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Changes in Large Lake Water Level Dynamics in Response to Climate Change

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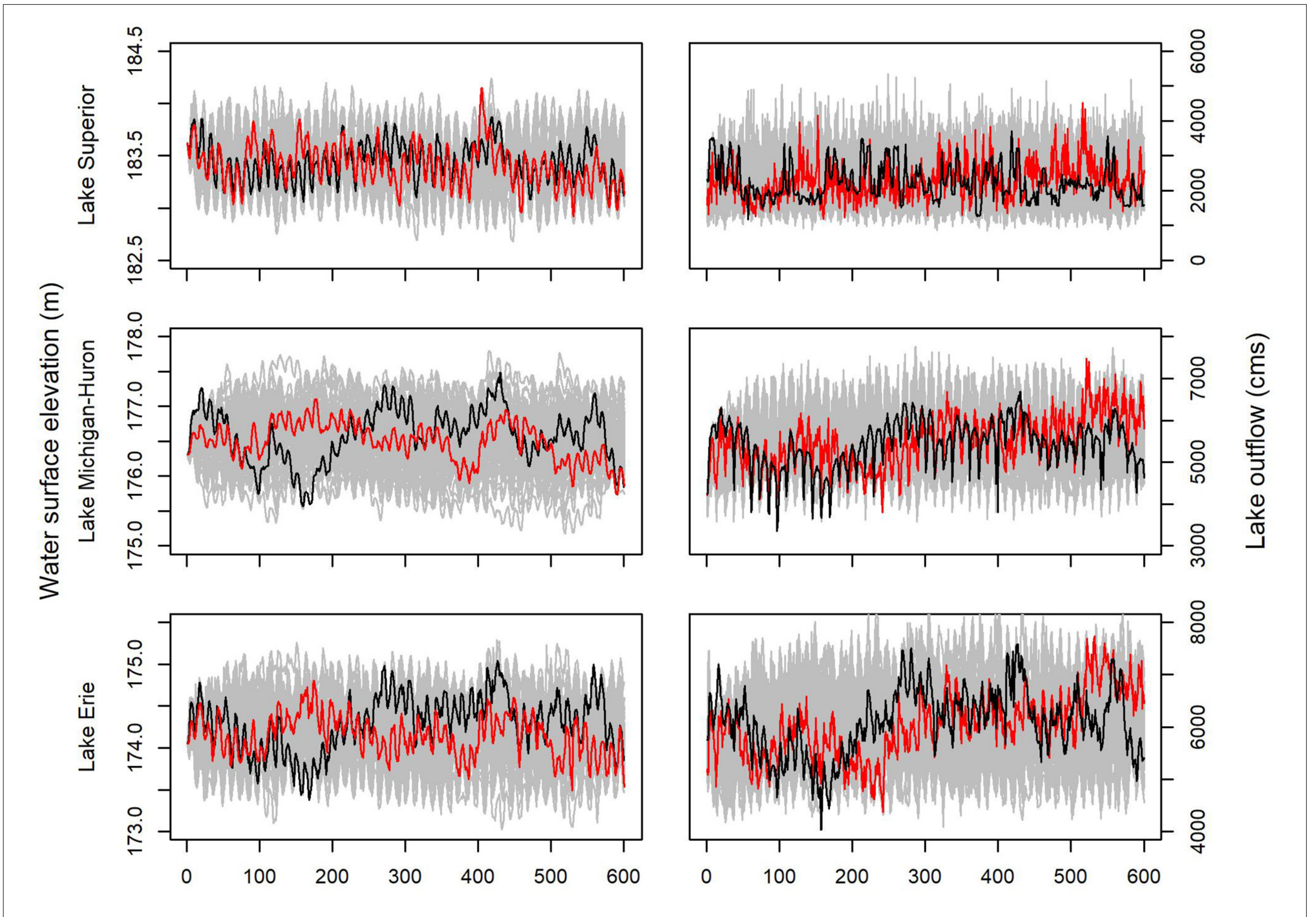

FIGURE 1 | Comparison between simulated and observed historical time series of water levels **(left)** and lake outflows **(right)** for Lakes Superior (top), Michigan-Huron (middle), and Erie (bottom) from January 1951 through December 2000. Gray lines represent 100 ensemble members from our model simulation (randomly sampled from 1,000 to facilitate reproducibility and clarity). Black lines represent observed values, and red lines represent a single ensemble member (same member for all panels) to reflect individual simulation variability.

TABLE 1 | Comparison of long-term average water levels (in meters) for each lake based on a historical simulation of the observed data period, and two future climate change scenarios.

	Lake Superior	Lake Michigan-Huron	Lake Erie
Baseline (Scenario 1)	183.42	176.54	174.18
Scenario 2	183.50	176.66	174.27
Scenario 3	183.45	176.60	174.24

Lake Erie. These values are well within the range of reasonable tolerance for historical simulations, particularly in light of the fact that most historical RCM-based simulations have biases that are either not reported, or well-exceed those presented here.

3.1.3. Water Level Change Analysis

Mean water levels for observed data, our historical model run, and two future water supply scenarios are summarized in **Table 1**.

Scenarios SC2 and SC3 indicate a slight net increase in average water level on Lake Superior, with increases of 8 cm (SC2) and 3 cm (SC3), respectively. Similar changes are expected on Lake Michigan-Huron (increases of 12 and 6 cm for SC2 and SC3, respectively) and on Lake Erie (increases of 9 and 6 cm for SC2 and SC3, respectively). Importantly, both future scenarios suggest an increase in long-term average water levels across all of the Great Lakes. These findings are consistent with the RCM-CNRM mid-century water level projections in Notaro et al. (2015) and are a plausible consequence of slight to moderate NBS increases projected by Mailhot et al. (2019) and Music et al. (2015).

