Forecasting Lake-Effect Precipitation in the Great Lakes region using NASA Enhanced Satellite Data

Michelle Cipullo[1], Andrew Molthan[2], Jackie Shafer[2], Gary Jedlovec[2], and Jonathan Case[3]

[1] North Carolina State University, Raleigh, NC
[2]NASA Marshall Space Flight Center/Short-Term Prediction Research and Transition (SPoRT) Center, Huntsville, AL
[3]ENSCO Inc./SPoRT Center, Huntsville, AL

1. Introduction

Operational forecasters in the Great Lakes region must frequently predict lake-effect precipitation, which occurs when cold air aloft travels over the warmer surface waters of the open lakes, generating instability. The most common time period for lake-effect precipitation is October through March. Water has a greater specific heat than air, causing it to cool at a slower rate, leading to a lake-air temperature difference common during the late fall and winter. This results in a period when water temperatures remain warmer than the air aloft. The temperature gradient and likelihood of lake-effect precipitation ends when the lake has had sufficient time to cool, or when the surface of the lake freezes. When atmosphere and surface temperatures are below freezing, snowfall is concentrated in organized bands, leading to "white-out" conditions and numerous hazards for those living in the vicinity of the Great Lakes.

2. Background

Niziol (1987) reviewed the meteorological conditions favorable for lake-effect snowfall in the Great Lakes region. The preferred synoptic scale pattern includes a low pressure system at 500 hPa near James Bay Canada, strong Arctic flow associated with a surface low, and an extension of the surface low in the form of a trough across the Great Lakes. The National Weather Service (NWS) in Buffalo found that directional wind shear greater than 30° between the surface and 700 hPa is associated with less organized development of snow bands. Directional shear above 60° will break down snow band structures, creating less concentrated snowfall and reduced precipitation (Niziol 1987). Instability produced by warm lake surface temperatures and cold air aloft drive the development of precipitation. As a general rule, an absolute temperature difference between the cold air aloft and the Great lakes of 13°C or greater is conducive to lake-effect snow development (Holroyd 1971).

The development of lake-effect snowfall also depends upon the length of the fetch across the open, warmer waters of a lake. A long fetch provides moisture from the lake surface and enhances convection through latent heat release, and often coincides with a relatively uniform wind direction and minimal shear. Warm waters over the open lakes increase latent and sensible heat fluxes and the potential for storm development, allowing for a deeper layer of instability and vertical motions (Niziol 1987). Heavy snow is less favorable in mixed layer depths less than 1 to 1.5 km, and inversion heights up to 3 km are commonly found in severe snowstorms (Hultquist et al. 2005).

Latent and sensible heat fluxes are also a factor in lake-effect precipitation development and intensity. Latent heat release can contribute to intensification of convective circulation, convergence and precipitation, while sensible heat release can contribute to lake-land temperature differences, thermally driven circulations, convergence and precipitation (Laird and Kristovich 2002). Ice cover over the lake decreases the magnitude of each flux, and can create either small positive flux values or negative flux values. Gerbush et al. (2007) have shown that with increasing ice cover over Lake Erie, the latent heat fluxes varied linearly, while sensible heat fluxes varied non-linearly. This implies that the sensible heat fluxes are greatly affected by spikes in surface temperatures, while the latent heat fluxes are affected less by temperature changes (Gerbush et al. 2007). Ice thickness also can affect flux values, with thicker ice being correlated with a decrease in flux values, and shorter storm duration. The shorter duration of the storm linked with thick ice cover leads to a decrease in the amount of snowfall totals generated by the lake-effect system (Cordeira et al. 2008).

Although the synoptic scale processes are well understood, individual forecasts still present challenges to operational forecasters. To supplement available observations, high resolution forecast models may provide value by predicting lake-effect precipitation. However, model forecasts are highly sensitive to their initial conditions, specifically an analysis of Great Lakes surface temperatures (GLSTs). Small changes in model conditions of GLSTs can lead to large differences in precipitation amounts predicted by forecast models (Leins et al. 2010).

The NASA Short-term Prediction Research and Transition (SPoRT) Center has created a GLST composite which uses infrared estimates of lake surface temperature obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard the Terra and Aqua satellites. Although Terra and Aqua are polar orbiting satellites, their combined coverage provides data four times per day over some portion of the Great Lakes and with an infrared spatial resolution (1 km), superior to current geostationary satellites. The SPoRT GLST product is produced by combining lake surface temperature observations from MODIS on cloud-free days, with coarser resolution infrared and passive microwave data when MODIS is unavailable. Multiple days of observations are weighted by their latency and used to produce the final temperature composite (Figure 1a).

In order to ensure that temperature retrievals represent open water and not ice, an ice cover mask from the NOAA Great Lakes Environmental Research Laboratory is used to identify ice covered areas. The NOAA GLERL gathers real time data from the Great Lakes and reports ice concentrations from zero to 100%. In the SPoRT GLST product, pixels are assumed to be ice covered if the GLERL product reports an ice concentration of at least 90% (Figure 1b).

