Addressing the Meteotsunami Risk in the United States

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Abstract:
Meteotsunamis are created by transitory weather disturbances moving over water, have a long history of impacting the United States (U.S.), and have resulted in loss of life and property. Many of these events have been historically mischaracterized as seiches, anomalous weather-related waves, or ignored altogether. In this paper, we review meteotsunami generation mechanisms common in the U.S., and highlight several classic historical cases of U.S. meteotsunami formation and impact. We then describe recent advances in sensing and understanding that led to the establishment of initial, rudimentary alerting capabilities for the U.S. Great Lakes and U.S. East Coast. Finally, we describe the major challenges and gaps that must be overcome to move the U.S. toward a comprehensive meteotsunami forecast and warning capability. We also discuss how we envision the various relevant offices of the National Oceanic and Atmospheric Administration (NOAA) working together to achieve this vision. These offices include the NOAA research laboratories, National Weather Service (NWS) Weather Forecast Offices and National Centers, National Ocean Service Center for Operational Oceanographic Products and Services, and NWS Tsunami Warning Centers.

Keywords: meteotsunami, detection, forecast, warning, mitigation, uncertainty, National Tsunami Warning Center, Great Lakes, East Coast, emerging technologies.

Introduction

Shallow-water gravity waves induced by transitory weather disturbances have a long history of affecting the U.S. Great Lakes, and East and Gulf Coasts. In general, these impacts have been assumed to be directly associated with other better-understood phenomena such as seiches, coastal wind-driven waves, submarine landslides, or surge. Indeed, U.S. efforts to anticipate, detect, measure, and forecast impacts of these meteorological tsunamis—hereafter referred to as meteotsunamis—have been considered only for about the past 10 years. Also, recently, this class of wave has been treated independently of the source weather disturbance in terms of operational National Weather Service (NWS) forecast and warning products.

Though still in an early development stage, the efforts made by the U.S. to achieve a real-time alerting capability are aimed at providing the public with advance notice of when and where these anomalous coastal waves are likely to strike. The science of meteotsunamis has developed rapidly in the last two decades, documenting the phenomenon along the coasts of all continents except Antarctica (Vilibić et al. 2016). Many different observational, forecasting, and research activities within the National Oceanic and Atmospheric Administration (NOAA), including the NOAA research laboratories, NWS Tsunami Warning Centers (TWC), the National Ocean Service's (NOS) Center for Operational Oceanographic Products and Services (CO-OPS), and NWS coastal Weather Forecast Offices (WFO) now are coordinating in novel ways to address this threat. Additionally, the U.S. looks to benefit from years of research work in many European countries such as Spain and Croatia. Their efforts have been particularly critical in understanding the hazard and to the eventual development of a forecast strategy (Vilibić et al. 2016; Šepić and Vilibić 2011; Renault et al. 2011). Moreover, while in the U.S. meteotsunamis do not present a level of risk as high as that posed by other phenomena such as tropical cyclones, severe weather, or seismically induced tsunamis, we are grateful for the progress made by our international partners and seek to incorporate their lessons learned as we begin to more fully consider meteotsunamis in terms of their contribution to broader, weather-induced coastal hazards.

In this overview paper, we give a brief history of some notable meteotsunami events that have impacted the U.S. We describe regional formation differences and associated challenges and provide a snapshot of our current operational capability. Finally, we preview potential future developments that will improve our ability to anticipate, and ultimately alert the public of, meteotsunami impacts.

1. Meteotsunamis in the U.S.

1.1. Formation overview and key parameters

Meteotsunamis are long waves with characteristics similar to seismically generated tsunamis and have wave periods from a few minutes up to 2 hours. Instead of being generated by an earthquake or landslide, meteotsunamis are formed in response to transitory atmospheric perturbations (Nomitsu 1935). Specifically, these perturbations include rapid changes in atmospheric pressure and to some degree, wind stress near the surface of the water that are most commonly associated with convective weather systems, atmospheric gravity waves, and both tropical and extratropical cyclones (Dusek et al. 2019; Rabinovich and Monserrat 1996; Bechle et al. 2016; Olabarrieta et al. 2017). To generate meteotsunamis, these weather systems must propagate with speeds close to the long wave velocities ($c=\sqrt{gH}$) or edge wave ($c=gT\tan[\beta(2n+1)]/2\pi$), where c is the wave speed, g is the acceleration due to gravity, H is water depth, T is wave period, β is the shelf slope, and n is mode number, thus achieving Proudman and Greenspan resonance, respectively. This allows sufficient energy transfer from the atmosphere to the water, resulting in amplification of the meteotsunami (Proudman 1929; Greenspan 1956; Rabinovich 2009; Orlić et al. 2010). Additional local amplification can also occur as the wave approaches the coast through shoaling, harbor resonance, and superposition through wave refraction and reflection (Hibiya and Kajiura 1982; Vilibić et al. 2008; Bechle and Wu 2014; Anderson et al. 2015). Recent work has also shown that meteotsunamis can result in rip current formation when they impact the shore (Linares et al. 2019).

For alerting purposes, the U.S. is most concerned with identifying meteotsunamis that have the potential to become fully disconnected from their source disturbances, since they would not always be covered by broader weather-related alerts that might otherwise be posted. This happens frequently in the Great Lakes as meteostunamis reflect off shorelines, but also occasionally on the U.S. East Coast due to complex wave refraction and/or reflection. This disconnect can become particularly significant if the meteotsunami interacts with the continental slope. The sharp discontinuity in tsunami phase velocity over a short distance can result in a substantial fraction of wave energy refracted and redirected toward populated coastlines (Pasquet and Vilibić 2013) even as the meteotsunami propagates into deep water (Fig. 1). In these cases, operational forecasters must account not just for the primary meteotsunami formation and propagation, but also be alert for energy reflected from shorelines and/or refracted from the continental slope that may arrive hours after the original disturbance has moved out of the area or dissipated.

Since the majority of significant meteotsunami impact in the U.S. has been in either the Great Lakes or the East Coast, we focus our attention on those formation zones. Meteotsunamis are known to occur in other U.S. locations. Meteotsunami formation along the Gulf Coast is known to be common (Olabarietta et al. 2017; Paxton, L.D. 2016; Paxton and Sobien 1998) and will likely be NWS' next region to consider expanding operational alerting efforts once rudimentary capability is established in the Great Lakes and East Coast. There have also been reports of meteotsunami formation on the U.S. West Coast (Rabinovich et al. 2020; Thomson et al. 2009) to include a possible meteotsunami that formed due to interaction with post-tropical cyclone Songda in October 2016 (Guérin et al. 2018). To date we are not aware of any significant destructive impacts due to meteotsunamis along the U.S. West Coast.

