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Storm wave runups and sea level variations for the September 2017 Hurricane Maria along the coast of Dominica, eastern Caribbean sea: evidence from field surveys and sea-level data analysis

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ABSTRACT

Dominica, along with several other Caribbean islands, was severely damaged by category-5 Hurricane Maria in September 2017. The hurricane left 68 people dead or missing, marking Maria as the worst natural catastrophe to hit this small island nation. Here, we report the results of our coastal runup field survey in February 2018 and of tide gauge sea-level data analysis. Analysis of tide gauge records shows that the duration of Maria's surge varied between 2.1 and 2.6 days in the Caribbean region and was 2.1 days at Marigot, Dominica. The surge amplitude was 75 cm in Marigot, which indicates that the size of the surge was small for a category-5 hurricane. The measured field survey runups were from 1.0 to 3.7 m, with the maximum runup at Scotts Head on the southern tip of Dominica. The largest measured runups were concentrated along the west coast of the southern half of the island and consistently decreased northwards. We attribute the observed damage to coastal structures to four mechanisms: surge/wave erosion; surge/wave forces/impacts; debris impacts to coastal structures involving in particular floating tree debris brought to the sea by river floods associated with Hurricane Maria; and intense coastal sedimentation, involving sediment brought to the sea by river floods. A flowchart of the hurricane-driven damage mechanisms is presented which provides the propagating sequence, or cascade, of events that contributed to damage and emphasizes the interactions between different processes in the hurricane.

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2017 Hurricane Maria; Caribbean sea; Dominica; coastal infrastructures; storm surge; wave runup

1. Introduction

The worst recorded natural catastrophe to affect the Caribbean islands of Puerto Rico and Dominica resulted from Hurricane Maria in September 2017. Maria formed as a tropical storm on September 16, 2017 in the West Atlantic Ocean (Figure 1) and moved toward the Caribbean region. On September 17, Maria was upgraded to a Category One (Cat-1) Hurricane in the Saffir–Simpson hurricane wind scale (SSHS, Figure 1) after reaching a wind speed of 75 mph (miles per hour) (120 km/h or 33.3 m/s). Relatively rapidly, Maria was reclassified as a Cat-5 hurricane on September 18, reaching wind speeds of 160 mph (258 km/h), shortly before arriving in Dominica (Brown and Blake 2017). The maximum wind speed gained by Maria was 175 mph (282 km/h) occurring south of Puerto Rico in the East Caribbean Sea (Figure 1(a)) and was correlated with a minimum central pressure of 908 mbar (WMO 2018). Maria was the second Cat-5 hurricane in the 2017 Atlantic hurricane season; the other was Hurricane Irma (Rahmstorf 2017; Craig 2018) which was active from August 30 to September 17. According to various media reports, Hurricane Maria left 216 people dead or missing in the Caribbean states and territories of Dominica, Dominican Republic, Puerto Rico, Guadeloupe (France), Haiti, Martinique (France), Virgin Islands (US) as well as the mainland USA (ACAPS 2018; NCDC 2017). The total damage to these countries surpassed US$ 91 billion (NCDC 2017).

In Dominica, Maria made landfall at approximately 9:00 PM local time on September 18 (Figure 1(a)), while it was classified as a Cat-5 hurricane. Maria affected the entire population in Dominica (approximately 75,000 people) causing 31 deaths, with 37 missing, as well as material damage with an estimated cost of US $1.37 Billion (PDNA 2017), corresponding to 224% of the island's GDP. The access to running water and electricity was disrupted and the communication lines were severely damaged. Based on estimates by the Dominica Red Cross, 98% of building roofs were damaged by the hurricane (IFRC 2017). In the 40 years prior to 2017, Dominica was devastated by five other hurricanes and tropical storms: Cat-5 hurricane David (1979) which caused 56 deaths (Bosart and Lackmann 1995); Cat-4 hurricane Lenny (1999)

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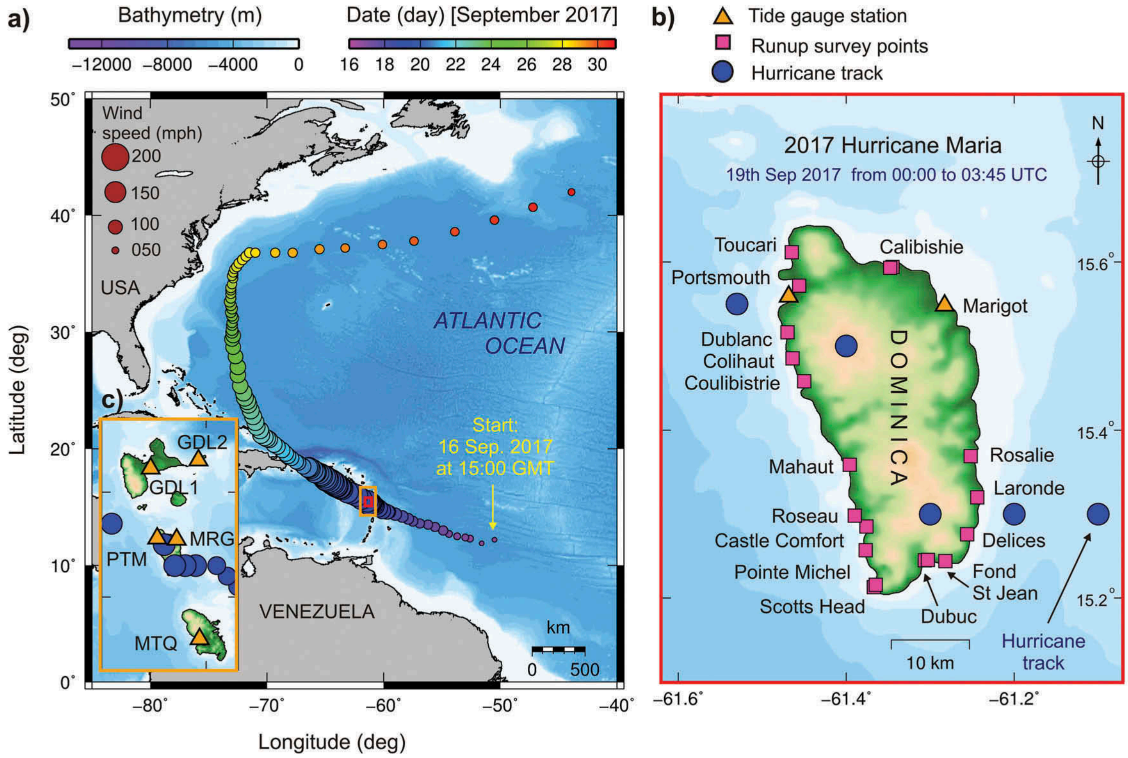

Figure 1. (a) Location map showing the spatial and temporal evolution of Hurricane Maria across the Atlantic Ocean, using data obtained from the USA National Hurricane Center (https://www.nhc.noaa.gov/). The sizes of the circles in both figures are proportional to the hurricane wind speed. (b) Map of Dominica showing the locations surveyed for storm surge and wave heights (rectangles). The triangles and circles are the tide gauges and the hurricane tracks, respectively. The scale for wind speed is given at the top-left of panel "a" which is the same for both panels "a" and "b". (c) Tide gauge stations (triangles) used in this study are shown with name abbreviations: GDL1, Pointe à Pitre (Guadeloupe); GDL2, La Desirade Island (Guadeloupe); PTM, Portsmouth (Dominica); MRG, Marigot (Dominica); MTQ, Martinique (Fort de France).

(Lawrence et al. 2001; Jessamy and Turner 2003); Cat-5 hurricane Dean (2007) with 2 deaths and US$162 million in damage (Franklin 2008); Cat-4 hurricane Omar (2008) (Beven and Landsea 2008); and tropical storm Erika (2015) with 30 deaths and US$ 483 million damage worth (IFRC 2015).

