Modeling five Great Lakes ice-wave-circulation system using unstructured-grid coupled models

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Summary An unstructured Finite Volume Community Ocean Model was modified by replacing the Euler forward scheme with the centered differencing scheme and applied to all five Great Lakes simultaneously to simulate ice-wave-circulation system and thermal structure from 1993 to 2018. Model results are compared to available observations of currents and temperature and previous modeling work. Maps of climatological circulation for all the five Great lakes were presented. The model successfully reproduced seasonal cycle of lake ice cover, wave parameters and climate, the lake-wide mean surface temperature and lake circulation. Seven simple, flexible, and efficient parameterization schemes originating from the WAVEWATCH III® IC4 were used to quantify the wave energy loss during wave propagation under ice. The reductions of wind energy input and wave energy dissipation via whitecapping and breaking due to presence of ice were also implemented (i.e., blocking effect). The simulation ran over the basin-scale, five-lake computational grid provides a whole map of ice-induced wave attenuation in the heavy ice year 2014, which suggests that except Lake Ontario and central Lake Michigan, lake ice almost completely inhibits waves in the Great Lakes. A practical application of the model in February 2011 reveals that the model can accurately reproduce the ice-attenuated waves when validated by wave observations from bottom-moored AWAC; moreover, the AWAC wave data show quick responses between waves and ice, suggesting a sensitive relationship between them and arguing that accurate ice modeling is necessary for quantifying wave-ice interaction. The interaction between waves, ice, and lake circulation are being investigated.

