

Meteotsunami of 29 August 1916 at Santo Domingo, Dominican Republic — analysis of the destruction of the USS Memphis

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Official revised records of a U.S. Navy Court of Inquiry concluded that the 29 August 1916 destruction of the armored cruiser USS Memphis anchored off Santo Domingo (Ciudad Trujillo) harbor of the Dominican Republic, Island of Hispaniola, was probably caused by a “tropical disturbance”, a “seismic storm”, or a “tsunami”. However, the present analysis of this naval disaster documents that the loss of the ship was not due to any of these causes, but to rogue waves of a meteotsunami generated from a rapid, significant and progressive drop in atmospheric pressure which began in the area around August 22 and was associated with a passing hurricane which at its closest point was about 250 nautical miles to the south. Also, storm waves from this hurricane moved towards Santo Domingo refracting in resonance near shore and were further amplified and transformed by the low barometric pressure, the shallow continental shelf and the local coastal features and bathymetry of the bay. The present analysis is based on careful examination of the ship’s log, and on observations of events by the crew and people on the shore.

Given the limited meteorological data of that time period, the present analysis used an empirical approach to roughly evaluate the Rayleigh distribution function, the upper limit of storm wave height variability away from the most intense wind fetches, as well as the maximum period, wavelength and deep-water heights of generated storm waves. Based on Airy and cnoidal wave theories, the deep water period and celerity of the most significant extreme wave was of meteorological origin which was transformed in shallower water by the resonant and superimposed arrival of two other waves which created a three step plateau on the face of a huge single rogue wave of the meteotsunami, estimated to be about 70 feet in height, with three distinct steps, two plateaus on its forward face, and a preceding trough estimated to be 300 ft. long. Based on this analysis, the present study concluded that it was this significant meteotsunami/rogue wave, in combination with concurrently arriving storm swells, that engulfed the USS Memphis at 1640 hour in the afternoon of 29 August 1916 — breaking the chains of its anchors and wrecking it on the rocks of Santo Domingo.

Keywords: meteotsunami, hurricane surge, resonance amplification, rogue waves, Shallow water Stokes waves.

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Introduction

Air-pressure disturbances associated with fast-moving weather events such as hurricane squalls, severe thunderstorms, and other storm fronts over a sea basin or even on an open coast, can generate progressive atmospherically-induced destructive ocean waves limited to the tsunami frequency band with periods ranging from about two minutes to two hours. Such rogue waves can be destructive and have been often characterized as “meteotsunamis” [10], which can travel long distances under synthetic gravity wave forcing and thus impact coastlines extensively [1, 6–9, 14].

While a rapid change in atmospheric pressure often plays a substantial role in the formation of meteotsunami waves, other storm-generated swells of long period, generated along wind fetches with directional focusing, or hurricane-generated waves along a hurricane’s region of maximum winds, may have a concurrent arrival with meteotsunami wave arrivals and their resonant contribution in shallow water, may increase the kinetic energy of extreme waves, augmenting in resonance their overall height, and resulting in the destruction of coastal facilities or even impacting adversely on ships anchored in shallow water offshore. Also, in an unidirectional wave field, enhanced displacement can occur when a long wave overtakes shorter period waves due to frequency dispersion.

According to [1], in a real, three-dimensional field of water waves, both dispersion and spatial (geometrical) focusing and interactions can generate localized extreme rogue waves. The interactions can be linear or non-linear and the mechanisms may include dispersion enhancement of transient wave groups, geometrical focusing in basins of variable depth, and wave-current interaction. Rogue waves are better understood presently and their physical mechanisms have been modelled.

Furthermore, the rise of water level on the open coast — taking into account the combined effects of direct onshore and alongshore wind-stress components of a storm on the surface of the water and the effects of the Coriolis force at that latitude, may result in a bathystrophic component contribution (the bathystrophic effect), and in different atmospheric pressure effects, thus augmenting the height and the destructiveness of the meteotsunami and of storm surges [10].

The present study evaluates such unusual phenomena, caused by a meteotsunami in combination with storm swells that arrived at the Island of Hispaniola (Fig. 1) on 29 August 1916 and resulted in the destruction of the armored cruiser USS Memphis anchored off Santo Domingo (Ciudad Trujillo), harbor of the Dominican Republic (Fig. 2). However, given the lack of adequate meteorological data available for that period, the present analysis used an empirical approach to roughly evaluate the Rayleigh distribution function of the distantly-passing hurricane, the upper limit of storm wave height variability away from the most intense of its wind fetches, as well as the maximum period, wavelength and deep-water heights of generated storm waves.

Based on Airy and cnoidal wave theories, the deep water period and celerity of the most significant extreme waves were of meteorological origin but which were transformed in shallower water by resonance, turbulence, and by the superimposed arrival of other swells of long period, originating from different fetches. The arrival of the most significant observed wave of the meteotsunami, coincided with the arrival of two other storm swells of long period, and created the observed huge single rogue wave, estimated to be about 70 feet in height, with three distinct steps, two plateaus on its forward face, and a preceding trough estimated to be 300 ft. long. In the absence of adequate meteorological data, the present analysis is



Fig. 1. The Island of Hispaniola divided between Haiti and the Dominican Republic

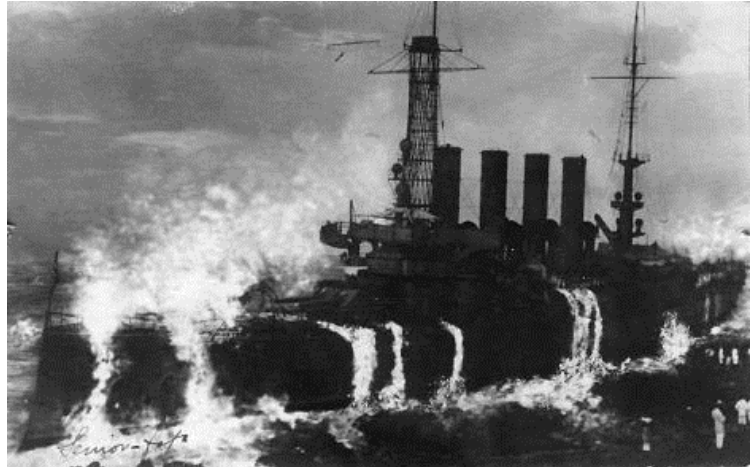


Fig. 2. The USS Memphis on the rocks of Santo Domingo being pounded by waves of the 29 August 1916 meteotsunami and of the superimposed storm swells

based on careful examination of the ship's log, and on observations of events by the crew and people on the shore. The study concludes that it was this significant meteotsunami wave, with augmentation by storm-generated swells that engulfed the USS Memphis at 1640 hour in the afternoon of 29 August 1916 — breaking the chains of its anchors and wrecking it on the rocks of Santo Domingo.

1. Background information of the USS Memphis and its 1916 mission in the Dominican Republic

The USS Memphis was a large 14,500-ton displacement armored cruiser that had been launched on 3 December 1904 and originally named “Tennessee”. Her armament included four ten-inch guns in twin turrets, sixteen six-inch guns, and twenty-two three-inch guns. The ship had two steam-powered engines and was capable of reaching a speed of 23 knots.

In 1916, an unstable government and political unrest at San Domingo (now the Dominican Republic) required the dispatch of U.S. Marines to protect U.S. interests on this Caribbean nation on the Island of Hispaniola. The USS Memphis was ordered to sail to the harbor of Santo Domingo, the capital, to support the U.S. Marines stationed there. Captain Edward J. Beach was the ship's commander. Also, the Memphis was the flagship of Rear Admiral Charles F. Pond, the ranking U.S. Navy Commander in the region. On a peacekeeping patrol off the rebellion-torn Dominican Republic the ship arrived at Santo Domingo Harbor in early August 1916 (Fig. 3).

