Reconstructing evaporation over Lake Erie during the historic November 2014 lake effect snow event

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Introduction

The extreme North American winter storm of November 2014 triggered a record lake effect snowfall (LES) event in southwest New York, which resulted in 14 fatalities, stranded motorists, and caused significant power outages. To date, there has not been an assessment of how state-of-the-art numerical models perform in simulating the turbulent latent and sensible heat fluxes, which is tied to evaporation over the Great Lakes during this extreme lake effect snowfall event.

Method

In order to examine the lake effect snowfall event from November 17th – 20th, 2014, heat fluxes and evaporation rates over Lake Erie were reconstructed using the unstructured grid, Finite-Volume Community Ocean Model (FVCOM). Nine different model runs were conducted using combinations of three different flux algorithms and three different meteorological forcings (Fig. 1). A few non-FVCOM model outputs were incorporated into the analysis including the Climate Forecast System version 2 (CFSv2), the North American Mesoscale Forecast System (NAM), and the Large Lake Thermodynamic Model (LLTM).

Figure 1	Model	Flux Algorithms	Meteorological Forcings	Resolution
FVCOM	The unstructured-grid, Finite-Volume Community Ocean Model	CICE (Los Alamos Sea Ice Model)	CFSv2 (Climate Forecast System version 2 Operational Analysis)	200 m – 3km Half hourly
		SOLAR (NOAA's Great Lakes Environmental Research Lab)	Interp (Interpolated Observations)	
		COARE (Met Flux Algorithm)	HRRR (High Resolution Rapid Refresh)	
CFSv2	Climate Forecast System version 2			0.2 degrees Hourly
NAM	North American Mesoscale Forecast System			12 km 6-hours
LLTM	Large Lake Thermodynamic Model			Basin Average Daily

Figure 1 shows the different models that were used to conduct the study and breaks down the nine different FVCOM runs by their flux algorithms and meteorological forcings.

Meteorological forcing elements were validated with buoy data at three separate locations in Lake Erie and the simulated heat fluxes were validated with eddy covariance measurements from the Great Lakes Evaporation Network (GLEN) and Lake Erie Center Sensor Network (LECSN) at two offshore sites; Long Point Lighthouse in north central Lake Erie and the Toledo water crib intake in western Lake Erie (Fig. 2). The model initial conditions were created by using satellite-based analysis of sea surface temperatures (SSTs). In an early analysis of the satellite-based SSTs, there was good agreement on November 10th but less agreement between the 11th and the 16th, possibly due to cloudiness. Therefore, the FVCOM model runs were initiated on November 10th at 0Z and continued through to November 23rd 0Z.

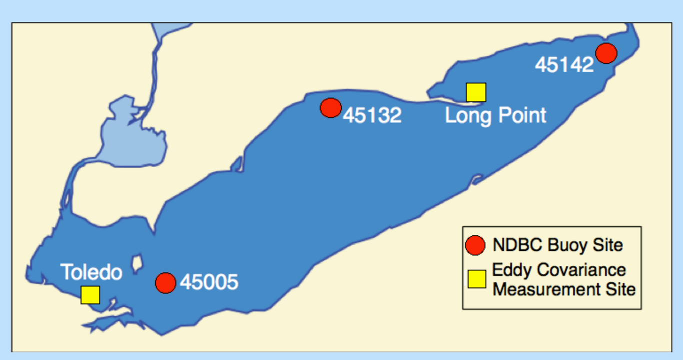


Figure 2. shows a map of Lake Erie. The red dots are the locations of the three different NDBC buoys. The yellow squares indicate the location of the two eddy covariance measurement sites; Long Point Lighthouse and the Toledo water crib.

Analysis

The water temperature in Lake Erie was validated at each of the three buoy sites using observational data (Fig 3a-c). The 3-D mean water temperature of the lake was also calculated and plotted over the time period to show the corresponding lake heat content (Fig 3d). The plots show good agreement with each other as well as the observations at the beginning of the runs and tend to diverge after November 18th with a spread 3 – 4 degree.