All three of our model runs yield comparable marginal distributions for mean water level, as shown in **Figure 2**. Overlapping distributions between the baseline simulation and future scenarios indicate that any individual model run (i.e., ensemble member) may fall within the range of simulated historical values and, in some cases, even indicate a decline in water levels. Therefore, our findings indicate that while an increase in water levels is likely across the

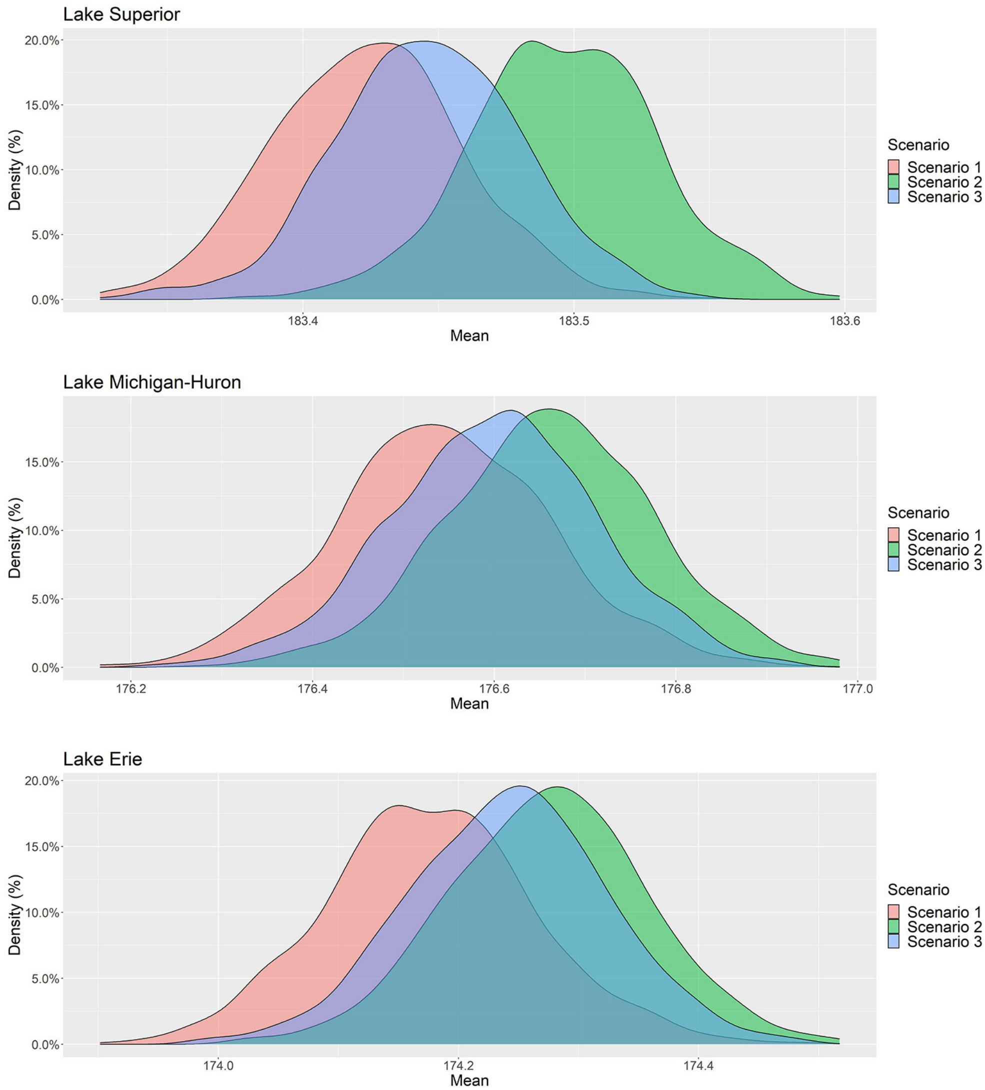

FIGURE 2 | Probability distribution of all (600) simulated water level sequences for SC1 (red), SC2 (green), and SC3 (blue) for Lakes Superior **(top)**, Michigan-Huron **(middle)**, and Erie **(bottom)**.

Great Lakes, our range of plausible water supply scenarios includes both the possibility of a rise or fall in long-term water levels. We notably find that continuation of observational trends in NBS components alone, *via* scenario SC2, results in greater water level rise than is demonstrated when RCM-based NBS component projections are incorporated *via* scenario SC3.

The seasonality of annual water level highs and lows is included in **Figure 3**. Scenario SC2 causes only slight shifts in the timing of annual maximum and minimum water levels, with changes of <1 week across all lakes. Peak water levels occurred an average of 3 days earlier on Lake Superior and Michigan-Huron relative to the baseline simulation, while water levels on Lake Erie peaked an average of 7 days later. The average date of annual minimum water levels did not change significantly for any lake under scenario SC2. In contrast, scenario SC3 results in a more significant shift in the seasonality of water levels across all three lakes. Water levels peak an average of 14 and 24 days sooner on Lake Superior, and Michigan-Huron, respectively, while Lake Erie remains unchanged. Lake Michigan-Huron displays the greatest shift in timing of the annual low water level, with this trough occurring an average of 11 days earlier under scenario SC3 than baseline simulations indicate.

While experiencing an insignificant shift in overall timing, Lake Superior does undergo an intensification of annual lows that occur during the month of March, indicating that a temporal concentration of this seasonal inflection point may occur. Our findings are consistent with both observational trends and climate projections that annual water level rises

