Winter ice-wave modeling with WAVEWATCH III in Lake Erie

Haoguo Hu[1*], Dan Titze[2*], Ayumi Fujisaki-Manome[1,2], Bryan Mroczka[4], Jia Wang[3], Nathan Hawley[4], Sophie Orendorf[1], Kaitlyn Frank[5], and Steve Ruberg[3]

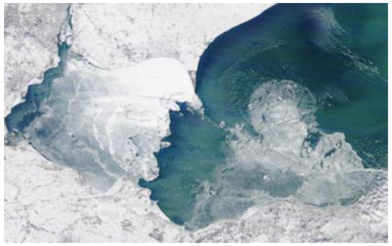
[1] Cooperative Institute for Great Lakes Research (CIGLR), University of Michigan, Ann Arbor, Michigan, USA.
[2] Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, Michigan, USA.
[3] NOAA, Great Lakes Environmental Research Laboratory (GLERL), Ann Arbor, Michigan, USA.
[4] Formerly at NOAA, GLERL, Ann Arbor, Michigan, USA
[5] Formerly at CIGLR, University of Michigan, Ann Arbor, Michigan, USA.

* Corresponding authors: Haoguo Hu, hghu@umich.edu Dan Titze dan.titze@noaa.gov

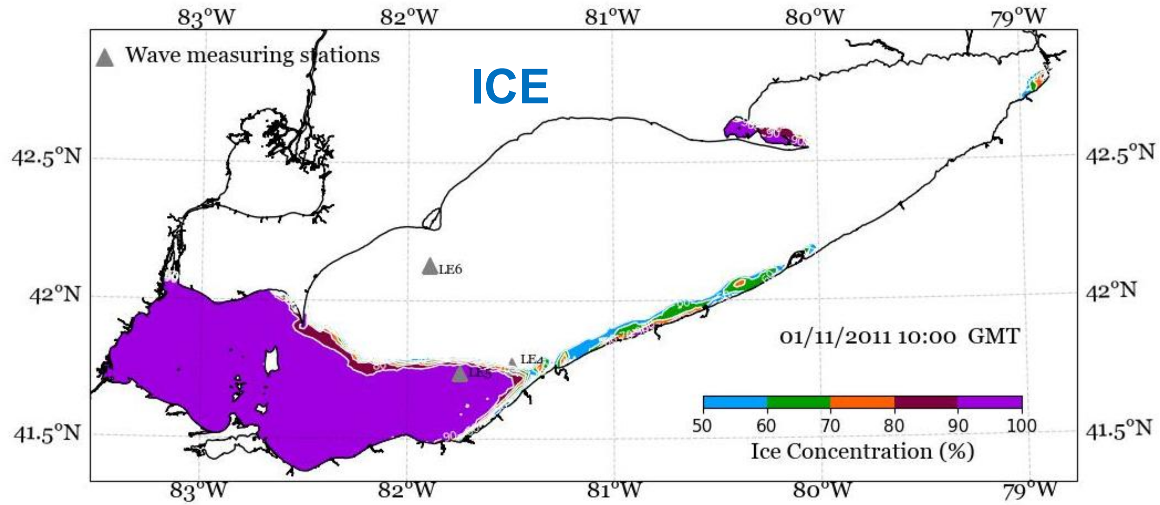
4th International Workshop on Waves, ,Storm Surges and Coastal Hazards
September 22-26, 2025. Santander, Spain

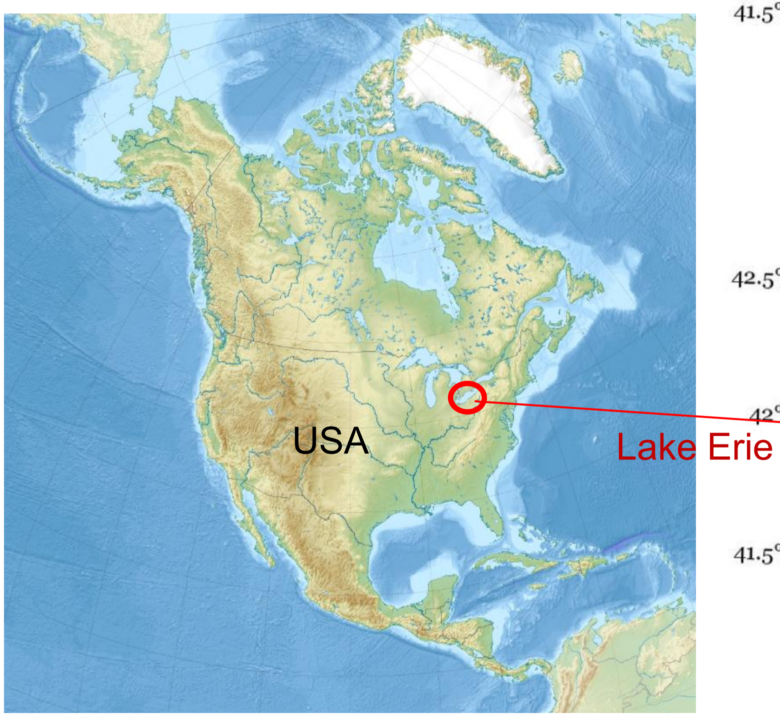
The problem: The current using of ice module IC0

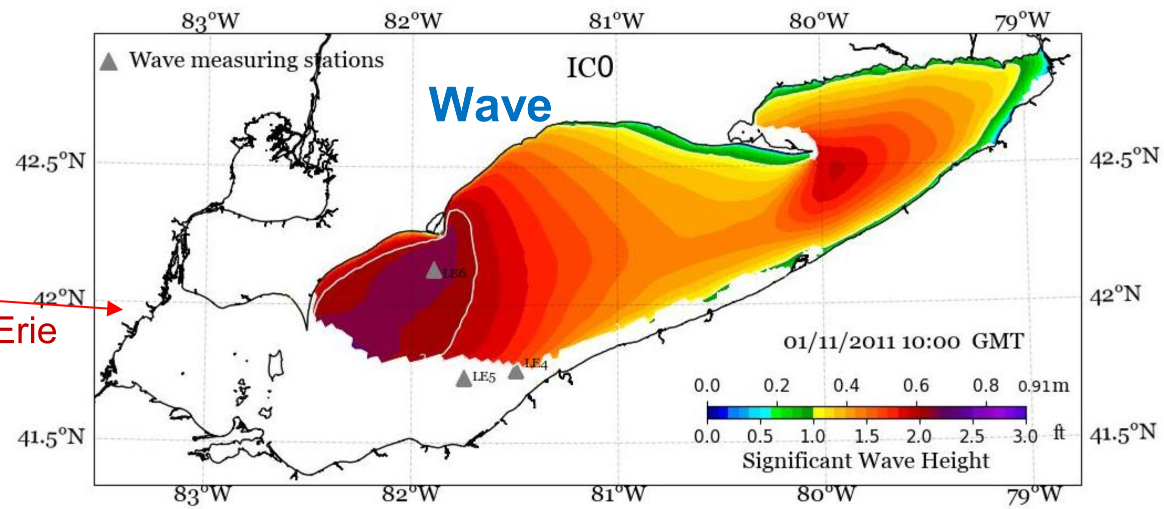
IC0 take ice covered area as land



Ice image from Moderate resolution Imaging Spectroradiometer MODIS







No wave in ice covered area with IC0

The problem: ice modules in WaveWatch3 (WW3)

