Current Applications for an Array of Water Level Gauge Stations

New Discoveries in the Seiche Band and the Meteorological-Oceanic Band

Las aplicaciones actuales de una matriz de estaciones de medición de nivel de agua: Nuevos descubrimientos en la Banda Seiche y en la Banda Meteorológica-Oceánica

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A Tide Gauge is a Water Level Gauge (WLG)

The term "tide-gauge" is inadequate to describe or contain all the current applications of this kind of oceanographic instrument. A more proper name should be a Water Level Gauge (WLG), because it measures changes or oscillations in water levels due to a myriad of oceanographic and atmospheric phenomena. Tides are just one contributor to water level variability. It is important to understand that to make sense of the water level data it is necessary to support it with meteorological data. Simultaneous high-resolution measurements of atmospheric pressure, wind speed & direction, and air temperature are necessary to interpret these water level measurements. Some applications for WLG data are: monitoring & prediction of water levels, oceanographic research, validation of altimeters & tidal models, and to detect the occurrence of a tsunami or a storm tide. In addition, it can measure the Sea Level Rise caused by Global Warming.

Physical Parameters Measured by WLG's

- A single station can record
    - Water Level Height
        - Amplitude of the oscillation
    - Time
        - Arrival time of a particular oscillation
        - Time scale of the oscillation
        - Period or Frequency of oscillation
    - Form
        - Linear or nonlinear form
        - Symmetric or asymmetric form
        - Single or mixed form

- An array of stations can determine the
    - Coherence between stations
    - Age or Delay time of any event. Important for warning systems.
    - Spreading or Spatial Coverage of an event
    - Wave Speed or Celerity
    - Pinpoint the Source Area of a particular event

Ocean Phenomena and Applications of Water Level Gauges

- **TIDES**
    - **HYDROGRAPHY**
        - **Prediction of Tidal Heights**
        - Requires hourly water heights for a pre-selected time period: 30 days or 1 year or 19 years
        - Harmonic Analysis of the water level record
        - **Tidal Datum**
            - MLLW – Mean Lower Low Water (Chart Datum)
                - The average of the lower low water height of each tidal day observed over the National Tidal Datum Epoch (NTDE), 19 years. The present NTDE is 1983 through 2001 and is actively considered for revision every 20-25 years
            - MHHW – Mean Higher High Water
            - HAT – Highest Astronomical Tide
                - The elevation of the highest predicted astronomical tide expected to occur at a specific tide station over the National Tidal Datum Epoch.
            - LAT – Lowest Astronomical Tide
            - MSL – Mean Sea Level
                - The arithmetic mean of hourly heights observed over the National Tidal Datum Epoch.
- **COASTAL SEICHES**
    - Coastal seiches are long, standing waves that oscillate at a characteristic resonant frequency and which occur when the shelf waters - between the shelf break and the coast - are disturbed by an external force.
        - Meteorological – pressure jumps, sudden shift in winds, etc.
            - Meteotsunami
                - The term Meteotsunami is used to designate a series of waves in a harbor (bay) that show a similar frequency or amplitude to that of a tsunami generated by earthquakes, landslides or volcanic eruption but unlike these, its origin is associated with an atmospheric disturbance able to generate a barotropic long

wave in the open sea, resonate with it (Proudman resonance) as approaches the coast. Once reaches the harbor (bay) is capable of forcing a number of waves, which enter in a second resonance with the harbor (bay) which amplifies it again. The meteotsunami only occurs in certain harbors (bays) where this double resonance is possible.

            - Atmospheric disturbances
                - a jump in barometric pressure
                - atmospheric gravity waves
                - the passage of a front
                - a line of strong winds (squall);
        - Oceanic
            - Internal Solitons or Solibores
                - Packets of internal solitary waves generated in deep ocean
        - Seismic
            - Tsunamis

- **METEOROLOGICAL-OCEANIC EFFECTS**
    - Changes in water levels due to meteorological and oceanic effects (short-term)
        - Changes in Atmospheric Pressure and Winds (low pressure systems such as: hurricanes and tropical storms; also high pressure systems)
            - Storm surge
                - Inverse Barometer Effect
                - Strong Winds – pushing waters toward the coast.
        - Changes in Ocean Circulation
            - Geostrophic currents
            - Oceanic eddies
            - Kelvin waves
            - Coastal trapped waves (CTW's)
            - Edge waves
        - Climatic Processes
            - Thermal Heating
- **LONG-TERM TRENDS OF SEA LEVEL**
    - Mean Sea Level Trend due to Global Warming
    - Vertical Motions of the Earth's Crust
- **VALIDATION**
    - Validate sea level measurements of the open ocean detected by satellite altimeters
    - Validate the output of tidal models

WLG's measure physical phenomena in a wide range of space-time scales

Phenomena	Time Scale
Coastal Seiches	6 minutes to 2 hours
Tides	3 hours to 18 years
Meteorological-Oceanic	Hours to Months
Long-term trends in sea level	Years to Centuries

Phenomena	Space Scale
Coastal Seiches	Less than 50 Kilometers
Tides	Hundreds or Thousands of Kilometers
Meteorological-Oceanic	Local to Regional
Long-term trends in sea level	Regional to Global

An Array of WLG's is a Sensitive Instrument Capable of New Discoveries

A WLG station measures simultaneously oceanic and meteorological parameters with a high time-resolution (1 to 6 min). But an array of these stations can characterize the spatial coverage of any physical phenomena. Increasing the space resolution and assuring a better analysis of the ocean's phenomena.

Let's see some recent discoveries made possible by the WLG's array.

- In the Seiche Band
    - 2011-Discovery of the Magueyes Cycle of extreme seiche activity (T= 6202.2 ± 1.3 days, 16.98 years)
    - 2011-Discovery of Meteotsunamis generated by pressure jumps associated with the arrival of strong tropical waves
    - 2013-First measurements of a Transatlantic Meteotsunami
- In the Meteorological-Oceanic Band
    - 2011-Discovery of Edge Waves trapped on the Cabo Rojo-Mayaguez Shelf, about 30 hours after the passage of Hurricane Irene over Puerto Rico
- In the Long-Term Band
    - 2012-Two stations confirm a positive trend of Sea Level Rise around Puerto Rico.

Seiche Band

2011-Discovery of Meteotsunamis generated by pressure jumps associated with the arrival of strong tropical waves

Summary

This study presents the first observation in Puerto Rico of a tsunami induced by an atmospheric disturbance; this phenomenon is known in the literature as a meteotsunami. The meteotsunami was small scale and no damage was reported in harbors. On August 16, 2011 between 12:24 and 21:18 AST, NOAA tide gauges recorded a marked increase in the height of coastal seiches at various ports and bays along 120 miles of Caribbean coastline in Puerto Rico; at the following locations: Port of Yabucoa, Santa Isabel, Magueyes Island, Bahia Salinas, Puerto Real, Puerto de Mayagüez and west of Mona Island. The largest seiches were recorded in Bahia Salinas and Puerto Real with heights of 0.61 ft (18.5 cm) and 0.48 ft (14.6 cm), respectively. Meteotsunami amplitudes in these two places were 0.305 ft (9.3 cm) and 0.24 ft (7.3 cm), exceeding by about 9 to 11 times the RMS amplitude of these locations. Even in Bahia Salinas wave height exceeded the vertical range of the tide. The meteotsunami was excited by a jump in atmospheric pressure of 0.7 mb and 2 ½ hours later by a second jump of 1.4 mb. Increases in atmospheric pressure were followed immediately by a line of strong wind gusts that reached up to 37 knots (42.6 MPH). These events are associated with the passage of a large tropical wave over the waters south of Puerto Rico. According to the National Hurricane Center in Miami, the tropical wave was moving westward about 20 MPH. Weather stations along the coast recorded the passage of the pulses, which moved westward at an average speed of 35.5 mph (15.8 m s-1). Tide gauges recorded the excitation of seiches after passage of the first pulse in barometric pressure on each of the locations. Seiches excited pulses progressively along each station, making it possible to calculate the velocity of propagation between 28.6 mph (12.7 m s-1) and 35.3 mph (15.7 m s-1), equal to the local velocities of a long wave propagating in water depths between 16.5 m and 25.1 m.

Figure 1. Location of NOAA/NOS water level stations and CariCOOS Buoy PR-1.
All these stations detected the meteotsunami.

