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The Island of Tubuai (French Polynesia) Landfall of Cyclone Oli on the 5th of February 2010

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Abstract

The Island of Tubuai (Australs Archipelago, South Pacific) was directly hit by the tropical cyclone (TC) Oli on February 5th, 2010. For the first time on an island in French Polynesia, we have been able to monitor the progress and the impact of TC Oli as revealed by the meteorological, GPS and sea level pressure data. TC Oli is one of the most intense cyclones that have crossed French Polynesia as evidenced by the pressure level that dropped to 957 hPa associated with wind gusts exceeding 180 km/h. Precipitable water time series deduced from the GPS data shows that the maximum occurred when the cyclone hit Tubuai, at the same time as the maximum of the rain rate. The sea surge reached 1.76 m. A simple model of the flooding of the island shows that our results are consistent with field observations.

Keywords

Tropical Cyclone Oli, Storm Surge, Precipitable Water, Flooding, Island of Tubuai

Subject Areas: **Atmospheric Sciences, Geomorphology, Oceanology**

1. Introduction: French Polynesia and the Australs Archipelago

French Polynesia is an overseas autonomous territory of France in the South Pacific, about halfway between South America and Australia [1]. It is composed of 118 high islands and low atolls (67 are inhabited) stretching over an expanse of more than 2000 km (55% of the surface of the United States), but its total land area is only 4167 km^2 (one-third the size of Connecticut). The total population of French Polynesia is 270,000, with 80% of Polynesian ethnicity, 10% of Chinese ethnicity and 10% of Caucasian ethnicity. French Polynesia is divided into five groups of islands: The Society, Tuamotu, Gambier, Marquesas and Australs archipelagos. Tahiti, which is located within the Society Islands, is the most populous island (180,000 inhabitants). The Australs Islands [2]

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are the southernmost group of islands in French Polynesia. They consist of two separate sub-archipelagos, namely in the northwest the Tubuai islands consisting from west to east of the Maria atoll, the high islands Rimatara, Rurutu, Tubuai Island proper and Raivavae, and in the southeast the Bass Islands composed of the main island of Rapa Iti and the small Marotiri rocks. The Australs Islands population is about 6300 and has a land area of almost 150 km^2. Tubuai, the main island of the Australs Archipelago, is located at 23˚23'00"S, 149˚27'00"W, 640 km south of Tahiti. Tubuai Island sustains a population of 2170 people on 45 km^2 of land. Its highest summit, Mount Taita'a, culminates at 422 m. The island is ringed by a lagoon and coral reef (see **Figure 1**). Due to its southerly position, Tubuai has a temperate to tropical climate, with temperatures ranging from 18˚C to 29˚C. Precipitations are intense and frequent in any season, with an annual average of 1888 mm. The island of Tubuai is one of the French Polynesia islands most affected by TCs (nine events in the last seventy years) [3]-[5]. In this paper, we describe the impact of the TC that hit this island on February 5th, 2010. The sea level surge (up to 1.76 m) was the main cause of damage, as it washed off all the northern coast of the island.

2. Cyclogenesis in the South Pacific

Since 1931, 47 tropical depressions and 34 TCs have hit the islands of French Polynesia, with a number of storms ranging between a minimum of 3 and a maximum of 17 per year. The majority of TCs occur during the hot and wet season, from November to April. TCs are most likely to form in January and February, at the peak of the southern hemisphere summer. The main factor in TC formation is the South Pacific Convergence Zone (SPCZ), where the south-east trade winds, from transitory anticyclones to the south, meet with the semi-permanent easterly flow from the eastern South Pacific anticyclone. TCs usually occur west of 160˚W between 5˚S and 20˚S. Nonetheless, during El Niño years, TC formation occurs further east, with some tracks extending as far as 135˚W (see **Figure 2**).

Earlier studies [7] have demonstrated the influence of El Niño Southern Oscillation (ENSO) on TC activity in the southwestern tropical Pacific basin, particularly as a function of factors associated with the Southern Oscillation (SO), such as Sea Surface Temperature (SST) and the Southern Oscillation Index (SOI) [8].

