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ORIGINAL PAPER

High swell warnings in the Caribbean Islands during March 2008

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Abstract Long and high swells are dangerous for many islands located in the Tropics because they can generate large breakers and long run up associated with large set up when reaching the coast. Most of the time those islands do not experience large waves especially in usually protected areas, for instance, by coral reefs or wind protected. Long waves have the ability to reach such areas, thanks to wave set up, shoaling and bottom refraction. This article describes an example of such high swell events and its impact on the islands. The buoy network used by the French National Weather Service and all available satellite observations related to waves are presented together with numerical sea-state models used to issue early warnings.

Keywords Swell · Wave buoys · Altimeter data · Numerical Wave models · Natural hazards

1 Introduction

Since 1999, Meteo-France has operated two marine automatic weather stations (MAWS), east of Guadeloupe and Martinique. Observations from these buoys provide early warning of severe weather and wave conditions during the hurricane season. In other seasons, high swell events may occur and only MAWS from NOAA, located north of the largest Caribbean Islands, can provide early warnings of such events. Sea-state model forecasts and altimeter measurements are also used to this end. In addition to the open-ocean locations, a network in coastal areas near shore waters has been implemented. Figure 1 shows the operating locations of the various moored buoys.

The meteorological data (pressure, wind) from these systems are not only assimilated into numerical weather prediction models (NWP), but are also used by forecasters to monitor developing weather conditions and also to provide ground truth for satellite

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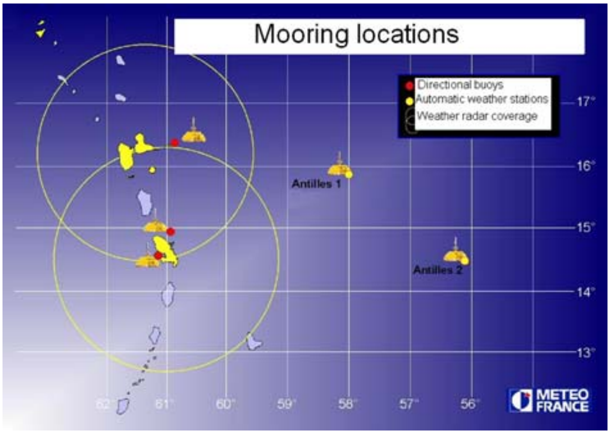

Fig. 1 Map showing the locations of the two French automatic weather stations (*yellow dots*) and three directional buoys (*red dots*) around the French Caribbean Islands. The buoy located just at the east of Guadeloupe has been moved close to the north of the island

calibration/validation. With time-series extending for almost 10 years, such data have become increasingly important in characterising the ocean climate.

2 Description of the moored buoys capability

Each automatic system measures air pressure, air and sea temperature, humidity, wind speed and direction, and wave height and period. All stations transmit their observations hourly—24 h a day, 365 days a year. The buoys are normally deployed for a few years with a routine annual sensor change and mooring inspection.

Each buoy has a dual set of sensors (which allows for cross-checking the data) that are cross-linked to two modular automatic weather stations (AWS), which in turn are cross-linked to two twin Meteosat communications systems. This cross-linking is designed to make the buoys systems resilient to individual component failures. The buoys are solar powered using twin panels, but will run for approximately 3 months on batteries alone. Out of the water, each buoy is 6-m tall, 3 m in diameter and weighs 4.5 tonnes.

Directional buoys are based on Datawell waveriders and data are transmitted using the Argos system for integrated parameter and HF system for wave energy spectra (Fig. 2).

3 Synoptic situation

During the period 17/18th March 2008, observations from the moored buoys located to the east of the USA showed very strong winds and extreme wave conditions. These were due to a low pressure system that deepened very quickly as it reached the ocean, as illustrated in Fig. 3.

