Meteotsunamis in the northeastern Gulf of Mexico and their possible link to El Niño Southern Oscillation

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Abstract Analysis of 20-year time series of water levels in the northeastern Gulf of Mexico has revealed that meteotsunamis are ubiquitous in this region. On average, 1–3 meteotsunamis with wave heights >0.5 m occur each year in this area. The probability of meteotsunami occurrence is highest during March–April and June–August. Meteotsunamis in the northeastern Gulf of Mexico can be triggered by winter and summer extra-tropical storms and by tropical cyclones. In northwestern Florida most of the events are triggered by winter storms, while in west and southwest Florida they appear both in winter and summer. Atmospheric pressure and wind anomalies (periods <6 h) associated with the passage of squalls originated the majority of the observed meteotsunami events. The most intense meteotsunamigenic periods took place during El Niño periods (1997–1998, 2009–2010 and 2015–2016). Meteotsunamis were also active in 2005, a year characterized by exceptionally intense tropical cyclone activity. Meteotsunami incidence varied yearly...
and at periods between 2 and 5 years. Results from cross-wavelet analysis suggested that El Niño and meteotsunami activity are correlated at annual and longer-period bands.

Keywords Meteotsunami · Northeastern Gulf of Mexico · Winter storminess · El Niño Southern Oscillation

1 Introduction

Meteorological tsunamis or meteotsunamis are sea-level oscillations with periods from a few minutes to a few hours (<6 h) (Monserrat et al. 2006). They are multiresonant waves initiated by moving atmospheric disturbances (sudden wind and/or atmospheric pressure changes), which are usually associated with frontal passages, squalls, thunderstorms and atmospheric gravity waves. Although not as well known as seismic- and landslide-generated tsunamis, their effects can be severe and become catastrophic in some regions (Rabinovich 2009). Meteotsunamis have been described extensively by Monserrat et al. (2006) and Rabinovich et al. (2009). A special issue of natural hazards (Vilibić et al. 2014) has been dedicated to the study of meteotsunamis.

The free-surface elevation response $g$ to a periodic atmospheric disturbance (either atmospheric pressure forcing or the divergence of wind stress) traveling at the speed $U$ and angle $\theta$ is given by (Lamb 1932; Proudman 1953; Vennell 2010):

$$g = \frac{\eta_0}{U^2 - gh} \exp(ik(x\cos \theta + y\sin \theta - Ut)) = \frac{\eta_0}{1 - F_r^2} \exp(ik(x\cos \theta + y\sin \theta - Ut))$$

where $\eta_0$ is the response of the ocean surface under stationary atmospheric disturbance, $h$ is the water depth, $x$ refers to the horizontal distance, $t$ is time, and $k$ stands for the wave number of the atmospheric disturbance. Maximum energy transfer to the ocean occurs when the speed of the atmospheric disturbance matches the shallow water wave celerity $C = \sqrt{gh}$, where $g$ is acceleration due to gravity) or, which is equivalent, when the Froude number $F_r$ approaches 1. This situation is known as Proudman resonance (Proudman 1929). In this case, the atmospheric forcing is bound to the ocean’s surface wave.

The amplitude of the meteotsunami generated under these circumstances depends on the intensity of the atmospheric perturbation, on its shape and on the time or distance in which the meteotsunami is bound to the atmospheric disturbance (the fetch). If the water depth changes along the trajectory of the atmospheric perturbation and the celerity of such disturbance remains unmodified, the formerly bound meteotsunami becomes a free wave and the energy transfer from the atmosphere decreases. Although Proudman resonance is the best-known process that initiates meteotsunamis, there are other resonance processes that can also contribute to the growth of meteotsunamis. The two most relevant are Greenspan (1956) and shelf (Monserrat et al. 2006) resonance. Greenspan resonance occurs when the alongshore component of the atmospheric perturbation velocity equals the phase speed of one of the edge-wave modes. Shelf resonance takes place when ocean waves propagating through the continental shelf have periods and/or wavelengths equal to the resonant modes of the shelf region. Because meteotsunamis are shallow water waves over the shelf and coastal regions (wavelength $\geq 20$ times the local depth), their amplitude can be affected by reflection, refraction, shoaling, diffraction and harbor resonance.
Pattiaratchi and Wijeratne (2015) reviewed the occurrence of meteotsunamis worldwide with the aim of determining whether these ocean waves are an underrated hazard. They concluded that the probability of meteotsunamis worldwide is higher in general because energetic atmospheric disturbances are more probable than tsunamigenic earthquakes. However, the relative probability might change locally. Furthermore, destructive meteotsunamis are exceptional as they are multiresonant waves that are nonetheless observed at a limited number of sites.

Pasket et al. (2013) described the main meteotsunami events detected within the TMEWS (toward a meteotsunami warning system along the US coastline 2011) project funded by the National Oceanic and Atmospheric Administration (NOAA). This project focused on the analysis of the meteotsunamis along the East Coast of the USA between 2006 and 2011. Tidal gauges along the Gulf of Mexico were not considered in that project, but are examined in this study.

One of the best-known examples of meteotsunamis affecting the East Coast of the USA was the event of Daytona Beach, Florida (July 4, 1992) (Churchill et al. 1995; Sallenger et al. 1995). The wave had a 3 m height and caused injuries to at least 75 individuals and damage to a dozen vehicles near the beach. This extreme wave was generated by a southward propagating squall line associated with a mesoscale convective system (MCS) (Churchill et al. 1995; Sallenger et al. 1995), a collection of thunderstorms. A comparable event occurred on March 25, 1995, when a 3 m high wave battered the west coast of Florida (Paxton and Sobien 1998). This ocean wave was forced by a train of atmospheric gravity waves associated with a MCS transiting southeastward over the eastern Gulf of Mexico (Paxton and Sobien 1998). A meteotsunami observed along the East Coast of the USA on June 13, 2013, was also triggered by a MCS that included a fast-moving quasi-linear squall line, known as a derecho (Wertman et al. 2014).

