# Improving historical precipitation estimates over the Lake Superior basin

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[1] Lake Superior, the northern-most of the Laurentian Great Lakes, is the largest (by surface area) freshwater lake on the planet. Due in part to its high water surface to land area ratio, over one-third of the Lake Superior basin water budget is derived from precipitation falling directly on the lake surface. For most of the Great Lakes (including Lake Superior), historical precipitation estimates extend back to the early 1880s, and are based primarily on land-based gauge measurements. While alternatives to gauge-based estimates have been explored, there is no clear history of applying regional climate models (RCMs) to improve historical over-lake precipitation estimates. To address this gap in regional research, and to advance the state-of-the-art in Great Lakes regional hydrological modeling, we compare 21 years of output (1980–2000) from an RCM to conventional gauge-based precipitation estimates for the same time period over the Lake Superior basin. We find that the RCM, unlike the gauge-based method, simulates realistic variations in over-lake atmospheric stability, which propagate into basin-wide precipitation estimates with a relatively low over-lake to over-land precipitation ratio in warm months (roughly 0.7 to 0.8 in June, July, and August) and a relatively high over-lake to over-land precipitation ratio in cold months (roughly 1.3 to 1.4 in December and January), compared to gauge-based estimates. Our findings underscore a need to potentially update historical gauge-based precipitation estimates for large lake systems, including Lake Superior, and that RCMs appear to provide a robust and defensible basis for making those updates. **Citation:** Holman, K. D., A. Gronewold, M. Notaro, and A. Zarrin (2012), Improving historical precipitation estimates over the Lake Superior basin, *Geophys. Res. Lett.*, *39*, L03405, doi:10.1029/2011GL050468.

## 1. Introduction

[2] The North American Laurentian Great Lakes are, collectively, the largest accessible surface freshwater resource on the planet [*Fuller et al.*, 1995]. In addition to supporting multiple sectors of the North American economy, the Great Lakes and their surrounding basin serve as a source of drinking water supply and a home to over 30 million people. The largest of the Great Lakes, Lake Superior, is also one of the largest freshwater bodies on the planet, with a water surface area of roughly 82,400 km$^2$ (the largest surface area of any freshwater lake) and a volume of 12,100 km$^2$ (only Lakes Baikal and Tanganyika have larger volumes). Consequently, understanding and predicting the water balance of the Great Lakes and, in particular, of Lake Superior, has been and will likely continue to be a high priority for future research [*Hartmann*, 1990; *Lofgren et al.*, 2002]. To advance this understanding, we focus here on evaluating procedures for improving precipitation estimates over the Lake Superior basin, and for appropriately partitioning the proportion falling over the land surface from that falling over the lake surface.

[3] Of the major components of the Lake Superior water budget, over-lake precipitation is the most significant (the entire Lake Superior basin, with a surface area of 209,000 km$^2$, is roughly one-third surface water, see Figure 1a), yet also one of the most difficult terms to quantify. Precipitation over the surface of Lake Superior has, historically, rarely been measured directly, which has motivated the development and application of a variety of techniques for estimating over-lake precipitation on Lake Superior, and similar large lakes around the world.

[4] Historical precipitation studies in the Great Lakes region often use gauge-based data from island and shoreline stations to estimate over-lake precipitation [*Weiss and Kresge*, 1962; *Changnon*, 1968; *Jones and Meredith*, 1972; *Bennett*, 1978]. These historical measurements from shoreline and island stations provide empirical evidence of significant differences between over-lake and over-land precipitation dynamics. *Blust and DeCooke* [1960], for example, determined that roughly 9% more (8% less) precipitation was recorded at shoreline stations than island stations during the warm- (cold-) season based on six precipitation gauges in the northeastern section of Lake Michigan between 1952–1958. These results are corroborated by other Lake Michigan studies [*Kresge et al.*, 1964; *Changnon*, 1968; *Jones and Meredith*, 1972]. However, *Kresge et al.* [1964] and *Blust and DeCooke* [1960] argue that gauge-undercatchment is a major source of observational bias and can even exceed the differences between lake and land stations [*Bolsenga*, 1979]. Because atmospheric stability varies by season, atmospheric dynamics that affect the partitioning of over-lake to over-land precipitation also vary by season. As a result, precipitation minimas (maximas), such as those identified by *Blust and DeCooke* [1960], are expected over large lakes, such as Lake Superior, during the warm (cold) season.