A low coming from the North American continent moved north-east with a strong and fast deepening when evolving over the ocean. As it reached 60° west, south of Newfoundland, it slowed and became nearly stationary (between 0000 on 17th and 1800 on 18th March). During more than 36 h, a large area of strong northerly winds with speeds

Fig. 2 The two MAWS buoys on the way for mooring (*left panel*), a directional wave buoy located close to Martinique (*right Panel*)

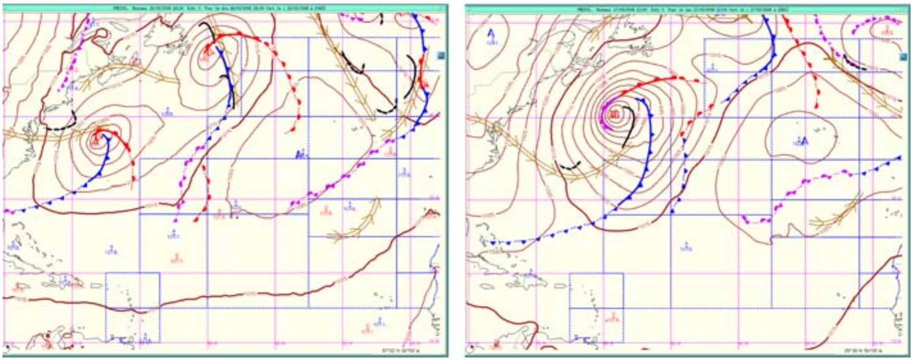

Fig. 3 Showing the location of the low on 16th March 1800 and 17th March 1200

above 40 kts, locally 60 kts, generated phenomenal sea (significant wave height above 14 m).

Figure 4 shows ECMWF (European Centre for Medium range Weather Forecasting) wind analyses at 1200 on 17th March and 0000 on 19th. As can be seen, there was a very large Fetch with high winds (only winds above 25 kts are reported on the maps), following on behind the centre of the depression.

Then, waves propagated into a powerful long swell in the direction of the Caribbean Islands. According to the National Weather Service (NWS) of the USA, it was the most powerful swell of the last 10 years reaching the Caribbean Islands from an extra-tropical system. After passing Porto Rico, the swell reached Saint-Martin and Saint-Barthélemy, on 20th March around 0500 local time, then Guadeloupe at 1000 local time and Martinique at 1500 local time. The swell finally reached French Guyana two days later, on 22nd March at 0700.

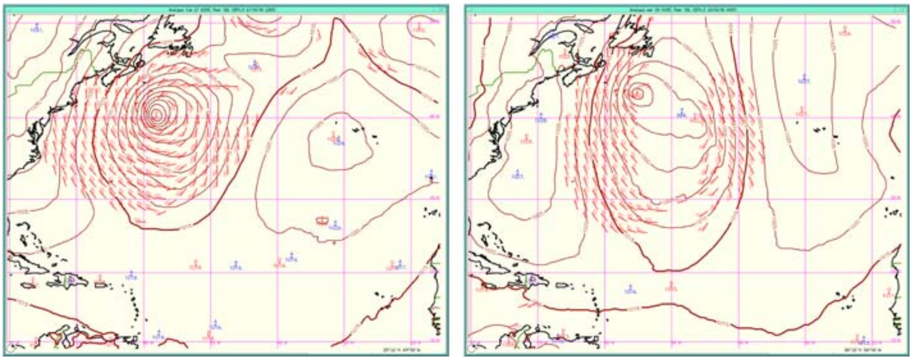

Fig. 4 ECMWF wind analyses for 1200 on 17th March 2008 and 0000 on 19th March

4 In situ observations from the moored buoys

The buoy located north of Porto-Rico (41043) is very useful to validate model forecast and to anticipate a few hours ahead large swells when generated off shore east coast of North America. Antilles buoys (41100 and 41101) are more dedicated not only to provide early warning for hurricane waves, but can also be used to validate model predictions for any situations.

Buoy	Latitude (°N)	Longitude (°W)
41043	20.99	−65.01
41100	15.90	−57.90
41101	14.6	−56.20

Observations from the MAWS network are exchanged internationally on the WMO global telecommunication system (GTS) in SHIP and Waveobs coded format for the MAWS network and in Waveobs coded format only for the directional buoys.

The moored buoys all have a Datawell heave sensor on board. This measures the significant wave height and wave period. The 'significant' wave height recorded is four times the RMS (root mean square) value of the water level above the average level of the water surface over a 17½-min period. The 'average' wave period, again over a 17½-min sample is also provided (Figs. 5, 6).