Model **FVCOM (Finite Volume Community Ocean Model)+UG-ICE+SWAVE**

Forcing **North America Regional Reanalysis (NARR)**

Data **In situ, satellite, and historical measurements**

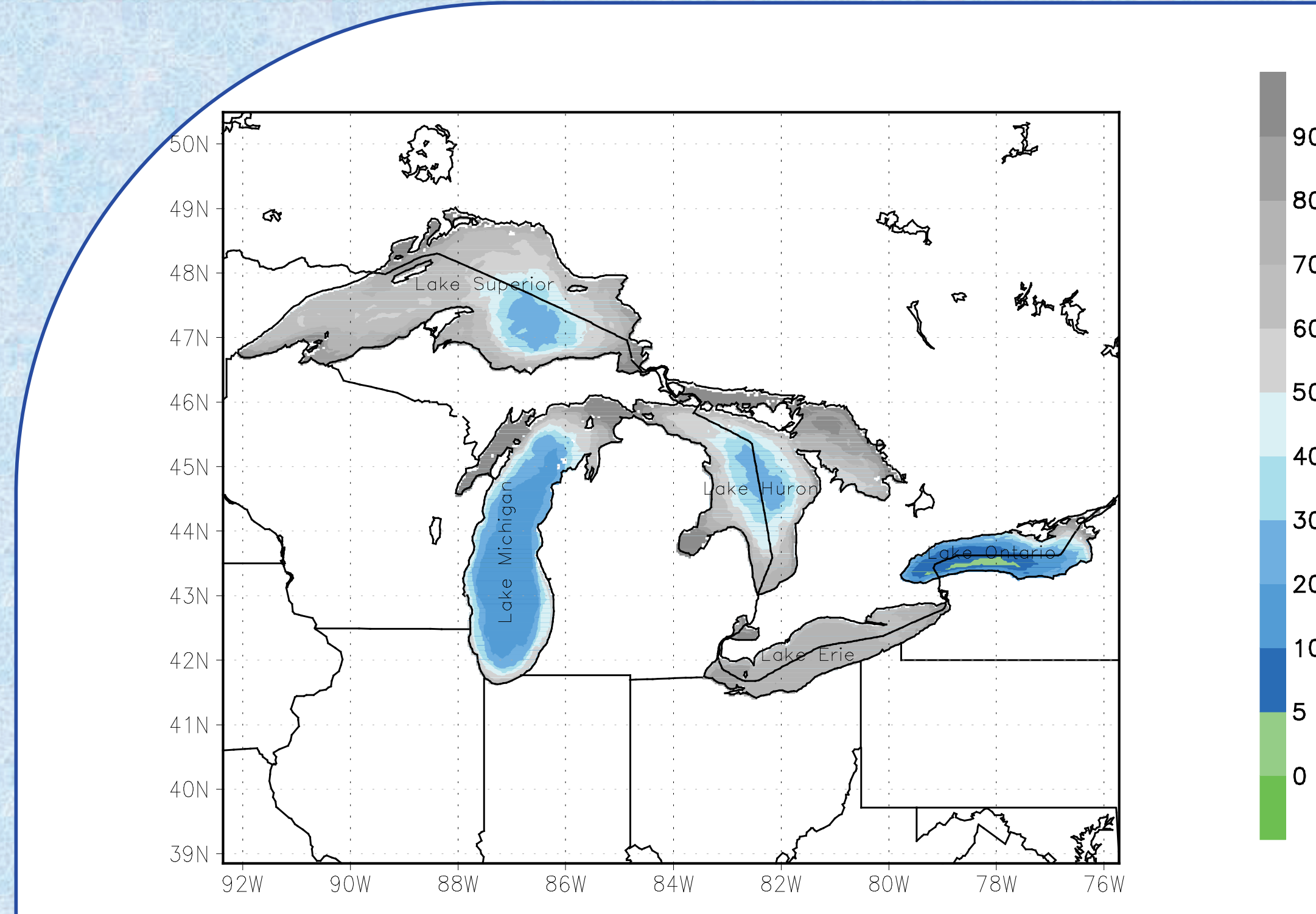

Figure 1. Long-term (1973-2002) mean annual maximum ice cover in the Great Lakes (Bai et al. 2011).