[5] More recently, studies have combined radar- and satellite-derived products with gauge measurements to estimate precipitation in ungauged areas [*Wilson*, 1977; *Bolsenga*, 1979; *Dyer and Garza*, 2004; *Watkins et al.*, 2007]. *Wilson* [1977], for example, used a combination of radar and rain gauge data to estimate precipitation over the entire Lake

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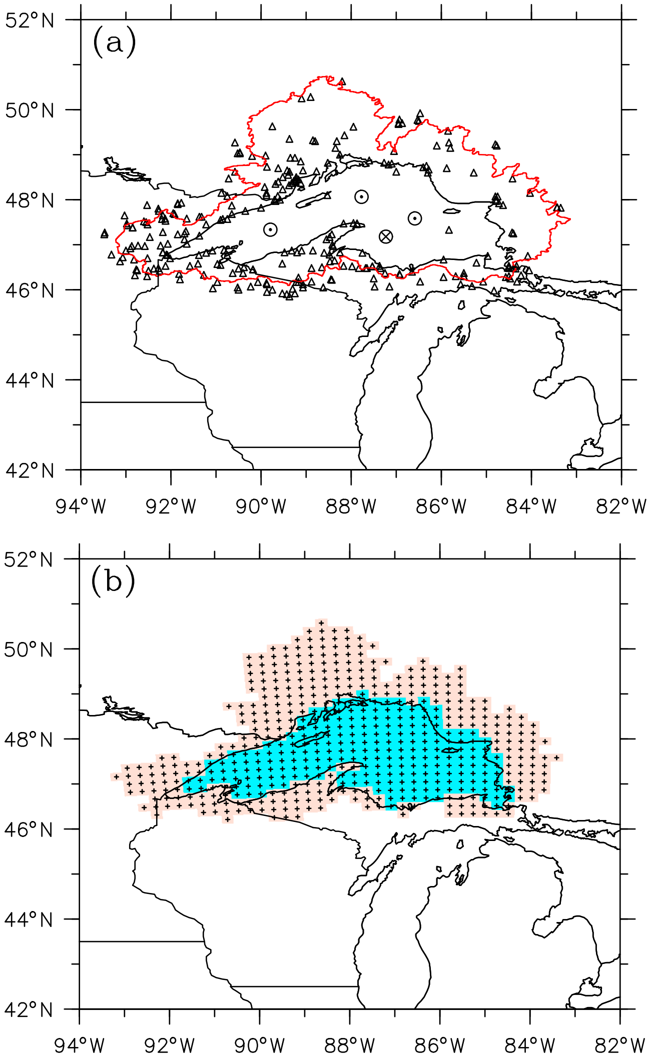


**Figure 1.** (a) Location of precipitation observation stations (triangles) within 30 km of the Lake Superior drainage basin (outlined in red), NOAA National Data Buoy Center buoys (circled dots), and the Stannard Rock Lighthouse station (circled cross). (b) RegCM4 depiction of the Lake Superior drainage basin. The plus symbols indicate the central location of each grid cell, and the blue and tan cells distinguish water from land.

Ontario basin, with precipitation minima (maxima) observed over the lake surface between May–September (November–March) of 1972–1973. *Augustine et al.* [1994] analyzed satellite-based rainfall estimates in the Great Lakes basin during the summer months between 1988–1990 and found average summer satellite-based rainfall estimates of over-lake precipitation on Lakes Michigan, Huron, and Superior were within 1–5% of over-lake precipitation estimates based on shoreline stations.

[6] While providing a basis for understanding the water budget of the Great Lakes basin, these historical data are rarely accompanied with an explicit acknowledgement of the difference between land-atmosphere and lake-atmosphere dynamics, and of the crucial role these dynamics play in precipitation processes, particularly over a large lake such as Lake Superior. The purpose of this paper is to assess the potential benefits of utilizing a regional climate model (RCM) to represent these dynamics and to generate more realistic and defensible estimates of precipitation over the Lake Superior basin.

## 2. Data and Methods

[7] In order to assess differences between conventional and alternative approaches to constructing historical precipitation estimates over Lake Superior, we compared output from the Abdus Salam International Centre for Theoretical Physics Regional Climate Model Version 4 (ICTP RegCM4) [*Elguindi et al.*, 2011; *Giorgi et al.*, 2012] to historical precipitation estimates from NOAA's Great Lakes Environmental Research Laboratory (GLERL) Hydrologic Database for the period 1980 to 2000 [*Croley and Hunter*, 1994], and to estimates from various other sources summarized by *Derecki* [1976]. We base our comparison primarily on the long-term ratio between monthly over-lake and over-land precipitation ($R_p$), a common metric for evaluating precipitation records, particularly in basins with a relatively large surface water area [*Kresge et al.*, 1964; *Changnon*, 1968; *Jones and Meredith*, 1972].