Guadeloupe buoys were reporting peak periods up to 18 s and significant wave height up to 5 m with maximum wave height over 7 m. Similar values have been reported by Antille1 buoy.

5 Satellite observations of wave heights

Satellite observations of wave heights are also used to monitor the sea-state. The Envisat satellite carries a radar altimeter (RA-2) which measures wave heights (to better than 5% or 0.25 m, for a single measurement at 1 Hz). Jason satellite also carries a radar altimeter

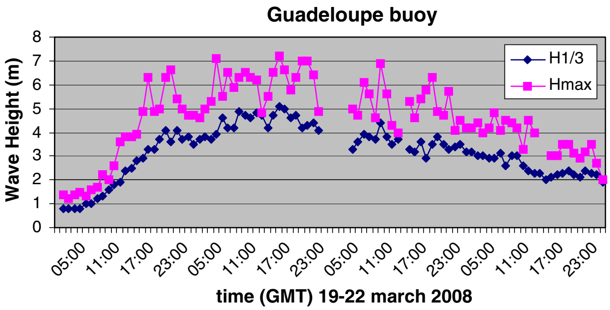

Fig. 5 Significant wave height (H1/3) and maximum wave height measurements from the Guadeloupe moored buoy for the period from 0000 on 19th to 2300 on 22nd March 2008

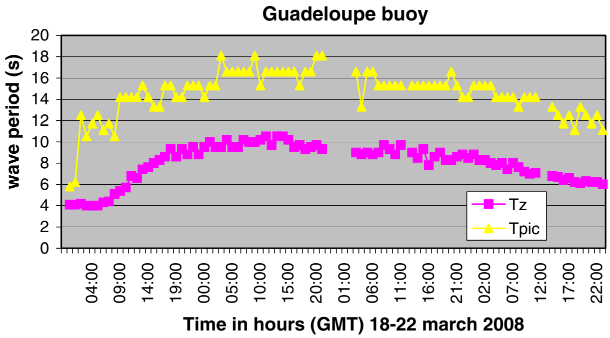

Fig. 6 Average wave period (T_z) and peak period (T_{pic}) measurements from the Guadeloupe moored buoy for the period from 0000 on 19th to 2300 on 22nd December 2007

(Poseidon-2) which measures wave heights (to better than 10% or 50 cm, for a single measurement). Envisat polar orbits are sun-synchronous polar at about 800-km altitude with each orbit taking just over 100 min, the repeat cycle of the reference orbit is 35 days. Jason orbit is not sun-synchronous and is at about 1,300-km altitude with each orbit also tacking about 100 min, the repeat cycle of the reference orbit is 10 days. Because RA-2 and Poseidon-2 have a narrow swath (a few km) they do not give global coverage in 1 day (even in 35 days and 10 days, respectively). It is therefore not very often that the core of the storm is caught by one of the altimeters. However, an Envisat RA2 track passed over the area of maximum significant wave height around 0131 on 18th March, track passing over the point 40° in latitude north and 60° in longitude west. While this track missed the highest waves, however, it recorded waves above 13 m. Later, when waves propagated southward, altimeters were able to follow them. The ENVISAT advanced synthetic aperture radar (ASAR) also captured the long swell signature. On 21st March, the swell has propagated over the Caribbean Sea and the masking effect of the islands along the Jason track can be seen in Fig. 7. A sharp gradient of the wave heights along the Jason track is followed by a slight increase as part of the swell energy passed through the channels.

6 Wave model forecasts on this occasion

Swell prediction is based on the use of models that solve the transport equation for the wave action (wave energy spectrum divided by the intrinsic frequency). These are phase averaging models and the state of the art in operational sea state forecasting are the third generation wave models (the WISE Group 2007) that solve the transport equation explicitly, without any assumption about the wave energy spectrum. Most of the national