In order to implement the NOAA GLERL ice mask into the SPoRT GLST product, the SPoRT GLST product sets pixels to a temperature of 270 K, representing the colder skin temperature of ice cover. Since this value is less than the 273.15 K threshold for ice covered waters in the WRF-EMS, simulations use the NOAA GLERL mask to set the ice cover used during the model forecast. These steps allow for the implementation of the NOAA GLERL ice mask without having to distribute and ingest an additional product (Figure 1b).

The SPoRT GLST data set is a stark contrast to the current representation of lake surface temperatures provided by the Real-Time Global Sea Surface Temperature (RTG SST) analysis. The RTG SST has a 1/12° grid resolution (~9 km), which uses an algorithm to interpolate observations from the most recent data retrieved from buoys, ships, satellite-retrieved data, and satellite-observed ice cover. Satellite retrieved data are averaged within individual grid boxes, with bias removal using the 7-day Reynolds-Smith climatological analysis (NCEP 2010). The RTG SST gathers its sea ice concentration from the Special Sensor Microwave Imager (SSMI), on the Defense Meteorological Satellite Program (DMSP F-13). The sea-ice concentration is computed using the NASA-Team ice concentration algorithm with a weather filter and measured brightness temperatures. After these measurements, sea surface temperatures are measured and used to remove falsely reported ice pixels created using the ice mask algorithm. This final filtering procedure creates an ice mask that removes ice cover in areas that show temperatures greater than 275 K (Grumbine 1996). Since the RTG SST data are averaged and provided at a relatively low resolution, the results often leave out small scale details in surface water temperatures that can be observed using MODIS (Case et al. 2009).

2.1 Simulation of Lake-effect Storm Echinacea

In this study, we examine the results of two model forecasts to determine the impacts of the SPoRT Great Lakes temperature product on the simulation of a lake-effect snowfall event. During the period of 27-29 January 2010, lake-effect snow occurred in the Great Lakes region, mainly downwind of lakes Erie and Ontario, and was titled "Lake-effect Storm Echinacea" by the National Weather Service Forecast Office in Buffalo, New York. Forecast model outputs are analyzed here, comparing a forecast initialized using the default Great Lakes temperatures available in the WRF-EMS against an otherwise equivalent forecast using the GLST product generated by SPoRT.

Lake-effect snow storm Echinacea was simulated using the WRF-EMS model, with configuration described in Table 1. The NASA SPoRT Center has implemented the SPoRT GLST product into the WRF-EMS model as part of a larger SST coverage domain. Here a forecast using the RTG representation of Great Lakes surface temperatures is compared against a similar forecast that uses the SPoRT GLST product as a different initial condition.

2.2 Synoptic Conditions

Lake-effect snow storm Echinacea began on 27 January and dissipated on 29 January 2010, with the majority of snowfall occurring on 28 January in western and northwestern New York. Synoptic conditions were favorable for lake-effect snow during this event. Wind speeds between the surface and the 700 hPa level indicate little change in wind direction, or minimal directional shear, large absolute temperature differences in portions of the lakes, and a low pressure system at 500 hPa in the vicinity of the Great Lakes area (Figure 2).

Echinacea produced a total of 10-12 inches of snow downwind of Lake Erie, and 8-18 inches downwind of Lake Ontario (Figure 3, NWS Buffalo). Lake-effect precipitation was favored due to the westerly and southwesterly flow, with surface winds passing over the open waters of each lake. Areas downwind of Lake Ontario received significantly more precipitation during this event, possibly attributable to differences in ice cover, where the open waters of Lake Ontario favor a greater fetch, and reduced directional wind shear over the lake, allowing for more organized snow bands.

Since differences in ice cover will impact the model simulation of lake-effect precipitation, the ice masks of the GLST and RTG products are compared (Figure 4). The GLST product has significantly less ice cover over Lake Erie than the RTG product (Figure 4), while both the RTG and GLST products indicate ice-free conditions over Lake Ontario. Water temperatures in the GLST are cooler for Lake Erie and Ontario. Differences in ice cover affect heat fluxes and open water fetch over each lake, relevant to the simulation of lake-effect snow development.

3. Results

The RTG SST and SPoRT GLST forecasts of Echinacea were compared to determine sensitivities to the representation of Great Lakes surface temperatures. An analysis of lake average temperatures and spatial variability reveals differences in the two products, but must also be evaluated in the context of different ice masking techniques. In both simulations, lake ice is defined where the respective water temperatures fall below the WRF-EMS ice threshold of 273.15 K. In this procedure, RTG water temperatures define an ice mask for the RTG product, while the SPoRT GLST sets ice points from the GLERL analysis to low values that will ensure an ice representation within the model forecast. Preliminary results show a much smaller ice mask in the SPoRT GLST product over Lake Erie (Figure 4), which incorporates the NOAA GLERL ice mask. Statistical analyses of the lake temperatures over open-water were compared from the RTG SST product and NASA GLST product using the RTG ice mask (Figure 5). The RTG ice mask was used in both models to ensure equal numbers of open water points for comparison.