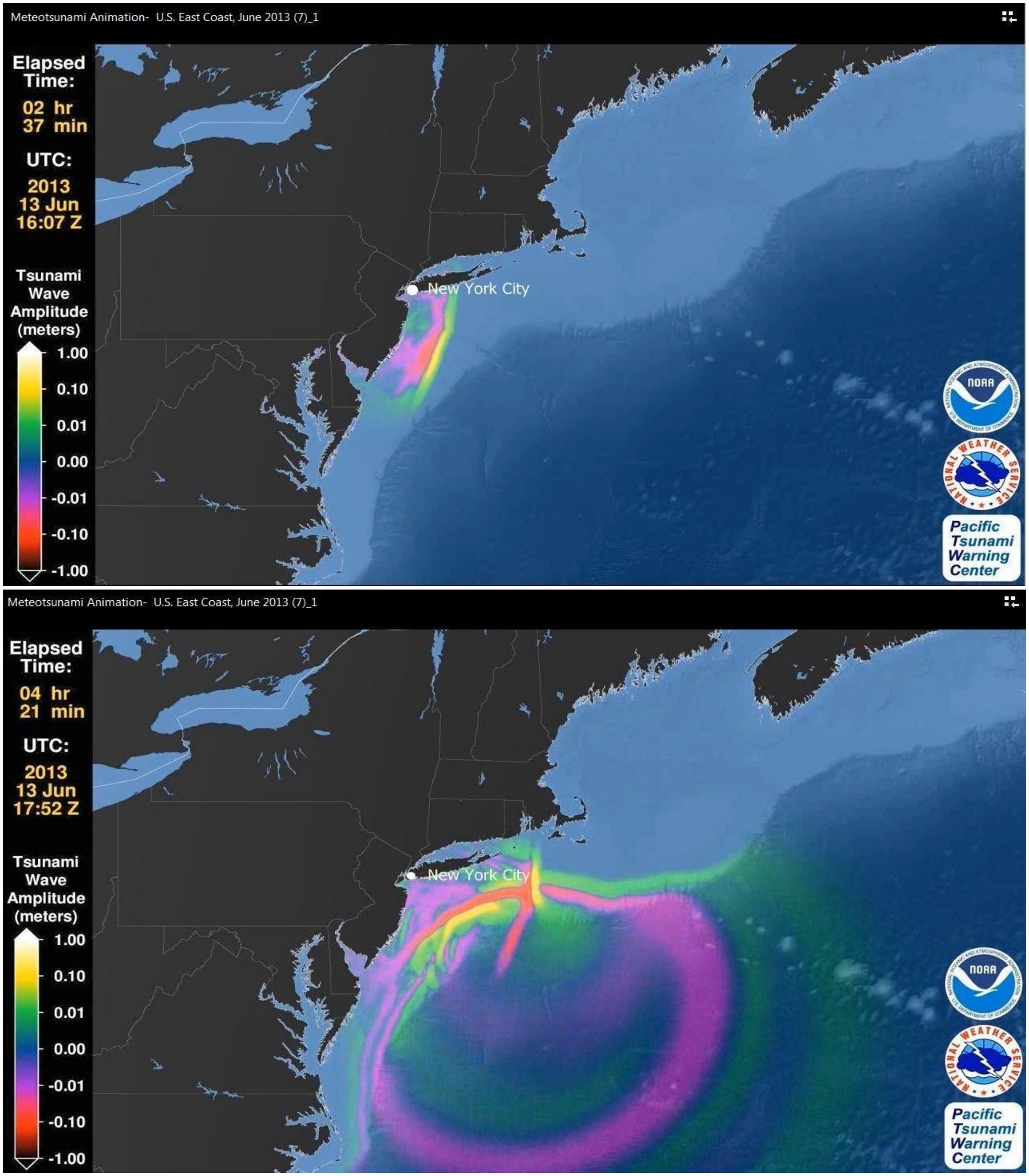

Fig. 1 Real-time Inundation Forecasting of Tsunamis (RIFT) depiction of the June 13, 2013, meteotsunami on the northeast U.S. coast as it moves along the shelf (top) and reflects off the shelf break back toward the coast (bottom) Credit: Pacific Tsunami Warning Center

1.2. Notable historical cases in the U.S.

There have been several substantial meteotsunami events documented in the U.S., many of which have included casualties or damage to boats and infrastructure. A few examples include:

- **Great Lakes, June 26, 1954:** An apparent meteotsunami event occurred on Lake Michigan, reportedly reaching 3 m above lake level (Bechle and Wu 2014; Ewing 1954). This event was one of the deadliest documented meteotsunamis in U.S. history; seven lives were lost near Chicago along the coast of southern Lake Michigan.

- **Atlantic Coast of Florida, July 3, 1992:** A meteotsunami with an estimated amplitude of 3 m was observed along the coastline of Daytona Beach. This event was perhaps the most damaging recorded meteotsunami along the U.S. East Coast. The unexpected run-up caused at least 75 minor injuries and damage to several dozen vehicles on the beach (Sallenger et al. 1995).

- **Gulf Coast of Florida, March 23, 1995:** A wave described by onlookers as being 3 m high inundated the coast from Tampa to Naples causing minor injuries and damage (Paxton and Sobien 1998).

- **Great Lakes, July 4, 2003:** A rip current event, likely induced by a meteotsunami, was responsible for the drowning of seven individuals near Warren Dunes State Park on the southeastern shore of Lake Michigan. (Linares et al. 2019).

- **Northeast U.S. Coast, October 28, 2008:** One of the more recent and better studied impactful events occurred when a reported 4 m (peak to trough) meteotsunami struck the coast of Maine and caused substantial damage to boats and infrastructure near Boothbay Harbor (Vilibić et al. 2014; Whitmore and Knight 2014).

- **Northeast U.S. Coast, June 13, 2013**: Perhaps the most well documented and observed U.S. meteotsunami event was measured by 16 NOAA tide gauges from North Carolina to Massachusetts. The gauges detected a wave reaching about 0.6 m peak to trough displacement in several locations (Bailey et al. 2014). In addition, the event triggered the Deep Ocean Assessment and Reporting of Tsunamis (DART®) buoy 44402 off the northeast Atlantic coast. At the time, the alert was not recognized as a meteotsunami. This event was caused by an intense squall line, known as a *derecho*, and resulted in property damage and several injuries along the New Jersey coast (Fig. 2). Analysis of the tidal data reveals that these waves reflected off the continental shelf break and reached the coast, where bathymetry and coastal geometry contributed to their hazard potential (Wertman et al. 2014).

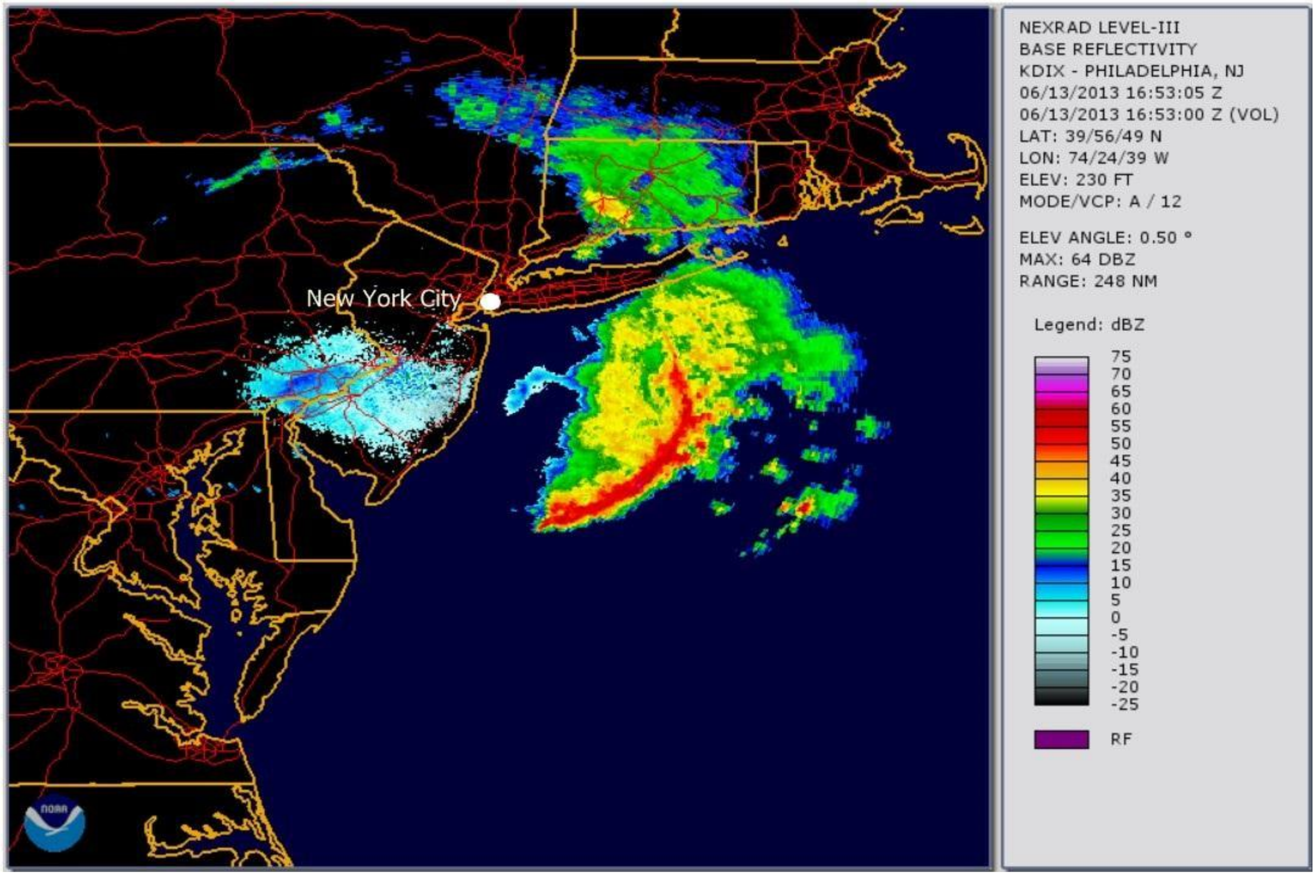

Fig. 2 WSR-88D radar image of the June 13, 2013, storm as it moved off the coast of New Jersey

- **Great Lakes, April 13, 2018:** A wave with a reported amplitude of about 2 m inundated the Lake Michigan shore near Ludington, Michigan, causing substantial shoreline and harbor damage. (Anderson and Mann 2020; O'Hare 2019)

- **Northeast U.S. Coast, May 15, 2018:** The NWS' National Tsunami Warning Center (NTWC) detected a tsunami wave signal on DART buoy 44402. The wave was measured (4 cm) on the DART buoy at 2330 UTC, and up to 35 cm (peak-to-trough) on several NOAA tide gauges. Using a draft protocol developed after the meteotsunami event of June 13, 2013, the NTWC contacted coastal NWS Weather Forecast Offices (WFO) in Philadelphia, Boston, and New York. These offices then issued special weather and marine weather statements to alert the public of possible coastal impacts from a meteotsunami.