3. The TC Oli Event

On January 29th, 2010, convective clusters organized into a large depression 3000 km from Tahiti, centered roughly 300 km north-west of Fiji, in the South Pacific Convergence Zone (**Figure 3**). On February 1st the

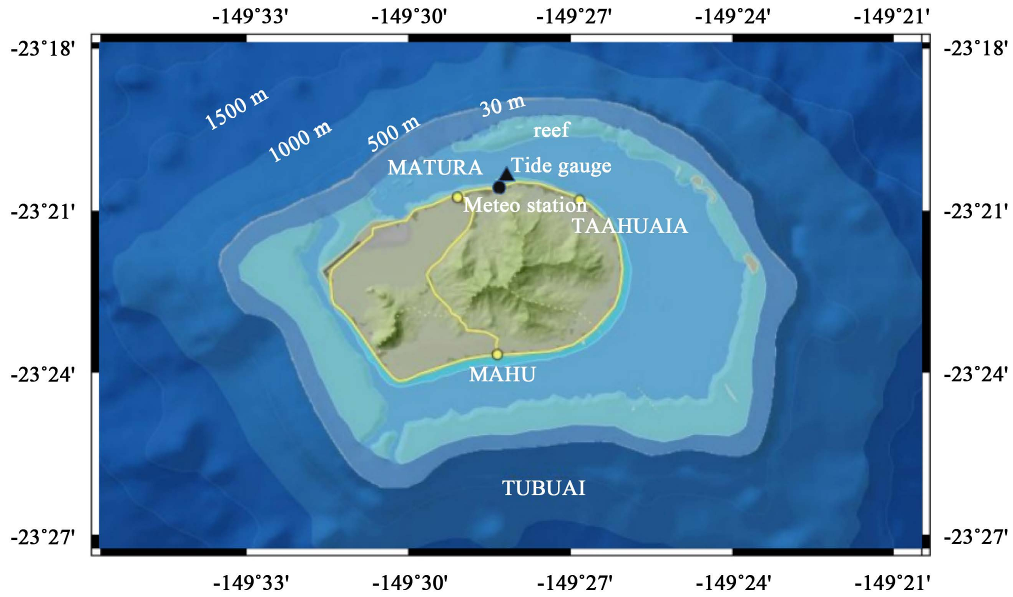

Figure 1. The Island of Tubuai (45 km^2) is part of the Australs Archipelago of French Polynesia. It is located 640 km south of Tahiti. The Tubuai tide gauge and weather stations are located on the north shore of the island (23˚20'30"S, 149˚28'30"W) [6].

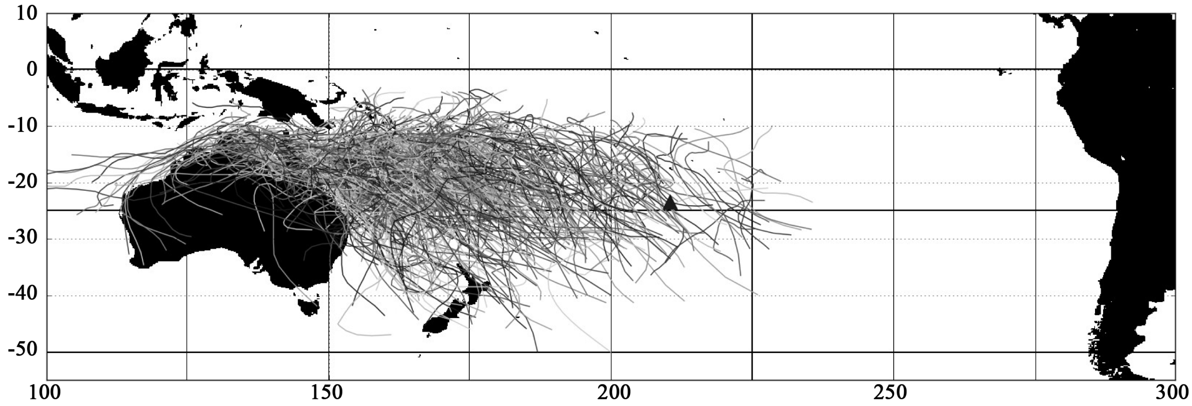

Figure 2. TC tracks in the South Pacific Ocean from 1944 to 2011 [9]. The island of Tubuai is indicated by the small triangle in the figure.