IC0 IC1 IC2 IC3 IC4M1 IC4M2 IC4M3 IC4M4 IC4M5 IC4M6 IC4M7 IC5

	Description	Attenuation coefficient empirical relationship	Values of tunable parameters used	References
IC0	Simple ice blocking	N/A (see references for description)	N/A	WW3DG (2019)
IC1	Simple ice damping	$\alpha = 2C_1$	C_1 (damping coefficient, m^{-1}): 2.0×10^{-5}	Rogers and Orzech (2013), WW3DG (2019)
IC2	Viscoelastic damping with ice modeled as continuous thin elastic plate	N/A (see references for description)	C_1 (ice thickness, m): 0.15 C_2 (eddy viscosity, $m^2 s^{-1}$): 1.0×10^{-5} C_3 (water depth, m): 20	Rogers and Orzech (2013), WW3DG (2019)
IC3	Viscoelastic damping with ice modeled as frazil ice floes	N/A (see references for description)	C_1 (ice thickness, m): 0.15 C_2 (effective viscosity of ice, $m^2 s^{-1}$): 3 C_3 (ice density, kg m^{-3}): 917 C_4 (effective shear modulus of ice, Pa): 0	Wang and Shen (2010), WW3DG (2019)
IC4M1	Empirical exponential damping as a function of wave period (T), with higher damping for smaller-period waves	$\alpha = e^{\left(\frac{-2\pi C_1}{T} - C_2\right)}$	C_1, C_2 (empirical): 0.18, 7.3	Collins and Rogers (2017), Wadhams et al. (1988), WW3DG (2019)
IC4M2	Empirical polynomial-fit damping as a function of wave period (T), designed to be flexible	$\alpha = C_1 + C_2\left(\frac{T}{2\pi}\right) + C_3\left(\frac{T}{2\pi}\right)^2 + C_4\left(\frac{T}{2\pi}\right)^3 + C_5\left(\frac{T}{2\pi}\right)^4$	C_1–C_5 (empirical): 0, 0, 2.12×10^{-3}, 0, 4.59×10^{-2}, 1.1	Collins and Rogers (2017), Meylan et al. (2014), WW3DG (2019)
IC4M3	Empirical quadratic decay as a function of wave period (T) and ice thickness, with higher attenuation for thicker ice and smaller-period waves	$\alpha = exp[-3.203 + 2.058\,C_1 - 0.9375\,T - 0.4269\,C_1^2 + 0.1566\,C_1 T + 0.0006\,T^2]$	C_1 (ice thickness, m): 0.15	Collins and Rogers (2017), Horvat and Tziperman (2015), WW3DG (2019)
IC4M4	Empirical damping as a step function of significant wave height (Hs), with linear damping for Hs ≤ 3 m and capped damping for Hs > 3 m	$\alpha = \begin{cases} 2C_1 & \text{for } H_s \le 3\text{ m} \\ 2C_2 H_s^{-1} & \text{for } H_s > 3\text{ m} \end{cases}$	C_1, C_2 (empirical): 5.35×10^{-6}, 16.05×10^{-6}	Collins and Rogers (2017), Kohout et al. (2014), WW3DG (2019)
IC4M5	Empirical damping as a step function of wave period (T), with four user-defined steps and damping coefficients	$\alpha = \begin{cases} 2C_1 & \text{for } T^{-1} < C_5 \\ 2C_2 & \text{for } C_5 \le T^{-1} < C_6 \\ 2C_3 & \text{for } C_6 \le T^{-1} < C_7 \\ 2C_4 & \text{for } T^{-1} \ge C_7 \end{cases}$	C_1–C_4 (damping coefficients, m^{-1}): 5.0×10^{-6}, 7.0×10^{-6}, 15.0×10^{-6}, 100.0×10^{-6} C_5–C_7 (step bounds, Hz): 0.10, 0.12, 0.16	Collins and Rogers (2017), WW3DG (2019)
IC4M6	Empirical damping as a step function of wave period (T), with up to ten user-defined steps and damping coefficients	$\alpha = \begin{cases} 2C_{A1} & \text{for } T^{-1} < C_{B1} \\ 2C_{A2} & \text{for } C_{B1} \le T^{-1} < C_{B2} \\ \dots & \\ 2C_{A9} & \text{for } C_{B8} \le T^{-1} < C_{B9} \\ 2C_{A10} & \text{for } C_{B9} \le T^{-1} < C_{B10} \end{cases}$	C_{A1}–C_{A10} (damping coefficients, m^{-1}): 5.0×10^{-6}, 7.0×10^{-6}, 1.5×10^{-5}, 1.0×10^{-4}, 0, 0, 0, 0, 0, 0 C_{B1}–C_{B10} (step bounds, Hz): 0.10, 0.12, 0.16, 99.0, 0, 0, 0, 0, 0, 0	Collins and Rogers (2017), WW3DG (2019)
IC4M7	Empirical damping as a function of wave period (T) and ice thickness	$\alpha = 0.2T^{-2.13}C_1$	C_1 (ice thickness, m): 0.15	Doble et al. (2015), WW3DG (2019)
IC5	Viscoelastic damping with ice modeled as thin elastic plate restricted to one dimension	N/A (see references for description)	C_1 (ice thickness, m): 0.15 C_2 (effective viscosity, $m^2 s^{-1}$): 1.6×10^7 C_3 (ice density, kg m^{-3}): 917 C_4 (effective shear modulus, Pa): 4×10^{12}	Mosig et al. (2015), WW3DG (2019)

Which one should we use ?