Following Hurricane Maria, a survey team from UK universities (University of Portsmouth, University College London and Brunel University London) was formed to carry out a combination of remote sensing investigations and on-the-ground fieldwork with the aim of understanding the impacts of Hurricane Maria upon the population and the environment of Dominica. The survey team visited Dominica in January and February 2018 to record the impact of the various physical processes associated with the hurricane upon buildings and infrastructures, to evaluate the social impacts and the effectiveness of mitigation actions, and to provide reconstruction recommendations to the Government of Dominica. Areas of expertise within the team included engineering, geology, geomorphology, remote sensing, and community resilience. In this paper we focus on the characteristics and impact of the storm surge: we report the hurricane storm surge runup heights around Dominica and describe the associated damage to coastal structures.

2. Data and methods

2.1. Tide gauge data

We used five tide gauge records of Hurricane Maria from stations in Dominica and the adjacent islands of Guadeloupe and Martinique (see Figure 1(c) for locations and Figure 2 for the sea level records). The sampling interval of the sea level records is 1 min and the records include the period from 13 to 24 of September, 2017. In addition to the two tide gauge stations on Dominica of Marigot (MRG) and Portsmouth (PTM), three other stations (GDL1, GDL2 and MTQ) from neighboring islands are studied here, to provide regional insights about Maria's storm amplitudes and duration (Figures 1(c), 2). Guadeloupe and Martinique islands are located approximately 100 km to the north and south of Dominica, respectively (Figure 1(c)). The sea level data for the tide gauge stations of GDL1, GDL2, PTM and MTQ are provided by the sea-level monitoring facility of the Intergovernmental Oceanographic Commission of the UNESCO (http://www.ioc-sealevelmonitoring.org/); while that of MRG came from OceanWise Limited's marine data in the Caribbean Sea region (https://geomatica.port-log.net/live/map.php). The Portsmouth gauge was damaged by Maria and only recorded sea level changes during the approach of the hurricane, with no data for the period when the eye of the hurricane was closest to Portsmouth

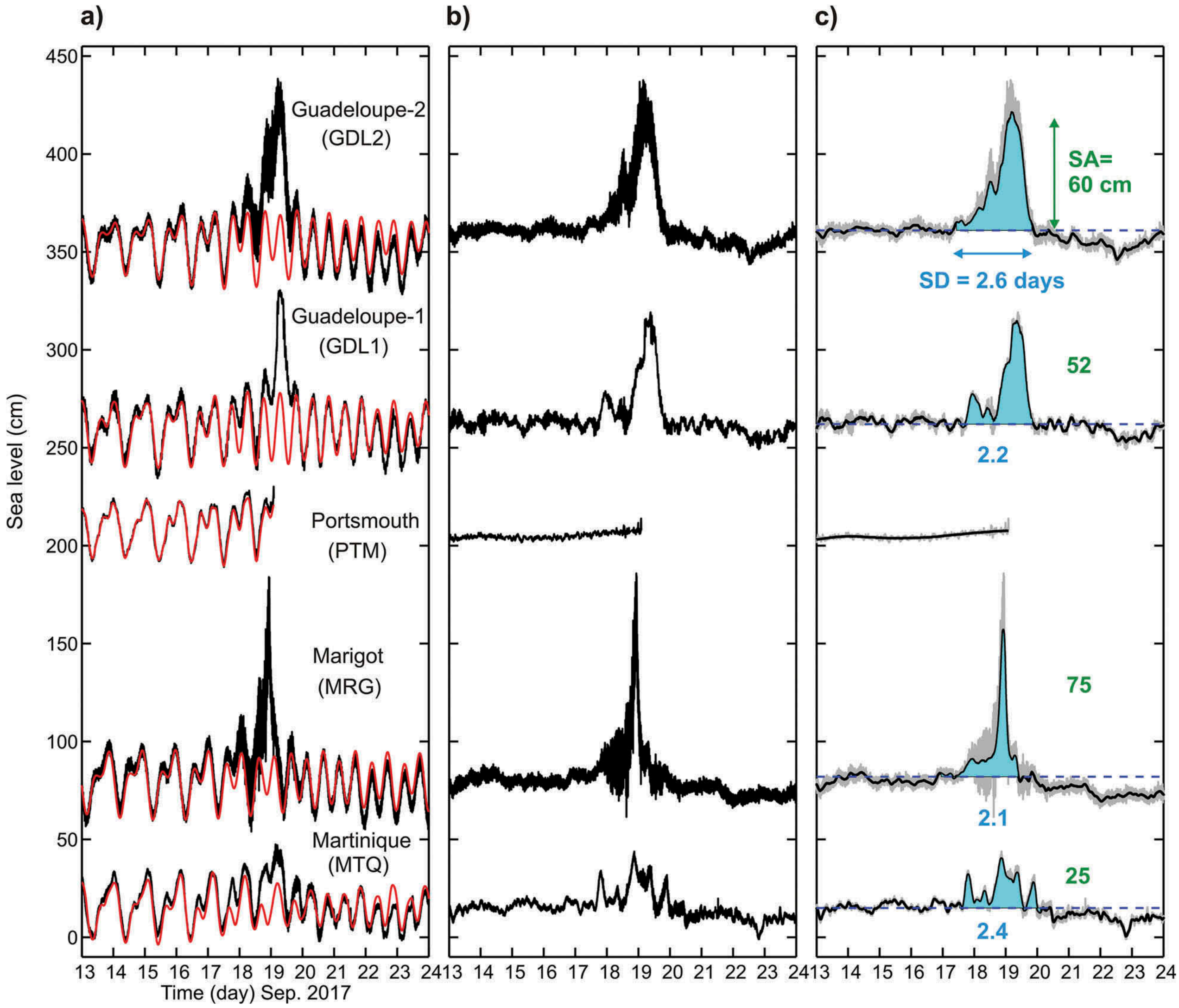

Figure 2. Tide gauge records of the storm surge and waves during Hurricane Maria at different locations. (a) The original tide gauge records (black) along with the tidal prediction (red). (b) The de-tided tide gauge waveforms showing both storm surge and wave amplitudes. (c) The one-hour averaged waveforms representing the storm surge amplitudes (the solid black lines and the blue shading), along with the storm wave oscillations (gray lines). Abbreviations are: *SA*, storm surge amplitude and *SD*, surge duration.

and when winds would have been expected to be both the strongest and most variable in direction (Figure 2).

The tidal signals were calculated by applying the tidal analysis package of TIDALFIT (Grinsted 2008), and then were removed from the original sea level records to produce de-tided waveforms. Using the de-tided waveforms, the storm surge and wave amplitudes were measured. Storm surge level was calculated by taking a one-hour moving average of the de-tided waveforms (Figure 2(c), black lines and the blue shading). To calculate the duration of storm at each station (SD in Figure 2(c)), the average amplitude of the de-tided waveforms before storm was calculated; then, storm duration was assumed to be the time interval that the amplitude is above this level (Figure 2(c), the blue shading). Storm waves are defined as short-period oscillations (i.e. periods <1 min) beyond the surge levels (Figure 2(c), the gray levels). Therefore, in each station, the surge amplitude (SA) is calculated. Wave amplitude can be obtained by subtracting the tidal variations and SAs from the original tide gauge records. A sum of these two amplitudes gives the total amplitude of Hurricane Maria in each tide gauge station. We note that our approach gives reliable estimates for SA while it may underestimate the wave amplitude because accurate wave amplitude estimation requires high frequency sampling rates (e.g. one sample per at least 5 s), while our data have a sampling rate of one sample per minute. In addition, because of the nature of traditional tide gauges, which use a stilling well connected to the sea by a narrow pipe to measure tide levels, they filter out part of the short-period storm wave oscillations. Therefore, we do not report wave amplitude here, although some noise created by under-sampled storm waves can be seen in Figure 2(c) (the gray amplitudes beyond the solid-line surge amplitudes in Figure 2(c)).

