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A CATALOG OF TSUNAMIS IN LA RÉUNION ISLAND FROM AUGUST 27TH, 1883 TO OCTOBER 26TH, 2010*

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ABSTRACT

The PREPARTOI project ("Prevention and research for the mitigation of the tsunami risk in the French territories of the Indian Ocean", the French acronym equivalent to « get-ready »), began in early 2010. The first stage of this integrated tsunami risk assessment project consisted in evaluating the tsunami hazard on La Réunion Island by collecting and synthesizing all available data about past tsunamis and their effects. This first step was implemented through archive and field research during 2010. Seven tsunami occurrences were identified as having impacted La Réunion Island between 1883 (explosion of the Krakatau volcano) and October 2010 (end of the field research). All these events had sources along the Indonesian margin and were triggered by earthquakes of magnitude higher or equal to Mw=7.7, affecting the island with maximal runups reaching 7m. These tsunamis mostly affected the harbors damaging many boats, especially in 2004. Although historically the tsunami hazard is quite moderate on the island's coasts, the high concentration of people along the shore and in low elevation areas, highlights considerable stakes and high vulnerability resulting in significant risk, especially in Saint-Paul, a city which was completely flooded in 1883.

Keywords: tsunamis; teletsunamis; Indian Ocean; La Réunion; catalog

1. INTRODUCTION

La Réunion Island, a French territory in the Indian Ocean, is a partly active volcanic island in the Mascarene archipelago, located northeast of Madagascar. Although the island is located in a tsunami hazardous basin, the scientific community never compiled a historical catalogue of the tsunami hazard. Only the December 26th, 2004 and the October 25th, 2010 tsunamis were investigated by field surveys (Okal et al. 2006; Sahal and Morin accepted).

In 2010, the "PREPARTOI" research program ("Prevention and research for the mitigation of the tsunami risk in the French territories of the Indian Ocean", French acronym equivalent to "get-ready", www.prepartoi.fr) began assessing the tsunami risk on the island, in response to an institutional demand for better preparedness for future tsunamis. PREPARTOI program initiated field and archive investigations to study the historical tsunami hazard of La Réunion Island. This paper presents and discusses the methods and results of this investigation.

2. METHODS

The methodology to compile this catalog is comparable to the one used recently in New Caledonia (Sahal et al. 2010). It consists in establishing a list of tsunamis that impacted territories in the Indian Ocean, as well as potentially tsunamigenic earthquakes (events of high magnitude), using on-line databases (Dunbar 2010) and previously published regional catalogs (Rastogi and Jaiswal 2006), with a critical point of view. Local earthquakes were also considered. Newspapers and administrative archives were consulted (Table 1), searching for sea level disturbance records for the selected dates (and following days).

For the more recent events, witnesses were also sought out on-site to specify and/or complete recorded observations. Through several field trips, the authors were able to calculate runup values on-site or deduce them from old maps. The physical effects were measured using the zero level of the marine charts as a reference (lowest tides).

