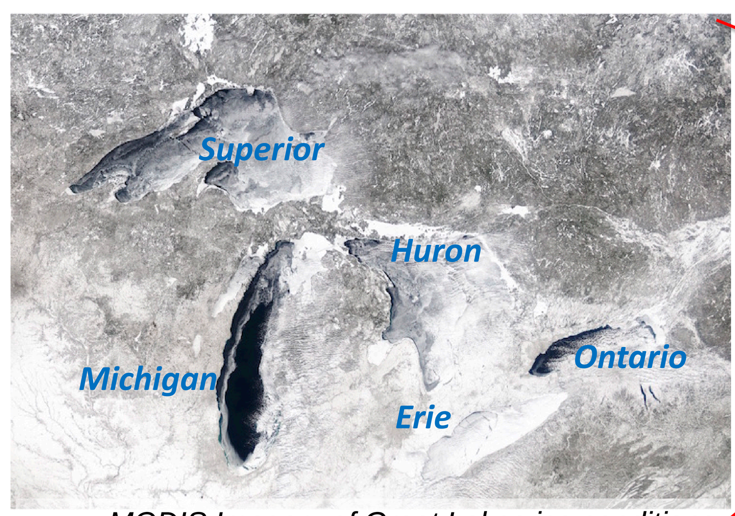
Precipitation impacts on lake ice and water temperature in the North American Great Lakes

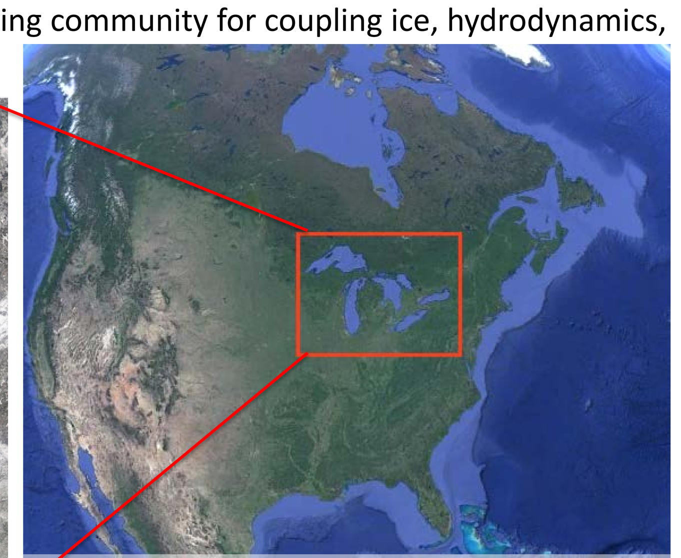
Ayumi Fujisaki-Manome[1,2], Eric J. Anderson[3], James Kessler[3], Philip Y. Chu[3], Jia Wang[3], and Andrew D. Gronewold[4]
[1]Climate & Space Sciences and Engineering, University of Michigan, Ann Arbor, Michigan, [2]Cooperative Institute for Great Lakes Research (CIGLR), University of Michigan, Ann Arbor, Michigan
[3]Great Lakes Environmental Research Laboratory (GLERL), National Oceanic and Atmospheric Administration (NOAA), Ann Arbor, Michigan, [4]School for Environment and Sustainability, University of Michigan, Ann Arbor, Michigan

Introduction

While the role of precipitation has been recognized as a major factor in water balance from a hydrology perspective, precipitation impacts on ice and water temperature across Earth's large lakes are relatively undocumented. In mid- and high-latitude lakes, there are a few rationales for why precipitation can be important in these processes. First, snow accumulation on lake ice, which is a manifestation of winter precipitation, has two opposing effects on lake ice, i.e. the increase of surface albedo resulting in delay in ice melting, and the heat insulation resulting in slowed growth of ice. Second, the air-lake heat transfer associated with precipitation can be significant. This heat transfer can be divided into two components, i.e. the sensible and latent components. The sensible heat flux from precipitation occurs due to the temperature difference between rain droplets/snow flakes and the lake surface. In the North American Great Lakes (hereafter Great Lakes), the large atmosphere-lake temperature difference (>10 ºC) during fall and winter, and, as well as massive snowstorms over the lakes may cause significant sensible and latent heat flux due to precipitation. There is a growing momentum in the coastal modeling community for coupling ice, hydrodynamics, and hydrologic processes. Examining precipitation impacts on the Great Lake ice and water temperature would be a suitable contribution to ensuring accurate interactions at the lake surface in coupled model applications.