Regional Variability

1.2.1. Great Lakes

In the Great Lakes, meteotsunamis occur on average more than 100 times per year for heights above 0.3 m (Bechle et al. 2016) and have been observed in each of the lakes. Although significant lake-scale oscillations, known as seiches, occur frequently in the Great Lakes, meteotsunamis are distinguished as propagating waves, as opposed to standing waves as in the case of a seiche. Furthermore, meteotsunamis are defined as having wave periods less than 2 hours, whereas seiches in the lakes are defined as having periods greater than 2 hours. Using these criteria, water level gauge data and historical accounts indicate that meteotsunamis occur most frequently in southern Lake Michigan and Lake Erie. This is likely due to the proximity of these regions to areas of frequent convective system activity. In addition, lake depths yield long wave (or edge wave) speeds often similar to the typical storm propagation speeds that generate or amplify meteotsunamis (Fig. 3). As illustrated in Fig. 3, due to relatively shallow depths, it does not take an unusual storm for the Great Lakes to reach the critical phase speed to amplify meteotsunamis. For example, a storm speed of approximately 20 m/s and 30 m/s would match the wave propagation speed for significant portions of Lake Erie and Lake Michigan, respectively, to create resonance and cause amplification. This relationship seems to be the most reasonable explanation for the large number of events observed at water level gauges. The substantial number of events in this region with human impacts (e.g., drowning, boat capsizing, etc.) are likely associated with higher coastal populations and the large number of recreational users in Lake Erie and southern Lake Michigan.

As enclosed basins, the lakes are particularly susceptible to the dangers associated with wave reflection, refraction, and superposition, wherein the inducing atmospheric perturbation (storm) disassociates with the meteotsunami as the wave interacts with the coastline. Many of the notable meteotsunami events in the Great Lakes with associated fatalities or injuries have occurred when the waves appeared at a shoreline several hours after the passage of the inducing storm and under relatively quiescent atmospheric conditions (Bechle and Wu 2014; Anderson et al. 2015). Furthermore, in terms of key parameters for meteotsunami creation in the Great Lakes, several studies have shown wind stress and pressure have a similar contribution to meteotsunami height (Donn and Ewing 1956; Bechle and Wu 2014; Anderson et al. 2015). This finding is somewhat contrary to what generally has been established from a global perspective, where atmospheric pressure disturbances are the dominant forcing and wind stress is assumed to have a lesser impact (Orlic et al. 2010).

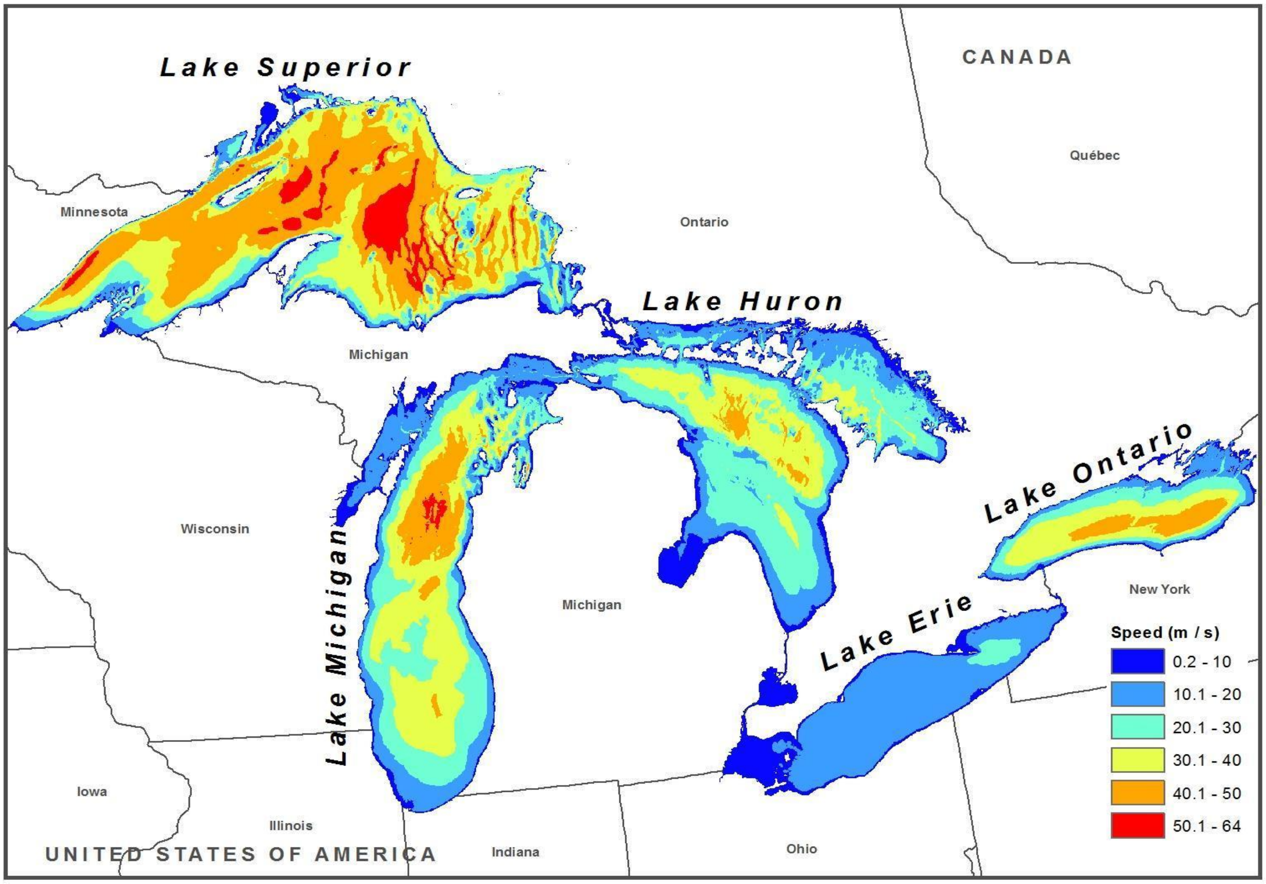

Fig. 3 Shallow water wave phase speed linear approximation in the Great Lakes based on bathymetry. The relatively uniform depths of lower Lake Michigan and most of Lake Erie are ideal for meteotsunami formation

1.2.2. East Coast

About 25 meteotsunamis of at least 0.2 m in height are observed each year along the U.S. East Coast (Dusek et al. 2019). Most of the events recorded by NOAA tide gauges are small. On average, only one event each year reached or exceeded a height of about 0.6 m. Meteotsunami activity in different portions of the East Coast is partially dictated by season. The Northeast is much more active in the winter due to the formation and occurrence of winter storms, while the Mid-Atlantic, especially the Chesapeake Bay and Delaware Bay, tends to observe a greater number of events in the spring and summer months due to convective weather. The Carolinas experience a relatively high level of meteotsunami occurrence throughout the year. NOAA tide gauges at Duck, North Carolina, and Myrtle Beach, South Carolina, observe an average of six and seven meteotsunamis per year, respectively. Other locations where meteotsunami occurrence is prevalent include the Long Island Sound region, in particular near New Haven, Connecticut, and Providence, Rhode Island, gauges (five per year for each), and central to northern Florida at the Port Canaveral, Florida, gauge (three per year). The precise locations where meteotsunamis are observed on the East Coast tend to be either due to exposure (e.g., a gauge on an extended pier along a stretch of open coast) or topographic conditions favorable for creating or enhancing resonance (e.g., in an estuarine location which amplifies the wave signal).