The Gulf of Mexico is a prominent cyclogenesis region (Bosart and Sprigg 1998) where MCSs occur frequently as squall lines (e.g., Karan et al. 2010). These squall lines are most often observed ahead of some cold fronts and are linked to the intrusion of cold and dry air wedged under the warm and moist air from the Gulf of Mexico. Increased convection appears in the low levels of the troposphere from air convergence and subsequent ascent, typically within the atmospheric boundary layer. Many destructive squalls have been formed in this area. For example, the Superstorm of March 1993 (e.g., Alfonso and Naranjo 1996) carried heavy snow, heavy rains, high winds, tornadoes and coastal “storm surges” that caused fatalities and hundreds of millions of dollars in property damage (Bosart and Sprigg 1998). Meteotsunamis were not identified during this specific storm. However, we suspect that the extreme water levels during this storm could be affected by meteotsunamis. Due to the lower time resolution of the tidal gauges for this period the verification of this hypothesis has not been possible.

Other types of meteorological events that can cause meteotsunamis, such as tropical cyclones and cold fronts, occur commonly in the northern and northeastern Gulf of Mexico. Previous studies have shown that the frequency and intensity of tropical cyclones and winter cold fronts in this area are affected by climate variability. For example, Eichler and Higgins (2006) found Gulf of Mexico cyclogenesis occurred more often during the warm El Niño Southern Oscillation (ENSO) phase, because of strengthening of the southern branch of the jet stream over North America (Smith et al. 1998) and increased sea surface temperature in the Gulf of Mexico (DeGaetano et al. 2002). Thompson et al. (2013) corroborated the previous findings and identified a multidecadal increase in storm frequency from early to late twentieth century along the Gulf of Mexico and over the southeastern coast. There is an extensive body of literature relating ENSO and North
Atlantic Oscillation (NAO) oscillations with the tropical cyclone activity and tracks in the North Atlantic. As explained by Colbert and Soden (2012), numerous studies have found a decrease in both basin wide and landfalling storms in the Atlantic during El Niño years (Bove et al. 1998; Xie et al. 2005; Kossin et al. 2010). Changes in tropical cyclone tracks associated with the phase of the NAO have also been identified. During the positive NAO phase, the East Coast of the USA becomes more susceptible to landfalling storms, whereas during the negative NAO phase the Gulf Coast becomes more susceptible to landfalling storms (Owens 2001; Elsner 2003).

Although meteotsunamis have been reported historically in the Gulf of Mexico, their frequency, severity and the specific conditions that favor their growth have not been addressed to date. In the northeastern Gulf of Mexico the continental shelf is wide and uniform, with mean water depths of the order of 40–60 m. These water depths correspond to shallow water wave celerities that are well within the range of the typical speeds of atmospheric disturbances (20–40 m/s) (e.g., Monserrat et al. 2006). The main hypothesis of this study is that the combination of the shelf characteristics and the high cyclogenesis activity of the region can result in frequent meteotsunami generation in the northeastern Gulf of Mexico. Since the tropical cyclone activity and winter storminess are affected by climate variations, we also hypothesize that the meteotsunami activity might also be affected by climate variability.

This study focuses on the analysis of meteotsunami events detected by NOAA tidal gauges in the northeastern Gulf of Mexico. The aim is to verify the main hypotheses, by characterizing the occurrence and severity of meteotsunamis in this region and by exploring the influence of climate variability, in particular ENSO and NAO indices, on meteotsunami activity. The western Gulf of Mexico has been excluded from the analysis since all the available tidal gauges in this area are located inside estuaries, and therefore the meteotsunami signal might have been damped or blocked by estuary mouths.

2 Methodology

Water-level records at 3 coastal stations (Fig. 1a) along the western coast of Florida were obtained from NOAA archives to analyze the occurrence of meteotsunamis and their statistics: Panama City Beach (8729210), Clearwater Beach (8726724) and Naples (8725110). These stations are located in exposed coastal waters, where meteotsunamis are not damped or blocked by estuary mouths. The analysis considered 20 years of water level, atmospheric pressure, wind speed and direction and atmospheric pressure measurements, from January 1, 1996, to November 1, 2016, with a sampling interval of 6 min. Wind and air temperature measurements were not available at Naples station. A low-pass filter PL64 (Beardsley et al. 1985) with a cutoff period of 6 h was used to separate the low- and high-frequency sea level, atmospheric pressure and wind speed (when available) residuals or anomalies. The low-frequency water-level oscillations included the astronomic tides and storm surges, whereas the high-frequency residual captured the meteotsunami signal.