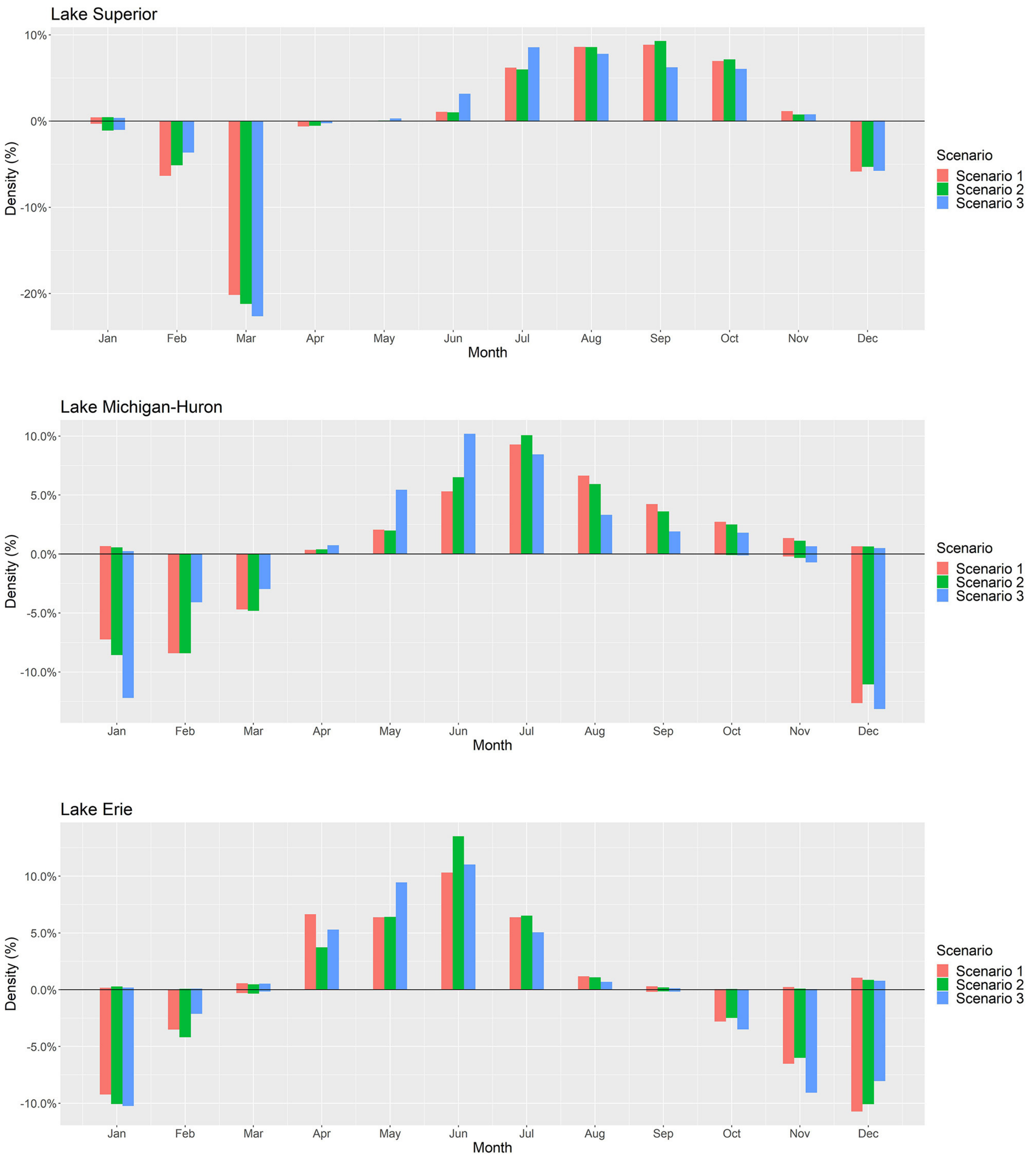

FIGURE 3 | Frequency of occurrences of annual water level maximums (above the x-axis) and minimums (below the x-axis) for SC1 (red), SC2 (green), and SC3 (blue) for Lakes Superior **(top)**, Michigan-Huron **(middle)**, and Erie **(bottom)**.

and falls are occurring earlier, particularly annual maximum levels on Lake Superior (Lenters, 2001; Gronewold and Stow, 2014a). However, we find this shift in water level seasonality to be significantly greater in annual maximums than in annual minimums. The most apparent plausible change in the seasonal cycle of water levels is a shift earlier in the year, while there is relatively little compelling evidence for amplification or dampening effects.

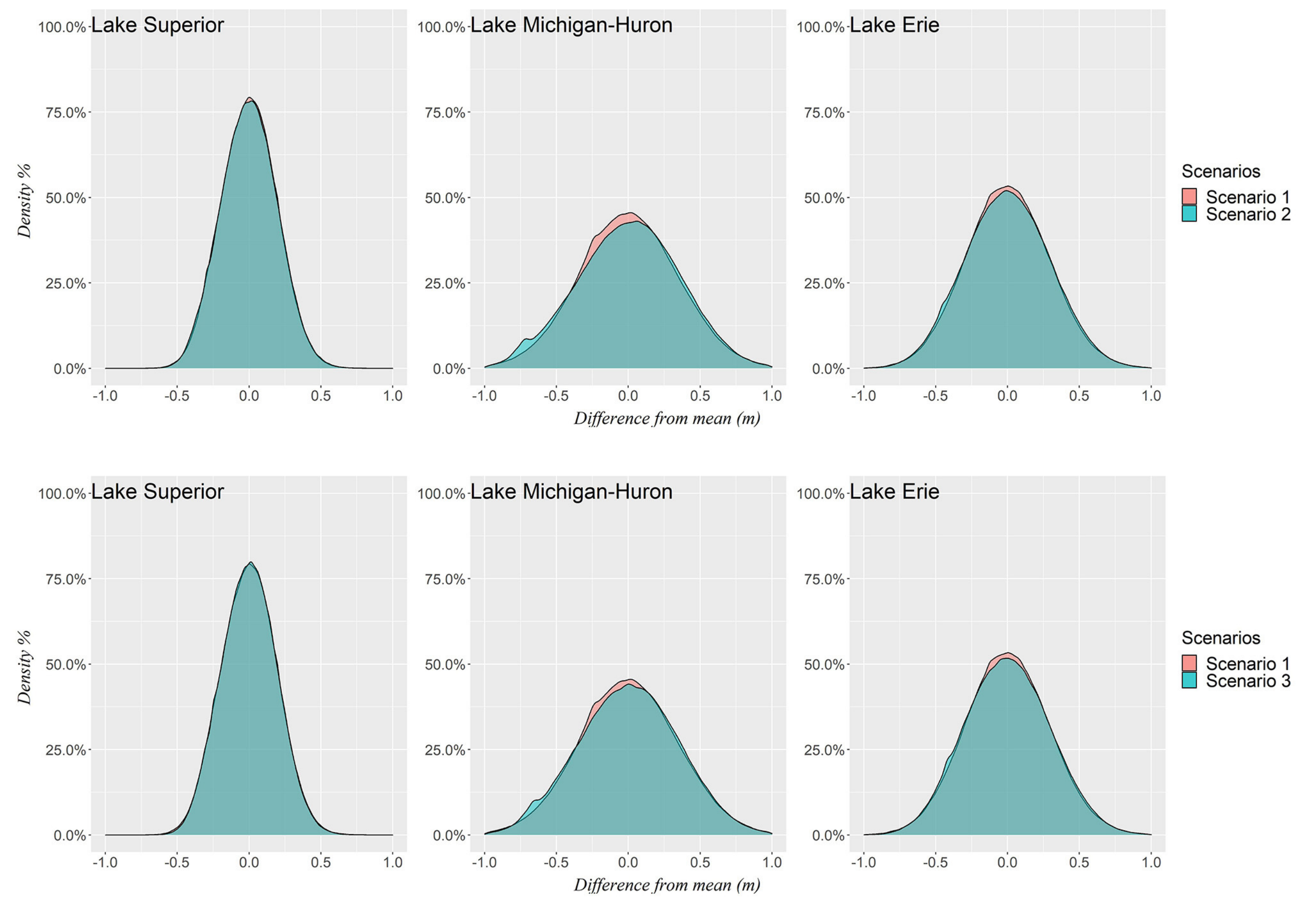

FIGURE 4 | Comparison of zero-centered probability distributions of all simulated water levels between SC1 and SC2 **(top)** and SC1 and SC3 **(bottom)** for Lakes Superior, Michigan-Huron, and Erie.

