The M_w 7.5 Tadine (Maré, Loyalty Is.) earthquake and related tsunami of December 5, 2018: seismotectonic context and numerical modelling~~: implications for tsunami hazard assessment in New Caledonia~~

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Abstract. On the 5th of December 2018, a magnitude M_w 7.5 earthquake occurred southeast of Maré, an island of the Loyalty Archipelago, New Caledonia. This earthquake is located at the junction between the plunging Loyalty R~~r~~idge and the ~~southernmost~~ southern part of the Vanuatu A~~a~~rc, in a tectonically complex and very active area regularly subjected to strong seismic crises and ~~events~~ earthquakes higher than magnitude 7 and up to 8. Widely felt in New Caledonia, it has been immediately followed by a tsunami warning, confirmed shortly after by a first wave arrival at the Loyalty Islands tide gauges (Maré and Lifou), then along the east coast of Grande Terre of New Caledonia and in several islands of the Vanuatu Archipelago. Two solutions of the ~~S~~seafloor initial deformation are considered for tsunami generation modelling, one using a non-uniform finite source model from USGS, and the other being a uniform slip model built from the GCMT solution, the geological knowledge of the region and empirical laws establishing relationships between the moment magnitude and the fault plane geometry. ~~linke~~ Both ~~d to~~ tsunami generation and propagation ~~has been modeled with MOST numerical code using earthquake parameters available from seismic observatories. Then the wave propagation has been~~are ~~modeled~~ simulated using SCHISM, an open-source~~other~~ modelling code solving the shallow water equations on an unstructured grid ~~based on a new regional DEM of ~180 m resolution and~~ allowing refinement in many critical areas.~~– Finally, t~~The results of numerical simulations ~~have been~~are compared to tide gauge records, field observations and testimonials from 2018. The arrival times, wave amplitude and polarities obtained with the composite model ~~present good~~ are globally coherent~~similarities~~, especially in far-field locations (Hienghène, Port-Vila and Poindimié). Careful inspection of wave heights and wave energy maps for the two simulated scenarios shows clearly that the heterogeneous deformation model is inappropriate, while it raises the importance of fault plane geometry and azimuth on tsunami amplitude and

directivity. Due to interactions between the tsunami waves and the numerous bathymetric structures like the Loyalty and Norfolk Ridges in the neighborhood of the source~~Maximum wave heights and energy maps for two different scenarios highlight the fact that the orientation of the source (strike of the rupture) played an important role~~, ~~focusing the maximum energy path of~~ the tsunami propagating toward the south of Grande ~~-~~Terre and the Isle of Pines is captured by these structures acting like waveguides, allowing it to propagate to the north-northwest, especially in the Loyalty Islands and along the east coast of Grande Terre. ~~However, both scenarios indicate~~A similar observation results from the propagation in the Vanuatu islands, from Aneityum to Efate ~~toward Aneityum, Vanuatu southernmost island, the bathymetry acting like a waveguide~~. ~~This study has a significant implication in tsunami hazard mitigation in New Caledonia as it helps to validate the modelling code and process used to prepare a scenarios database for warning and coastal evacuation.~~

1 ~~General settings~~Introduction

At 04:18:08 UTC on December 5, 2018 (15:18:08 local time in New Caledonia – UTC+11), a major earthquake of magnitude M_w7.5 occurred 165 km east-south-east of Tadine, Maré, the southernmost inhabited island of the Loyalty Archipelago (Figure 1). Being strongly felt in New Caledonia (Loyalty Islands and the Grande Terre) as far as Nouméa, more than 300 km west from the source (Roger et al., 2019a, 2019b, 2019c), it has been also weakly felt in Port-Vila, capital of Vanuatu, about 470 km to the North according to a CBS News interview of Mr. McGarry, media director at the Vanuatu Daily Post. There is no report of damage linked to the earthquake.

Within minutes, its location and magnitude were determined by the Seismological Observatory of New Caledonia (http://www.seisme.nc, https://bit.ly/2IMkmgM) [M_w7.6, 22.01°S, 169.33°E, 30 km], by USGS [M_w7.5, 21.968°S, 169.446°E, 10 km] and by the Global CMT project as a quick CMTS [M_w7.5, 21.95°S, 169.25°E] (Dziewonski et al., 1981; Ekström et al., 2012). Maximum distance between these three locations is ~15 km, in agreement with the acceptable location errors between the different observatories. The current hypocenter location of the event provided by USGS, GCMT, and GEOSCOPE is now respectively 21.950°S, 169.427°E, 10 km, 21.95°S, 169.25°E, 17.8 km and 21.969°S, 169.446°E, 12km.

The seismic moment M_o of this event has been evaluated to 2.49 x 10^{20} N.m (M_w7.53) by USGS, 2.52 x 10^{20} N.m by GCMT project (M_w7.5), and 2.95 x 10^{20} N.m (M_w7.58) by the SCARDEC method (GEOSCOPE-IPGP).

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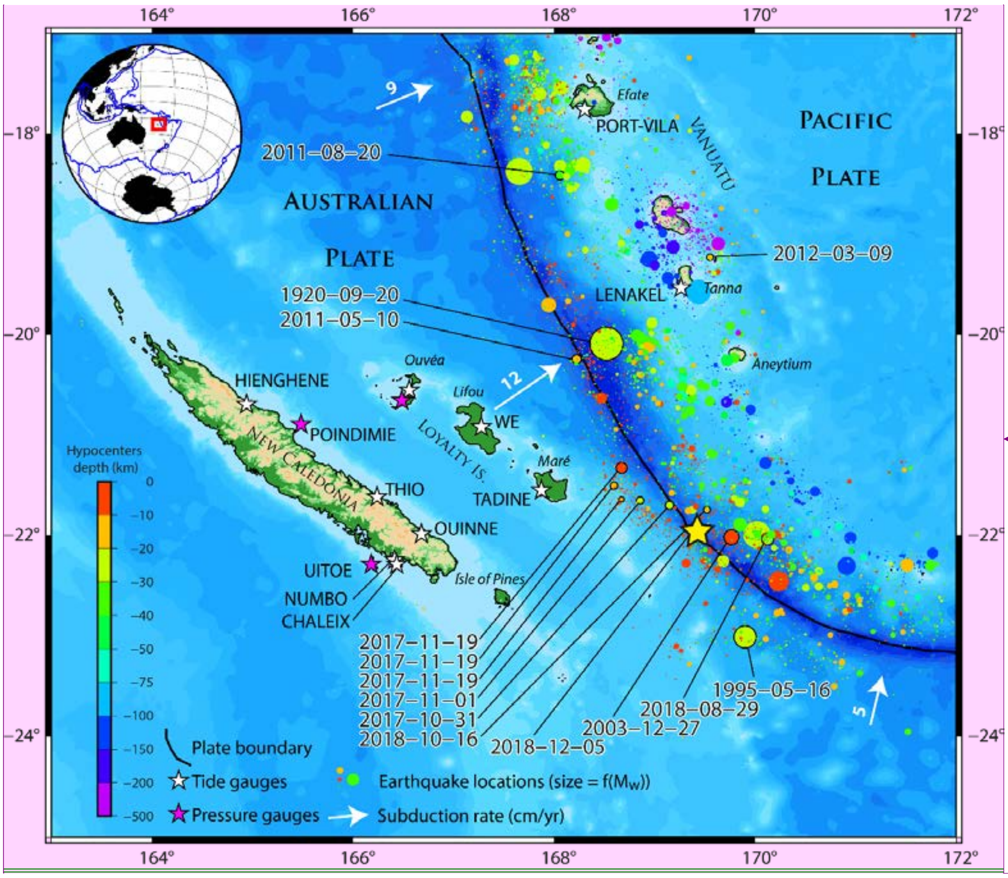

Figure 1 : ~~Figure 1: The~~ New Caledonia~~/~~ and the ~~S~~south Vanuatu Subduction zone. The colored dots represent the seismicity from the USGS database for the period from January 1, 1900 to January 24, 2019, with the size of dots being proportional to event's magnitude. Tsunamigenic earthquakes having been recorded in New Caledonia (Roger et al., 2019b) are highlighted with a black circle and linked to dates. The white arrows symbolize the subduction directions and rates of the subducting Australian Plate under the Pacific plate. Tide and pressure gauges able to record tsunami waves are respectively symbolized with white and purple stars. The yellow star locates the December 5, 2018 earthquake's epicenter. The study area is located within the red rectangle in the southwestern Pacific Ocean.

Considering the strong magnitude of this shallow earthquake, a tsunami alert was released locally by the IRD seismological laboratory to the New Caledonia civil security service (DSCGR) and regionally by the NOAA/PTWC shortly after the earthquake occurred. A tsunami was confirmed by real-time tide gauges measurements within minutes at first in the Loyalty Islands, then in most places of the New Caledonia/Vanuatu region.

This earthquake is added to the list of ~~two~~ local earthquakes reported by the past in the south Vanuatu Subduction zone and especially to the two shocks that triggered major tsunamis in the Loyalty Islands in March 28, 1875 and September 20, 1920 (Sahal et al., 2010) with estimated magnitude of 8.1-8.2 and 7.5-7.8 respectively (Ioualalen et al., 2017), and to the M_w7.7 May 17, 1995 event which occurred close, and south, to

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Formatted: Caption, Line spacing: single the December 5, 2018 event showing a similar focal mechanism (i.e. normal faulting in the plunging plate), as~~ as~~ explained here~~above~~under. Th~~is~~e ~~event~~earthquake of 1995 was followed by a tsunami that was well observed at the entrance of the first lagoon and on Erakor Island in Port Vila, located south of Efate, Vanuatu (Lardy, 1995).

This study aims to (1) simulate the December 5, 2018 tsunami in New Caledonia and Vanuatu, comparing the ~~simulated~~computed maximum amplitudes and the synthetic waveforms to those observed and/or recorded on tide gauges and (2) discuss the role of earthquake source parameters through sensitivity tests. The first part of the article deals with the particular seismotectonic context of the region between New Caledonia and Vanuatu and its ability to trigger tsunamigenic earthquakes. The second and third parts focus~~es~~ respectively on the December 5, 2018 tsunami observations and records and tsunami numerical modelling and the ~~third~~fifth and sixth ones present and discuss~~ is a discussion about~~ the modelling results and provide ~~and~~ study prospects.

~~Considering the strong magnitude of this shallow earthquake, a tsunami alert was released locally by the IRD seismological laboratory to the New Caledonia civil security service (DSCGR) and regionally by the NOAA/PTWC soon after the earthquake occurred. A tsunami was confirmed by real-time tide gauges measurements within minutes at first in the Loyalty Islands, 45 minutes before high tide in Tadine (high tide at 4:30 PM local time and tsunami arrival recorded at 3:43 PM local time) and about one or two minutes after high tide in Hienghène (high tide at 4:25 PM local time and tsunami arrival recorded at 4:26-4:27 PM local time).~~

~~1.1~~2 Seismo~~T~~tectonic context

2.1 Junction of the Loyalty Ridge and the Vanuatu subduction zone

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The December 5, 2018, M_w 7.5 earthquake is located southeast of Maré (Loyalty Islands, New Caledonia), immediately west of the southern part of the ~~New Hebrides/~~Vanuatu (former New Hebrides) trench in the junction area between the Loyalty Ridge and the ~~New Hebrides/~~Vanuatu arc (Figure 1). The Vanuatu trench and arc mark a segment of the convergence zone between the two major plates of the Southwest Pacific region (Australia and Pacific plates).

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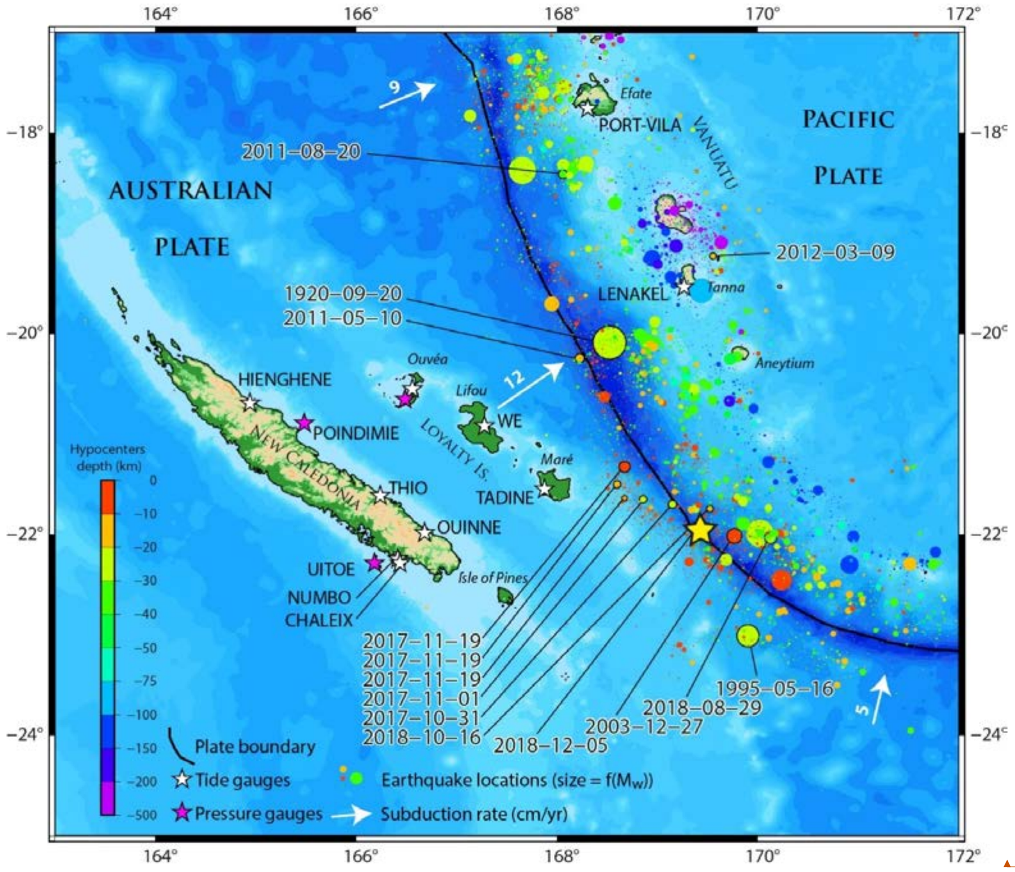