A train of meteotsunami waves was characterized by the maximum observed wave height and total duration of the wave train (Fig. 1b). Specifically, meteotsunamis were defined from water-level residuals that exceeded (in absolute value) 6 times the standard deviation of the high-frequency water-level residual (the threshold varied from 0.11 m at Panama City Beach to 0.13 m in Naples). This was higher than the threshold suggested by Monserrat et al. (2006), but was more appropriate for these specific sites because it ensured
the exclusion of waves triggered only by the inverse barometer effect. The beginning and end of each wave train (marked with red dots in Fig. 1b) were defined when the filtered envelope of the residual was below 2 times the standard deviation. The envelope was computed using the Hilbert transform and high-pass filtered with a cutoff period of 6 h. Each event was considered independent from the preceding when the time span between consecutive wave trains was 1.5 days. The three main variables analyzed were the monthly occurrence of meteotsunami events, the maximum observed meteotsunami wave energy \( \mathcal{R} (= \frac{1}{8} \rho g H^2) \) where \( \rho \) is water density and \( H \) the maximum meteotsunami wave height) and the monthly integrated meteotsunami energy \( \sum \mathcal{R} \). The latter was indicative of the meteotsunami activity as it combined intensity and occurrence. Atmospheric pressure and wind time series were also filtered to isolate those oscillations with periods lower than 6 h. For each meteotsunami event detected with the free-surface elevation time series, we manually checked that pressure and/or wind speed disturbances occurred within 6 h before and after the meteotsunami event. Meteotsunamis can travel faster or slower than the atmospheric pressure disturbance that generated them. For the analysis of the specific meteotsunami events described in “results” section we considered the NOAA stations between New Canal (Louisiana) and Naples (Florida) shown in Fig. 1a.

The Niño 3.4 and the North Atlantic Oscillation (NAO) indices were used to determine linkages between climate variations and meteotsunami activity. Monthly time series for these indices were obtained from the NOAA National Centers for Environmental Information and from the Climate Prediction Center. Relationships between the climate indices and \( \sum \mathcal{R} \) were analyzed first by computing the wavelet-power spectrum of the standardized variables and then calculating cross-wavelet transforms and wavelet coherence between the climatic indices and the standardized \( \sum \mathcal{R} \), using the package developed by Grinsted et al. (2004). A Morlet wavelet (with a non-dimensional frequency = 6) was selected to compute the continuous wavelet transform.
3 Results

The number of meteotsunami events (defined as those with wave heights >6 times the standard deviation) during the period 1996–2016 was 360 in Panama City Beach, 508 in Clearwater Beach and 366 in Naples. The lower number of events observed in Panama City Beach was related to the absence of data during a period of 5 years (between January 2008 and September 2013). On average, 18 and 25 meteotsunamis were detected per year in Naples and Clearwater Beach, respectively, while in Panama City Beach the mean was ~23. Only considering meteotsunamis with heights higher than 0.5 m, an average of 1–2 meteotsunamis per year was expected in Panama City Beach and 2–3 in Clearwater and Naples.

3.1 Annual distribution of meteotsunami events

The annual distribution of meteotsunami events was bimodal at Clearwater Beach and at Naples, with maximum number of events during winter or dry season (November–April) and summer or wet season (June–September). The number of events was higher during the winter (Fig. 2a). In Panama City Beach most of the meteotsunamis occurred during the dry season (Fig. 2a). In all stations the most energetic events occurred between January and March (Fig. 2b).

Recent examples of dry and wet season meteotsunamis were observed in Panama City Beach in March 2014, in Naples in May 2016 and during the formation and evolution of Hurricane Hermine (September 2016), respectively. These events are described in detail as examples of winter and summer meteotsunamis. These were the most energetic events of each type observed in the last 4 years. For the analysis we considered the free-surface

![Fig. 2](image-url)
elevation, atmospheric pressure, wind and air temperature measurements from the stations available along the northeastern Gulf of Mexico. Meteorological measurements were unavailable for the event of May 2016.

**Example of a winter event: observations of March 28–29, 2014**

On March 28–29, 2014, unusual non-tidal sea-level oscillations were reported in gauges along the northeastern Gulf of Mexico, from New Canal (LA) to Naples (FL) (Fig. 3). The water level reached 1.2 m above predicted at Panama City Beach (FL) soon after 17:20 UTC March 28. The residual water level (observed–predicted) represented the combined contribution of a Gaussian shape (3 days and ~0.3 m high) sea-level oscillation, a ~0.1-m-m high ocean wave with ~7.7 h and a rapid (~<2.2 h) ~0.9 m high oscillation. The main variation on the free-surface elevation was associated with a sudden and abrupt change in weather marked by a squall. Atmospheric pressure dropped by 5.0 hPa in 2.3 h and increased by 4.0 hPa in less than 24 min as the squall passed.

High-frequency water-level time series (Fig. 3) showed the occurrence of three main meteotsunamis associated with the passage of a late March 2014 storm. The main meteotsunami (Wave 1) appeared in the coastal area between Dauphin Island and Panama City Beach (stations 3 and 5 in Fig. 3). Its generation was associated with an atmospheric pressure drop of 5.0 hPa, followed by a fast increase. This pressure pulse propagated eastward at ~19–20 m/s, which is equivalent to the phase celerity of a long wave.
propagating over water depths of 40 m (similar to the values observed on the shelf between the Mississippi Delta and Pensacola). The atmospheric pressure disturbance initially appeared near Dauphin Island, and its shape remained unchanged between 15:00 and 18:00 UTC on March 28. The atmospheric pressure change was reduced to ~1 hPa between Panama City Beach and Apalachicola station. At Dauphin Island the meteotsunami amplitude was a few centimeters but increased as it propagated toward Panama City Beach, where it attained its maximum elevation (~0.9 m). Records also showed that the atmospheric pressure change and the meteotsunami traveled in phase. This indicated that the wave was bound to the atmospheric pulse, which allowed its amplification. However, the atmospheric pressure pulse was not visible by Apalachicola (station 7 in Fig. 3), but the meteotsunami did arrive with diminished amplitude and with a delay of 2.5 h relative to Panama City Beach (station 5 in Fig. 3). Disengagement of the surface wave from the atmospheric pulse in this case suggested a free wave behavior. Panama City and Apalachicola tide gauges are located inside estuaries, and therefore, the wave must have damped by diffraction and/or bottom friction.