Figure 4 displays the zero-centered probability density function of water levels for each simulation. While all three model simulations yield similar water level distributions, differences are evident in the tails of the distributions, representing a change in the occurrence of extreme water levels. Two standard deviations from the zero-centered mean of the historical simulation on each lake is used as a threshold to measure the frequency of extreme values. This results in a threshold of 0.3, 0.47, and 0.45 m deviations from the mean for Lake Superior, Michigan-Huron, and Erie, respectively. Water levels fall outside of these thresholds an average of 3.0% more frequently across lakes under scenario SC2 than is historically simulated, while frequency increases by an average of 2.1% under scenario SC3. Our findings also demonstrate that the increased frequency of extreme water levels is of comparable magnitude at both the high and low ends of the distribution, and that water levels are less concentrated around the mean under both scenarios. This indicates that future water levels may demonstrate greater dispersion from the mean in both directions relative to the historical record, supporting ongoing speculation about future increased variability of Great Lakes water levels (Gronewold and Rood, 2019). Increased dispersion of water levels is also consistent with the possibility of an enhancement in the annual cycle of water supply (Manabe et al., 2004; Mailhot et al., 2019), though we do not find compelling evidence of an overall amplification of seasonal water level dynamics in this study. Increasing magnitudes of both precipitation and evaporation provide another plausible explanation for greater water level variability, as imbalances in these competing hydrologic forces can result in significant water level deviations from the long-term average (Gronewold et al., 2021).

4. CONCLUDING REMARKS

Great Lakes hydroclimate studies prior to 2011 widely used the "change-factor" method and consistently simulated significant declines in future water levels (Croley, 1990; Hartmann, 1990; Angel and Kunkel, 2010; Hayhoe et al., 2010). These findings led to a regional narrative reflecting a future of drought, aridity, and chronic low water levels (Gronewold and Stow, 2014b). The low water levels in many of these simulations, however, was a consequence of misguided modeling assumptions based

Supplementary Material
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Precipitation Mean Perturbation Scenario 1

Month	Superior	Michigan−Huron	Erie
Jan	+0.00000	+0.00000	+0.00000
Feb	+0.00000	+0.00000	+0.00000
Mar	+0.00000	+0.00000	+0.00000
Apr	+0.00000	+0.00000	+0.00000
May	+0.00000	+0.00000	+0.00000
Jun	+0.00000	+0.00000	+0.00000
Jul	+0.00000	+0.00000	+0.00000
Aug	+0.00000	+0.00000	+0.00000
Sep	+0.00000	+0.00000	+0.00000
Oct	+0.00000	+0.00000	+0.00000
Nov	+0.00000	+0.00000	+0.00000
Dec	+0.00000	+0.00000	+0.00000

Lake

Precipitation Mean Perturbation Scenario 2

Month	Superior	Michigan−Huron	Erie
Jan	+0.20982	+0.00000	+0.00000
Feb	+0.23545	+0.00000	+0.00000
Mar	+0.00000	+0.00000	+0.00000
Apr	+0.22609	+0.18560	+0.00000
May	+0.00000	+0.00000	+0.38760
Jun	+0.00000	+0.00000	+0.37478
Jul	+0.00000	+0.00000	+0.00000
Aug	+0.00000	+0.00000	+0.00000
Sep	+0.00000	+0.00000	+0.00000
Oct	+0.00000	+0.00000	+0.00000
Nov	+0.00000	+0.00000	+0.00000
Dec	+0.31043	+0.27763	+0.00000

Lake

Precipitation Mean Perturbation Scenario 3

Month	Superior	Michigan−Huron	Erie
Jan	+0.06300	+0.00000	+0.00000
Feb	+0.39200	+0.32000	+0.40000
Mar	+0.00000	+0.32000	+0.36000
Apr	+0.50900	+0.49700	+0.40000
May	+0.40000	+0.40000	+0.43700
Jun	+0.00000	+0.00000	+0.11100
Jul	+0.00000	+0.00000	+0.00000
Aug	+0.00000	+0.00000	+0.00000
Sep	+0.00000	+0.00000	+0.00000
Oct	+0.36000	+0.32000	+0.00000
Nov	+0.32000	+0.00000	+0.32000
Dec	+0.09300	+0.08400	+0.40000

Lake

Evaporation Mean Perturbation Scenario 1

Month	Superior	Michigan−Huron	Erie
Jan	+0.00000	+0.00000	+0.00000
Feb	+0.00000	+0.00000	+0.00000
Mar	+0.00000	+0.00000	+0.00000
Apr	+0.00000	+0.00000	+0.00000
May	+0.00000	+0.00000	+0.00000
Jun	+0.00000	+0.00000	+0.00000
Jul	+0.00000	+0.00000	+0.00000
Aug	+0.00000	+0.00000	+0.00000
Sep	+0.00000	+0.00000	+0.00000
Oct	+0.00000	+0.00000	+0.00000
Nov	+0.00000	+0.00000	+0.00000
Dec	+0.00000	+0.00000	+0.00000

Lake

Evaporation Mean Perturbation Scenario 2

Month	Superior	Michigan−Huron	Erie
Jan	+0.00000	+0.00000	+0.00000
Feb	+0.00000	−0.13522	+0.00000
Mar	+0.00000	+0.00000	+0.00000
Apr	−0.03459	+0.00000	+0.00000
May	+0.00000	+0.00000	+0.00000
Jun	−0.03203	−0.06622	+0.00000
Jul	−0.05897	+0.00000	+0.00000
Aug	+0.00000	+0.00000	+0.00000
Sep	+0.00000	+0.00000	+0.00000
Oct	+0.00000	+0.00000	+0.00000
Nov	+0.00000	+0.00000	+0.00000
Dec	+0.00000	+0.00000	+0.00000

Lake

Evaporation Mean Perturbation Scenario 3

Month	Superior	Michigan−Huron	Erie
Jan	+0.00000	+0.00000	+0.00000
Feb	+0.56000	−0.04050	+0.00000
Mar	+0.44000	+0.28000	+0.00000
Apr	−0.00900	+0.00000	+0.00000
May	+0.00000	+0.32000	+0.40000
Jun	+0.31100	+0.49900	+0.40000
Jul	+0.46200	+0.64000	+0.32000
Aug	+0.60000	+0.56000	+0.32000
Sep	+0.48000	+0.48000	+0.32000
Oct	+0.56000	+0.44000	+0.32000
Nov	+0.36000	+0.32000	+0.28000
Dec	+0.00000	+0.00000	+0.00000