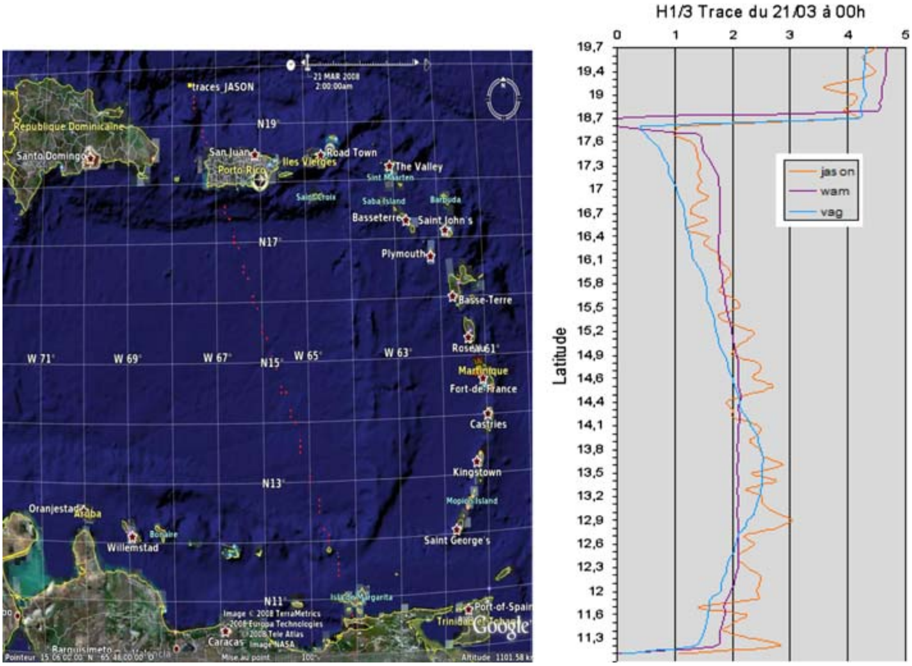

Fig. 7 Ground track of Jason altimeter (*red dots on left panel*), significant wave height from Jason along track (*orange line*), from ECMWF wave model (*purple line*), from Meteo-France wave model (*blue line*) on 21st March 2008 around to 2100 (*right panel*)

weather services (NWS) are running, or are about to run such models. For large domains, the most common of these models are WAM (WAMDI Group 1988; Komen et al. 1994), WaveWatch3 (Tolman 1989). For shallow water in coastal zones, SWAN (Ris 1997) is the most common spectral model. Meteo-France forecasters are using outputs from global and regional wave models (VAG, Fradon et al. 2000; Lefèvre et al. 2003) to provide analyses and forecasts of the sea state. They have at their disposal, outputs from the Météo-France 1° resolution global wave model and from a regional model implemented for the Caribbean Sea with a higher resolution (0.1°), which supports a range of user applications (Figs. 9, 10). In particular, the Caribbean Sea wave model produced very reliable forecasts inside the Caribbean Sea, as shown in the above Fig. 7. The global model also provided reliable forecasts which show a region of waves with significant wave heights in excess of 15 m (Fig. 8). They also use ECMWF and NCEP (National Centre of Environment Prediction) wave model outputs.

Wave models compute the evolution of the two-dimensional wave spectrum which gives wave energy as a function of frequency and direction at each grid points.

The large number of components implies to provide integrated parameters that can be more easily interpreted and used. The most widely used parameters are the significant wave height (SWH), the peak or mean wave period (significant period), the mean wave direction. Each of those parameters can be computed for the total sea, the wind sea, the total swell, the dominant swell, the secondary swell and other swell components. In addition to the height of the swell, the peak period and direction of the swell are very important