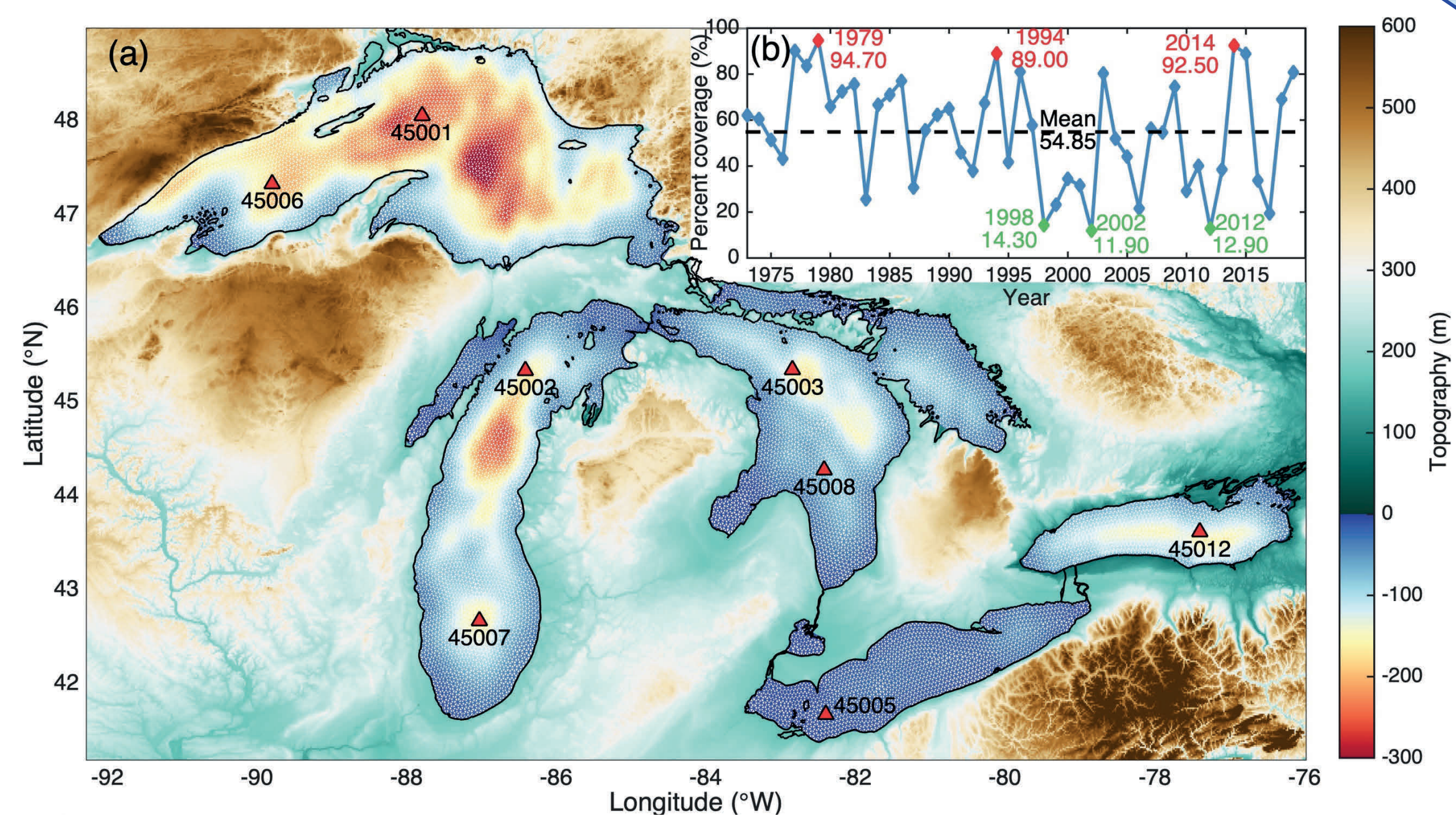

Figure 2. (a) Unstructured grid for FVCOM in the Great Lakes, red triangles show locations of NDBC buoys. (b) Great Lakes annual maximum ice coverage from 1973 to 2019.

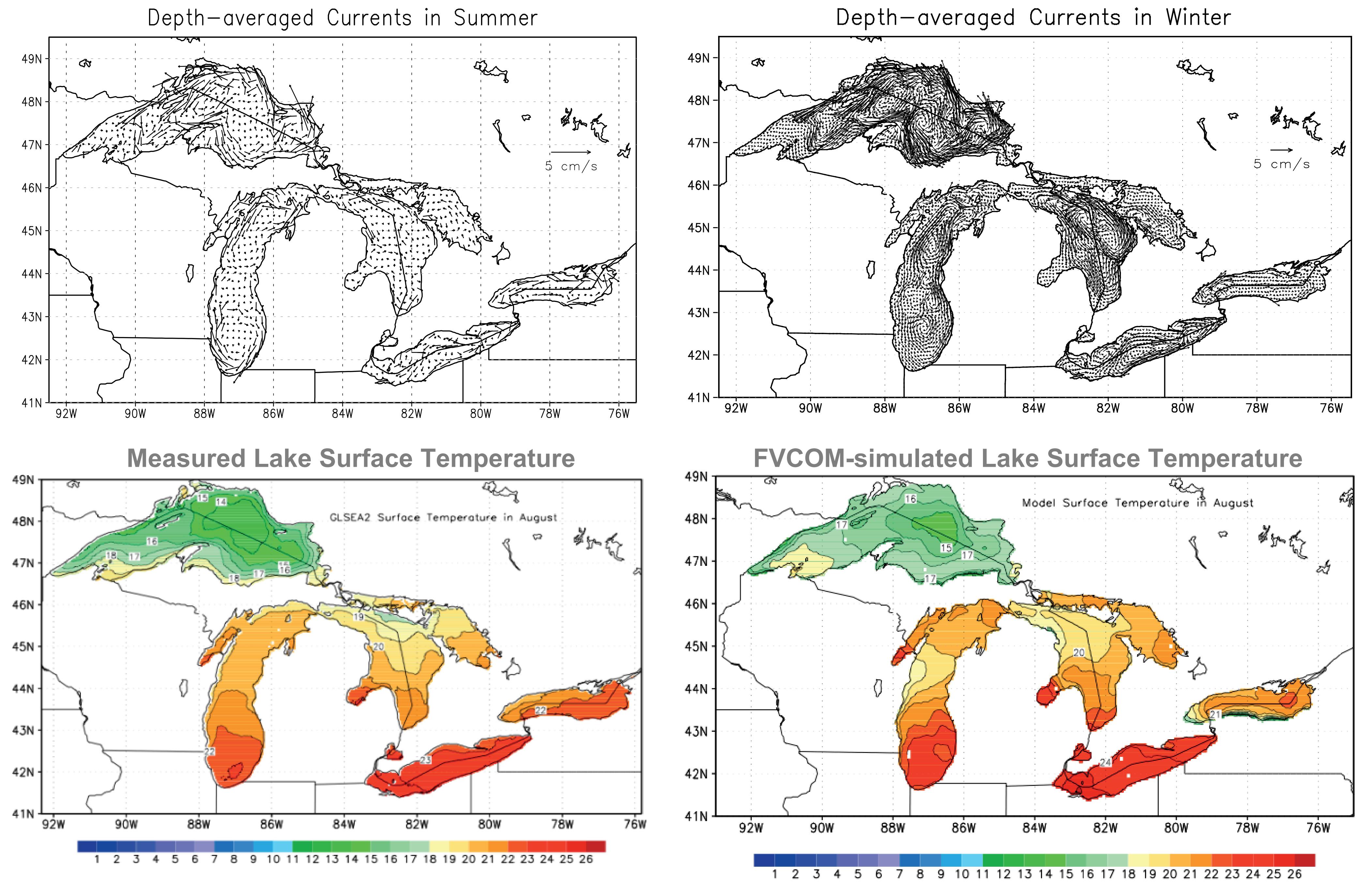

Figure 3. FVCOM-simulated summer circulation (upper left), winter circulation (upper right), and August lake surface temperature (lower right); Satellite measured August lake surface temperature is on the lower left).