Latent and sensible heat fluxes were compared for Lake Ontario using the RTG

SST product and SPoRT GLST product from 04 Z to 21 Z on 27 January 2010. Median values of latent heating predicted using the GLST product generally decreased (Figure 6). Sensible heat fluxes were also compared over Lake Ontario using RTG SST and NASA GLST products. Similar to the changes in latent heat fluxes, sensible heat fluxes in the SPoRT GLST forecast were generally less than those in the RTG SST forecast (Figure 7). The average median of latent heat flux over Lake Ontario during the measured 18-hour forecast decreased an average of 64% using the SPoRT GLST product, while the average median of sensible heat flux over Lake Ontario decreased approximately 54%. The minimum and maximum values in sensible and latent heat fluxes may have been affected by surface temperature spikes and drops, so these averages were not compared on a quantitative scale.

Differences in ice cover, temperature, and heat fluxes will contribute to differences in precipitation. Storm total, liquid equivalent precipitation (STP) was compared between the two forecasts, with NCEP Stage IV radar estimates and surface gauge reports representing observations. The NCEP Stage IV product is a good indication of location of precipitation, but is not always accurate as to storm total precipitation, due to differences in snowfall characteristics and the difficulty in obtaining accurate gauge estimates of liquid equivalent precipitation. Both RTG and GLST models predicted that the precipitation would occur south of observed snowfall shown by the Stage IV analysis (Figure 8). The GLST product produced lower precipitation amounts, but with greater coverage over Lake Erie. The reduced precipitation amounts in the GLST are consistent with the decreased latent and sensible heat fluxes and cooler lake surface temperatures, while a greater amount of open water in the GLST forecast permitted a greater coverage of light precipitation.

4. Conclusions

The SPoRT GLST product combines MODIS high resolution satellite data, coarser resolution infrared and passive microwave data when MODIS is unavailable, and the NOAA GLERL ice mask, to produce a Great Lakes temperature composite for use in the WRF-EMS model, which can be used by NWS forecast offices to support local forecast operations. The WRF-EMS was used in this study to forecast lake-effect snow storm Echinacea, comparing results using the SPoRT GLST and the current RTG SST product to determine what the forecast impacts of the SPoRT GLST product were during a lake-effect snow event.

This project illustrated that the SPoRT GLST produced significantly less ice cover over Lake Erie when using the NOAA GLERL ice mask than the current RTG SST product. The SPoRT GLST product also showed a general decrease in temperature over Lakes Erie and Ontario, as well as decreases in sensible and latent heat fluxes, and decreases in precipitation. The decrease in temperature correlates to the decrease in heat fluxes and precipitation, highlighting the role of Great Lakes water temperatures in the development of lake-effect snow storms.

Future work will include additional case studies comparing the current RTG SST and SPoRT GLST products, guided by validation against available buoy reports. In addition, future plans for the SPoRT GLST product include the use of optimal interpolation (OI) to provide cloudy pixels with more timely updates from nearby clear pixels during short-term, cloudy periods. The GLST product with OI is expected to provide a smoother depiction of surface temperatures, and reduction in overall data latency, contributing to more accurate forecasts. The NWS will explore how to use this product in their local forecasts of lake-effect precipitation.

Acknowledgements

This research was funded by the North Carolina Space Grant. Special thanks to the NASA SPoRT Center for their help and support on this project, as well as Mona Miller and Tina Haymaker at the Marshall Space Flight Center Education Office for all their hard work and organization of the Undergraduate Student Research Program (USRP). I also want to thank my office mates and fellow USRP interns, Danielle Kozlowski and Robert James, for their friendship and support making this a fun and educational experience.

References

Case, J. L., G. J. Jedlovec, P. Santos, and J. M. Medlin, 2009: The transition of high-resolution NASA MODIS sea surface temperatures into the WRF Environmental Modeling System. Abstracts, *34th Annual National Weather Association Meeting,* Norfolk, VA, National Weather Association, 76-77.

Case, J. L., S. V. Kumar, J. Srikishen, and G. J. Jedlovec, 2010: A modeling and verification study of summer precipitation systems using NASA surface initialization datasets. Preprints, *24th Conf. on Hydrology,* Atlanta, GA, Amer. Meteor. Soc., 3B.3. [Available online at http://ams.confex.com/ams/pdfpapers/162748.pdf]

Gerbush, M. R., D. A. R. Kristovich, N.F. Laird, 2007: Mesoscale Boundary Layer and Heat Flux Variations over Pack Ice-Covered Lake Erie. *J. App. Met. Clim.,* **47**, 668-682.

Grumbine, R.W., 1996: Automated Passive Microwave Sea Ice Concentration Analysis at NCEP. [Available online at ftp://polar.ncep.noaa.gov/pub/ice/publications/ssmi/ssmi120.pdf]

Holroyd, E.W., 1971: Lake-Effect Cloud Bands as Seen From Weather Satellites. *J. Atmos. Sci.*, 28, 1165-1170.