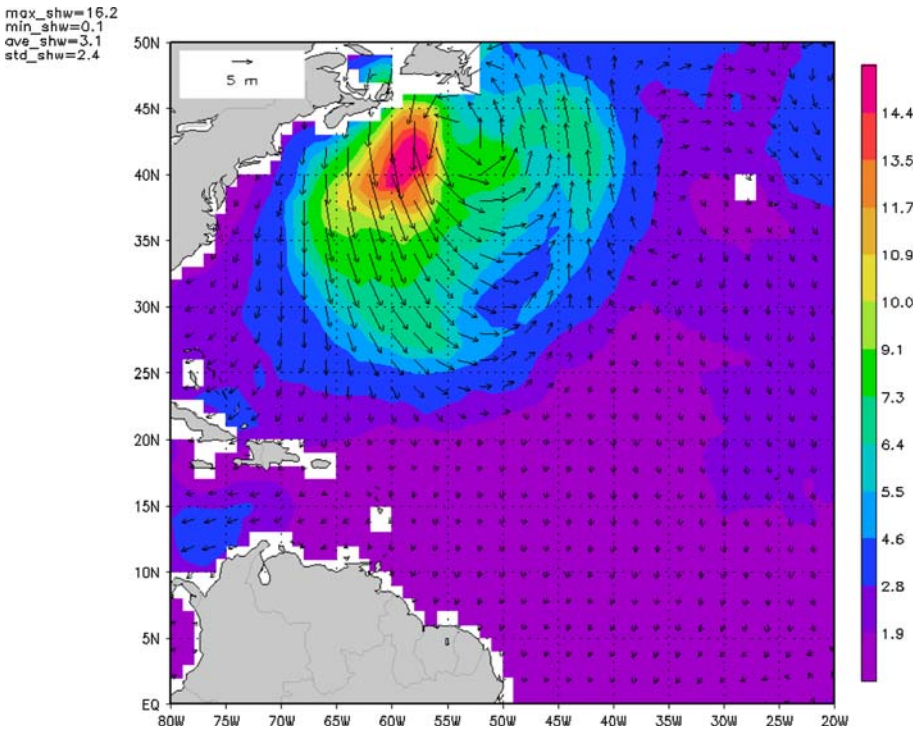

Fig. 8 The significant wave height (m) at 1200 on 18th March 2008 from Meteo-France wave model

parameters since they provide information about the potential danger of waves in shallow water areas and coastal zones.

7 Potential dangers of long waves

As noted earlier, this swell was the largest from the last 10 years from an extra-tropical system ever reported that reached Caribbean Islands from north. Moreover, the peak period of the swell was very large (up to 18 s). Long waves are much affected by two processes which influence energy levels in shallow water areas. These processes are called wave refraction and shoaling. Wave refraction represents changes in the propagation direction of the waves, causing wave energy to be focused or defocused due to geometry of bathymetry. As a consequence, refraction causes change also in wave height. Shoaling represents changes in the height of the waves due to changes in the propagation velocity and the conservation of the wave energy flux which is proportional to the wave energy times the energy velocity. When waves travel from deep water to shallower water, the wave speed is affected by the depth. In such shallower regions, waves from deeper water are slowed down resulting in more energy coming into area than energy going out. The waves are growing and finally breaking when approaching the shore. The breaking wave height is as big, as the wave period is large for a given wave height in deep water. Also, long waves are generating set up and large run up, and some exposed coasts are flooded. Particularly dangerous are shallow reefs because long waves will break when propagating across such