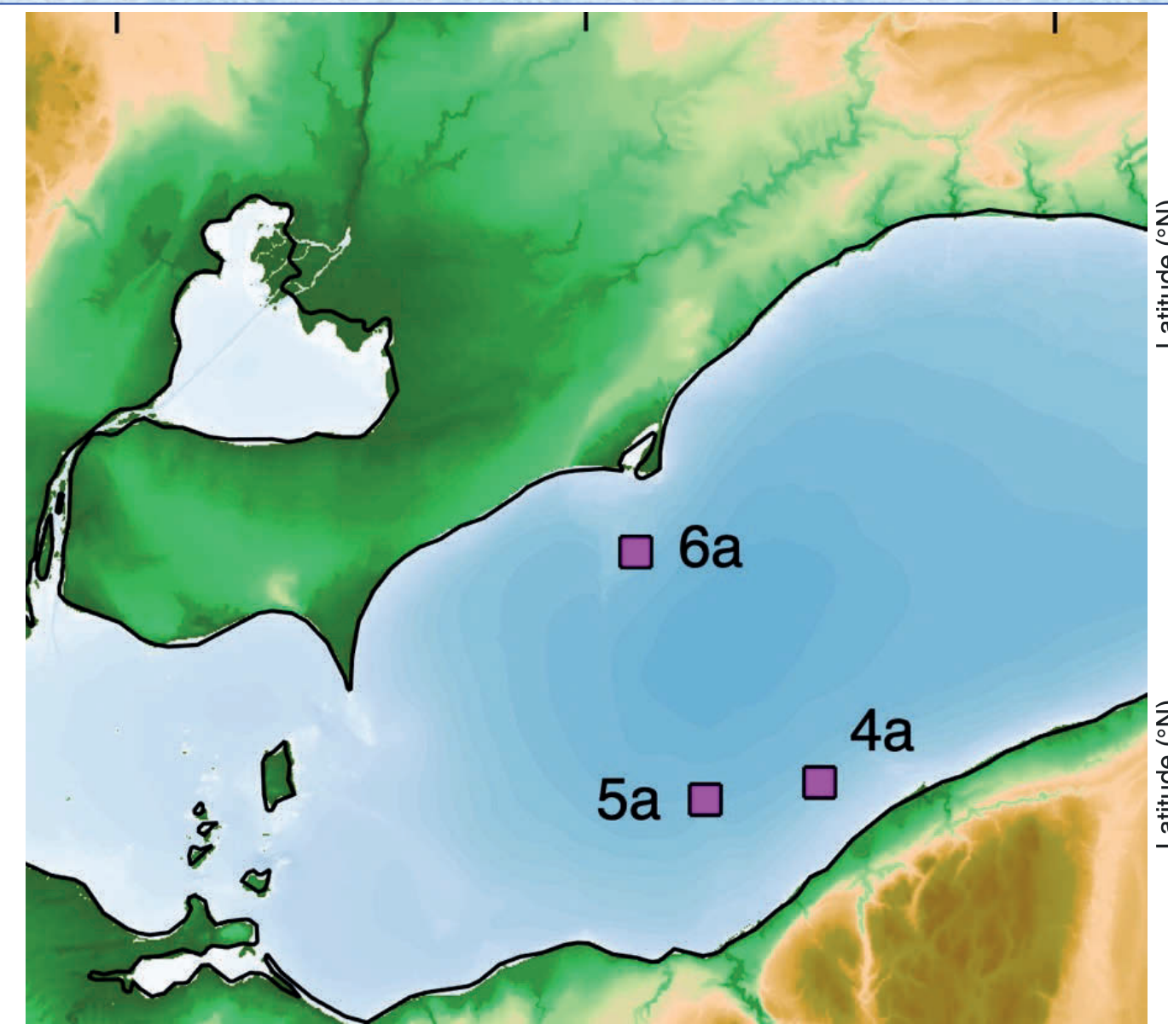

Figure 4. AWAC mooring locations (purple squares) in Lake Erie.