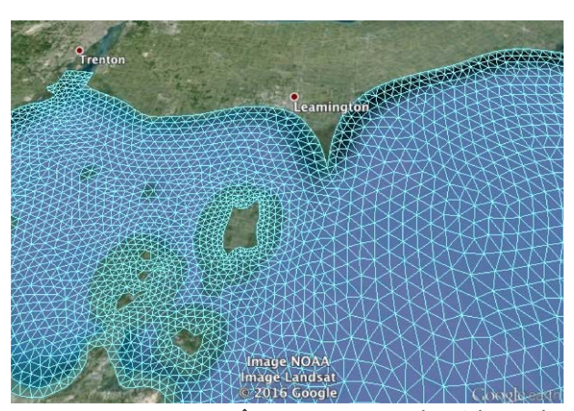
MODIS Imagery of Great Lakes ice conditions


Location of the Laurentian Great Lakes. Cited from Google Earth

Coupled Ice-Hydrodynamic Model

FVCOM (the unstructured grid, Finite Volume Community Ocean Model, Chen et al. *Oceanography*, 2006) was used for the hydrodynamic model.

UG-CICE (the unstructured grid version of the Los Alamos Sea Ice Model, Gao et al. *JGR*, 2011) was used for the ice model.


↑ Unstructured-grid mesh

Precipitation Heat Fluxes

Sensible heat flux : $H_{sp} = -\rho_w c_{pw} P (T_{sfc} - T_{precip})$

Latent heat flux: $H_{lp} = -\rho_w L_w P$

ρ_w : the density of water
c_{pw} : the specific heat of water
L_w : the latent heat of melting for water
P : the rate of precipitation
T_{sfc} : the water surface temperatures
T_{precip} : the temperature of rain droplet or snow flake, which is approximated as the wet-bulb temperature T_b.

Numerical Experiments

Expt. 1: Control experiment (Expt. 1), no precipitation is considered.

Expt. 2: Precipitation experiment. The heat fluxes including H_{sp} and H_{lp} were dynamically calculated.

Expt. 3 : Supplemental precipitation experiment. The other heat flux components than H_{sp} and H_{lp} were prescribed from Expt. 1. In Expt. 2, both water temperature and the other heat flux components were allowed to respond to the precipitation heat fluxes (i.e. perturbation), while in Expt. 3, only water temperature was allowed to respond to the perturbation because the other heat flux components were fixed. Therefore, the impacts on water temperature are meant to be maximized in Expt. 3.