Table 1. Consulted newspapers and archives

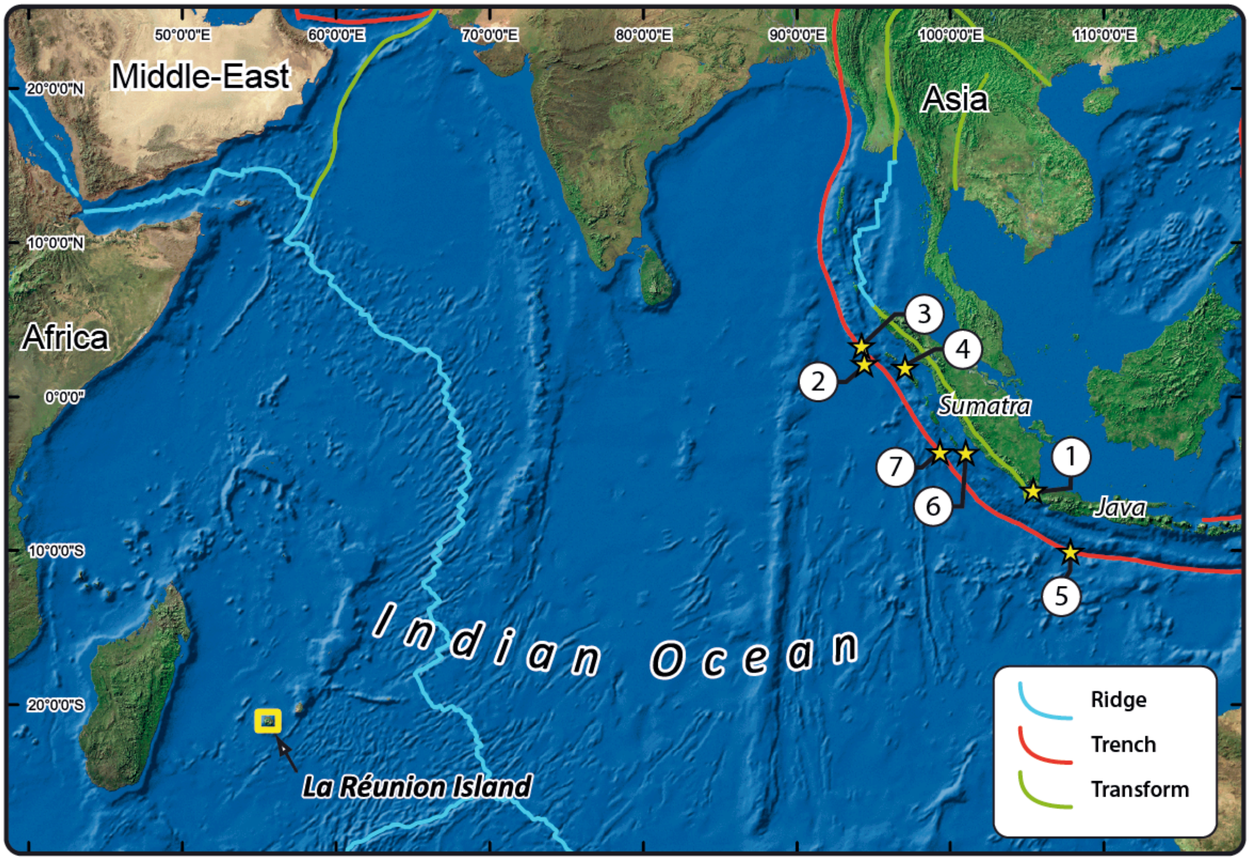
Tsunami event	*Newspaper*	*Observations*
25/11/1833	*Annales Maritimes et Coloniales*	NO
16/02/1861	*Annales Maritimes et Coloniales*	Unavailable
13/08/1868	*Annales Maritimes et Coloniales*	NO
	Malle (La)	NO
	Courrier de Saint-Pierre (Le)	Unavailable
	Courrier Républicain (Le)	Unavailable
	Moniteur (Le)	Unavailable
	Journal Communal de l'Île de La Réunion	Unavailable
10/05/1877	*Annales Maritimes et Coloniales*	NO
	Moniteur (Le)	Unavailable

27/08/1883	*Journal de l'Île de La Réunion*	YES
	Créole de l'Île de La Réunion (Le)	YES
	Malle (La)	YES
	Courrier de Saint-Pierre (Le)	Unavailable
	Moniteur (Le)	Unavailable
	Nouveau Salazien (Le)	Unavailable
	Port de Saint-Pierre (Le)	Unavailable
	Créole du Lundi (Le)	Unavailable
04/01/1907	*Journal de l'Île de La Réunion (Le)*	YES
	Patrie Créole (La)	YES
27/11/1945	*Progrès (Le)*	NO
	Démocratie (La)	NO
	Peuple (Le)	Unavailable
19/08/1977	*Journal de l'Île de La Réunion (Le)*	NO
	Quotidien (Le)	NO
02/06/1994	*Journal de l'Île de La Réunion (Le)*	NO
	Quotidien (Le)	NO
	Témoignages	NO
26/12/2004	*Journal de l'Île de La Réunion (Le)*	YES
	Quotidien (Le)	NO
28/03/2005	*Journal de l'Île de La Réunion (Le)*	YES
	Quotidien (Le)	NO
17/07/2006	*Journal de l'Île de La Réunion (Le)*	YES
	Quotidien (Le)	NO
12/09/2007	*Journal de l'Île de La Réunion (Le)*	YES
	Quotidien (Le)	YES
20/03/2010	*Journal de l'Île de La Réunion (Le)*	NO
	Quotidien (Le)	NO
25/10/2010	*Journal de l'Île de La Réunion (Le)*	YES
	Quotidien (Le)	YES

1. RESULTS

Seven tsunamis were identified as having impacted La Réunion Island in the past. All of them were of transoceanic origin (also called teletsunamis). Figure 1 illustrates the location of these sources as well as their local effects.