2.2. Field surveys

A field survey was made to document the hurricane water-marks/debris-marks and structural damages to coastal communities and to measure the runup heights. The coastal field work was conducted in January 21–31, 2018 and involved survey sites at 17 locations around Dominica (Figure 1(b)). Runup height is the difference between normal high-tide sea level and that of the maximum extent of the sea surge/wave penetration point. The runup values measured in this study are the sum of both surge and wave amplitudes beyond the high tide levels; it is not usually possible to separate between surge and wave amplitudes. As sea level positions change at different times due to astronomical tides, all runup measurements during the field survey were corrected relative to the high-tide level at the time of Hurricane Maria (9:00–12:00 PM local time on September 18, 2018). In other words, the runup height in each location was measured relative to the high-tide level at the time of the survey; then, the high-tide level of the survey time was compared to that of the hurricane time and the corresponding correction was made for each location (Table 1).

As the field survey was conducted four months after the hurricane, the runup points were determined by a combination of interviews with local residents and the identification of surviving water-marks and debris-marks (Table 1, Figures 4–6). Runup points were measured using a laser range finder with built-in inclinometer of series TruPulse 200 by Laser Technologies Inc. (http://www.lasertech.com/TruPulse-200-B-Rangefinder.aspx), a reflector (Leica GMP111-0 Basic Mini Prism), hand-held GPS devices (Montana 680t by Garmin Inc.: https://buy.garmin.com/en-GB/GB/p/523677) and leveling staffs. Water-marks, debris-marks and debris impact damage, and indications provided by eyewitness testimony regarding inundations of the hurricane, were photographed and their locations were determined using GPS devices. Some uncertainties are associated with runup field measurements (IOC 2014). The estimated uncertainties of our runup field measurements are:

- The uncertainty in vertical height difference measurements made with the laser range finder and its internal inclinometer, which depends on the distance between shoreline and the runup survey point but are generally small (±5 cm) because the distances from the shoreline to the runup survey points were generally less than 30 m;
- The uncertainty of runup point indication (±10 cm);
- The uncertainty of eyewitness reports (±10–15 cm).

We note that the uncertainty of eyewitness reports could be different from one event to another. We anticipate a total uncertainty range of up to ±25–30 cm for the runup measurements reported in this study (e.g. Bourgeois et al. 1999; Leonard and Bednarski 2014; Contreras-López et al. 2016; Fritz et al. 2007; Mas et al. 2015).

3. Tide gauge records of the 2017 Hurricane Maria

Original tide gauge records and the de-tided waveforms of the 2017 Hurricane Maria are shown in Figure 2. Based on the de-tided waveforms, values of storm surge amplitude (SA) and surge duration (SD) are calculated and shown in Figure 2(c). Among the examined tide gauge records, the largest SA was recorded in Marigot (75 cm). The two Guadeloupe stations, GDL1 & GDL2 located to the north of Dominica, registered SAs of 60 and 52 cm, respectively, while Martinique station, located to the south of Dominica, recorded a SA of 25 cm. The relatively higher storm surge amplitudes

Table 1. Geographical locations of the runup survey points, the method of runup determinations, the runup height corrections and the final runup values for Hurricane Maria in Dominica.

Location	Lon (°W)	Lat (°N)	Method of runup determination	Raw runup value (m)	Tide level correction (m)	Final runup value (m)
Pointe Michel	−61.377	15.257	Witness	2.6	−0.03	2.6
Dubuc	−61.307	15.245	Debris-mark	1.9	−0.13	1.8
Dubuc	−61.303	15.245	Debris-mark	1.8	−0.13	1.7
Fond St Jean	−61.282	15.244	Witness	3.1	−0.13	3.0
Scotts Head	−61.367	15.213	Witness/water-marks	3.7	0.0	3.7
Scotts Head	−61.365	15.216	Witness/water-marks	3.1	0.0	3.1
Roseau	−61.390	15.298	Witness/water-marks	3.0	+ 0.02	3.0
Castle Comfort	−61.376	15.285	Debris-mark	3.5	0.0	3.5
Rosalie	−61.252	15.369	Debris-mark	3.0	−0.04	3.0
Delices	−61.256	15.276	Debris-mark	2.9	−0.04	2.9
Laronde	−61.244	15.320	Debris-mark	2.5	−0.04	2.5
Mahaut	−61.396	15.359	Witness/water-marks	2.6	+ 0.03	2.6
Coulibistrie	−61.450	15.458	Witness	2.8	+ 0.03	2.8
Colihaut	−61.464	15.485	Witness/Debris-mark	2.3	+ 0.03	2.3
Dublanc	−61.470	15.516	Witness/Debris-mark	1.9	+ 0.03	1.9
Calibishie	−61.345	15.594	Witness	1.0	−0.04	1.0
Calibishie	−61.348	15.593	Witness	1.2	−0.04	1.2
Portsmouth	−61.456	15.572	Witness/Debris-mark	1.0	+ 0.04	1.0
Toucari	−61.465	15.612	Witness/Debris-mark	1.4	+ 0.04	1.4

in Dominica and Guadeloupe can be attributed to the hurricane track along or close to these two islands whereas Martinique was located to the south of the track (Figure 1(c)). SD was more than 2 days in all examined stations with a maximum value of 2.6 days in GDL2. The largest SA, recoded in Marigot, was a consequence of Maria's track, which crossed the center of Dominica (Figure 1(c)) and the strongest winds in the hurricane eye were over the island; hence, larger surge amplitudes occurred here compared to the neighboring islands. Still, the modest surge amplitude of 75 cm in Marigot indicates that the size of the hurricane-related surge in Dominica was moderate, despite the intensity of the hurricane, which implies that only moderate damage from hurricane surge/wave should be found in Dominica if that measurement is representative of the island as a whole. This implication is compared in the next section to the results of our field survey.

Analysis of tide gauge records also reveals that the maximum wave oscillations and surge amplitude occur at different times. For instance, in Marigot (Figure 2(c)), the maximum wave oscillations occurred during the first day of the Hurricane Maria (Figure 2(c), gray lines) while maximum surge amplitude belongs to the second day (Figure 2(c), blue shading). This time lag between maximum wave and surge has important implications for the damage sustained by coastal structures because the combined surge-wave height would be much higher if they occur at the same time.

4. Results of runup field survey and measurements

The runup measurement points and the results are presented in Table 1 and Figure 3. Some of the coastal locations, in which runup measurements were made, are shown in Figure 4–6. Most of the runup observation points are located in the south and west of the island. This is because most of the population centers in Dominica are located at the south and west; thus we mainly concentrated on those areas for the runup survey because it was combined with the damage survey. The runup heights recorded are in the range 1.0–3.7 m (Table 1, Figure 3). A maximum runup of 3.7 m was observed in the village of Scotts Head, located in the south-west of Dominica. Scotts Head was severely damaged by the hurricane's surge/waves, especially the parts of the village located on a low-lying gravel-cobble beach ridge, and approximately 1 km of the coastline was fully washed away: a survivor showed us the remnants of his house, where only the concrete foundation could be seen (Figure 4(c)). The storm