Mechanisms for meteotsunami formation along the East Coast can vary (Pasquet et al. 2013), but they are commonly associated with convective systems, and most notably summertime severe thunderstorms (Sepic and Rabinovich 2014), leading to the peak in meteotsunami occurrence in June and July (Dusek et al. 2019). This peak corresponds well with the most frequent occurrences in the Great Lakes, where severe weather often propagates from the Midwest to the East Coast. Winter storms, and especially Nor'easters have also been observed to force meteotsunamis up and down the East Coast, leading to a secondary peak in meteotsunami occurrences in December and January. In addition, tropical cyclones have been associated with at least 19 East Coast meteotsunamis since 1996 (Dusek et al. 2019).

2. Current State of Operations

2.1. Overview

Although all meteotsunamis share the same underlying physics, within the U.S. there are notable differences in detection, forecasting, and alerting capabilities based on location. These variations are due to significant differences in the nature of the source of weather disturbances, the density of available observations, differences in occurrence frequency, and overall perceived risk. For the purposes of this overview, we broadly describe current U.S. capabilities in two generalized regions: U.S. Great Lakes and East Coast. There have also been research initiatives associated with investigating meteotsunami occurrence along the U.S. Gulf Coast (Olabarrieta et al. 2017; Paxton and Sobien 1998), but no systematic efforts are yet in place to address these occurrences on an operational level.

2.2. Great Lakes

The Great Lakes contain a dense network of coastal water level gauges—primarily NOAA/NOS (NOAA Tides and Currents 2019)—that span both U.S. and Canadian sides of the international border. In addition, several meteorological stations are positioned near or on the shorelines of the lakes and are supplemented by additional offshore buoys in the ice-off period, particularly in southern Lake Michigan and Lake Erie where meteotsunami occurrence is highest (Bechle et al. 2016). This observing network, augmented by weather radar when available, has been integral to capturing and reconstructing meteotsunami events in recent years. Given that the prominent weather propagation direction in the Great Lakes is generally from west to east, many meteotsunami-inducing weather conditions can be detected upwind of the lakes with sufficient data to compute storm propagation speeds and direction. When a meteotsunami is generated, 6-minute water level gauges have been used often to estimate meteotsunami arrival times and amplitudes in post-analysis (Bechle et al. 2014; Anderson et al. 2015), though limitations in observing the peak amplitudes likely exist due to the lack of higher-temporal frequency observation (e.g., 1-minute water levels). Real-time operational application has not been demonstrated.

Recent work (Linares et al. 2019) has shown that an empirical modeling approach potentially can predict maximum meteotsunami height at water level gauges based on observed atmospheric pressure and wind conditions from upwind meteorological stations. The model uses a combination of historical wind and pressure records, 6-minute water level records, and precomputed hydrodynamic modeling scenarios to develop relationships between observed weather conditions and meteotsunami response. Although this approach needs to account for meteotsunami timing, structure, and detailed impacts, it has the potential to provide an early warning for meteotsunami conditions.

The NWS is currently working to establish messaging protocols using the existing Great Lakes product suite for beach, marine, and lakeshore flooding hazards. Given these products are widely used within the beach manager, marine customer, and lakeshore property owner communities, they could serve as the primary messaging path for communicating meteotsunami threats. NWS will use these protocols when it observes supporting meteorological forcing via upstream surface observations, radar, and water level gauges. Additionally, NWS is developing tools to inform operational forecasters of potential meteotsunami-producing conditions.

2.3. East Coast

Meteotsunami risk for the U.S. East Coast was given little consideration until 2011. It was then that, through a federal grant, NWS sponsored the Institute of Oceanography and Fisheries of Croatia to “build the procedures and protocols for issuing meteotsunami warnings in the U.S.” (Vilibić et al. 2013). The original funding period ran through June 2013, but budgetary constraints resulted in terminating this project after one year. Ironically, it was the impact of the June 13, 2013 meteotsunami along the U.S. East Coast that convinced NWS to recognize and consider meteotsunamis as a specific, previously unaddressed hazard.

Current U.S. East Coast meteotsunami detection and forecasting capabilities are limited, with readings from NOAA’s DART network often serving as the first definitive indicator of meteotsunami formation. When NOAA expanded the initial operational DART network in March 2008, it chose most locations based on proximity to known tsunamigenic subduction zones. But there were a few additional sites identified based on potential landslide sources, including the Hudson Canyon (DART buoy 44402) and the Big Island of Hawaii (DART buoy 51407) (Spillane et al. 2008). The Hudson Canyon DART has proven particularly fortuitous with regard to U.S. East Coast meteotsunami detection. NOAA DART buoy 44403 near the Grand Banks (Fig. 4) is also well positioned to detect meteotsunamis, though none have been confirmed on that instrument as of this writing. It is expected that deep ocean pressure sensors in these locations will help provide unambiguous detection of meteotsunamis caused by either fast-moving eastward propagating mesoscale convective systems (e.g., derechos or Nor'easters) or accelerating post-tropical cyclones. The fact that these sensors are in deep water but in proximity to the coastal shelf allows forecasters to take advantage of the large difference in tsunami phase velocity when meteotsunamis encounter the continental slope, and potentially alert the public to waves that may be refracted from shelf break. Due to the relatively slow tsunami phase velocities *on the shelf*, forecasters could have as much as 1–3 hours after the DART detection before the waves reflected from the shelf break are observed at coastal gauges. Figure 5 depicts this lag between DART detection and coastal observations of the June 13, 2013, meteotsunami event. Of course, meteotsunamis detected by DART can typically only provide lead-time for waves reflected from the shelf break. As such, directly induced waves present greater challenges, since the only reliable means of detection are coastal observations. In these cases, forecasters would be limited to attempting to project "downstream" propagation from the point of confirmed detection.