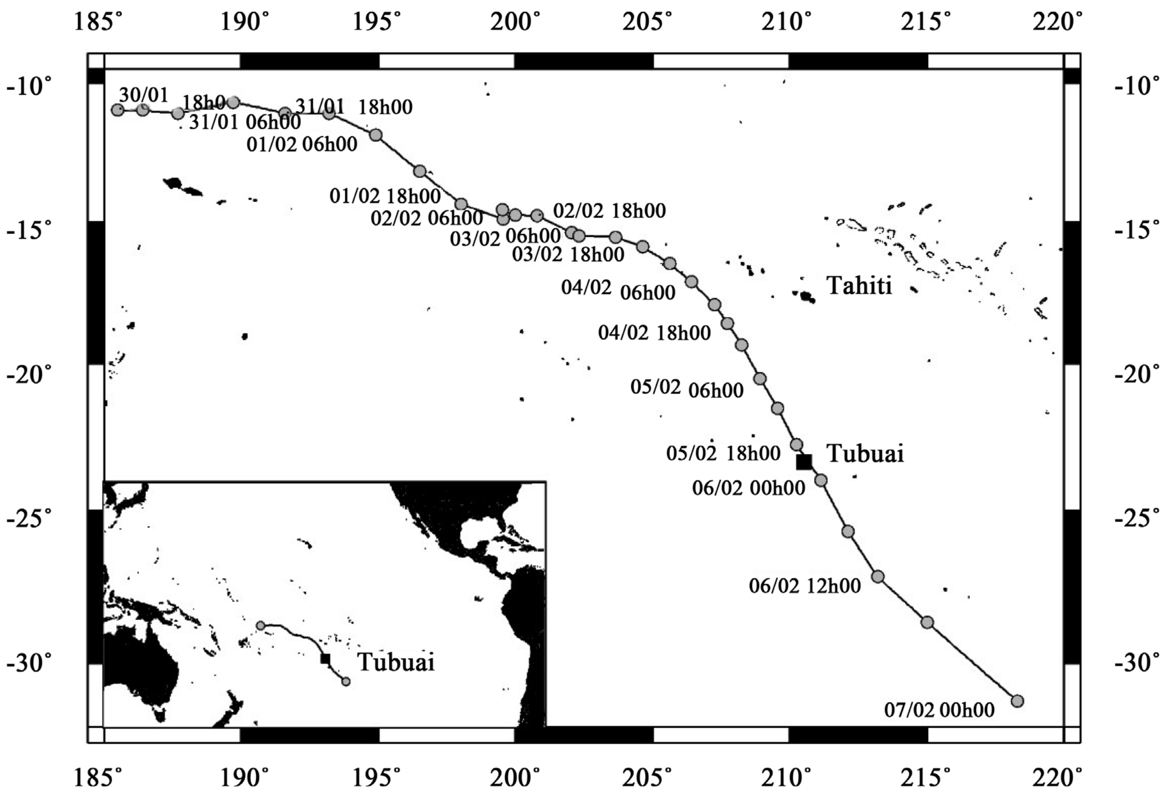

Figure 3. The track of TC Oli in French Polynesia. On January 29th, 2010, convective clusters organized into depression 3000 km from Tahiti, centered roughly 300 km north-west of Suva, Fiji, in the South Pacific Convergence Zone. On February 1st the depression intensified north of the Cook Islands into moderate tropical depression and was called Oli. Oli decreased in intensity on February 7th in the south Pacific seas, after hitting the Island of Tubuai (Australs Archipelago) on February 5th.

depression intensified north of the Cook Islands into a moderate tropical depression and was named Oli. It traveled 5000 km in the southwestern Pacific Ocean and through French Polynesia from February 1st to 6th, 2010 (**Figure 3**). The center of Oli was located south-west of the Leeward Islands, 160 km from Maupiti on February 3rd in the afternoon and 300 km from Tahiti on the night of February 3rd. TC Oli has been the most destructive TC in French Polynesia since TCs Orama (1982), Veena (1983), Osea (1997) and Kim (2000) [10]. It is the first severe tropical cyclone (Category 4 on the Saffir-Simpson scale) within the central basin of the South Pacific Ocean.