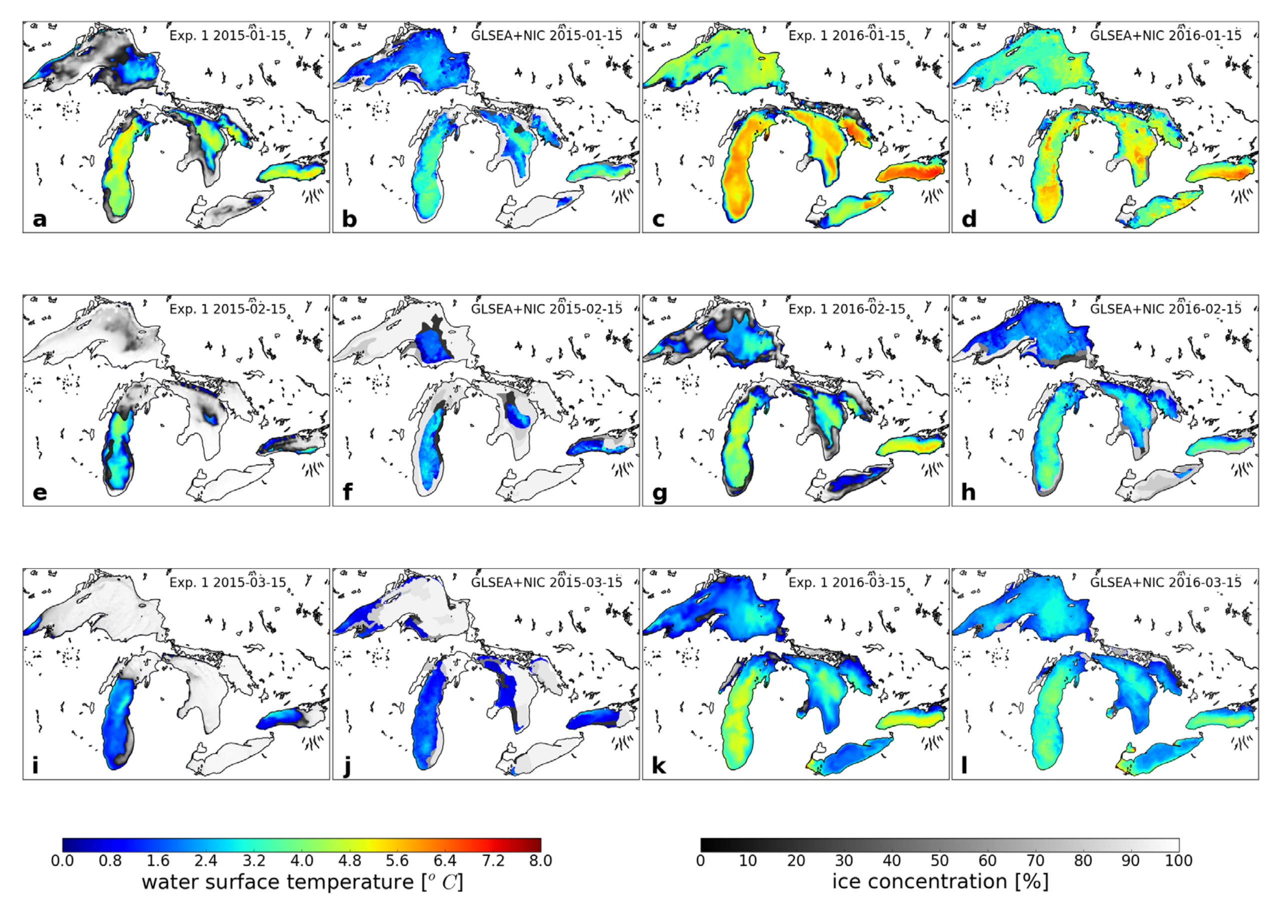
FVCOM+UG-CICE details

Governing equations	Primitive equations
Resolution	100 m-2.5 km (horizontal), 21 layers (s coordinate)
Turbulence Model	Mellor and Yamada 2.5-level Closure Model (vertical) Smagorinsky (horizontal)
Atmospheric Forcing	High Resolution Rapid Refresh (since 2015). Hourly.
Heat Flux Algorithm	The Coupled Ocean-Atmosphere Response Experiment (COARE, Fairall et al. 2003) algorithm. Downward radiations were prescribed by HRRR. For Exp. 3, the heat fluxes were prescribed from Exp. 2, but H_{sp} and H_{lp} were dynamically calculated.
Ice dynamics	Elastic-Viscous-Plastic rheology, five ice thickness categories, ice strength based on Hibler (1979)'s method)
Ice thermodynamics	Vertical heat diffusion model with 4 layers. Albedo as a function of surface temperature and thickness, distinguished for four spectral bands
Simulation Period	2014-01-01 – 2017-01-01 Results for December 1, 2014 – January 1, 2017 were used for the analyses.