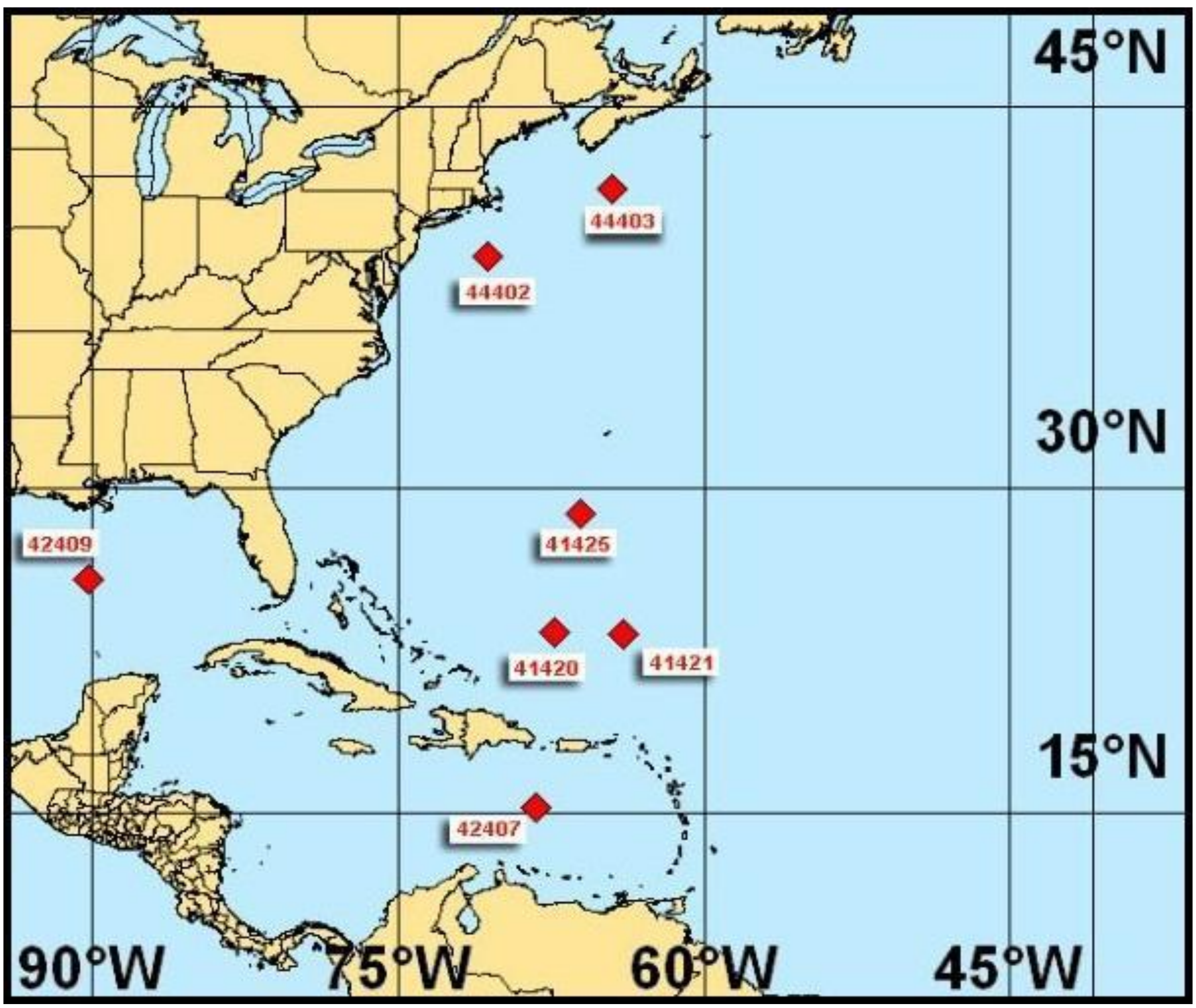

Fig. 4 Atlantic DART buoy locations

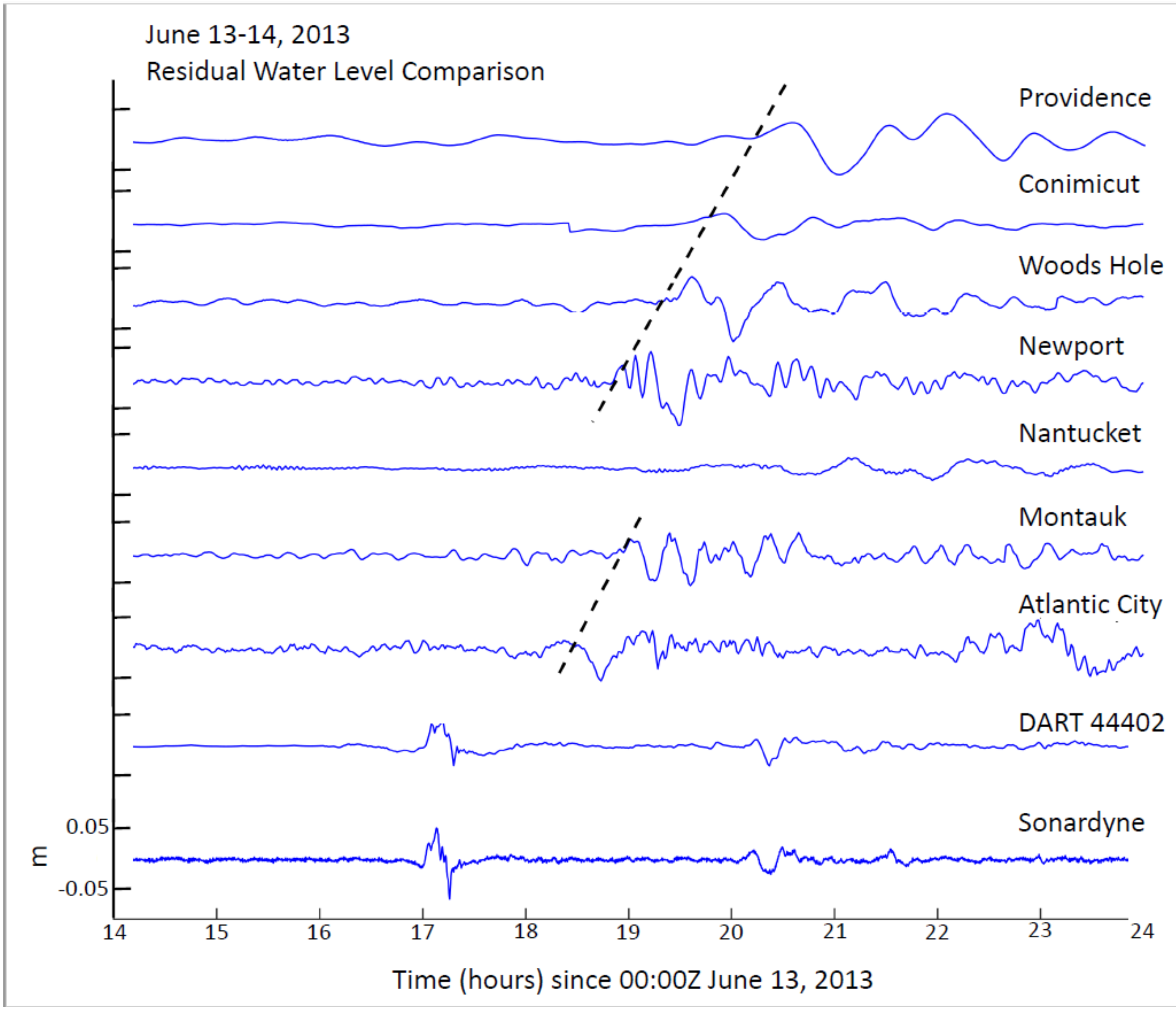

Fig. 5 Time series of de-tided water level changes during the June 13, 2013, event filtered for the tidal components using a Butterworth bandpass filter for wave periods between 1 minute and 2 hours. Dashed lines indicate wave arrival times at coastal tide gauges (top) compared with DART and Sonardyne bottom pressure recorder (bottom)

Presently, there are no operational capabilities that allow forecasters to accurately model a meteotsunami source to determine precise propagations in real-time even if a positive detection is made. NOAA's current meteotsunami alerting capability along the East Coast therefore carries a large amount of uncertainty and involves significant coordination between coastal WFOs and the U.S. NTWC located in Palmer, Alaska. Current alerting protocols normally begin with the NTWC receiving an alarm from one of the DART systems described above. The NTWC relays this information, which includes the exact time of detection and amplitude, to the servicing coastal WFO. The WFO attempts to correlate the DART detection with a source of weather disturbance. Based on the location of the disturbance, and the time of detection, the WFO—in consultation with the NTWC— may be able to estimate the time and extent of which coastal communities may be impacted. This estimation will be broad and based primarily on travel-time calculations from the presumed source. If a general correlation between the DART reading and a transiting weather disturbance can be made, the WFO *may* decide to put out a special weather statement and/or a marine weather statement alerting the public of the ongoing coastal threat. The purpose of issuing both statements is to alert land and maritime users, such as marinas, since unusually strong currents are a concern with meteotsunamis. NWS potentially could issue warnings or other alerts for extreme circumstances when coastal amplitudes are anticipated to be significant (e.g., greater than 1 m of sea-level change) *and the meteotsunami is fully disconnected from the source weather disturbance.* It is this sort of "good weather" meteotsunami (as categorized by Rabinovich 2020) that is most concerning, since no other weather-related alerts would likely be in place to warn the public of potential danger. However, since there is not a current operational capability to perform real-time meteotsunami source characterization and propagation modeling, there would likely need to be strong corroborating indicators, such as a verified coastal gauge report, before issuing a warning-level alert. At least two meteotsunamis have been confirmed by DART buoy systems on June 13, 2013, and May 15, 2018. In the case of the latter, WFOs Mount Holly, New Jersey (Fig. 6), New York, New York, and Boston, Massachusetts, issued Special Weather Statements and Marine Weather Statements.

It should be noted that NOAA's operational DART array is deployed based on known seismic (and in a few cases, notional mass-failure-induced) tsunami sources. While there may be opportunities in the future to reposition DART stations to cover a broader range of potential tsunami sources, at this time the network is not tuned to meteotsunami detection; there are wide gaps in potential meteotsunami formation zones that must be factored in by both tsunami duty scientists and WFO forecasters. Furthermore, it is unknown if deep-ocean tsunameters such as DART are the most effective means for meteotsunami detection and measurement. Prior to procuring or deploying additional instruments, NWS must perform a detailed sensitivity analysis to address both the expected coverage gaps and false alarm rates to determine costs and benefits of relying on deep-ocean pressure sensors to serve as a long-term meteotsunami detection network. At present, the DART network represents an "instrument of opportunity" to potentially detect meteotsunamis (or other long-waves) that propagate into deep water that would otherwise go unnoticed by NWS forecasters.