~~Figure 1: The New Caledonia/South Vanuatu Subduction zone. The colored dots represent the seismicity from the USGS database for the period January 1, 1900 to January 24, 2019, with size of dots proportional to event's magnitude. Tsunamigenic earthquakes having been recorded in New Caledonia (Roger et al., 2019b) are highlighted with dates. The white arrows symbolize the subduction directions and rates of the subducting Australian Plate under the Pacific plate. Tide and pressure gages able to record tsunami waves are respectively symbolized with white and purple stars. The yellow star locates the December 5, 2018 earthquake's epicenter.~~

The junction area around 22°S is very active tectonically (Monzier et al., 1984). The plunging Loyalty Ridge supported by the Australia Plate enters and partially clogs the trench. Considering the geometry of the Loyalty Ridge, the strike of the trench and the current orientation and rate of convergence (12 cm/y on ENE-WSW), the subduction/collision of the ridge tends to increase and would have started around 0.3 Ma (Monzier et al., 1990). The data obtained by multibeam mapping and submersible diving (Daniel et al., 1986; Monzier et al., 1989 and 1990) at the junction zone (21.5°S and 22.2°S) indicate: 1) a spectacular collapse of the ridge as it approaches the trench (reef limestones affected by normal faulting are at 4,300 m deep), 2) a migration of the deformation front on the outer wall of the trench with the unusual presence of folds, 3) a narrowing and an eastward retreat of the trench by around 20 km relatively to its supposed initial position, 4) an uplift of the inner wall and 5) the development of E-W trending scarps suggesting left-lateral strike-slip motion. The rapid variation of the convergence vector and the presence of numerous left-lateral strike-slip faulting earthquakes around 22°S, at the

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front of the junction zone and along or at the rear of the Matthew-Hunter arc segment, also suggest that the subduction/collision of the Loyalty Ridge causes the development of a new left-lateral plate boundary through the overlapping plate, connecting the trench to the spreading center of the North Fiji basin and thus isolating a microplate (the Matthew-Hunter microplate) at the southern end of the arc~~, strongly coupled to the Australian plate~~ (Louat and Pelletier, 1989). The rate of motion on this transform fault zone was estimated by these authors at 10.5 cm/year. However, its precise geometry and location are not known, and several variants have been proposed (Louat and Pelletier, 1989; Maillet et al., 1989; Monzier, 1993; Patriat et al., 2015). As these authors have partially indicated, it is likely that this ~~senestral~~ left-lateral shear zone is complex and that a bookshelf tectonic occurs at the southernmost part of the Vanuatu trench (21°S-23°S), by associating with the main senestral motion, dextral and extensive movements along NW-SE trending faults and pull-apart basins.

Series of GPS geodetic measurements on the Loyalty Ridge (Walpole, Mare, Lifou) and the Vanuatu ~~arc~~ Arc (Matthew, Hunter, Aneityum, Tanna) sites from 1992 to 2000 have confirmed the presence of the left-lateral transform fault zone (Pelletier et al., 1998; Calmant et al., 2003). The data indicate that the convergence rate (Australia fixed) of 120 mm/year at N248° north of the ridge-arc junction (Tanna, Aneityum) is partitioned toward the south into a convergence rate of 50 mm/year perpendicular (N197°) to the trench (Matthew) and a senestral movement of 90 mm/year along an E-W trending transform zone, crosscutting the arc around 22°S and thus isolating the Matthew-Hunter microplate at the southern end of the arc (Calmant et al., 2003). In addition, GPS derived vectors of the New Caledonia sites are in good agreement with the movement of the Australian plate, suggesting therefore no significant intra-plate deformation between islands of the New Caledonian Archipelago. The termination of the southern Vanuatu back arc basins north of the junction zone, the increase in seismic activity and the shift towards the trench of the seismogenic zone in front of the junction zone, the short length of the Wadati-Benioff plane south of Aneityum (less than 200 km), the weak development of the volcanic arc at the front of the junction zone, the particular chemistry of the volcanism of the termination of the arc south of the ridge-arc junction (calco-alkaline magnesian and boninitic series) as well as the offset of the central spreading axis in the North Fiji basin have also been linked to the subduction/collision of the Loyalty Ridge (Monzier et al., 1984, 1990; Louat and Pelletier, 1989; Maillet et al., 1989; Monzier, 1993).

~~1.2~~2.2 Seismicity at the Loyalty Ridge-Vanuatu Arc junction

The Loyalty ~~island~~ Islands region and especially the Loyalty Ridge-Vanuatu Arc junction area around 22°S, 169.5°E is very active seismically. Nine large shallow earthquakes with magnitude equal or greater than seven occurred in this junction area since 1900. The largest was a M7.9 in August 9, 1901, located at 22°S, 170°E. A M7.6 earthquake occurred in March 16, 1928 at 170.24°E, 22.45°S. The seven others occurred during seismic crises in the last 40 years: a M_w7.4 in October 25, 1980; a M_w7.7 in May 16, 1995; a M_w7.3 in December 27, 2003; a M_w7.1 in January 03, 2004; a M_w7.0 in November 29, 2017; a M_w7.1 in August 29, 2018 and a M_w7.5 in December 15, 2018. Among these seven M7+ events, four of them have occurred to the west of the trench, as the result of shallow normal faulting within the Australia downgoing plate, including the two largest 7.7 and 7.5 events~~ at a worldwide scale~~.

All earthquakes occurring during the crises and the period 1976-2020 and having a focal mechanism solution (CMTS) have been plotted on Figure 2a.

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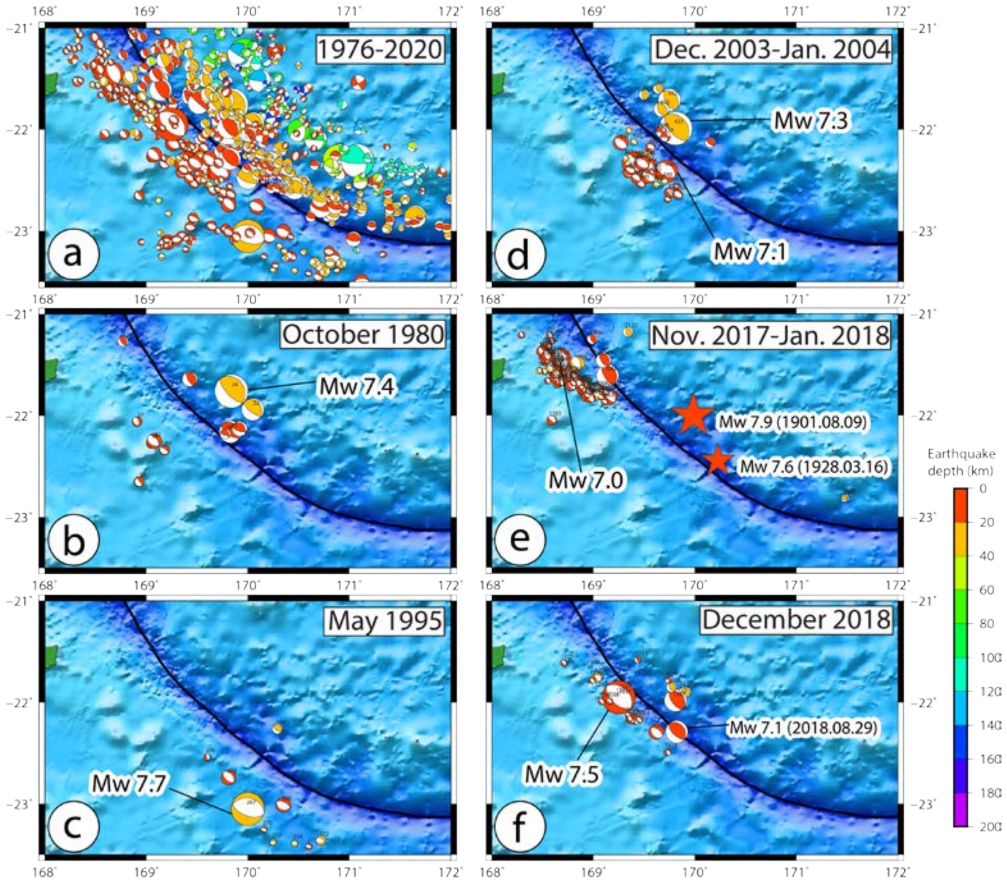

Figure 2: Focal mechanism solutions from CGMT project plotted for the period 1976-2020 with focus on 5 different seismic crises showing 9 large shallow earthquakes at the Loyalty Ridge-Vanuatu Arc subduction zone.

In October 1980 more than 100 events have been recorded by the worldwide network (Vidale and Kanamori, 1983). The sequence includes twelve M5.4+ events (Figure 2b). Six of them are thrust faulting earthquakes east of the plate boundary (among the two M6.5 + foreshocks and the M7.4 main shock) and five of them are normal faulting earthquakes in the downgoing plate west of the trench. Active sequence began by the three main thrust fault events and followed by the alternance of normal and thrust fault events.

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During the May 1995 seismic crisis 13 events with magnitude greater than 5 were located around 23°S, 170°E (Figure 2c). Most of them are normal faulting type southwest of the trench including the M_w 7.7 main shock, 125 km to the southeast of the December 2018 event. This M_w7.7 event is the largest normal faulting earthquake known in the World in a plunging plate on the trench outer slope (Rouland et al., 1995). In detail, this earthquake and its associated aftershocks are located at the foot of the Loyalty Ridge in the adjacent South Fiji Basin. These normal type events affecting the crust of the South Fiji Basin (from 169.75°E to 171°E) are further far from the axis of the trench relatively to the normal faulting events of the December 2003 and 2018 sequences which are on the Loyalty Ridge (169.5°E). This difference could be explained by a different rheological behavior (more buoyancy of the ridge).

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Between December 25, 2003 and January 5, 2004, a shallow seismic swarm very similar to the one of 1980 occurred (same zone, same magnitude and same spatial organization of fault types; Figure 2d) (Régnier et al., 2004). More than 1000 events were recorded by the local IRD seismic network, among which about 270 by the worldwide network including 37 events with magnitude greater than 4.9, 12 with magnitude equal or greater than 6 and two greater than 7. The sequence started with normal faulting events with magnitude up to 6.8 west of the trench, continued by several interplate thrust faulting events including the large M_w7.3 event on December 27 and located immediately to the east of the trench, and ~~terminated~~ ended by normal faulting events including a large M_w7.1 event on January 3 located again southwest of the trench.

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An important seismic crisis occurred from November 2017 to January 2018 with several thousands of events located about 70 km-100 km northwest of the December 2018 swarm (Figure 2e). Among them, 350 M4+ events have been recorded and most of the 80 M4.7+ events are normal faulting earthquakes located west of the trench along the northern edge of the Loyalty Ridge. However, in detail, the sequence began by a M_w6.7 and then a M_w5.9 thrust faulting earthquakes on October 31, 2017 and continued by numerous normal faulting foreshocks and the M_w7.0 normal faulting main shock on November 19, 2017.

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The December 5, 2018 M_w7.5 earthquake can be considered as part of a seismic crisis that began on August 29, 2018 with a M_w7.1 interplate thrust faulting earthquake located southeastward (Figure 2f). The M_w7.5 normal faulting main event located west of the trench was preceded 4 minutes. before by a M_w6.3 event (magnitude estimated as 5.8 by the local ORSNET network) and more interestingly was followed 2h25 later by a M_w6.8 interplate thrust faulting east to the trench. During December 2018, about 89, 49 and 18 aftershocks of M 4+, M4.5 and M5+ respectively have been recorded by the local network.

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It appears clearly that the successive seismic crises are quite similar and included both interplate thrust fault type earthquakes northeast of the trench and normal fault type events southwest of the trench in the plunging plate (Figure 2). The strong spatiotemporal pattern between these two types of events suggests that static stress interactions may account for triggering non-distant earthquake, normal faulting on the plunging plate triggering interplate thrust faulting or the reverse.

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~~2~~ 3 T~~T~~he December 5, 2018~~ earthquake and~~ tsunami

The tsunami following the December 5, 2018 M_w7.5 earthquake has been recorded by tide gauges in New Caledonia and Vanuatu but also at a regional scale (Figure 3). In addition, several observations of tsunami waves in locations not equipped with sensors provided important information to consider in the study of the event (Figures 3 and 4).