Figure 2 locates the places cited in the text. Time is expressed in 24h format.



	Date	Mw or Ms	Depth (km)	Ditance (km)	Observed TTT	Max runup (m)	Loc Max runup
①	27/08/1883	Vol.		5620	7h39	7	Saint-Paul
②	04/01/1907	7.8	30 ¤	4950	7h29	~2	Saint-Pierre
③	26/12/2004	9.0	30	4990	6h55	2.74*	Port Est
④	28/03/2005	8.6	30	5170	8h10	?	Sainte-Marie
⑤	17/07/2006	7.7	34	5700	8h26	0.51	Saint-Leu
⑥	12/09/2007	8.5	34	5260	7h20	?	Sainte-Marie
⑦	25/10/2010	7.8	20.6	5100	7h20	1.72	Sainte-Marie

Figure 1. Location of the sources and local effects of tsunamis that affected La Réunion Island since 1883 (in italics when uncertain; Sources: plates boundaries from Coffin et al. (1998); ¤: Kanamori et al. (2010); *: Okal et al. (2006); background ESRI).

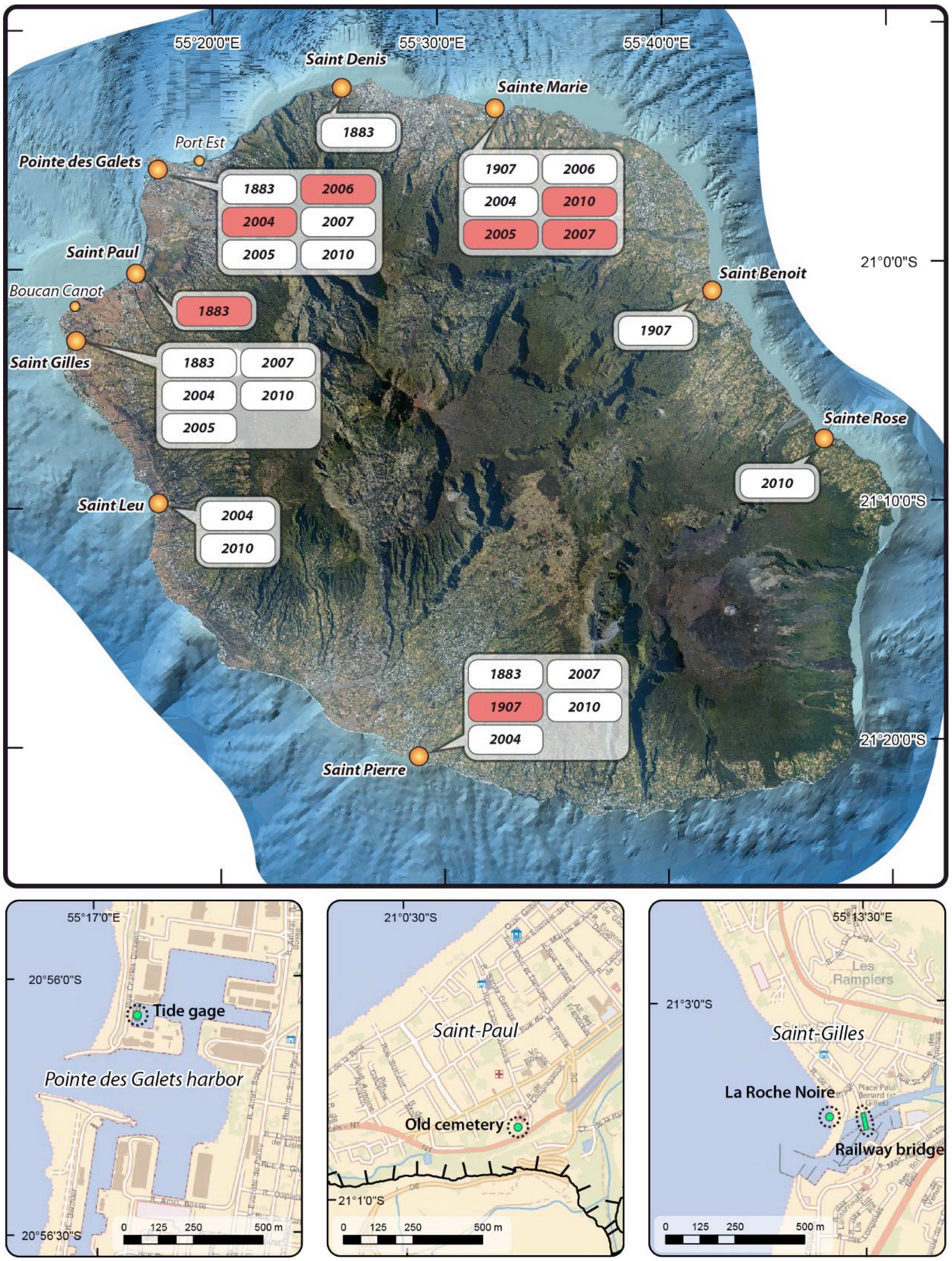


Figure 2. Synthesis of local effects of tsunamis of transoceanic origins (in red the most affected place for each tsunami) and locations mentioned in the text (background data from IGN, SHOM and DDE).

1.1. August 27th, 1883 Tsunami

On August 27th, 1883, at 9:58 LT in Indonesia (UTC+7:07:12), the explosion of the Krakatau volcano (Indonesia) triggered a tsunami with waves reaching 30 meters high and runup up to 40m along the Sundra Strait, killing 36,000 people (Choi et al. 2003; van Den Bergh et al. 2003; Pelinovsky et al. 2005). Its impact was felt in the Indian Ocean, including the Seychelles Islands (0.3m runup), Mauritius (0.8m) and Rodrigues Island (1.8m) (Choi et al. 2003; Dunbar 2010).

In La Reunion Island, the newspaper *Le Créole de l'Île de la Réunion* of August 29th, 1883 records the observation of a several feet high tidal bore in Saint-Denis on August 27th, entering the Barachois river for a few minutes. This was followed by a recession with a "brutal" current, carrying boats away despite chains and anchors. The whole water movement occurred several times, emptying the basin and drying the surrounding beaches during withdrawal. The September 2nd, 1883 issue of the newspaper *La Malle,* reported impacts in other places, and evaluation of a greater impact on the southern part of the island's west coast. At the Pointe des Galets cape, the sea "rose violently"; in Saint-Gilles. The sea reached the still-existing railway, with a runup value of 3.5m; the sea level variation was even more intense in Saint-Pierre where it started at 11 with a bore and ended around midnight. In Saint-Pierre, the harbor