The USS Memphis got underway for the West Indies in July 1916, and arrived at San Domingo on 23 July. The ship anchored at about 55 ft. depth close to the mouth of the Ozama River and near the 1,177-ton U.S. gunboat “Castine”. Anchorage on this southern side of the island was poor, because of its exposure to storms from the south and the southeast. Fig. 4 is a fairly recent photo of the Santo Domingo coastline.



Fig. 3. Map of the Dominican Republic showing the location Santo Domingo Harbor

Fig. 4. Alamy recent stock photo of the Santo Domingo coast where the USS Memphis perished

1.1. Weather conditions at Santo Domingo in August 1916 — ship preparations

The Caribbean Island of Hispaniola — shared presently by Haiti and the Dominican Republic — lies in the middle of the hurricane belt and is subject to severe storms and hurricanes from June to October. Concerned that it was hurricane season, Captain Beach proposed to keep four boilers of the Memphis going at all times to enable the ship to get out of the harbor quickly if a hurricane approached. However, because of U.S. Navy economy measures, Admiral Pond advised Captain Beach to keep only two of the ship’s boilers going for auxiliary machinery, but to keep the other four boilers ready in case of emergency.

Around August 22, the barometric pressure dropped and the weather began to deteriorate. Fearing that a storm or a hurricane was approaching, Captain Beach ordered the other four boilers of the ship to be fired and all arrangements to be made to get underway. The feared hurricane did not occur but the preparedness exercise was useful in demonstrating that the required steam pressure to power the ship’s engines could be raised in about 40 minutes.

1.2. Chronology of events in the afternoon of 29 August 1916 leading to the loss of USS Memphis

The following chronology of events summarizes entries from the ship’s log, from observations by the crew and people on the shore, from findings of a Court of Inquiry, and from testimony at the court martial of the ship’s captain, following the loss of the ship.

29 August 1916 — The few days after 22 August 1916 were uneventful. Both the Memphis and Castine were riding gently in smooth sea, anchored off Santo Domingo. No storm warnings had been received but the barometric pressure had dropped. However, in the early afternoon of 29 August, even though there was no wind, suddenly the waves became significantly higher. Both the Memphis and the Castine began to roll considerably at their anchorages. Long period waves could be seen coming into the harbor from the east and breaking on the rocks.

15.30 — Concerned about the increasing wave activity, an order was issued to the engine room of the Memphis to raise steam pressure. However, major difficulties were reported from the engine and boiler rooms. Water spray was entering through the ventilators on the ship's deck, which had not been properly secured. Some of the ventilators on the deck were subsequently shut off, but a lot of water had already entered the engine rooms, creating problems in raising steam pressure. The engine room reported to the bridge that there would be adequate steam pressure from the four boilers to power the engines by 16.35.

15.35–15.40 — In the next few minutes the swells in the harbor increased considerably. The Memphis was rolling very heavily and seas were now covering her decks. Spray continued to come down the ventilator funnels. According to officers on the bridge, the waves were so enormous that the ship's keel bumped the seabed once or twice. Given the fact that the ship was presumably anchored in 55 feet of water, this meant that the waves must have been about 40 feet in height.

16.00 — Huge breakers capsized a motor launch returning to the Memphis. There was nothing that could be done to help the crew and passengers struggling in the water. By that time, the gunboat Castine had managed to increase steam pressure, start its engines and raise her anchor. In an effort to rescue those in the water, the gunboat came into the surf. However, the seas were too rough to lower a boat and the Castine got dangerously close to the rocks. Fearing that the Castine may end up on the rocks, the rescue effort was abandoned but lifejackets were thrown in the water. Castine's commander ordered to head out. The battered gunboat struggled past the Memphis, but managed to get safely out to deeper water.

16.30 — By that time the swell was even greater. The Memphis kept on rolling 60 and perhaps as much as 70 degrees. Her decks were being washed over by the waves and repeatedly she was battered into the harbor bottom. With each wave, the ship appeared to be lifting and dragging towards the rocks on the shore. Captain Beach ordered the drop of a second anchor, but the order was cancelled when the engine room informed him that steam pressure would be adequate in five minutes to start the engines. With the ship rolling that much and the seas washing over the decks, attempting to drop the second anchor was impossible.

16.35 — An immense wave estimated to be about 70 feet in height was seen approaching the harbor.

16.38 — The engine room could not generate sufficient steam pressure for the engines. The ship's anchor cable was straining and appeared that it would break. With only 90 lb. of steam pressure, Captain Beach had no choice and could not wait for more steam. In an effort to at least turn the ship's bow into the approaching huge wave, he ordered the starboard engine full astern and the port engine full ahead. It was a futile effort. There was simply not sufficient steam pressure to turn the ship ninety degrees and complete the maneuver.

16.40 — The enormous wave was quickly approaching the Memphis. It could be seen churning sediments of sand and mud from the sea bottom. It appeared that it would hit the ship broadside — the most vulnerable position. The shallower water depth had slowed the wave down a bit but its height had increased. In front of it, a 300 ft long trough had formed. Its peak began to break as the wave got closer to Memphis. The top of the breaking crest was now about 30–40 feet above on the ship's bridge. The waveform appeared to consist of three distinct steps, each separated by a large plateau. The huge wave broke thunderously upon the Memphis, completely engulfing it (Fig. 2). Two seamen trying to release the second anchor were washed overboard. The wave's impact injured members of the crew. Other

Photo # NH 99959 USS Memphis wrecked, 29 August 1916



Fig. 5. The USS Memphis grounded on the rocky shore of Santo Domingo and pounded by subsequent waves of the meteotsunami and of breaking, long period storm swells (U.S. Naval Historical Center Photographs)

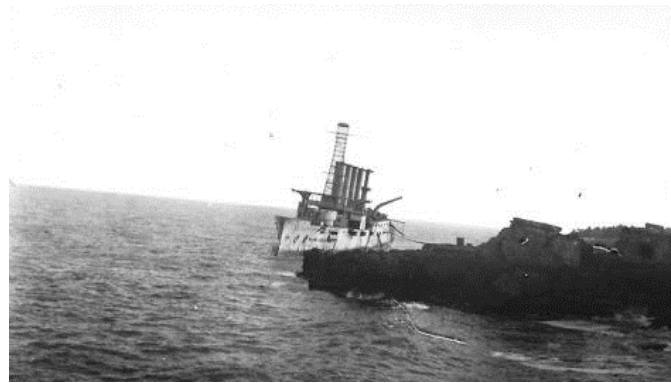


Fig. 6. The USS Memphis grounded after the meteotsunami and the storm swells subsided (U.S. Naval Historical Center Photographs)



Fig. 7. The wreck of the USS Memphis on the shore of Santo Domingo (U.S. Naval Historical Center Photographs)

crewmembers were injured or killed by steam or by steam inhalation when the ship boilers exploded. The ship did not capsize but recovered to an upright position but hit bottom hard, which normally would be about twenty-five feet below her keel. The battering caused great damage on her hull.

16.45 — Slowly, dragging her anchor, the Memphis struck the first rocks (Fig. 5). As each succeeding wave pounded her, she was forced a little further ashore until her port side crushed against the rocks, which pierced this side repeatedly. The Memphis was still rolling from side to side, although now firmly aground (Fig. 6).

17.00 — At about 17.00 the battered ship was given one final push by the waves, thus moving her hard aground on Santo Domingo's rocky coast in water depth ranging from 12–19 feet and only 40 feet from the cliffy shoreline (Fig. 7). Observers on the shore could see large holes in the ship's hull.