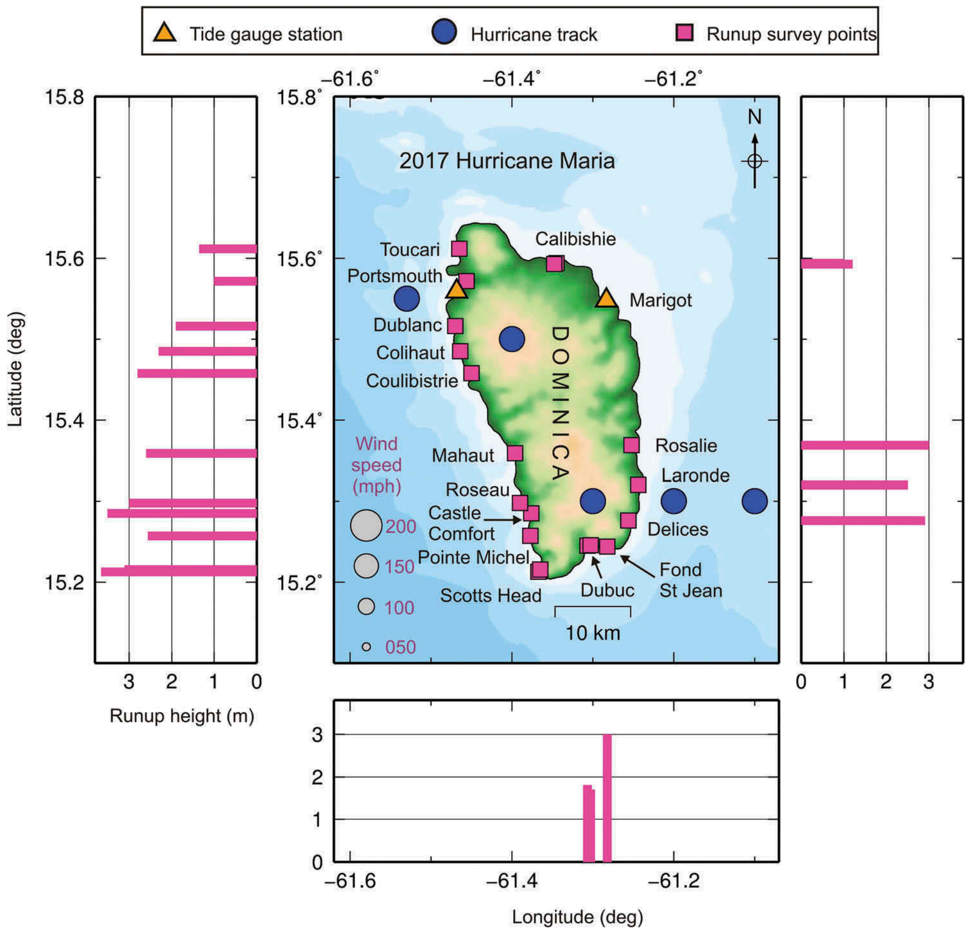

Figure 3. Results of runup measurements along coastal areas of Dominica due to Hurricane Maria. See Table 1 for exact values and the geographical location of each runup survey point.

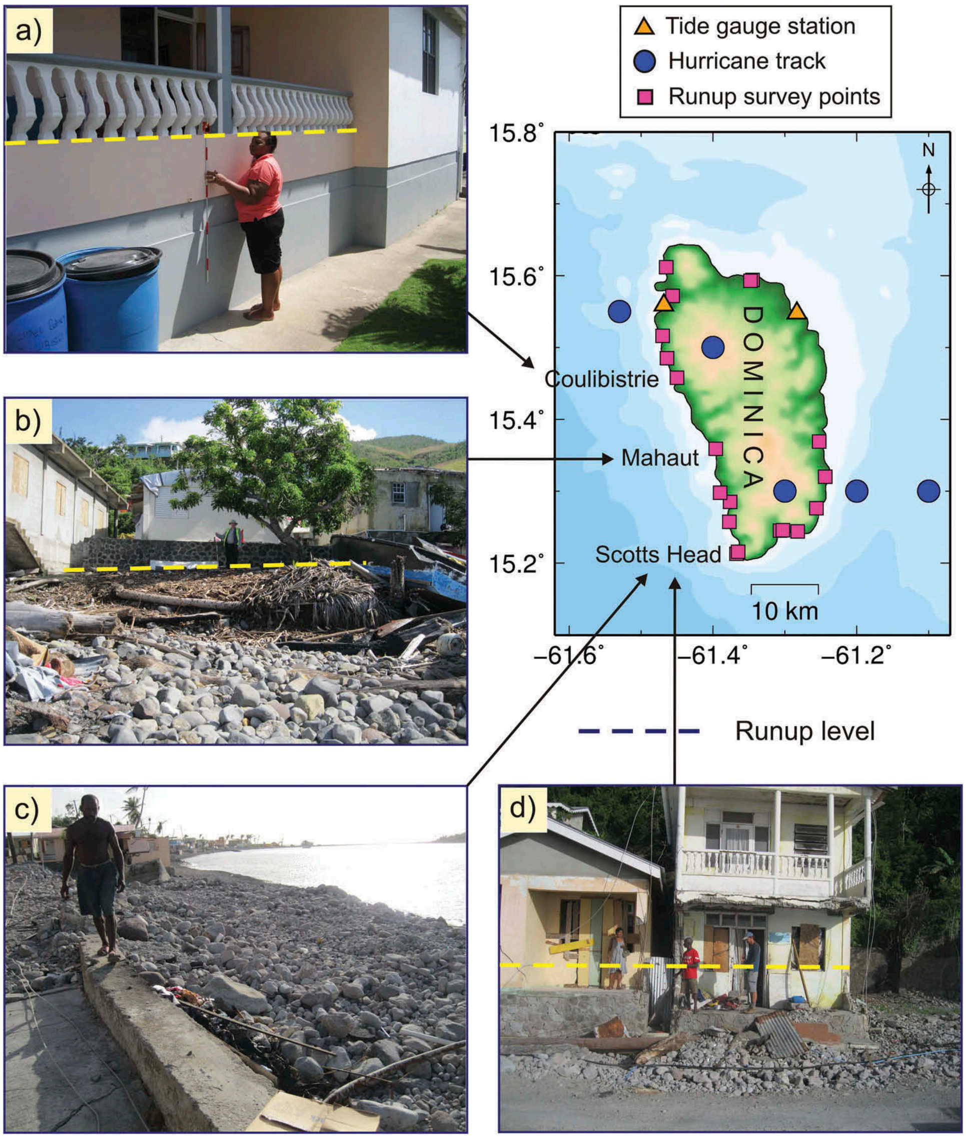

Figure 4. Photographs showing runup measurement points (yellow lines) around the coasts of Dominica, observed during the February 2018 field survey of Hurricane Maria damage in Dominica (part 1).

damage to four locations in the southeast is shown in Figure 5 which demonstrates accumulation of intense timber debris along the coast at various locations. Figure 6 presents photos of storm damage along the north coast indicating moderate damage in comparison to the south coast.

The distribution of the runup reveals that the largest runups occurred at the southern half of the island (i.e. 3.7 m) and decreased northwards to a minimum observed value of 1.0 m. This consistent decrease of runup from south to north can be established from Figure 3. The surveyed runup height of around 1 m at the northern part of the island (Figure 3; latitude 15.5−15.6°N) also correlates with the tide gauge surge amplitude of 0.75 m observed at Marigot station at the same latitude range. We note that the combined surge and wave amplitude at Marigot is expected to be around 1 m, as inferred from Figure 2(c). In summary, the surge/waves from Maria caused severe damage at the southern locations of Scotts Head, Fond St Jean and Castle Comfort, where the runups were the highest (Figure 3, Table 1); the associated damage in other parts of the island was moderate.

5. Damage to coastal structures

Figures 7–8 show examples of damage to coastal communities and structures observed during the field survey. Four types of damage were observed:

5.1. Damage due to wave/surge erosion of structure foundations

Damage to the coastal sea wall along the main road near the village of Scotts Head (Figure 7(a)) was a direct result of Hurricane Maria storm surge impact and wave erosion of the beach and sea wall foundation. A total of 36 m of the length of the sea wall, formed by six blocks each 6 m long, were displaced and separated; some fell over onto their faces. We infer that these failures were