Lake

Runoff Mean Perturbation Scenario 1

Month	Superior	Michigan−Huron	Erie
Jan	+0.00000	+0.00000	+0.00000
Feb	+0.00000	+0.00000	+0.00000
Mar	+0.00000	+0.00000	+0.00000
Apr	+0.00000	+0.00000	+0.00000
May	+0.00000	+0.00000	+0.00000
Jun	+0.00000	+0.00000	+0.00000
Jul	+0.00000	+0.00000	+0.00000
Aug	+0.00000	+0.00000	+0.00000
Sep	+0.00000	+0.00000	+0.00000
Oct	+0.00000	+0.00000	+0.00000
Nov	+0.00000	+0.00000	+0.00000
Dec	+0.00000	+0.00000	+0.00000

Lake

Runoff Mean Perturbation Scenario 2

Month	Superior	Michigan−Huron	Erie
Jan	+0.09758	−0.23308	+0.00000
Feb	+0.10000	+0.00000	+0.00000
Mar	+0.00000	+0.00000	+0.00000
Apr	+0.00000	+0.00000	+0.00000
May	+0.00000	+0.00000	+0.32000
Jun	+0.00000	+0.00000	+0.21643
Jul	+0.18750	+0.00000	+0.00000
Aug	+0.17632	+0.00000	+0.00000
Sep	+0.24800	+0.00000	+0.00000
Oct	+0.00000	+0.00000	+0.00000
Nov	+0.00000	+0.00000	+0.00000
Dec	+0.10667	+0.00000	+0.00000

Lake

Runoff Mean Perturbation Scenario 3

Month	Superior	Michigan−Huron	Erie
Jan	+0.43000	+0.53100	+0.40000
Feb	+0.47000	+0.64000	+0.52000
Mar	+0.00000	+0.00000	+0.00000
Apr	+0.00000	+0.36000	+0.00000
May	+0.52000	+0.00000	+0.49600
Jun	+0.00000	+0.00000	+0.06600
Jul	+0.05700	+0.00000	+0.00000
Aug	+0.05400	+0.00000	+0.00000
Sep	+0.07500	+0.00000	+0.00000
Oct	+0.00000	+0.00000	+0.00000
Nov	+0.00000	+0.00000	+0.00000
Dec	+0.31300	+0.40000	+0.40000

Lake

Figure S1. Slope factors used in each climate scenario (blocks of columns on each page) for each combination of month (rows), lake (columns from left to right in each block), and water balance component (separate for each page).

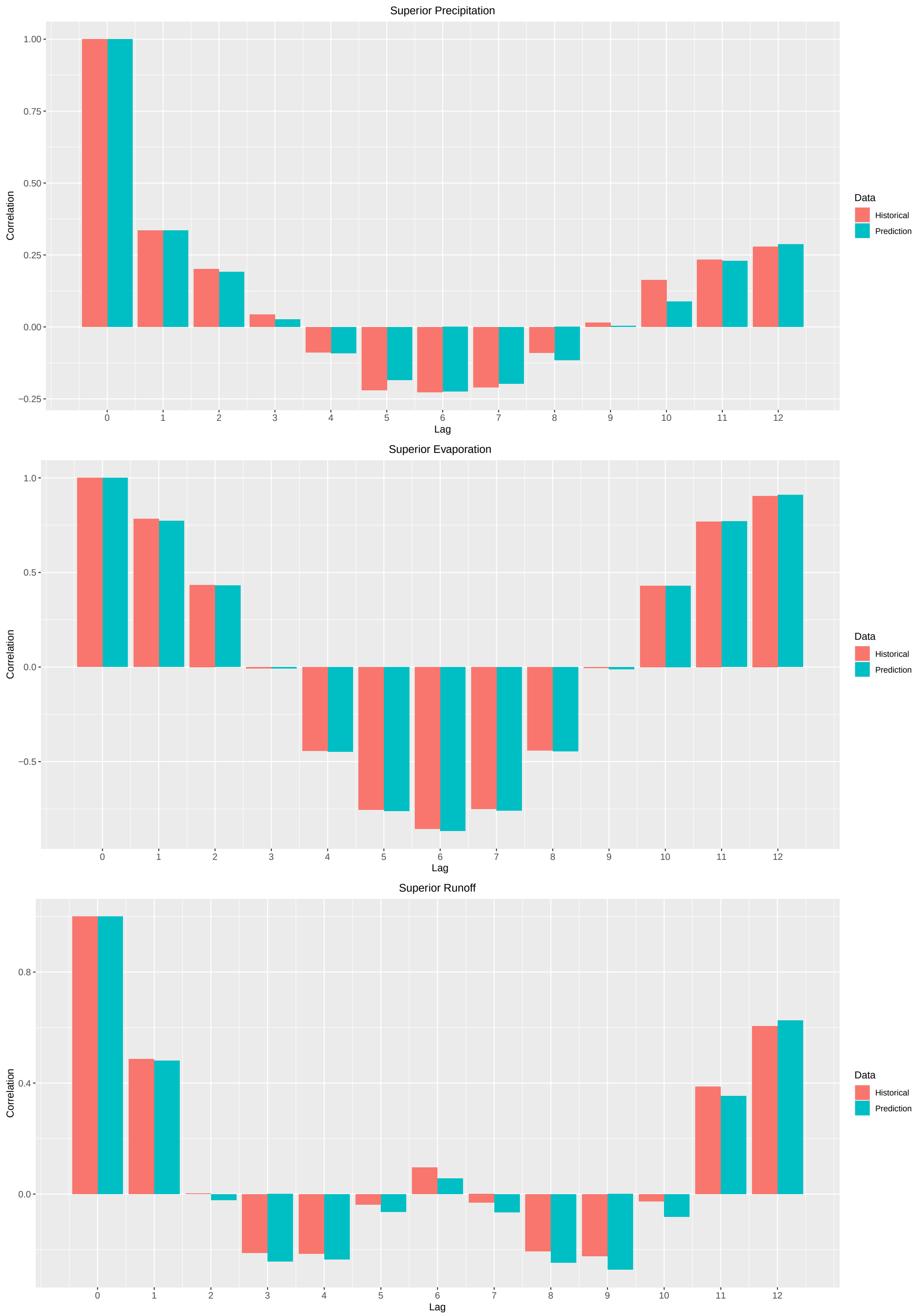

Figure S2. Comparison of autocorrelation function for Lake Superior water balance components based on predictions (copula) and historical observations.

Figure S3. Comparison of autocorrelation function for Lake Michigan-Huron water balance components based on predictions (copula) and historical observations.

Figure S4. Comparison of autocorrelation function for Lake Erie water balance components based on predictions (copula) and historical observations.