1.3. Securing the wreck of the Memphis

Actions that followed the grounding of the Memphis are not of direct relevance to the evaluation of causes that caused this disaster and details are omitted since they have been

adequately documented in U.S. Navy archives and the literature. It will suffice to say only that, as soon as the *Memphis* had gone firmly aground, Captain Beach ordered the crew to fully secure the ship with ropes to the shore. This was accomplished with the assistance of U.S. Marines and hundreds of Dominicans on the cliffy shore of the harbor. Then the captain ordered the evacuation of the injured, followed by the evacuation of 850 others. This was done in an orderly and safe fashion, using hawsers on land and ropes.

1.4. Death toll and injuries — damage to the ship

What had started as a normal routine afternoon on board the *USS Memphis* on 29 August 1916, in a matter of about one hour, turned into a major disaster. Forty-three people lost their lives that fateful afternoon. Twenty-five crewmembers died when the ship's motor launch capsized in huge breakers at about 14:00, as it was attempting to return to the ship. Another eight members of the crew were lost when three boats sent to sea sank or were wrecked attempting to reach shore after dark. Ten more died either by being washed overboard or from burns and steam inhalation when the ship's boilers exploded. The total casualties, numbered 43 dead and 204 injured.

The ship itself sustained irreparable damage (Fig. 7). Though she appeared to be nearly normal in appearance above the water, the *USS Memphis* was a total loss. Her bottom was driven in, her hull structure was badly distorted and her boilers had exploded. Her 23,000 horsepower steam power plant had been destroyed. The *Memphis* would never sail again. Although her guns and other components were eventually salvaged, her punctured and twisted hull remained an abandoned wreck on the cliffs of Santo Domingo for 21 years — before being dismantled by ship breakers (Fig. 8).

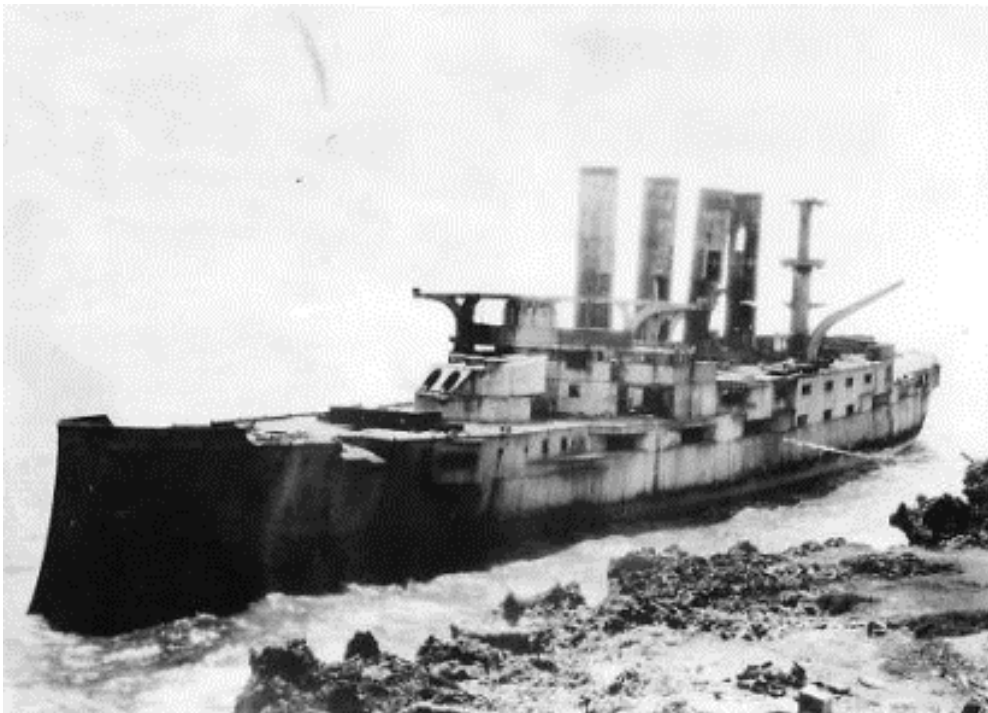


Fig. 8. The wreck of *USS Memphis* years later on the rocky shore of Santo Domingo, with the guns stripped

1.5. Conclusions of the Court of Inquiry as to what caused the loss of the Memphis

A Court of Inquiry and the court martial of Captain Edward J. Beach, the ship's commander, followed the loss of the Memphis. The court concluded that conditions had deteriorated very rapidly to save the Memphis. Also, that the heavy rolling of the ship and the flooding from the ventilator funnels was the reason that steam pressure could not be raised in time to fire the engines and head out to sea, as the gunboat Castine had barely managed to do. Complications in the engine room were blamed for the failure. The Court found that Captain Beach was guilty of not keeping up sufficient steam to get underway at short notice and of not properly securing the ship for heavy weather. The huge waves that engulfed and wrecked the Memphis and drowned the sailors were wrongly attributed to a "tropical disturbance", a "seismic storm", but also to a "tsunami" that originated from a seismic event somewhere in the depths of the Atlantic Ocean or Caribbean Sea.

2. Analysis of the naval disaster

The Navy's conclusion that the loss of the Memphis was due to a "seismic storm" or a tsunami was erroneous. There is no such thing as a "seismic storm". Furthermore, no tsunami occurred in late August 1916 in the Caribbean Sea or the Atlantic Ocean. The characteristics of the waves observed breaking on the coastline of Santo Domingo in the afternoon of 29 August 1916 were not those of a tectonically generated tsunami.

Tectonic earthquakes generated most of the historical tsunamis in the Caribbean region. A review of historical catalogs of tsunamis does not show an event specifically occurring on August 29, 1916. The only earthquake and tsunami in the vicinity, which could have affected Santo Domingo, occurred on April 24, 1916 north of Puerto Rico, probably in the Mona Passage. Another earthquake/tsunami occurred in the vicinity of Guatemala/Nicaragua on January 31, 1916. This event could not generate a tsunami at Santo Domingo. Another small tsunami was generated on the Pacific side of Central America that same year. However, there were no earthquakes of significance in the region during the latter part of August 1916. Similarly, there is no historical record of volcanic eruptions or major underwater landslides for August of 1916.

The Navy officers who participated in the Court of Inquiry and the court martial of the ship's captain did not appear to have much technical experience or training about storm-generated waves, hurricanes or tsunamis. In 1916, Oceanography and Meteorology had not developed sufficiently as fields of science. There was no effective way of tracking hurricanes or reporting vital weather data to the U.S. Navy Command. Weather forecasting was at a rudimentary state and there was no effective monitoring system or synoptic observations, which could be shared in real time. Finally, communications were not very good in those days. Thus, it appears that the U.S. Navy Command did not even have information on the three hurricanes that had passed close to Santo Domingo in the month of August 1916. In fact, on 18 August, one of these hurricanes had made landfall at Corpus Christi, Texas, and had been responsible for widespread destruction there. Even if this information was known, it appears that it was not conveyed to the captains of the USS Memphis or the USS Castine at Santo Domingo.

The following is an account of the hurricanes that passed near the Dominican Republic in August 1916 and an analysis of the storm waves of the particular hurricane that contributed to the meteotsunami and to the loss of the USS Memphis.

2.1. The USS Memphis was wrecked by a meteotsunami and storm swells generated by a passing hurricane

As previously mentioned, the location at Santo Domingo where the USS Memphis and the USS Castine were anchored was very vulnerable to approaching storm waves from the east and southeast. The water depth of 55 feet where the Memphis had dropped anchor was too shallow and within the breaking depth zone of potential significant waves of longer period and wavelength, generated by hurricanes.