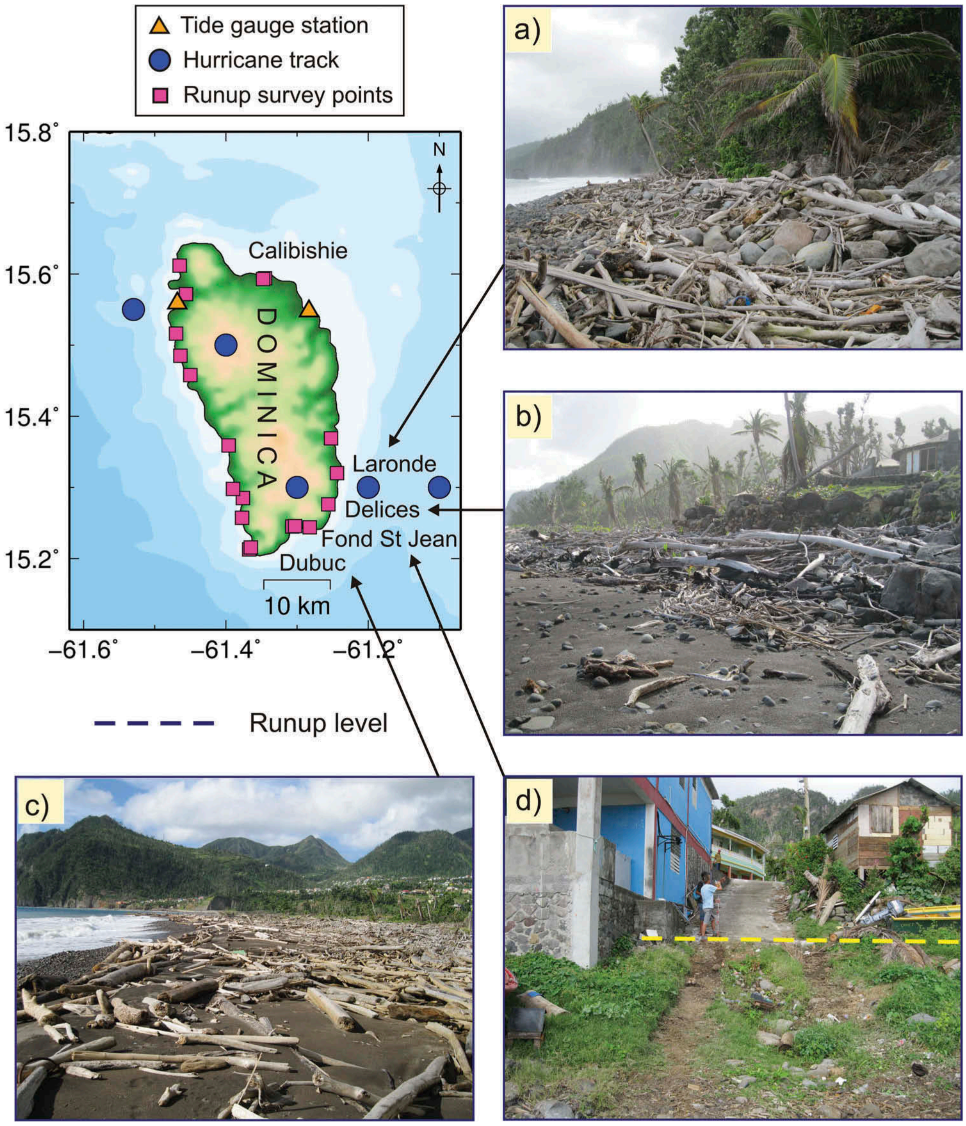

Figure 5. Photographs showing runup measurement points (yellow lines) around the coasts of Dominica during the February 2018 field survey of Hurricane Maria damage in Dominica (part 2).

due to scouring of the beach sediments and erosion beneath the foot of the wall. Minor displacements of adjacent blocks were also observed. As the road was only protected by a sea wall at this location, it was left defenceless against wave-related erosion after the collapse of the sea wall blocks. The road section behind the displaced and separated blocks was washed away due to wave action, with the concrete slabs of the road broken into many pieces (Figure 7(a)). We infer that this sequence of events was due to a combination of the large storm surge/wave heights in the Scotts Head area (3.1–3.7 m; Table 1, Figure 3) and the lack of any rock/concrete armor protection at the toe of the sea wall (Figure 7(a)). It is normal practice to protect the foundations of sea walls, and in particular the seaward toe of the sea walls, against wave actions by installation of particulate rock/concrete armor units, such as riprap, tetrapods, and concrete blocks (Sorensen 2005). However, no such armor was placed in front of the long sea wall along the road leading to Scotts Head.

5.2. Damage due to direct wave/surge forces and impacts

Direct surge/wave hydrodynamic forces and wave impacts were responsible for damage on various parts of the Dominica coastline. An example of this type of damage is shown in Figure 7(b) where a large community center was damaged in Scotts Head. A deflection of 35 cm can be seen from base to top of a side wall of this center, while most of the building was washed away by the surges/waves. Numerous examples of these types of failure were observed during the field survey. Although in other cases it is likely that the direct wave/surge forces and impacts were enhanced by large debris carried by the waves, in the case of Scotts Head there are no nearby sources of large debris objects, thus we infer that the damage there was due primarily to hydrodynamic forces and water impacts.

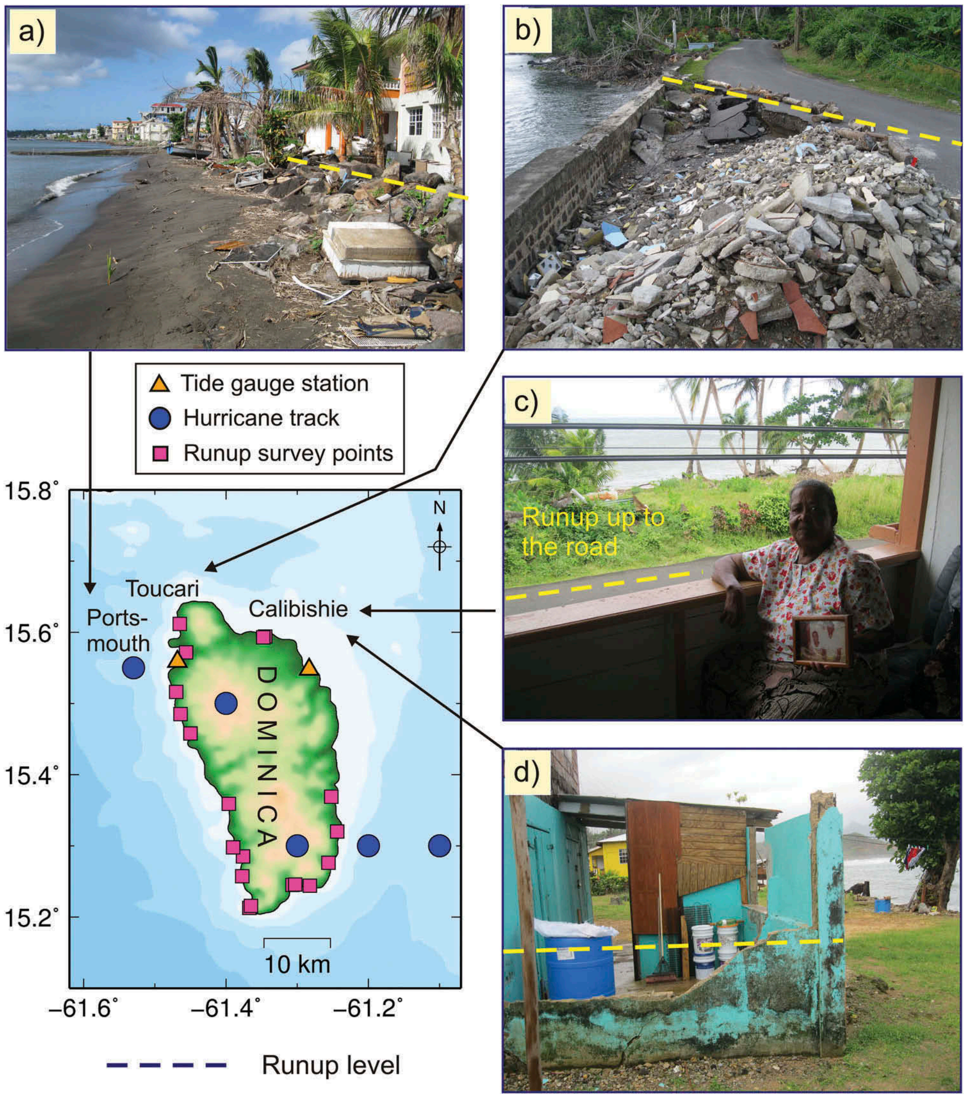

Figure 6. Photographs showing runup measurement points (yellow lines) around the coasts of Dominica during the February 2018 field survey of Hurricane Maria damage in Dominica (part 3).