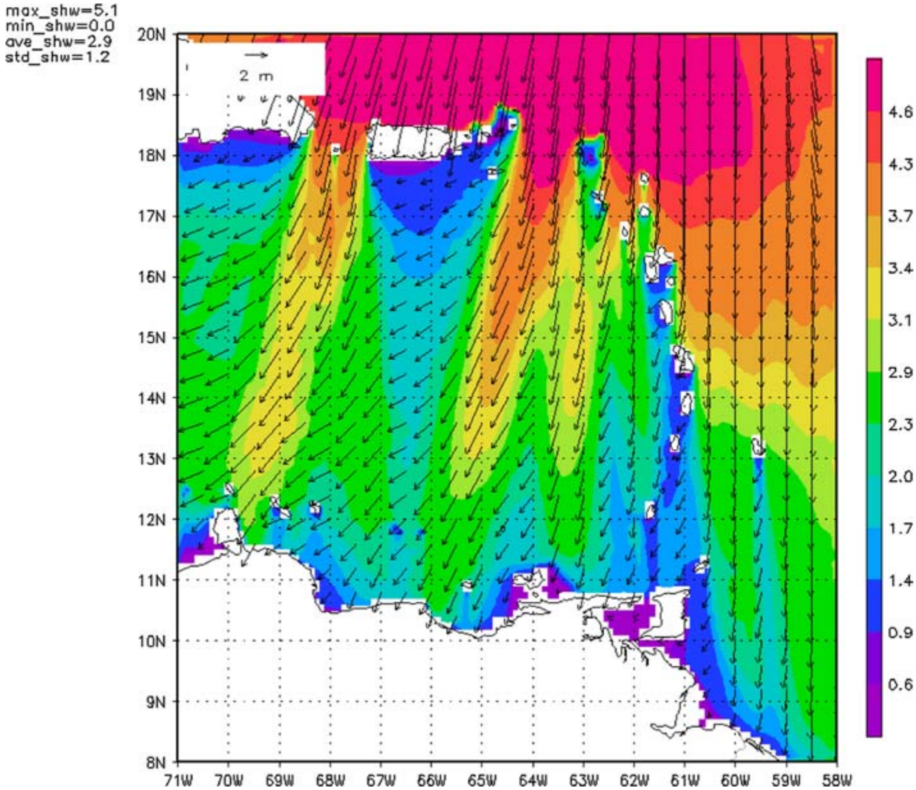

Fig. 9 The significant wave height (m) at 1200 on 20th March 2008 from Meteo-France wave model analysis

areas generating local 'freak' waves. Small crafts are particularly vulnerable to such waves.

8 Impact of the swell on the islands

Saint Barthelemy, Saint Martin and Guadeloupe's weather services have issued early warnings, and so, the maritime traffic has been interrupted for a while and swimming was not allowed. Significant impacts have been reported for these islands together with French Guyana, but only little impact has been reported in Martinique, thanks to the masking effect of the islands located north to Martinique.

In Saint Barthelemy, most of the ships moored in the main harbour left for a more safe location. The long swell brought some damage to some light structures in the harbour. In Guadeloupe, exposed cities have been flooded with serious damage to roads and some houses had to be evacuated. Raining water pipes have been filed by sand. A submarine electric cable has been cut between la Désirade island and Guadeloupe, the main island. A few tents have been swamped by the swell, though local authorities had warned people not to stay on the beaches.

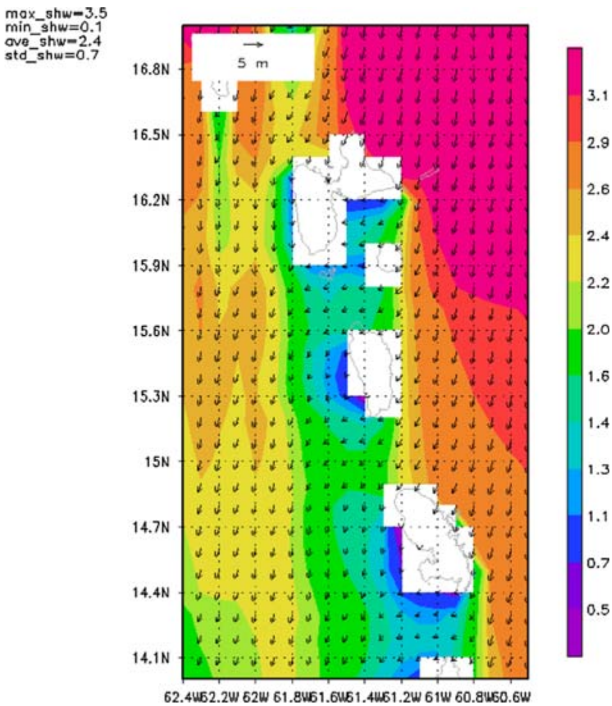

Fig. 10 The significant wave height (m) at 1200 on 20th March 2008 from Meteo-France wave model 24 h forecast

9 Discussion

Long and high swells are dangerous for many islands located in the Tropics because they can generate large breakers and long run up associated with large set up when reaching the coast. Most of the time, those islands do not experience large waves especially in usually protected areas, for instance by coral reef or wind protected. Long waves have the ability to reach such areas, thanks to wave set up, shoaling and bottom refraction. Out of the hurricane season, very early warnings (a few days before) can be issued, thanks to the quality of wave model forecasts associated to appropriate buoy networks, altimeter data and other remote sensed data such as provided by synthetic aperture radars. However, one of the remaining difficulties is to anticipate the impact of the waves everywhere and to warn people and local authorities adequately.

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