A second meteotsunami (Wave 2) was also observed from 6:40 to 7:55 UTC on March 29 propagating eastward between New Canal (station 1) and Shell Beach (station 2). This wave was related to an atmospheric pressure change of ~2 hPa. The second meteotsunami was not detectable eastward of Shell Beach nor the atmospheric pressure pulse that generated it. A third meteotsunami (Wave 3) occurred between 18:00 and 20:00 UTC on March 29. This was mainly generated by another southward propagating atmospheric pressure disturbance of 2 hPa at Cedar Key (station 8) that intensified to 3 hPa. The maximum elevation of this meteotsunami (0.5 m) was observed at Clearwater Beach.

![Fig. 4](image_url) Time series of high-frequency anomaly (blue) and low-frequency (red) free-surface elevation, atmospheric pressure, atmospheric radar reflectivity, wind speed and temperature at Panama City Beach.
(station 9) after a jump of atmospheric pressure, suggesting that this was a bound wave. However, the meteotsunami at Naples (station 10) appeared just after the atmospheric pressure increase, meaning that the wave was free at this particular site.

Wind shifts and air temperature drops (Fig. 4) accompanied the atmospheric pressure changes that originated these specific meteotsunami events. At Shell Beach a 3 °C drop in air temperature and a wind increase of 14.1 m/s in mean speed and of 17.5 m/s in gust speed followed the atmospheric pressure change that forced Wave 2. At Dauphin Island, an atmospheric pressure jump of 4 hPa was measured at 15:10 UTC on March 28. Temperature decreased 4 °C in 30 min after the atmospheric pressure minimum. The mean wind speed increased from 5 m/s to 19.1 m/s and changed from southeasterly to northerly. The meteotsunami at Clearwater Beach also coincided with a drop in air temperature of ~8 °C, a local increase of mean wind speed of ~8 m/s and again a sudden change in the wind direction from southeasterly to northerly. All atmospheric pressure jumps were followed by smaller amplitude pressure fluctuations (which did not produce appreciable meteotsunami waves), small temperature variations (<0.3 °C) and weaker wind speed changes (up to 15 m/s). Wind direction shifts associated with these atmospheric pressure fluctuations were <5°.

Surface weather maps for March 28 and 29 (Fig. 5) showed a cold front connecting a low pressure system located in Ohio (indicated as C1 in Fig. 5a), and another system found
at the boundary between Arkansas and Oklahoma (indicated as C2). A high precipitation area could be identified (in green Fig. 5a) south of the cold front, between the coasts of Louisiana and West Florida. This precipitation was related to a surface trough or prefrontal squall line (orange dashed line, indicated as SQUALL in Fig. 5) that expanded radially (southward) from March 28 to March 29.

Atmospheric radar reflectivity mosaics showed high reflectivity in regions of sharp changes in atmospheric pressure (Fig. 5b), which corresponded to water-level peaks in Pensacola (at 15:00 UTC) and Panama City Beach (at 17:20 UTC). All the maps clearly showed squall lines, identified with the red thin bands of maximum reflectivity in the radar reflectivity mosaics. The orientation of the squall was perpendicular to the coastline but propagated parallel to it from Dauphin Island to Naples. The location of the squall line coincided with the position of the meteotsunami in all stations analyzed. For example, at 17:20 UTC March 28 the squall was over Panama City Beach, when the peak water levels were observed. One day later, at 18:00 UTC the squall was over Clearwater Beach, also coincident with the peak water elevation at this gage.

Example of a summer event produced by an extra-tropical cyclone: observations of May 4, 2016

A cold front propagating from north to southeast characterized the weather situation during the May 4, 2016, in south Florida. Associated with this cold front, a squall developed north of Clearwater Beach between 8:00 and 10:00 am UTC (Fig. 6b). The squall increased in size as it travelled southeastward, in the direction parallel to the coast.

(a) Water level (top) and atmospheric base radar reflectivity (bottom) time series at Naples

(b) National atmospheric radar reflectivity mosaics from NOAA

Fig. 6 a High-frequency (blue) and low-frequency (red) water level and base radar reflectivity time series at Naples (FL) and b national atmospheric radar reflectivity mosaic maps derived for the NOAA climate service during May 4 (2016)
The squall and the associated ~0.65 m high meteotsunami (Fig. 6a) hit Naples at 17:30 pm UTC. Although atmospheric pressure and wind measurements were not collected at Naples tidal gauge or nearby stations, information gathered from local newspapers indicated that heavy rain and severe thunderstorms accompanied this squall.

Example of a tropical cyclone-induced summer event: observations of August 29–September 3, 2016

During the formation and evolution of Hurricane Hermine, between August 28 and September 5, several meteotsunami events were observed on the west coast of Florida. Tropical Storm Hermine formed about 640 km southwest of Apalachicola, Florida. Late on August 31, Hermine began to propagate northeastward while gaining intensity. At 18:55 UTC on September 1, the National Hurricane Center upgraded Hermine to hurricane status after the Hurricane Hunters (airplanes that fly to the eye of the hurricane) observed winds of 75 mph (120 km/h).

