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Meteotsunamis in the Great Lakes and Investigation into Recent Events on Lake Erie and Lake Superior

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Background

Meteotsunamis have been documented around the world, causing destructive impacts to coastal communities while being difficult to forecast [*Candela et al., 1999; Jansa et al., 2007; Vilibic´ et al., 2008; Dragani et al., 2009; Sepic´ et al., 2009; Thomson et al., 2009; Asano et al., 2012; Pasquet and Vilibic´, 2013; Vilibic´ et al., 2014*]. Meteotsunamis are waves with periods between 2 minutes to 2 hours that are generated by an atmospheric disturbance **[Fig. 1]**, which most commonly entails a sharp gradient in pressure, though wind stress has also been shown to be of significant importance to meteotsunami generation in the Great Lakes [*Bechle and Wu, 2014; Sepic´ and Rabinovich, 2014*]. Investigations in the Great Lakes have also raised the issue of dangers posed by meteotsunamis in enclosed basins due to the reflection and interaction of meteotsunami waves, in which the destructive waves can arrive several hours after the atmospheric disturbance has passed [*Bechle and Wu, 2014; Anderson et al., 2015*]. As a result the Great Lakes may pose a unique paradigm in meteotsunami formation, suggesting the need for further exploration of the atmospheric drivers and formation of these high-frequency water level oscillations with particular interest in: **(1)** frequency of occurrence, **(2)** vulnerability of coastal communities, and **(3)** methods to improve meteotsunami forecasting

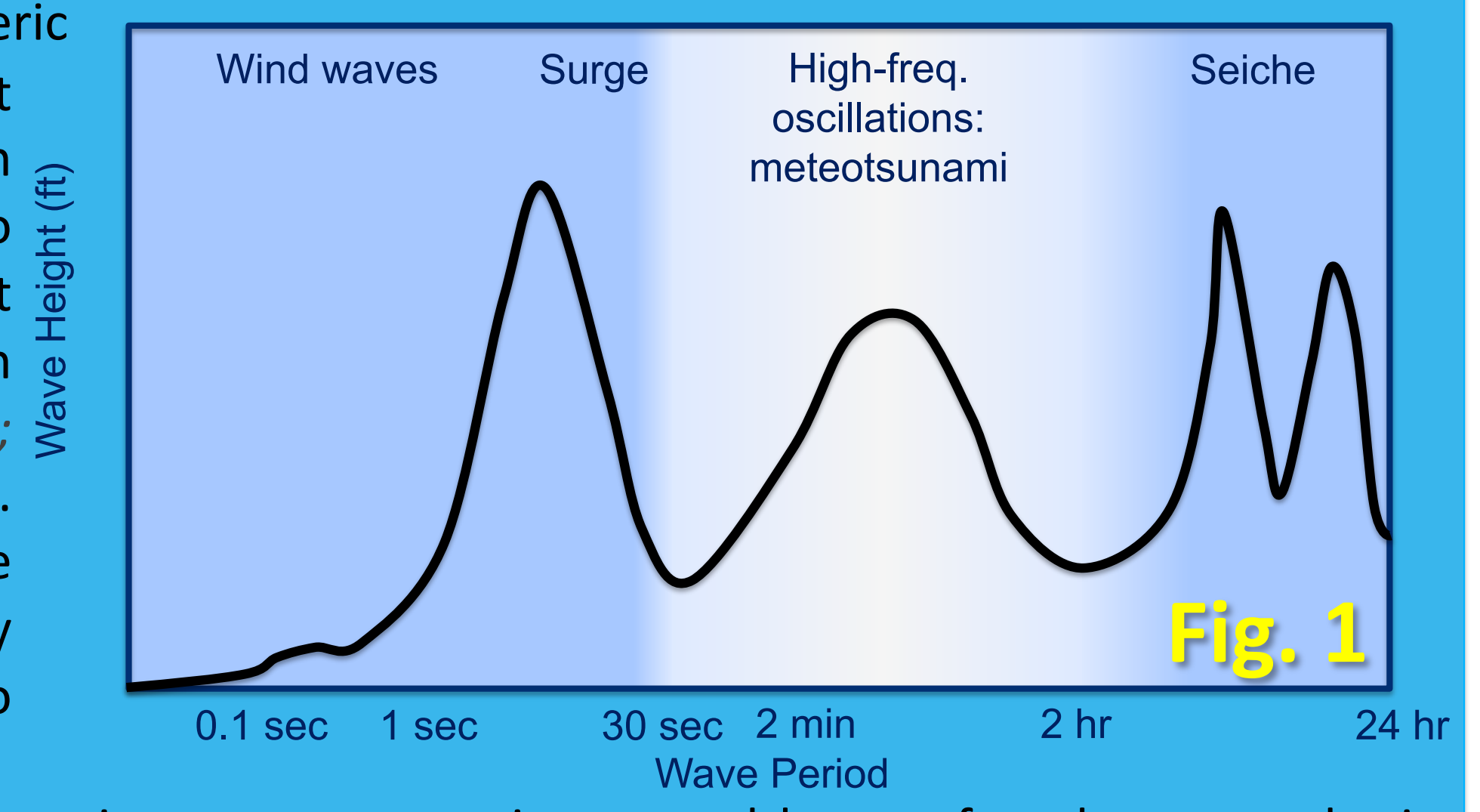

Fig. 1

Meteotsunami Occurrence

Recent work by *Bechle et al.,* [2016] has shown that meteotsunamis occur in each of the Great Lakes, resulting in death and destruction to coastal communities **[Fig. 2a]**, with the largest number of detected meteotsunamis recorded in southern Lake Michigan and along the southern shore of Lake Erie. The largest meteotsunami recorded occurred near Chicago, IL in 1954 [*Bechle and Wu, 2014*]. Results suggest that the majority of meteotsunamis in the Great Lakes are driven by complex and linear convection **[Fig. 2b]**, though the peak occurrence varies by lake, likely due to variability in the resonant characteristics of each lake and the relationships between atmospheric conditions and water depth.