They are mostly based on the Arctic and Antarctic researches

We have tested all 12 modules

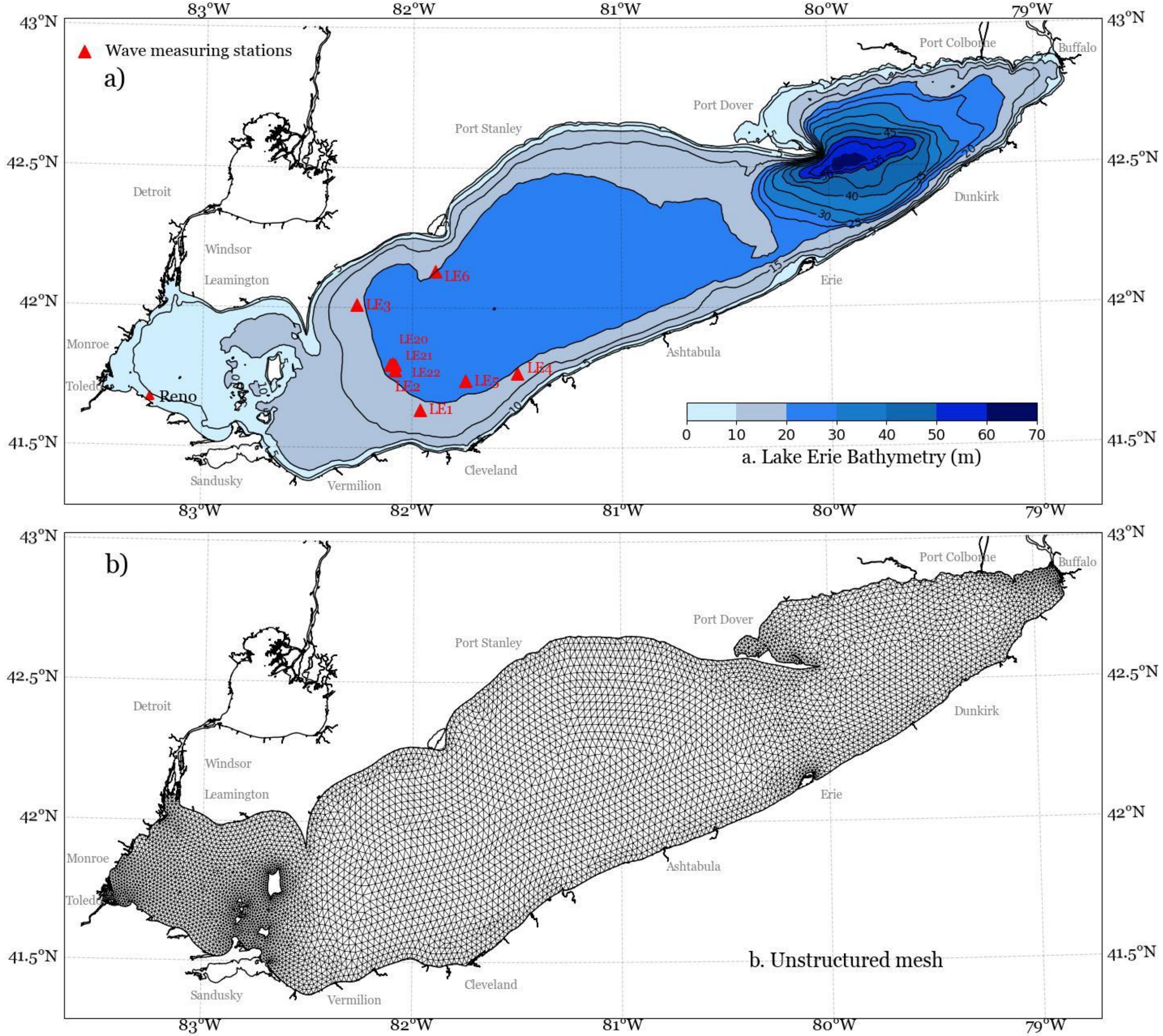
IC0 take ice as land

IC1 and IC4M4 are similar with constant parameters
IC4M4 with wave height considered

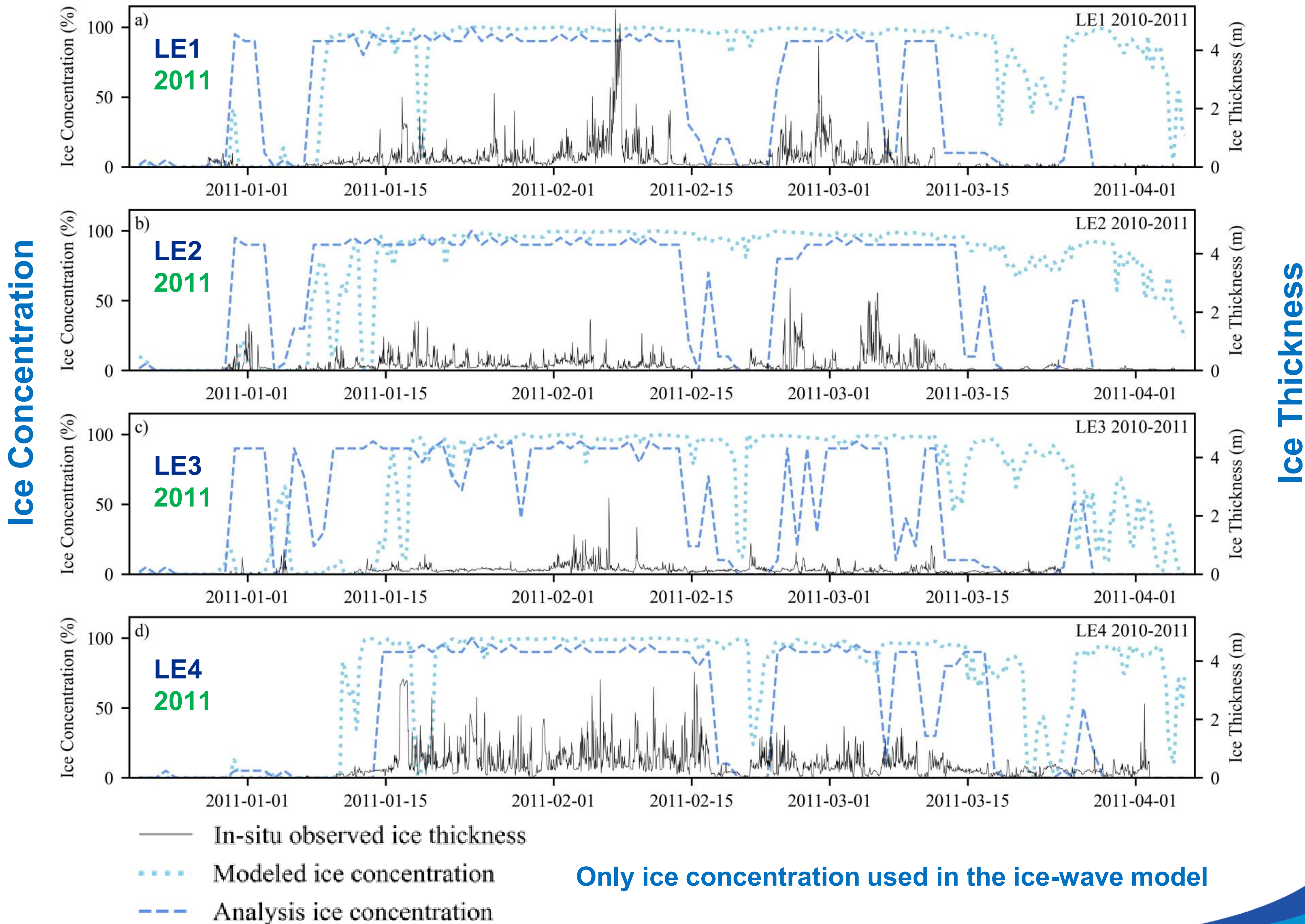
All other ice modules are related to wave frequency