Hultquist , T., G. Mann, R. LaPlante, 2005: Lake-effect Snow, NOAA/NWS Cleveland Winter Weather Workshop.

Laird, N.F. and D.A.R. Kristovich, 2002: Variations of Sensible and Latent Heat Fluxes from a Great Lakes Buoy and Associated Synoptic Weather Patterns. *Journal of Hydromet.,* **3**, 3-12.

Leins, D and R. LaPlante, 2010: Simulating Lake Effect Snow with the WRF: An Overview of Sensitivity to the Temperature of the Great Lakes.

National Centers for Environmental Predictions (NCEP), cited 2010: Real-time, global, sea surface temperature (RTG_SST_HR) experimental analysis.

[Available online athttp://polar.ncep.noaa.gov/sst/ophi/]

Niziol, T. A., 1987: Operational Forecasting of Lake Effect Snowfall in Western and Central New York. *Wea. Forecasting,* **2**, 310-321.

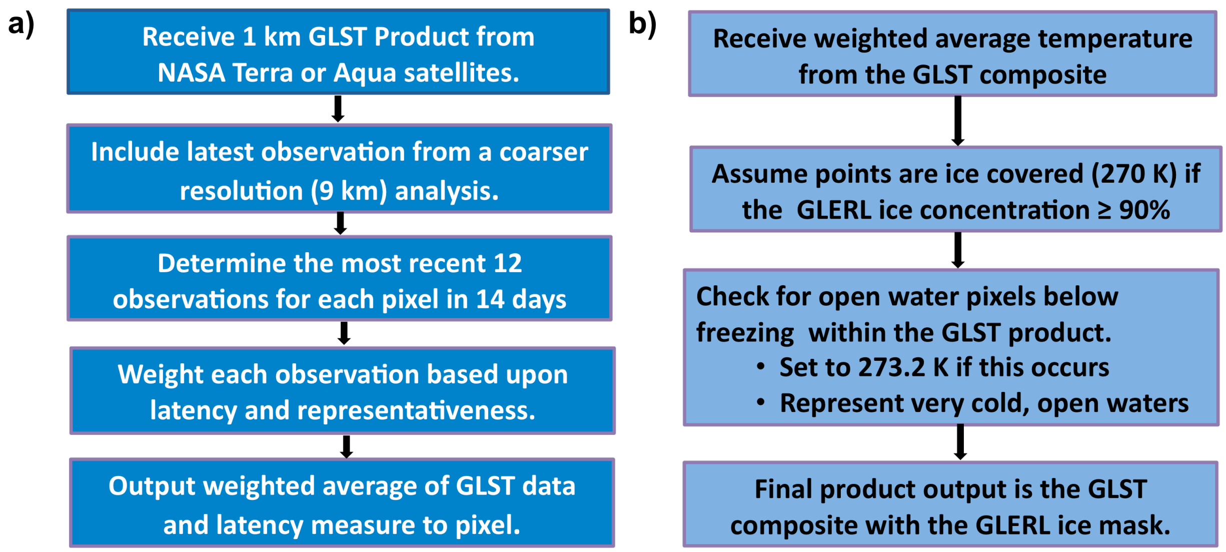


Figure 1: 1a) Description of satellite data and how it is weighted. Data latency is a way to weigh the data and give the newest data more weight. **1b)** Description of how the ice mask is produced in the SPoRT GLST product. The combined steps lead to the final SPoRT GLST product.

Table 1: Model parameterization used in case study.

Parameter	Physics Package
Levels	45
Physics Schemes	No cumulus Parameterization
Microphysics	New Thompson Graupel Scheme
Planetary Boundary Layer	Mellor-Yamada-Janjic-NAM operational scheme
Land Surface Physics	Noah Land Surface Model-Unified NCEP/NCAR/AFWA scheme
Long and Short Wave Radiation	RRTMG (Rapid radiative transfer scheme)