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~~2.1 Earthquake crisis~~

~~**At 04:18:08 UTC (15:18:08 local time in New Caledonia) on December 5, 2018, a major earthquake (around M_w7.5) occurred 165 km east south east of Tadine, Maré, the southernmost inhabited island of the Loyalty Archipelago. Being strongly felt in New Caledonia (Loyalty Islands and the Grande Terre) as far as Nouméa, more than 300 km west from the source (Roger et al., 2019a, 2019b, 2019c), it has been also weakly felt in Port-Vila, capital of Vanuatu, about 470 km to the North according to a CBS News**~~

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~~interview of Mr. McGarry, media director at the Vanuatu Daily Post. There is no report of damage linked to the earthquake.~~

~~Within minutes, its location and magnitude were determined by the Seismological Observatory of New Caledonia (http://www.seisme.nc, https://bit.ly/2IMkmgM) [M_w7.6, 22.01°S, 169.33°E, 30 km], by USGS [M_w7.5, 21.968°S, 169.446°E, 10 km] and by the Global CMT project (Dziewonski et al., 1981; Ekström et al., 2012) as a quick CMTS [M_w7.5, 21.95°S, 169.25°E]. Maximum distance between these locations is ~15 km, in agreement with the acceptable location errors between the different observatories. The current location of the event is now 21.950°S, 169.427°E, 10 km, 21.95°S, 169.25°E, 17.8 km and 21.969°S, 169.446°E, 12km by USGS, GCMT, and GEOSCOPE respectively.~~

~~The seismic moment Mo of this event has been evaluated to 2.49 x 1020 N.m (M_w7.53) by USGS, 2.52 x 1020 N.m by GCMT project, and 2.95 x 1020 N.m (M_w7.58) by the SCARDEC method (GEOSCOPE-IPGP).~~

~~The location of the event and the different solutions of its focal mechanism solution indicate that the earthquake is the result of shallow normal faulting along a fault plane trending NW-SE within the plunging Australia Plate on the northern border of the Loyalty Ridge. The proposed parameters for the rupture (strike, dip, rake) are [298°, 43°, -111°], [312°, 36°, -90°] and [297°, 55°, -108°] for USGS, GCMT and GEOSCOPE (SCARDEC) respectively.~~

~~Data indicate rupture duration of about 50 s and 3 patches of displacement during the rupture. USGS proposes a fault model (strike 298°, dip 43°) of 160 km x 30 km with a slip ranging up to 3 m mainly distributed in the 10 km upper part of the fault plane (hypocenter being at 12 km) and a maximum displacement patch at an along strike distance around 40 km northward of the hypocenter (https://earthquake.usgs.gov/earthquakes/eventpage/us1000i2gt/finite-fault).~~

~~2.2 Tsunami~~

~~This earthquake is added to the two local earthquakes reported by the past in the south Vanuatu Subduction zone that triggered major tsunamis in the Loyalty Islands in March 28, 1875 and September 20, 1920 (Sahal et al., 2010) with estimated magnitude of 8.1-8.2 and 7.5-7.8 respectively (Ioualalen et al., 2017), and to the M_w7.7 May 17, 1995 event which occurred close and south to the December 5, 2018 event showing a similar focal mechanism (normal faulting in the plunging plate) as explained hereabove. This event of 1995 was followed by a tsunami that was well observed at the entrance of the first lagoon and on Erakor Island in Port Vila, located south of Efate, Vanuatu (Lardy, 1995).~~

~~Considering the strong magnitude of this shallow earthquake, a tsunami alert was released locally by the IRD seismological laboratory to the New Caledonia civil security service (DSCGR) and regionally by the NOAA/PTWC soon after the earthquake occurred. A tsunami was confirmed by real-time tide gauges measurements within minutes at first in the Loyalty Islands, 45 minutes before high tide in Tadine (high tide at 4:30 PM local time and tsunami arrival recorded at 3:43 PM local time) and about one or two minutes after high tide in Hienghène (high tide at 4:25 PM local time and tsunami arrival recorded at 4:26-4:27 PM local time).~~

~~2~~3.~~2.~~1 Tide gauge records

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~~Tide gauge records used in this study come directly from the pressure sensors (Maré, Ouinné, Thio, Hienghène), from the SHOM Refmar database (Lifou ; http://refmar.shom.fr/en/lifou), from the IOC Sea Level Station Monitoring Network (Lénakel and Port-Vila ; http://www.ioc-sealevelmonitoring.org/) and the ReefTEMPS project (Poindimié ; Varillon et al., 2018). They are visible on Figure 8.~~

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The tide gauge of Maré Island, located in Tadine's Harbor on the southwest coast of this island, was the first to record the tsunami signal at 4:43 UTC (3:43 PM local time – UTC+11), 25 minutes after the main shock~~ (Figure 8)~~ even if local people reported an earliest arrival at the southeasternmost point of this island ~15 minutes after the earthquake. Then, the wave train reached the other tide gauges located in New Caledonia (4:43 UTC in Wé, Lifou Is.; 5:11 UTC in Ouinné; 5:10 UTC in Thio; 5:27 UTC in Hienghène) as well as several pressure gauges like in Poindimié, east coast of New Caledonia. According to Roger et al. (2019b) for what concerns New Caledonia only, a maximum tsunami height of ~60-70 cm was recorded by Ouinné tide gauge.

In ~~the ~~Vanuatu, it reached~~ Tanna Island first (4:41 UTC in Lenakel) where it has been recorded by~~ the tide gauge located at Lenakel harbor (Tanna Island) at 4:41 UTC, showing a maximum height of ~1.5 m (amplitude of ~75 cm a.s.l.). In Efate (5:06 UTC in Port-Vila), the tsunami has been also recorded on the tide gauge located at Port Vila where it reached a maximum height of ~50 cm (maximum amplitude of ~25 cm a.s.l.).

Afterwards, it has been also recorded by tide gauges in other locations of the southwestern Pacific region, as far as Port Kembla, Australia, about 2200 km away from the source, North Cape, New Zealand (~1400 km southward), or Pago Pago in the American Samoa's (more than 2250 km northeastward). As far as known, e~~E~~xcept in New Caledonia and Vanuatu, it never reached more than 30 cm high. Figure 3 locates the different tide gauges that were able to record the tsunami within the southwestern Pacific Region and illustrates the recorded maximum wave height (ITIC communication from Stuart Weinstein, 2018).

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Tide gauge records used in this study come ~~directly ~~from different origins.

For Maré, Ouinné, Thio and Hienghène, the data ~~are coming~~comes directly from the raw dataset of t~~t~~he pressure sensors~~-~~.~~(Maré, Ouinné, Thio, Hienghène), ~~ For Lifou, the data have been provided by ~~from ~~the SHOM (~~Refmar database (Lifou ; ~~http://refmar.shom.fr/en/lifou). The data used for Lenakel and Port-Vila ~~are coming~~comes~~,~~ from the IOC database (~~Sea Level Station Monitoring Network (Lénakel and Port-Vila ; ~~http://www.ioc-sealevelmonitoring.org/) and the data for Poindimié ~~are coming~~comes from a local New Caledonia coastal water monitoring project (ReefTEMPS project: ~~ (Poindimié ;~~http://www.reeftemps.science/en/data/, Varillon et al., 2018).~~ They are visible on Figure 8.~~

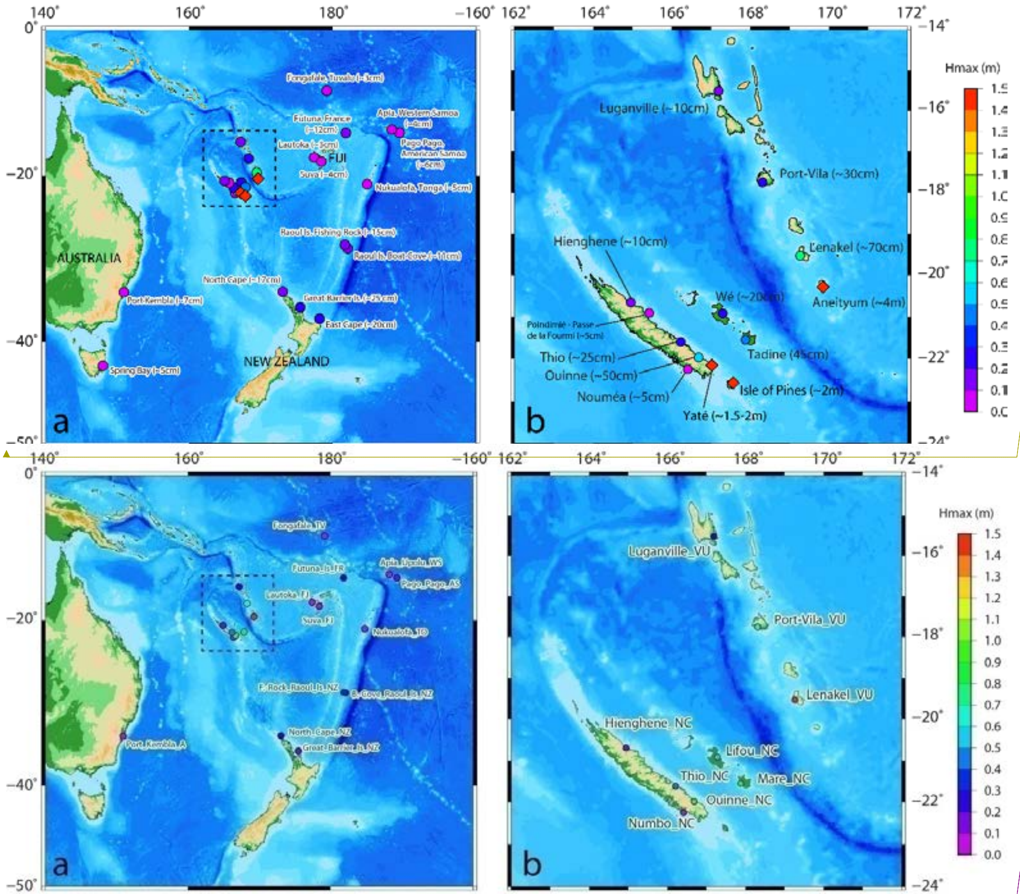

Figure 3: Tsunami maximum wave ~~height~~ amplitude of the December 5, 2018 tsunami ~~recorded on each tide gauge~~ ~~of~~in the southwestern Pacific R~~r~~egion. Monitored elevation are represented with circles while those coming from witness observations are represented by diamonds.

Note about the tide

The arrival time in Tadine Harbor corresponds to 48 minutes before high tide (high tide at 4:30 PM local time) and about one or two minutes after high tide in Hienghène (Northeast of Grande Terre, New Caledonia)~~:~~ where high tide was at 4:25 PM local time and the tsunami arrival was recorded at 4:26-4:27 PM local time).

~~2.2~~3.2 Eye-witnesses' observations

In the aftermath of this event, two videos ~~have been collected for~~ showing the tsunami arrival at two different locations have been collected~~: Yaté (Figure 4a), southeast coast of Grande Terre and the Méridien Resort, Isle of Pines, southernmost island of New Caledonia (Figure 4b)~~.

~~-~~The first video from Yaté~~,~~ (Figure 4a), southeast coast of Grande Terre, circulating on social networks the day of the event, is very informative. It shows the arrival of the tsunami over the fringing reef shelf exposed out of

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the water by a first important withdrawal of the sea between ~100 and 200 m; note that the sea was reaching nearly high tide at the moment of the tsunami arrival with a predicted maximum water level of 1.55 m at 4:31 PM local time at Ouinné, the nearby tide gauge, corresponding to a water depth of ~1.2-1.3 m over the reef shelf in Yaté. Two quantitative information come from the video analysis. The first one is an estimate of the tsunami speed from ~ 5 to 10 m.s^{-1} (18 to 36 km.h^{-1}). The second one is the maximum tsunami height of ~2.3 m reached in ~20 s (after the withdrawal), derived using one isolated mangrove tree exploited as a flood scale afterwards (Figure 4E).

The second video and additional pictures show the tsunami arrival and consequences at Le Méridien Resort (Figure 4b), Isle of Pines, southernmost island of New Caledonia and have been provided courtesy of M. Bretault (Technical Director of Le Méridien Resort of the Isle of Pines). The video shows the tsunami travelling into the shallow channel that encircles the resort complex and its surrounding~~.~~ (Figure 4B1). With the help of aerial orthophotos (Government of New Caledonia, tile n°55-17-IV, https://georep-dtsi-sgt.opendata.arcgis.com/pages/orthophotographies), one can derive the tsunami speed in the channel of around 5 m.s^{-1} (18 km.h^{-1}). The pictures have been taken after the tsunami and reveal the damages on several bungalows and around the swimming pool, and show the run-up extent of the waves (Figure 4B2).

In Vanuatu, the tsunami has been reported in several places from Aneityum Island in the south, to Tanna, and Efate Islands. It reached Aneityum first, where the impact has probably been the worse in the whole concerned region by this tsunami, especially in Umetch area where it washed ~~literally the village~~the coast and the plantations with waves reaching ~4 m (Tari and Siba, 2019) and penetrating more than 200 m inland (Vanuatu Daily Post, December 6, 2018) as shown on Figure 4c, leaving people homeless. It has also badly damaged Mystery Island and its airport on the southwest of Aneityum, a major source of incomes for the island. Other places like Anelghowhat have also experienced the tsunami but without important damage~~s~~ as reported in the Vanuatu Daily Post (December 8, 2018). Then it reached Tanna where it has been recorded by Lenakel tide gauge as reported hereabove but it has also been reported by the manager of Ipikel, a village on the southeastern coast of the island (Sulphur Bay), as having reached the first houses without any damage~~s~~, about 80 m from the shoreline and ~1.5 m high (Isaac, manager of Ipikel, pers. comm., 2019). In Efate, witnesses reported a small inundation on Erakor Island, south of Port Vila (Figure 4d).