[8] The NOAA GLERL Lake Superior precipitation estimates are based on applying a Thiessen polygon interpolation scheme [*Croley and Hartmann*, 1985] to land-based NOAA National Climatic Data Center (NCDC) weather station observations (including Canadian gauges) located within the Lake Superior watershed and within a 30 km-wide buffer region along the outer watershed boundary (Figure 1a). A noted benefit of this method is its ability to accommodate daily changes in the spatial distribution of available NCDC station data [*Bolsenga and Hagman*, 1975].

[9] The RegCM4 domain includes a 20-km horizontal resolution grid covering much of the eastern United States, with 18 sigma levels. Initial and lateral boundary conditions for the RegCM4 simulation were specified by the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset [*Kalnay et al.*, 1996] and the Global Sea-Ice and Sea Surface Temperature (GISST) gridded dataset [*Rayner et al.*, 1996]. RegCM4 also utilizes the Grell convection scheme [*Grell*, 1993], and is coupled with the Biosphere-Atmosphere Transfer Scheme (BATS) [*Dickinson et al.*, 1993] and the one-dimensional, interactive Hostetler lake model [*Hostetler et al.*, 1993]. The simulation, which ran from 1978–2000, includes a 1.5 year spin-up period. Following the simulation, we extracted from the RegCM4 domain those grid cells located within the Lake Superior basin (Figure 1b).

[10] While RegCM4 is a relatively novel tool for evaluating Lake Superior precipitation estimates, validation runs based on simulations from two earlier versions of the model, RegCM1 and RegCM2, indicate that it is capable of reproducing temperature, precipitation, and lake ice cover dynamics across the Great Lakes basin [*Bates et al.*, 1993, 1995]. In addition, the Hostetler lake model has been used in previous regional climate studies of the Great Lakes basin [*Bates et al.*, 1995; *Hostetler et al.*, 1993]. Here, we validate RegCM4 using NCEP/NCAR sea-level pressure (SLP) data and gridded air temperature observations from the University of Delaware dataset [*Willmott and Matsuura*, 2000]. Comparisons show that RegCM4 reproduces the broad patterns of sea-level pressure and surface air temperature across the domain, both annually and by season, although with a