5.3. Debris impacts

Many structures along the coast were affected by impacts of debris brought back to the shore by the waves/surges. For example in Mahaut, a corner column of a two-story reinforced-concrete building, located at the shoreline, was broken by impacts of large timber debris, in the form of abraded tree trunks several meters long and several tens of centimeters in diameter (Figure 8(a)). The reinforced concrete floor slab supported by the column then collapsed. Several large hurricane-originated timbers are seen trapped by the collapsed floor slab at the foot of this building (Figure 8(a)). Although some timbers might have been wind blown, the majority were most likely brought down to the sea by river floods and then transported along the shore by storm/wave-induced drift: Several rivers entering the sea near Mahaut experienced extreme floods during Hurricane Maria that transported abundant tree debris, some of which was left stranded on river banks or was trapped in debris dams or beneath bridges, but some of which also seems to have entered the ocean. This is a classic example of debris impacts on structures during storms and tsunamis. Such impacts were previously reported during other events such as the 2013 Super Typhoon Haiyan (Takagi et al. 2017) and the 2010 Chilean tsunami (Robertson, Chock, and Morla 2012; Naito et al. 2013; Como and Mahmoud 2013).

5.4. Intense coastal sedimentation

At several coastal locations close to river mouths, evidence of intense sediment transport and deposition were observed (Figure 8(b)). The example in Figure 8(b) shows the Roseau river mouth: this location accumulated a large amount of river flow sediments, resulting from the erosion and landslides caused by Hurricane Maria's heavy rainfall inland and which were subsequently deposited as flood waters decelerated on entering the ocean. Such focused sedimentation has the potential to block the river mouths, increasing the potential for river

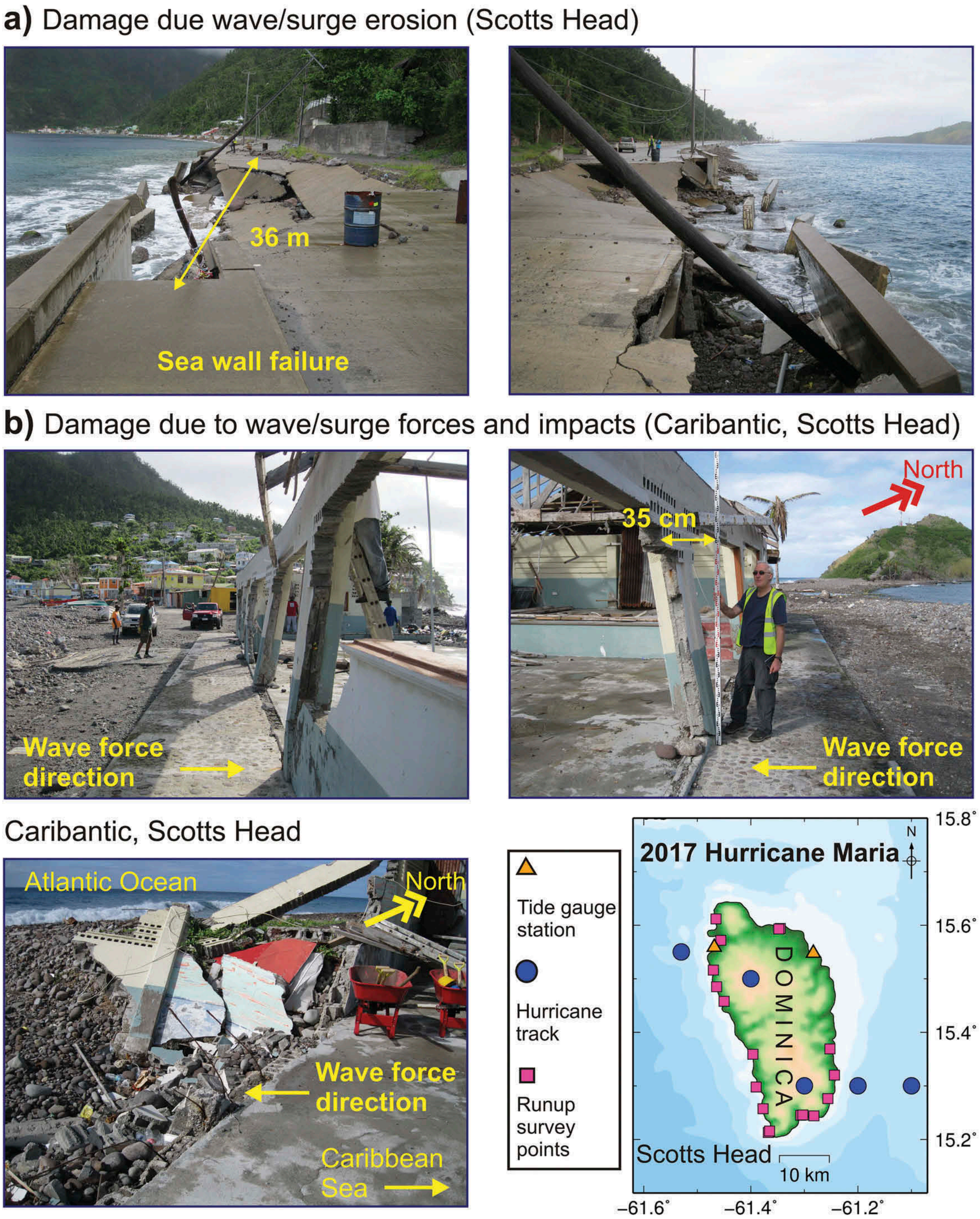

Figure 7. Different types of damage to coastal structures from Hurricane Maria in Dominica, observed during the field survey (part 1).

overbank flooding upstream. Dredging operations to remove such sediment were ongoing in Roseau's main river channel at the time of the survey, around four months after Hurricane Maria (Figure 8(b)). These dredging operations to remove such intense sediment loads are costly and take a long time to complete but are vital to prevent further reworking of the sediments and flooding. In addition, such large volumes of sediments have the potential to change the coastal dynamics and to impact the coastal ecosystems, which have not yet been evaluated.

6. Discussion

Storm surges are one of the most dangerous effects of hurricanes. Yet, in relation to other intense Atlantic/Caribbean hurricanes and Pacific typhoons with comparable wind speeds, the storm surge/wave runups produced by Cat-5 Hurricane Maria on Dominica were relatively small. For instance, the 2005 Cat-3 Hurricane Katrina produced runup heights of more than 10 m along the south coast of the USA (Fritz et al. 2007) and the 2012 Cat-3 Hurricane Sandy's runup heights were up to 6.5 m along the USA coasts (Irish et al. 2013).