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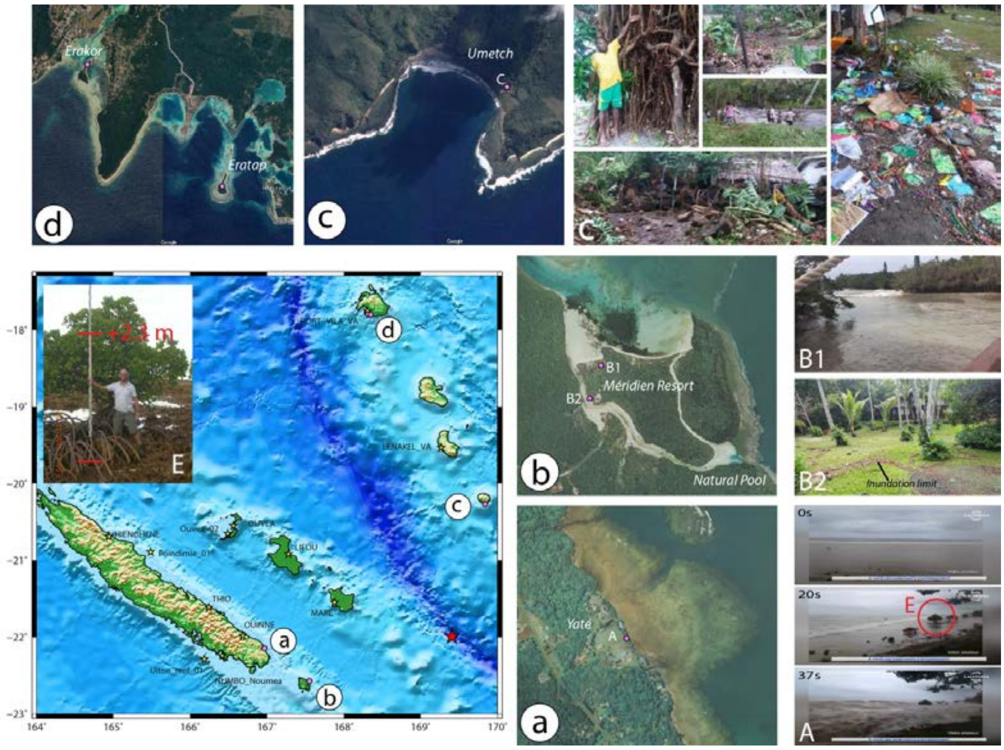

Figure 4: Observations of the tsunami arrival and height in several places in New Caledonia and Vanuatu. a: Yaté; b: Pine Island-Meridien Resort; c: south Aneityum, d: south of Port Vila, south Efate. (Photos credit: a, b: © Georep New Caledonia 2021; c, d: © Google Earth 2021 - CNES/Airbus; A: Caledonia TV; B1 & B2: Moana Bretault; C: Vanuatu Meteorology and Geohazards Department; E: authors).

~~3~~ 4 Tsunami modelling

~~Numerical models are commonly used to assess the tsunami hazard.~~ In this section, details about the Digital Elevation Model (DEM) used in computational grid generation, ~~a suite of~~ models used to simulate bottom deformation, tsunami generation and propagation and ~~their settings are presented, including details about the Digital Elevation Models (DEM) used in computational grid generation. Tsunami modelling~~ sensitivity tests to detail the rupture model ~~is~~ are presented. ~~and~~ ~~f~~~~Finally, tsunami simulation results are compared to tide gauges records and/or observations.~~

~~3~~4.1 Input data

~~3~~4.1.1 Bathymetric grids

It is well known that tsunami's behavior is dependent upon the bathymetric features and the coastal geometries (e.g., Matsuyama, 1999; Hentry et al., 2010; Yoon et al., 2014). When it approaches coastlines or seamounts, the wave shoaling leads to the rising-up of the amplitude and slows down the tsunami as the water depth reduces. It is even worse when the tsunami enters harbors, bays, lagoons or fjords able to produce resonance, a phenomenon particularly well studied during the two last decades (e.g., Barua et al., 2006; Rabinovich, 2009; Roger et al., 2010; Roeber et al., 2010; Bellotti et al., 2012; Vela et al., 2014; Aranguiz et al., 2019). It is also possible that a resonant behavior occurs between neighboring islands like it happened in Hawaii during the 2006 Kuril tsunami (Munger and Cheung, 2008).

For these reasons, it is necessary to model tsunami propagation on bathymetric grids keeping the most relevant details. There are two main traditional downscaling strategies in wave and tsunami modelling. One uses a sequence of nested structured-grid models; the other relies on a single unstructured-grid model. Both techniques aim at obtaining high-resolution wave fields in shallow area and provide similar results (Harig et al., 2008 ; Pallares et al., 2016), even if several studies have highlighted that the use of only one unstructured mesh grid for tsunami modelling provides better reproduction of tsunami observations and records in comparison to nested grids scheme use (e.g. Harig et al., 2008; Shigihara and Fujima, 2012). When considering the presence of many archipelagos forming the Melanesian volcanic arc (Solomon Islands and Vanuatu, Figure 3) and peculiar details along the New-Caledonia's coastline (Figure~~s~~ 4), the unstructured grid method provides multiple advantages. This technique allows more flexibility in mesh design and can capture more coastline details than regular meshes at the same computational cost.

~~In this study, bathymetric grids have been built using: 1) Smith and Sandwell (1997) v. 8.2 dataset, 2) an extended ~180 m resolution DEM covering the whole economic zone of New Caledonia and Vanuatu produced especially for the assessment of tsunami hazard in New Caledonia and 3) 10 m resolution data on harbors where tide gauges and/or witnesses' observations are located. These latest data are coming from digitized nautical charts, aerial pictures interpretation and multibeam bathymetric surveys. The first grid consists of a 7 km resolution regular grid covering the source area and it is mainly used to model the bottom deformation using the Okada's fault plane model (Okada, 1985). ~~The b~~second one~~athymetric grid is an unstructured mesh forming a triangular irregular network (TIN) DEM (Figure 5~~a, b and c~~) with varying mesh size (from 5 m along the coastline to 2150 m in the deep ocean, with a median value of 70 m, corresponding to the target size for grid resolution along the coastline), ~~and is ~~used for calculation of tsunami generation, propagation and interaction with the shallow water features.

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The TIN DEM generation has been made with Shingle 2.0 (Candy and Pietrzak, 2018), an automatic grid generation algorithm, using: 1) Smith and Sandwell (1997) v. 8.2 dataset, 2) an extended ~180 m resolution DEM covering the whole economic zone of New Caledonia and Vanuatu, based on single and multibeam echosounder data and produced especially for the assessment of tsunami hazard in New Caledonia and 3) 10 m resolution data on harbors where tide gauges and/or witnesses' observations are located. The~~se~~is latest data ~~are~~ ~~coming~~comes from digitized nautical charts, aerial pictures interpretation and multibeam bathymetric surveys. ~~.~~A variable mesh size function is designed to capture the evolution of the tsunami wave with a spatial discretization of 30 points per wavelength. Along the coastline or places with shallow features and gauge stations, additional mesh refinement rules are imposed in the mesh size function. Figure 5b, 5c and 5d~~c~~ ~~show~~ illustrate the increase of spatial resolution when approaching the barrier reef and the coastline.

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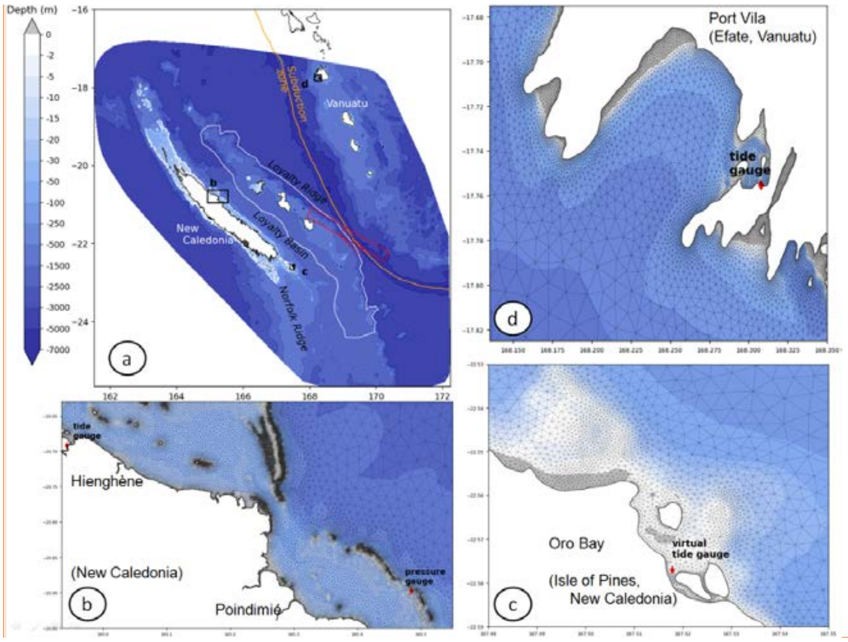

Figure 5: Triangular irregular network (TIN) DEM including New Caledonia and South Vanuatu Islands. The three insets show mesh details and location of some gauges (see black boxes b, c and d for exact location). In a), extents of both the non-uniform and uniform slip models considered in this study are displayed with solid and dashed red lines respectively. The white contour indicates the area of the Loyalty Ridge where the ocean bottom is modified to further investigate the impact of this ridge on the wave propagation (see Discussion and Figure 10).

~~3~~4.1.2 ~~Earthquake parameters~~Initial deformation

The location of the March 5, 2018 earthquake and the different focal mechanism solutions indicate that the earthquake was the result of shallow normal faulting along a fault plane trending NW-SE within the plunging Australia Plate on the northern border of the Loyalty Ridge. USGS, GCMT and GEOSCOPE (SCARDEC) propose a magnitude M_w 7.5 to 7.6 and parameters for the rupture (strike, dip, rake) of respectively [298°, 43°, -111°], [312°, 36°, -90°] and [297°, 55°, -108°].

Analysis of seismic data by USGS indicates a rupture duration of about 50 s and 3 phases of displacement during the rupture (https://earthquake.usgs.gov/earthquakes/eventpage/us1000i2gt/finite-fault). Using inversion in the wavelet domain of teleseismic broadband data and long period surface waves (Ji et al., 2002), USGS proposes a non-uniform fault model (called NUM hereafter) ~~(strike 298°, dip 43°)~~ of 272 km x 40 km composed of 272 fault segments of 8 km x 5 km with a slip ranging from a few millimeters up to 3 m mainly distributed in the 15 km upper part of the fault plane (hypocenter being at 12 km) and a maximum displacement patch at an along strike distance around 40 km northward of the hypocenter. All segments have the same orientation parameters for azimuth (298°) and dip (43°).

Considering the variability of parameter values, the geological and tectonic context and the effects of the tsunami along the shores of New Caledonia, as well as the role played by submarine features in the tsunami propagation, sensitivity tests have been computed through uniform slip rupture scenarios to assess the importance of each

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Formatted: No underline, Font color: Auto, Subscript seismic parameters on the tsunami amplitude at key locations. A uniform slip model scenario (called UM hereafter) based on the GCMT solution has been built choosing its parameters in agreement with the geological knowledge of the region and the empirical relationships from Strasser et al. (2010) and Blaser et al. (2010). These relationships link the earthquake seismic moment magnitude to the geometry of the fault plane considering the faulting condition (interslab or intraslab). It helps to estimate a rupture length *L* of 80 km and a rupture width *W* of 30 km (i.e. a rupture surface *A* of 2400 km²) corresponding to the seismic moment M_o of 2.52 e+20 N-m estimated by GCMT. The relationship $s = \frac{M_0}{\mu A}$ gives the coseismic slip on the fault plane s = 3.5 m with a rigidity (or shear) modulus μ of 3 x 10^{11} dyne cm^{-2}.

Each seafloor initial deformation has been computed using the Okada (1985)'s static surface deformation analytical expressions modelling an earthquake rupture in an elastic half-space. The shape of this initial deformation is directly linked to essential parameters like the depth of the hypocenter and the movement on the fault plane. This initial deformation is transmitted to the water surface above for further tsunami simulations assuming an incompressible fluid.

Table 1 details fault geometries and orientation parameters (Φ: strike, δ : dip and λ: rake) for NUM and UM.

Table 1 : Rupture parameters used for each scenario NUM and UM.

Scenario	Length	Width	Moment	Depth	Slip distribution	Strike	Dip	Rake
NUM	272 km	40 km	2.49 e+20 N-m	4 to 28 km	0 to 3.0 m	298°	43°	-80° to -150°
UM	80 km	20 km	2.52 e+20 N-m	17 km	3.6 m	312°	36°	-90°

As there is a large body of evidence that small changes in Φ, δ and λ angles may impact both the wave propagation over rugged seafloor (for example see Burbidge et al. 2015) and amplitudes of leading tsunami waves in exposed points (Necmioglŭ and Özel, 2014), sensitivity tests have been also conducted using different sets of fault orientation parameters. As detailed in Table 2, we use variations in Φ/ δ /λ angles from values used in the UM case. The range of tested values for Φ/δ /λ is based on the geological knowledge of the region's faults.