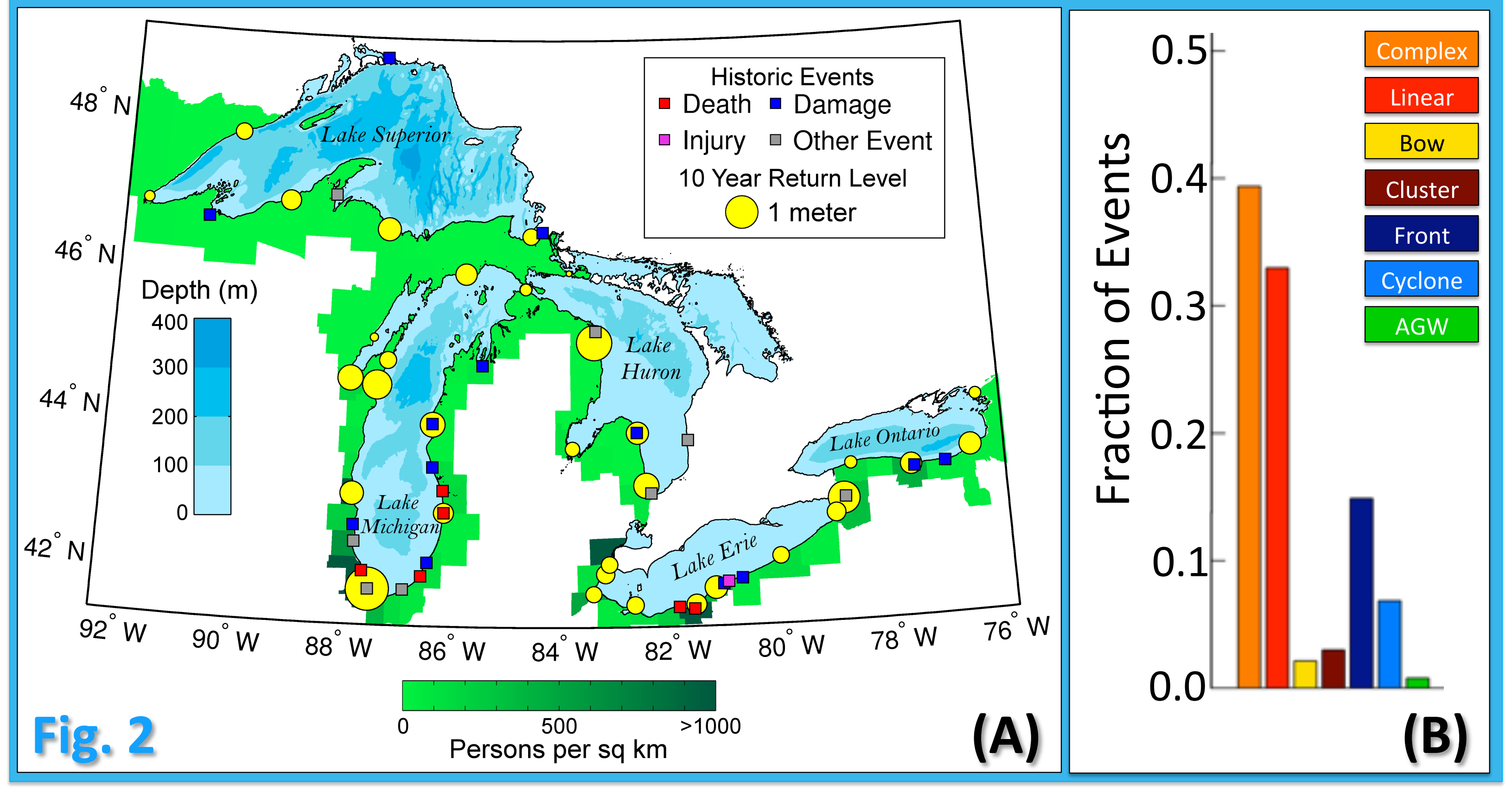

Fig. 2

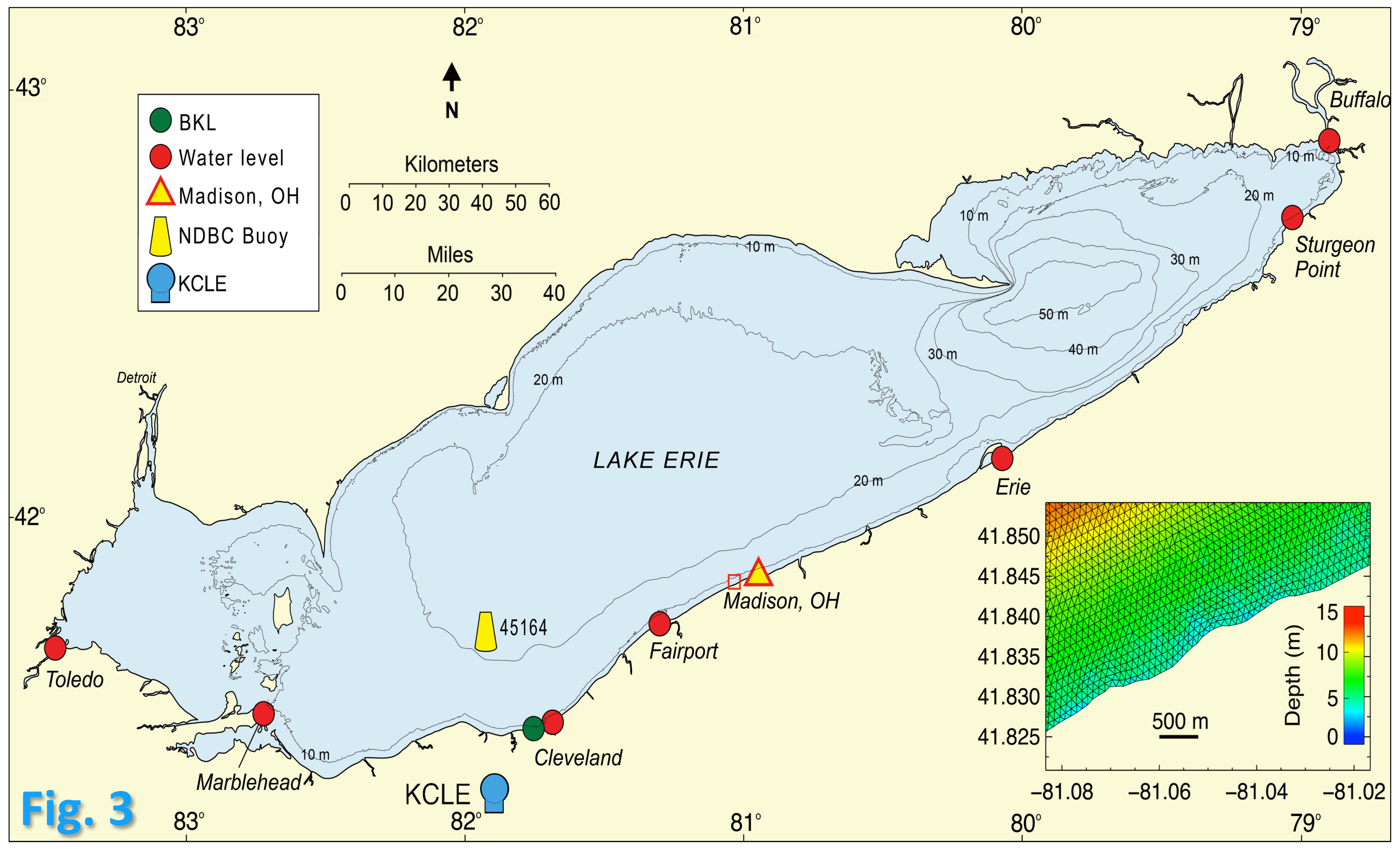

Fig. 3

Lake Erie 2012

On 27 May 2012, atmospheric conditions gave rise to two convective systems that generated a series of waves in the meteotsunami band on Lake Erie **[Fig. 4, 5]**. The resulting waves swept three swimmers a 0.5 mi offshore, inundated a marina, and may have led to a capsized boat along the southern shoreline. Analysis of radial velocities from a nearby radar tower in combination with coastal meteorological observation indicates that the convective systems