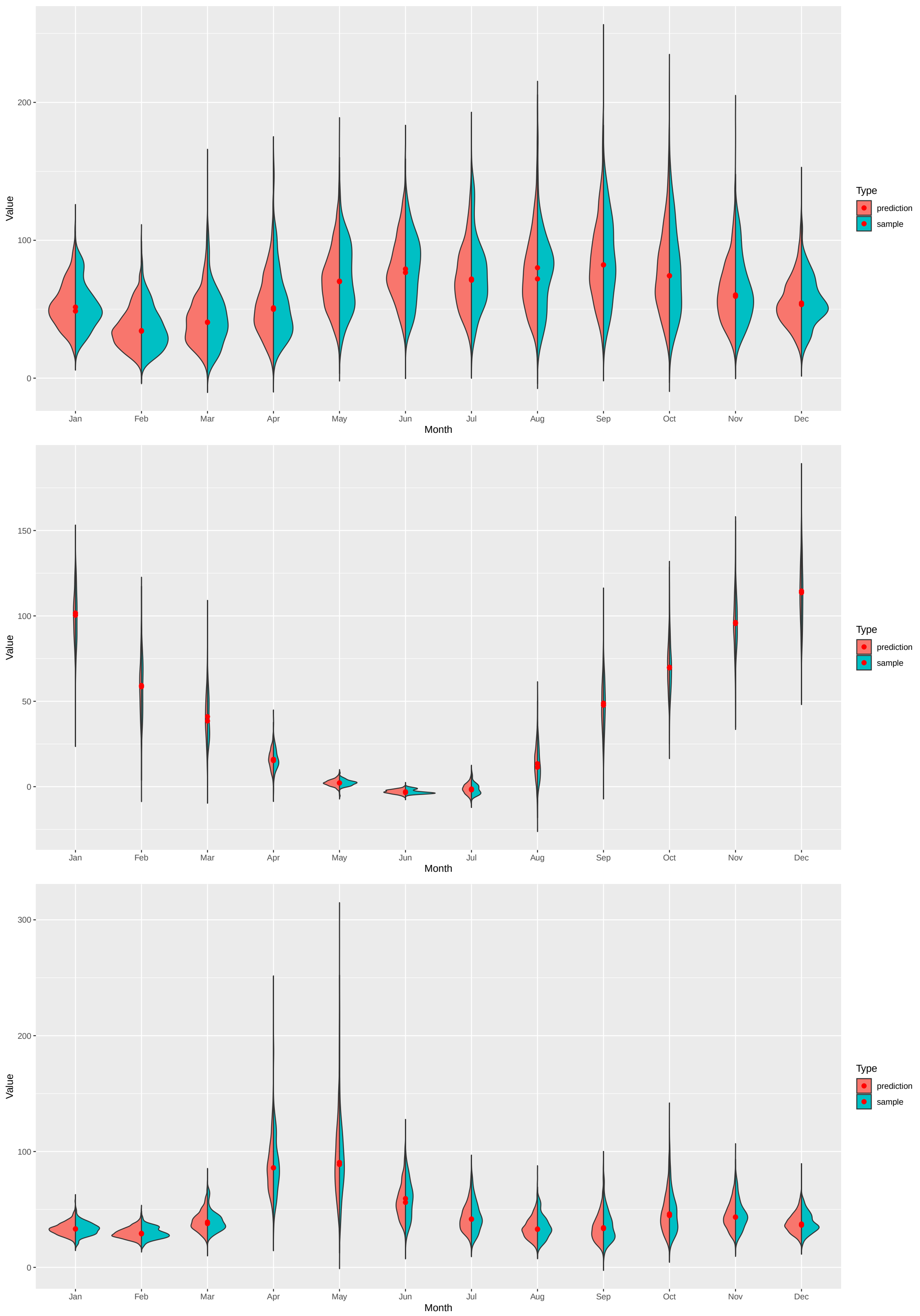

Figure S5. Violin plot comparing marginal probability distributions of monthly water balance components (from top to bottom: precipitation, evaporation, runoff) for Lake Superior based on predictions (copula) and observations.