Oli intensified again on February 4th. The eye of the hurricane made landfall on the island of Tubuai on February 5th at about 3h00 am, local time (13h00 UTC). Preceded by a heavy swell, waves up to 8 m high battered the eastern side of Tubuai provoking a storm surge of about 2 m over-coast. The surge flooded the northern part of the island which is the most urbanized and populated area. Beaches retreated from 2.06 to 9.75 m, and the vertical lowering ranged between 27 and 40 cm [11]. According to the location, the volume of sand moved is estimated to be between 0.5 and 3 m^3/m. The over wash deposits extended inland as far as 150 m [11]. The strong east wind weakened around 2h00 am (12h00 UTC), then resumed again in the opposite direction around 7h00 am (17h00 UTC). The Tubuai weather station recorded a minimum pressure of 957 hPa with a maximum mean wind of 100 km/h and gusts exceeding 180 km/h (**Figure 4**). There were no human casualties, but 200 houses

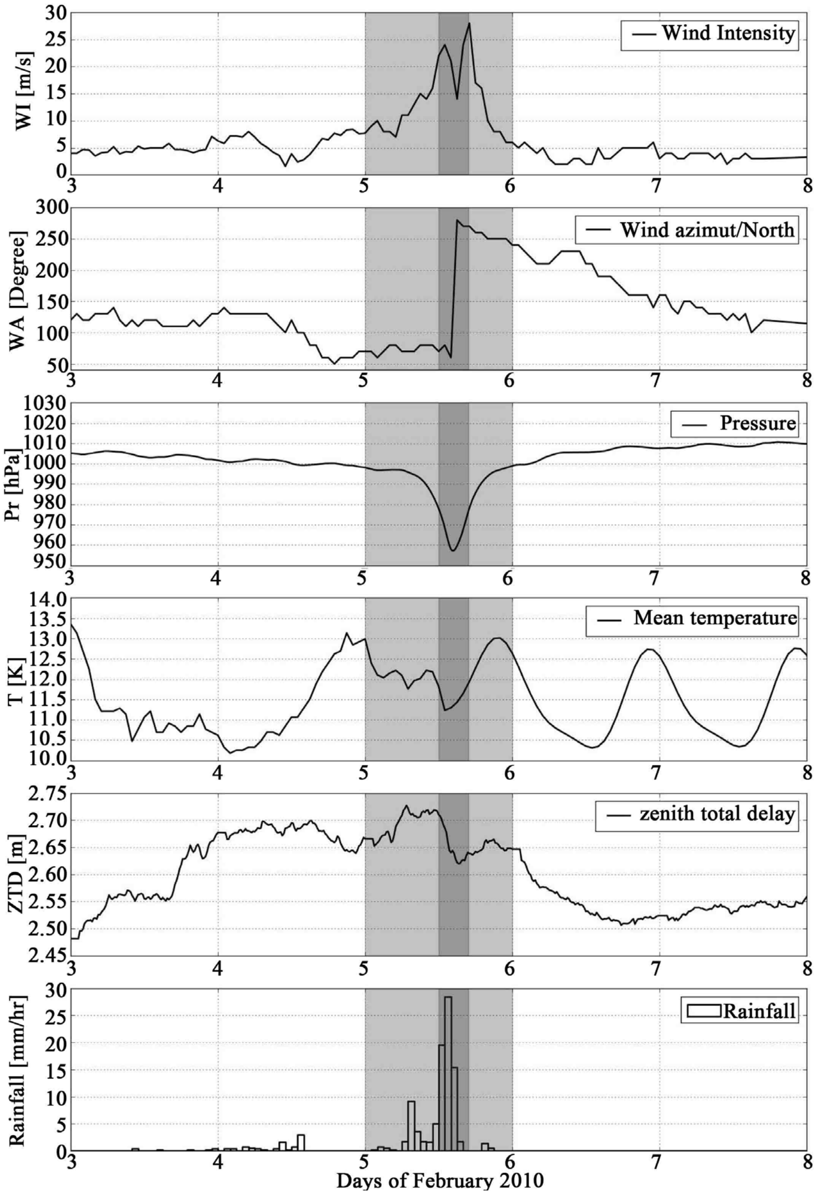

Figure 4. Meteorological and Zenith Total Delay (ZTD) data recorded during the landfall of the TC Oli on the Island of Tubuai (dark gray: 12h00-17h00 UTC). The meteorological station of Météo-France recorded temperature, wind intensity, wind direction, pressure and rainfall data with hourly sampling. The tropospheric mean temperature T_m (fourth line) is estimated from the surface temperature T_s and the physical characteristics of the TC. All the sensors operated normally during the cyclone landfall except the temperature sensor which ceased functioning on February 5th. The surface temperature record was reconstructed thereafter, see paragraph 4.2.

were destroyed and 172 inhabitants were made homeless [10]. Moreover, TC Oli was responsible for important economic losses in Tubuai (USD 11 million estimated costs), especially for farmers, whose fields were flooded by seawater. Overall in French Polynesia, the storm caused a total of USD 13 million in damages [10].