Table 2 : Rupture orientation parameters investigated in sensitivity tests

Strike (Φ, degrees)	Dip (δ, degrees)	Rake (λ, degree
290.0/298.0/305.0/312.0/320.0	25.0/36.0/43.0/55.0/60.0	-120.0/-110.0/-100.0/-90.0/-80.0

~~Most of tsunami modelling codes are using Okada (1985)'s surface deformation expressions related to an earthquake rupture. The calculation of this deformation is directly linked to crucial parameters like the depth of the hypocenter and the movement on the fault plane.~~

~~Several locations of the hypocenter as well as magnitudes and focal mechanism solutions for the December 5, 2018 earthquake have been proposed by the different observatories (USGS, GCMT, IPGP/SCARDEC). However, there are quite similar: a M_w 7.5 to 7.6 normal fault type event along the northern border of the Loyalty ridge entering the subduction zone. Considering the geological and tectonic context and the effects of the tsunami along the shores of New Caledonia, the parameters the authors have decided to use for this study are~~

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~~issued from the GCMT catalog: latitude -21.95°S, longitude 169.25°E, depth 17 km, strike of the ruptured fault plane 312°, dip 36° and rake -90°.~~

~~Taking a rupture length *L* of 80 km, a rupture width *W* of 30 km, (a surface *A* of 2400 km²), a M_o of 2.52 e+20 N-m and a rigidity (or shear) modulus μ of 3 x 10^{11} dyne cm^{-2}, the relationship~~ ~~$s = \frac{M_0}{\mu A}$~~ ~~gives the coseismic slip on the fault plane *s* = 3.5 m. A uniform slip distribution along the fault plane is considered in the modelling exercise.~~

~~3.2 Numerical modelling strategy~~

~~3.2.1. Seafloor deformation calculation~~

~~Most of tsunami modelling codes are using Okada (1985)'s surface deformation expressions related to an earthquake rupture. The calculation of this deformation is directly linked to crucial parameters like the depth of the hypocenter and the movement on the fault plane.~~

~~The seafloor deformation is derived using the Okada (1985)'s fault plane model implemented in the bottom deformation module of MOST (Method Of Splitting Tsunami, Titov and Synolakis 1995, 1996, 1997). Different fault plane parameters are tested with this module onto the 7 km computational grid to provide Okada's static solutions noted b0 hereafter. Then, these bottom motion solutions are added to the TIN DEM for further tsunami simulations.~~~~the parameters the authors have decided to use for this study are issued from the GCMT catalog: latitude -21.95°S, longitude 169.25°E, depth 17 km, strike of the ruptured fault plane 312°, dip 36° and rake - 90°.~~

~~Taking a rupture length *L* of 80 km, a rupture width *W* of 30 km, (a surface *A* of 2400 km²), a M_o of 2.52 e+20 N-m and a rigidity (or shear) modulus μ of 3 x 10^{11} dyne cm^{-2}, the relationship~~ ~~$s = \frac{M_0}{\mu A}$~~ ~~gives the coseismic slip on the fault plane *s* = 3.5 m. A uniform slip distribution along the fault plane is considered in the modelling exercise.~~

~~3~~4.2~~32.2.~~ Tsunami generation and propagation modelling

Tsunami waves generated by the ~~moving~~ seafloor displacement and their propagation are computed using the Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM), an unstructured ocean model developed by the Virginia Institute of Marine Science (Zhang et al. 2015, 2016a) based on the former 3D ocean model SELFE from Zhang and Baptista (2008). It is an open-source community-supported ocean model heavily tested and under continuous improvement in laboratories worldwide, oriented towards a handful of different modelling domains using specific modules like wind-wave modelling (e.g. Roland et al., 2012; Hsiao et al., 2020), sediment transport modelling (e.g. Pinto et al., 2012; Lopez and Baptista, 2017) or tsunami modelling (e.g. Zhang et al., 2016b; Priest and Allan, 2019). Modelling of tsunami propagation and coastal interaction is performed through unstructured grids like TIN. Inundation could also be calculated but the authors have decided not to do it due to the ~~bad quality~~inadequacy of topographic data. According to Horrillo et al. (2015), SCHISM has passed successfully the United States of America NTHMP (National Tsunami Hazard Mitigation Program)

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benchmarks from the OAR-PMEL-135 standard providing a list of ~~problems ~~exercises like the famous 1993 Okushiri tsunami exercise (https://nctr.pmel.noaa.gov/benchmark/index.htm~~l~~l).

SCHISM is capable of solving the 3-D Reynolds-Averaged Navier-Stokes (RANS) equations. It uses a semi-implicit Galerkin finite-element and finite-volume method on unstructured grids (Zhang and Baptista, 2008; Zhang et al., 2016a, 2016b) with time stepping with no CFL (Courant-Friedrich-Lewy) stability/convergence condition. This way, large time steps could be applied even with high resolution meshes. In this study, SCHISM is used in barotropic mode with hydrostatic assumption and ~~only ~~one layer. In 2-D mode, RANS equations are depth-integrated, and the circulation is described using Non-linear Shallow-water Wave equations (NSW), a simplification widely used to model tsunamis. Neglecting wind stress, earth tidal potential and atmospheric pressure forces, the NSW equations used in SCHISM 2-D at point (x,y) with depth h below the geoid are :

Continuity equation: $\frac{\partial(\eta - b)}{\partial \mathrm{t}} + \nabla.(\mathrm{uH}) = 0$

Momentum equation: $\frac{\partial \mathrm{u}}{\partial t} + (\mathrm{u}.\nabla)\mathrm{u} = f(v, -u) - g\nabla\eta - f_{hd} - \frac{\tau_b}{H}$

Here, *t* is time, u(x,y,t) the depth averaged horizontal velocity with components (*u*,*v*), η the sea surface elevation above the geoid, *b* the seabed displacement (positive for uplift), H the total water depth ($H=\eta-b+h$), *f* the Coriolis factor, *g* the gravity acceleration, f_{hd} the horizontal eddy viscosity (set to 10^{-4} $m^2.s^{-1}$) and τ_b the bottom drag following a quadratic form:

$$\tau_b = g\frac{{M_n}^2}{H^{1/3}}\|\mathrm{u}\|\mathrm{u}$$

where M_n is Manning's roughness coefficient set spatially uniform with a value of 0.025 $s.m^{-1/3}$. All tsunami simulations were performed assuming that prevailing tide was static (no flow) and equal to high water (+1.6m). To limit undesirable wave reflection, a Flather radiation condition (Flather, 1987) is applied along the open boundaries with specified outer values 0 $m.s^{-1}$ and 1.6 m for U and η respectively.

In a first step, SCHISM is used to generate the sea-surface initial deformation and flow dynamics in response to the bottom motion. The dynamic displacement of the seafloor can be described in SCHISM by adding a time dependent seafloor displacement term *b* incorporated in NSW governing equations. This is done by multiplying Okada's static solution b_0 by a uniform rate function of the rising time. In agreement with seismic records, ~~we ~~a rising time of~~used~~ 50 s ~~for the rising time~~has been used and ~~ran ~~SCHISM was run with a time stepping dt = 1 s. During the rising time, the seafloor anomaly b_0 is progressively injected to give the initial condition for the free surface and horizontal momentum conditions. Then, to simulate tsunami propagation, the model runs with dt = 30 s for a duration of 3 hours. It is worth noting that using the default value of 10 s for the rising time, like ~~done~~ used by many authors, ~~gives ~~leads to marginal effects on results.

To detect changes due to fault parameters, total wave energy (*E*, unit j.m-2) is added in SCHISM outputs, as the sum of two components, kinetic energy (first term) and gravitational potential energy (second term):

$$E = \frac{1}{2}\rho H U^2 + \frac{1}{2}\rho g \eta^2$$

It is ~~again~~ important to underline that the sea-level has been set to a high tide value of 1.6 m, which was approximately ~~corresponds to~~ the situation in most places when the tsunami reached New Caledonia and Vanuatu on December 5, 2018.

~~3.3~~5 Simulation results

5.1 Waves energy

Figure 6 presents the maximum wave energy maps obtained after 3 hours of tsunami propagation over the TIN DEM for ~~the USGS non uniform slip model (~~NUM and ~~) and a uniform slip model incorporating the GCMT solution (~~UM~~)~~. The first observation is that NUM is accompanied by much less tsunami wave energy than UM. Within the two tsunami beams propagating from the rupture location, there are differences in wave energy higher than 10% in the deep ocean. But, in shallow areas, like banks and seamounts near the rupture, there is a 100% change. In exposed locations, like Isle of Pines and Aneityum in the SW and NE quadrants, respectively, wave energy anomalies are higher than 50%, implying lower simulated wave amplitudes in those locations using NUM instead of UM. It is also very striking that despite its proximity and facing the NUM rupture fault, simulated wave energy along the western coast of Maré is lower compared to UM.

The second observation is that, ~~I~~in both cases, the maximum wave energy field is mainly oriented in the direction perpendicular to the ~~strike~~azimuth of the fault, i.e. NE-SW, with respect to the slip angle (=rake) (Okal, 1988).

Even if it is less obvious for NUM than UM, the wave energy is clearly captured by the Loyalty Ridge, which supports the Loyalty Islands, and the Norfolk Ridge which is the extension of the Grande Terre of New Caledonia towards the south. ~~It highlights the important role played by the strike angle of the fault plane. This parameter should absolutely be chosen accurately in good agreement with the geology. A 298° (USGS) and a 312° (GCMT) strike will lead to a different behavior of the tsunami, focusing its main energy path generally perpendicularly to the strike of the fault plane with respect to the slip angle (=rake) (Okal, 1988). But if the waves encounter submarine features like seamounts or ridges, the trajectory of the tsunami could be dramatically modified as these features act as wave guides,~~ This refocusing of the wave train in another direction is due to the fact that the tsunami speed relies only on the bathymetric depth in the open ocean (Satake, 1988; Titov et al., 2005; Swapna and Srivastava, 2014). Thus, if the waves encounter submarine features like seamounts or ridges, which means that the sea depth decreases, the trajectory of the tsunami could be considerably modified. In the present case, the Loyalty and Norfolk Ridges acting like waveguides help the waves to propagate in the azimuthal direction toward the northwest (Loyalty Islands and Grande Terre).

~~That is exactly what happens in the presented case: the 312° strike proposed from the CGMT observatory sends larger wave energy towards the south of New Caledonia (Isle of Pines) than the 298° strike from USGS.~~In addition, the sensitivity analysis of the azimuth of the composite source from 290° to 320° shown on figure 7 underlines that, keeping all other parameters stable, the wave amplitudes recorded at some key locations like in front of Le Méridien Resort Isle of Pines (New Caledonia) or at Mystery Island (Aneityum, Vanuatu) can vary by more than 40%. It is the same with the dip and rake to a lesser extent: variations of the dip from 25° to 60° and of the rake from -120° to -80° lead to variations of the wave amplitude range of respectively 20% and 30% in the same locations.

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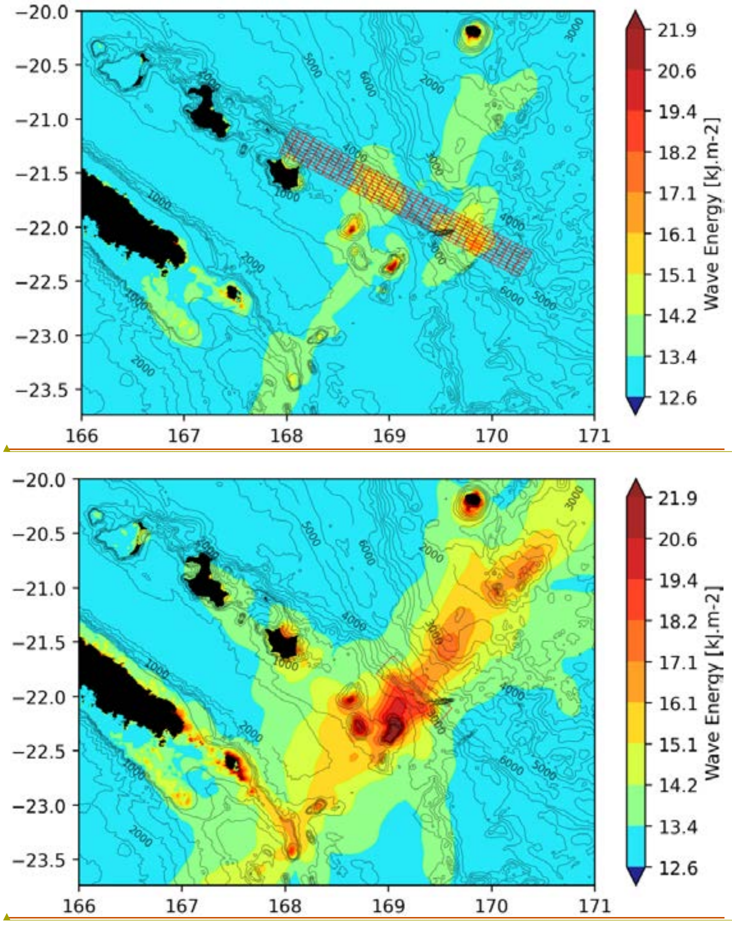
The wave energy difference between the two models shown on figure 6 highlights that the main coastal differences concern the Isle of Pines, Maré and Aneityum within a range of 20 to 60% more energy from UM. Along the east coast of the Isle of Pines, the energy increase ~~in energy~~ is in the range 20% to 30% and up to 50% near specific coastal features like bay entrances ~~(15 to 25 kJ.m^{-2} there with CGMT settings)~~. Along the south coast of Aneityum, the ~~only~~ closest observation site ~~located in~~in the main energy path of the tsunami, the total wave energy ~~decreases~~ increases by about ~~10~~30%~~. (20 to 30 kJ.m^{-2} there with CGMT settings). Naturally, the choice to keep the CGMT solution allows to keep maximum energy toward the Isle of Pines without reducing drastically the energy sent toward Aneityum.~~



