UNDERSTANDING AND FORECASTING METEOTSUNAMI IN THE GREAT LAKES

Fellow: Adam Bechle
Principal Investigators: Allen Burton (UM-CILER), Chin Wu (UM-CILER)
NOAA Technical Contacts: Eric Anderson (NOAA-GLERL)

Overview and Objectives:

Meteotsunamis (or meteorological tsunamis) are propagating long water waves generated by fast moving atmospheric disturbances (squall line). Meteotsunamis exhibit many similarities with seismic tsunamis, having wave periods of 2 minutes to 2 hours and undergoing resonant amplification that transforms relatively small waves in the open water into destructive forces at the coast [Ravinovich and Stephenson 2004]. The meteotsunami impact in the Great Lakes is illustrated through many events which have resulted in destruction and death [Cleveland Plain Dealer 1882; New York Times, 1912; Grand Haven Tribune 1929; Toledo Blade 1942; Donn et al. 1956; NOAA 1998]. The most vivid Great Lakes meteotsunami on record occurred in 1954 on Lake Michigan when a 3 meter wave struck Chicago and swept many fishermen off a pier, killing seven [Ewing *et al.* 1954]. Recently, on May 27, 2012 a large meteotsunami unexpectedly swept three swimmers far into Lake Erie. Fortunately the swimmers survived, but the meteotsunami threat to the Great Lakes was made vividly clear. Other recent meteotsunamis have been observed at Sault Ste. Marie, MI (September 4, 2014) Traverse City, MI (June 10, 2015) with minor damage and flooding reported. While the threat of meteotsunamis in the Great Lakes is apparent, no characterization of meteotsunamis in the Great Lakes has been conducted and no infrastructure is available to reliably forecast an impending meteotsunami. To address these issues, the goal of the project was to develop a meteotsunami observation and modeling system to characterize meteotsunamis formation in the Great Lakes and apply this knowledge to improve prediction and awareness of this coastal hazard for enhanced public safety. The specific objectives of the project were:

- Characterize the Great Lakes meteotsunami climate from historical water level and meteorological records; addressing the questions *Where and how often do meteotsunamis occur?*and *What meteorological mechanisms cause meteotsunamis?*
- Establish hydrodynamic modeling requirements to simulate meteotsunamis in research and operational modes; *What spatio-temporal scales are necessary to model meteotsunamis?*

Accomplishments:

To investigate the recent occurrence of meteotsunamis in the Great Lakes, 6-minute water level data from 1996 to present were analyzed from the 10 NOAA National Oceanic Service gauges distributed throughout the Lake Michigan. Meteotsunami events were identified from the water level records based on the criteria given by Monserrat et al. [2006] and recurrence levels were established using a Pareto Type 1 fit to the event heights. For example, the annual meteotsunami height at Calumet Harbor, IL is 0.75 meters with a 20-year return level of 1.4 meters. The seasonal distribution of meteotsunamis reveals spatial differences in occurrence, with a majority of the events in northern Lake Michigan occurring in April-May-June, meteotsunamis in southern Lake Michigan occurring primarily in May-June-July, and meteotsunamis in Green Bay occurring primarily in June-July-August. We also examined the storm structures associated with meteotsunamis at each station. At all stations, a majority of meteotsunamis were associated with strong linear or complex convective storms. Meteotsunamis in southern Lake Michigan were almost exclusively convectively forced while stations in northern Lake Michigan experienced up to 45% of meteotsunamis caused by frontal storms. These results provide valuable information into the causative meteorology behind meteotsunamis to help identify conditions conducive to meteotsunami formation. This work will be summarized in the manuscript "The meteorological tsunami climate of in the Great Lakes", currently in preparation for submission to the Journal of Geophysical Research Oceans. Furthermore, we have extended this analysis to all 36 NOAA/NOS water level gauges throughout the Great Lakes to understand the regional meteotsunami climate. Lake Michigan experiences the largest meteotsunamis followed by Lake Erie and Lake Huron, with much smaller meteotsunamis occurring in Lakes Superior and Ontario. Lakes Michigan, Huron, and Ontario share similar meteotsunami seasonality (late spring to early summer) while Lake Superior experiences meteotsunamis primarily in the summer season and Lake Erie exhibiting a primary summer meteotsunami season with a secondary fall seasons. This difference is likely attributed to lake depth, as Lakes Michigan, Huron, and Ontario are all of similar depths while Lake Erie is much shallower and Lake Superior far deeper. *These results provide important answers to the questions of where and when meteotsunamis occur throughout the Great Lakes.* This work will be summarized in the manuscript "Great Lakes meteotsunami occurrence", currently in preparation for submission to Geophysical Research Letters. This work was recently presented the 2015 IAGLR Annual Conference of Great Lakes Research in the paper "**Meteotsunami Occurrence and Trends: Great Lakes and Beyond".**

A hydrodynamic model of Lake Erie was configured to simulate meteotsunamis in response to a range of possible meteorological forcings to advance towards meteotsunami predictability. In particular, we simulated the May 27, 2012 meteotsunami near Cleveland, OH which swept three swimmers far into Lake Erie.