As it will be demonstrated, the series of huge breakers and the enormous wave that wrecked the ship on the afternoon of 29 August 1916 were generated by an approaching hurricane. The most significant of the waves that contributed to wrecking the Memphis were generated within this hurricane's zone of maximum winds. Once outside the fetch region of generation, these storm waves had outrun the slower moving hurricane system and raced as swells across the Caribbean towards the harbor of Santo Domingo. The rapidly dropping atmospheric pressure that had been observed beginning on 22 August at Santo Domingo, coupled with the shallower bathymetry, generated a meteotsunami with the superimposed storm swells adding to its height.

The following is an account of the hurricanes that passed near the Dominican Republic in August 1916 and an analysis of the waves that contributed to the loss of the USS Memphis.

2.2. The hurricanes of 1916

This region of the Caribbean is in the middle of the hurricane belt and is subject to severe tropical storms and hurricanes from June to October. As shown by the hurricane-tracking diagram (Fig. 9, below), there were numerous hurricanes that traversed the region in 1916.

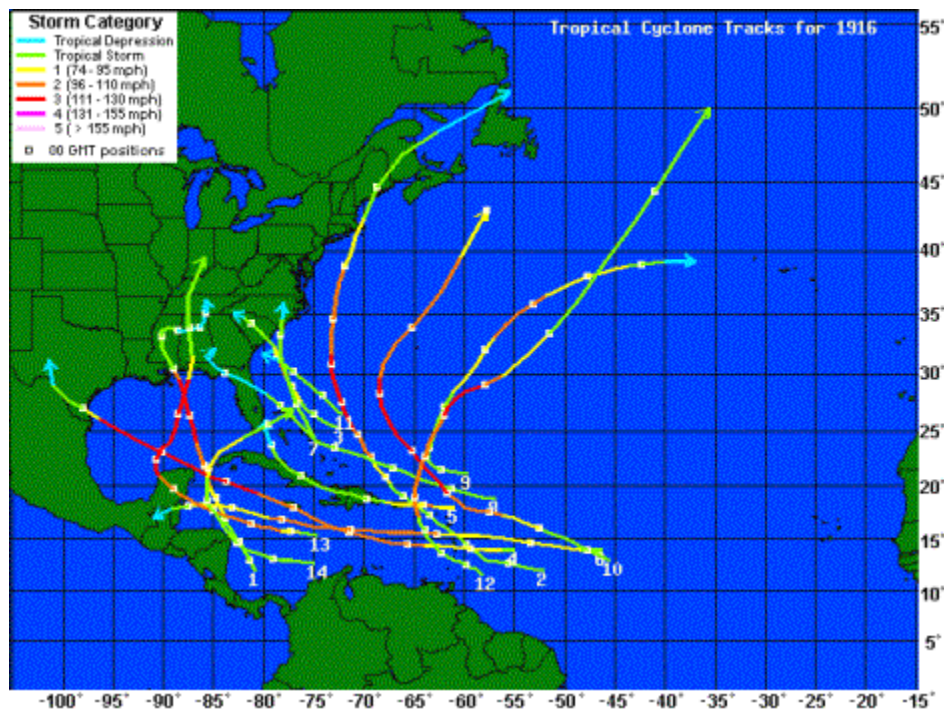


Fig. 9. Tracks of Hurricanes in 1916 in the Caribbean Sea and the Western Atlantic (Source: Wikipedia)

Most of them developed in the Atlantic Ocean as tropical storms but when they reached winds of more than 75 miles per hour, they were classified as hurricanes. Three of these storm systems became hurricanes in August 1916. Two of them crossed the Central Caribbean Sea, south of Santo Domingo, and one headed north.

The first of the unnamed hurricanes in August 1916 (8/12–8/19) reached Category 3 and made landfall at Corpus Christi, Texas — causing extensive destruction there. The second unnamed hurricane (8/21–8/25) reached briefly a Category 2 status as it passed near the Island of Hispaniola, but quickly degenerated into a tropical storm. Finally, the third unnamed hurricane in late August (8/27–9/2) reached a Category 2 status with sustained winds of over 100 miles per hour. It passed south of Santo Domingo on August 29. It is believed that it was this hurricane that generated the huge waves at Santo Domingo. Because its waves wrecked the USS Memphis, we shall refer to it as “Hurricane Memphis”.

2.3. The unnamed hurricane of August 12 — August 19, 1916

As the tracking indicates (Fig. 10), this hurricane reached Category 3 status passing south of Santo Domingo on 14–15 of August. It continued in a northwest direction, making landfall at Corpus Christi, Texas on August 18.

There is no information on any unusual wave activity at Santo Domingo around August 14–15 when this hurricane passed about 275 nautical miles to the south. It appears that the directionality of the hurricane’s path was the reason that no significant waves struck the coast of Santo Domingo. However, this hurricane was very destructive in the Corpus Christi, Texas region. In fact it was the strongest storm since the Great Galveston storm of 1900 had struck the area south of Corpus Christi. Although this hurricane caused some damage, it moved very fast over the Texas coastal area, thus resulting in low loss of life. Only 15 people died. However, property damage was significant and was estimated at \$1,600,000 (1916 dollars). Most affected were the cities of Bishop, Kingsville and Corpus Christi. In Corpus Christi, all the wharves and most of the waterfront buildings were destroyed. There

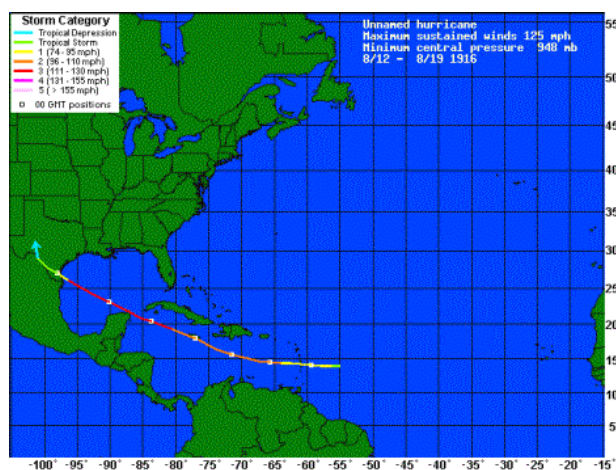


Fig. 10. Track of unnamed hurricane that passed south of Santo Domingo on 14–19 August 1916 and struck Corpus Christi, Texas (Source: Wikipedia)

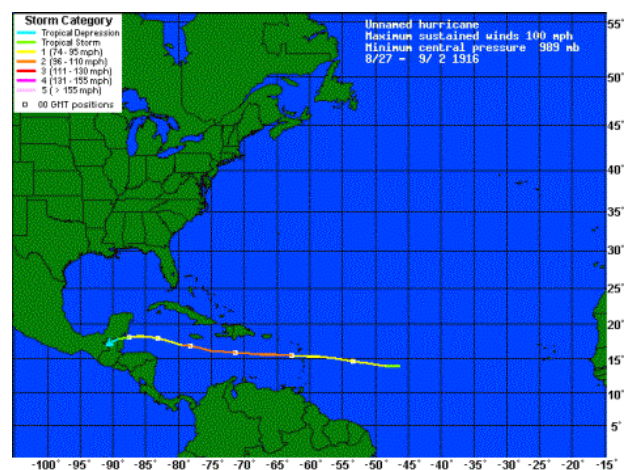


Fig. 11. Track of unnamed hurricane that passed south of Santo Domingo on 27–29 August 1916 — named hurricane “Memphis” by the author (Source: Wikipedia)

was hardly any property that was not damaged. Most of the damage resulted from the hurricane surge flooding and the superimposed storm waves.