The first major meteotsunami event was observed in Naples between 0:00 and 4:00 UTC on September 1 (Fig. 7a). The meteotsunami was triggered by a squall propagating in the eastward direction. The maximum meteotsunami height observed in Naples was ~0.4 m, and it was coincident with an atmospheric pressure pulse of 1.1 hPa. Radar reflectivity mosaics indicated the speed of the squall to be ~14 m/s. This squall would produce maximum Proudman resonance at 20 m water depths. The meteorological station at Naples does not measure wind speed and air temperature, and, therefore, it is uncertain whether the squall was also accompanied by gusty winds and sudden changes in wind direction. The inverse barometer effect associated with a 1.1 hPa change in atmospheric pressure change would create a wave of 1.1 cm height. Considering that the ocean long wave due to the inverse barometer effect was generated at water depths of ~120 m, the shoaling coefficient at 1 m water depth, according to Green’s law, would be 3.31. Because observations show that the total amplification coefficient was ~36, other processes such as resonant amplification should have contributed to the observed wave amplification.

The second major meteotsunami event during the formation and propagation of Hurricane Hermine, was observed some hours later at Clearwater Beach (Fig. 7b). Between 18:00 UTC September 1 and 18:00 UTC September 2, the atmospheric dynamics were characterized by high-frequency atmospheric pressure, wind speed and temperature anomalies. Several squalls associated with the hurricane rain bands affected Clearwater Beach during that period (Fig. 8). These rain bands featured sudden jumps in atmospheric pressure and in wind speed and direction. Air temperature changes of up to 4°C accompanied atmospheric pressure and wind pulses. In all these cases the atmospheric anomalies (either atmospheric pressure and/or wind vectors) that produced meteotsunamis coincided with increases in atmospheric base radar reflectivity (Figs. 7, 8).

3.2 Annual variability of the meteotsunami activity

In Clearwater Beach most meteotsunami occurrences were observed in 1996, 1998, 2003, 2005, 2008, 2010, 2014 and 2016 (Fig. 9a). In Naples the number of events was greatest in 1996, 2005, 2009 and 2016. Panama City Beach station was not analyzed further because of the 5-year gap in measurements. However, the recent 2015–2016 winter period showed 6 meteotsunamis with heights >0.5 m. Maximum meteotsunami energy at Naples was detected in 1998, 1999, 2005 and 2010 (Fig. 9b). In Clearwater Beach maxima were observed in 1999, 2004, 2010, 2013 and in late 2014. The meteotsunami activity, defined as the monthly integrated meteotsunami energy \( \sum R \), showed maximum values in 1998, 1999, 2005, 2010 and 2016 at both stations (Fig. 9c).
Clearwater Beach and Naples revealed commonalities in meteotsunami activity as shown by the standardized wavelet-power spectra (Fig. 10). During the years of most energetic meteotsunamis (1998, 2005, 2010 and 2016) the variability increased primarily at the semi-annual and annual periods. In Clearwater Beach, meteotsunami activity showed maximum spectral power in 2010 and 2016 (at the semi-annual and annual bands).

Fig. 7  a High-frequency (blue) and low-frequency (red) water level, atmospheric pressure disturbance and atmospheric base radar reflectivity time series at Naples (FL) and b high-frequency (blue) and low-frequency (red) water level, atmospheric pressure disturbance, atmospheric base radar reflectivity, wind intensity and temperature time series at Clearwater Beach (FL). The vertical axis of the high-frequency and low-frequency anomalies is on the left and right, respectively.
Although the wavelet-power spectrum of Clearwater Beach showed increased spectral energy at the annual band during 2005 and 1998, values fell below the 95% confidence level. In Naples, statistically significant meteotsunami activity was detected in 1998, 2005, 2010 and 2016. In 1998 and 2010 most of the variability was observed at the annual band, whereas in 2005 it was more pronounced at the semi-annual. Longer-period variability was also noticeable at both stations. In Naples, the wavelet-power spectrum showed a peak between 36 and 54 months, whereas in Clearwater Beach the peak was significant in the band around 64 months. The variability at these longer periods was more persistent in time than at the annual and semi-annual bands.

4 Discussion

4.1 Types of meteorological conditions that produced meteotsunamis

Results showed that meteotsunamis are ubiquitous in the northeastern Gulf of Mexico. Atmospheric radar reflectivity mosaics and surface weather maps from NOAA were analyzed for each meteotsunami detected. Results revealed that mainly 3 types of storms can produce meteotsunamis in the NE Gulf of Mexico (Figs. 11 and 12): a) extra-tropical cyclones generated during the winter over the Great Plains or western Gulf of Mexico, b) tropical cyclones and c) summer MCSs.
During the winter, especially during February–March, low atmospheric pressure systems form along the US Great Plains and in the western Gulf of Mexico. These extratropical cyclones usually move eastward. The interaction of such cyclones with the relatively more humid and warmer air masses over the Gulf of Mexico can trigger MCSs, thunderstorms and squalls. Atmospheric pressure troughs or prefrontal squall lines occasionally develop ahead of the cold front. These prefrontal squall lines are characterized by

Fig. 9 Time series of a number of meteotsunami events observed monthly, b maximum meteotsunami wave energy observed monthly, c monthly integrated meteotsunami energy

Fig. 10 Wavelet-power spectrum of the standardized monthly integrated meteotsunami energy, at Clearwater Beach and Naples stations. Contour lines in the wavelet-power spectrum indicate the 95% confidence level against red noise. Translucent portions of the diagrams portray the cone of influence

During the winter, especially during February–March, low atmospheric pressure systems form along the US Great Plains and in the western Gulf of Mexico. These extratropical cyclones usually move eastward. The interaction of such cyclones with the relatively more humid and warmer air masses over the Gulf of Mexico can trigger MCSs, thunderstorms and squalls. Atmospheric pressure troughs or prefrontal squall lines occasionally develop ahead of the cold front. These prefrontal squall lines are characterized by
sudden atmospheric pressure changes, air temperature drops and wind shifts (as shown by the observations). The long ocean waves observed in Panama City Beach on March 28, 2014, were an example of a meteotsunami produced by winter storms. On February 12, 2010, another winter meteotsunami was observed in Clearwater Beach with a 1.0 m wave height (Fig. 11). This is one of the most intense meteotsunamis that has been measured at this location.