FZUS71 KPHI 160119
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Marine Weather Statement
National Weather Service Mount Holly NJ
919 PM EDT Tue May 15 2018
ANZ430-431-450>455-161200-

Delaware Bay waters north of East Point NJ to Slaughter Beach DE-
Delaware Bay waters south of East Point NJ to Slaughter Beach DE-
Coastal waters from Sandy Hook to Manasquan Inlet NJ out 20 nm-
Coastal waters from Manasquan Inlet to Little Egg Inlet NJ out 20 nm-
Coastal waters from Little Egg Inlet to Great Egg Inlet NJ out 20 nm-
Coastal waters from Great Egg Inlet to Cape May NJ out 20 nm-
Coastal waters from Cape May NJ to Cape Henlopen DE out 20 nm-
Coastal waters from Cape Henlopen to Fenwick Island DE out 20 nm-

919 PM EDT Tue May 15 2018
...Abnormal water surges are expected along the oceanfront, inlets, and back bays through the overnight hours...

Air pressure sensor and tidal gage readings in and near the coastal waters indicate that a weather-generated tsunami has been triggered by the line of thunderstorms as it moved over the ocean.

Impacts are expected along the oceanfront, inlets, and back bays from Perth Amboy New Jersey to Fenwick Island Delaware.

Water level fluctuations of several inches to one foot above normal astronomical tide in localized areas can be expected along the oceanfront, inlets, and back bays for the next several hours as a series of surges make their way to the coast.

The duration of this event is uncertain, though similar events have lasted from several hours to one day. It is not recommended to return to the water until at least Wednesday morning.
The strong currents associated with these surges could pose a danger to those in or near the water.

Recommended actions are listed below...
Boat Owners...
Prepare now for the following hazards...
* Strong, unpredictable currents
* Surging up to one foot above normal sea level

Swimmers...Surfers...and Boaters
It is recommended you leave the beach now to avoid the following hazards...
* Strong currents
* Potentially dangerous surges of water.

This kind of tsunami is generated by abrupt changes of atmospheric pressure in the causative storm system, which is a line of thunderstorms that moved over the ocean in this case. The combination of the air pressure effect on the ocean surface and the speed at which the pressure disturbance travels can generate tsunami like waves in certain situations. The National Tsunami Warning Center is monitoring this event.
Additional statements will be issued if necessary through National Weather Service Forecast Office in Mount Holly, NJ.
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Fig. 6 Marine Weather Statement issued by WFO Mt. Holly, New Jersey for the May 15, 2018 event

2.4. Synergies and Common Practice

Given significant regional differences, as well as wide variance in perceived meteotsunami risk, it is important for NOAA to establish consistency with terminology and operational products when conveying the threat to the public.

Terminology

As previously noted, NWS had not explicitly addressed meteotsunamis before the June 13, 2013 event. After this occurrence, and especially in light of significant media interest in the phenomena, a wide-ranging internal discussion ensued to determine the best suite of terminology. There was reluctance among some East Coast WFOs to use the term "meteotsunami" when describing this phenomenon in operational products because the public associated tsunamis with large-scale inundation events related to submarine earthquakes. It also has proven challenging to reach a consensus on terminology to describe meteotsunamis in the Great Lakes. NWS operational products will therefore continue to focus on the outcomes and impacts by using phrasing like "sudden water level rise" or "rapid inundation." This consistency allows meteotsunami impacts to be described in both the Great Lakes and East Coast without creating new or special products that could spark public confusion or worse—panic.

Operational Products

Aside from terminology, NWS also had to reach consensus on the types of operational products to issue if a meteotsunami threat is anticipated, as well as which operational activities were best able to deliver those products. Within the NWS, NOAA's NTWC closely monitors tsunami detection networks, such as DART, and understands tsunami propagation and impact. NWS coastal WFOs are staffed 24 hours a day/7 days a week and are focused on weather events that may trigger meteotsunamis. These offices routinely issue Watch and Warning products familiar to the media and public. Though both NTWC and WFOs add value in identifying the threat, it was determined that NWS WFOs are best positioned to address meteotsunamis in operations.

As previously stated, there are significant challenges associated with WFOs issuing operational products based on meteotsunamis, especially on the East Coast. Limited meteotsunami training and awareness and lack of refined operational procedures have left forecasters unprepared to respond to these events in real-time operations. Further, the current NWS product suite and dissemination methods are not designed to meet the short-fused alerting needs presented by meteotsunamis, thereby potentially limiting the public's and core partners' ability to take action.

3. Gaps and Challenges

Though the U.S. has developed initial capabilities to address the meteotsunami threat in the highest risk areas, much work remains to realize a truly comprehensive detection, forecast and warning capability. Given resource constraints and competing priorities, it is unclear how aggressive the U.S. will be to fully develop these capabilities. That said, capability gaps related to meteotsunami forecast and warning have become better recognized, and some options to address these gaps in terms of sensing, forecasting, and operations, are described below.

3.1. Sensing

Dedicated Bottom Pressure Recorders (BPR)

Although a dense network of coastal tide gauges exists along much of the U.S. coastline, offshore water level stations are limited to the oceanic DART system. There are currently only two DART systems well positioned to detect meteotsunamis that form on the eastern U.S. continental shelf and propagate into the deep waters of the western Atlantic. This network provides limited coverage for meteotsunamis that form on the central or southern portions of the shelf. In addition, there is little DART coverage in the meteotsunami formation-prone vicinity of the Canadian Maritime Provinces. Additional DART systems, at significant expense, would be needed in these areas to establish a reliable and comprehensive bottom pressure network for meteotsunami detection. An added complication is that certain atmospheric perturbations and meteotsunami propagation pathways can result in impacts at the shoreline without triggering offshore DART sensors. This result is always the case in the Great Lakes, where there are no offshore pressure sensors or meteotsunami wave-detecting infrastructure.

It is therefore uncertain if NOAA will consider expanding the DART network for the expressed purpose of meteotsunami detection and measurement.

Coastal Water Level Gauges and Air Pressure Sensors

NOAA water level gauges are a critical component to observing and detecting meteotsunami events. Most recent meteotsunami detection research has focused on observations from NOAA gauges, including the climatologies discussed in this paper from both the Great Lakes (Bechle et al. 2016) and East Coast (Dusek et al. 2019). The detection approach used by Dusek et al. (2019) was highly automated. A similar approach potentially could be used to detect a meteotsunami at NOAA gauges in near real-time. Since meteotsunamis propagate according to well-understood reflection and/or refraction patterns, adding this capability to WFO operations could allow forecasters to issue short-term forecasts for downstream locations when a detection is made.

A limitation of the NOAA water level network is the relatively low spatial resolution, resulting in observation gaps over long stretches of coastline. Existing gauges might not be optimally positioned for meteotsunami detection and measurement (e.g., many gauges are protected to limit ocean wave “noise” in the mean water level signal). This limitation could be mitigated by deploying low-cost water level sensors such as in-situ pressure sensors or remote ultrasonic sensors (e.g., deployed above the water’s surface on a pier or bridge). These types of sensors could enhance and supplement the existing gauge network, while serving as multi-purpose sensors, by measuring inundation from tidal flooding and storm surge as well as meteotsunamis.

Most meteotsunamis in the Great Lakes region are induced by the combination of wind stress and transiting air pressure disturbances. Therefore, a well-established, strategically located meteorological network that reports real-time, high-frequency wind speed and atmospheric pressure is critical in building forecasting and early warning capabilities. Since 2018, the Great Lakes Environmental Research Laboratory (GLERL) has been working with private industry to install additional barometers and upgrade reporting frequency in multiple coastal meteorological stations around the Great Lakes. In addition, GLERL is working with the National Data Buoy Center to design algorithms to detect and report abnormal pressure changes in the next generation of offshore buoys.

High-Frequency (HF) Radar

High-Frequency (HF) radar has been proposed as a sensing technology capable of detecting meteotsunamis. Its range of measurements extends to several tens of kilometers offshore, and it is capable of detecting tsunami currents that exceed a certain threshold (approximately 0.15–0.20 m/s). The use of HF radar is well suited for shallow waters, including the continental shelf (Grilli et al. 2017) where the strongest tsunami currents are expected. Use of this technology for meteotsunami detection and measurement shows promise (Lipa et al. 2014); however, it is still unclear whether HF radar can provide the necessary information for real-time modeling and impact-forecasting at the coast. A major concern associated with identifying tsunami currents using HF radar is the need to limit false alarms. NTWC is investigating techniques to analyze HF radar returns as a potential means of near-shore tsunami detection, but no operational capability exists at this time.