2.4. Evaluation of hurricane “Memphis” of 8/27–9/02, 1916

As the tracking diagram indicates (Fig. 11) this particular system developed from a tropical storm on 27 August to a Category 1 hurricane on 27 August and early on 29 August to Category 2 hurricane. It reached sustained winds of over 100 miles an hour and maximum probable wind speeds and gusts of 125 miles per hour (Table, below). This was a dynamic storm system, which advanced into the Caribbean Basin rapidly. The hurricane’s speed of translation eastward is estimated at about 15–20 nautical miles per hour, since it traversed approximately 400 nautical miles on 29 August. At its closest point, the hurricane center was about 250 nautical miles south of Santo Domingo. The region of maximum winds was closer. The following is tracking information for hurricane “Memphis”, followed by an analysis of the storm waves it generated and of the subsequent swells that travelled towards the Island of Hispaniola.

Tracking information for unnamed hurricane (hurricane Memphis) passing South of Santo Domingo on 29 August 1916

Time (h), Date (m/d/y)	Lat (grad)	Lon (grad)	Wind (mph)	Storm type
6 GMT 8/27/1916	14.0N	46.3W	70	Tropical Storm
12 GMT 8/27/1916	14.0N	48.5W	70	Tropical Storm
18 GMT 8/27/1916	14.3N	51.2W	75	Category 1 Hurricane
0 GMT 8/28/1916	14.7N	53.5W	75	Category 1 Hurricane
6 GMT 8/28/1916	15.1N	56.0W	80	Category 1 Hurricane
12 GMT 8/28/1916	15.3N	58.5W	85	Category 1 Hurricane
18 GMT 8/28/1916	15.4N	60.5W	85	Category 1 Hurricane
0 GMT 8/29/1916	15.5N	62.8W	90	Category 1 Hurricane
6 GMT 8/29/1916	15.6N	65.1W	100	Category 2 Hurricane
12 GMT 8/29/1916	15.6N	67.6W	100	Category 2 Hurricane
18 GMT 8/29/1916	15.7N	69.2W	100	Category 2 Hurricane
0 GMT 8/30/1916	15.9N	71.3W	100	Category 2 Hurricane
6 GMT 8/30/1916	16.0N	73.1W	100	Category 2 Hurricane
12 GMT 8/30/1916	16.2N	75.1W	100	Category 2 Hurricane
18 GMT 8/30/1916	16.6N	76.7W	100	Category 2 Hurricane
0 GMT 8/31/1916	16.8N	78.2W	100	Category 2 Hurricane
6 GMT 8/31/1916	17.0N	79.6W	100	Category 2 Hurricane
12 GMT 8/31/1916	17.4N	81.0W	90	Category 1 Hurricane
18 GMT 8/31/1916	17.7N	82.0W	90	Category 1 Hurricane
0 GMT 9/ 1/1916	18.0N	83.2W	85	Category 1 Hurricane
6 GMT 9/ 1/1916	18.1N	84.1W	85	Category 1 Hurricane
12 GMT 9/ 1/1916	18.2N	85.3W	80	Category 1 Hurricane
18 GMT 9/ 1/1916	18.2N	86.4W	80	Category 1 Hurricane
0 GMT 9/ 2/1916	18.1N	87.6W	75	Category 1 Hurricane
6 GMT 9/ 2/1916	17.9N	89.3W	65	Tropical Storm
12 GMT 9/ 2/1916	17.0N	91.0W	35	Tropical Depression

2.5. Hurricane “Memphis” wind field — directionality of hurricane fetches, duration and significant storm waves and swells

Maximum winds were blowing up to 87 knots, in a counterclockwise pattern on 27 August 1916 when Memphis attained Hurricane 1 status soon after crossing the Lesser Antilles Islands Arc, south of Puerto Rico and rapidly approached the Island of Hispaniola (Fig. 11). Memphis became a Category 2 hurricane on 29 August and significant storm waves of longer periods began developing within the radius of maximum winds, within fetches of 10 to 20 nautical miles and over durations of 1 to 2 hours.

As the hurricane progressed quickly westward in the early morning hours of 29 August, the fetches of maximum winds kept on changing direction in the same counterclockwise pattern. Initially the winds generated huge storm waves travelling in an easterly direction. At the time, the wave field in front and on either side of the hurricane center consisted of locally generated seas and additional travelling swells from other regions of the storm system. The storm waves were generated, not only along the east-west fetches of maximum winds, but also along fetches with a southeast-northwest orientation and perhaps along fetches with northward orientation towards the Island of Hispaniola. However, in the next few hours, as the hurricane center was approaching the longitude of Santo Domingo, winds and atmospheric pressure changes, coupling with the local bathymetry, contributed to the formation of a meteotsunami — progressive waves limited to the tsunami frequency band of wave periods of two minutes to two hours — and to huge storm waves.

Subsequently, later on 29 August, the longer period storm swells began to outrun the moving storm system and sorted out as distinct wave trains travelling towards the southern coasts of the Dominican Republic. Because of the hurricane’s eastward movement and orientation of the fetches of maximum winds, the waves that were generated in the early afternoon, became very directional towards Santo Domingo as the meteotsunami also did because of the rapidly dropping atmospheric pressure. To quantify and differentiate these changes is not possible without synoptic data collection. However, based on the counterclockwise rotation of the winds around the storm center, it is estimated that the direction of approach of converging surge swells was from the south initially, then from the southeast, from the east-southeast, then from the southeast again.

2.6. Estimates of heights and periods of the most significant deep water storm waves generated by hurricane “Memphis” and of the swells that contributed to the height of the meteotsunami waves at Santo Domingo

Based on the limited data for this 1916 hurricane and its unknown parameters, mathematical modelling is not possible. However, for the purpose of the present analysis, an empirical approach is sufficient to roughly evaluate the Rayleigh distribution function, the upper limit of storm wave height variability, as well as the maximum period, wavelength, and deep-water height of the most significant of the storm waves. Based on this analysis it can be concluded that significant long period waves, combined in resonance with other storm waves and the most significant waves of the meteotsunami, finally resulted in the huge breaker that engulfed the USS Memphis at 16:40 on 29 August 1916 — wrecking it on the rocks of Santo Domingo. Before discussing further, the terminal and resonance characteristics of the disastrous breaking waves, let us first estimate the heights and periods of the most significant deep-water storm waves and swells that were generated by Hurricane “Memphis” that contributed to the height of the meteotsunami.

2.6.1. Airy waves in deep water and transformation by shallow bathymetry

For storm swells in deep water (denoted by subscript “0”, the water surface elevation η above or below the still water level (SWL), can be modelled for Airy waves by a time series at any point x (the distance from the wave crest in the direction of wave propagation) and time t using radians (Airy, 1845):

$$\eta(x, t) = \frac{H_0}{2} \cos \left\{ 2\pi \left(\frac{x}{L_0} - \frac{t}{T_w} \right) \right\} = \frac{H_0}{2} \cos \theta \quad (1)$$

where H_0 is the deep-water height, L_0 — the deep-water wavelength, and T_w is the wave period. In the second form of the equation, θ is the wave phase, given by:

$$\theta = \frac{k_0 x - \omega t}{2\pi} \quad (2)$$

where k_0 is the deep-water wave number $2\pi/L_0$ and ω is the radian frequency $2\pi/T_w$. However, this equation becomes invalid when such waves propagate into shallow water because of a change in their dimensions and shape [3]. Furthermore, the wave profile is displaced upward with respect to the SWL, so that the crest is higher above the latter than the trough is below it.

The significant height H_0 and period T_w of the most significant wave generated in deep water at a point on the radius R of maximum wind of a hurricane could be calculated mathematically, provided that the hurricane’s pressure differential from the normal D_p is known, as well as the hurricane’s forward speed, its maximum gradient wind speed near the water surface (30 feet above), and the Coriolis parameter f at that latitude. The mathematical equations for this calculation are omitted here since the existing data is deficient.

