3.0 m, showing an amplification factor greater than 6 comparatively to the Papeete harbour. In the same way 1.5 m was the maximum amplitude measured (0 to crest) in Nuku Hiva tide gauge, while the maximum run-up measured in another bay on the South Est coast of Nuku Hiva, in Taipivai bay, was more than 4.5 m (thus a 3 factor). Hence the tsunami amplitudes measured by the tide gauges reflect only the concerned site response, but not the distribution of amplitudes of a whole island; the conclusion is that such disparities incited to be doubly careful regarding the tsunami hazard, specially about the levels of evacuation of the population for a given island. Table 3 summarizes the principal characteristics of the first three observed tsunami waves for each of the eight tide gauges.

VI. CONCLUSIONS

A sufficiently dense network of tide gauges stations is a key for the protection of the populations in a huge oceanic region like French Polynesia. The aim of this network is not to provide an early warning (this is the domain of teleseismic detection and DART buoys [3]), but to constrain by high quality data the predicted run-ups for a large set of disaster scenarii. Clearly, displacing too often a large number of people for an observed 30 cm tsunami could lead to thousands of drowned people in a future mega-event. The coordinated network of tide gauges in French Polynesia is still in its infancy, and long time series have to be acquired to obtain accurate tide models. This network will also permit to monitor local mean sea level changes due to the global warming for at least the fifty years to come. We plan in the near future to assimilate our tide gauges data in tsunami models like the MOST model of NOAA [10] to help constrain far field tsunami patterns in our area and to obtain better forecasts of run-ups [9], and to perform spectral analysis of the tsunami signals.

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