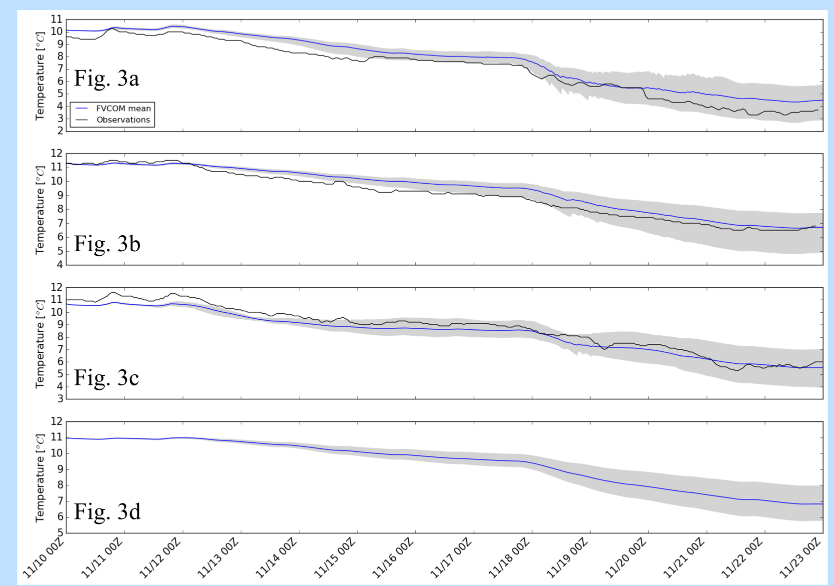


Figure 3(a) shows water temperature at buoy 45005 between November 10th, 2014 and November 23rd, 2014. Figure 3(b) shows water temperature at buoy 45132 and 3(c) at buoy 45142. Figure 3(d) shows mean water temperature.

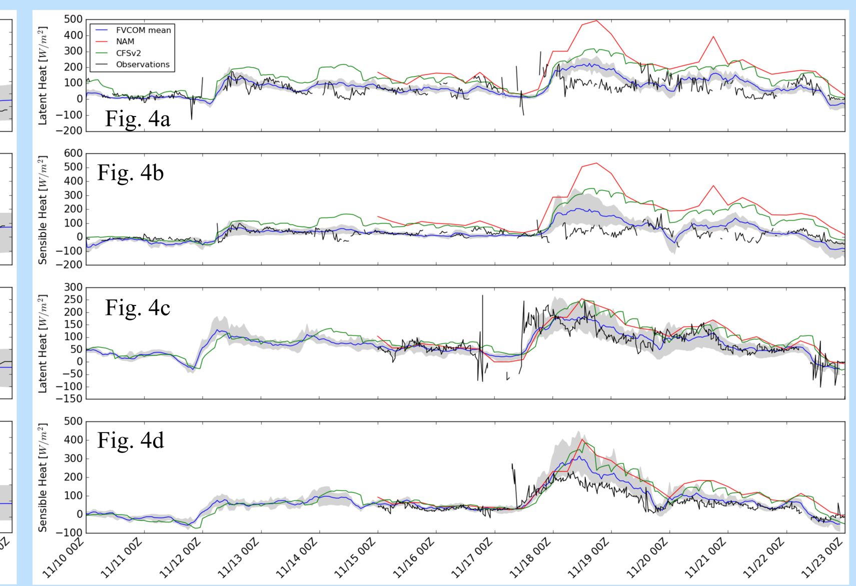
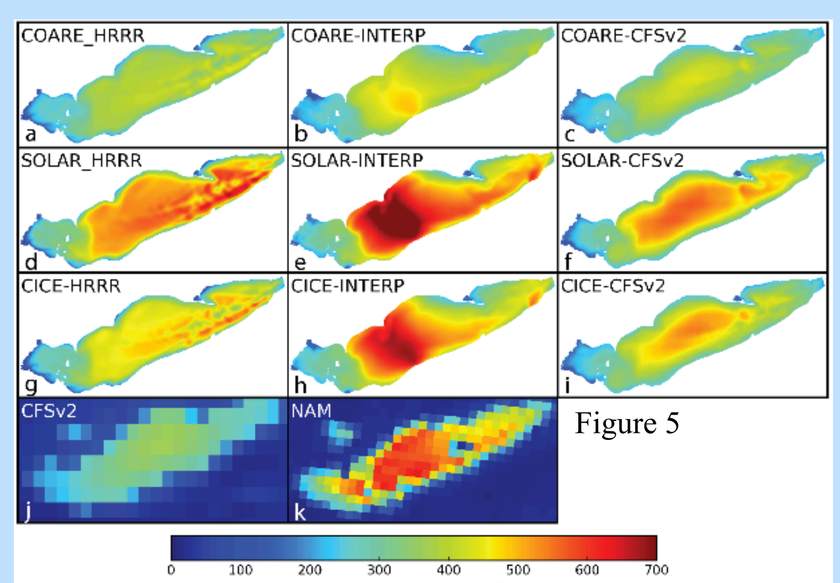


Figure 4(a) and (b) show latent heat flux and sensible heat flux respectively at the Long Point Lighthouse in north central Lake Erie. Figure (c) and (d) show latent heat flux and sensible heat flux respectively at the Toledo crib intake in western Lake Erie.