produced a series of outflow bands that were the likely atmospheric cause of the meteotsunami **[Fig. 4]**.

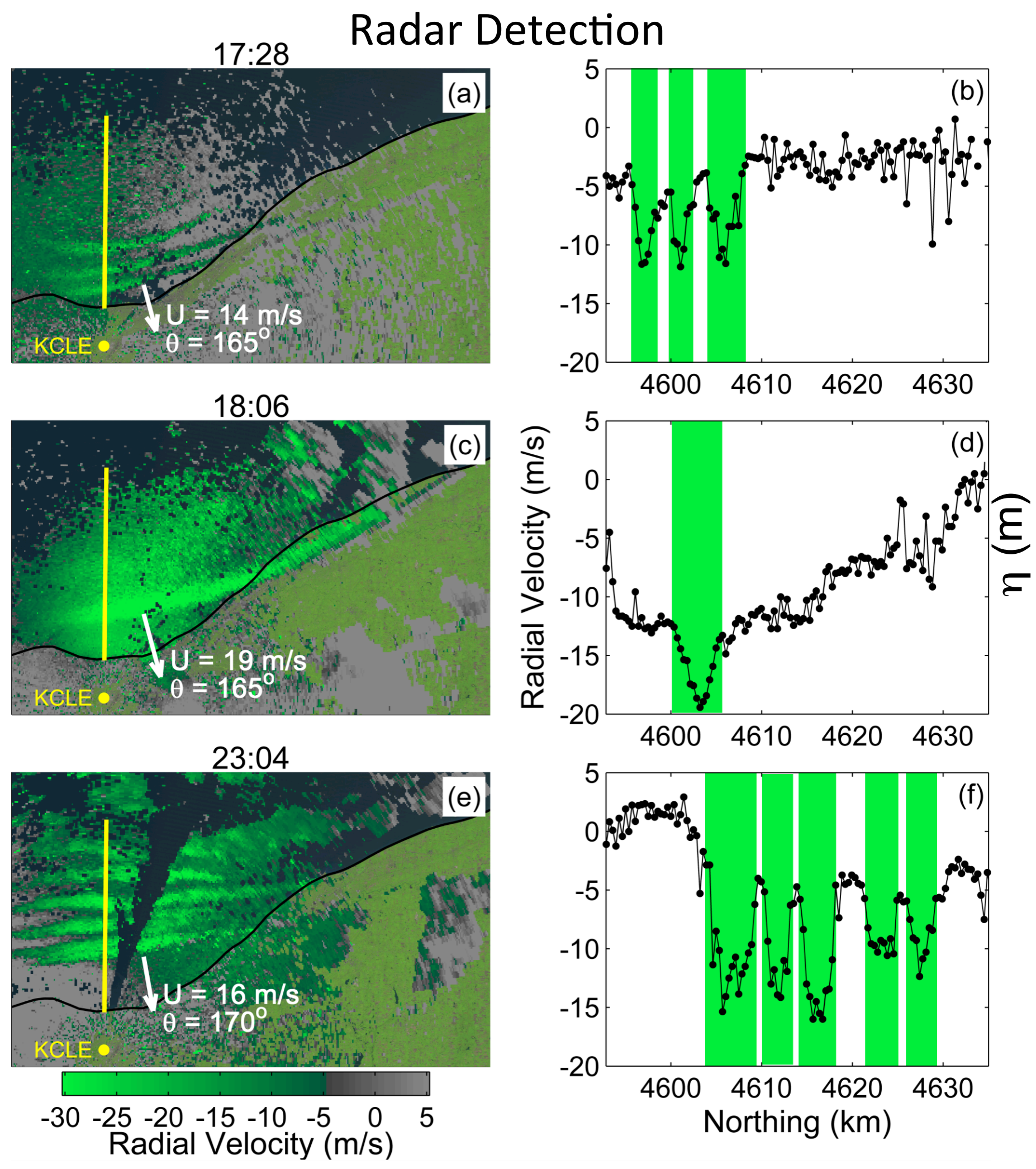

Fig. 4: Radial velocity observations illustrate three distinct bands of outflows as a result of the storm fronts. Band 1 (top), moving at 14 m/s contains 3 waves with a period of 5 minutes. Band 2 (middle) contains one outflow wave traveling at 19 m/s, period 6 minutes. Band 3 (bottom) contains 5 outflow waves, traveling at 17 m/s, with periods of 5 minutes. Outflows from each band are highlighted on the right panels.