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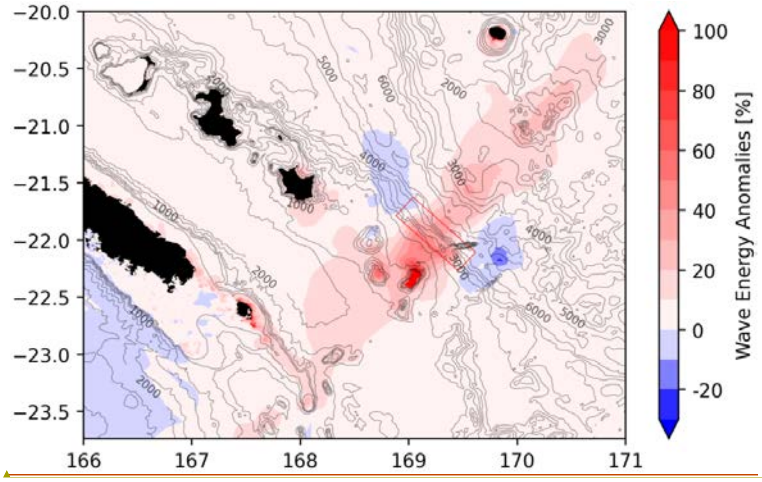

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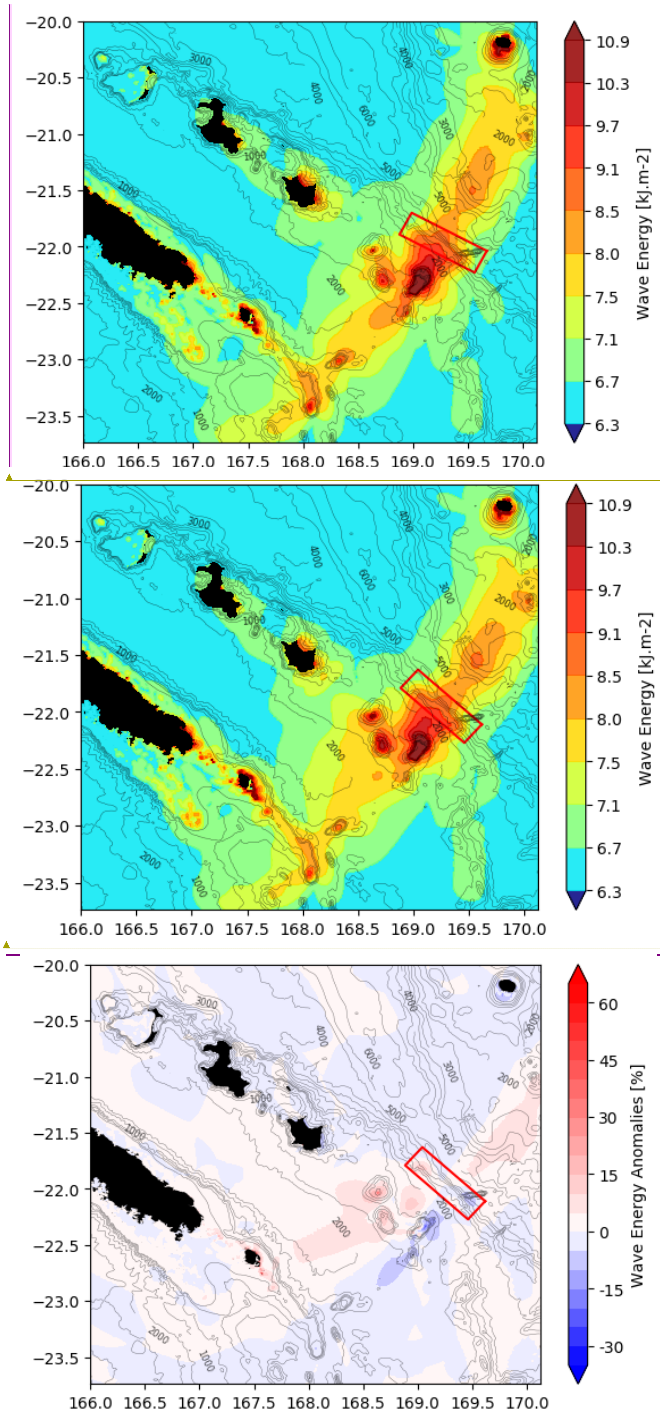

Figure 6: Total wave energy ~~E~~ maps for two different~~ strikes~~ models: ~~298° (top~~left, ~~USGS non uniform slip settingsmodel (~~NUM~~)~~ with strike = 298° (top)~~)~~ and ~~312° (center~~right, ~~GCMT uniform slip model (~~UM~~settings~~) with

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strike = 312° (middle) and relative ~~E~~ energy anomaly between the two (bottom)~~.~~. The bathymetric contours underline the features ~~able to influence the~~playing a possible role in tsunami wave propagation. The extent of the sources is symbolized ~~by~~with the ~~black~~red rectangles:~~.~~ small boxes (top) denote the 272 fault segments solution from USGS where heterogeneous slip distribution (NUM) is applied along a 270km long rupture fault. In the UM case (middle), uniform slip deformation is applied over the 80km long rupture model.

5.2 Tide gauges' records

Simulated time series of sea level variation from the two scenarios are compared to maregraphic records on Figure 7. Clearly, at all stations, NUM does not fit well the recorded amplitudes: the simulated amplitudes of the first leading waves are very low in comparison to records. In terms of arrival times, it is globally in good agreement with the UM scenario except for Maré, as a consequence of the exaggerated extension of the rupture fault toward this island provided by USGS. There is some evidence that the heterogeneous slip distribution and geometry from USGS is not appropriated and a simple model for rupture like UM is still more justified for that event. In this basis, further investigations will continue with UM leaving aside the NUM scenario.

Synthetic time series obtained with UM show that,

- at Tadine, Maré, the modelling is not able to reproduce correctly the tide gauge record in terms of arrival time and wave amplitude (Figure 9a). It shows a delay of ~5 min, the modelling being faster than the reality. Also, it does not reproduce the oscillation of period ~4-5 min with amplitudes more than three times those that are modeled.
- at Wé (Lifou), the simulated signal exhibits some strong similarities with the real one recorded in terms of polarity, wave amplitude and periodicity, but there is a delay of more than 5 minutes, the modelling being faster than the reality (Figure 9b).
- at Thio, the modelling is able to reproduce the real record for what concerns the polarity, the amplitude or the periodicity but not exactly the arrival time, being still early of a couple of minutes (Figure 9c).
- at Ouinné, the modelling is not able to reproduce the recorded signal, except for the first wave polarity, showing a strong delay of nearly 5 min, the modelling being the fastest (Figure 9d). An oscillation with a period of ~6-8 min seems to occur after the first arrival.
- at Poindimié - Passe de la Fourmi, there is a good agreement between the modelling and the reality: the arrival time only exhibits a small delay of 1-2 min, the modelled signal being the fastest (Figure 9e). The wave amplitude and polarity are quite good, and the periodicity shows only a few differences that will be discussed further.
- at Hienghène, there are differences in arrival time (~2-3 min) between the modelled and the real tide gauge records, the modelled one being the fastest (Figure 9f). The wave polarity and periodicity are well reproduced, but the amplitude is slightly overestimated by the modelling.
- in Vanuatu, at Lenakel, Tanna, there is good agreement between the arrival time and first wave amplitude of the modelled and real tsunami signal (Figure 9g). But the periodicity and amplitudes are strongly different, the modelling being unable to reproduce what looks like a resonant oscillation with a period of ~6 min and a maximum amplitude reaching nearly 40 cm around 25 min after the first tsunami wave arrival.
- at Port-Vila the simulated signal well reproduces the tide gauge record in terms of arrival time ~40 min after the earthquake (exhibiting only a small delay of ~1-2 min), but also in terms of polarity, wave

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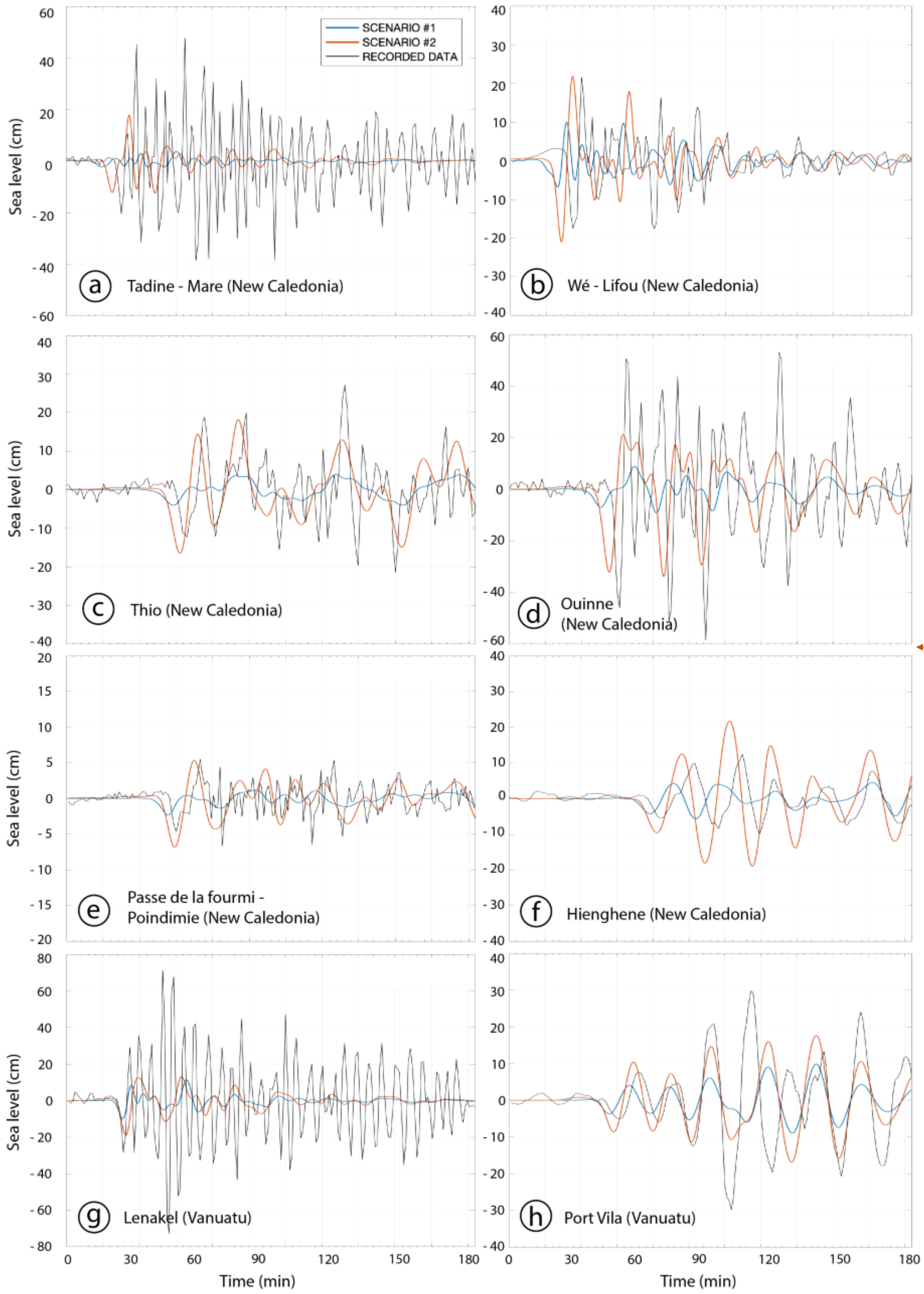
amplitudes and periodicity (Figure 9h). Note that the biggest through and peak occurring after 100 min are not sufficiently high in the simulation.

It is worth noting that sea level records from several stations located in bays and harbors exhibit large oscillations typical of harbor resonance triggered by the first leading waves. It is worth noting that with the actual model settings for SCHISM (30 nodes per tsunami wavelength and time step dt = 30 s), the model seems unable to reproduce resonance in harbor (Wé, Tadine, Lenakel) or semi-enclosed bay like Ouinné. Since such wave amplification processes represent a significant, but undocumented threat in New Caledonia, future works will be devoted to the representation of harbors and bay resonances due to tsunami with SCHISM.



605 Figure 7 : Comparison between real (black) and simulated records (blue: NUM; red: UM) for 8 different tide gauges located in New Caledonia (a, b, c, d, e, f) and Vanuatu (g, h). These tide gauges are located on figure 3b. Time is related to the earthquake occurrence time (4:18 UTC). Be careful to the sea level scale for each figure.