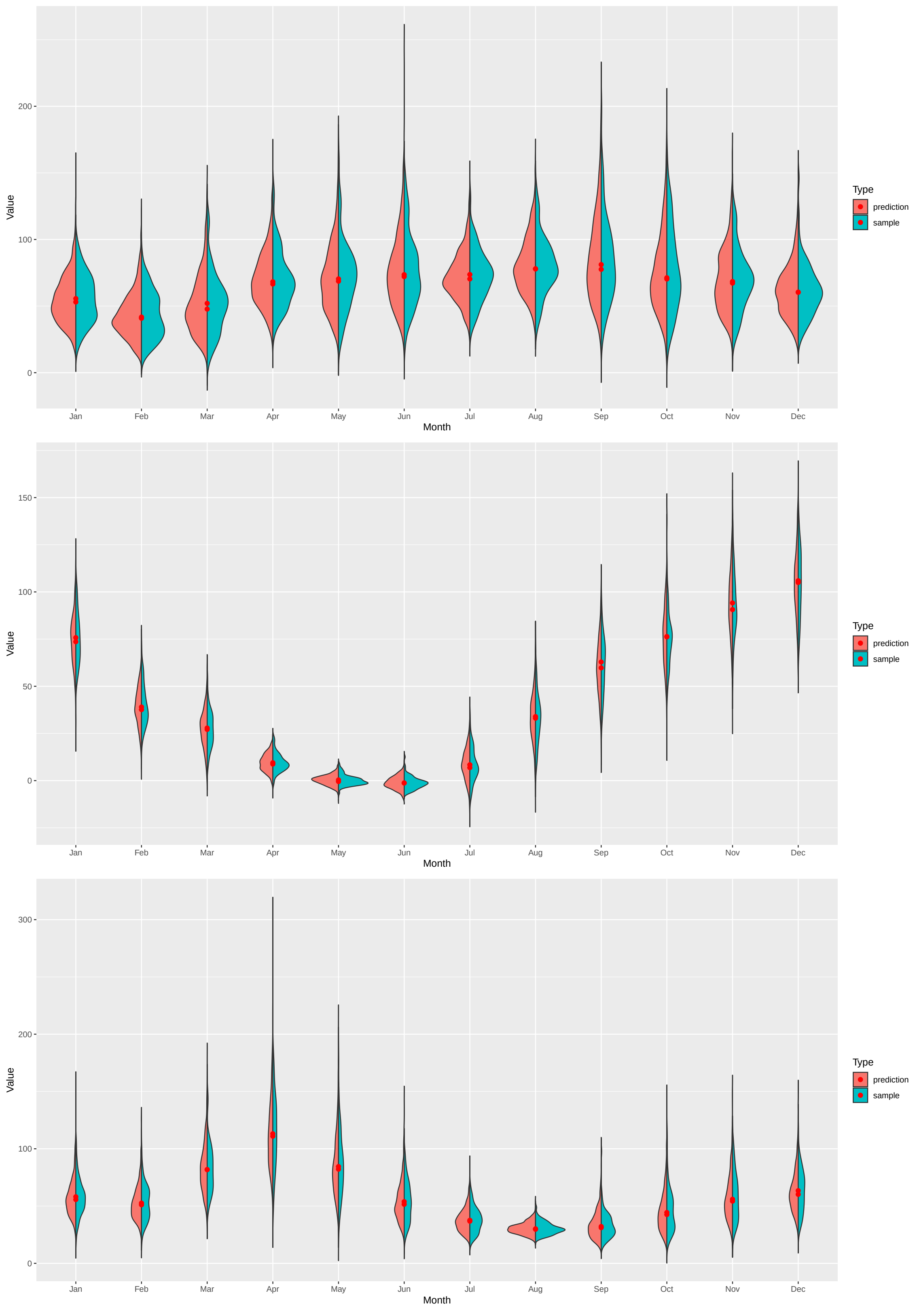

Figure S6. Violin plot comparing marginal probability distributions of monthly water balance components (from top to bottom: precipitation, evaporation, runoff) for Lake Michigan-Huron based on predictions (copula) and observations.

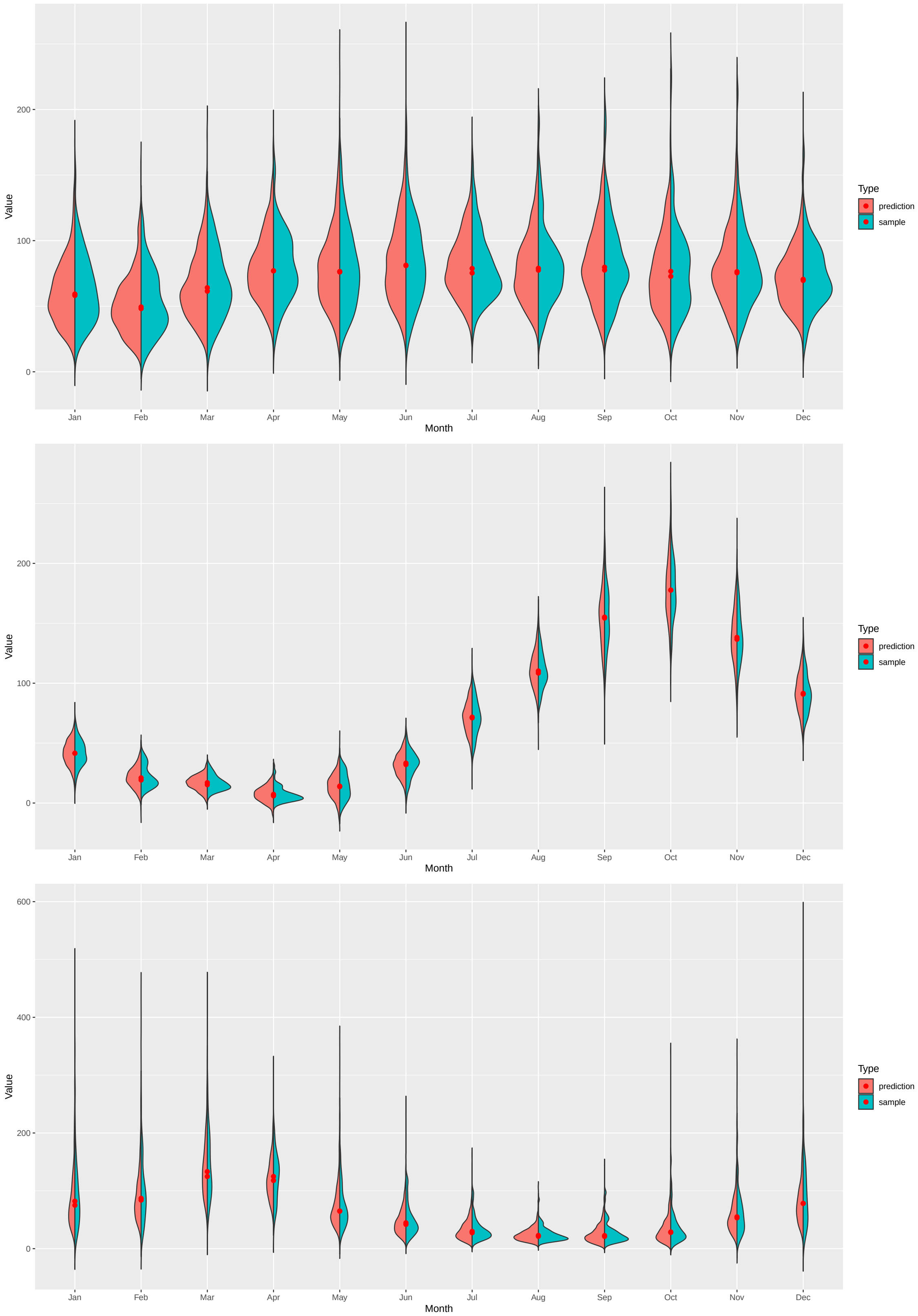

Figure S7. Violin plot comparing marginal probability distributions of monthly water balance components (from top to bottom: precipitation, evaporation, runoff) for Lake Erie based on predictions (copula) and observations.