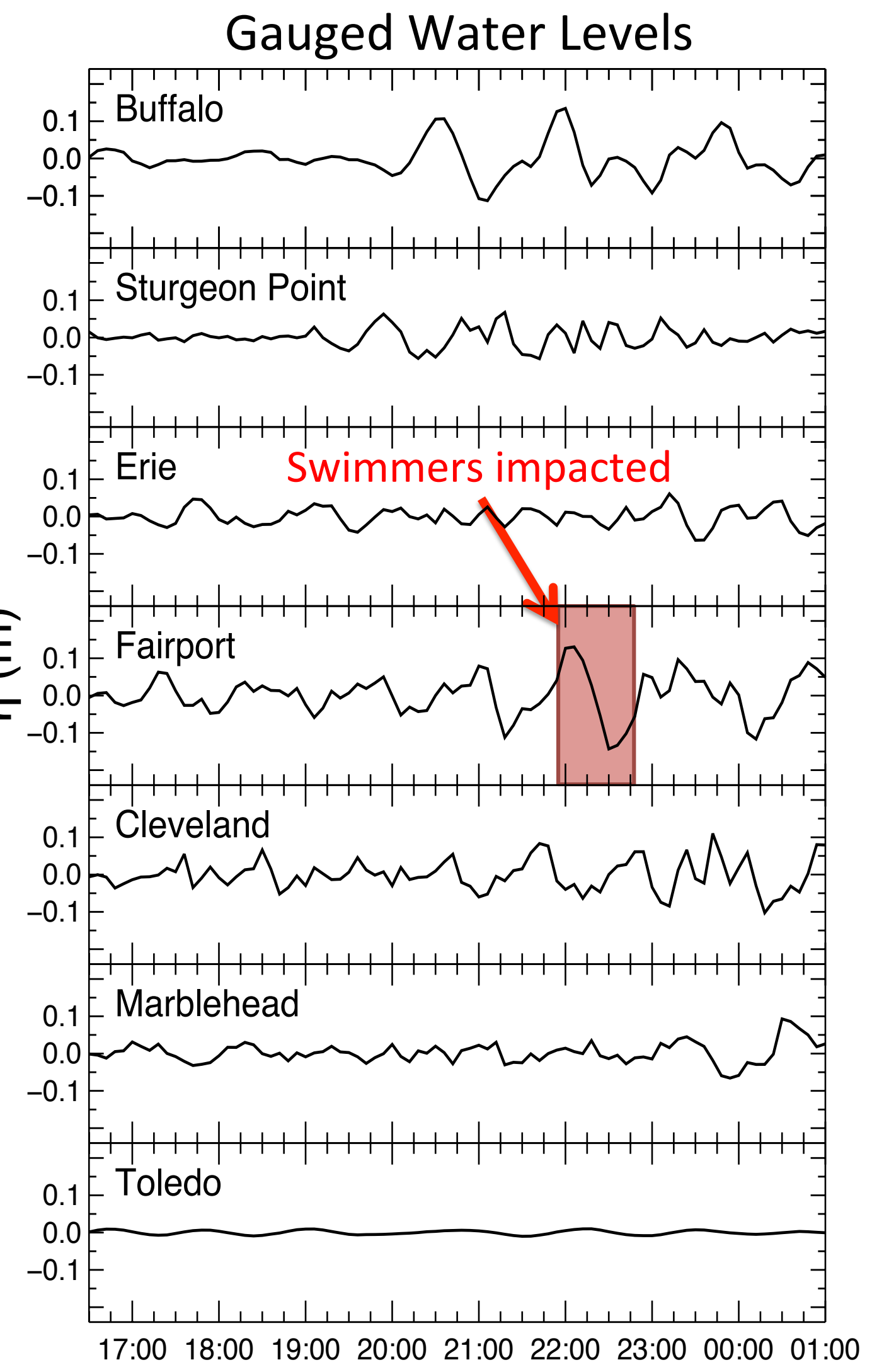

Fig. 5: Observed water levels at southern Lake Erie gauges, high-pass filtered for meteotsunami frequency band. Beach goers impacted near Fairport, OH just after 22:00 GMT.

Atmospheric Conditions

In order to explain the processes that led to meteotsunami generation, we model the hydrodynamic response to three meteorological forcing scenarios: **(i)** the reconstructed atmospheric disturbance from radar analysis, **(ii)** simulated conditions from a 1-km WRF model, and **(iii)** interpolated meteorological conditions from the NOAA Great Lakes Coastal Forecasting System (GLCFS) **[Fig. 6, 7]**.