4. Measurements Taken during the Course of the Cyclone

4.1. Tide Gauge Data

Although waves reached up to 8 m during the TC, the tide gauge continued recording throughout. Sea level measurements were obtained as 60 s averages both from the radar sensor which is located about one meter above the average sea level and pressure sensor which is located about one meter below the average sea level. For more information on the tide gauge network in French Polynesia, we refer the reader to [12].

4.2. Meteorological Data

The meteorological station of Météo-France is located 2 km from the tide gauge along the coastline (see **Figure 1**). Data recorded every hour are wind speed and azimuth, rainfall, surface pressure and surface temperature (respective accuracies of 0.5 hPa and 0.5 K). All the sensors operated normally during the cyclone landfall except the temperature sensor which ceased functioning on February 5th. A least-squares interpolation is used to extend the temperature series later than February 5th. The least-squares estimates were obtained with diurnal, semi-diurnal and forced annual harmonic components from the Météo-France station data over a window of 2 months (January to February) centered on February 5th, with an rms deviation of 0.93 K.

4.3. GPS Data

The GPS observations from the GPS tide gauge station consisted of data streams of 30 s undifferentiated dual-frequency carrier-phase and pseudorange measurements from six to eight satellites. The GAMIT software [13] was used to process the data, along with precise orbits solutions from the Scripps Orbit and Permanent Array Center (SOPAC) to estimate zenith total delay (*ZTD*) with an hourly sampling data rate at the tide gauge site [14]. The processing window was 24 hours wide and stepped forward in increments of 12 hours. The *ZTD* data rms deviation was found to be less than 7 mm.

5. Data Analysis

5.1. Surface Winds

Figure 4 shows the variations of wind intensity and direction between February 3rd and 8th, 2010. Outside of the TC event, the dominant wind is east-southeasterly with speed of about 18 km/h (5 m·s^{-1}). On February 4th, as the TC is approaching Tubuai, the direction changes to north-east and the wind speed increases gradually to reach 90 km/h (25 m·s^{-1}). At the time of arrival of the storm eye on Tubuai, we can see a lull in wind intensity with a sudden change in direction towards north-west. However, the hourly sampling rate does not allow us to fully quantify this reduction since the drop is only 36 km/h (10 m·s^{-1}). The pressure gradient at sea level near the center of Oli is very large, as shown by the pressure curve in **Figure 4**. It is the large magnitude of the pressure gradient that accounts for the high wind velocities. Indeed, we observe a relatively constant variation with low diurnal oscillation before and after the TC and a sharp drop in pressure during its passage with a minimum value of 957 hPa on February 5th at 13h00 UTC when it was located at the station.

5.2. Precipitable Water (PW)

Precipitable water vapor is useful in predicting heavy rainfall during extreme weather conditions. However, our knowledge of the determination of PW from GPS data during a tropical cyclone remains patchy [15] [16]. The determination of PW is dependent on the determination of the mean tropospheric temperature T_m [17]. Even for extreme weather conditions such as tropical cyclones, the mean tropospheric temperature T_m can be determined from only the surface temperature T_s [18]. We used this method in this paper and obtained an uncertainty in T_m of about 1.9 K, which corresponds to a 1% uncertainty in PW [10]. **Figure 5** shows the variations of the estimated PW with time from February 1st to 8th. On the long term, the normal PW level is about 40 kg/m^2 (see