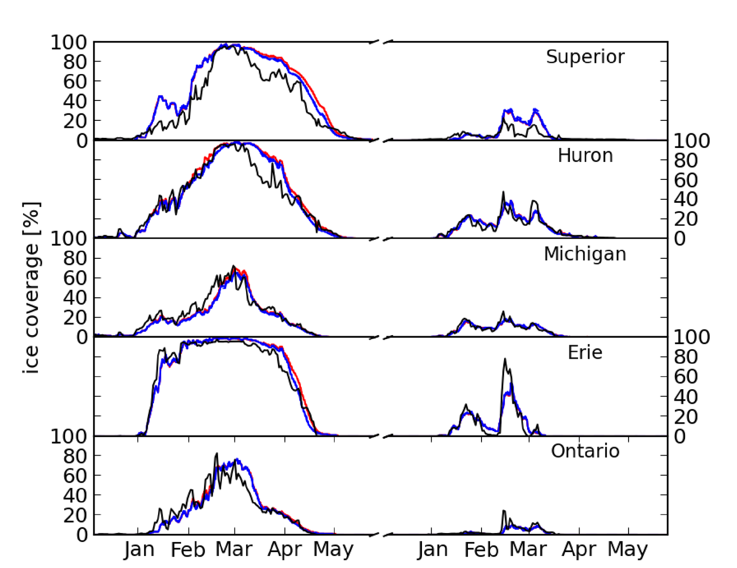
Key Points

- Precipitation impacts on Great Lakes ice cover and water temperature were evaluated using a coupled ice-hydrodynamic model.
- The model results showed that snow cover on the ice reduced the net production of ice and mean ice thickness, which resulted in slightly earlier decay of ice cover.
- The latent heat flux from snow melting cooled the water surface slightly while the sensible heat flux from rain/snow barely impacted the water surface temperature.

Ice Extent and Volume

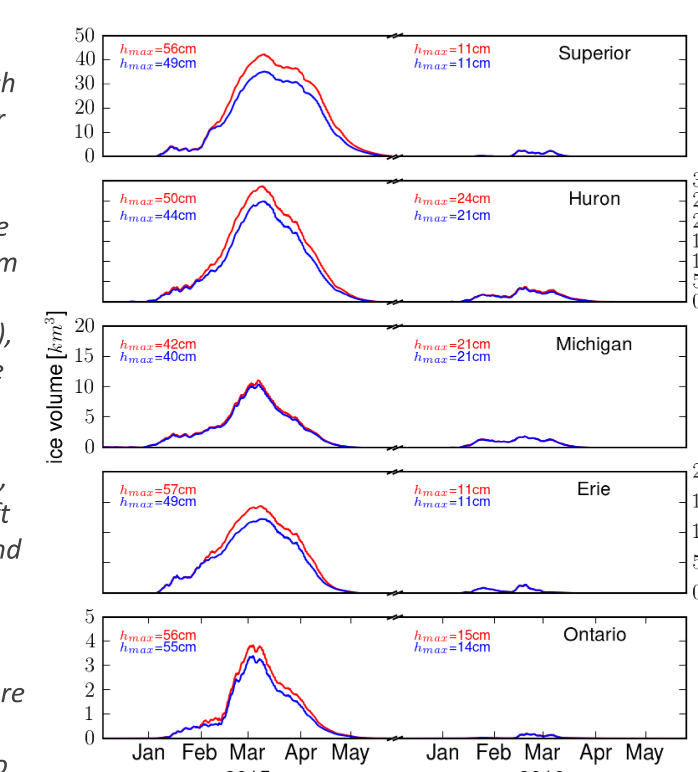


← The spatial patterns of ice concentration [%] and water surface temperature [ºC] on January 15 (a,b,c,d), February 15 (e,f,g,h), and March 15 (i,j,k,l). The model results from Exp. 1 (control) are shown for 2015 (a,e,i) and 2016 (c,g,k) and the observational analyses from the National Ice Center (NIC) and the Great Lakes Surface Environmental Analysis (GLSEA) are shown for 2015 (b,f,j) and 2016 (d,h,l).