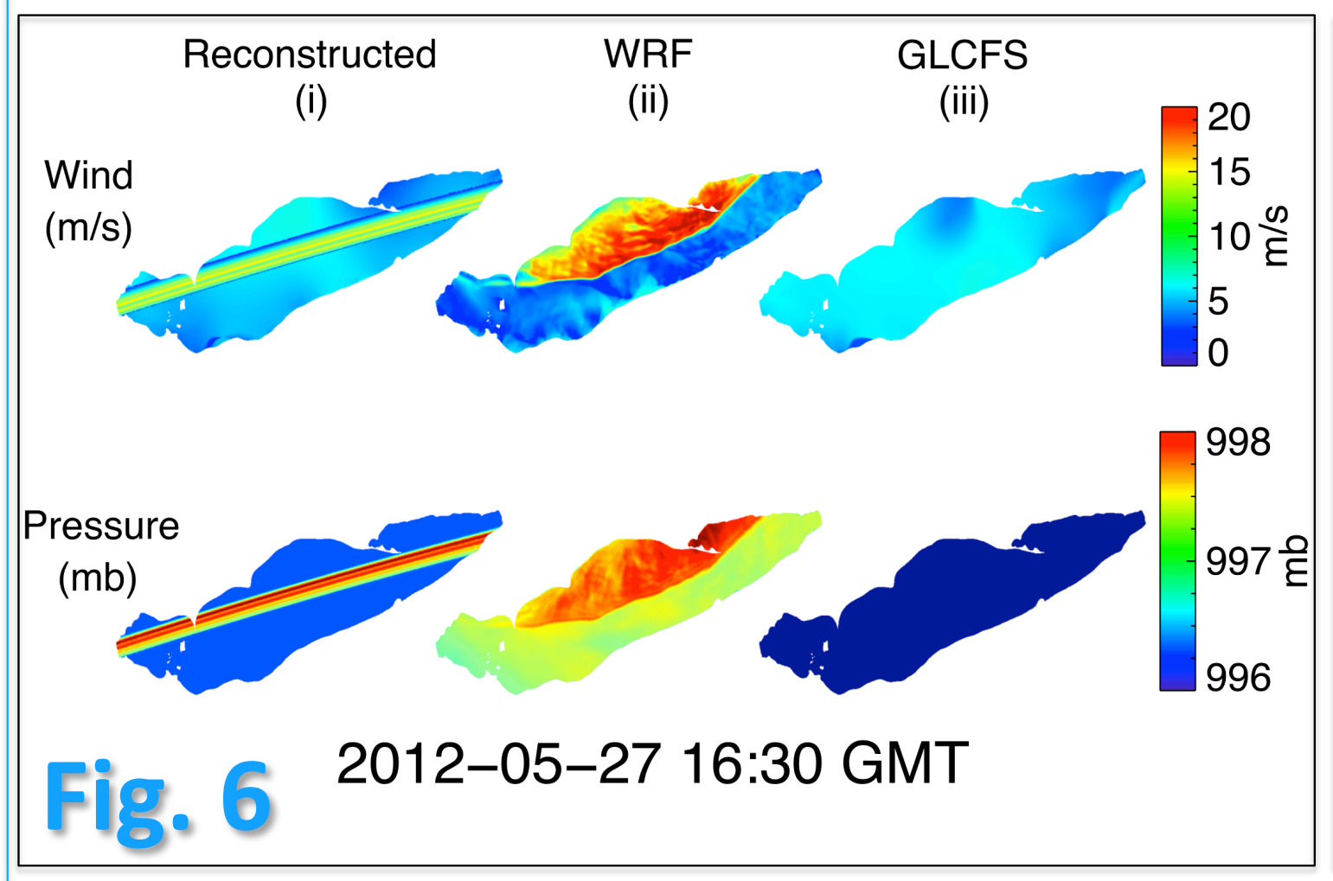

Fig. 6

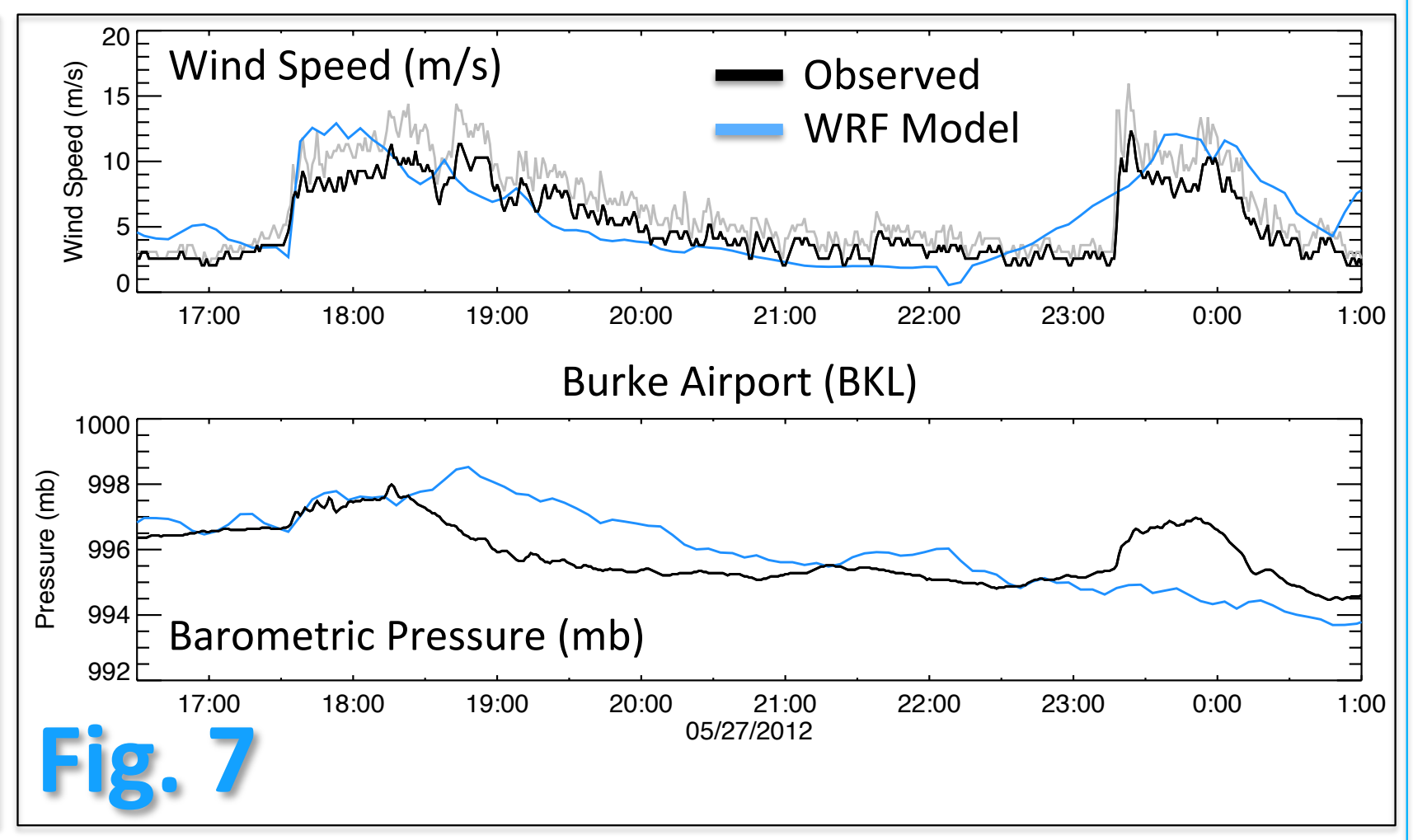

Fig. 7

Hydrodynamic Response

An FVCOM model of Lake Erie **[Fig. 3 inset]**, developed for the next-generation NOAA Great Lakes Operational Forecast System (GLOFS) is used to model the hydrodynamic response to the May 27 event. Through observed **[Fig. 5]** and modeled water levels **[Fig. 8, 9]**, the first of two convective systems from the north generated a series of waves in the meteotsunami band that reflected off the southern and then northern shores of the lake, returning to the southern shore. Due to the concavity of the northern shore, the reflected wave was spatially focused as it propagated southward back towards the southern shore, producing a larger displacement than found during the initial storm front.

The combination of these waves produced edge waves that traveled westward along the shoreline, resulting in a dramatic and rapid rise and fall of the water level that impacted recreational users at a time when weather conditions were relatively calm.