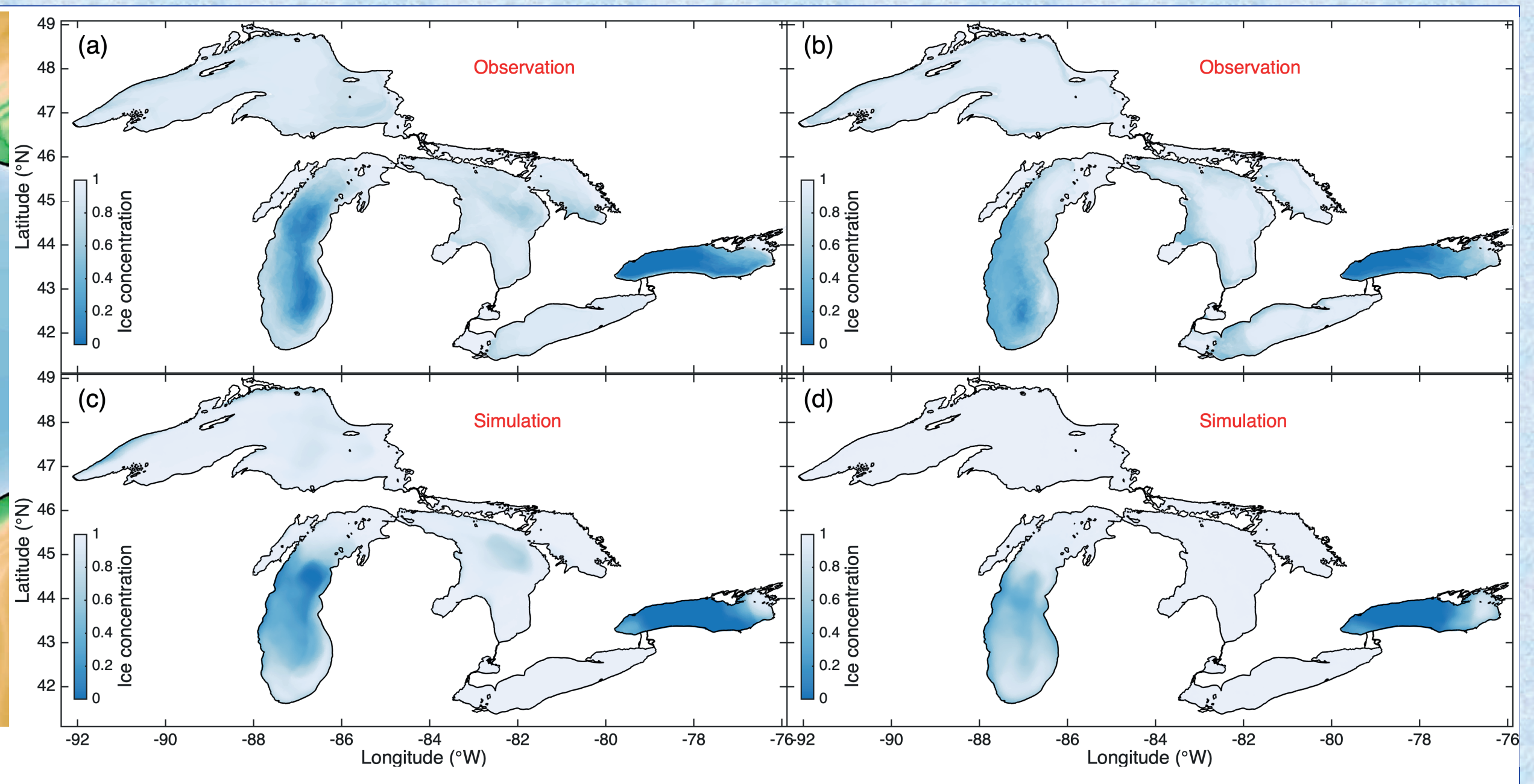

Figure 5. (a) and (b) The monthly-mean NIC satellite-measured ice concentration over the Great Lakes in February and March, 2014, respectively. (c) and (d) show the simulated spatial distribution of monthly-averaged ice concentration over the Great Lakes in February and March, 2014, successively.