front basin was filled and emptied twice every 10 minutes with currents characterized as "strong". In Saint-Paul, "the sea rose just as quickly, flooding the whole town and even, carrying graves and coffins away from the old cemetery". According to the newspaper *le Journal de l'île de la Réunion* dated August 28th, 1883, "the phenomenon reached the cliffs leaving great amounts of sand". This old cemetery is located at the Rosalie Javouhey church, 630m inland, at a 7m altitude. Unfortunately, the resulting deposits were not found during the field investigations.

The same phenomenon was observed as starting at 11 LT on August 27th, in Saint-Pierre. In 1883, La Réunion's local time corresponded to UTC+3:41:52. The sea disturbance was first observed and timed at approximately 7:18 UTC on the 27th (T_0+4h16). The propagation models estimate the corresponding tsunami travel time from the Krakatau volcano to La Réunion Island to be around 7h45 (TsuDig, NGDC). It seems impossible that the tsunami that reached La Reunion Island could have been triggered during the paroxysmal phases of the eruption of Krakatao (9:58 LT, third blast), even if some sea level disturbances were triggered atmospherically by the explosion (Garrett 1970). A more accurate estimation of the time the tsunami initiated would correspond to 6:30 Indonesian time (LT). This corresponds to the 6:36 LT Krakatau's second blast, collapse of the Danan peak and formation of its caldera (Choi et al. 2003). Considering the 6:36 LT blast as the one responsible for triggering the tsunami that struck La Reunion Island, an arrival at **T_0+7h39** can be estimated. However, it is noteworthy that the major effects felt in Saint-Paul started at 15:00 LT in La Réunion, which is more in accordance with the Indian Ocean tide gauge records (Choi et al. 2003).

1.2. January 4th, 1907 Tsunami

On January 4th, 1907, at 5:19 UTC (Dunbar 2010), a magnitude Ms=7.8 earthquake occurred close to the location of the December 26th, 2004 tsunami source (Kanamori et al. 2010), triggering a tsunami which hit Indonesia and Sri Lanka. Around 16:30 LT, workers in Saint-Pierre's harbor basin gave the alert, observing a 2m rise in water level. The water surged into the harbor channel and gently flooded the harbor banks. The seawater disturbance was still observed on the evening of January 4th (newspaper *Le Journal de l'Île de La Réunion,* dated January 8th).