We have tested them all

Bathymetry and model grid

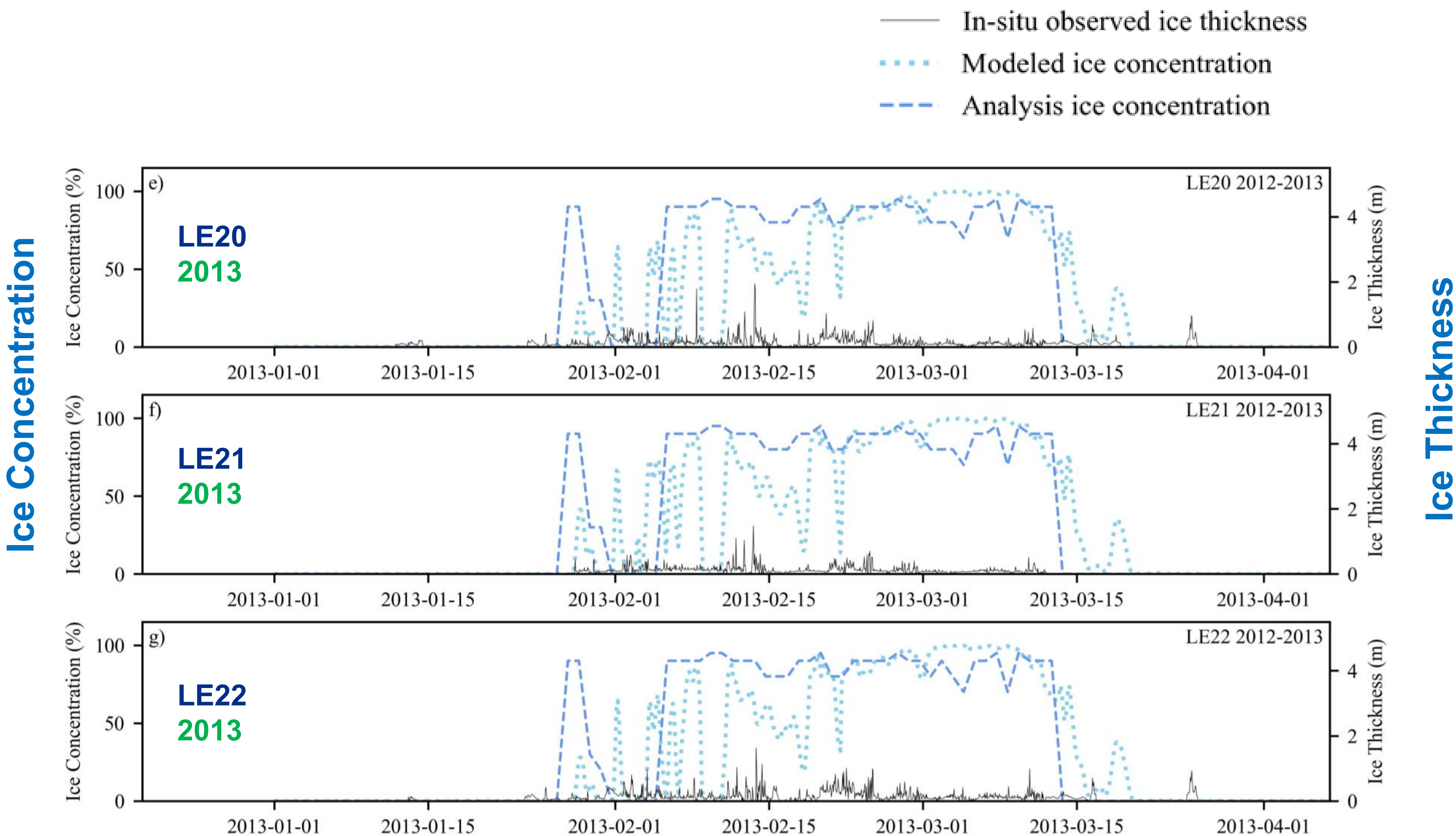


Ice data (observed, modeled, and analyzed)



Only ice concentration used in the ice-wave model

Ice data (observed, modeled, and analyzed)



Wave height from 12 ice modules (modeled vs observed, at LE4, 2011)

IC4M4 performs the best

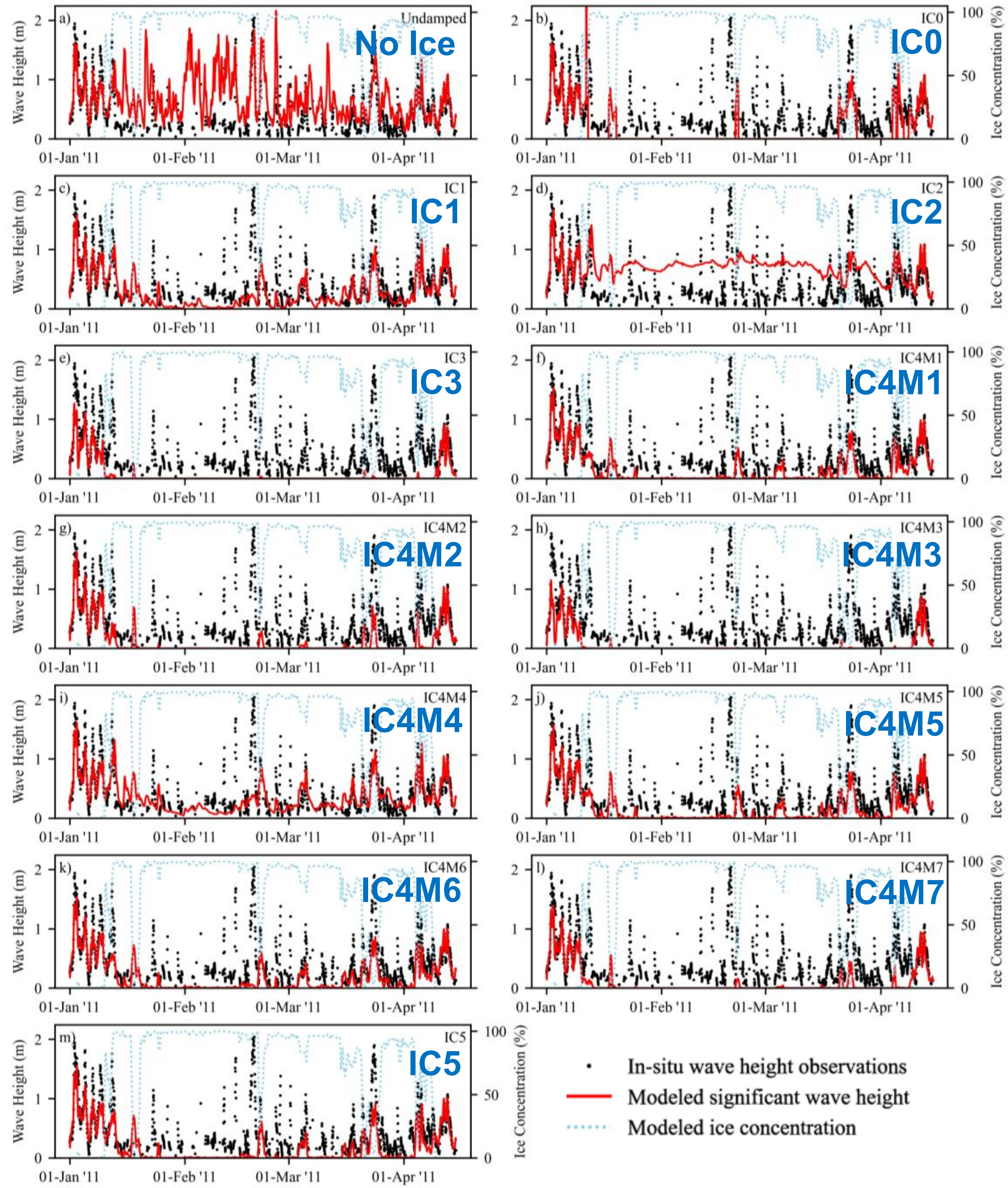
Table 4
Skill Statistics for Ice-Wave Damping Cases, Calculated by Comparing Modeled Significant Wave Height to In-Situ Observed Significant Wave Height From 1 January to 15 April 2011