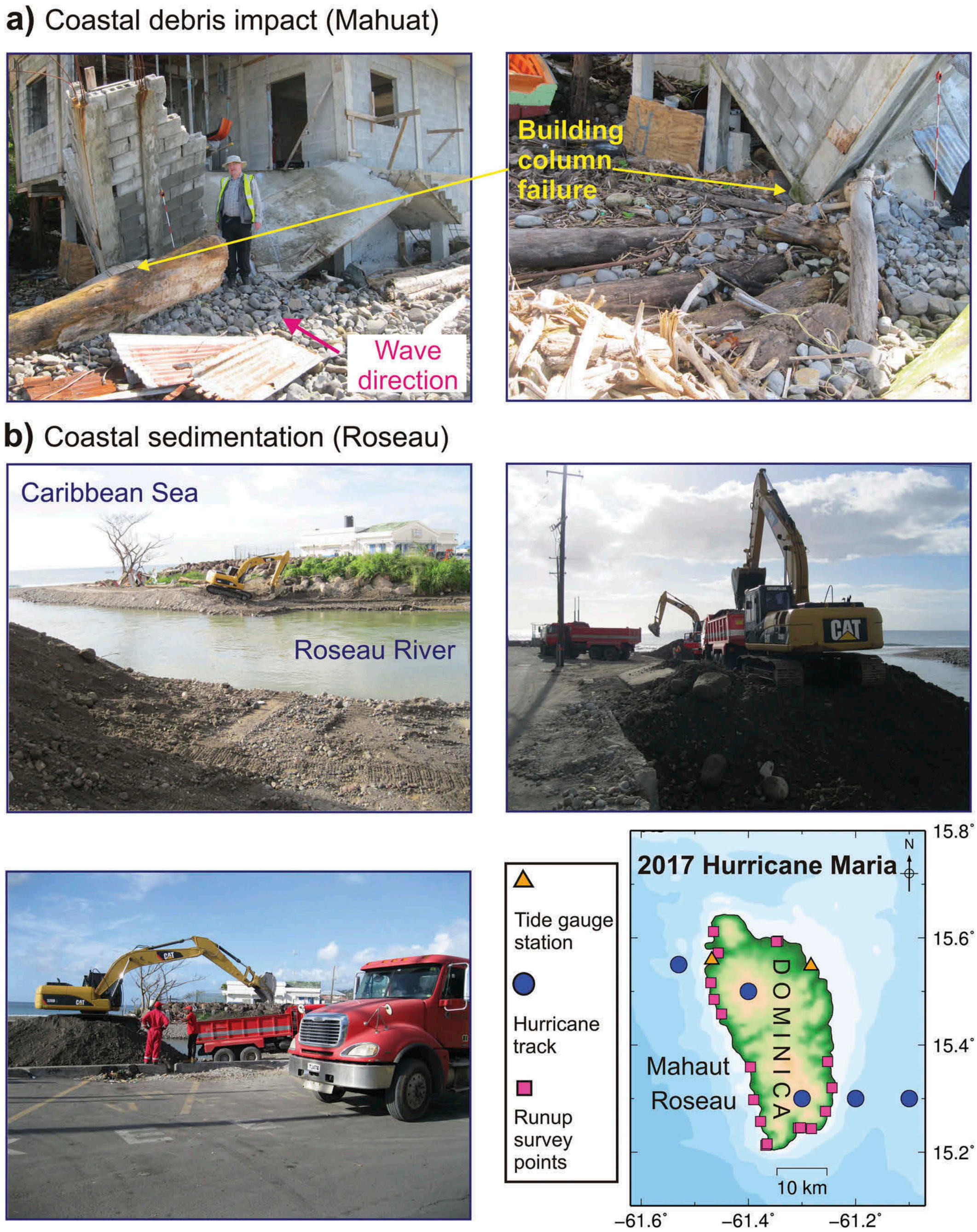

Figure 8. Different types of damage to coastal structures from Hurricane Maria in Dominica, observed during the field survey (part 2).

Super typhoon Meranti (October 2016) produced a maximum runup height of 8.6 m along the north coast of the Philippines (Tajima et al. 2017). In general, various factors contribute to the surge/wave heights of a hurricane, notably: high-velocity winds acting on the ocean surface (Harris 1957); local bathymetry and related effects such as funneling (Mori et al. 2014); the hurricane pressure field acting on the ocean surface; and hurricane path relative to the coast, which determines the fetch length (Raichlen 2013). The highest surges are expected where the hurricane winds have long fetch lengths (Harris 1957). With regard to hurricane pressure field dimensions, the wide continental shelf and a long continuous coastline of the eastern seaboard of North America is in marked contrast to Dominica, which is a relatively small, steeply-sloping island with 1–2 km deep water channels to the north and south (Figure 1). Therefore, it is to be expected that runup heights in Dominica will be smaller than in the case of hurricanes striking extended coastlines with long shallow shelf; thus, it is invalid to link the hurricane surge/wave heights to only the intensity of the hurricane (i.e. wind velocity), without also considering the role of local and regional bathymetry. Fritz et al. (2007) also showed that a simple direct correlation between hurricane intensity and the resulting coastal surge/wave height is not successful.

To further explain the effect of local/regional bathymetry on the storm surge, the bathymetry contours around Dominica are shown in Figure 9(a,b). The offshore regions to the south and to the east and north of Dominica are sheltered by the two neighboring islands of Martinique and Guadeloupe, respectively, while the southwest and west coasts of Dominica are exposed to deep waters. In terms of fetch length, longer fetches affect more the west and southwest coasts than at the east and north. As a reference, we measured the shelf width (water depth <100 m) (W) in front of each runup measurement point and compared it with the runup values (R) (Table 2, Figure 9(c)). In contrast to the study by Shimozono et al. (2015), no correlations can be established between W and R. This is similar to the result previously reported by Tajima et al. (2017) for Super Typhoon Meranti (October 2016). The lack of correlation between W and R can be attributed to other factors, such as the sheltering effects of neighboring islands which could protect Dominica against the storm waves (Tajima et al. 2017). In addition, as there are many small islands in the east Caribbean Sea (Figure 1(c)) which form a discontinuous border with several straits between them, any wind-dragged water mass piled up along the coasts will likely leak through the straits between the islands; consequently storms may not gain significant heights along the coasts of the east Caribbean Sea.

The runup distribution pattern shows an apparent correlation with hurricane-related death reports which showed that most of the fatalities were concentrated at the southern half of Dominica. According to Dominica Police records, the urban areas of Pointe Michel, Roseau, Loubiere (between Castle Comfort and Pointe Michel) and Grand Bay (Dubuc and Fond St Jean) suffered most of the fatalities (see Figure 3 for these locations). However, the relationship between the storm surges/waves and the distribution of deaths is an indirect relationship, given the fact that most of the deaths in Dominica were caused by floods and debris flows on steep gradients inland from the coast itself. We note that based on the newspaper reports, at least