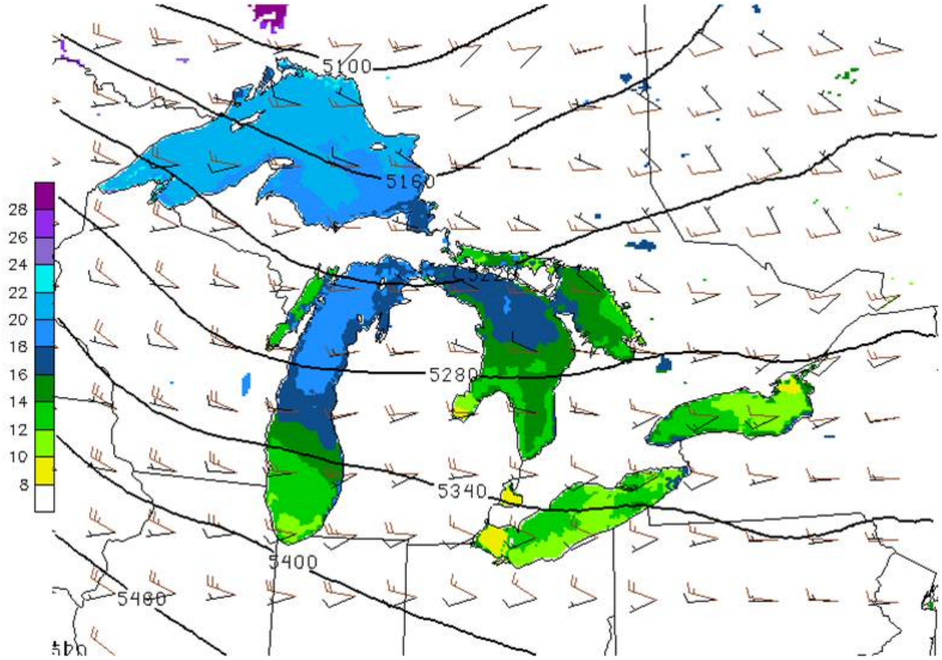


Figure 2: Synoptic conditions shown with 500 hPa heights (black contours), 10 m winds (black barbs), 700 hPa winds (brown barbs), and absolute temperature difference between lake surface and 850 hPa (color fill).

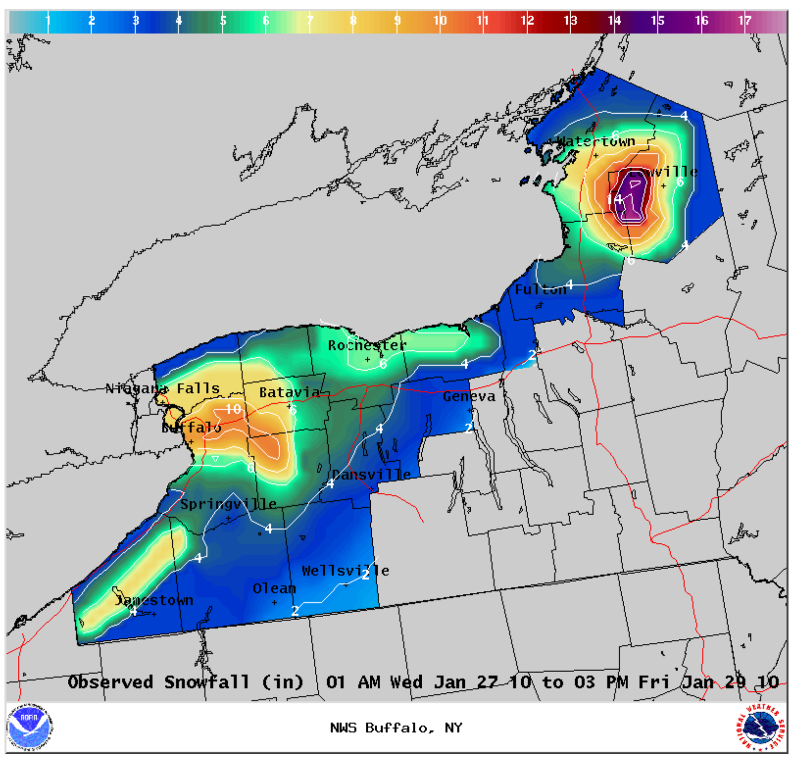


Figure 3: Storm total accumulation for lake-effect storm Echinacea, courtesy of the National Weather Service of Buffalo, NY.