	LE4 (n = 1,482)		LE5 (n = 1,080)		LE6 (n = 637)	
	RMSE	Bias	RMSE	Bias	RMSE	Bias
Undamped	0.37	+0.15	0.30	+0.06	0.27	+0.11
IC0	0.46	−0.23	0.59	−0.34	0.54	−0.23
IC1	0.34	−0.13	0.43	−0.19	0.43	−0.12
IC2	0.41	0.19	0.44	+0.18	0.34	+0.12
IC3	0.54	−0.38	0.68	−0.52	0.59	−0.40
IC4M1	0.42	−0.26	0.56	−0.37	0.51	−0.23
IC4M2	0.47	−0.31	0.63	−0.45	0.55	−0.28
IC4M3	0.55	−0.39	0.69	−0.52	0.61	−0.43
IC4M4	0.32	−0.06	0.38	−0.11	0.39	−0.08
IC4M5	0.41	−0.24	0.55	−0.34	0.50	−0.21
IC4M6	0.39	−0.22	0.52	−0.32	0.49	−0.21
IC4M7	0.49	−0.34	0.66	−0.48	0.56	−0.32
IC5	0.40	−0.23	0.53	−0.32	0.50	−0.21

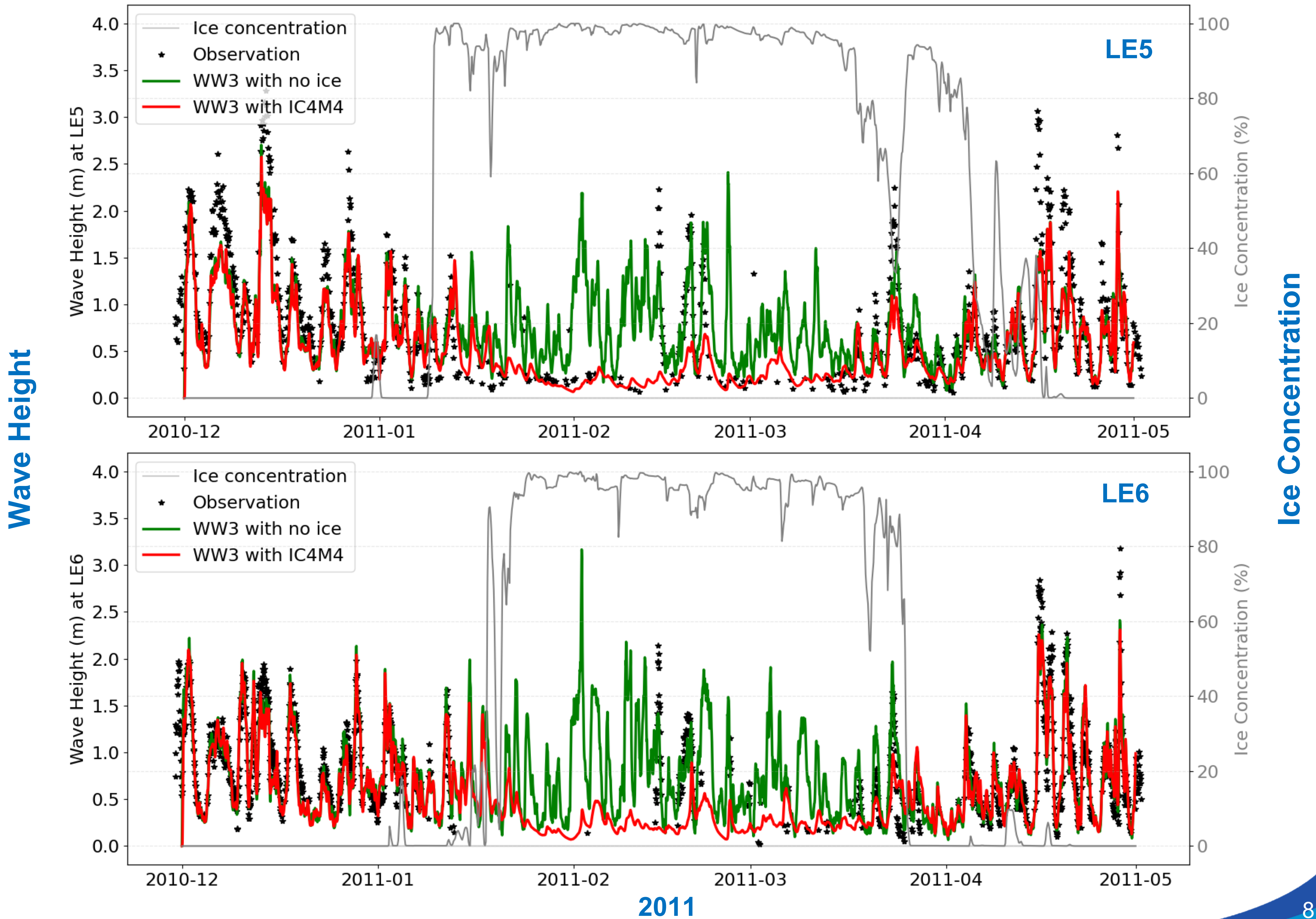
IC4M4 Empirical damping as a step function of significant wave height (Hs), with linear damping for Hs ≤ 3 m and capped damping for Hs > 3 m

$$\alpha = \begin{cases} 2\,C_1 & \text{for } H_s \le 3\text{ m} \\ 2\,C_2\,H_s^{-1} & \text{for } H_s > 3\text{ m} \end{cases}$$

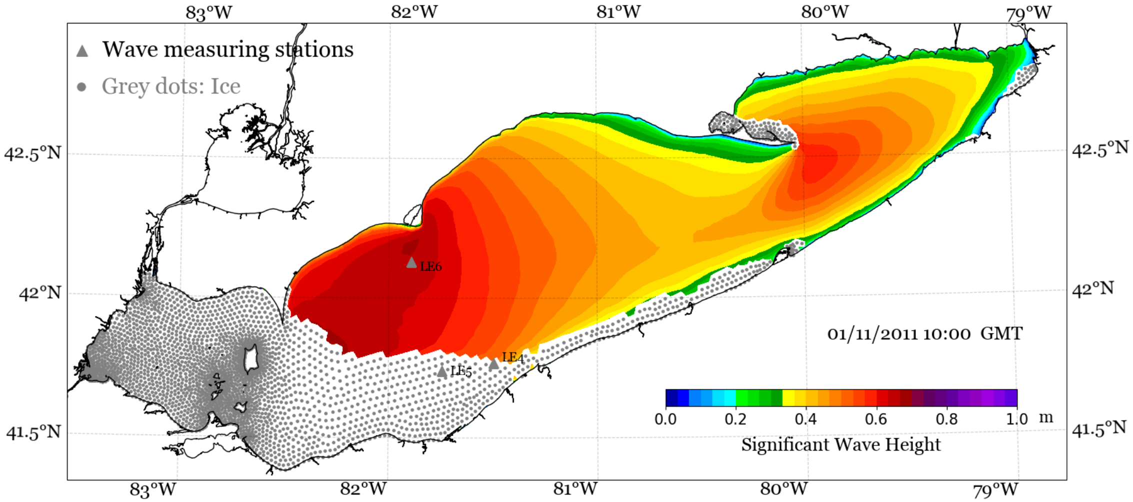
IC1 Simple ice damping $\alpha = 2\,C_1$