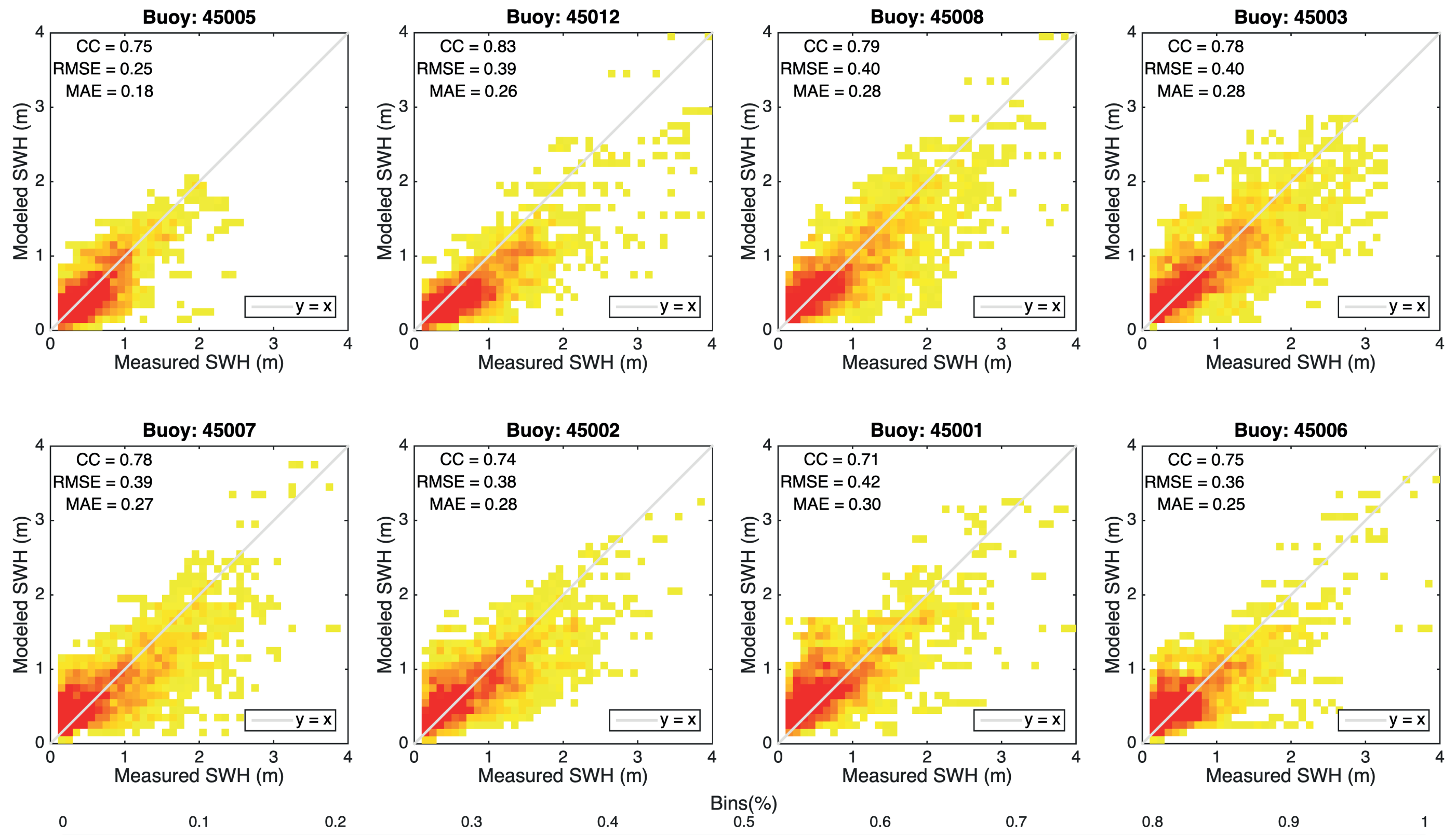

Figure 6. Scatter diagrams of significant wave height: modeled results (Exp. R0) against the NDBC buoy observations. Scatter diagrams are created by binning the data into 0.1 m bins, and the gray lines indicate function *y*=*x*.