Ionospheric Perturbations

The Global Navigation Satellite System (GNSS) constellation (~128 satellites in 2020), together with other satellite systems capable of measuring tsunami-induced disturbances to the total electron content (TEC) in the ionosphere, may provide an opportunity to detect and measure meteotsunamis from space. All tsunamis create gravity waves in the atmosphere that become detectable when they propagate into the ionosphere and alter its electron density equilibrium. Although tsunami-induced ionospheric electron density perturbations propagate at a speed similar to that of tsunami waves in deep water, detection by land-based GNSS stations before tsunami landfall is possible because ionospheric disturbances detected by satellites orbiting over the ocean can be relayed to land-based receivers.

GNSS TEC measurements are sensitive to tsunami/meteotsunami waves as far as 1,500 km away from the coastline. This sensitivity is a function of the geometry between GNSS receivers on land and GNSS satellites over the ocean. Receivers on land can track distant GNSS satellites low on the horizon and resolve changes in the ionosphere caused by large waves. Because it takes about 25 minutes for a gravity wave to propagate up to the ionosphere, the GNSS TEC approach could provide forecasters with up to 1.5 hours of lead-time in areas where there are real-time GNSS networks with sufficient site density (Fig. 7). A retrospective analysis detected the July 13, 2013, East Coast meteotsunami using this method (Komjathy et al. 2019). Significant research and development is needed before operationalizing this capability. Further, full access to real-time GNSS data streams must be ensured in high-risk areas.

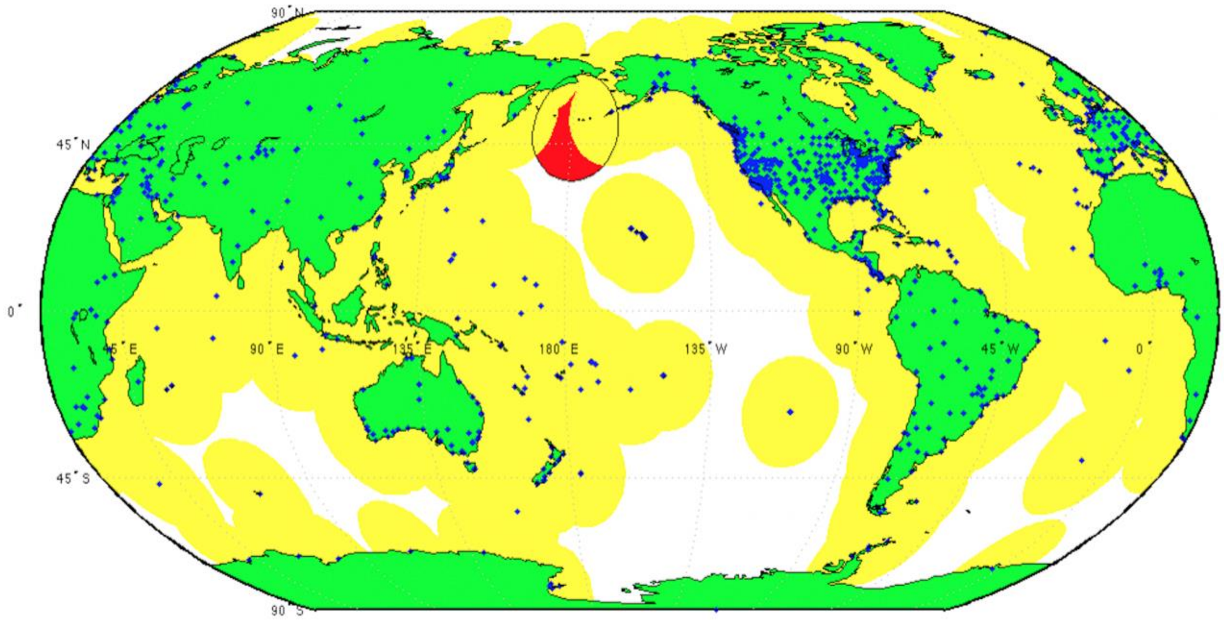


Fig. 7 Potential GNSS network ionosphere detection capabilities for tsunami/meteotsunami waves using known GNSS sites. GNSS sites (blue diamonds) can track disturbances in the ionosphere at distances of 1,500 km (yellow circles) from the site. Data for GNSS sites shown are freely available, but many are not streaming in real-time. The area in red has insufficient GNSS site coverage for ionosphere detection. Figure courtesy of National Aeronautics and Space Administration

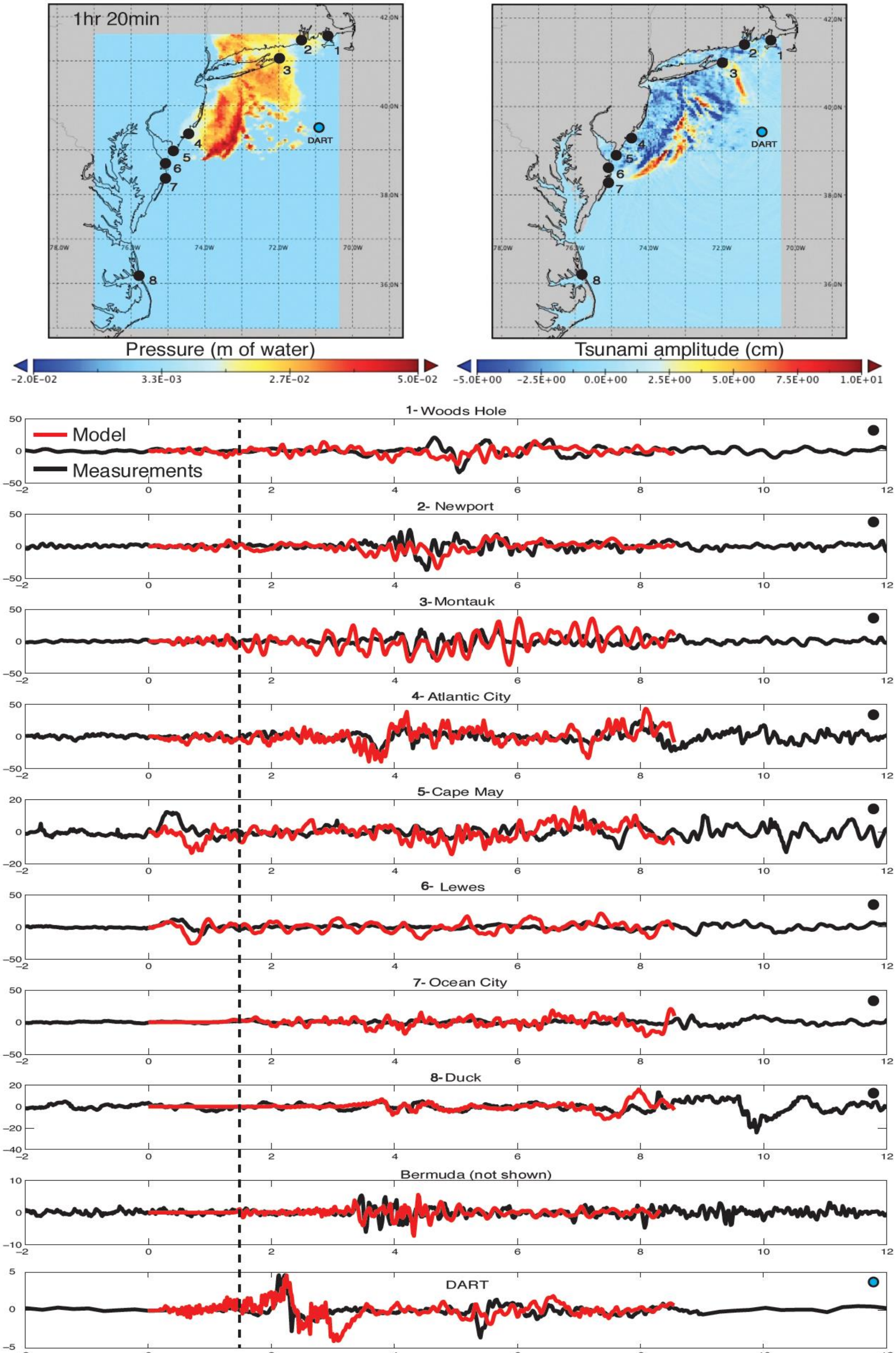
3.2. Forecasting

As previously mentioned, bottom pressure measurements serve to verify that a meteotsunami has been generated, but these observations alone are not enough to pinpoint source locations, much less provide accurate impact-forecasts for coastal populations. To address this limitation, NOAA is experimenting with the development of meteotsunami formation algorithms (Linares et al. 2016). These algorithms combine high-resolution numerical weather prediction schemes, such as the High-Resolution Rapid Refresh (HRRR) model, with known bathymetries to simulate meteotsunami resonance and propagation in near-real-time. This technique shows promise but also risks generating false alarms. As a result, the goal of an operational near-real-time meteotsunami detection and forecast algorithm remains aspirational.