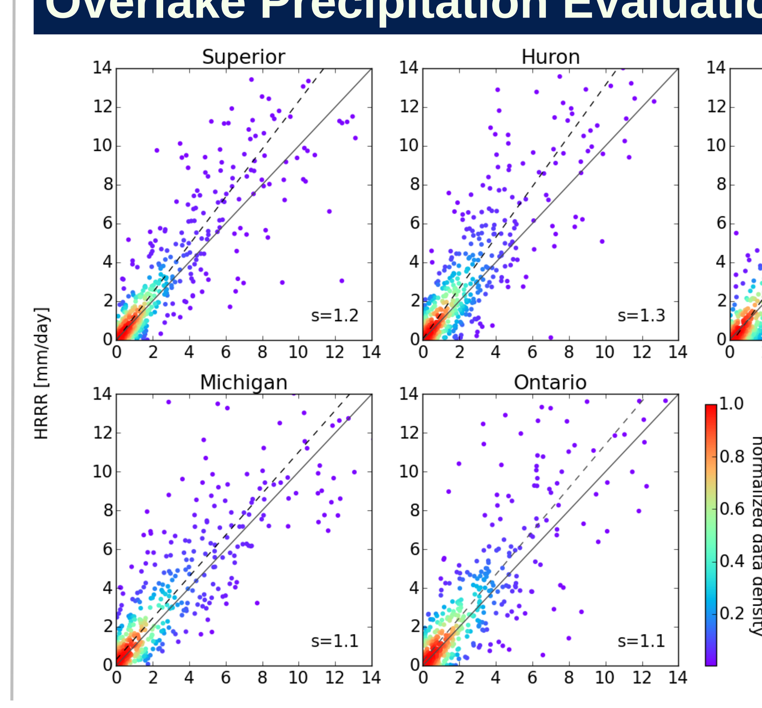


↑ Timeseries of ice coverage [%] for each of the Great Lakes for the winters of 2014-2015 and 2015-2016. Black lines are from the observational analysis from the National Ice Center (NIC). Red and blue lines are the model results from Expt. 1 (control) and Expt. 2 (precipitation), respectively. The results from Expt. 3 are not included, as they are nearly identical to those in Expt. 2.

→ Timeseries of ice volume [km3] for each of the Great Lakes for the winters of 2014-2015 and 2015-2016. Red and blue lines are the model results from Expt. 1 (control) and Expt. 2 (precipitation), respectively. h_{max}, the maximum value of mean ice thickness in the middle of winters, is shown on upper left on each panel (red and blue fonts indicate Expt. 1 and Expt. 2 respectively). The results from Expt. 3 are not included, as they are nearly identical to those in Expt. 2.



Overlake Precipitation Evaluation

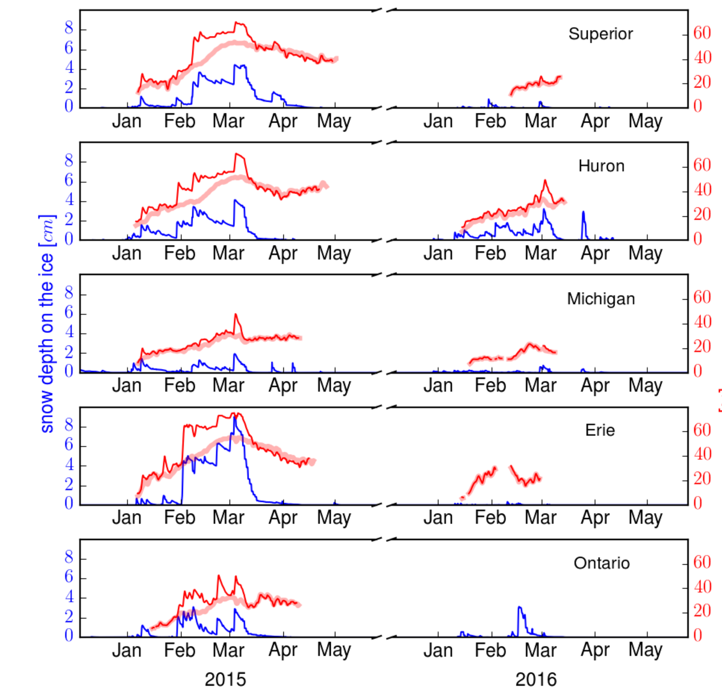


←Comparison of daily lake-wide mean precipitation [mm/day] over each of the Great Lakes between the CAPA-MPE analysis and the High Resolution Rapid Refresh (HRRR) 1-hr forecast. Color indicates normalized data density estimated using Gaussian kernels. Solid line shows the y=x line and dashed line shows a linear fitted line. A s value on lower right indicates the slope of the corresponding linear fitted line.

CaPA-MPE, the merged dataset using both the Canadian Precipitation Analysis and the Multi-sensor Precipitation Estimate (Gronewold et al. 2018), is used for precipitation verification.