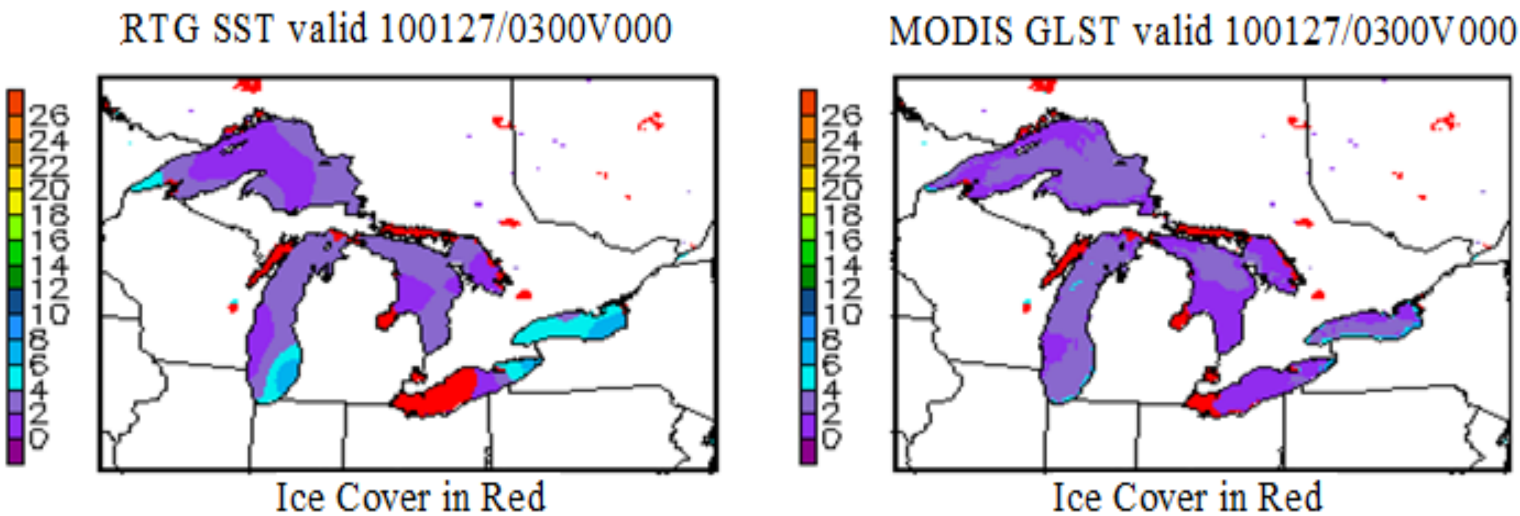


Figure 4: Comparison of the RTG SST and the SPoRT GLST with GLERL ice mask products. This is valid for 0300 UTC 27 January, prior to lake-effect storm Echinacea.

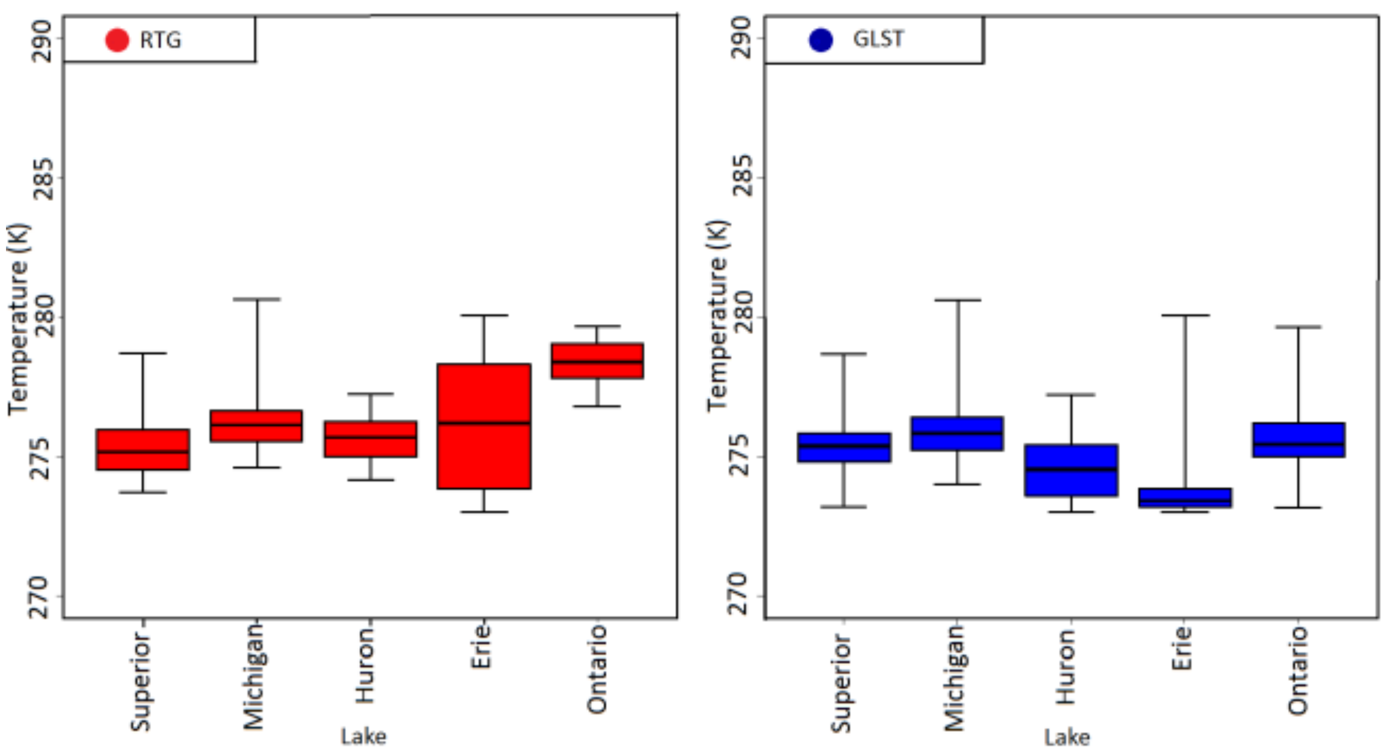


Figure 5: Box and whisker plots of lake surface temperatures using open water points in RTG SST and GLST with RTG ice mask. RTG ice mask used in both to ensure equal number of open water points.