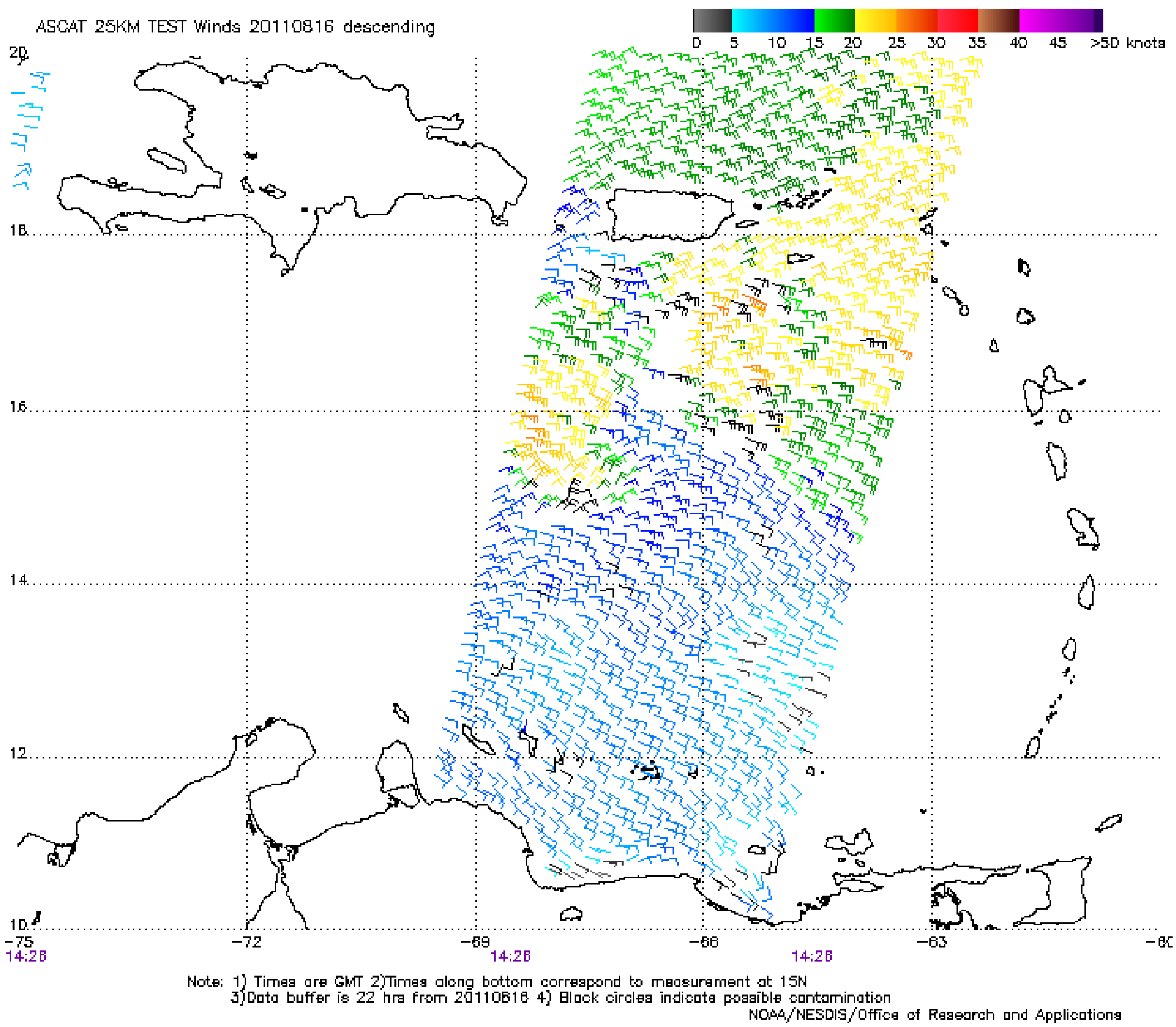
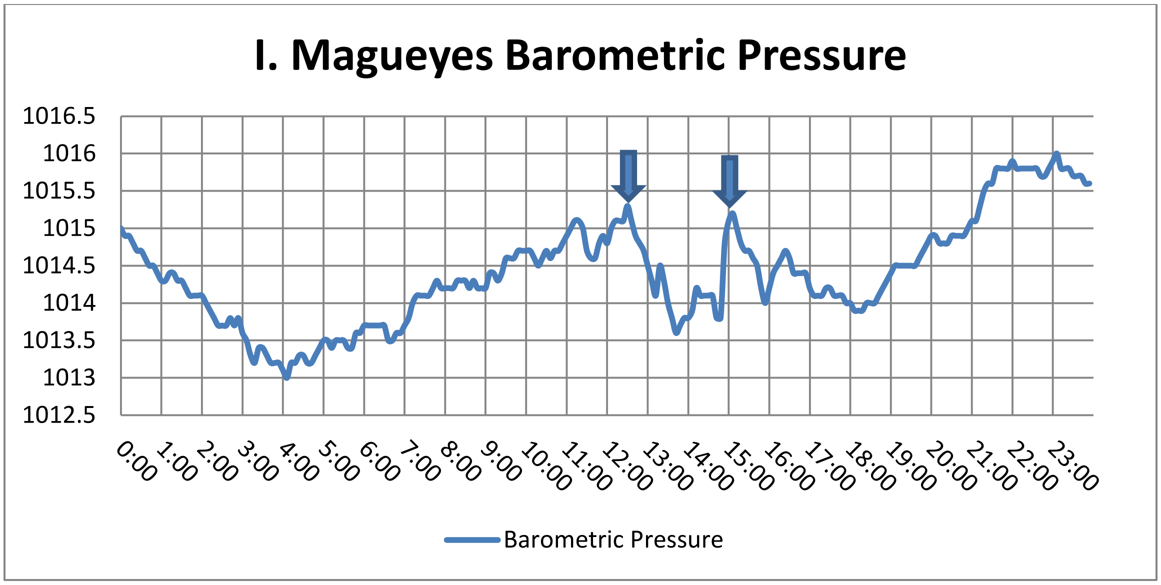


Figure 1. Wind speed and direction on 8/16/2011 14:25 GMT (10:00 AST). Satellite Sensor ASCAT at 25 km resolution. Cortesy of NOAA/NESDIS/Office of Research and Applications.



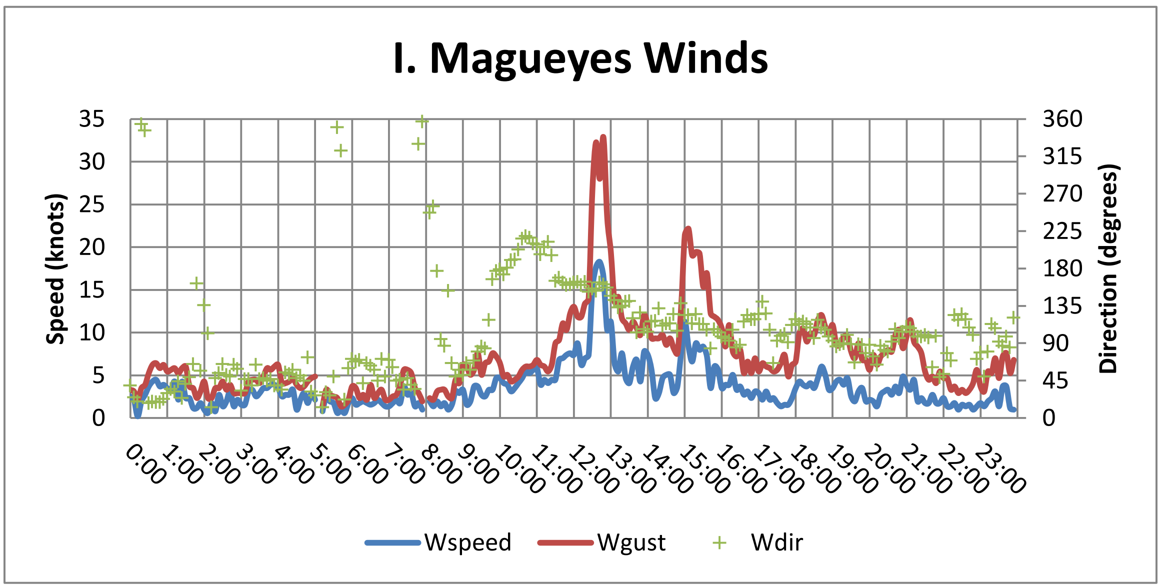


Figure 3. Atmospheric Pressure, wind speed and direction measured on 8/16/2011 at Magueyes Island. Two pressure jumps occurred at 12:30 and 15:06 AST, reaching a maximum value of 1015.3 and 1015.2 mb, respectively. Immediately they were followed by strong winds from the SSE (161°) and ESE (124°), with speeds of 32.8 Kt and 22.2 Kt, respectively.

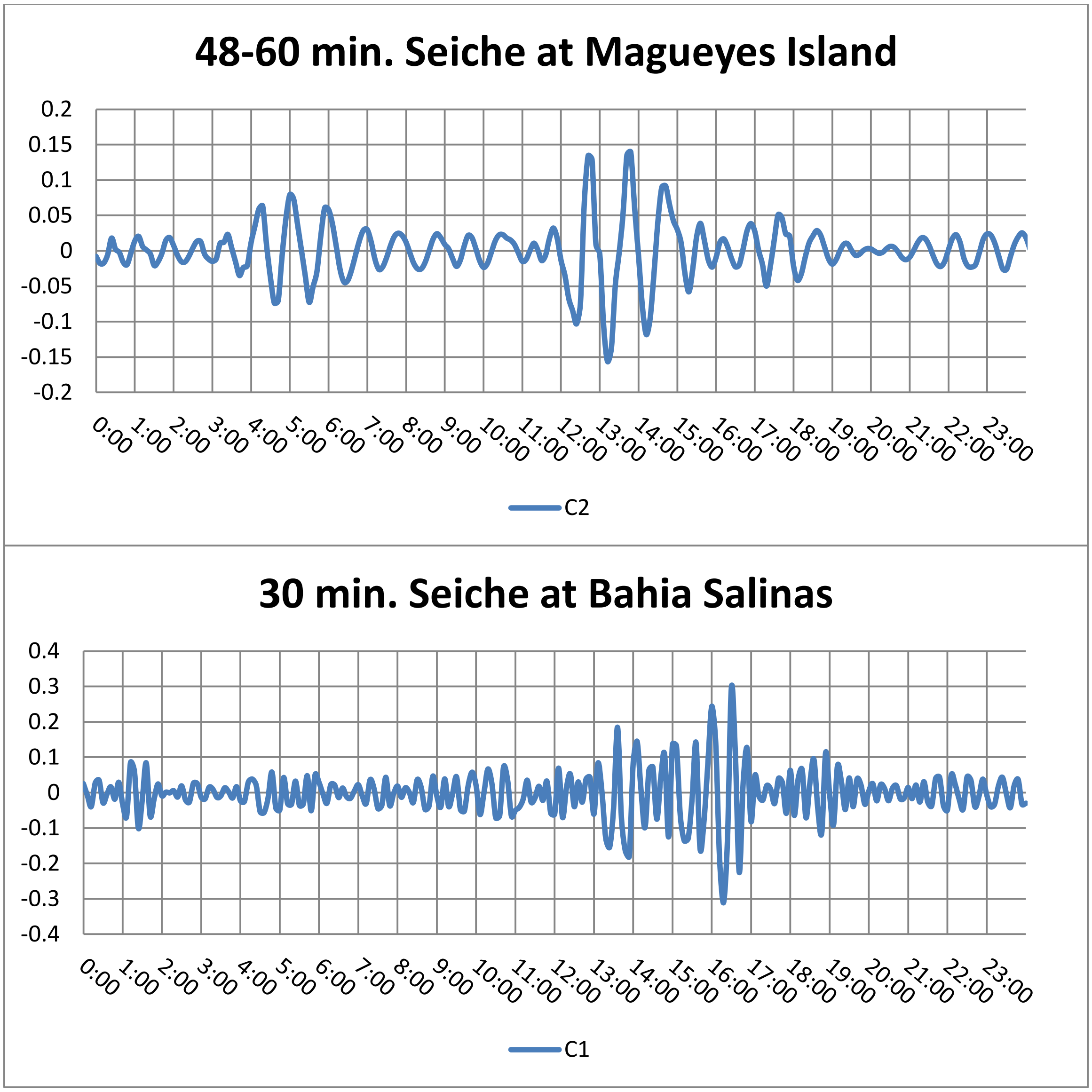


Figure 4. Meteotsunami detected by WLG's at Magueyes Island and Bahia Salinas, Cabo Rojo.