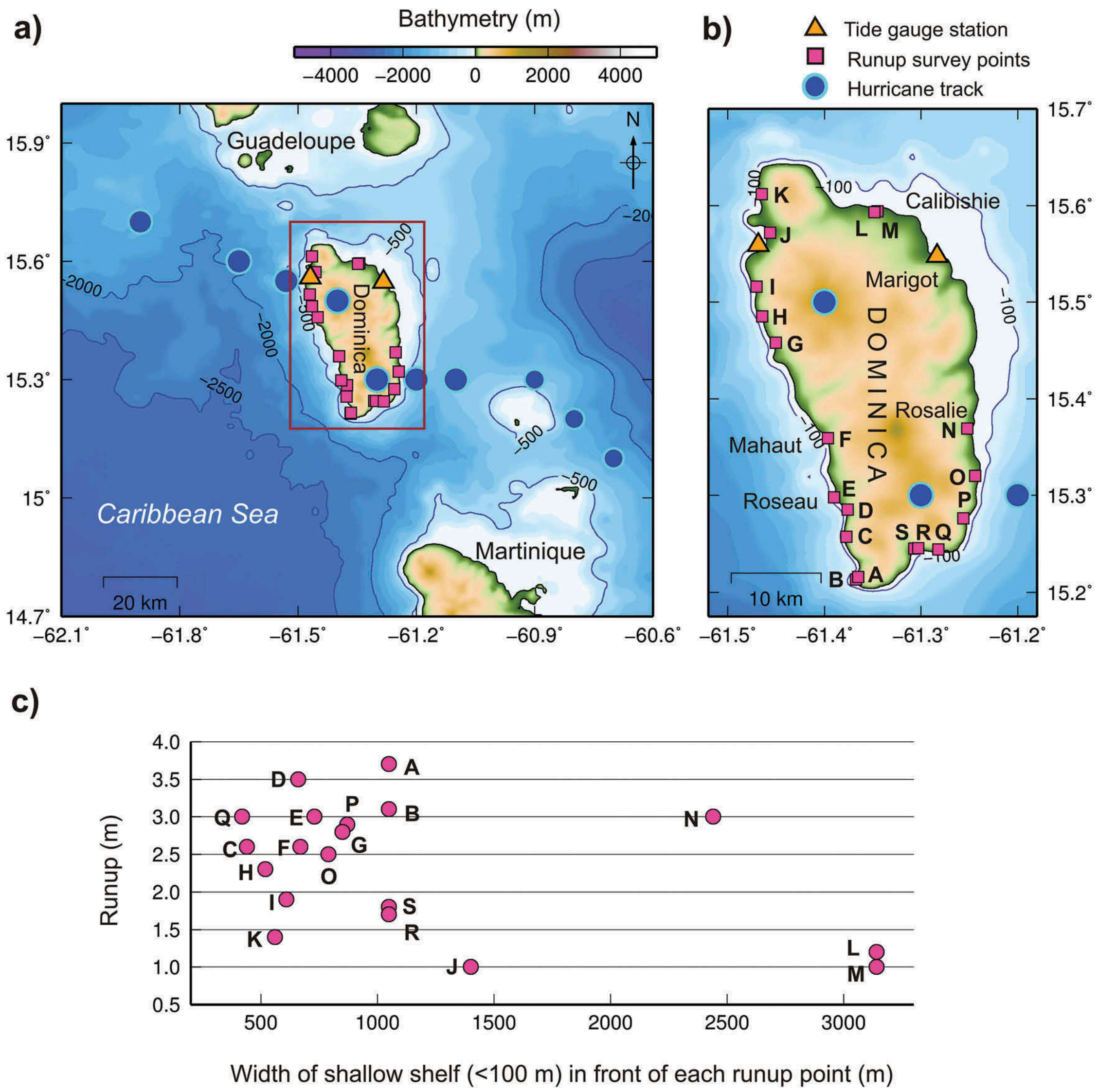

Figure 9. (a,b): Bathymetry contours in the Caribbean Sea around Dominica. (c): relationship between runup heights and the width of shallow shelf (depth <100 m) in front of each runup measurement point. The letters A-S are used to pair runup locations and heights in panels "b" and "c".

Table 2. Corrected runup heights (R) of Hurricane Maria in Dominica versus the width of the shallow shelf in front of each runup measurement point (W) and the respective ratio.

Location	Final runup value (m) [R]	Width of the shallow shelf (m) (<100 m) [W]	R/W ($\times 10^{-3}$)
Pointe Michel	2.6	440	5.91
Dubuc	1.8	1050	1.71
Dubuc	1.7	1050	1.62
Fond St Jean	3.0	420	7.14
Scotts Head	3.7	1050	3.52
Scotts Head	3.1	1050	2.95
Roseau	3.0	730	4.11
Castle Comfort	3.5	660	5.30
Rosalie	3.0	2440	1.23
Delices	2.9	870	3.33
Laronde	2.5	790	3.16
Mahaut	2.6	670	3.88
Coulibistrie	2.8	850	3.29
Colihaut	2.3	520	4.42
Dublanc	1.9	610	3.11
Calibishie	1.0	3140	0.318
Calibishie	1.2	3140	0.382
Portsmouth	1.0	1400	0.714
Toucari	1.4	560	2.50

one death in Scotts Head was directly linked to the storm waves. It is likely that the very strong onshore winds on the west and south coasts of Dominica produced both storm surges/waves and intensification of rainfall and triggered landslides and debris flows over the steep west-facing and south-facing slopes: thus, the apparent correlation between the storm surge/wave runup distribution and the mortality distribution may reflect a common cause to both distributions, rather than a cause and effect relationship between them. In other words, the Dominica field survey revealed that there is a complex correlation between various damage/death mechanisms, making it difficult to determine the level of contribution of each individual mechanism.

Figure 10 summarizes the interactions of the hurricane-driven damage mechanisms observed in this Dominica field survey. The various damage mechanisms occur in a partly coupled sequence of events (described as a "cascade" in the terminology of Pescaroli and Alexander 2016). We identify three particular cases in which the partial coupling between these intensified the damage:

- In the first example, thousands of landslides (approximately 10,000 slope failures, according to http://www.unitar.org/unosat/node/44/2762), led to large amounts of tree debris entering the rivers and then being transferred into the sea. The river debris contained numerous large tree trunks: these were carried back to the shore by surge and wave actions and impacted coastal communities, increasing coastal damage, e.g. failure of a two-story reinforced concrete building on the Mahaut seafront due to tree debris impacts (Figure 8(a)).
- A second example of a coupled sequence or "cascade" is provided by storm surge and onshore waves forming debris barriers at river mouths, causing rivers to back up and producing increased overbank flooding, as well as sedimentation in river mouths, e.g. at Coulibistre, Roseau and Colihaut (Figure 3).
- A third example was seen in Scotts Head (Figure 7(a)) where the coastal road was damaged as a result of erosion of the road foundation which itself was a result of the failure of the protecting seawall.

In terms of coastal resilience against hurricanes, it is important to understand the sequence of events that lead to a particular damage to an infrastructure and to increase resilience by breaking the chain of events where possible before the damage is made. In such a context, Figure 10 guides where the investment should be focused to increase the resilience. For instance, wave-related coastal erosion can be prevented by protecting coastal infrastructure by an appropriate seawall to stop the waves or by a breakwater to dampen wave actions.

7. Conclusions

We studied the tide gauge records of the September 2017 hurricane Maria in the Caribbean Sea and conducted a field survey to document the surge/wave runup heights and the damages to coastal structures. The main findings are:

(1) Based on the regional tide gauge records, the hurricane surge duration was 2.1–2.6 days in the region, with 2.1 days observed for Marigot, Dominica. The recorded surge amplitudes were: 75 cm in Marigot, 52–60 cm in Guadeloupe (located ~ 100 km to the north of Dominica) and 25 cm in Martinique (located ~ 100 km to the south of Dominica). The maximum surge amplitude of 75 cm highlights the moderate size of the hurricane-related surge and wave amplitudes in Dominica.

(2) The field survey resulted in the measurement of the surge/wave runup heights all around the island. The runup was in the range of 1.0–3.7 m, with maximum runup of 3.7 m observed in the village of Scotts Head at the south-west tip of Dominica. The largest runups were concentrated at the southern half of the island where the hurricane first made landfall and consistently decreased toward the north.

(3) Four different types of damage from surges/waves to coastal structures were observed: (i) damage due to surge/wave erosion; (ii) damage due to surge/wave forces/impacts; (iii) debris impacts to coastal structures; and (iv) intense coastal sedimentation.

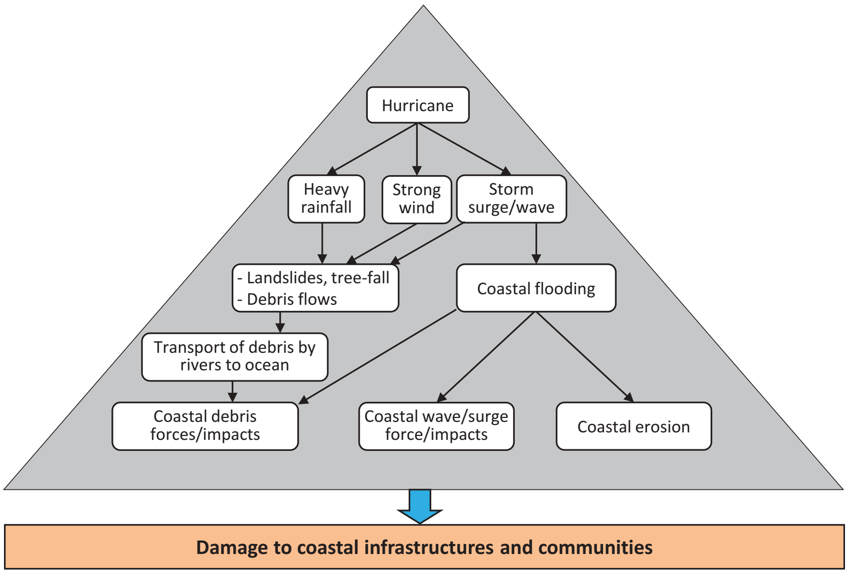

Figure 10. Chart showing interactions of various Hurricane Maria hazards and damage mechanisms to coastal communities observed in the Dominica field survey.

(4) Interactions between the coastal processes of storm surge/waves, and the onshore effects of the hurricane, particularly those that created debris and sediment inputs, exacerbated the damage caused by the coastal processes in the south and west of the island.

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