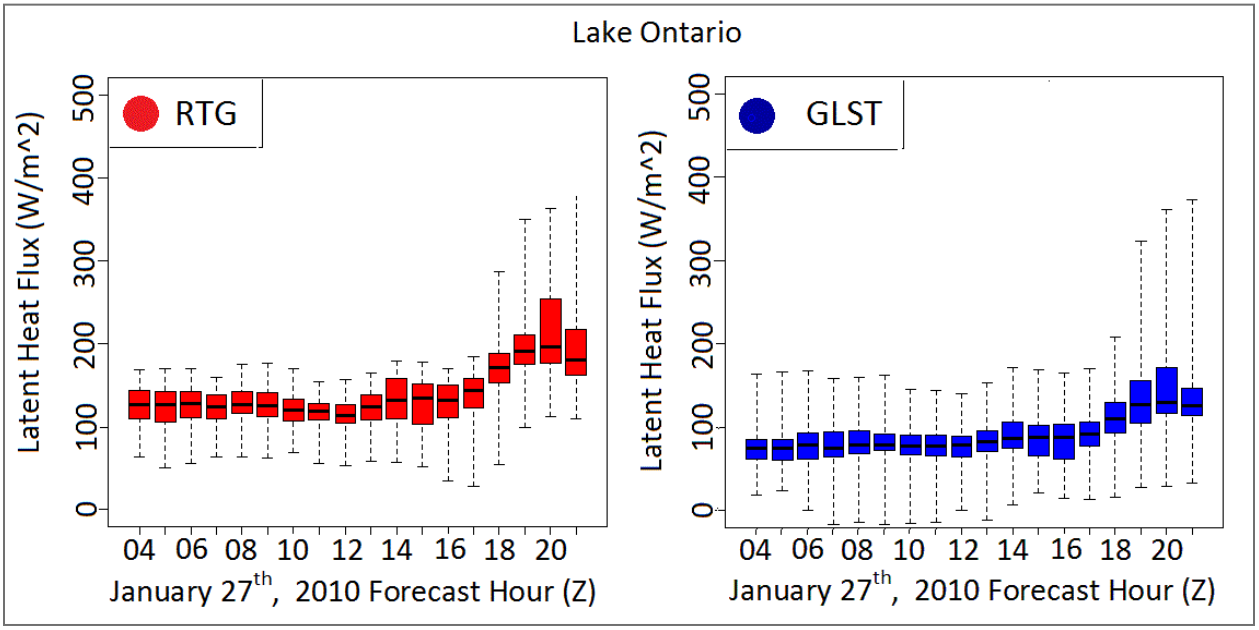


Figure 6: Latent heat flux measurements using Lake Ontario open water points from RTG SST product and GLST product using GLERL ice mask. Measurements from 04Z to 21Z on 27 January.