In addition to heuristic models that relate observed meteorology to meteotsunami height in near-real-time, NWS has employed atmospheric and hydrodynamic models to simulate historical meteotsunami events. These models are often higher-resolution, specifically-tuned versions of the models used for operational forecasting, such as the HRRR (Benjamin et al. 2016) and the Great Lakes Operational Forecast System (Anderson et al. 2018). High-temporal frequency of modeled atmospheric conditions (e.g., 1- or 5-minute output) is typically required to resolve the sharp gradients in atmospheric pressure and wind stress needed to generate meteotsunamis. The need for high-temporal resolution observations is a significant limitation of existing operational numerical weather prediction (NWP) configurations; however, even with increased temporal resolution and spatial resolution, it remains difficult to simulate mesoscale convective systems that lead to meteotsunami generation. Recent work has shown that coarse hydrodynamic models similar to those used operationally are somewhat capable of simulating meteotsunamis, but only if the atmospheric conditions are accurately represented (Anderson et al. 2015). Thus, atmospheric modeling and forecasting is likely the greatest barrier to near-real-time meteotsunami forecasting. A possible exception might be for cases driven by atmospheric gravity waves, such as from strong tropical or extra-tropical storms where atmospheric models with similar configurations to operational versions have shown accuracy in simulation of observed pressure gradients (Anderson and Mann 2020).

Another modeling forecast approach has been tested using the June 13, 2013, meteotsunami along the East Coast as a proof of concept study (Titov 2018). The method uses existing modeling and detection potential to test forecast capability for meteotsunamis that may be developed into automated real-time forecasts. Data from weather radar, combined with real-time coastal and deep water tsunami detection, could provide enough input for models to forecast coastal amplitudes before coastal impact of a meteotsunami. In the study, a sequence of weather radar reflection images were used as a proxy for time-dependent pressure input for meteotsunami computations. Higher reflection signals were assumed to correlate with higher pressure areas. The atmospheric pressure level was scaled by the pressure record at one of the local tide gauge locations.

The tsunami wave generated by the propagating pressure field has been simulated using the nonlinear shallow-water numerical model Method of Splitting Tsunami (MOST), (Titov et al. 2016). Simulated time-series were compared with coastal gauges and DART records (Fig. 8). Despite obvious oversimplifications of the model forcing procedure and coarse numerical model resolution, the comparisons of the model results with the observations are reasonable. Model predictions of coastal arrival times for significant waves correlate well with observed recordings. The model coastal amplitudes are within the range of the tide gauge measurements. Better model comparison with the deep-ocean DART record (which is free from local coastal effects) implies that a higher resolution model near the coasts may provide even better prediction for the coastal sea-level records. Titov (2018) provides the detailed discussion of the model results for the study. The study shows promise for developing meteotsunami model forecast capability based on available real-time measurement data. The MOST model is already implemented as a real-time tsunami forecast model at NOAA’s TWCs, making that component of a meteotsunami forecast capability straightforward.



1hr 20min
Pressure (m of water)
Tsunami amplitude (cm)
DART
1- Woods Hole
Model
Measurements
2- Newport
3- Montauk
4- Atlantic City
5- Cape May
6- Lewes
7- Ocean City
8- Duck
Bermuda (not shown)
DART

Fig. 8 Results of proof-of-concept modeling of the June 13, 2013, meteotsunami. Upper panel: snapshots of proxy pressure forcing (left) and resultant tsunami amplitudes (right) at approximate time of tsunami separating from the forcing system (1 hour 20 minutes since the pressure systems entered ocean). Black dots indicate location of tide gauges; blue dot is DART location. Lower panel: comparison of the modeled amplitudes (red) with tide gauge observation (black), ordered with decreasing latitude with northernmost location shown at the top. DART comparison is shown as the bottom graph. Dashed vertical line indicates the time of the snapshot shown at the upper panel

3.3. Public Alerting

Current capabilities do not allow WFOs to issue alerts until a meteotsunami has been detected and verified (i.e., "Warn on Detection"). As such, the NWS standard "Watch, Warning, and Advisory" products cannot be easily adapted for meteotsunamis because the majority of these products are long-fused and normally issued at least 24 hours in advance. This reality, combined with the fact that WFOs currently cannot reliably model source parameters in real-time—even when meteotsunamis are detected—limits the lead-time and accuracy of any alerts NWS does issue related to meteotsunamis.

With continuing progress in forecasting algorithms as described in section 3.2, however, NWS may be able to move toward a capability that would allow propagation forecasts to be produced soon after meteotsunami detection is verified. This would provide both additional lead-time as well as greatly improved accuracy related to meteotsunami impacts, and would represent a significant capability improvement over today's standard.

Additionally, and while strictly aspirational, it is at least conceivable that as meteotsunami understanding, detection, forecasting techniques, and high-resolution NWP improve in coming years, meteotsunami formation could be predicted reliably up to 24 hours, or even 48 hours in advance. If such a prediction carried a large enough expected amplitude (e.g., >1 m at coastal locations), there may eventually be the potential for NWS to issue Watches (e.g., significant impact possible within 48 hours) for anomalous waves associated with meteotsunamis in the Great Lakes and/or the East Coast. These Watches could then be either upgraded to Warnings (if forecasted amplitude remains >1 m), revised to Information Statements (if forecasted amplitude drops to <1 m), or canceled altogether (if meteotsunami development no longer predicted) within 24 hours of impact based on subsequent NWP results. Such a capability would more closely resemble the "warn-on-forecast" alerting procedures NWS employs for other hazards such as winter storms or severe weather.

It is important to note, however, that while identifying the basic parameters of such a forecast capability may be theoretically within reach, most U.S. meteotsunamis are still relatively low impact events, and NWS must ensure false alarms are as rare as possible. Extensive testing and development would therefore need to occur before NWS could adopt any level of warn-on-forecast meteotsunami protocols in operations. Until then, NWS forecasters will continue to work with the tools available to provide at least some level of public awareness when meteotsunamis are detected.

4. Summary and Next Steps

Meteotsunamis have a long history of impacting the U.S., but because they are normally associated with other aspects of active weather disturbances, they have only recently been specifically identified and addressed in public alerting protocols. Most importantly, some meteotsunamis can become completely disassociated with the generating weather disturbance. When this occurs, and it does with some frequency in both the Great Lakes and East Coast, meteotsunamis must be treated as stand-alone hazards to best protect coastal communities.

Capabilities to detect, measure, and forecast meteotsunamis are limited, and due to the relative infrequency and perceived low-impact, it is unlikely the U.S. will make substantial capital investments to explicitly improve meteotsunami detection capability. However, there is a broad network of sensors that can be leveraged to detect meteotsunamis soon after they form, including the U.S. tsunami detection network's array of DART buoys and the NOAA NOS coastal water level network. A number of emerging capabilities, including additional real-time reporting meteorological network stations, HF radar, and ionospheric inversion techniques may prove important in developing a dense meteotsunami detection capability requiring little in the way of new, targeted investments. Most importantly, operational implementation of such emerging technologies would directly benefit detection and forecasting capabilities related to *all* tsunamis, independent of source.

In the near-to-medium term, the U.S intends to focus on using real-time sensing in combination with detailed bathymetry and high-resolution NWP to develop operational algorithms capable of alerting forecasters of meteotsunami formation and potential impact in sufficient time to issue actionable public alerts. This approach has been investigated in other parts of the world where the threat is more regular and significant such as the Balearic Sea (Renault et al. 2011). Continuing to educate both operational forecasters within NWS and the general public regarding the unique threat posed by meteotsunamis is also a critical component of our near-term strategy.

In the longer term, it may be possible to accurately predict meteotsunami formation using long-range NWP schemes, but this is currently outside the scope of our current investigations due to the large uncertainties involved.

5. Ethics declarations

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

6. Disclaimer

The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the author(s) and do not necessarily reflect the views of NWS, NOAA, or the Department of Commerce.

This is GLERL contribution number 1960.

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