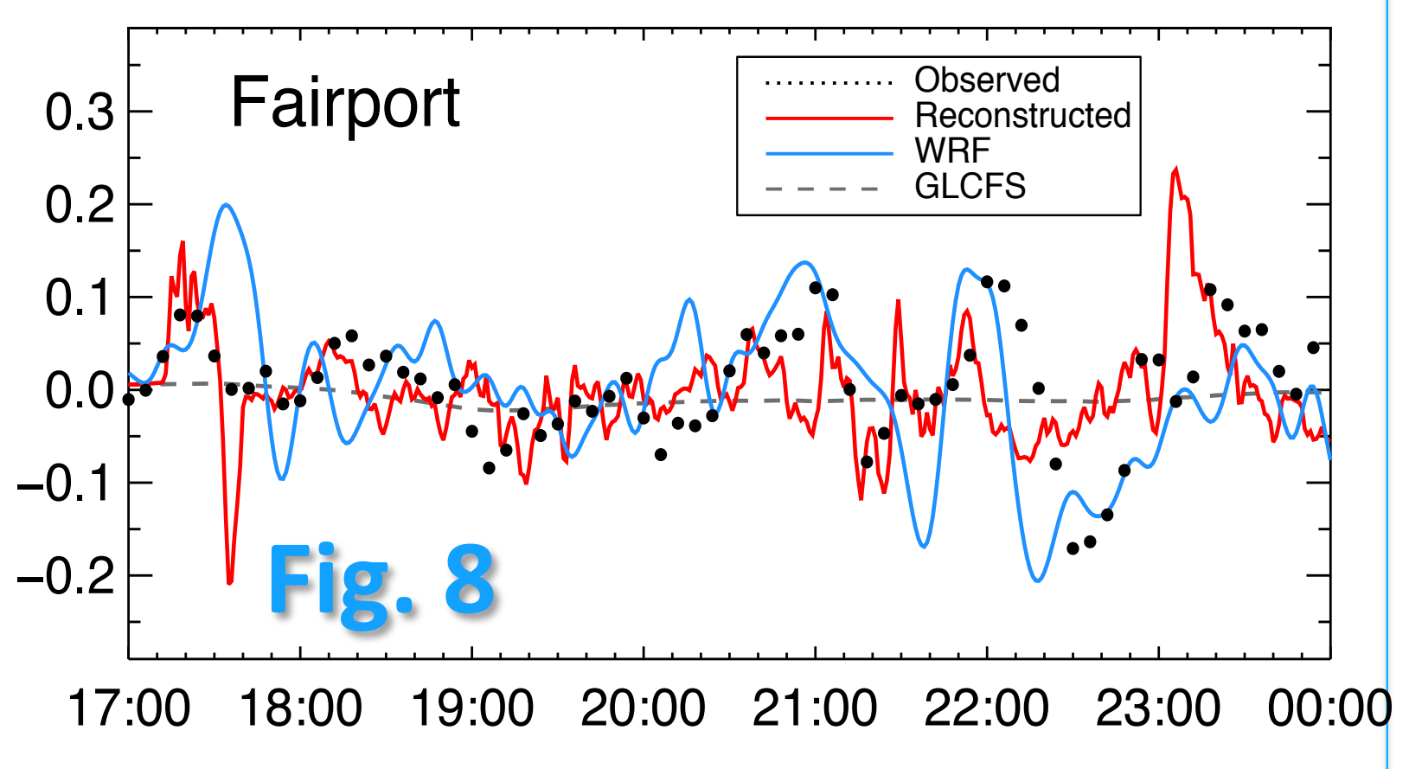

Fig. 8

High-resolution WRF simulations **(ii)** produced the best representation of the observed displacement found at the Fairport gauge **[Fig. 8]**, illustrating the importance of resolving sharp gradients in wind stress and pressure as well as the current modeling gaps in the GLOFS forcing **(iii)**.