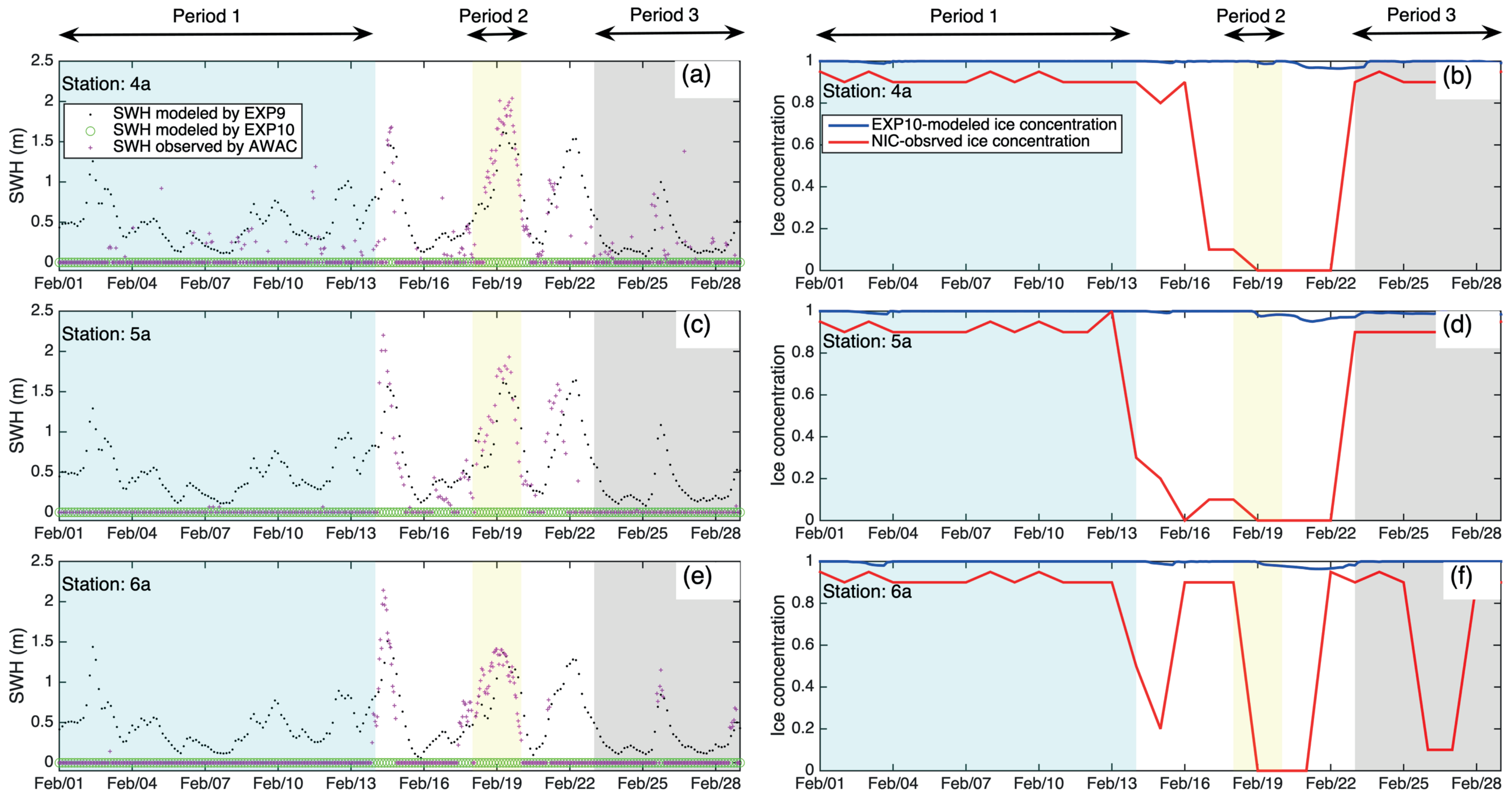

Figure 8. Comparisons of H_s modeled by the wave-only (EXP9) and coupled-wave-ice (EXP10) experiments with H_s observed by AWAC at stations 4a, 5a, and 6a in February 2011. (b), (d), and (f) The comparisons between the EXP10-modeled ice concentration and the NIC product for stations 4a, 5a, and 6a, respectively. Cyan, yellow, and gray shadings mark off Period 1 (February 01–February 14, 2011), Period 2 (February 18–February 20, 2011), and Period 3 (February 23–March 02, 2011), respectively.