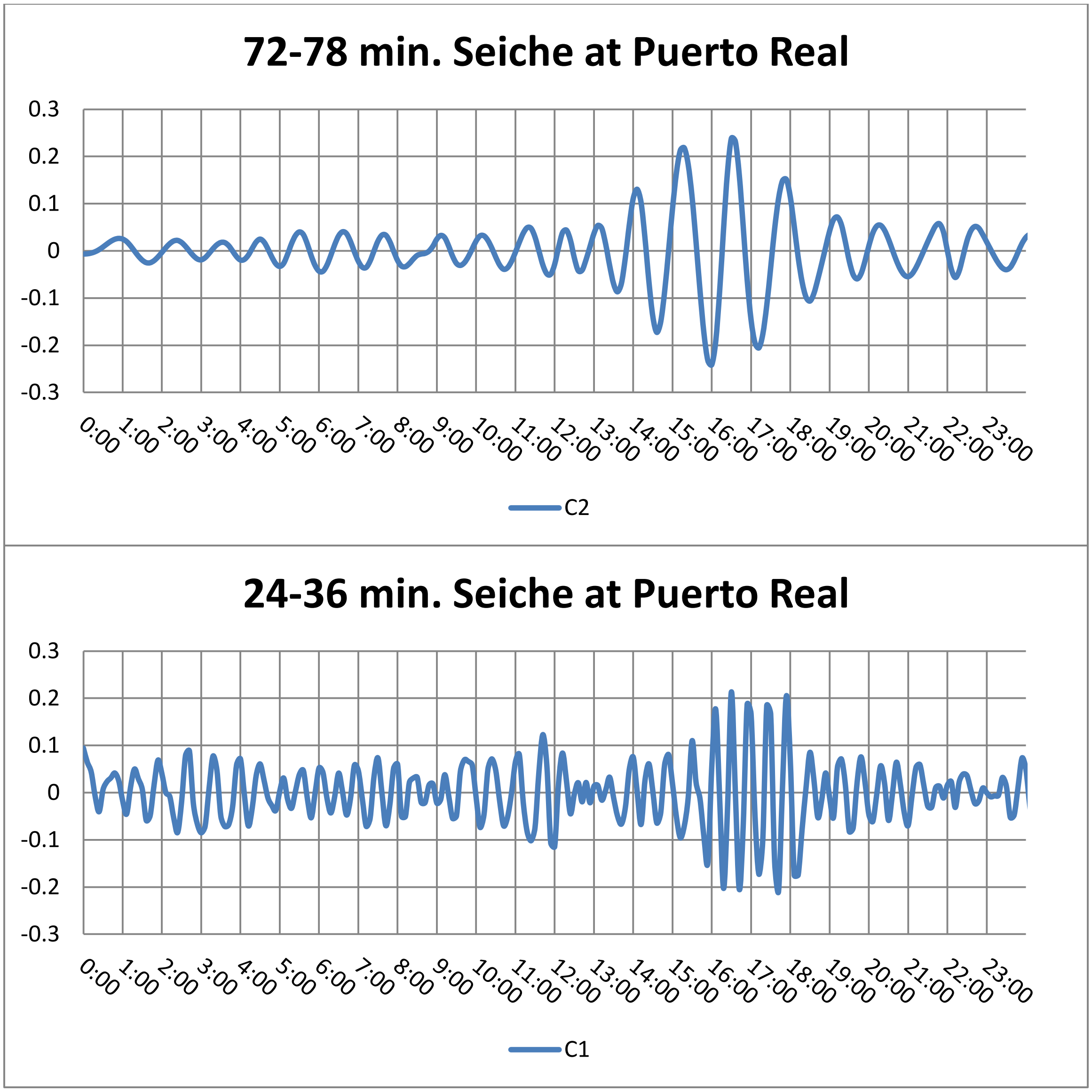


Figure 5. Meteotsunami detected by WLG's at Puerto Real, Cabo Rojo.

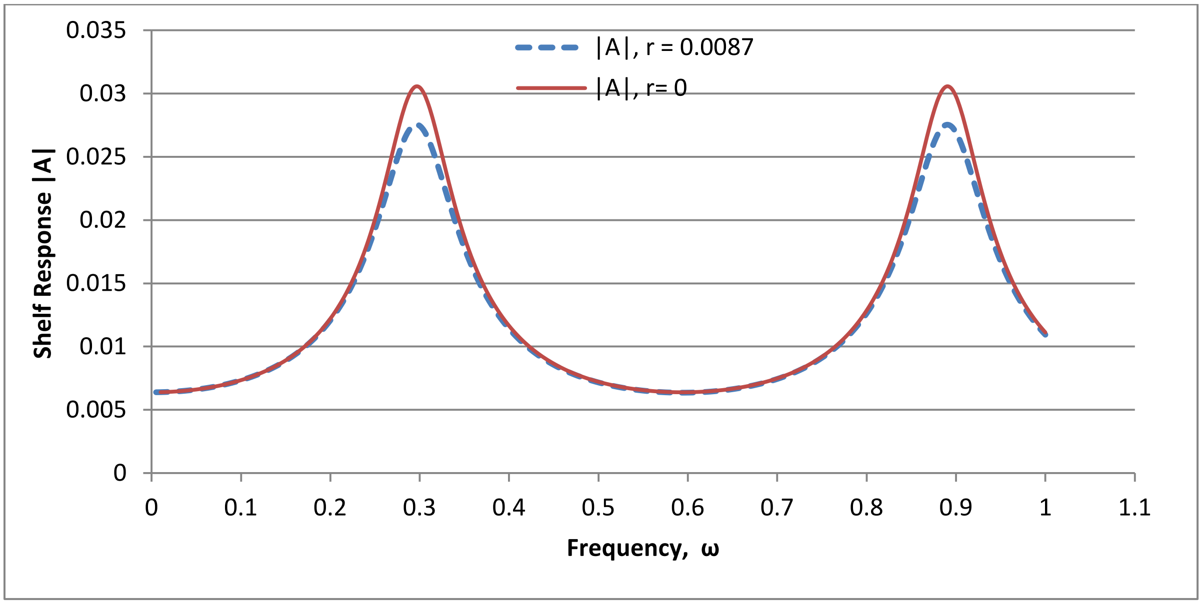


Figure 6. Theoretical Shelf Response after a meteotsunami hits outside of Puerto Real. The resonant frequencies are 0.78 CPH and 2.33 CPH. These frequencies are equivalent to periods of 76.6 min and 25.7 min., respectively.

ω scaled	ω (rad/s)	freq. (CPH)	Period (min)
0.296852603	1.367E-03	0.78	76.6
0.885	4.074E-03	2.33	25.7

Seiche Band

2013 Discovery: First measure of the speed of a Transatlantic Meteotsunami

Overview

On June 13 2013, a pressure disturbance caused a tsunami-like wave along the East Coast of the United States. It is not clear the exact origin point of this oceanic long wave. But at 1705 GMT was detected by the DART II Buoy (see Figure 1), NDBC Station 44402, located at Southeast Block Canyon - 130 NM SE of Fire Island, NY. The station's water depth was 2443 m. Long waves speed is a function of water depth. Assuming this location as the Meteotsunami's departure point, it was possible to calculate the distance and travel time of the long wave to various tsunami capable tide stations. These tidal stations are separated from the Dart Buoy by a long distance (> 1400 miles) and deep waters (> 3000 m), allowing us to easily calculate the Meteotsunami's deep water speed. The 1-minuted sampled data was provided by the NOAA/NOS/CO-OPS website and the DART II Buoy data was obtained from the NDBC website. This valuable data allowed us to calculate for the first time the transatlantic Meteotsunami's long wave speed.

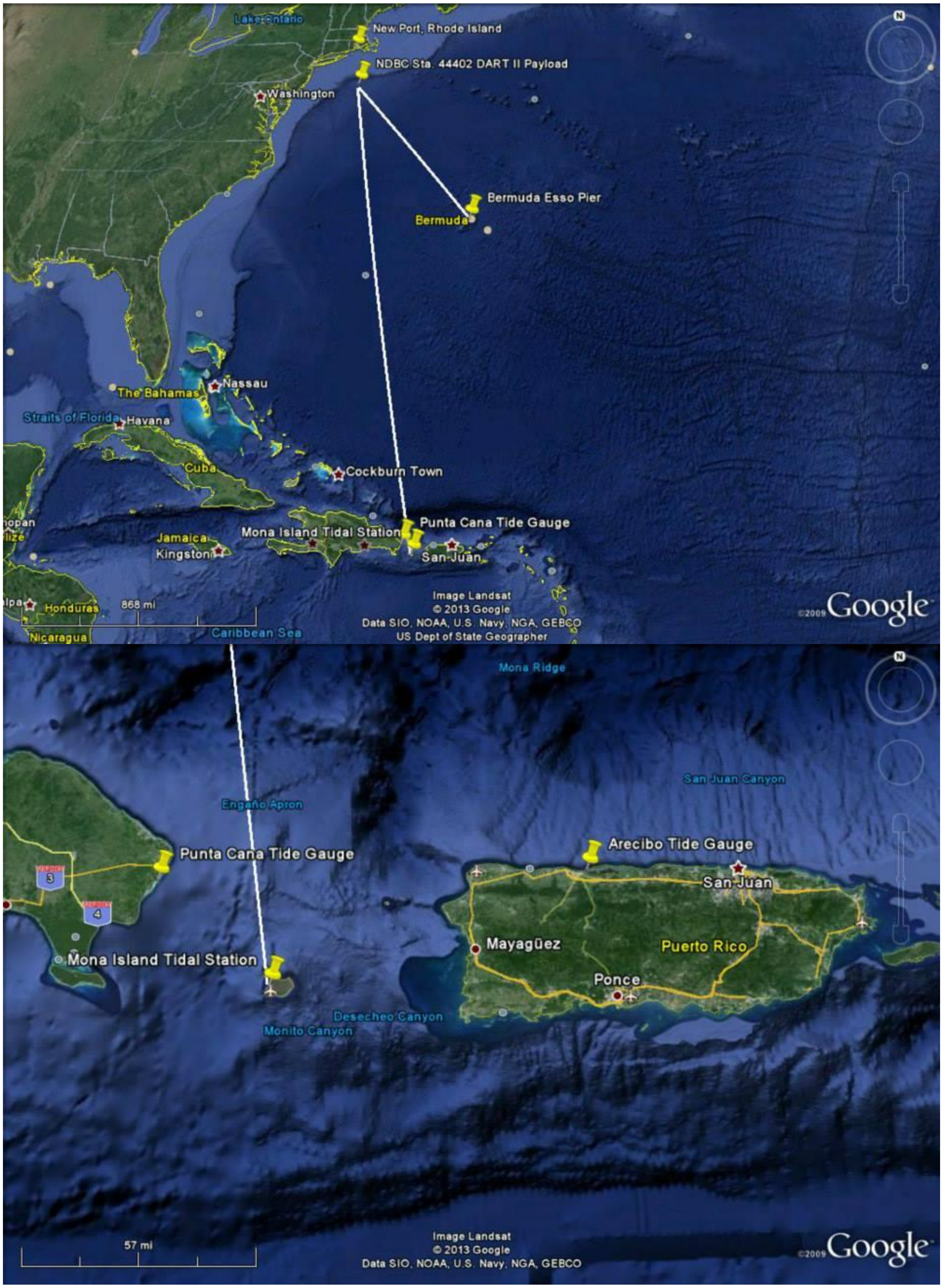


Figure 1. Top. Meteotsunami's Travel Distance between Water Level Gauges and DART II Buoy, NDBC Sta. 44402. Bottom. Location of Water Level Gauges.