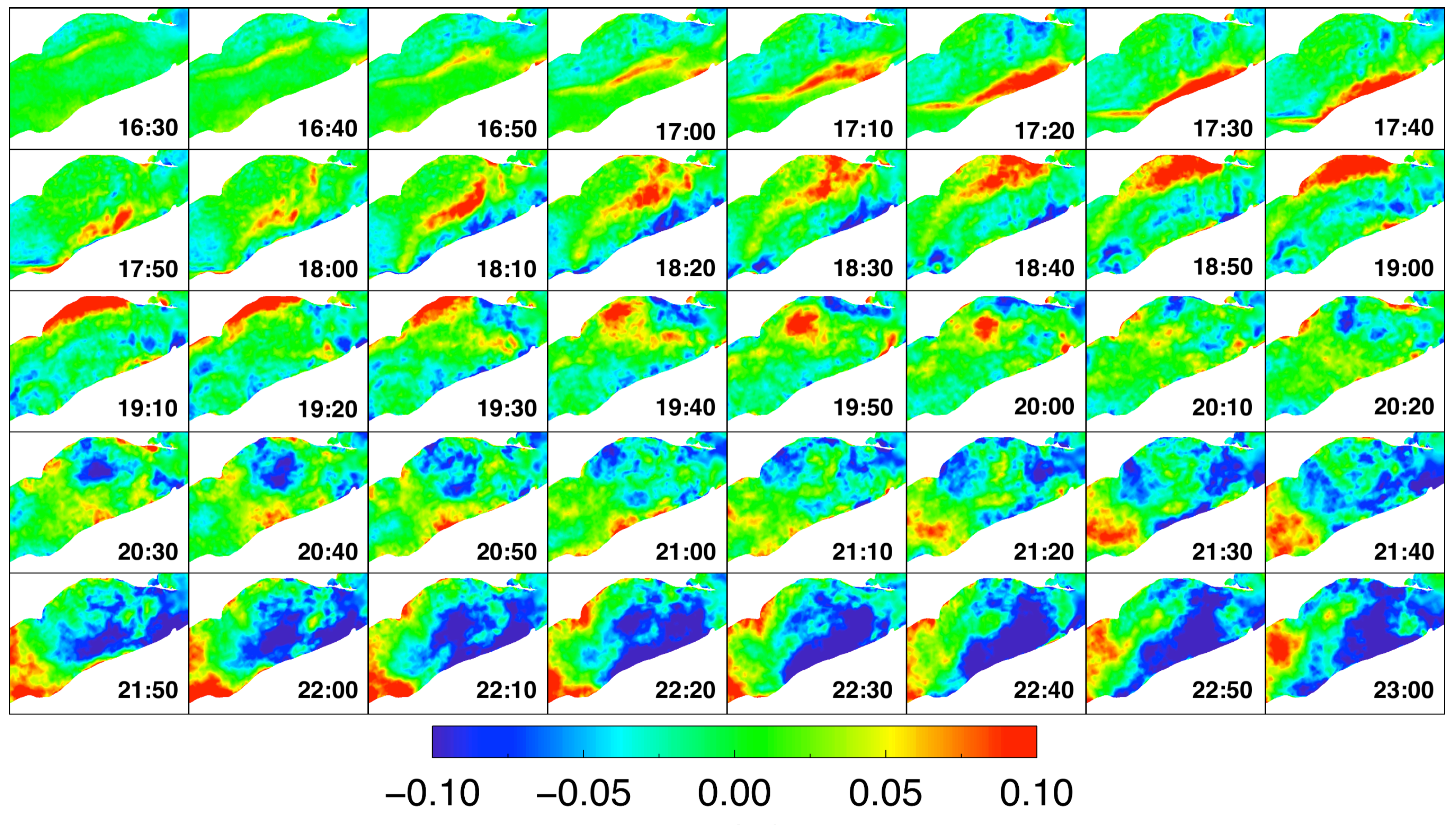

Fig. 9: Simulated water level response using WRF meteorology (case *ii*) over Lake Erie on May 27, 2012 (times in GMT). Displacements (η) are shown for the range -0.10 to 0.10 m to highlight wave reflection and refraction, where displacements outside of this range given a constant color (purple or red, respectively).

Conclusions

- Meteotsunamis occur in all Great Lakes, connected to rip current incidents
  - Southern Lake Michigan and Lake Erie are most vulnerable
- Great Lakes meteotsunamis driven by complex and linear convective storms
- Meteotsunami-inducing storms can move undetected through observation networks
- Radar-based velocity allows for detection of meteotsunami-inducing front
- Wave reflection, focusing, and edge waves play important role in enclosed basins
- High-resolution models can capture the mechanisms behind meteotsunami formation
- Advanced weather models can resolve spatio-temporal features of meteotsunami-inducing storms
  - NOAA High-Resolution Rapid Refresh (HRRR; 3km meteorology)
  - Next-Generation NOAA GLOFS models use HRRR forcing

Lake Superior 2014

On September 4, 2014, a complex convective storm moved eastward (28 m/s, 115°) across the upper peninsula of Michigan and along the southern shore of Lake Superior **[Fig. 10]**, producing a sharp wise in wind speed (> 10 m/s) and drop in atmospheric pressure (>0.2 mb/min) at the eastern end of the lake **[Fig. 11]**. The storm generated a 70-minute wave that excited a 4-hour mode in Whitefish Bay **[Fig. 12]**, with displacements close to 1 meter, inundating the shores on the east end of Superior.