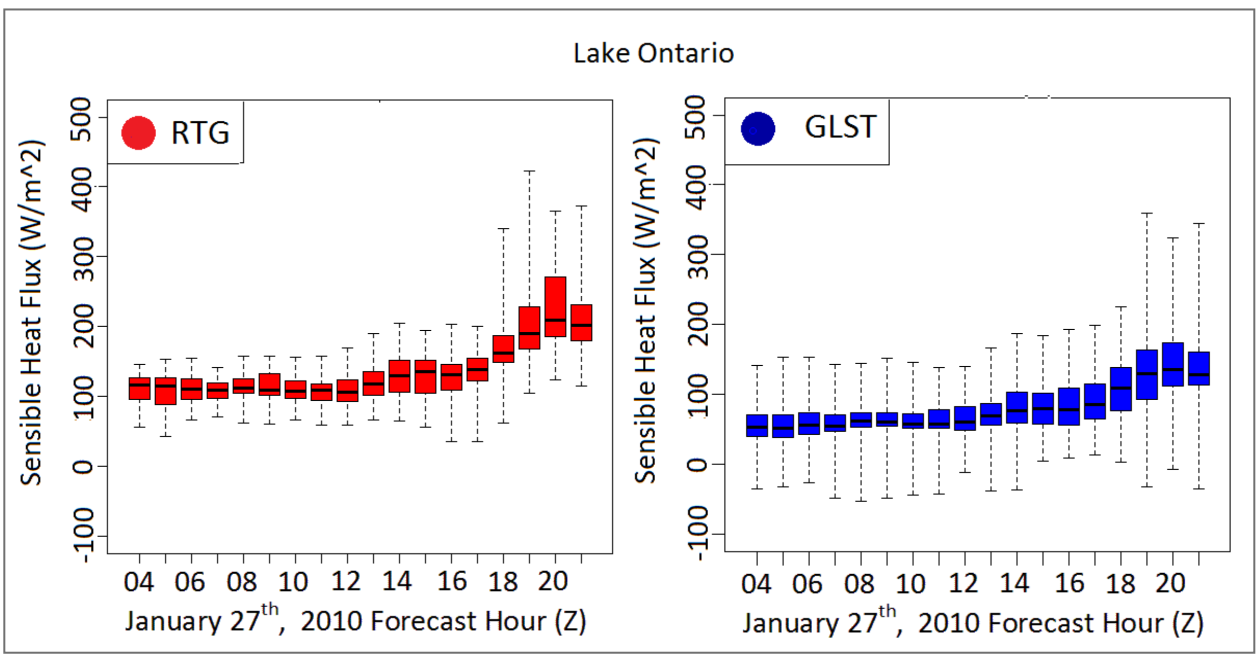
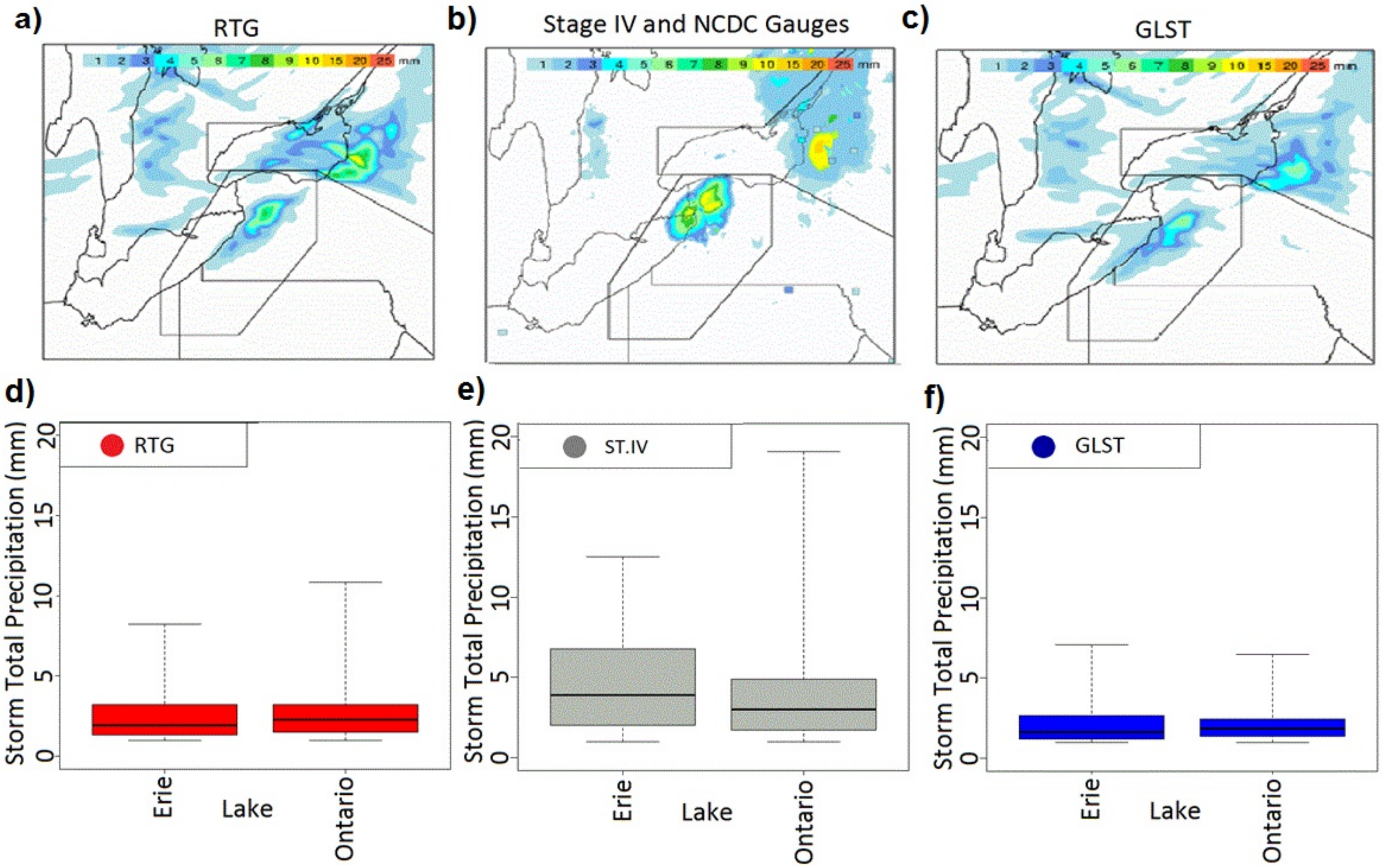


Figure 7: Sensible heat flux measurements using Lake Ontario open water points from RTG SST product and GLST product using GLERL ice mask. Measurements from 04Z to 21Z on 27 January.



a)
RTG
b)
Stage IV and NCDC Gauges
c)
GLST
1 2 3 4 5 6 7 8 9 10 15 20 25 mm
d)
RTG
Storm Total Precipitation (mm)
0
5
10
15
20
Erie
Lake
Ontario
e)
ST.IV
f)
GLST