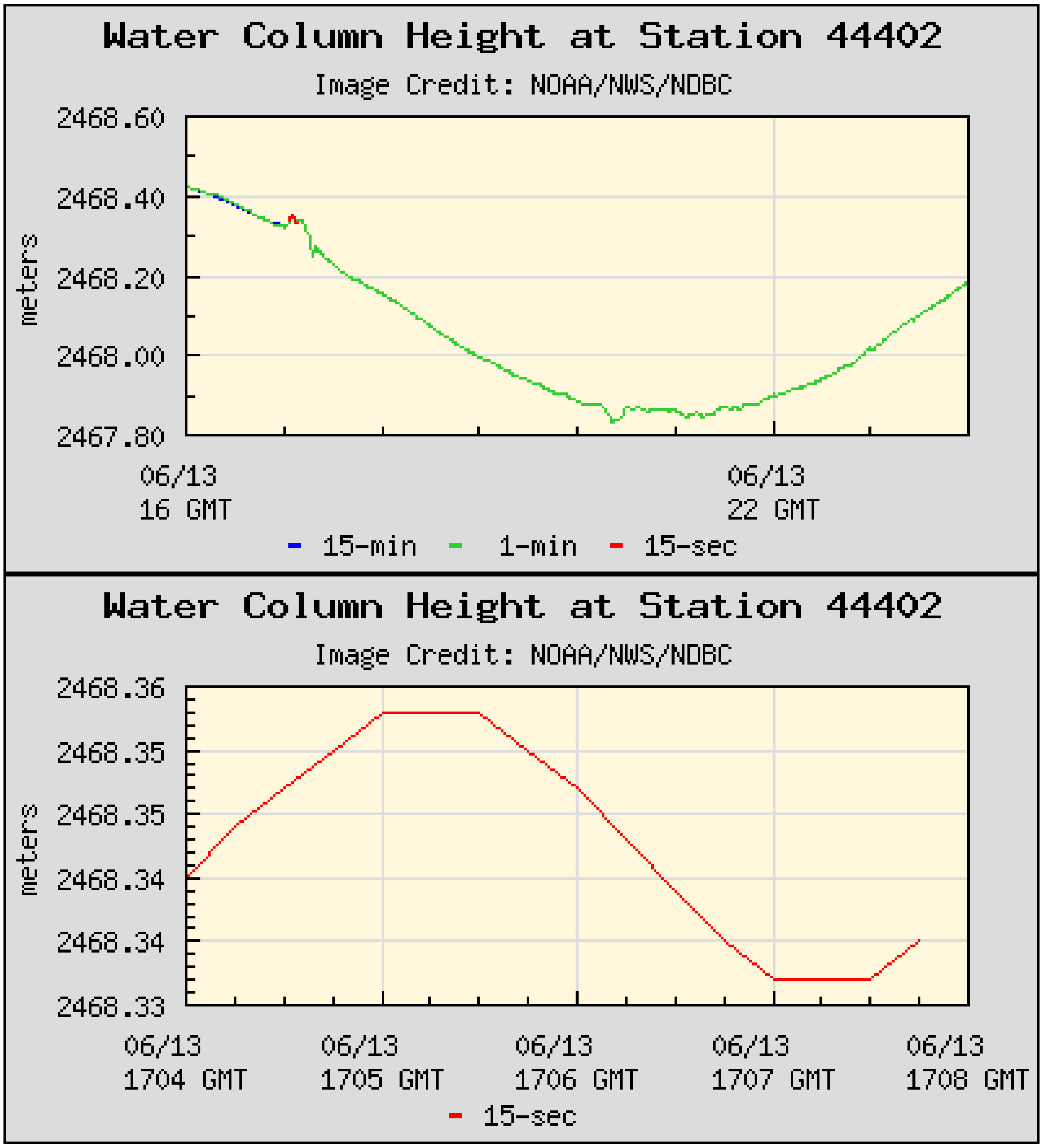
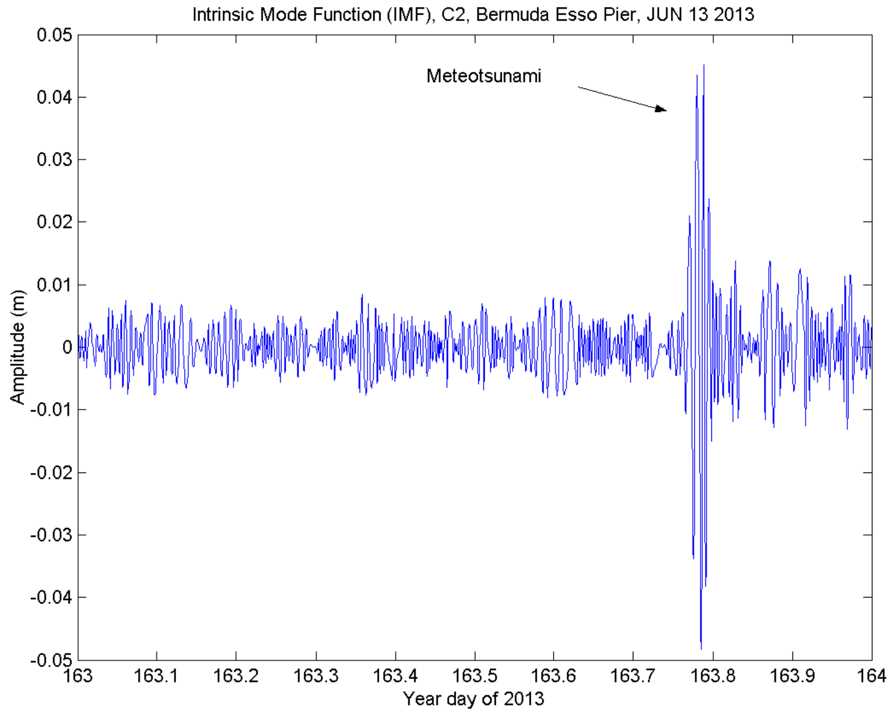


Figure 2. Top. One minute sampling signal. Bottom. Zooming into 15 second signal. Clear detection of the Meteotsunami by DART program discus buoy located at 39.399 N and 70.942 W at a water depth of 2443 m.



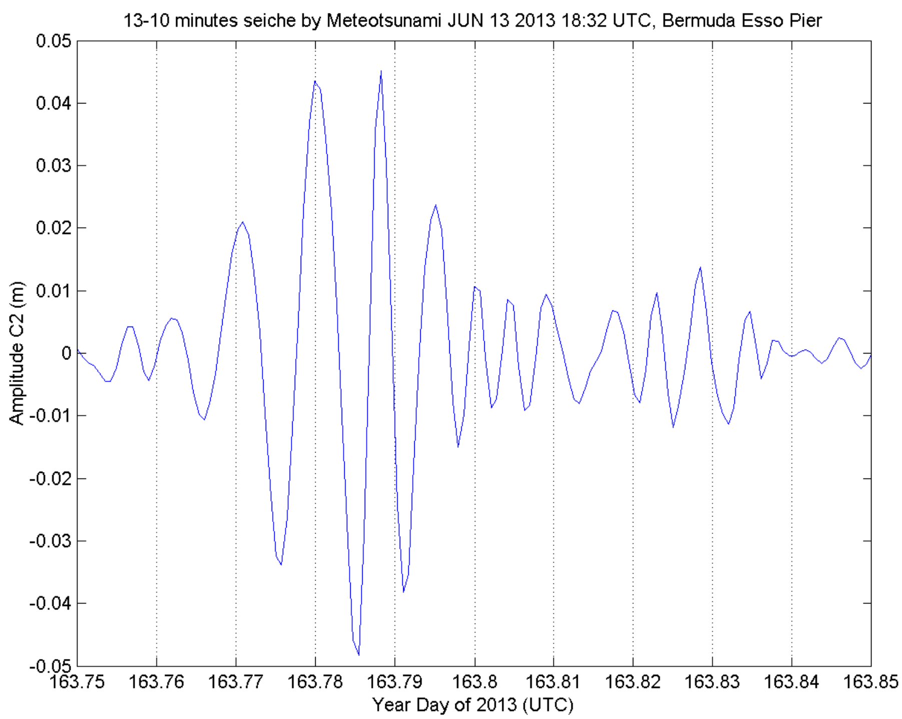
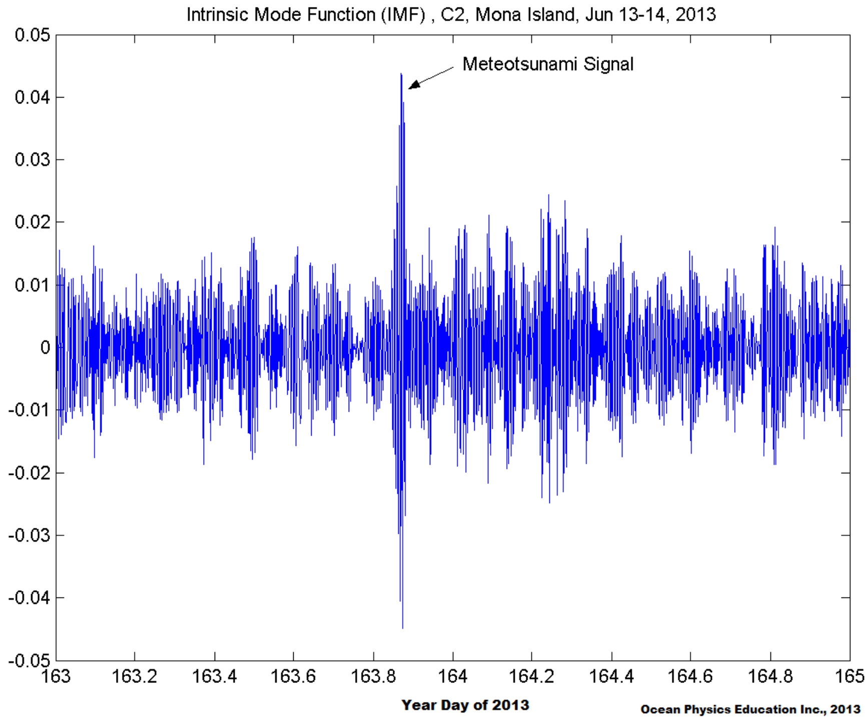


Figure 3. Top. C2, the Intrinsic Mode Function (IMF) of the water levels at Bermuda Esso Pier represents the coastal seiche excited by the Meteotsunami. Bottom. Zoom view of the coastal seiche shows its non-stationary and nonlinear waveform.