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5.3 Tsunami maximum wave amplitude

~~Thus, the following results have been obtained using a strike set to 312° (GCMT solution).~~

The tsunami energy is partially captured by the submarine ridges oriented perpendicular to its main propagation way, leading to amplifications in the Loyalty Islands (via the Loyalty Ridge) and around the Isle of Pines (via a series of seamounts and guyots constituting the south-eastern seamounts complex of the Pines Ridge). ~~The maximum wave amplitude shows the same pattern especially for scenario 2 (Figure 8a).~~ The TIN DEM allows zooming onto specific areas like Aneityum (Figure ~~7b~~8b), the Isle of Pines (Figure ~~7c~~8c), Yaté (Figure ~~7d~~8d), ~~and~~ Port-Vila (Figure ~~7e~~8e) and Sulphur Bay, Tanna Island (Figure 8f) helping to further compare the testimonials to the modelling results. ~~There is i~~Important coastal amplifications of the tsunami are located along the south coast of Aneityum from ~~Anelghowhat~~ Mystery Island to Umetch ~~(Figure 4c)~~, showing maximum wave amplitude of more than 1.5 m between Mystery Island and the main island (Figure ~~7b~~8b). Coastal amplification is also relatively important in some restricted locations along the east coast of the Isle of Pines (Figure ~~7c~~8c) showing wave amplitude of more than 1 m in front of the Le ~~Meridian~~ Méridien Resort but also ~ 40-50 cm in the bay of Ouameo on the west coast and the Crab's Bay in the north of the island. Wave amplification along the coast of Yaté (south-eastern part of Grande Terre, Figure ~~7d~~8d) leads to maximum wave amplitude of ~50 cm in front of the church of Touaourou and in the Yaté River estuary. ~~Finally, f~~Focus on Port-Vila, located along the south coast of Efate Island (Figure ~~7e~~8e) and on Sulphur bay, southeast of Tanna Island (Figure 8f), show wave amplification in a few places, reaching ~40 cm maximum in both cases.

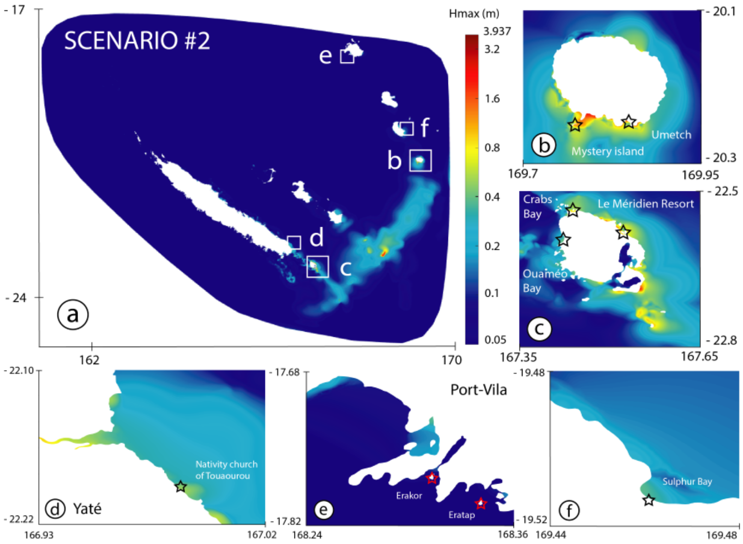

Figure 8: Maximum wave ~~height~~ amplitude maps (H_{max}) obtained after 3 hours of tsunami propagation on the TIN DEM for scenario ~~1 (NUM: top) and~~ 2 (UM~~: bottom~~) ~~the December 5, 2018 event~~ in New Caledonia and South Vanuatu. a: ~~for~~ across the entire area, b: Aneityum island, c: Isle of Pines, d: Yaté; e: Port vila, Efate; f: Sulphur Bay, Tanna. Stars stand for eye-witnesses observation points.

~~Tide gauge simulation results of the two scenarios are compared to real maregraphic records on~~ ~~Figure 9~~Figure 8~~. For Maré, Ouinné, Thio and Hienghène, the data shown are coming directly from the raw dataset of the~~

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~~pressure sensors. For Lifou, the data have been provided by the SHOM (http://refmar.shom.fr/en/lifou). The data shown for Lenakel and Port Vila are coming from the IOC database (www.ioc-sealevelmonitoring.org/) and the data from Poindimié are coming from a local New Caledonia coastal water monitoring project (ReefTEMPS project: http://www.reeftemps.science/en/data/)~~.

~~At all the tide gauges, the scenario from the USGS non uniform slip model does not fit the recorded amplitudes. Concerning the results obtained with the uniform slip model,~~

- ~~at At Tadine, Maré, the modelling is not able to reproduce correctly the tide gauge record in terms of arrival time and wave amplitude (Figure 8a9a). It shows a delay of ~5 min, the modelling being faster than the reality. Also, it does not reproduce the oscillation of period ~4-5 min with amplitudes more than three times those that are modeled.~~
- ~~At at Wé (Lifou), the simulated signal exhibits some strong similarities with the real one recorded in terms of polarity, wave amplitude and periodicity, but there is a delay of more than 5 minutes, the modelling being faster than the reality (Figure 8b9b).~~
- ~~aAt Thio, the modelling is able to reproduce the real record for what concerns the polarity, the amplitude or the periodicity but not exactly the arrival time, being still early of a couple of minutes (Figure 8c9c).~~
- ~~aAt Ouinné, the modelling is not able to reproduce the recorded signal, except for the first wave polarity, showing a strong delay of nearly 5 min, the modelling being the fastest (Figure 8d9d). An oscillation with a period of ~6-8 min seems to occur after the first arrival.~~
- ~~aAt Poindimié – Passe de la Fourmi, there is a good agreement between the modelling and the reality: the arrival time only exhibits a small delay of 1-2 min, the modelled signal being the fastest (Figure 8e9e). The wave amplitude and polarity are quite good, and the periodicity shows only a few differences that will be discussed further.~~
- ~~aAt Hienghène, there are differences in arrival time (~2-3 min) between the modelled and the real tide gauge records, the modelled one being the fastest (Figure 8f9f). The wave polarity and periodicity are well reproducedreproduced, but the amplitude is slightly overestimated by the modelling.~~
- ~~Iin Vanuatu, at Lenakel, Tanna, there is good agreement between the arrival time and first wave amplitude of the modelled and real tsunami signal (Figure 8g9g). But the periodicity and amplitudes are strongly different, the modelling being unable to reproduce what looks like a resonant oscillation with a period of ~6 min and a maximum amplitude reaching nearly 40 cm around 25 min after the first tsunami wave arrival.~~
- ~~Aat Port Vila the simulated signal well reproduces the tide gauge record in terms of arrival time ~40 min after the earthquake (exhibiting only a small delay of ~1-2 min), but also in terms of polarity, wave amplitudes and periodicity (Figure 8h9h). Note that the biggest through and peak occurring after 100 min are not sufficiently high in the simulation.~~

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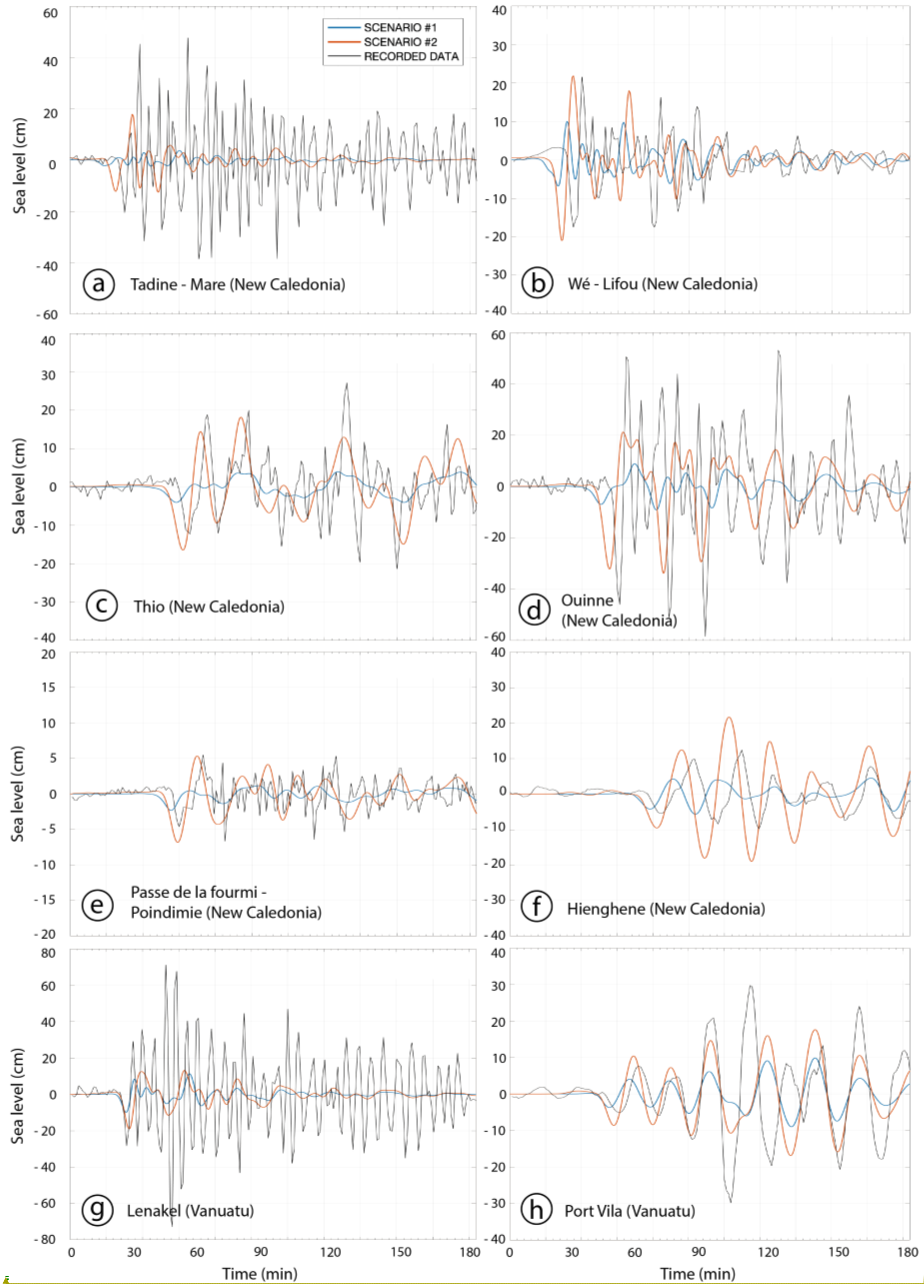

~~Figure 98: Comparison between real (black) and simulated (red) records (blue: NUM; red: UM) for 8 different tide gauges located in New Caledonia (a, b, c, d, e, f) and Vanuatu (g, h). These tide gauges are located on figure 3b. Time is related to the earthquake occurrence time (4:18 UTC). Be careful to the sea level scale for each figure.~~

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5.4 Sensitivity study

Table 3 and Figure 9 detail model results concerning the sensitivity of uncertainties in fault angle parameters (Φ: strike, δ: dip and λ: rake) on the maximum generated tsunami wave amplitude (H_{max}) and tsunami travel time (TTT) at key locations in New Caledonia and Vanuatu. Table 3, row a., gives the range of variation for all key locations for both H_{max} as a function of Φ, δ and λ. In general, changing azimuth (Φ) of the UM source from 290° to 320° and keeping all other parameters stable, result in large variations in exposed locations like in front of Le Méridien Resort Isle of Pines (New Caledonia) or at Mystery Island (Aneityum, Vanuatu) with change of about 62 and 86% respectively. It is the same with the dip and rake to a lesser extent: variations of the dip from 25° to 60° and of the rake from -120° to -80° lead to relative variations of H_{max} of about 20% and 55% respectively at the same places. It is worth noting that the location exhibiting the largest change to strike angle uncertainties (with a 100% change) is We, Lifou, aligned with the rupture fault. But, in term of strike sensitivity ($\frac{dH_{max}}{d\Phi}$), the slope computed from linear regression between H_{max} and Φ (see relationships on Figure 9, left panel), the sensitivity to Φ at exposed location like Isle of Pines is twice the value at We, Lifou (1.2 against 0.6 cm.degree^{-1} respectively).

But uncertainties in Φ/δ/λ angles have also significant control on the arrival time of the first leading wave as investigated in Table 3, row b. and in the right panel of Figure 9. Results indicate that it is the dip angle δ that could exert large variation in TTT, with variations up 5 to 6 minutes at Hienghène and Port-Vila, the more remote location from the rupture fault considered in the model domain. Obviously, possible uncertainties in Φ/δ and λ may explain some lags between model results and observations.

	Hienghène	Poindimié	Thio	Ouinné	We, Lifou	Tadine, Maré	Yaté	Meridien Res. Pines Island	Umetch, Aneityum	Mystery Isl., Aneityum	Lenakel, Tanna	Port-Vila, Efate
Row a. Maximum change in H_{max} in cm (in percent from the minimum value)												
Strike Φ [290:320]	0.5 (2.6)	0.7 (13.9)	2.8 (16.8)	6.1 (32.1)	18.3 (102.1)	5.6 (46.0)	6.9 (22.9)	40.7 (61.8)	39.2 (44.0)	47 (85.8)	2.5 (14.9)	0.8 (4.2)
Dip δ [25:60]	6.6 (49.1)	2.0 (61.5)	4.5 (34.3)	4.4 (20.4)	5.9 (32.7)	4.0 (28.5)	7.8 (28.6)	16.0 (19.0)	24.3 (27.4)	17.8 (29.0)	1.8 (11.8)	9.1 (56.1)
Rake λ [-120:-80]	1.2 (6.3)	0.4 (8.3)	2.1 (13.4)	8.0 (41.8)	0.8 (3.6)	2.4 (15.3)	5.2 (16.1)	15.6 (17.8)	16.8 (19.4)	26.1 (53.5)	1.0 (6.2)	0.5 (2.6)
Row b. Maximum change in TTT (minutes)												
Strike Φ [290:320]	2	0	0	1	2	1	2	3	2	1	2	1
Dip δ [25:60]	6	2	2	4	2	2	5	6	4	3	3	5
Rake λ [-120:-80]	4	2	2	2	2	1	1	0	2	1	2	3

Table 1 : Results of our sensitivity tests at keys locations using three sets of parameters acting on the rupture fault orientation. There are: strike, dip and rake with values incremented as detailed in Table 2. Row a.: impact on the maximum Elevation (H_{max}). Row b.: impact on the travel time (TTT).