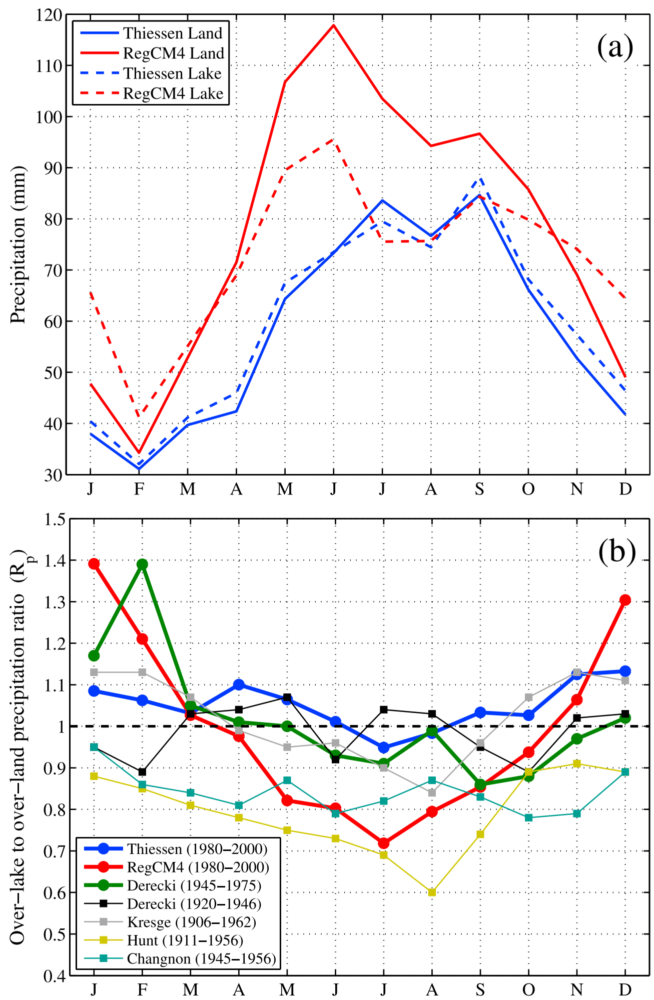


**Figure 2.** (a) Average monthly over-land (solid) and over-lake (dashed) precipitation estimates from the Thiessen polygon procedure (blue) and RegCM4 simulation (red) from 1980–2000 over the Lake Superior basin. Temporal correlations between the two monthly over-land and over-lake precipitation datasets are 0.90 and 0.82, respectively. (b) Average monthly $R_p$ values from the RegCM4 simulation and gauge-based precipitation estimates (each covering a different time period, indicated in the legend). Circles indicate values for the Lake Superior basin, and squares indicate values for either the Lake Michigan or Lake Erie basin. For more information, see *Hunt* [1959], *Changnon* [1961], and *Derecki* [1976, 1980].

summertime warm bias (Figures S1 and S2 in the auxiliary material).[1] These comparisons indicate that RegCM4 is an appropriate RCM for supporting climate research within the Great Lakes region.

[11] In an effort to further understand seasonal differences between gauge-based and RCM-simulated estimates of precipitation (and, in particular, of $R_p$), we also investigate the role of atmospheric stability (defined as the air temperature overlying the lake surface minus the lake surface water temperature ($T_{air}$-$T_{lake}$)) in modulating over-lake precipitation. We base this comparison on RegCM4-simulated differences between lake-wide air and surface water temperatures (1981–1999), three NOAA National Data Buoy Center (NDBC) buoys located across Lake Superior (also from 1981–1999, see Figure 1a), monthly air temperature data from the NDBC Stannard Rock lighthouse station (from 1994–2000 at 32.6 m; 47.18°N, 87.23°W), and monthly water surface temperature estimates from NOAA's Great Lakes Surface Environmental Analysis (GLSEA), which are based on Advanced Very High Resolution Radiometer output aboard NOAA polar-orbiting satellites [*Schwab et al.*, 1992]. The average lake depth at the location of the three NDBC buoys is 227.4 m. Air temperature at the buoys is recorded 4 m above the water surface, while observed water temperature is recorded 0.6 m below the surface. Simulated air temperatures from RegCM4 are the result of output recorded at 2 m above the lake surface, while the lake temperature is simulated 0.5 m below the lake surface.

## 3. Results

[12] Our comparison between RegCM4-simulated and Thiessen polygon average monthly precipitation values from 1980–2000 (Figure 2a) indicates that while both procedures reflect a somewhat similar seasonal dynamic, there are important differences in how each represents the relative magnitude of over-land and over-lake precipitation, and the time of year when one becomes greater than the other. The three months with the highest average over-land precipitation from RegCM4 are May, June, and July, while the three months with the highest average over-land precipitation estimates from the Thiessen polygons are July, August, and September. We also found that RegCM4-simulated average annual over-land and over-lake precipitation (929 mm and 870 mm, respectively) were both higher than corresponding precipitation values from the Thiessen polygon estimates (829 mm and 805 mm, respectively). In fact, average monthly precipitation values for over-land precipitation from RegCM4 are higher than those from the Thiessen polygon scheme for every month of the year, while average monthly over-lake precipitation from RegCM4 exceeds the Thiessen polygon estimates 10 months of the year (June and September are the exceptions).

[13] Our comparison (Figure 2b) between RegCM4-based average monthly $R_p$ values and those from multiple gauge-based precipitation estimates (including GLERL's estimates, as well as those summarized by *Derecki* [1976]) indicates that the RegCM4-based values reflect seasonal dynamics that are not only stronger than any other gauge-based estimate, but that are also much closer to what we might expect from a large lake-dominated system. More specifically, we find that monthly average $R_p$ values from RegCM4 range from a maximum of 1.39 in January to a minimum of 0.72 in July, and are less than 1.0 from April-October. In contrast, the difference between winter and summer average monthly $R_p$ values from the Thiessen procedure is roughly 0.18. In one set of estimates (Derecki [1920–1946]), the $R_p$ values in July and August are higher than those in January and February indicating that, in general, gauge-based estimates collectively underestimate both the impact of the intensity and duration of seasonal atmospheric instability on over-lake precipitation. Only the Derecki (1945–1975) gauge-based estimates of $R_p$ reflect the stability dynamics we might expect. Not surprisingly, these estimates are based on a

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL050468.