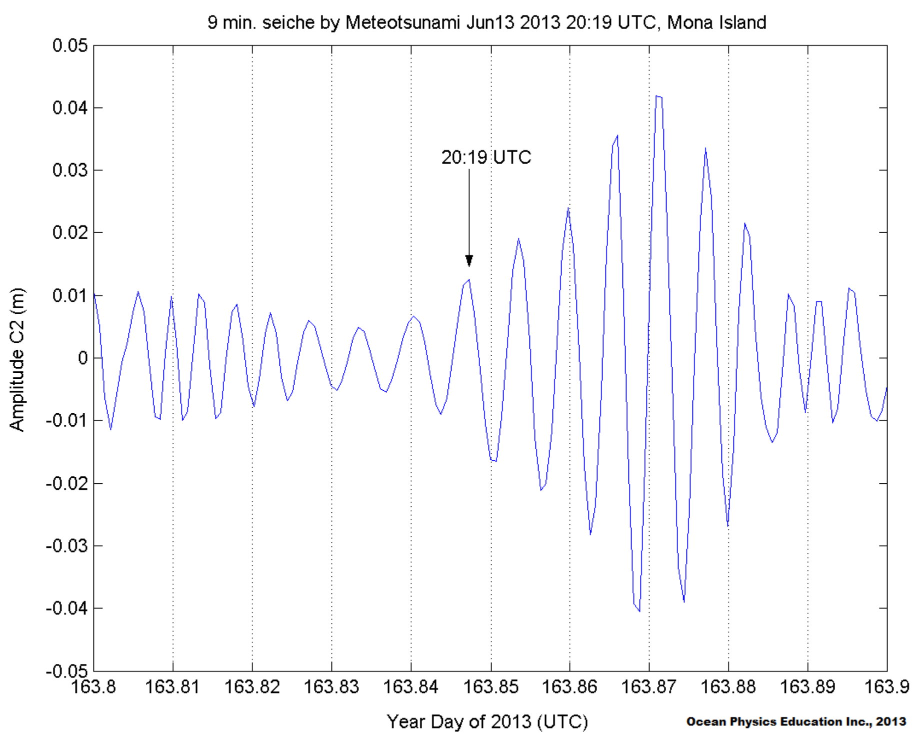


Figure 4. Top. C2, the Intrinsic Mode Function (IMF) of the water levels at western Mona Island represents the coastal seiche excited by the Meteotsunami. Bottom. Zoom view of the coastal seiche shows a nonlinear waveform but it is more stationary than the Bermuda signal.

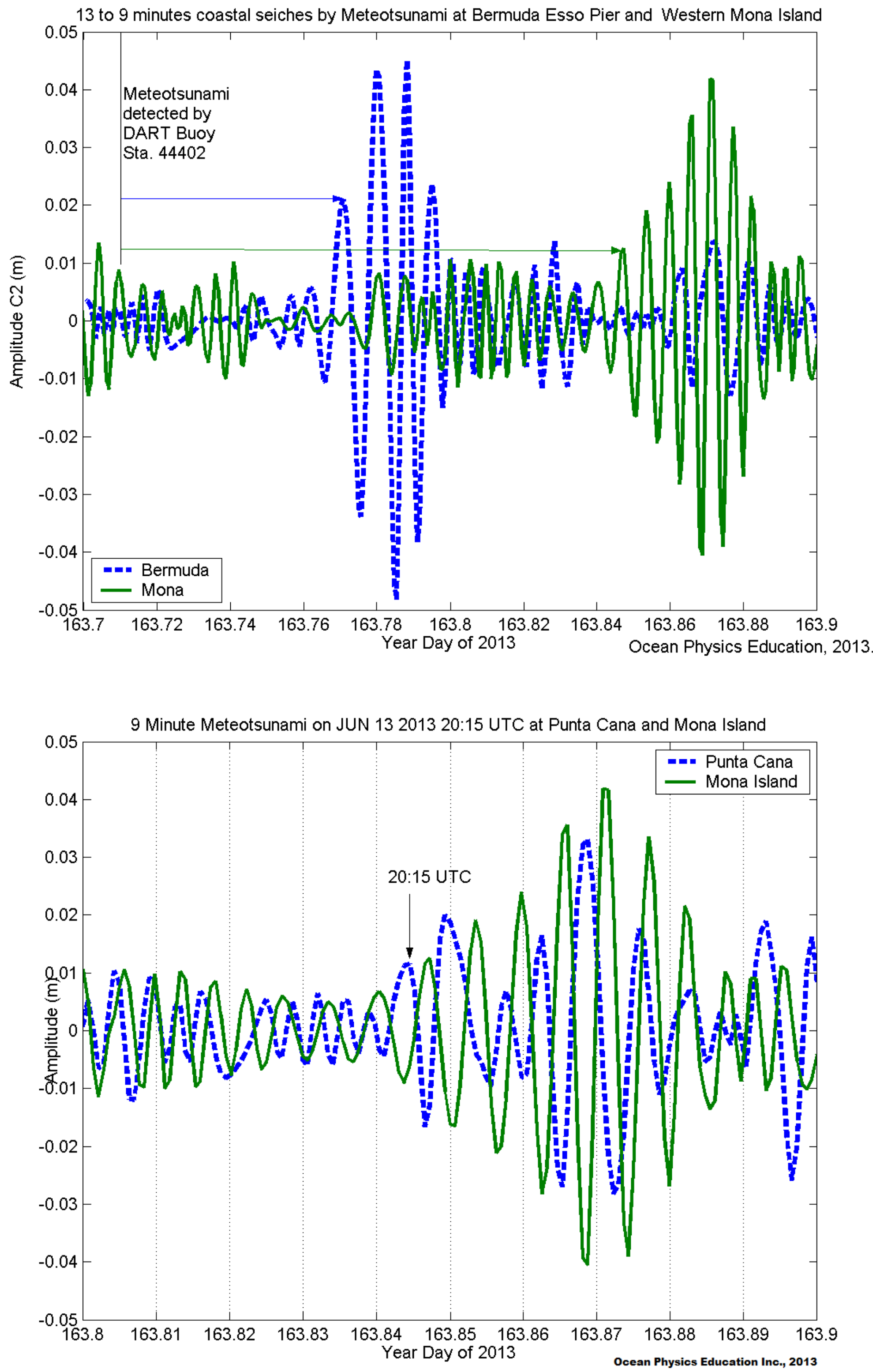


Figure 5. Top. Different Arrival Times of the Meteotsunami at Bermuda Esso Pier and Western Mona Island. The amplitudes are similar despite the long distance separating both events. Bottom. The Meteotsunami reached Punta Cana first at 20:15 GMT and 4 minutes later at Mona Island.

Meteotsunami arrival times, travelled distance and speeds. (Ocean Physics Education, Inc., 2013)					
Gauge	**Year Day**	**Start Meteotsunami**	**Δt (hours)**	**ΔX (miles)**	**Δx/Δt (MPH)**
Sta. 44402[1]	163.7118	6/13/2013 17:05	-	-	-
Bermuda (Esso Pier)	163.7722	6/13/2013 18:32	1.45	597.21	411.87
Punta Cana	163.8443	6/13/2013 20:15	3.18	1447.34	455.06
Arecibo	163.8458	6/13/2013 20:18	3.22	1462.95	454.80
Mona Island	163.8471	6/13/2013 20:19	3.25	1478.50	455.31
[1] 2.6-meter discus buoy. Owned and maintained by National Data Buoy Center					
DART II payload					
39.399 N 70.942 W (39°23'58" N 70°56'30" W)					
Site elevation: sea level					
Water depth: 2443 m					

Meteorological-Oceanic Band

2011 - Discovery of Edge Waves trapped on the Cabo Rojo-Mayaguez Shelf, about 30 hours after the passage of Hurricane Irene over Puerto Rico

Summary

About 30 hours after the passage of Hurricane Irene over Puerto Rico, three tidal gauges located along the Southwest Coast of Puerto Rico detected a sudden increase in coastal seiche amplitude of around 0.25 feet (7.6 cm). Rapid and small atmospheric pressure oscillations were observed simultaneously. The distance and time lag between the maximum peak amplitudes suggest an edge wave trapped on the shelf that was moving north at 36.7 MPH (16.4 m/s). These observations demonstrate that sudden changes in water levels at the coast can occur one day after the hurricane event.

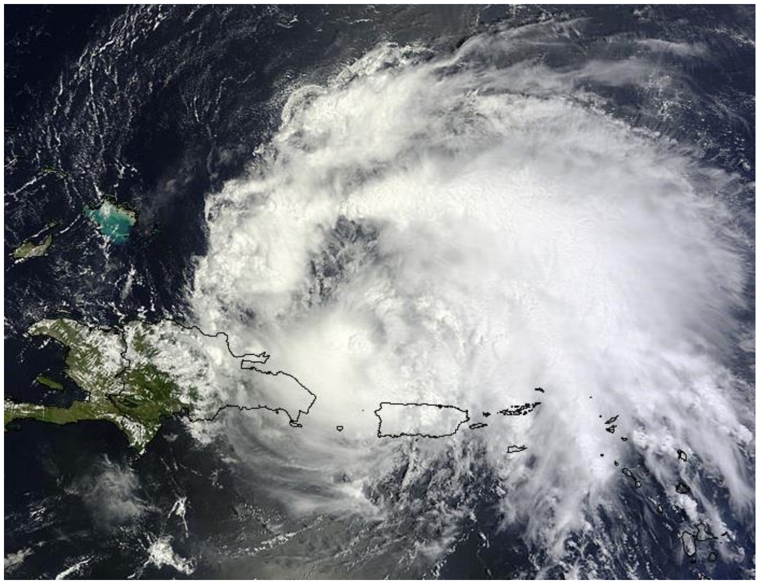


Figure 1. Hurricane Irene over Puerto Rico. The center is located north of the Mona Passage. The southern quadrant of the hurricane shows only high clouds and lack of thunderstorms. Most of the thunderstorm activity is located at the northeastern quadrant. MODIS image taken on August 22, 2011 at 1700 UTC