The latent heat flux (LE) and sensible heat flux (H) was plotted and compared to the observations at each of the two eddy covariance sites, Long Point Lighthouse and the Toledo crib intake (Fig. 4a-d). For the nine FVCOM runs, the model grid points for comparison were selected based on the estimated flux footprint and spatial pattern of the root mean square error (RMSE), which was lower on the upwind side. All the model runs captured the sharp rise in LE and H at the Toledo station on the 17th, although there was varying amplitudes. At the Long Point station, the rise in the observed fluxes was not as significant as the Toledo station. This could be due to the land influence at the location. At Long Point, NAM and CFSv2 significantly overestimated LE and H, likely due to their coarser spatial resolution.



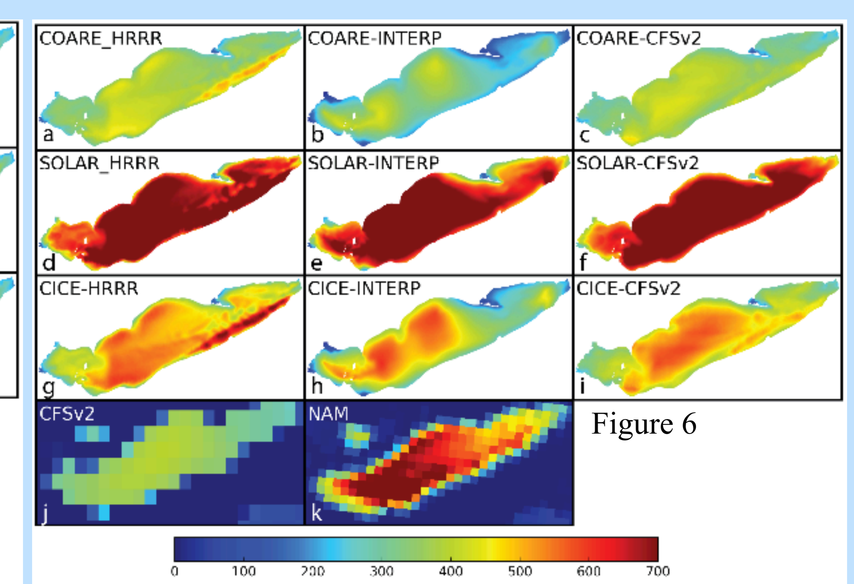


Figure 5 and 6 show the spatial pattern of simulated LE and H respectfully for each of the FVCOM model runs (a-i) as well as CFSv2 (j) and NAM (k) on November 18th at 12Z.

The latent heat flux (Fig. 5) and sensible heat flux (Fig. 6) was spatially plotted over Lake Erie on November 18th at 12Z during the peak heat loss. Both LE and H tended to be larger offshore than near shore. The magnitudes are overall larger with the SOLAR algorithm (d,e,f in Figs. 5 and 6) and lower with the COARE algorithm (a,b,c in Figs. 5 and 6). Even with the same forcings, the modeled LE and H presented significantly different results with the different flux algorithms. Some detailed patterns are seen with the HRRR forcings (a,d,g in Figs. 5 and 6) as a benefit of its high spatial resolution.

The lake-wide average LE and H were calculated and the Large Lake Thermodynamic Model was added into the analysis (Figs. 7a-b). All of the model runs recognize a sharp increase in LE and H on the 17th with the greatest variability in H (Fig 7b). The peak values vary from ~300 W/m² with COARE-Interp to ~700 W/m² with SOLAR-CFSv2. Among the non-FVCOM model outputs, the lake-wide LE and H from CFSv2 and LLTM are relatively small, while those from NAM are more comparable to the FVCOM models. This could be related to the lower resolution of CFSv2 and LLTM in both space and time.