During the rainy season, late spring and early summer, MCS development in the interior of the eastern USA is common (Wertman et al. 2014). Some of these MCSs propagate southward and reach the coast of Florida. In the summer, it is common to observe MCSs with long-lasting squall lines propagating almost parallel to the coastline. The Daytona Beach “Rogue Wave” of June 1992 (Churchill et al. 1995; Sallenger et al. 1995) was an example of a meteotsunami produced by a squall line of a MSC that propagated southward along the East Coast of Florida. Moreover, the extreme weather of the rainy season in this area is also characterized by the formation and passage of tropical cyclones. For example, the landfall of Hurricane Wilma on October 24, 2005, produced one of the highest meteotsunamis on record in Naples (0.9 m wave height). The meteotsunami was also detected in Clearwater Beach, but the maximum wave height was smaller (~0.35 m). Hurricanes Dennis (2005), Katrina (2005), Hermine (2016) and tropical storm Colin (2016) also produced meteotsunamis that impacted Naples and Clearwater Beach. These were linked to the radial rain bands or squalls associated with hurricanes.

The bimodal distribution of the total number of monthly events observed in Naples and Clearwater Beach, could be explained by the seasonality of the storminess in the area. Energy transfer from the atmosphere to the ocean depends on the direction of propagation, celerity, intensity and shape of the atmospheric disturbance and the bathymetry of the shelf and the coast. As inferred from the radar reflectivity mosaics, the direction of propagation of the extra-tropical storms is eastward during winter and more southward during summer. The fetch in Panama City Beach for squalls propagating from the western Gulf of Mexico is higher than for squalls propagating southward. Conversely, the fetch on the shelf at Clearwater Beach and Naples is higher for those systems propagating southward. This might be the main reason why meteotsunamis are more frequent and intense in Panama.
City Beach in winter, while summer meteotsunamis are relevant in Naples and Clearwater Beach.

Meteotsunami events that coincided with the passage of a tropical cyclone over the central and eastern Gulf of Mexico were identified with the NOAA Tropical Cyclone activity reports and categorized into tropical cyclone meteotsunamis. The remaining events were categorized into winter (November 1 to April 30) and summer (May 1 to October 31) meteotsunamis. In general, annual meteotsunami activity levels were similar for winter and summer meteotsunamis and lower for those induced by tropical cyclones (Fig. 13).

The time series of the annual meteotsunami activity for winter and tropical cyclone meteotsunamis were similar between the stations. Conversely, the summer activity differed substantially from one station to the other. These results suggest that while tropical cyclones and winter MCSs have a spatial influence over the northeastern and eastern Gulf of Mexico, the effect of summer storms is more localized than winter events. Given the
sparse distribution of open coastline tide gauges, it is possible that the present analysis was unable to detect some local events between tide gauges.

### 4.2 Possible influence of climate variability

Hagemeyer and Almeida (2005), using NCEP reanalysis data for the period 1948 to 2002, observed that the North Atlantic Oscillation (NAO) and the Pacific/North America (PNA) teleconnections could also affect the annual dry season storminess in the Florida region. They derived a linear regression model to predict the dry season storminess as a function of the Niño 3.0, NAO and PNA indices:

\[
\text{Storminess}_{(\text{Nov-Apr})} = 6.34 + 2.9 \cdot \text{Nino3.0}_{(\text{May-Apr})} + 1.6 \cdot \text{PNA}_{(\text{Nov-Apr})} - 2.1 \cdot \text{NAO}_{(\text{Nov-Apr})}
\]

According to this model, the influence of NAO and PNA is related to the storminess level during moderate ENSO periods. Negative NAO and positive PNA periods coinciding with strong El Niño events maximize the storminess in the eastern Gulf of Mexico. The winter storminess during 1997–1998 and 2010, which were the strongest El Niño events between 1996 and 2015 (that also coincided with negative NAO phases), was higher than average (Fig. 13). The annual winter meteotsunami activity was above average during these specific years in all stations considered. The mean storminess index during the period analyzed is ~8, whereas in 1997–1998 and 2010 it increased to ~15. Nonetheless, the meteotsunami activity was also high during the winter of 2014, but this peak in activity was not captured by the storminess index. In addition, the winter of the recent 2015–2016 El Niño produced increased storminess (~15) and meteotsunami activity. The
meteotsunami activity induced by tropical cyclones is, as expected, linked to the tropical cyclone activity in the eastern Gulf of Mexico (Fig. 13).

The strongest tropical cyclone and meteotsunami activity in the area were observed in 1998, 2004, 2005, 2008 and 2012. The year 2005 was characterized by moderate NAO and Niño 3.4 indices (Fig. 14) but exceptionally intense tropical storm activity in the region. In particular, 4 hurricanes of category 5 (Saffir–Simpson scale) impacted the Gulf of Mexico that year.