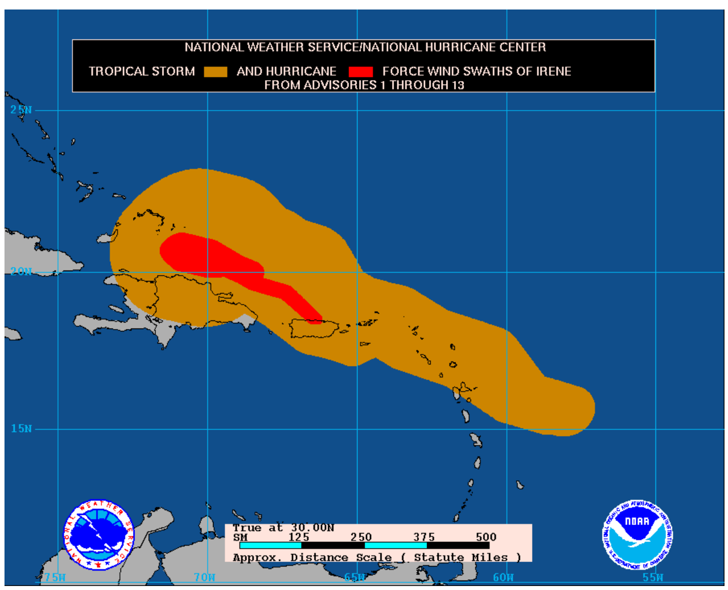


Figure 2. Hurricane Irene's Wind History (Advisory 1-13) up to 23-Aug-2011 15:00 UTC by the NWS NHC. All the Southwest Coast of Puerto Rico was under tropical storm force winds.

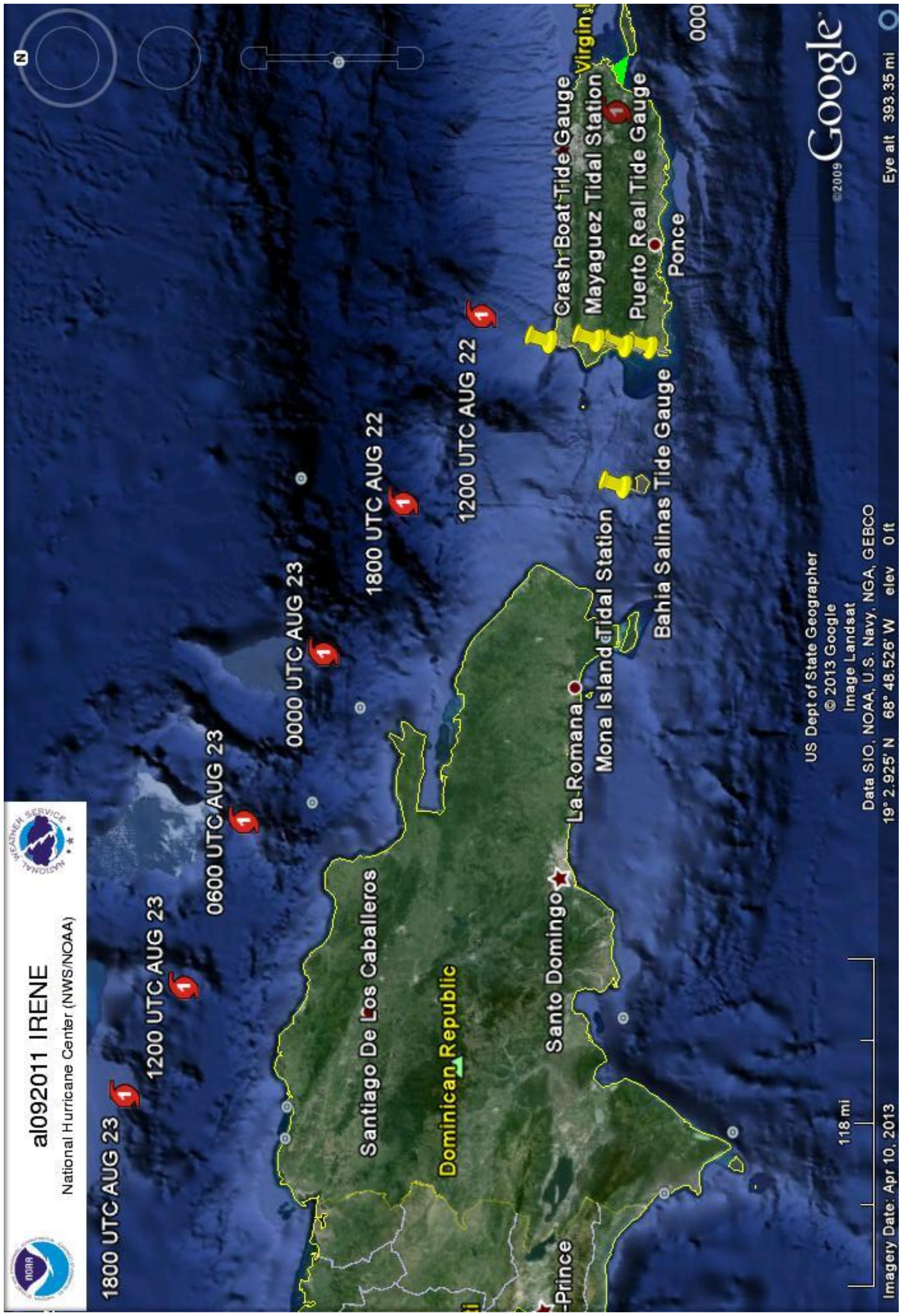


Figure 3. Best Track of Hurricane Irene by NWS National Hurricane Center.

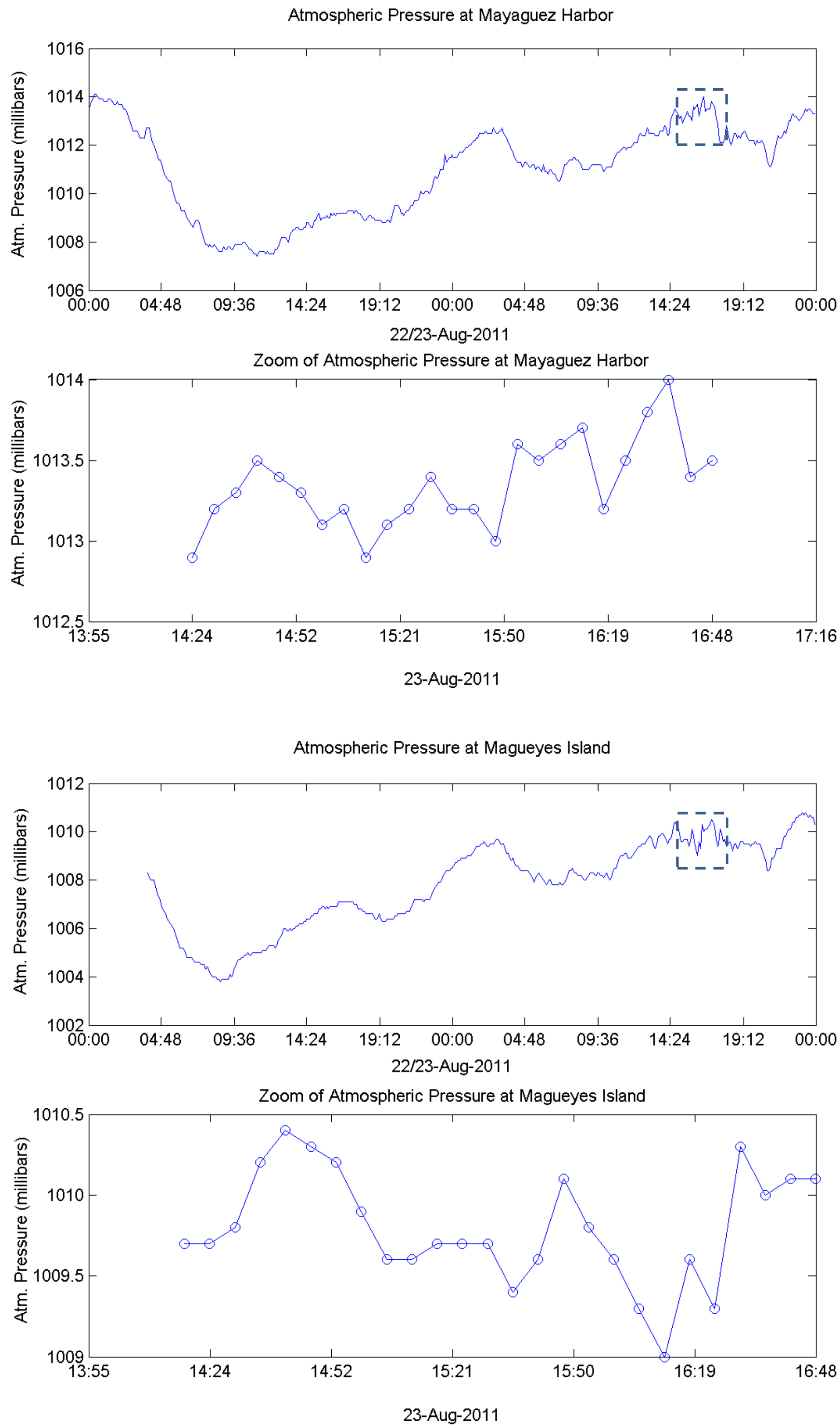


Figure 4. Atmospheric pressure measured at Mayaguez Harbor and Magueyes Island. Lowest value at Magueyes Island (1003.8 mb) was recorded on 22-Aug-2011 08:42 UTC. The dashed rectangle indicates the rapid fluctuations in atmospheric pressure. (Below) Zooming into the rectangle the record from 23-Aug-2011 14:24 UTC to 16:48 UTC.