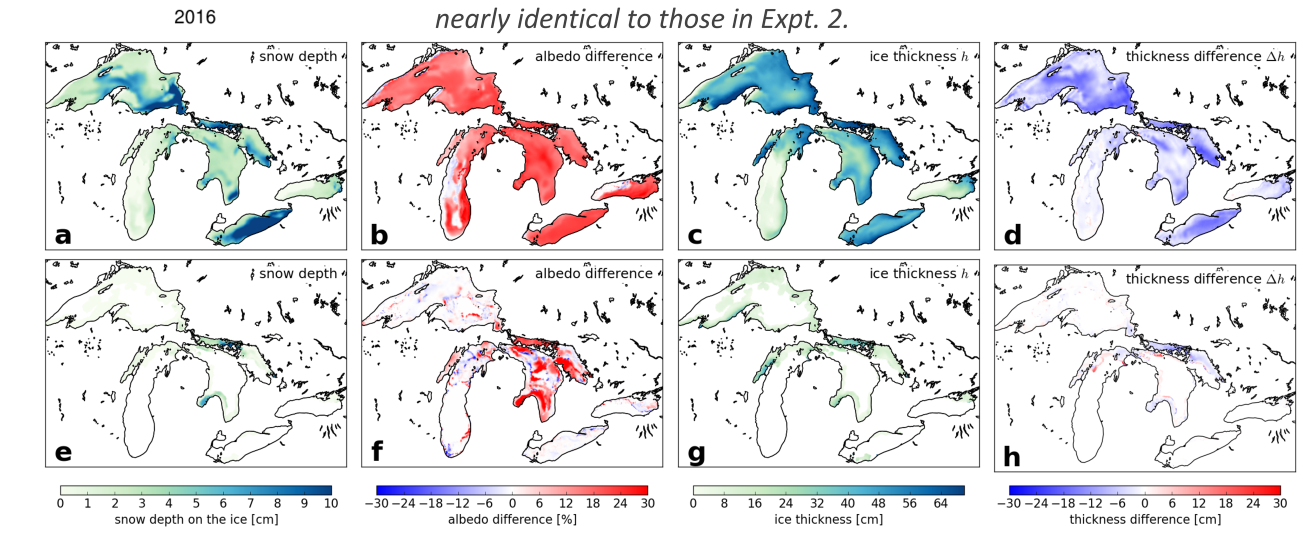
Overlake precipitations from HRRR and CaPA-MPE presented reasonable agreement.

Surface Albedo and Snow Depth

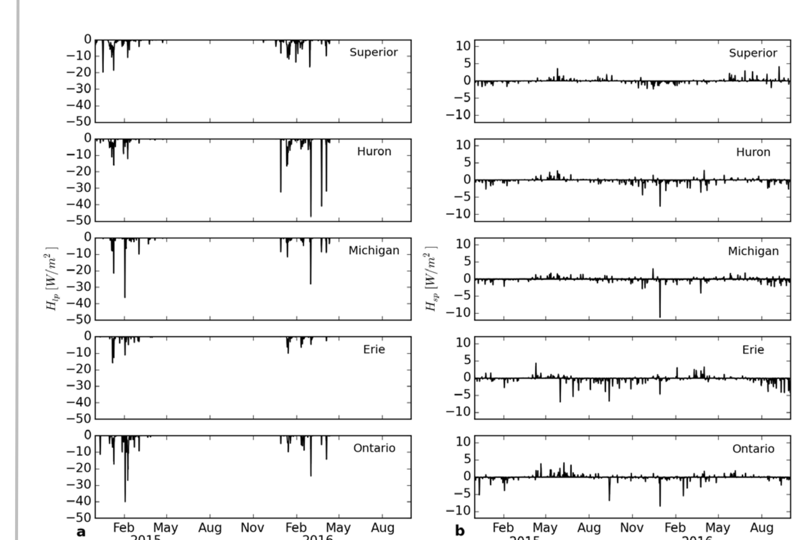


← Timeseries of snow depth on the ice [cm] (blue) and ice surface albedo [%] (red) for each of the Great Lakes for the winters of 2014-2015 and 2015-2016. For ice surface albedo, the results from Exp. 1 (control) are shown with wide thin lines and the results from Exp. 2 (precipitation) are shown with narrow lines.