Wave height comp (no ice vs IC4M4, and overlayed with observations)

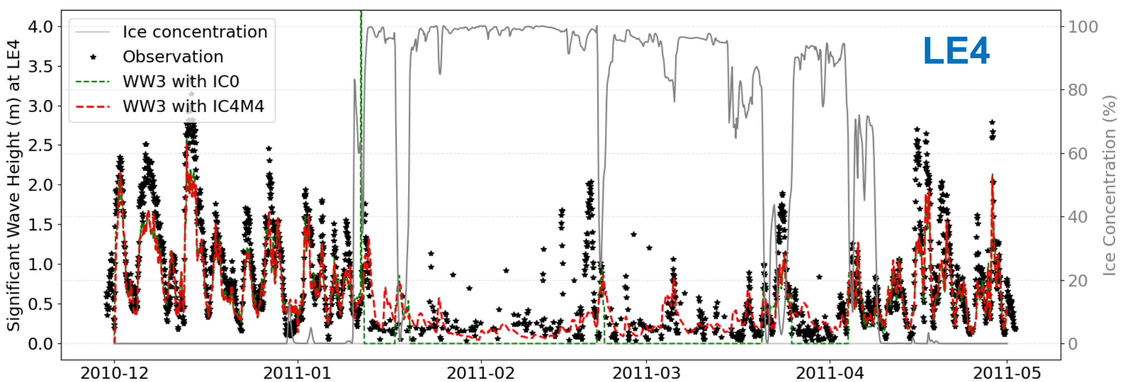


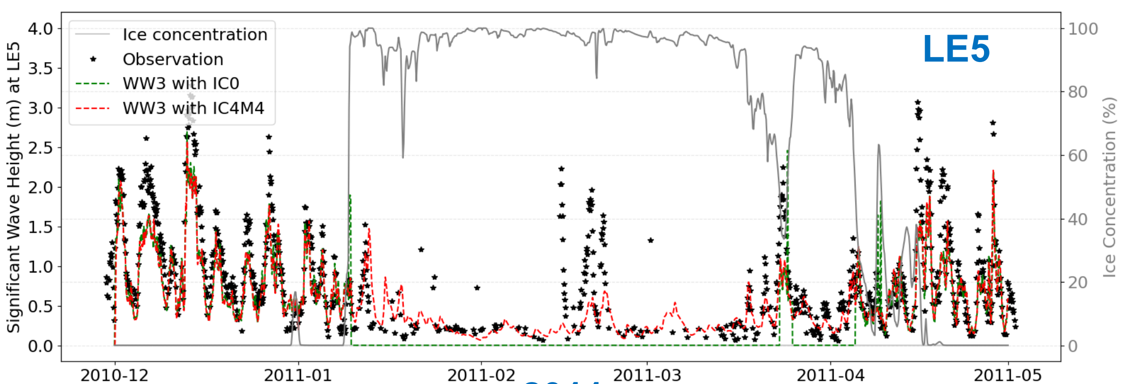
Wave height comp zoom in (IC0 vs IC4M4, and overlayed with observations)