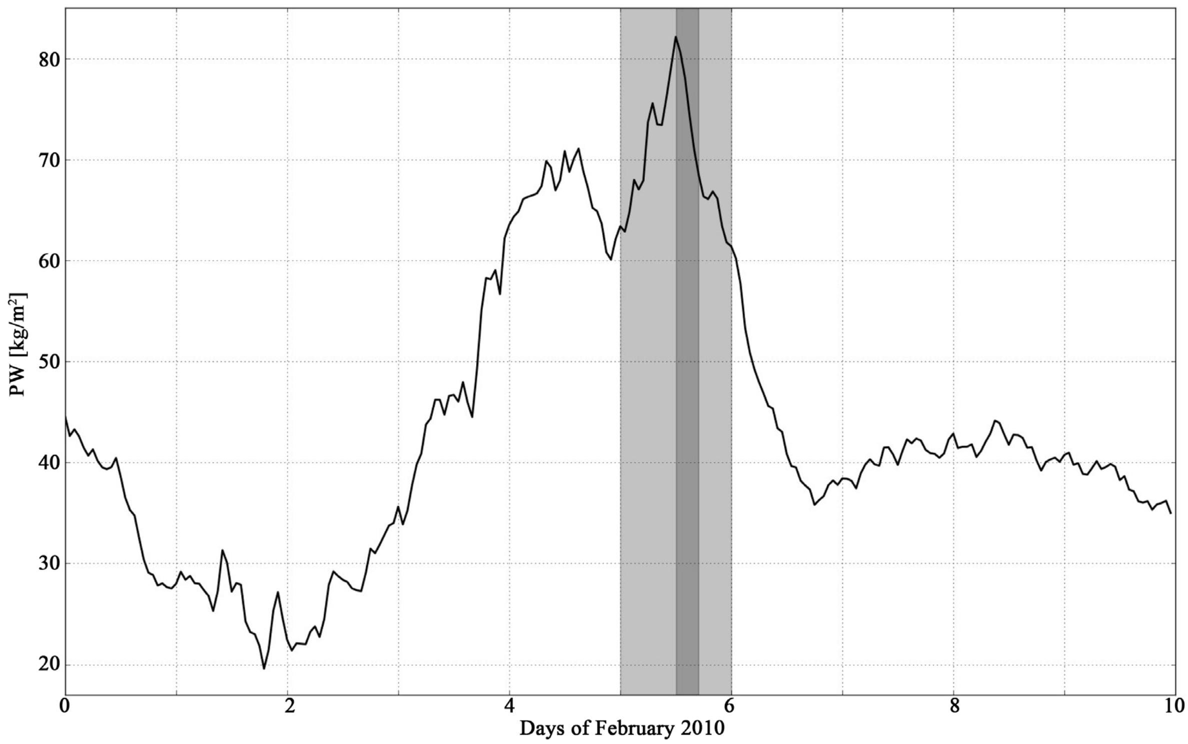

Figure 5. *PW* recording during the landfall of the TC Oli. One can see in this time series a drying event followed by a rapid increase, then a rapid decrease shortly after the landfall. We also find sub-peaks on the 2-day *PW* high, suspected to be related to small-scale variability in the PW field (dark gray: from noon to 17h00 UTC).

Figure 5). Before the cyclone hit Tubuai, the PW decreased to 20 kg/m^2 on February 2nd (see also **Figure 5**). Such decrease has been observed in similar conditions [15], but not consistently [16]. We believe that the decrease might be caused by the TC to compensate subsidence in the mid-troposphere. From February 2nd to 5th the PW shows a gradual increase to values higher than 80 kg/m^2 (at midday), which is consistent with previous studies [15] [16]. The increase of PW as the TC approaches Tubuai correlates with the increase of rainfall as recorded by the rain gauge. In our case, a maximum of 80 kg/m^2 PW corresponds to about 30 mm/h in precipitation rate (see **Figure 4** and **Figure 5**).

5.3. Storm Surge

The sea level variations during the passage of the TC Oli, available from the tide gauge, are shown in **Figure 6**. The pressure gauge recorded a maximum rise of 150 cm. In order to analyze the signal associated with TC Oli, we separated the cyclone storm surge height from the lunisolar tide height [12]. The storm surge is the result of five components: the pressure effect, the direct wind effect, the effect of the Earth's rotation, the effect of waves, and the rainfall effect. The effect of the waves is negligible because of the steep external slope of the island. We assume that the rainfall effect is also negligible because of the small size of the island, however, we are not sure about the impact of the lagoon, and as we have seen, the maximum of the rain rate is coincident with the maximum of the sea level rise (**Figure 4** and **Figure 6**). The effect of the Earth's rotation is dependent on the orientation of the coast, and was included to model the flooded areas on the island [19]. The storm surge around tropical volcanic islands [20] is generally low compared to storm surge observed along continental coastline, where sea level rises well above 6 m [21]. Unlike a storm surge that affects continental coasts, the contribution of the wind in a storm surge on island is not dominant on the inverse barometer effect. However, the lagoon around an island may induce resonances, in which case the reef barrier may act as either a natural flood protection or as a flood enhancer depending on the incident wave conditions [22]. The bathymetric depth around these islands sharply increases from the oceanic floor (4000 m) to the edge of the lagoon (**Figure 1**) and the land area of the islands is relatively small (45 km^2 in Tubuai). The influence of the island bathymetry on the variation of sea level is