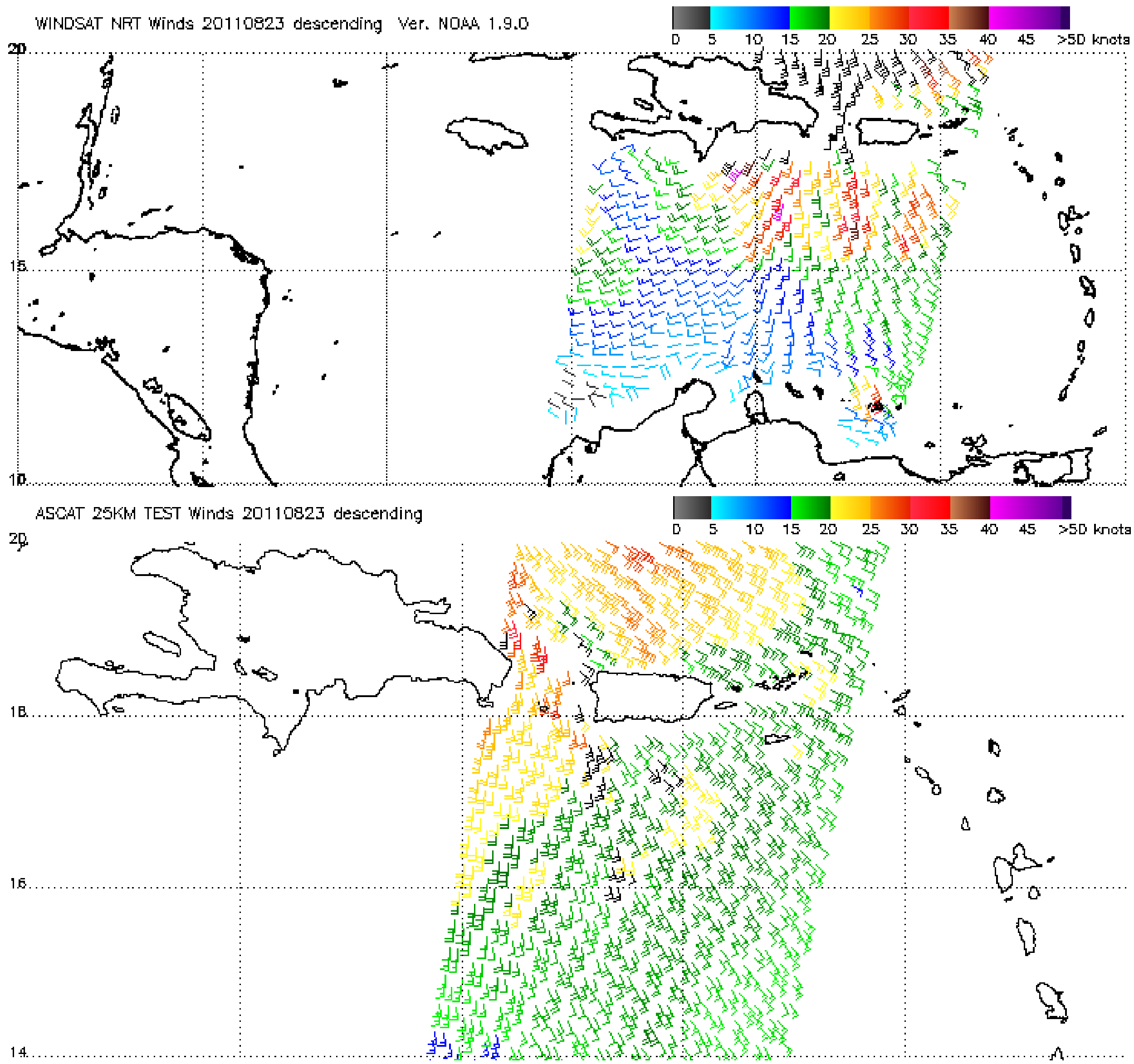


Figure 5. Wind field measurements by WINDSAT NRT satellite sensor on 23-Aug-2011 10:51 UTC. (Below) Wind field measurements by ASCAT satellite sensor on 23-Aug-2011 13:41 UTC.

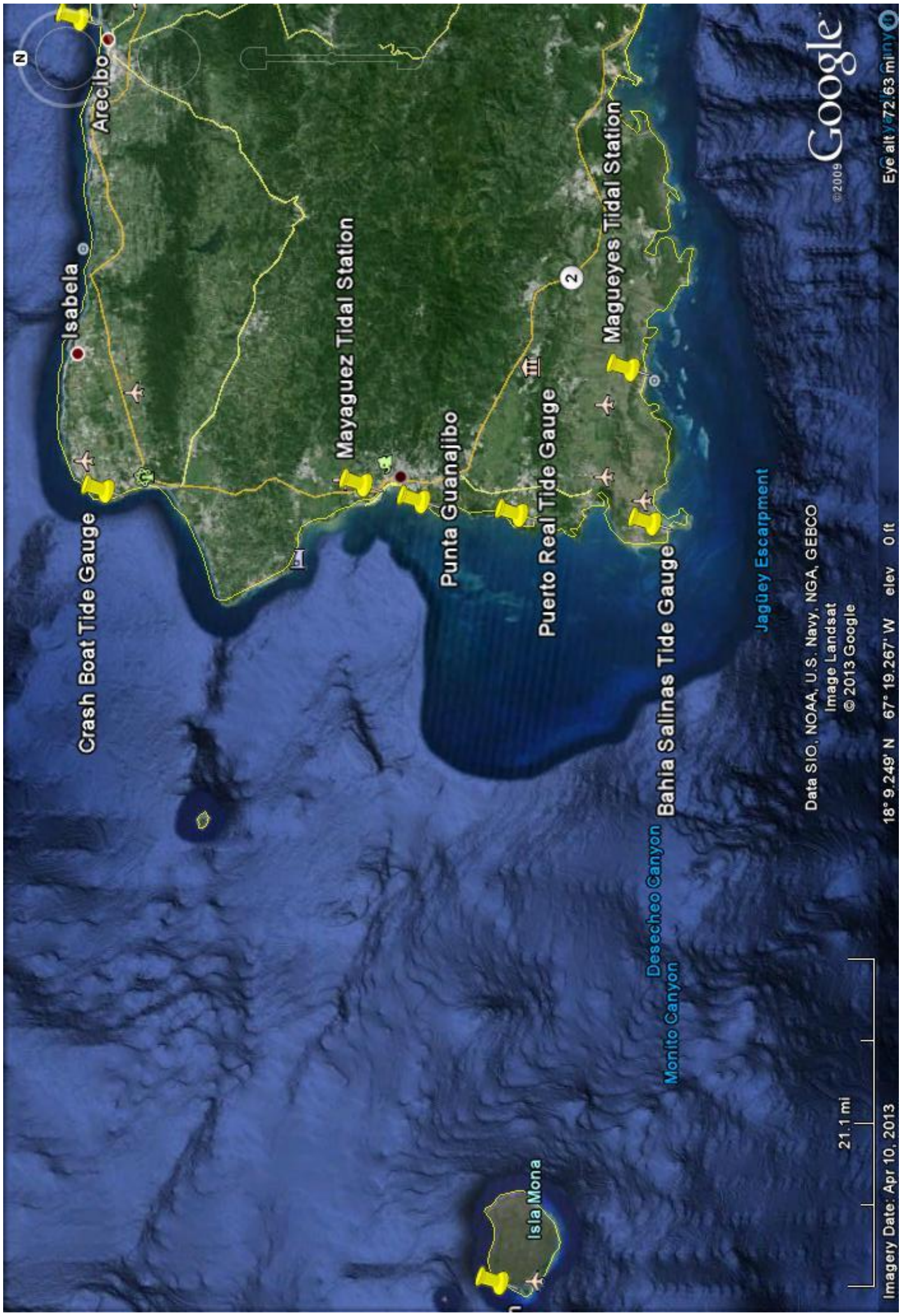


Figure 8. The Puerto Rico Southwestern Platform and the location of tide gauges.

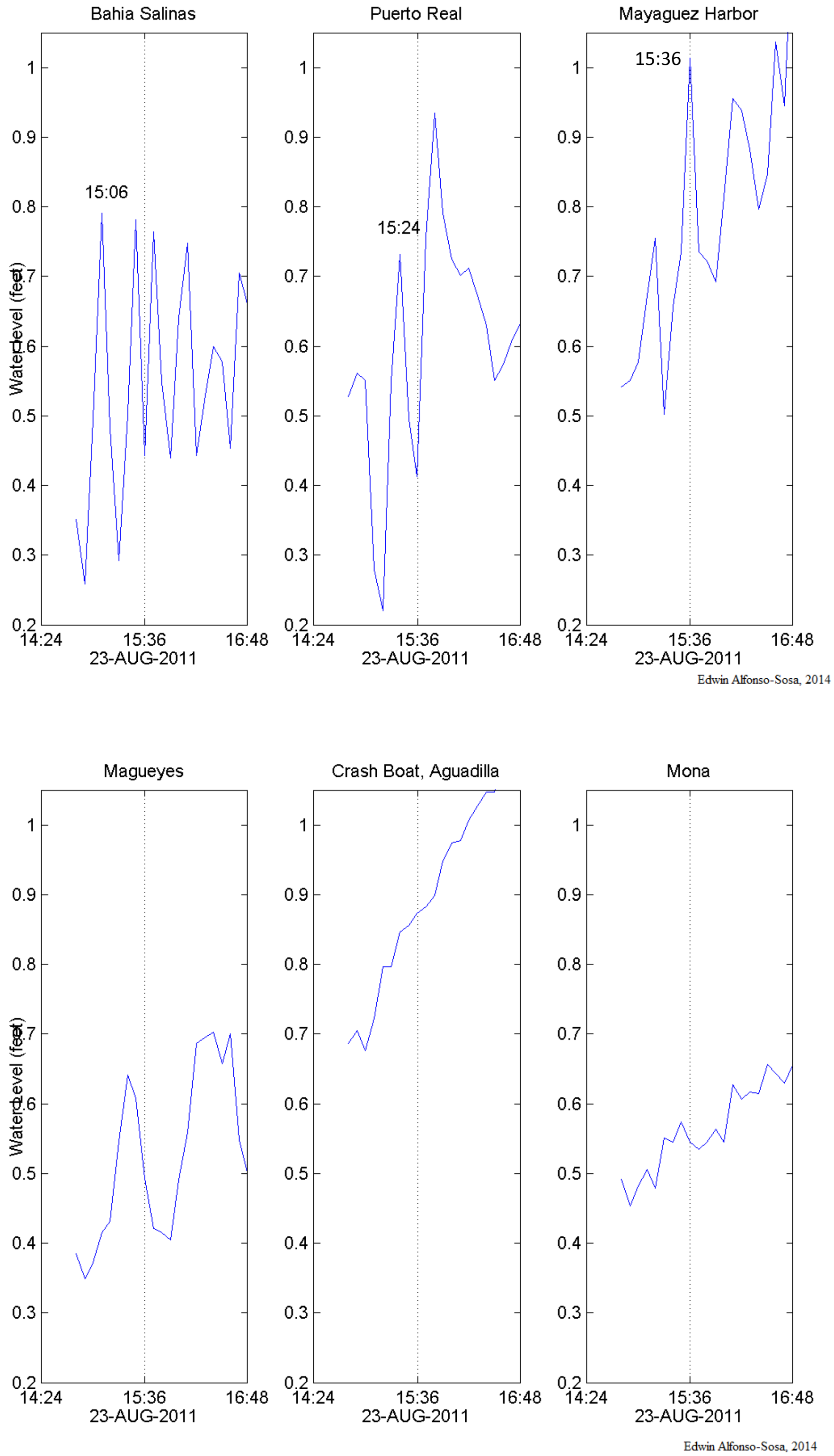


Figure 9. Water level measured (in feets) by the tide gauges between 14:48 and 16:48 UTC on 23-Aug-2011 for the following locations: Bahia Salinas, Puerto Real and Mayaguez Harbor. The time stamp indicates when the largest oscillation occurs.