Wave prediction rely on the accuracy of ice forecast

Wave Height

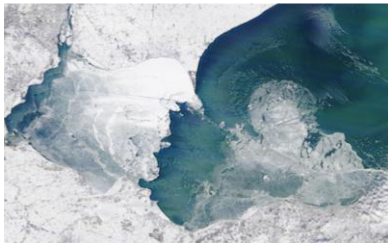




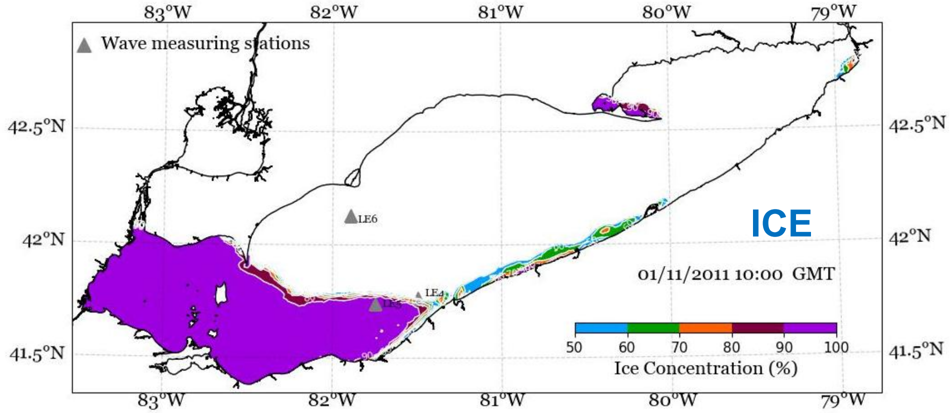
Ice Concentration

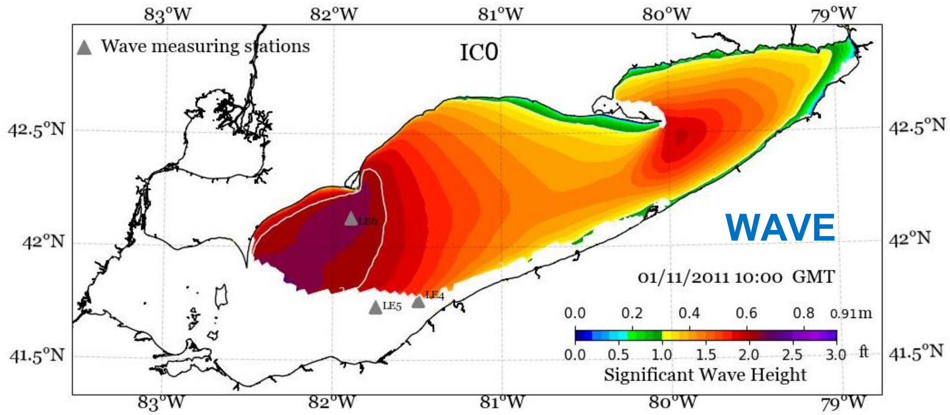
2011

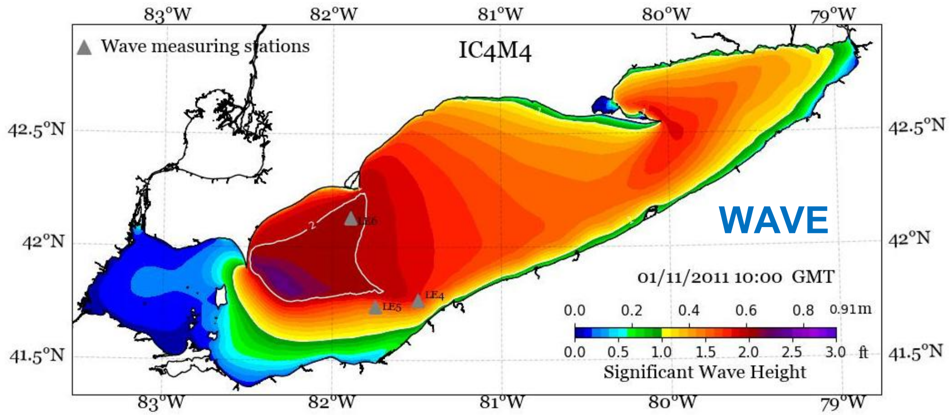
An example of ice event (IC0 vs IC4M4)



Ice image from Moderate resolution Imaging Spectroradiometer MODIS On Jan 11, 2011



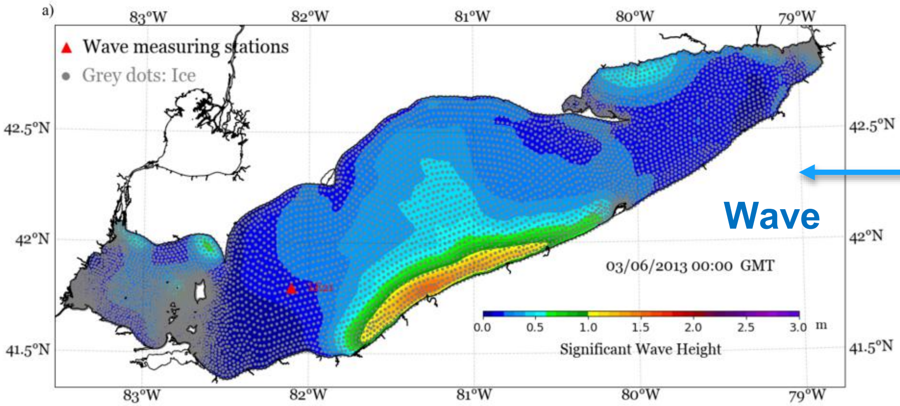




Right panels: model results

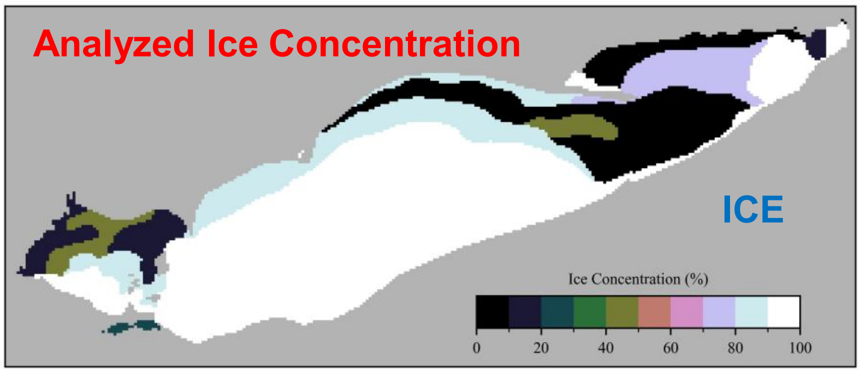
Another example of ice event with IC4M4

a)

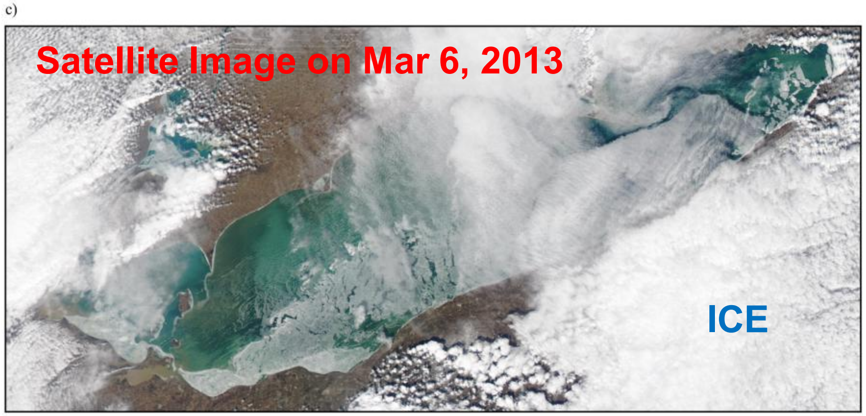


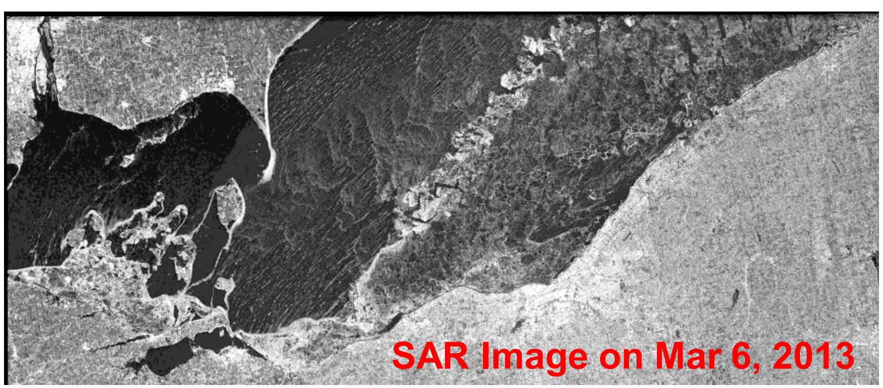
Modeled wave height overlayed with ice (dots) On Mar 06, 2013

b)

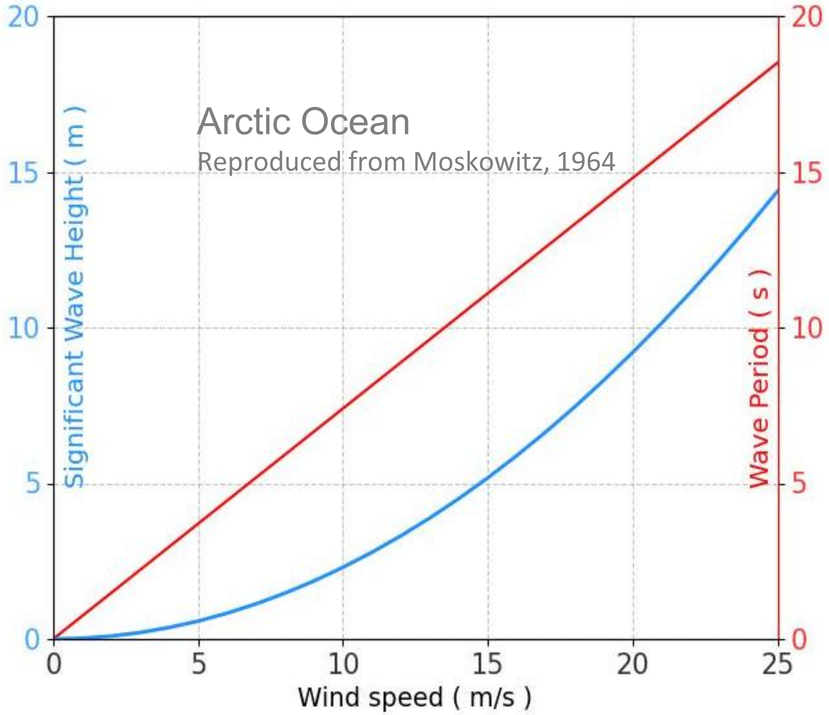


c)