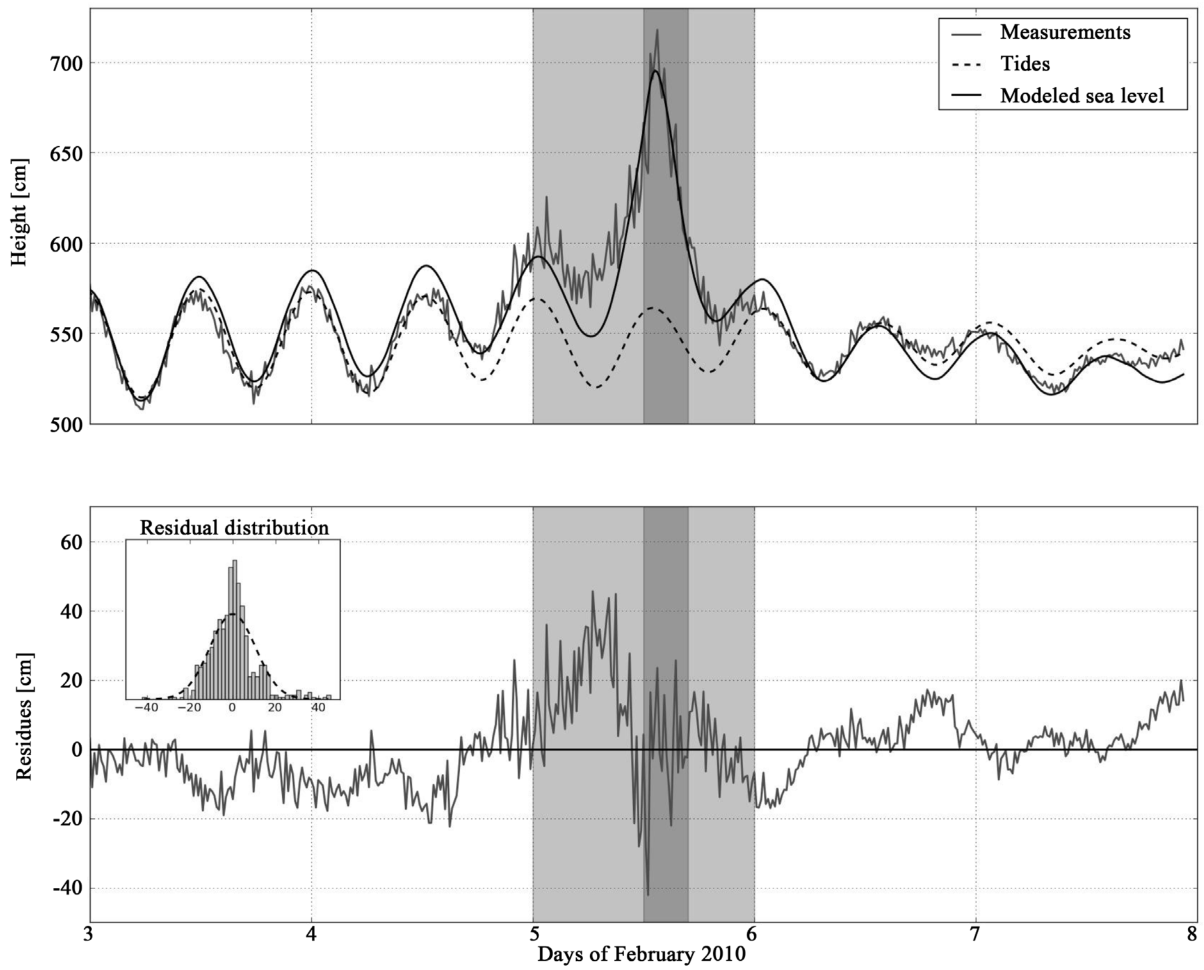

Figure 6. The top figure shows the time series of sea level measured (gray line) and modeled (black line) and the tides (dashed line) estimated during the landfall of the TC Oli (dark gray: from noon to 17h00 UTC). The bottom figure shows the time series of the difference between the measurements and the sea level model.

thus negligible.