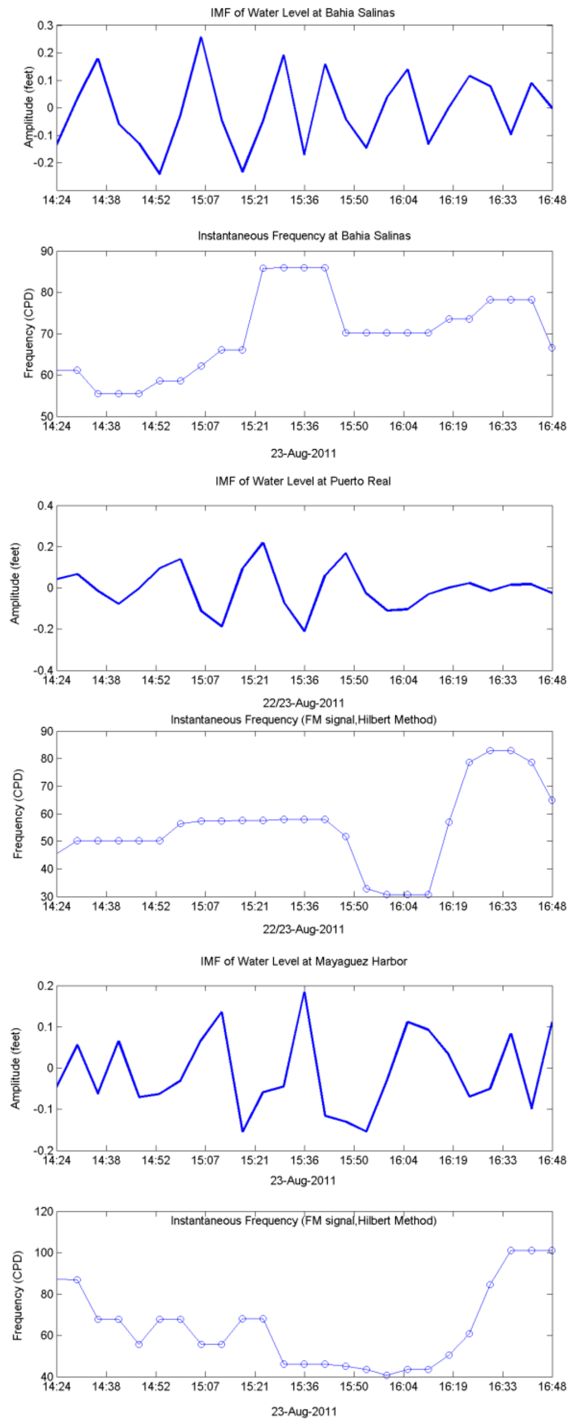


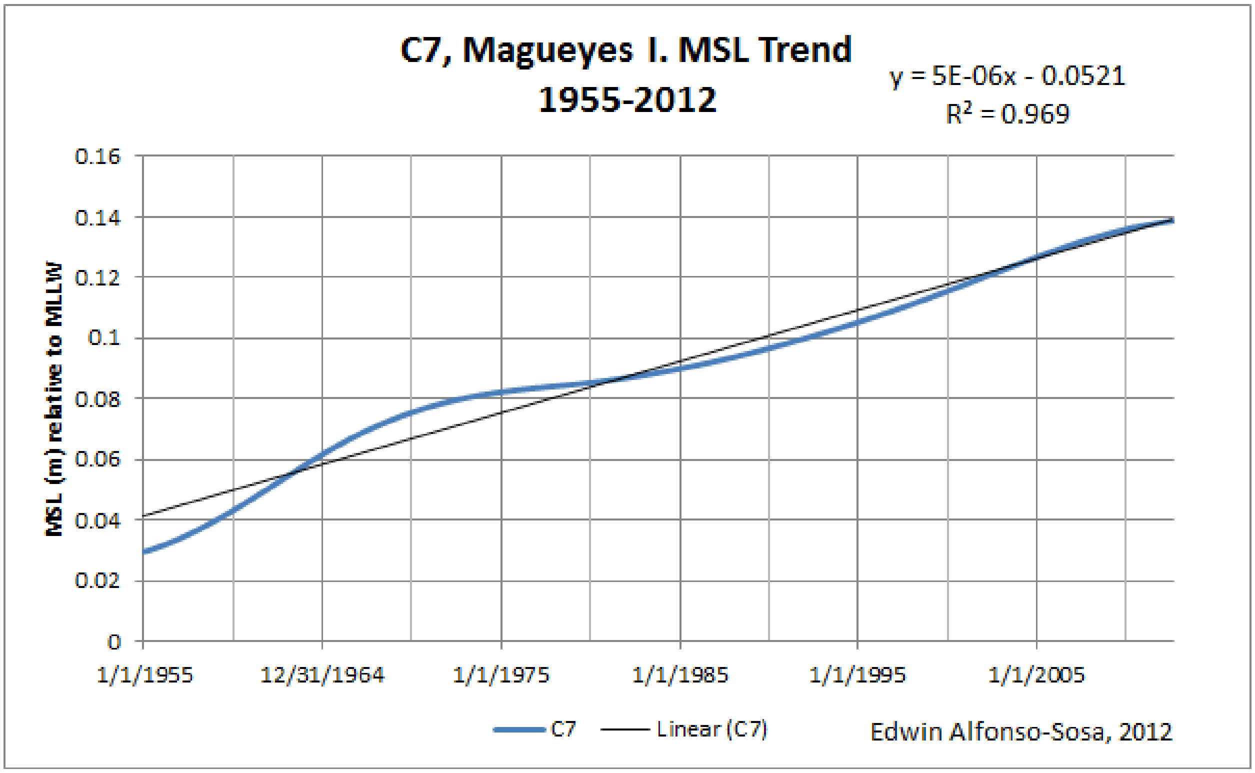
Figure 11. The amplitude (in feet) of the first IMF of water level and below its instantaneous frequency in cycles per day (CPD) for the following locations: Bahia Salinas, Puerto Real and Mayaguez Harbor, from 23-Aug-2011 14:48 to 16:48 UTC.

Table 1. . IMF's maximum amplitudes and their respective instantaneous frequencies. The time interval between maxima and their respective distances allowed us to estimate the wave speed. Average speed is 36.7 MPH (16.4 m/s).

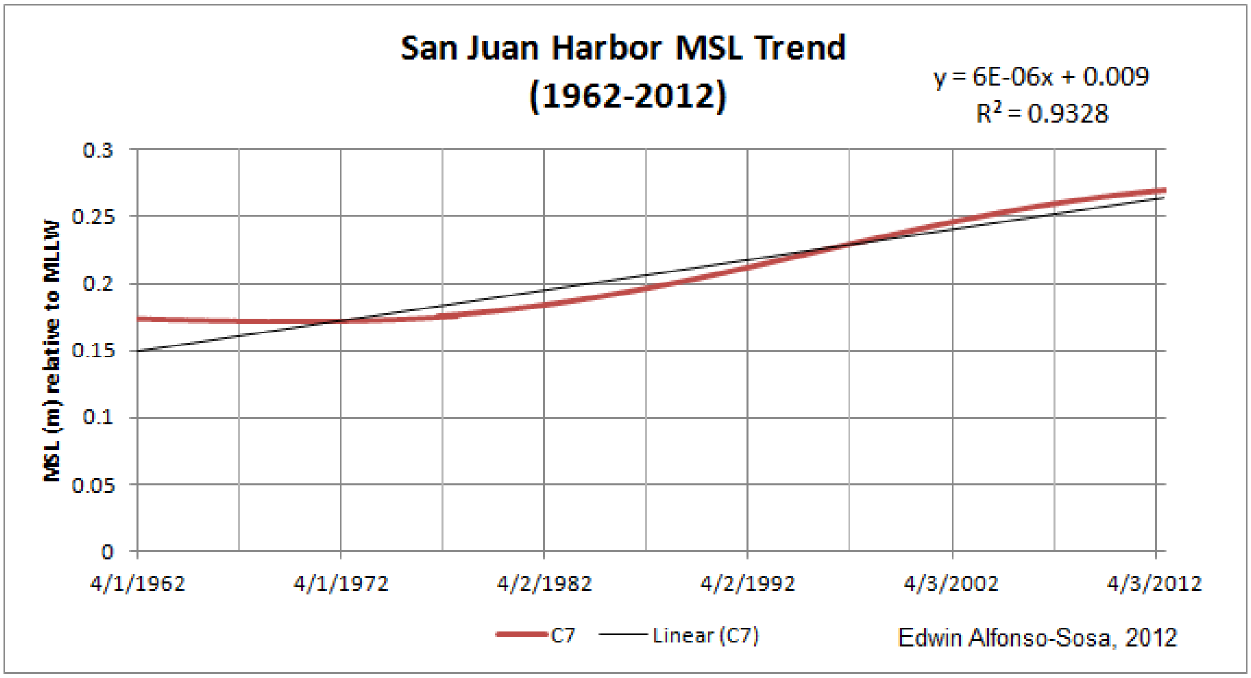
Location	MAX Amplitude (feet)	Time of MAX Amplitude (GMT)	Instantaneous Frequency (CPD)	Period (Min.)	Distance from Bahia Salinas along the Platform (miles)	Time Interval (h)	Speed (MPH)
Bahia Salinas	0.25	8/23/2011 15:06	62	23.2		0.0	
Puerto Real	0.21	8/23/2011 15:24	57	25.3	10	0.3	33.4
Mayaguez Harbor	0.18	8/23/2011 15:36	46	31.3	20	0.5	40.1
		Average	55	26.2			36.7

Long-Term Band

2012-Two stations confirm an increase of Sea Level Rise around Puerto Rico.



Start Date	1/1/1955	0.048
End Date	9/1/2012	0.154
Diference (yr)	57.67	0.105
Annual rate	mm/yr	1.83



Start Date	4/1/1962	0.15
End Date	10/1/2012	0.26
Difference (yr)	50.5	0.11
Annual Rate	mm/yr	2.19

Acknowledgement

We acknowledge the use of water level data from NOAA/NOS/CO-OPS.

http://www.co-ops.nos.noaa.gov/

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