Neither the wave nor the causative storm were resolved by the Great Lakes Coastal Forecasting System (GLCFS), so understanding the mechanics of this event as well as modeling requirements necessary to simulate this event is vital to improving the meteotsunami predictive capacity in the Great Lakes. Analysis of surface meteorological and radar records revealed that three fast moving storms crossed Lake Erie within the timeframe of the meteotsunami, none of which were captured by the hourly interpolation-based scheme used to provide input winds to the GLCFS. The pressure and wind fields of these storms were reconstructed from these observations for use as input into a hydrodynamic model (FVCOM) of Lake Erie with 100 meter resolution. The hydrodynamic simulations revealed that the meteotsunami was the result of a storm traveling southward which struck the Cleveland area around 17:30 UTC on May 27. This storm produced a series of long waves which reflected off the southern shore of Lake Erie and then subsequently reflected off the northern shore back towards Cleveland. Owing to the concave shape of the north shore of Lake Erie, these reflected waves became spatially focused, growing the waves to their destructing and dangerous height. Furthermore, reflection made the meteotsunami waves appear long after the causative storms, giving recreationists a false sense of security of calm conditions after the storm. In light of these findings, we worked closely with Dr. Greg Mann at the Detroit National Weather Service Weather Forecasting Office to simulate the meteorological conditions with a high-resolution (4km) Weather Research and Forecasting (WRF) model for use as input into the hydrodynamic model. The WRF model was able to simulate wind and pressure perturbations associated with the causative storms and the subsequent hydrodynamic modeling produced meteotsunami waves similar to the observed event. *Overall, this study provides insight into the requirements for model-based forecasts of meteotsunamis, particularly the need for high resolution in both the spatial (km scale) and temporal domains (minute scale)*. This work is summarized in the manuscript "Reconstruction of a meteotsunami in Lake Erie and the effects of enclosed basins on hydrodynamic response" which is in review at the Journal of Geophysical Research Oceans. This work was also recently presented at the 2015 IAGLR Annual Conference of Great Lakes Research in the paper "**Detection and Reconstruction of a Meteotsunami on Lake Erie".**

Publications:

Bechle, A.J. and Wu, C.H., 2014. The Lake Michigan meteotsunamis of 1954 Revisited. Natural Hazards, 74(1), 155-177.

Bechle, A.J. and Wu, C.H., 2014. An entropy-based velocity method for esturaine discharge measurement, *Water Resources Research*, 50(7), 6106-6128.

Anderson, E.J., Bechle, A.J., Wu, C.H., Schwab, D.J., Mann, G.E., and Lombardy, K.A.; Reconstruction of a meteotsunami in Lake Erie and the effects of enclosed basins on hydrodynamic response. *Journal of Geophysical Research Oceans*, Accepted under revision.

Bechle, A.J., Kristovich, D.A.R., and Wu, C.H.; Meteorological tsunamis occurrence in Lake Michigan. *Journal of Geophysical Research Oceans, in review.*

Bechle, A.J., Wu, C.H, Anderson, E.J., and Schwab, D.J., Great Lakes meteotsunami occurrence. *In preparation for submission to Geophysical Research Letters*

Bechle, A.J., Wu, C.H, Schwab, D.J. and Anderson, E.J., Meteotsunamis: Global occurrence and trends. *In preparation for submission to Nature*

Presentations:

Anderson, E.J., Bechle, A.J., Wu, C.H., Schwab, D.J., Mann, G.E., and Lombardy, K.A., **"Detection and Reconstruction of a Meteotsunami on Lake Erie";** International Association for Great Lakes Research (IAGLR), 58th Annual Conference on Great Lakes Research, Burlington, VT; May 26, 2015.

Bechle, A.J. and Wu C.H., "Meteorological Tsunami Occurrence and Trends: Great Lakes and Beyond"; IAGLR, 58th Annual Conference on Great Lakes Research, Burlington, VT; May 26, 2015.

Wu, C.H., Linares, A., Anderson, E.J., and Bechle, A.J.; "Meteorologically induced high-frequency water level fluctuations in northern Lake Michigan"; IAGLR 58th Annual Conference on Great Lakes Research, Burlington, VT; May 26, 2015.

Bechle, A.J. and Wu, C.H.; "Real-Time Water Imaging System: A Ground-based Water Quality Monitoring Tool"; 39th Annual Meeting of the American Water Resources Association – Wisconsin Section, Oconomowoc, WI; March 5, 2015.

Outreach Activities:

We plan to translate our research findings into tools that can be used to mitigate the risk of meteotsunamis throughout the Great Lakes. We have submitted a proposal to a Illinois-Indiana and Wisconsin Sea Grant Joint Request to fund the development of a Cyberinfrastructure for Risk Assessment and Forecasting Tool (CRAFT) that would translate our findings on meteotsunami occurrence into a user-friendly tool to help local planners, emergency managers, and forecasters understand the probability of destructive meteotsunami occurrence, as well as the potential damage associated with these events. In this proposed project, we would collaborate closely with the NWS offices to incorporate NWS needs and experiences into CRAFT. We would also work Sea Grant to communicate risk posed by coastal inundation and appropriate protective actions to the public.