However, based on the limited data available for this August 1916 hurricane (“Memphis” — Category 2 hurricane), and assuming that its radius of maximum winds was about 35 nautical miles away from the storm center (a reasonable approximation for a hurricane of this type), the forward speed of the storm is estimated at 20 knots, and the barometric pressure differential at about 2.3 inches of mercury, the most significant deep water height H is calculated to be about 59 feet. The deep-water period of the most significant swell is calculated to be about 16 seconds — indeed a long period. Once outside the hurricane region, this significant swell maintained its wavelength and period, but attenuated somewhat in height during its travel towards Santo Domingo.

2.6.2. Bathystrophic alteration of the storm waves and swells

Mathematical models using the Bathystrophic Storm Tide Theory include a steady-state integration of the wind stresses of hurricane winds on the surface of the water from the edge of the Continental Shelf to the shore, taking into consideration some of the effects of bottom friction and wind surface friction, the along-shore flow caused by the Earth’s rotation (the Coriolis effect), as well as other incipient conditions, such as astronomical tides and barometric pressure changes [10].

The height and period of the storm swells of Hurricane “Memphis” were altered by a bathystrophic contribution which can be explained as follows: in the northern hemisphere the winds of a hurricane approaching a coast have a counterclockwise motion around the moving storm center and maximum winds at some distance away from the storm center generate the highest storm waves. On 29 August 1916 the radius of the maximum winds of this particular hurricane was much closer to the coast of the Island of Hispaniola than the passing storm center to the South. Because of the Coriolis effect and the Ekman spiral effect,

the flow of surface water induced by the counterclockwise-blowing cyclonic winds deflected the surface water flow by 45° to the right of the wind direction, causing a rise in the water level along the coast of the island. Therefore, the “bathystrophic storm tide” and the “Ekman” spiral effect were important in producing maximum surge on the shore, even when the winds were blowing parallel to the coast. Also, the rapidly dropping barometric pressure of the fast moving storm system, coupled with the shallow water bathymetry, augmented the generation and height of a meteotsunami along the coast. Additionally, resonance effects and coastal morphology affected the extent of rise of water [10].

In this particular case, the coastal morphology affected the extent in the height of surge rise by swells with long periods of about 15–16 seconds — thus contributing to the waves of the meteotsunami that began arriving at Santo Domingo around 15:30 of 29 August 1916. At 16:40, the enormous wave that was observed quickly approaching the USS Memphis, struck the ship broadside. The shallower water depth had slowed the huge wave down a bit but its height had increased. As previously mentioned, the breaking crest of this wave was about 30–40 feet above on the ship’s bridge and the waveform appeared to consist of three distinct steps, each separated by a large plateau. The USS Memphis was anchored in too shallow depth (55 feet) to ride a huge wave of such long period and wavelength — which had tremendous kinetic energy upon breaking and thus completely engulfed the ship, broke its anchor chains and wrecked it on the rocky shore.

Unfortunately, back in 1916 there was no sufficient meteorological data of the passing hurricane to enable accurate three-dimensional estimates of the energy flux and flooding that it caused and to take into account the combined effects of the direct onshore and alongshore wind-stress components of the storm on the surface of the water, the effects of the Coriolis force (the bathystrophic effect), and of the different atmospheric pressure effects. Quasi-one-dimensional, two-dimensional, or three-dimensional numerical schemes that enabled such calculations were developed in later years [10].

If such data existed for this particular hurricane, the following equations could have provided the components that contributed to the maximum height of water level and of the superimposed hurricane surge arriving with the meteotsunami on the shore at Santo Domingo on 29 August 1916. These components would have included the advection of momentum, the Coriolis contribution, the effects of the surface slope (on inshore flooding), the inverse barometric pressure effects of the meteotsunami, the astronomical tide contribution, the stress of winds on the surface of the sea, the effects of bottom friction, and of other minor components as shown by the equations below [10].

$$\frac{\partial U}{\partial t} + \frac{\partial M_{xx}}{\partial x} + \frac{\partial M_{yy}}{\partial y} = +fV - gD \frac{\partial S}{\partial x} + gD \frac{\partial \xi}{\partial x} + gD \frac{\partial \zeta}{\partial x} + \frac{\tau_{ax}}{\rho} - \frac{\tau_{bx}}{\rho} + W_x P,$$

Advection of Momentum	Coriolis	Surface Slope	Inverse Barometer	Astro. Tide Potential	Wind Stress	Bottom Stress	Rainfall Rate
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$$\frac{\partial V}{\partial t} + \frac{\partial M_{yy}}{\partial y} + \frac{\partial M_{xy}}{\partial x} = +fU - gD \frac{\partial S}{\partial y} + gD \frac{\partial \xi}{\partial y} + gD \frac{\partial \zeta}{\partial y} + \frac{\tau_{ay}}{\rho} - \frac{\tau_{by}}{\rho} + W_y P,$$

$$\frac{\partial S}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = P.$$

However, it should be noted that such one-dimensional hydrodynamic equations of motion and continuity were integrated numerically by the author in the past to compute the nonlinear storm surge at selected points along a traverse of maximum winds, striking a shore at a right angle. This was done for the purpose of determining the safety of nuclear power plants [10]. The hurricane surge height was only estimated for a selected traverse and the height of the calculated surge was a composite of water elevation obtained from components of the astronomical tide, the atmospheric pressure, the initial rise, the rises due to wind and bottom friction stresses, and wave setup. This model was calibrated and verified with data of actual historical hurricanes [10]. Obviously such a basic model has its limitations. A hurricane is not stationary, and as it moves towards the coast, the wind speeds may increase and wind vectors will change direction changing frictional effects on the water surface. Such changes cannot always be predicted with accuracy to introduce them into the model. Furthermore, they do not include the possible contribution to surge height resulting from a meteotsunami, or the synthetic compositions and contributions of other forcing factors — which are very difficult to quantify and use even with more recent numerical models [14].

2.7. Wave transformation in shallow water — effects of near shore refraction and resonance

Let us now review some of the effects of refraction, resonance and terminal transformation of the meteotsunami and of hurricane Memphis' swells arriving at Santo Domingo in the early afternoon of 29 August 1916.

The first of the longer period storm waves — which outrun the hurricane system's eastward progression — began arriving as swells at Santo Domingo at about 15:00 on 29 August. Up to that time the sea had been smooth and there were no reports of winds or a significant drop in barometric pressure. At that time, the hurricane's center was still fairly far away at about 15.6°N and 67.6°W, approximately 300 nautical miles southeast of Santo Domingo. However, the initial swells that began arriving at 15:00 had been generated much earlier, mainly from east-west fetches when the hurricane was as far as 600 nautical miles away. These swells had travelled almost twice as fast as the overall storm system.

In the next hour, additional storm swells were observed closer to Santo Domingo — but coming from a changing east-southeast direction and begun to outrun the moving hurricane and interfere with other swells arriving from further east. The direction of the waves approaching Santo Domingo kept on changing, but when these swells reached shallower water, the bottom effects began to affect their heights. Near-shore refraction unified the waves' directional approach towards the harbor of Santo Domingo and the location where the Memphis and the Castine were anchored. Some of the waves had similar periods and wavelengths, arrived in resonance, and begun to superimpose on each other — thus augmenting additionally their heights. The longer period swells began to break in water deeper than the 55 feet where the USS Memphis was anchored. These breaking swells, some striking broadside, washed over the decks of the Memphis, and thus water went into the ventilator shafts. This in turn caused problems in raising steam for the engines of the ship. The anchor was still holding, but probably slightly dragging on the sea floor. Apparently not enough scope had been let out on the anchor's chain. Dropping a second anchor would not have helped the Memphis since not enough scope could be released for the anchor to grab and be effective.