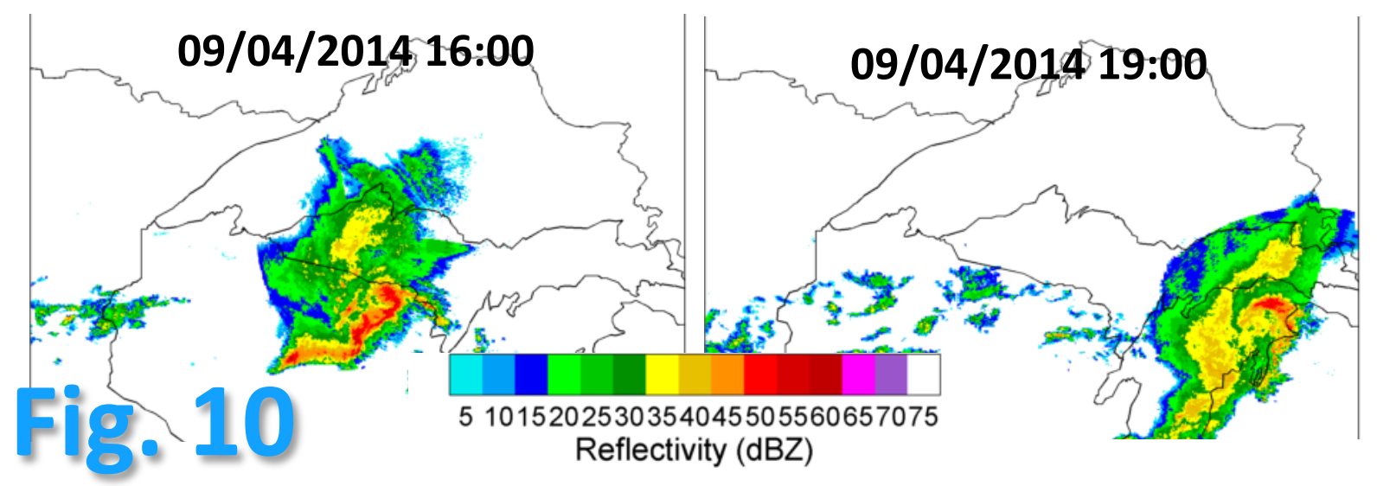

Fig. 10

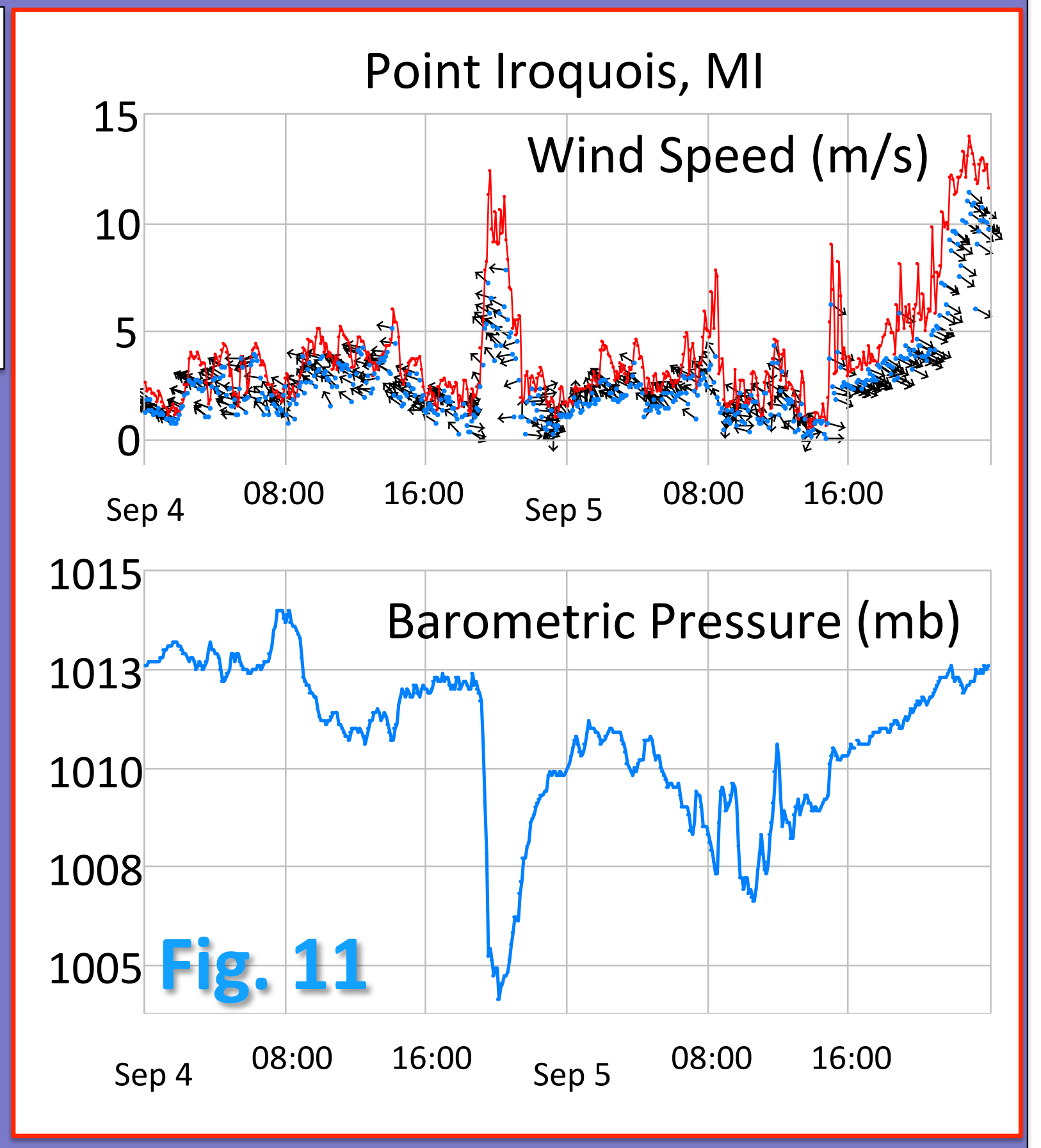

Fig. 11

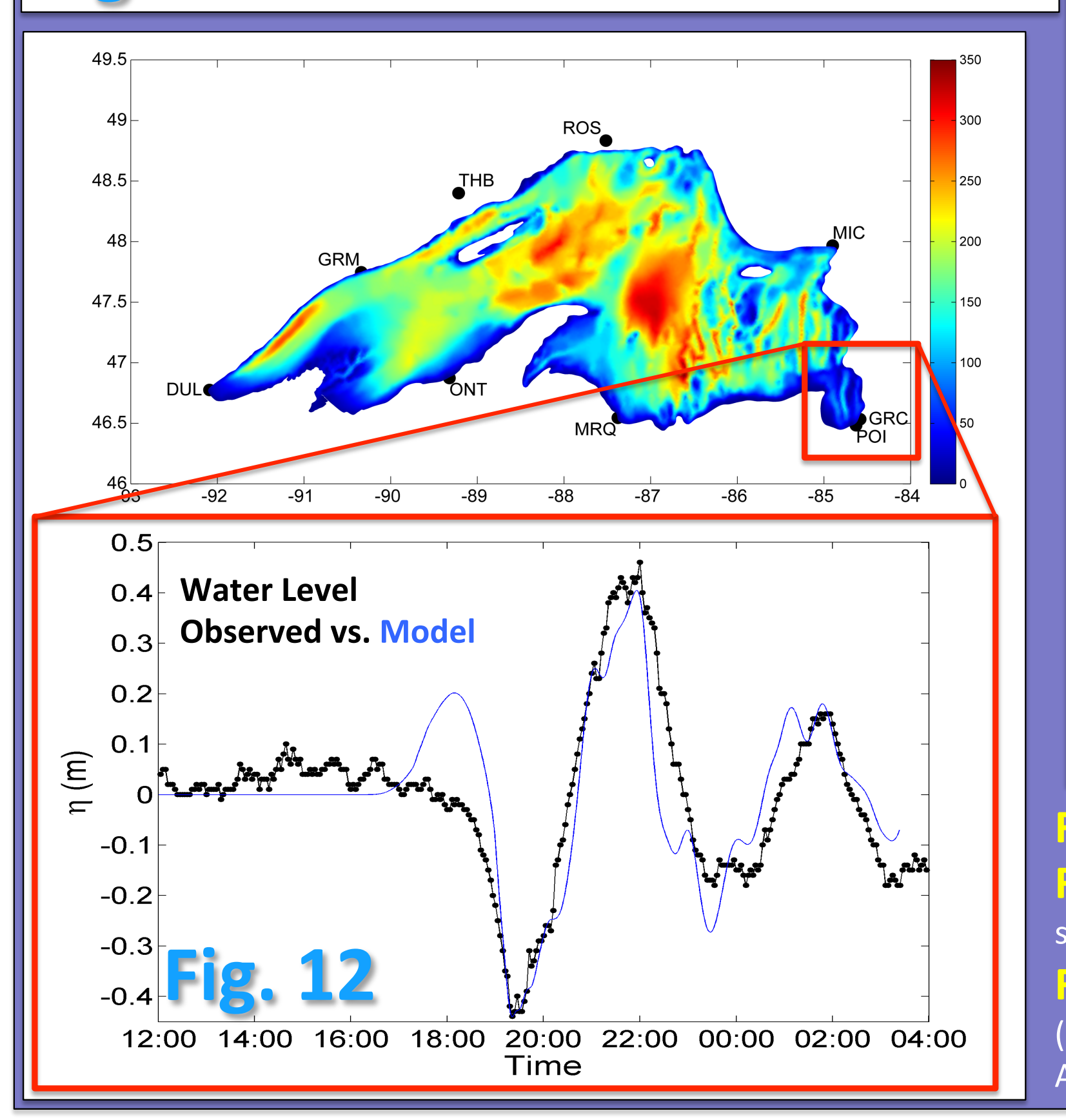

Fig. 12

Fig. 10: Radar reflectivity from storm over southern Lake Superior

Fig. 11: Recorded wind speed and barometric pressure during the storm system, located near the southeastern edge of the lake.

Fig. 12: Observed water level at the NOS Point Iroquois gauge (black circles) and hydrodynamic model results (blue line). Atmospheric forcing was reconstructed from observed meteorology.

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