The meteotsunami activity parameter ($\sum \hat{R}$) showed variability at 6, 12, 36 and 64 months. The Niño 3.4 index (Fig. 14) also showed variability at 9–14 months (corresponding to the duration of El Niño/El Niña events) and at the 24–36 months band (related to the periodicity of El Niño events: 5 occurred in the decade between 2000 and 2010, on average one every 2.5 years). Significant variability was also observed for the NAO index at 6-month periods. The variability was concentrated in the 6-month band during 1997–1998 and increased during 2009–2011 in the band of 9–12 and 24–36 months. Annual variability increased during 2015–2016.

A potential linkage between the occurrence of meteotsunamis and ENSO and NAO was explored with cross-wavelet (Fig. 15) and wavelet coherence (Fig. 16) analysis. In general, $\sum \hat{R}$ revealed stronger common power with Niño 3.4 than with NAO. The cross-wavelet between $\sum \hat{R}$ and Niño 3.4 showed common power (with a 95% confidence) in the semi-annual and annual bands during 1997–1999, 2005, 2010 and 2015–2016 at both stations. In the annual band both signals were out of phase between 0° and 90°, meaning that increased meteotsunami activity occurred after the positive peaks of Niño 3.4. In the semi-annual band the signals were out of phase 180°, which might indicate that the maximum meteotsunami activity is greater during the winter than during the summer. The stronger common power with Niño 3.4 than with NAO, and the fact that the peak in the meteotsunami activity occurs after the peak in the Niño 3.4 index, suggests that winter meteotsunamis activity is the main source of the common power with Niño 3.4. At Clearwater Beach, significant common power (with Niño 3.4) at periods around 36 months was

![Fig. 14](image-url)
observed during 2009 and 2010. At this particular band, the meteotsunami activity was $-90^\circ$ out of phase with Niño 3.4. The cross-wavelet with NAO showed common power at the annual and semi-annual periods, but this was only significant during 2010.

At both stations, meteotsunami activity and Niño 3.4 showed statistically significant coherent variability at the semi-annual and annual bands during years 1998–1999, 2005 and 2010–2011. Meteotsunami activity and Niño 3.4 were coherent in the band between 24 and 32 months at both stations. At Clearwater Beach the wavelet coherence was persistent in time, whereas at Naples it was statistically significant only between 1996 and 2007. In general, the wavelet coherence with the NAO index lacked statistical significance.

A limitation of this analysis is that the time series available capture only three extreme/moderate ENSO events. Such number of El Niño events during 1996–2016 provides only suggestive rather than definitive findings. However, the results have shown increased meteotsunami activity during the most intense El Niño periods, which could be related to increased winter storminess. This increased activity during El Niño years could be explained by the frequent interactions of cool, dry air from land with moist, warm air from the Gulf of Mexico. During 2005, extreme meteotsunami activity was associated with frequent incidence of tropical cyclones in the area.
5 Summary and conclusions

Meteotsunamis are ubiquitous in the northeastern Gulf of Mexico and can be triggered by winter and summer extra-tropical storms and by tropical cyclones. In Panama City Beach most of the meteotsunami events occurred during the winter/dry season, whereas in Naples and in Clearwater Beach meteotsunami activity was also relevant during the summer/wet season. A total of 15 to 25 meteotsunamis per year were observed in the stations analyzed, and on average, 1 to 3 meteotsunamis per year were \( \geq 0.5 \text{ m} \).

Meteotsunamis in this area are produced by the passage of squalls characterized by sudden atmospheric pressure, wind and air temperature changes. These high-frequency atmospheric anomalies coincide with increased atmospheric radar reflectivity. In most of the meteotsunami studies available in the literature, the formation of meteotsunamis is associated with atmospheric pressure anomalies. The methods applied in the present analysis are unable to separate the relative contribution of the wind divergence and atmospheric pressure fluctuations to the growth of meteotsunamis. However, the wind speed and direction anomalies suggest that the wind divergence can also contribute to their
generation and growth. Further analysis with numerical and analytical models is needed to
determine the relative contribution of these forcings.

The most intense meteotsunamigenic spans took place during El Niño periods
(1997–1998, 2010 and 2015–2016). Meteotsunamis were also active in 2005, a year
characterized by exceptionally intense tropical cyclone activity. Cross-wavelet analysis has
shown that the meteotsunami activity in Naples and Clearwater Beach had statistically
significant common wavelet power with Niño 3.4 in the semi-annual, annual and longer-
period bands. The signals were also coherent in these specific bands. This suggested that El
Niño periods enhance meteotsunami activity in the northeastern Gulf of Mexico. The
coherence and the common power between NAO and meteotsunami activity were not
statistically significant in any of the stations analyzed.

Although these results are restricted to meteotsunami activity in the northeastern Gulf of
Mexico, climate variability could affect the probability of meteotsunami occurrence in
other parts of the world. This climate variability should be analyzed further and included in
probabilistic meteotsunami hazard assessment procedures. This study has also shown that
meteotsunamis are frequently triggered by tropical cyclones and other extreme storms.
Meteotsunamis, reaching heights around 1 m in the northeastern Gulf of Mexico, can
provide the maximum water levels during extreme storms. These events thus increase the
risk for flooding, dune erosion and sandspit or barrier-island breaching in coastal regions.
Future efforts should be directed at incorporating the effects of these waves for accurate
flood risk forecast and assessment.