2.8. The most significant of the observed swells in resonance with the meteotsunami

Let us now review the meteotsunami and the resonance interaction with storm swells. Most of the meteotsunamis that have been reported in the literature have been observed in many places around the world — including the Gulf of Mexico, the Atlantic Coast, the West Mediterranean and Adriatic Seas as well as the Great Lakes. Their height estimates were as much as 3 meters or more and their characteristics were very similar to those of tectonically generated tsunamis, which made them rather difficult to distinguish. Let us now review their transformation and their postulated interaction with storm swells and the barometrically induced changes in height from deep to shallow water.

There have been many studies of wave transformation for different deep-water wave height/length ratios for sinusoidal, fully developed Airy linear-shape, deep-water waves to typical Stokes and cnoidal wave profiles in the breaker zone, for a variety of sea floor coastal slopes and bathymetry [3–5, 12, 13, 15]. Specific definitions of Airy, Stokes and cnoidal waves are given in oceanographic manuals and a tsunami glossary of the Intergovernmental Oceanographic Commission of UNESCO (compiled by [11]).

2.8.1. *Effect of the Proudman resonance*

A recent mathematical study of meteo- and landslide tsunamis addressed the effect of the Proudman resonance in deeper water in estimating the resonant response in shallow waters of a water body travelling by atmospheric disturbance, when the speed of the disturbance was close to the long wave speed. Accordingly, the study of the linear water waves equations and of dispersion estimates, allow the investigation of the resulting sea level amplitude change [8].

In the present case — and given the limitations of existing data — the effects of resonance of the meteotsunami with concurrently arriving storm swells at Santo Domingo on 29 August 1916 can only be inferred by the visual observations. According to the crew on the USS Memphis, the increasing wave activity began at 15:30. However, the huge wave, which was observed approaching at 16:40, had an estimated height of about 70 feet. The wave must have been the most significant of the storm swells generated by the hurricane which was estimated earlier to have a maximum deep water height of 58.9 feet and a period of 16.1 seconds — when it left the fetch in the hurricane's region of maximum winds (estimated at about 125 knots/hour). Moreover, superimposed on this huge wave was the meteotsunami wave that had been generated by the rapidly dropping atmospheric pressure — observed earlier in the afternoon of 29 August. Assuming that the height of the storm swells was not significantly changed before beginning to break in the shallow offshore region near Santo Domingo, the maximum height of the meteotsunami wave is roughly estimated to have been about ten feet (3 meters).

As mentioned earlier, when this huge wave got closer to Memphis, the crewmembers observed that it had three distinct steps and two plateaus on its forward face. Also, they reported that a trough, which was estimated to be 300 ft. long, preceded the crest. These observations suggest that this wave's overall wavelength was about 600 feet and that two storm swells were superimposed on it when refraction and final transformation begun to take place in the shallows off Santo Domingo. Since the period of the storm swells was calculated to be 16 seconds in deep water (unchanged by refraction), the deep water wave speed of the storm swell can be estimated — based on Airy and cnoidal wave theories — to have been: $C = L/T = 600/16 = 37.5$ ft/sec (independent of depth). However, in water shallower than

one half the wavelength (in this case less than 300 feet), refraction by decreased bathymetry and the effects of resonance begun to take place — thus combining in the height of this huge wave which included two other significant, long period swells, perhaps approaching from different hurricane wind fetches and directions. This explains the three steps and the plateaus that were observed at 16:40 on the face of the huge wave.

2.8.2. *Effect of cnoidal transformation*

Furthermore, in shallower water the cnoidal transformation of a breaking wave occurs when the depth of the water is less than $1/8$ to $1/10$ of the wavelength and its surface profile is expressed in terms of the Jacobian elliptic function “cn u ” (hence the derived term “cnoidal”) [11]. In the present case, the cnoidal transformation and impact of turbulence were insignificant and did not contribute much to the height of the breaking wave.

The transformation of the huge wave had begun about two minutes earlier than 16:40. When the wave reached water depths ranging less than $1/2$ its wavelength (less than 300 feet), the refraction effects became more significant. Its speed was reduced considerably. The wave speed was now dependent on the depth of the water and was governed by the shallow water wave equation, which can be simplified as: $C = \sqrt{gd}$ — where d is the depth of the water, and g is the Earth’s gravitational acceleration for that particular latitude. Based on solitary

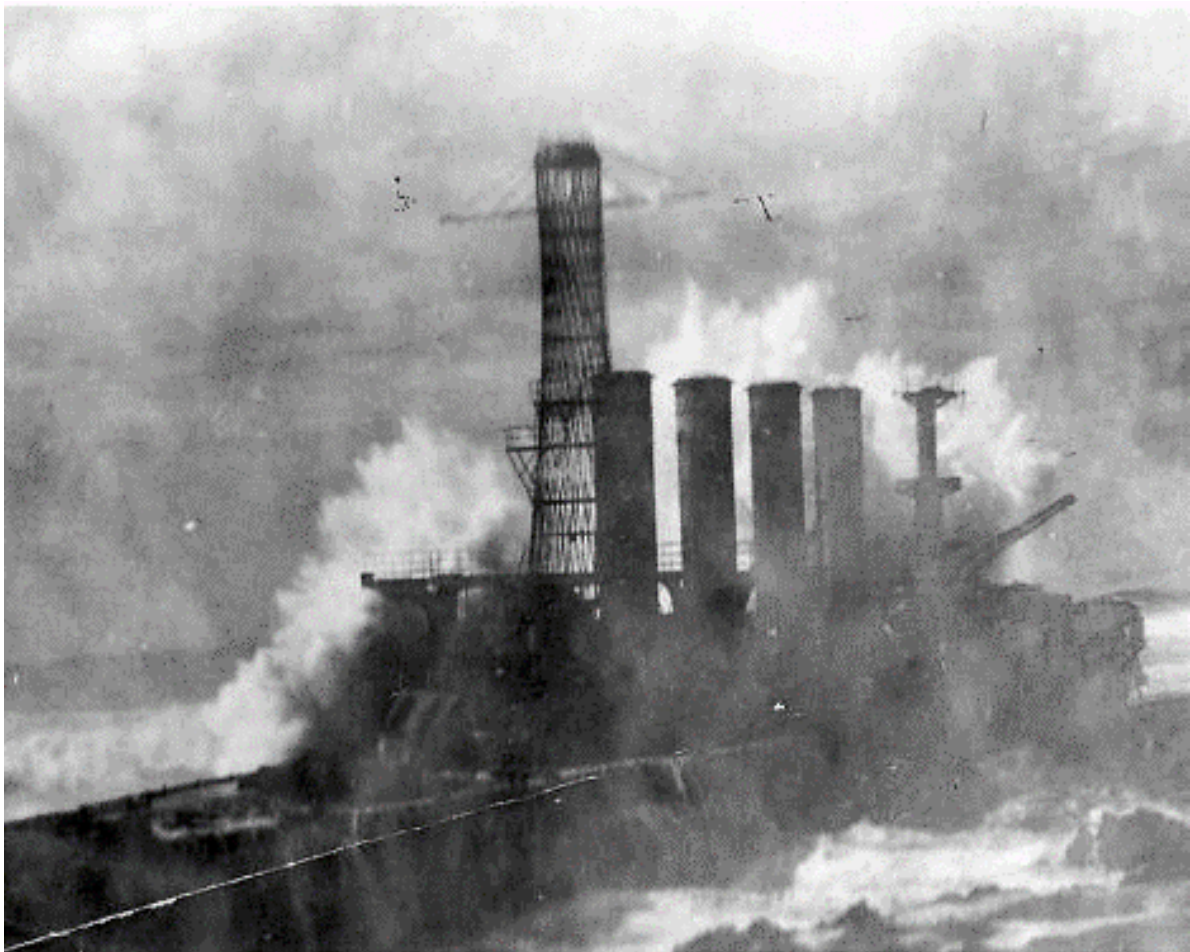


Fig. 12. The USS Memphis pounded by waves, months after she was wrecked

wave theory, and without knowing the slope profile off Santo Domingo harbor, an estimate of the breaker height can be made based on the relationship between the breaker height H_b to the breaking depth D_b .