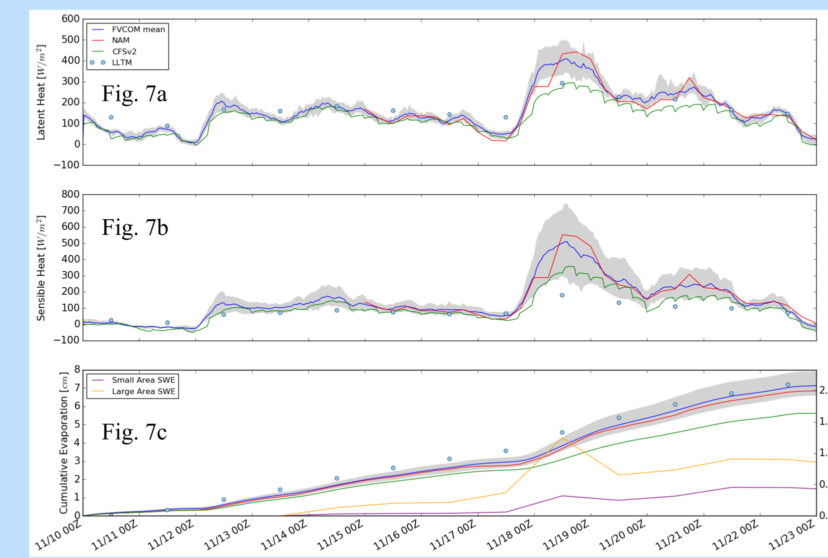


Figure 7 shows time series of the lake-wide mean (a) latent heat and (b) sensible heat fluxes from the model results as well as (c) modeled cumulative evaporation and the spatially integrated snow water equivalent (SWE). In (c), the secondary y-axis shows the total cumulative water loss due to evaporation from the lake.

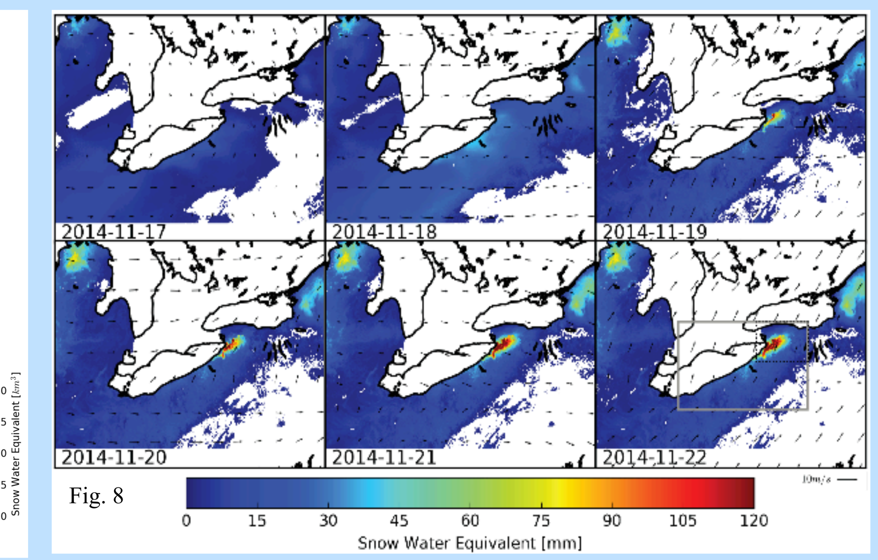


Figure 8 shows accumulating SWE products from the SNOw Data Assimilation System SNODAS) beginning on Nov 17th (upper left figure) through Nov 22nd (lower right figure). SNODAS is a modeling and data assimilation system developed by the NOAA National Operational Hydrologic Remote Sensing Center (NOHRSC).

The lake-wide LE was computed into lake-wide cumulative evaporation for each of the model runs (Fig. 7c). The model ensemble presented drastic evaporation over the modeled time period. Figure 8 shows accumulating snow water equivalent (SWE) over the significantly affected regions from November 17th to November 22nd. In Figure 8f, two domain boxes are drawn, a small domain around Buffalo, NY and a larger domain. The SWE was integrated over each of the domains and plotted along side the accumulated evaporation (Fig 7c). The cumulative evaporation during the event was 2 – 2.5 cm over 2.5 days. The total volumetric water loss from the lake during the event was 0.6 – 0.8 km³. Comparing with the peak SWE 1.2 km³ of over the larger area affected by the LES event, indicating the lake evaporation likely accounts for the majority of the snowfall, rather than from moisture from the large-scale atmosphere.

Conclusion

This study evaluated the turbulent heat fluxes from Lake Erie during the extreme LES event in November 2014 using an ensemble of numerical models. Meteorological elements such as water temperature and heat fluxes were compared to direct measurements from buoys and eddy covariance sites in Lake Erie. The analysis, although indirectly, showed that majority of the moisture from the LES event came from lake-wide evaporation from Lake Erie.

Observations of meteorological data have been very important in this study. Eddy covariance sites are scarce in the Great Lakes but are key to the continued study of heat fluxes. Better modeling of heat fluxes in the future will aid in the forecasting of LES events in the Great Lakes.

Acknowledgements & References

This work is supported by the National Oceanic and Atmospheric Administration (NOAA) Costal Storms Program (CSP).

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