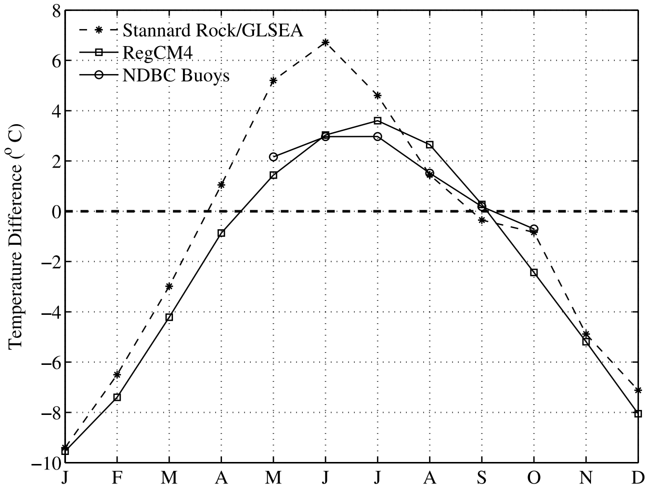


**Figure 3.** Average monthly temperature difference ($T_{air}$-$T_{lake}$) based on Stannard Rock and GLSEA data (1994–2000), NDBC buoy observations (average of three buoys), and RegCM4 (average of all lake cells) during 1981–1999. The relatively high air-water temperature difference recorded at Stannard Rock relative to NDBC buoy observations (most notable during spring and early summer months) reflects a combination of higher recorded air temperatures at Stannard Rock relative to the air temperatures recorded at the NDBC buoys (largely attributable to the difference in elevation between the two sets of sites) and relatively little difference in recorded water temperatures.

group of gauges located on Madeline Island, off the southwestern shore of Lake Superior. While additional details of remaining gauge locations for the data sets in Figure 2b are given by *Derecki* [1976], we note here that most of these (with the exception of the gauges for the Derecki, 1945–1975 analysis) are based exclusively on shoreline (rather than island-based) gauges.

[14] The RegCM4-simulated differences between overlying air and surface water temperatures on Lake Superior (Figure 3) reflect fluctuations in seasonal stability similar to what we might expect based on historical observations on other Great Lakes [see *Derecki*, 1976, Figure 4–97] and the three Lake Superior NDBC buoys (Figure 3). In addition, the difference in temperature between the Stannard Rock lighthouse and lake surface estimates from GLSEA show seasonal variability that is very similar to RegCM4, with the largest positive differences during May and June. Historical air-water temperature differences on other Great Lakes, for example, indicate that stable atmospheric conditions prevail from roughly late March or early April until August or early September. The expected peak in air-water temperature differences on Lake Superior is in June or July, because this is when the lake stratifies [*Austin and Colman*, 2007]. The RegCM4-simulated data in Figure 3 appropriately reflects Lake Superior atmospheric stability fluctuations and, more importantly, appears to propagate those fluctuations into regional precipitation patterns.

## 4. Discussion and Conclusions

[15] The results of our comparison between gauge-based and RegCM4-simulated estimates of precipitation over the Lake Superior basin suggest that shoreline meteorological stations alone are insufficient for understanding the dynamics of over-lake precipitation on relatively large inland lakes, including the North American Laurentian Great Lakes. Monthly and annual-scale operational hydrological forecasting in the Great Lakes region currently depends largely on models which use an ensemble of weighted historical gauge-based precipitation estimates, leading to a need for alternative methods for reconstructing the historical precipitation record and for incorporating those methods into practice [*Gronewold et al.*, 2011].

[16] More specifically, RegCM4 reasonably simulates the Great Lakes' influence on seasonal patterns of atmospheric stability, based on comparisons between simulated and observed air-water temperature differences across the lake surface. As a result, RegCM4 is more likely than shoreline, gauge-based estimates to capture the effects of large lakes on overlying atmospheric stability and resulting precipitation fields. Future efforts to accommodate RCM results into improved estimates of the historical Great Lakes precipitation record (e.g., applying RegCM4-based $R_p$ values to Thiessen-based historical precipitation estimates) should account for the seasonal relationship between over-lake and over-land precipitation. Because most current operational procedures for estimating over-lake precipitation do not account for atmospheric stability and seasonal variations in the ratio of over-lake to over-land precipitation, it is imperative that we incorporate alternative methods to improve precipitation estimates over large lakes in order to better quantify, balance, and forecast individual water budgets and lake levels, not only in the Great Lakes basin, but around the world.

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