In Saint-Benoit, at the same time – i.e. 16:30 LT – the sea quickly receded 100m "behind the capes of St Benoit's reef" without seeming rough. Some witnesses rushed to the cleared sea floor to pick up fish, but soon abandoned their catch: the sea level rose back, flooding inland over the highest tide limits. Several similar cycles were observed until 21:00 LT when the sea level went back to normal (*Le Journal de l'Île de La Réunion* dated January 8th).

La Patrie Créole newspaper, dated January 8th, confirms these observations. It also adds the record of a sea withdrawal in Sainte-Marie that exposed rocks that are never visible, even at the lowest tides.
In 1907, LT in La Reunion Island was still UTC+3:41:52. So it was 12:48 UTC at the beginning of the observations, which corresponds to an arrival at $\mathbf{T_0}$**+7h29** after the earthquake.

1.3. December 26th, 2004 Tsunami

On December 26th, 2004, at 00:58 UTC, a magnitude Mw=9.0 earthquake triggered a tsunami which impacted most countries bordering the Indian Ocean, killing 227.898 people (Dunbar 2010).
Shortly after the December 2004 disaster, an International Tsunami Survey Team (ITST) was sent to La Reunion Island. The results of the field survey (Okal et al. 2006) show that the whole island was impacted, with a maximal effect on the northwestern coast between Pointe des Galets and Saint-Gilles. Maximal runup values were recorded at the La Roche Noire beach - which is not protected by a coral reef - reaching 2.44m high and in the basin of the Pointe des Galets harbor reaching 2.74m (Okal et al. 2006). Seventeen boats sank at Sainte-Marie harbor, located on the northern shore of the Island (Figure 2).

Additional results from the PREPARTOI program allowed to gather original testimonies indicating a sea level recession of 1.8m in Saint-Gilles, followed by a 1.78m runup, equivalent to a "very fast tide". Seven motorboats sank. In Sainte-Marie, 11 motorboats sank. At La Roche Noire beach (Saint-Gilles), according to the lifeguards, one could walk to the entrance of the harbor, which confirms the previously mentioned 1.8m sea level drop. In Port Réunion, a public harbor located inside the Pointe des Galets basin, the staff observed a 1m high tidal wave entering the basin. It was followed by a 10-min period recession and elevation of sea level. In Port Est harbor, the 12 moorings of a 40,000t container ship (MSC "Uruguay") were broken by the sea disturbances at 15:30 LT. The Pointe des Galets tide gauge recorded the arrival of the tsunami at 11:55 LT (7:55 UTC), corresponding to $\mathbf{T_0}$**+6h55**. The sea level disturbance was recorded until the morning of December 28th.

1.4. March 28th, 2005 Tsunami

On March 28th, 2005, at 16:09 UTC, a magnitude Mw=8.6 earthquake was recorded in the same area as those of 1907 and 2004, also triggering a tsunami. "A 3m tsunami damaged the port and airport on

Simeulue" (ITIC 2005). According to ITIC, the maximal recorded runup reached 2m on the west coast of Nias Island (located off Sumatra's coast).

At La Reunion Island, in the night of the 28-29th, at 5:00 LT a 0.4m sea level elevation was recorded in Saint-Gilles' harbor. The sea level disturbance lasted until 6:30 LT. In Sainte-Marie, the harbor staff observed a similar phenomenon reaching 0.2 to 0.3m higher than the highest tides. The staff recorded the occurrences of small eddies and wrinkles. The water looked particularly turbid (*Le Journal de l'Île de La Réunion* dated March 30th, 2005). The Pointe des Galets tide gauge recorded the sea level disturbance from 4:20 to 9:00 LT, that is from 0:20 to 5:00 UTC (**T_0+8h10**)

1.5. July 17th, 2006 Tsunami

On July 17th, 2006, at 8:19 UTC, a magnitude Mw=7.7 earthquake (USGS) was recorded off Java Island, triggering a tsunami which devastated Java's southern coast (Lavigne et al. 2007).
At La Reunion Island the Pointe des Galets tide gauge recorded the tsunami from 20:45 LT on the 17th to 19:00 LT on the 18th. It corresponds to an arrival at 16:45 UTC, **T_0+8h26**. A listener of Radio FreeDom (popular local radio station) called the radio station to report having observed unusual waves in Sainte-Marie harbor at 23:00 LT (*Le Journal de l'Île de La Réunion* dated July 19th).
An 0.8m sea level rise was observed in Pointe des Galets harbor, with "strong currents", as well as in Saint-Pierre harbor. At the Port Est commercial harbor, at 6:30 LT on the 18th, the sea disturbances broke the moorings of the MSC "Napoli", a 62,000t capacity bulk carrier. Additionally, a 0.51m runup was measured in Saint-Leu.