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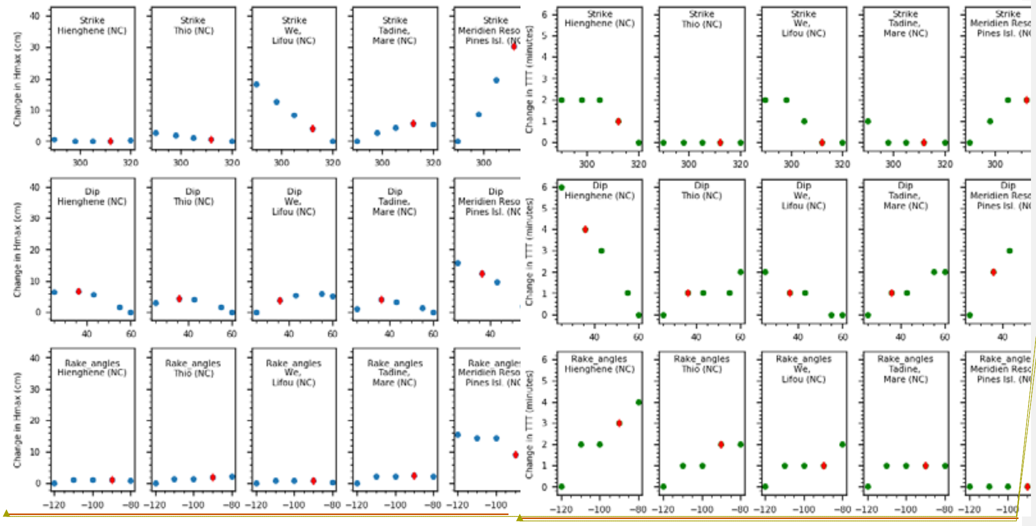

Figure 9 : Examples of relationship between H_{max} (left panel), or TTT (right panel) and the fault deformation angle (either strike, dip or rake). Results are extracted from the sensitivity tests at 4 places located in New Caledonia.

~~4~~ 6 Discussion

The comparison of the maximum energy path ~~of the tsunami as a function of strike on the energy maps shown on~~ derived from the two scenarios (~~F~~figure 6) and the sensibility tests shown on figure ~~7~~9 highlights ~~the fact~~ that UM exhibiting~~that~~ a 312° angle has a ~~slightly~~ bigger impact on the Isle of Pines and Aneityum Island matching much better with the observations than ~~Na~~ UM with an azimuth of 298°~~ angle~~. ~~The~~ In addition, the maximum wave height maps calculated over a high-resolution TIN grid (Figure ~~7~~8) clearly indicate~~s~~ that the modelling results obtained with UM are in good agreement with the direct observations of the tsunami in both New Caledonia and Vanuatu~~ on December 5, 2018~~. In fact, the coastal places where the modelling shows maximum amplitudes (> 0.4-0.5 m) are also the places where witnesses reported the tsunami (Isle of Pines, Aneityum, Yaté, Tanna, Erakor Island) and sometimes damages (Isle of Pines- Le Mé~~e~~ridien resort, Aneityum, Mystery Island and southern coast to Umetch.

In addition, the tide gauge record comparisons show that globally ~~the chosen seismic parameters~~the UM and therefore, the tsunami generation and propagation model, are together able to reproduce the tsunami records, in terms of arrival times ~~(Figures 8e, g & h)~~ especially in far-field location (Poindimié, Tanna and Port-Vila tide gauges) (Figures 9e, g & h), polarity (Figures ~~8b~~9b, d, e, f, g & h), and amplitude (Figures ~~8b~~9b, e & h).

Except for Poindimié-Passe de la Fourmi where there is pressure sensor offshore the reef barrier, the observed delay between the simulations and the reality (the modelled signal being always the fastest) on all the New Caledonia coastal tide gauges managed by the SHOM (hydrographic service of the French navy) is mainly explained by the fact that there are some transmission issues from the gauge to the datacenter. Also, it has been demonstrated that the waves slow down during propagation due to reverse dispersions for the long periods for

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numerous reasons not considered in the presented modellings, leading to delays between the observed and simulated travel times up to 15 minutes for transoceanic tsunamis (Watada et al., 2014).

–But small variations in fault orientation, like the dip for example, may also exert a control on the timing of the first leading wave in remote and shallow locations. As indicated in Table 3, in row.b, places outside the lagoon (Poindimié) or devoid of lagoon (Wé, Tadine) show little TTT sensitivity to dip variations, on contrary with Hienghène or Port Vila, indicating complicated interactions between changes in fault geometry and orientation parameters (Φ/δ/λ), seafloor details (like ridges and seamounts) and others geomorphological features (reef, lagoon, bay) on the tsunami wave propagation.

As a straightforward demonstration of the impact of both uncertainties in earthquake source parameters and influence of ridges on the wave propagation, two maps of $\frac{dH_{max}}{d\Phi}$ using slopes of the linear regression between H_{max} and Φ are provided. In Figure 10, left panel, the rugged seafloor of the Loyalty Ridge is simplified, with a flattening of shallow depths above 2500m (the flattened region is indicated on figure 5), while the original bathymetry is preserved in the right panel. From the map comparison, there is evidence that the Loyalty Ridge interacts with the tsunami waves at the first stage of propagation and that a part of tsunami energy is focused onto the Loyalty Ridge by wave refraction. Similar mechanism of refocusing is at work along the eastern flank of the New Caledonia Ridge (Norfolk Ridge), trapping a portion of tsunami energy toward the Loyalty Basin. Finally, as pointed out earlier using the H_{max}/Φ relationship at Wé (Lifou), locations aligned with the rupture fault have a large sensitivity to bottom features, in particularly the northeastern shore of Maré.

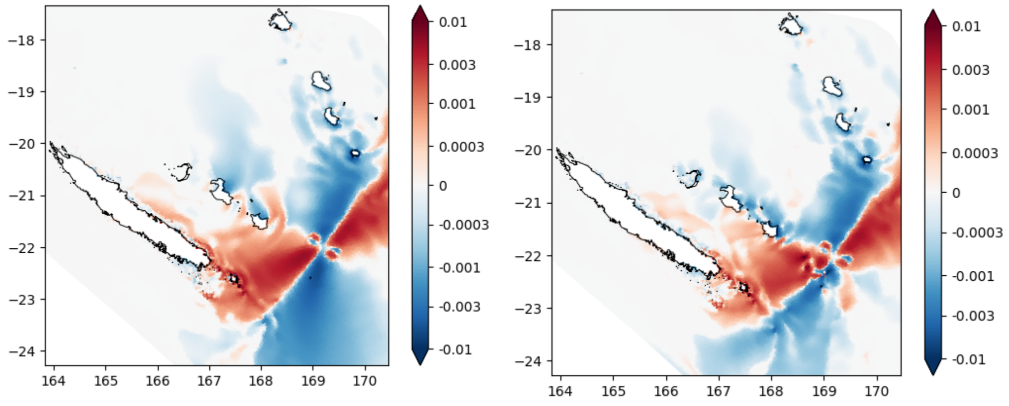

Figure 10 : Spatial distribution of $\frac{dH_{max}}{d\Phi}$ across the model domain for the case with the simplified Loyalty Ridge (left panel) ; the case with preserved bathymetry (right panel). Scalebar units are in cm/degree.

Concerning the high frequency oscillations that the model~~ling~~ is not able to reproduce, especially at Maré, Ouinné and Lenakel, it is presumably the result of resonant behavior of the tsunami waves interacting with semi-enclosed water bodies represented by Maré Harbor, Ouinné Harbor and Lenakel’s Bay, and fringing reefs as well explained for other places in the literature (e.g. Horillo et al., 2008; Rabinovich, 2009; Aranguiz, 2015). The fact that the high-resolution coastal zones surrounding the location of the tide gauges have been built from sparse

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Formatted: Font: 9 pt, Bold, No underline, Font color: Auto bathymetric data coming from low resolution nautical charts and aerial pictures interpretation could explain that the model~~ling~~ is not able to reproduce the resonance as the shape of the water bodies~~,~~ and thus their natural oscillation modes are not exactly the same. According to previous studies, it is a safe bet that either a source refinement (complex source showing slip heterogeneity for example) or high-resolution bathymetric data coming from multibeam or LIDAR surveys would be able to reproduce such phenomenon in these small and complicated places (e.g. Sahal et al., 2009; Vela et al., 2014).

Considering both maximum amplitude maps compared to the testimonials (locations and amplitudes) and the tide gauges simulation results comparison to the real recorded data, the simple fault plane rupture scenario chosen for this study provides quite good results compared to the more sophisticated one from USGS, based on heterogeneous slip distribution. Observed and simulated TTT at Maré may suggest that the USGS fault geometry is inappropriate. This raises questions about their fault model inversion results for that event and a need to devote more effort in the settings of accurate earthquake fault model at the Loyalty Ridge-Vanuatu Arc junction.

~~.~~

It is interesting to notice that, nearly two years after the tsunami occurred, hidden observations are still transmitted by witnesses. Tsunami modelling showing that the north and west coasts of the Isle of Pines would have also been impacted by the tsunami, several people were questioned during a field survey: a fisherman living at the Crab's Bay indicated that the sea receded from the bay and came back quickly in a rolling foam; ~~we questioned~~ the diving center and the Kodjeu Hotel located within the Ouaméo bay indicated~~: the final testimony is~~ that the diving club boat, supposed to be load at high tide, was laying on the sand instead at the exact arrival time of the tsunami (P.-E. Faivre, pers. comm., 2020). Then the water came back and the sea rose above its natural maximum reaching the foot of the trees (according to a local fisherman, 2019), measured ~1 m above high tide~~(according to a local fisherman, 2019)~~.

~~5~~ 7 Conclusions

~~The m~~Model~~ling~~ results presented in this ~~paper~~ study and dealing with the December 5, 2018 ~~South Vanuatu~~Tadine tsunami indicate that using a simple fault plane rupture scenario is enough in such case of near field event to reproduce the tsunami correctly ~~with a hazard management point of view~~in terms of maximum wave amplitude and polarity.

While there are some issues in simulated travel times, having serious implications for neighboring islands like Maré (TTT< 20 min), the more exposed places in New Caledonia (with Lifou and Ouvéa) to tsunami waves generated from the Vanuatu Subduction Zone, a probable origin may stem from inaccurate rupture parameters, like orientation angles, strike, dip and rake. The role of sharp changes in depth and tsunami wave refraction at the crossing of the Loyalty Ridge raises the question of wave energy refocusing and trapping toward the Loyalty Basin, as demonstrated by flattening the local bathymetry. The question of possible wave amplification due to refocusing and reflection within the New Caledonia Archipelago will deserve future investigations using SCHISM, in order to increase our local knowledge on tsunami hazards for remote and sheltered locations.

In terms of study perspectives, it would be interesting to investigate how tides and lagoon hydrodynamics interact with tsunami waves. The role played by the tide in tsunami impact has been demonstrated by several studies (e.g. Ford et al., 2014; Nakada et al., 2016). Such small amplitude event occurring at low tide could be dramatic as lots of people could be looking for shells and octopuses on the fringing reef.

Finally, considering the sea-level rise due to global warming in combination with storm surge or exceptionally high spring tides would also help to assess the future impact of small to moderate tsunami like the December 5, 2018, over island communities with a question that arises: would the growth of coastal ecosystems such as corals and mangroves be able to adapt quickly enough to rising sea level to maintain their protective role against small events?

~~In fact, tThe study of this local event helps to assess the accuracy of tsunami modelling with the open source MOST and SCHISM models SCHISM and also, the quality of the DEM used, especially the TIN DEM. Coupled with the study of other historical tsunamis (regional and ocean scales) also recorded on New Caledonia tide gauges, it represents the basement of the building of a scenario database, with tsunami sources located all around the Pacific Ocean ring of fire.~~

~~As In terms of study perspectives, it would be interesting to look at the tsunami effects at low tide, to compare to other similar events in terms of amplitude/periodicity that have absolutely not been perceived by the coastal population. tThe role played by the tide in tsunami impact has having been demonstrated by several studies (e.g. Ford et al., 2014; Nakada et al., 2016). Also, sSuch small amplitude event occurring at low tide could have been dramatic as lots of people are could be looking for shells and octopuses on the fringing reef. FinallyAlso, new modellings at high tide considering the sea level rise due to global warming would help to assess the future impact of such small tsunami over island communities with a question that arises: would the growth of coastal ecosystems such as corals and mangroves be able to adapt quickly enough to rising sea level to maintain their protective role against small events~~?

Comment [JR9]: JL : on peut introduire le PTHA ici

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Authors' contribution:

JR: study supervision; field investigations; DEM construction; ~~MOST~~ numerical modelling; writing; figures preparation.

BP: study supervision; field investigations; writing; figures preparation.

MD: unstructured grid construction; data processing; figures preparation.

JL: ~~MOST & SCHISM~~numerical modelling; writing; figures preparation.

JA: funding acquisition; data processing; results discussion.

PL: seismic data processing.

BT: mapping; data processing.

CB: seismic network maintenance.

DV: seismic network maintenance.

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