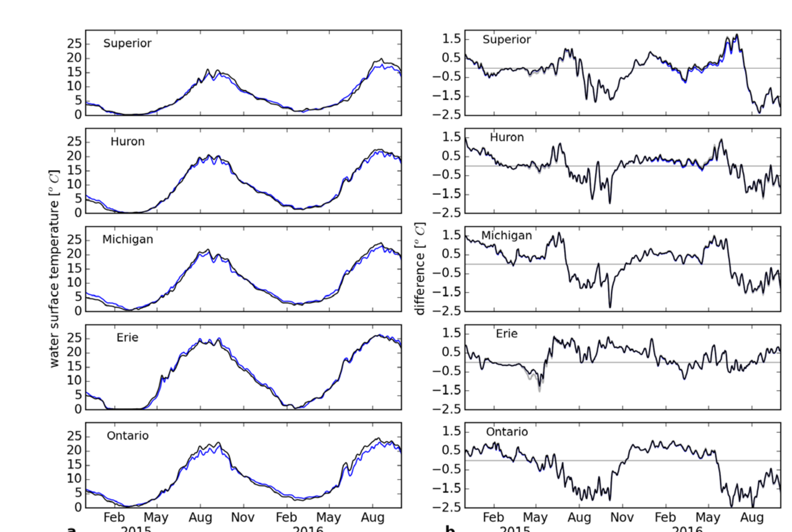
↓ Spatial patterns of snow depth on the ice [cm] from the precipitation experiment Expt. 2 (a,e), surface albedo difference [%] between Expt. 1 and Expt. 2 (b,f), ice thickness h [cm] from the precipitation experiment (c,g), and thickness difference Dh [cm] between the control (Expt. 1) and precipitation (Expt. 2) experiments (d,h). First row (a,b,c,d) shows the results on March 5, 2015 and the second row (e,f,g,h) shows the results on March 5, 2016. The results from Expt. 3 are not included, as they are nearly identical to those in Expt. 2.



Precipitation Heat Fluxes H_{sp} and H_{lp}



↓Timeseries of the daily lake-wide mean precipitation heat fluxes over each of the Great Lakes from Expt. 2. (a) the latent heat flux due to snow melting H_{lp}. (b) the sensible heat flux due to snow or rain H_{sp}. The results from Expt. 3 are not included, as they are nearly identical to those in Expt. 2.



↑ (a) Time series of 5-day running mean surface water temperature from GLSEA (black) and Expt. 1 (blue), and (b) differences of the model results from GLSEA, where grey, black, and blue lines are for Expt. 1 (control), Expt. 2 (precipitation), and Expt. 3 (precipitation with prescribed heat fluxes). In (b), the three lines overlap each other for most of the time.

Summary

It was found that snow cover increased the reflection of solar radiation, but at the same time, prevented lake ice from the growing, resulting in less formation of ice and slightly earlier melting. The earlier ice melting also allowed earlier warming of the water surface in spring. Major snowstorms caused slight cooling in the water surface temperature because snowflakes absorbed heat when it touched the water surface to melt. On the other hand, warmer rain barely changed the water surface temperature during summer. While more process-oriented observations are needed for over-lake precipitation, snow cover, albedo, and ice thickness to reduce model uncertainties, this study presented that winter precipitation is an important factor in the winter energy budget over ice and water in the Great Lakes.

Funding Acknowledgements

- NOAA Oceans Joint Technology Transfer Initiative, "Implementation of the FVCOM-Ice model for the Great Lakes Operational Forecasting System (GLOFS)" 2018-2020.

References

- Fujisaki-Manome et al., Simulating impacts of precipitation on ice cover and surface water temperature across large lakes, J. Geophysical Research, in revision.
- Anderson, E. J., Fujisaki-Manome, A., Kessler, J., Lang, G. A., Chu, P. Y., Kelley, J. G. W., et al. (2018). Ice Forecasting in the Next-Generation Great Lakes Operational Forecast System (GLOFS). J. Marine Science and Engineering, 6(123), 17 pages.
- Gao, G., Chen, C., Qi, J., & Beardsley, R. C. (2011). An unstructured-grid, finite-volume sea ice model: Development, validation, and application. J. Geophysical Research: Oceans, 116(9), 1–15.
- Chen, C., Beardsley, R. C., & Cowles, G. (2006). An unstructured grid, finite volume coastal ocean model (FVCOM) system. Oceanography, 19(1), 78–89.
- Fairall, C. W., Bradley, E. F., Hare, J. E., Grachev, A. A., & Edson, J. B. (2003). Bulk parameterization of air-sea fluxes: Updates and verification for the COARE algorithm. J. Climate, 16(4), 571–591.