1.6. September 12th, 2007 Tsunami.

On September 12th, 2007, at 11:10 UTC, a magnitude Mw=8.5 earthquake was recorded off Sumatra's coasts. At La Reunion Island, a rapid 0.3-0.4m sea level rise was observed in Saint-Gilles harbor at 22:45 LT. It was followed by a 0.2m recession and the disturbances repeated every 5-10 minutes. Very strong currents were observed. On that particular day, the tides were of a very low level, limiting the flood to a 1.13m altitude. Around 23:00 LT (19:00 UTC), the authorities recorded an unusual sea level elevation of 0.6m in Sainte-Marie harbor. It took the sea 2min to rise and 1min to recede, after a 2min transition. This alternation continued for 1h30. At the Pointe des Galets harbor, a 0.20-0.30m amplitude oscillation was observed. The tide gauge recorded a 0.24m amplitude oscillation at 22:30 LT (18:30 UTC, **T_0+7h20**). In Port Est, no effect was noticed. All boats had already been taken out of the harbor.

1.7. October 25th, 2010 Tsunami

On October 25th, 2010, a magnitude Mw=7.8 earthquake was recorded at 14:42 UTC in the Kepulauan Mentawai archipelago, in Indonesia. At La Reunion Island, the Pointe des Galets tide gauge recorded the tsunami from 22:00 UTC on the 25th to 19:00 UTC on the 26th (**T_0+7h20**).
A specific article was recently accepted by two of this article's authors about the October 25th event (Sahal and Morin accepted), describing its effects and how the authorities managed the crisis. The maximal measured runup reached 1.72m in Sainte-Marie harbor, sinking 4 motorboats.

Figure 3. Video footage extracts of the March 20th, 2010 wave train observed at Boucan-Canot. A: arrival of the wave train, B: flood, C: back to normal. Courtesy M. Ropert.

2. DISCUSSION

Precision of measured runup values depends entirely on the quality and reliability of information sources. The older an event is, the lower the quality of the information describing it is. Recent events are described by crosschecking various witnesses' records, while events prior to 2004 (1907 and 1883 events) are described accordingly to a single source, that is old newspapers. A probability exists for the occurrence of tsunami triggered locally from La Réunion island's flanks. Kelfoun et al. (2010), who recently modeled potential local sources that could affect La Réunion show important potential impacts for such sources. On March 20th, 2010, the OVPF-IPGP network recorded two low magnitude earthquakes on La Reunion Island. The first one occurred at 13:19 LT and was followed by the second – of a higher magnitude - at 14:43 LT. Their location, out of the sensors network, is estimated to be west of the island. A few minutes later, a series of 3 unexpected waves flooded the beaches of Boucan-Canot and La Roche Noire. These two beaches of the west coast are located 3km apart and are unprotected by a coral reef barrier. The lifeguards were "surprised" by this unusual phenomenon. Their offices, respectively 5 and 3m above the lowest tides in Boucan-Canot and the La Roche Noire beach were flooded. A maximal runup of 5.7m was measured in Boucan-Canot, where several people were injured when projected onto rocks. Others were taken out to sea by the reflux and needed boat rescue. A witness in Boucan-Canot filmed the arrival of the wave train and the consecutive flood (Fig 3). The study and time calibration of the video footage reveal an arrival at 15:08 LT (**T_0+0h25** after the second earthquake). The seismographs of the OVPF-IPGP network did not record a signal indicating a submarine landslide.