At the breaker depth of 300 feet, all of the huge wave's potential energy became forward kinetic energy — much to the detriment of Memphis. The relationship from which the depth of the water where the wave will begin to break can be obtained from $H_b = D_b/1.28$. Since the observation was made by members of the crew that the huge wave was about 30 to 40 feet above the bridge of the Memphis — and assuming that the bridge was about 30 feet above sea level, the height of the wave at breaking H_b , must have been 70 feet. Thus the huge wave must have begun breaking when it reached a depth of about 90 feet.

Had the Memphis been anchored in deeper water, like 120 feet instead of 55 feet, the entire disaster would have been prevented. The ship would not have sustained the earlier flooding of the engine room through the ventilators by the earlier waves and it would have been able to raise steam and sail to deeper water in a timely fashion. Alternatively, if the Memphis had been anchored in 100 or better 120 feet of water — instead of 55 feet — it would have been able to ride all the swells, including the huge 70-foot wave, without a problem.

Unfortunately, the Memphis was anchored in too shallow and unsafe water depth. When the huge rogue wave had reached a depth of about 90 feet, its crest peaked and the water particle velocity exceeded the wave's forward velocity (celerity). At that breaking depth, all of the wave's energy became kinetic and a huge volume of water begun to move forward at a speed of 25–30 miles per hour. When this huge breaker struck the Memphis broadside, it engulfed its decks and smokestacks and pushed it onshore with tremendous force. At that point in time, the Memphis was forever doomed. The anchor was of no use. The engines, even if they had more than the 90 lbs. of steam pressure, would have not saved the ship. Even if the maneuver of turning the ship's bow into the face of the wave had been completed, it would have been futile within the breaking zone of this huge wave. Neither the engine nor the anchor could have opposed the huge wave force.

2.9. Human errors contributed to the loss of the USS Memphis

Human errors were inadequately addressed by the U.S. Navy's Court of Inquiry into the disaster and by the court martial of the ship's captain. Complications in the engine room were blamed for the failure. The Court found that the only human errors responsible for the ship's loss was the captain's failure to keep sufficient steam pressure to get underway at short notice and of not properly securing the ship for heavy weather. However, the Navy's economy measures were the main reason that the boilers of the Memphis were not fired at all times to keep steam pressure up for the engines.

Also, as earlier mentioned, the huge waves that wrecked the Memphis at the harbor of Santo Domingo in the afternoon of 29 August 1916 were inaccurately attributed by the Court of Inquiry to a "tropical disturbance", a "seismic storm", but also to a "tsunami". The official Navy records still show that the loss of the Memphis was caused by a tsunami or a tropical disturbance — but without further explanation. As explained above, the waves that wrecked the Memphis were not those of a tsunami but were generated by a hurricane that passed south of Santo Domingo and by the rapid drop of atmospheric pressure that generated a meteotsunami. What is perplexing is that no one made a connection between this hurricane and the huge waves it generated or the effect of the rapidly dropping atmospheric pressure,

and the rapid movement of the hurricane center. It is apparent that storms were not properly monitored in 1916 and that communications on weather information were very poor.

Conclusions

A rapid change in atmospheric pressure caused by a rapidly-moving Category 2 hurricane passing far south of the Island of Hispaniola on 27–29 August 1916, was responsible for the generation of unusually high swells which superimposed and augmented the breaking waves at Santo Domingo of what was characterized as a meteotsunami. The directional focusing of these swells and their concurrent arrivals with the waves of the meteotsunami began suddenly at about 15.30 in the afternoon of 29 August. The long period swells and seiches which had been generated along different wind fetches of the hurricane's regions of maximum winds, superimposed on the meteotsunami, and coupled with the shallow offshore bathymetry in the vicinity of Santo Domingo harbor, became extremely high and destructive.

In shallow water, the huge breaking waves appeared to undergo both linear and non-linear transformations, apparent chaotic interactions, with increasing kinetic energy and height augmentation. The first of these superimposed waves caused flooding of the engine room of the USS Memphis and endangered the USS Castine — both ships anchored in relatively shallow water. An hour later (at about 16.30) superimposed waves, began lifting and dragging the USS Memphis towards the rocks on the shore. Finally, the most significant wave of about 70 feet in height begun breaking, dragging the ship to the rocky shore at 16:40. Its waveform appeared to consist of three distinct steps, each separated by a large plateau, with a large trough of about 300 feet in front which was similar to observations of extended troughs of other meteotsunamis elsewhere.

Although there are still remaining uncertainties regarding the mechanisms of generation of both meteotsunamis and of rogue waves, this event at Santo Domingo was most definitely associated with atmospheric disturbances caused by the rapidly moving hurricane and the dropping atmospheric pressure. Unfortunately, in 1916, there was lack of synoptic and frequent meteorological data. However even now, with meteorological data being provided in 6 hour increments, it is still difficult to estimate the potential individual heights of either rogue waves or meteotsunamis. Furthermore, the mechanism of formation of meteotsunamis and of rogue waves was relatively unknown until 1995 when an oil platform off the coast of Norway was struck by an enormous wave which was actually measured to be 25 meters in height — more than twice the height of a wave ever measured up to that time. Satellite photography also confirmed the frequent occurrence of rogue waves. Presently, it has been well established that rogue waves and meteotsunamis are frequent and result from superposition which occurs when wave crests of different storm waves combine crest to crest and a much large wave is linearly formed. However, superposition is not always linear and wave interactions are often chaotic.

As indicated earlier, since 1995 the scientific community has a better understanding of rogue waves and of meteotsunamis [1, 2, 9, 14]. Wind, tides, storms, water temperatures, stage of astronomical tides, bathymetry and many other factors contribute to their formation. The present study supports the premise that the linear effects of superposition convert to unpredictable non-linear processes of ocean waves during storms. Thus, non-linear chaotic contributions in height may be added to waves of certain periods and wavelengths during an extreme storm and these may be impossible or very difficult to measure or numerically model.

Acknowledgements. I wish to express my appreciation to Prof. Efim Pelinovsky for encouraging me to publish this paper as documentation that the unexpected huge waves at Santo Domingo in the afternoon of 29 August 1916, were indeed associated with a meteotsunami — as I had tentatively concluded — in spite of the difficulties concerning a lack of adequate meteodata.

Furthermore, I wish to thank Professor Leonid Chubarov for recommending publication of this paper with a minor revision in the pending journal “Computational Technologies”, and for recommending reviews of more recent publications that have helped the understanding of the generation mechanisms of meteotsunamis and of other rogue waves. The publications by Prof. Cristian Kharif, Prof. Efim Pelinovsky and Prof. Alexey Slunyaev, on the physical mechanisms of rogue waves, were particularly useful for this revision. Also, comments on a review by Prof. Alexander B. Rabinovich based on modern approaches in meteotsunami research, were particularly helpful, as well the publications he has co-authored with Prof. Ivica Vilibić, Prof. Jadranka Šepić, and Prof. Sebastian Monserrat, on recent advances in the understanding of atmospherically generated long ocean waves in the tsunami frequency band. Additionally, appreciated are comments by Dr. Slava Gusiakov for his corrections on historical tsunami catalogs for the Caribbean and for his suggestion that the meteotsunami of 29 August 1916 should be added as a new entry to the tsunami database.

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