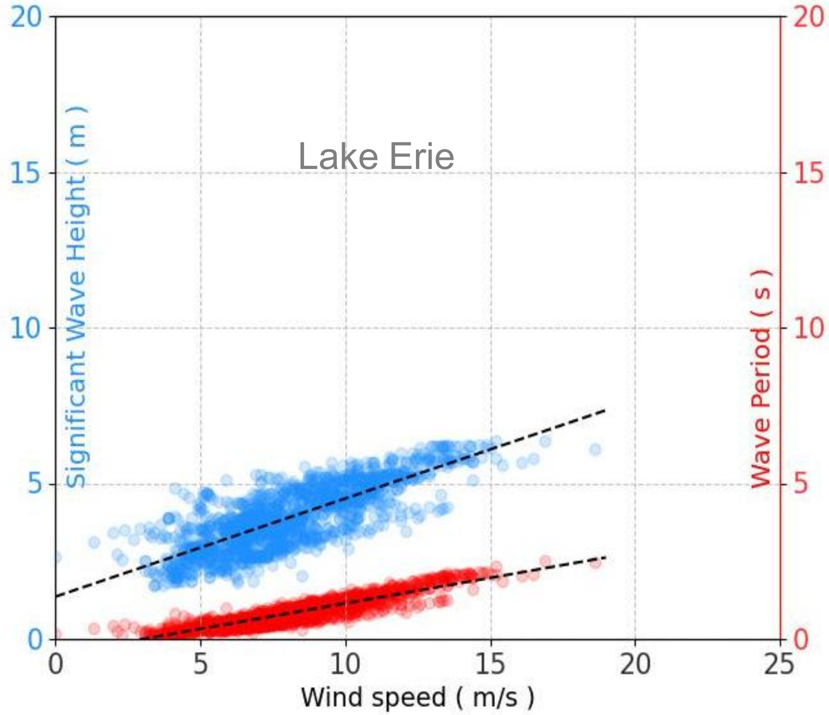




Wave height, period vs wind speed in Arctic Ocean and Lake Erie

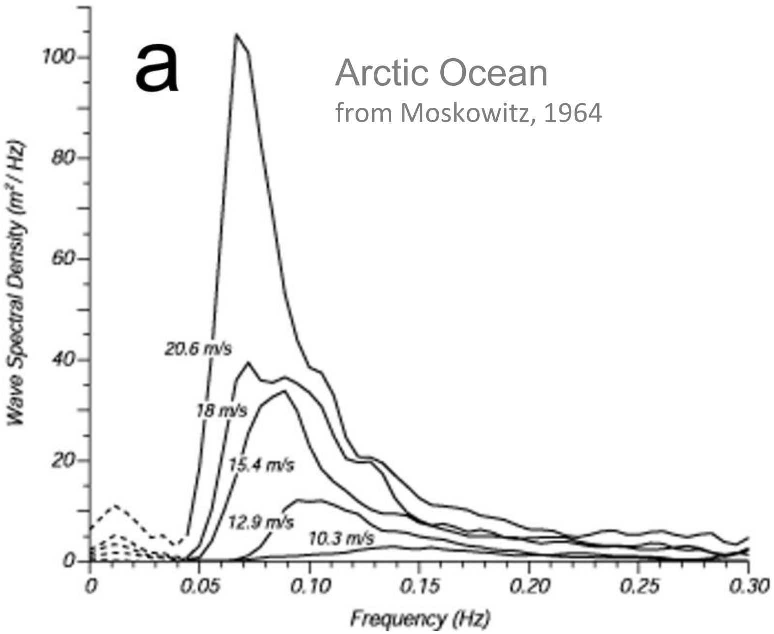


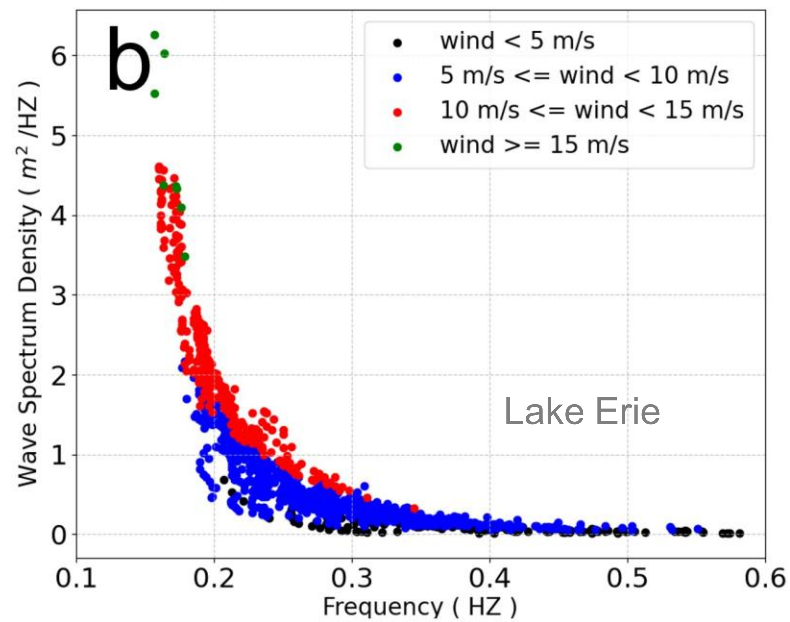
From Pierson and Moskowitz 1964



WW3 in Lake Erie

Wave spectra vs wind speed in Arctic and Lake Erie





From Moskowitz 1964

WW3 in Lake Erie

Wave energy dominants in 0.05~0,1 HZ in Arctic Ocean vs in 0.1~0.2 HZ in Lake Erie

Conclusion

- The ice module IC4M4 in the WAVEWATCH III (WW3, version 6.07.1) demonstrated the best performance among those tested, and consistently outperforms the IC0 simple blocking scheme currently used in the NOAA's operational Great Lakes Wave modeling system (GLWUv2.0) for both hindcast and forecast configurations.

- The ice modules in WW3 are mostly based on observations and studies from the Arctic Ocean and the Antarctic Ocean. Formulae based on frequency are not suitable for the Lake Erie where they cause too much damping. With the ice module IC4M4, although the module is also based on the Antarctic Ocean study, the wave attenuation is based on incoming wave height that also fits the shallow lakes.

Model implementation

Website: https://www.glerl.noaa.gov/emf/waves/WW3/