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References

Alfonso AP, Naranjo LR (1996) Genesis and evolution of a severe squall over western Cuba. A case study of
13 March 1993. Weather Forecast 11:89–102
Beardsley RC, Limeburner R, Rosenfeld LK (1985) Introduction to the CODE-2 moored array and large-
scale data report. In: Limeburner R (ed) CODE-2; moored array and large-scale data report: Woods
Hole Oceanographic Institution technical report, WHOI v. 85-35
Bosart LF, Sprigg WA (1998) The meteorological buoy and coastal marine automated network for the
United States. National Academy Press, Washington
Bove MC, Elsner JB, Landsea CW, Niu X, O’Brien JJ (1998) Effect of El Niño on U.S. landfalling
hurricanes, revisited. Bull Am Meteorol Soc 79:2477–2482
Churchill DD, Houston SH, Bond NA (1995) The Daytona Beach wave of 3–4 July 1992: a shallow water
gravity wave forced by a propagating squall line. Bull Am Meteorol Soc 76:21–32
Colbert AJ, Soden BJ (2012) Climatological variations in north atlantic tropical cyclone tracks. J Clim
25:657–673. doi:10.1175/JCLI-D-11-00034.1
DeGaetano AT, Hirsch ME, Colucci SJ (2002) Statistical prediction of seasonal East Coast winter storm
frequency. J Clim 15:1101–1117
Eichler T, Higgins RW (2006) Climatology and ENSO-related variability of North American extratropical cyclone activity. J Clim 19:2076–2093
Elsner JB (2003) Tracking hurricanes. Bull Am Meteorol Soc 84:353–356
Greenspan HP (1956) The generation of edge waves by moving pressure distributions. J Fluid Mech 1(6):574–592
Grinsted A, Moore JC, Jevrejeva S (2004) Application of the cross wavelet transform and wavelet coherence to geophysical time series. Nonlinear Process Geophys 11:561–566
Hagemeyer BC, Almeida RJ (2005) Toward greater understanding of inter-seasonal and multi-decadal variability and extremes of extratropical storminess in Florida. Preprints, 16th symposium on global change and climate variations. San Diego, CA, Amer Meteor Soc, P5.9 (on CD-ROM)
Karan H, Fitzpatrick Patrick J, Hill Christopher M, Li Yongzuo, Xiao Qingnong, Lim Eunha (2010) The formation of multiple squall lines and the impacts of WSR-88D radial winds in a WRF simulation. Weather Forecast 25:242–262
Kossin JP, Vimont DJ, Stitkowski M (2010) Climate modulation of North Atlantic hurricane tracks. J Clim 23:3057–3076
Lamb H (1932) Hydrodynamics, 6th edn. Cambridge University Press, Cambridge
Monserrat S, Vilibić I, Rabinovich AB (2006) Meteorological tsunamis: atmospherically induced destructive ocean waves in the tsunami frequency band. Nat Hazards Earth Syst Sci 6:1035–1051
Owens BF (2001) Atlantic hurricanes: skill in seasonal forecasting and the impact of the North Atlantic Oscillation. M.S. thesis, Dept. of Meteorology and Physical Oceanography, University of Miami
Pasquet S, Vilibić I, Šepić J (2013) A survey of strong high-frequency sea level oscillations along the U.S. East Coast between 2006 and 2011. Nat Hazards Earth Syst Sci 13:473–482
Pattiaratchi CB, Wijeratne EMS (2015) Are meteotsunamis an underrated hazard? Phil Trans R Soc A 20140377. doi: 10.1098/rsta.2014.0377
Paxton CH, Sobien DA (1998) Resonant interaction between an atmospheric gravity wave and shallow water wave along Florida’s west coast. Bull Am Meteorol Soc 79:2727–2732
Proudman J (1929) The effects on the sea of changes in atmospheric pressure. Geophys Suppl Mon Notices R Astron Soc 2(4):197–209
Proudman J (1953) Dynamical oceanography. Wiley, Methuen & Co., London, p 409
Rabinovich AB (2009) Seiches and harbor oscillations. In: Kim YC (ed) Handbook of coastal and ocean engineering. World Scientific, Singapore, pp 193–236
Sallenger AH Jr, List JH, Elfenbaum G, Stumpf RP, Hansen M (1995) Large wave at Daytona Beach Florida, explained as a squall line surge. J Coast Res 11:1383–1388
Smith SR, Green PM, Leonard AP, Brien JJO (1998) Role of multiple-level tropospheric circulations in forcing ENSO winter precipitation anomalies. Mon. Wea. Rev. 126:3102–3116
Thompson PR, Mitchum GT, Vonesch C, Li J (2013) Variability of winter storminess in the eastern United States during the twentieth century from tide gauges. J Clim 26:9713–9726. doi:10.1175/JCLI-D-12-00561.1
Vennell R (2010) Resonance and trapping of topographic transient ocean waves generated by a moving atmospheric disturbance. J Fluid Mech 650:427–442
Vilibić I, Monserrat S, Rabinovich AB (2014) Meteorological tsunamis on the US East Coast and in other regions of the World Ocean. Nat Hazards 74:1–9
Wertman CA, Yablonsky RM, Shen Y, Merrill J, Kincaid CR, Pockalny RA (2014) Mesoscale convective system surface pressure anomalies responsible for meteotsunamis along the U.S. East Coast on June 13th, 2013. Sci Rep 4:7143
Xie L, Yan T, Pietrafesa L, Morrison J, Karl T (2005) Climatology and interannual variability of North Atlantic hurricane tracks. J Clim 18:5370–5381