Taking into account the relative contribution of all these components, we used a simple linear model [23] to model the storm surge S in meters with respect to the barometric pressure P as $S = -2.72 (P - 1005.5)$, with P expressed in hPa [10]. Our result (**Figure 6**) shows a good agreement between the modeled sea level and the data. The residuals show that up to 40 cm of the sea level variation is due to the wind effect, which mostly happened prior to the TC Oli landfall.

The storm surge due to Oli roughly coincided with the time of landfall, at around 12h00 UTC. This high sea level episode lasted 36 hours, with a maximum from 12h00 to 17h00 UTC on February 5th (see **Figure 6**). Taking also into account the coast orientation with respect to the TC track, we estimate that the sea level surge varied from a few centimeters on the southern shores of the island to about 2.5 meters on the northeastern coast. We propose in **Figure 7** a map of the flooded areas of the island, with a comparison with the "ground truth" established by the Health Division of the municipality of Tubuai. The north coast was strongly flooded, because of its low topography and the fact that the sea level surge was higher in this area. The north-east region, which is largely used for agriculture was particularly affected from an economic point of view. The south-western and southern part of Tubuai was almost untouched by the flooding.

These floods had an important geomorphic impact. The mean horizontal retreat was important in the northern and eastern part of the island (9.75 m), medium on the north-west coast (2 m) and not apparent in the south coast [11].

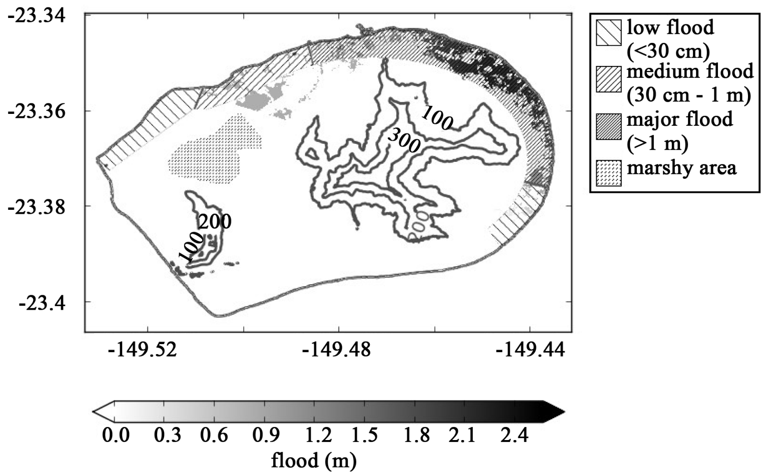

Figure 7. Representation of submerged areas estimated from our model (gradual gray areas) and established by the health division of the municipality of Tubuai (hatched areas), on the Island of Tubuai, during the landfall of the TC eye (February 5th, 14h00 UTC).

Our analysis has contributed to a better understanding of the impact of a TC on a small island and we are not aware of any other study of this type on small island, probably because it is always a major challenge to run equipment on an isolated island. The land based equipment combined with GPS data allow us to demonstrate a good correlation between the water vapor content and rainfall rate as also shown by [15] [16]. The tide gauge data shows that for a small island the effect of the barometric pressure is far greater than the effect of the wind.

6. Conclusion

Oli is classified as one of the most intense TCs that have impacted French Polynesia in the last forty years. We have been able to describe precisely the landfall of this TC on the island of Tubuai in terms of meteorological time series. One key parameter to model TCs and atmospheric rivers [24] is the integrated precipitable water vapor contents of the atmosphere (PW) [25]. In our case, a good correlation with the maximum rainfall is observed. One striking feature of the PW time series is the low values recorded before the landfall. Due to the morphology of the island, we showed that the sea level increase is mostly due to the barometric effect. The wind effect is mostly visible before and when TC Oli hit Tubuai. Our results are coherent with ground observations.

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