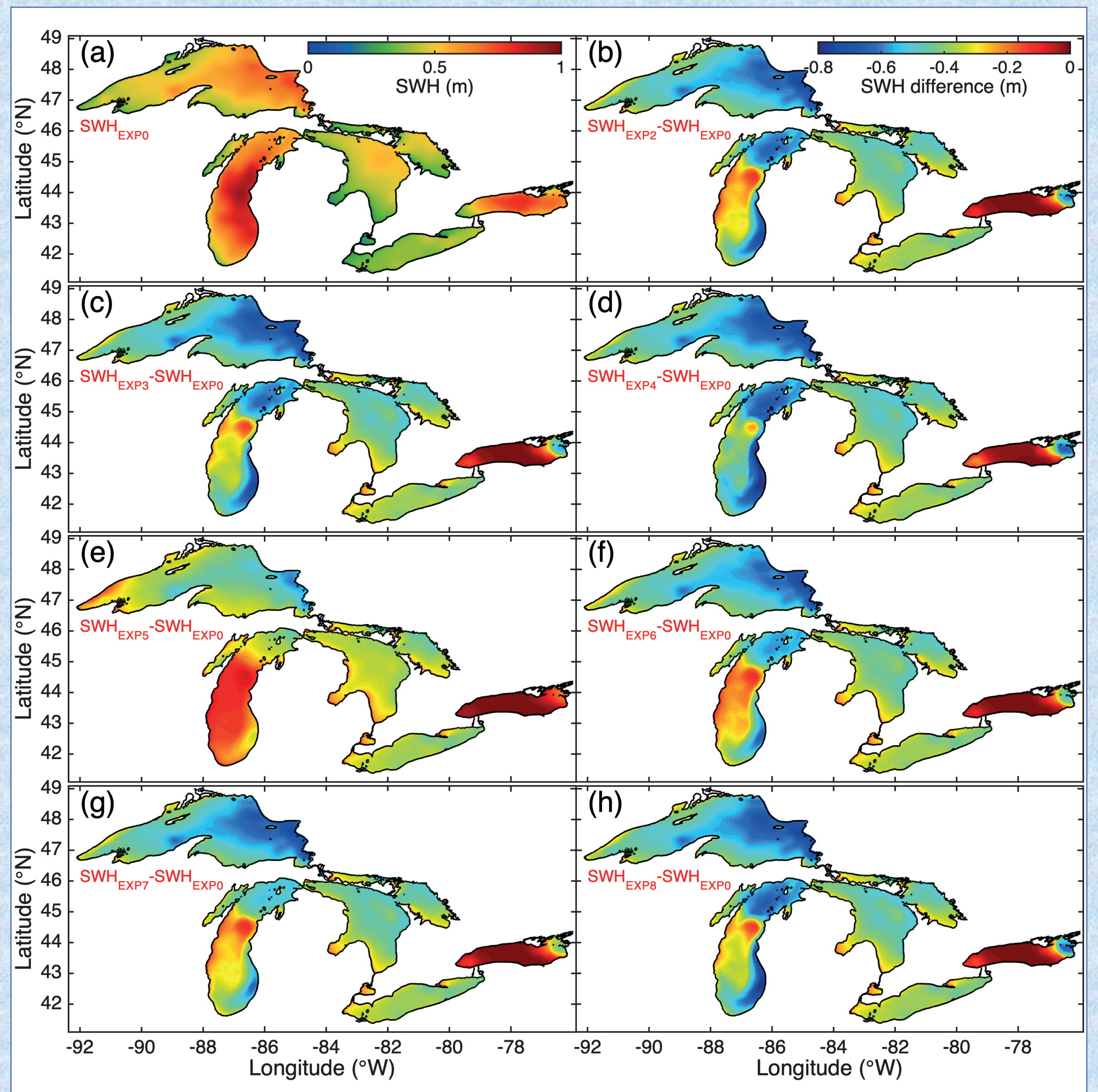

Figure 7. (a) Monthly-mean H_s in the Great Lakes simulated by FVCOM-SWAVE for February 2014. (b–h) Monthly-averaged differences in H_s (ice-induced wave attenuation) based on WAVEWATCH III® IC4M1–M7 in February 2014, respectively.

Concluding Remarks

1) The five-lake FVCOM+ice+wave model was implemented into the entire Great Lakes, which is the backbone model for the coupling to the regional WRF in the near future; the centered differencing scheme was used to replace the original Euler forward scheme to avoid inertial instability in the simulation; the new scheme produces better thermocline structure than the old scheme.
2) Following WAVEWATCH III® IC4, ice-induced wave attenuation was parameterized and implemented into the model, and applied to the Great Lakes.
3) Ice-induced wave attenuation and the ice concentration are positively correlated; in heavy ice year 2014, except Lake Ontario and central Lake Michigan, lake ice almost completely inhibited wave motions in the Great Lakes.
4) The model accurately reproduced the ice-attenuated waves in Lake Erie when validated by wave observations from bottom-moored AWAC.
5) The AWAC wave data show quick response between waves and ice, suggesting a sensitive relationship between them and arguing accurate ice modeling is necessary for resolving wave-ice interaction. "ice retreat-wave growth" positive feedback will be considered in next stage.

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Great Lakes Coastal Forecasting System (including ice): http://www.glerl.noaa.gov/res/glcfs/

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