The March 20th, 2010 event was neither covered by the media, nor noticed by the authorities. Only the beach surveillance services noticed the phenomenon and its consequences on swimmers. No certainty exists concerning the origins of this inundation (ground swells, unusually large swells or tsunami of a local origin?). The person who filmed the event also filmed surfers at the same place a few hours before the arrival of the "unusual" wave train. After studying both films, one noticed that on this day, the waves displayed an entirely different comportment than that of the flooding wave train.
Considering that this March 20th event was identified through word-of-mouth and not through official

or media means, one could suppose that similar event may have occurred in the past without being referenced. Also, potential regional sources of tsunamis (Madagascar, the Karthala volcano, etc.) are not represented in this catalog as no event of such origin was identified (Hartnady 2005a; Hartnady 2005b).

Concerning the 1883 Krakatau tsunami, the maximal runup measure is not in accordance with the ones measured in the rest of the Indian Ocean (Choi et al. 2003; Pelinovsky et al. 2005). Nevertheless, considering: (1) the number of newspapers referring to this event; (2) the precision of observations and their spatial distribution; (3) the fact that August is out of the cyclonic season; (4) the observed sea level recede; (5) and the fact that the only documented quantified effects in the Indian Ocean were based solely on tide gauge records (that often underestimate the coastal impact); the effects of the 1883 Krakatau tsunami can be considered as accurate in La Réunion Island.

A newspaper article recalls several inhabitants' memory of a past tsunami occurrence: the 1883 tsunami was "a violent tidal wave that looked just like the one observed in 1867, when the Peruvian earthquake occurred" (*La Malle*, dated October 25th, 1883). Such information raises several questions: could this be the August 13th, 1868 earthquake (Mw=8.5) and associated tsunami affecting La Réunion? Could a tsunami triggered in Peru or Chile have an impact in the western Indian Ocean, or is the journalist recalling effects observed in Peru? The 1868 tsunami had a maximal runup of 18m in Arica (Chile) and only reached 1.2m high in Sydney, the most western measured runup for this tsunami (Soloviev and Go 1974).

Due to lack of available archives, impact evidence could neither be found for the tsunami triggered by the November 24th, 1833 Indonesian earthquake (Mw=8.8-9.2, Zachariasen et al. 1999), nor for the February 16th, 1861 Indonesian one (Ms=8.5, Dunbar 2010), nor for the November 27th, 1945 Makran event (Ms=8.0, Rastogi and Jaiswal 2006; Mokhtari et al. 2008; Heidarzadeh et al. 2009).

The December 2004 event is the only one for which a regional field survey was conducted in the vicinity of La Réunion Island (Obura 2006; Okal et al. 2006). Therefore, very little information was available in the literature about the effects the tsunamis had in the region. Only tide gauge records are usually considered for mapping and studying far field tsunami effects. Field surveys and archive research appear to be of major importance in studying local tsunami amplification and effects. The PREPARTOI program will soon provide far field high resolution modeling of the shoaling effects along La Réunion Island's coasts using different tsunami sources, which will help the understanding of such phenomenon.

3. CONCLUSIONS

This first catalog of tsunamis that historically impacted La Réunion Island mainly shows teletsunamis that affected other countries of the Indian Ocean. All their sources are located on the Indonesian margin, which does not mean tsunamis from the Makran region would not affect La Réunion Island. It is essentially the west coast of the island which suffers the most important impacts, probably due to a "wrap around" phenomenon and an amplification at the opposite coast, as previously demonstrated by Hébert et al. (2007).

The observed travel times of the tsunamis triggered on the Indonesian margin range from 6h55 to 8h26 post earthquake, according to the witness records gathered. This amount of time, although reasonable for a response by the authorities, was not always enough to respond adequately to a tsunami threat (Sahal and Morin accepted). This response should improve from now on, thanks to the recent revision of the local alert and responses procedures. Finally, one must note that the Pointe des Galets tide gauge is not appropriately located in its harbor; it is in a protected basin, and always underestimates the impacts on the other harbors (Table 2). Relocating this tide gauge in its basin and implanting new tide gauges in Sainte-Marie and Saint-Pierre harbors would considerably improve the quantification of future tsunamis, for the benefit of La Réunion Island as well as other Indian Ocean countries.

Table 2. Maximal amplitudes during the identified tsunamis since 2004 as recorded by the Pointe des Galets tide gauge (located on Figure 2) and measured runup values (all in meters).

Tsunami event	***Maximal amplitude recorded by the tide gauge (crest-to-trough)***	***Maximal runup measured on the island***
26/12/2004	0.72	2.74
28/03/2005	0.19	*?*
17/07/2006	0.24	0.51
12/09/2007	0.24	*?*
25/10/2010	0.39	1.72

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