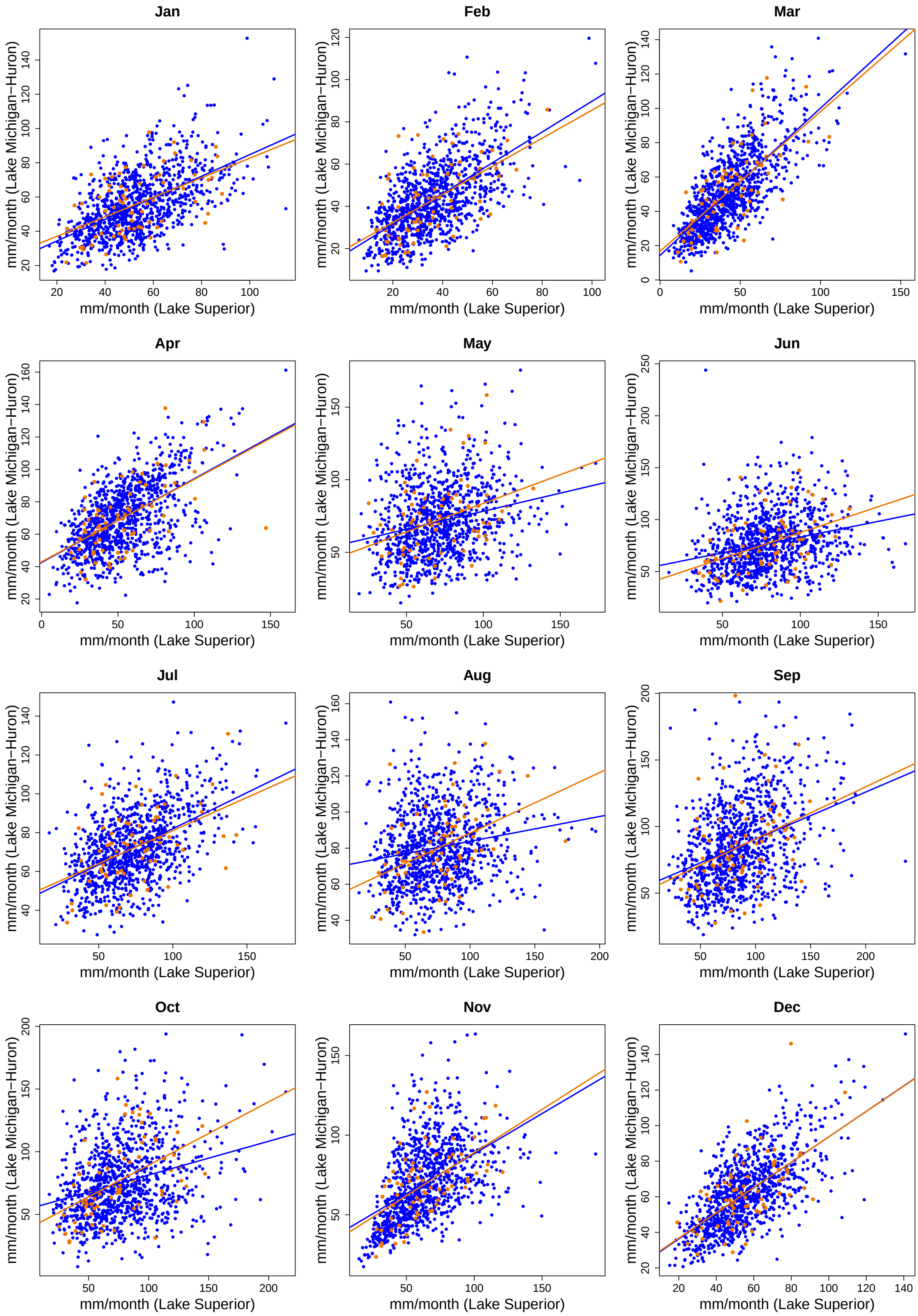

Figure S8. Spatial correlation (between Lakes Superior and Michigan-Huron) in monthly precipitation based on historical data (red) and copula simulations (blue).

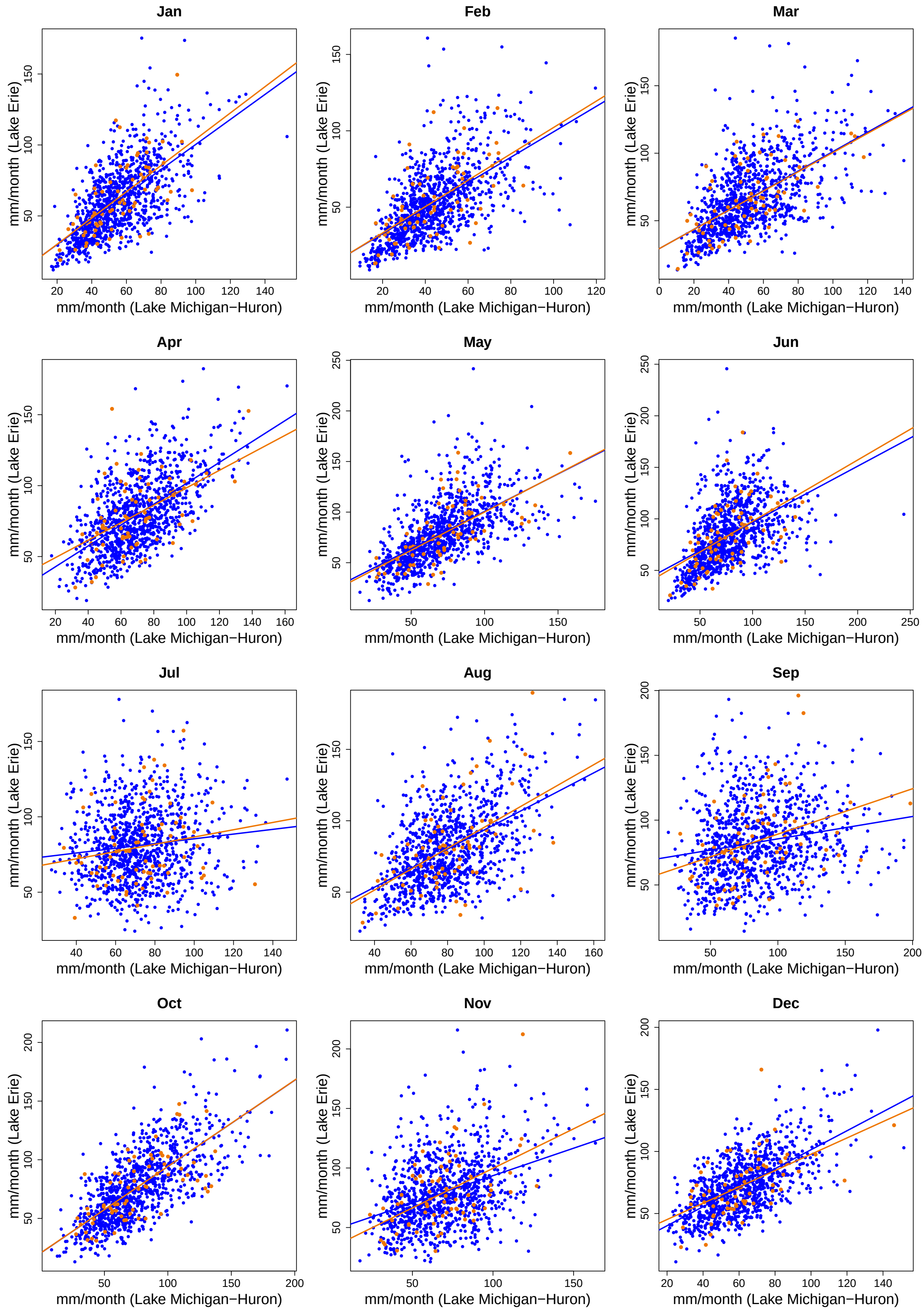

Figure S9. Spatial correlation (between Lakes Michigan-Huron and Erie) in monthly precipitation based on historical data (red) and copula simulations (blue).

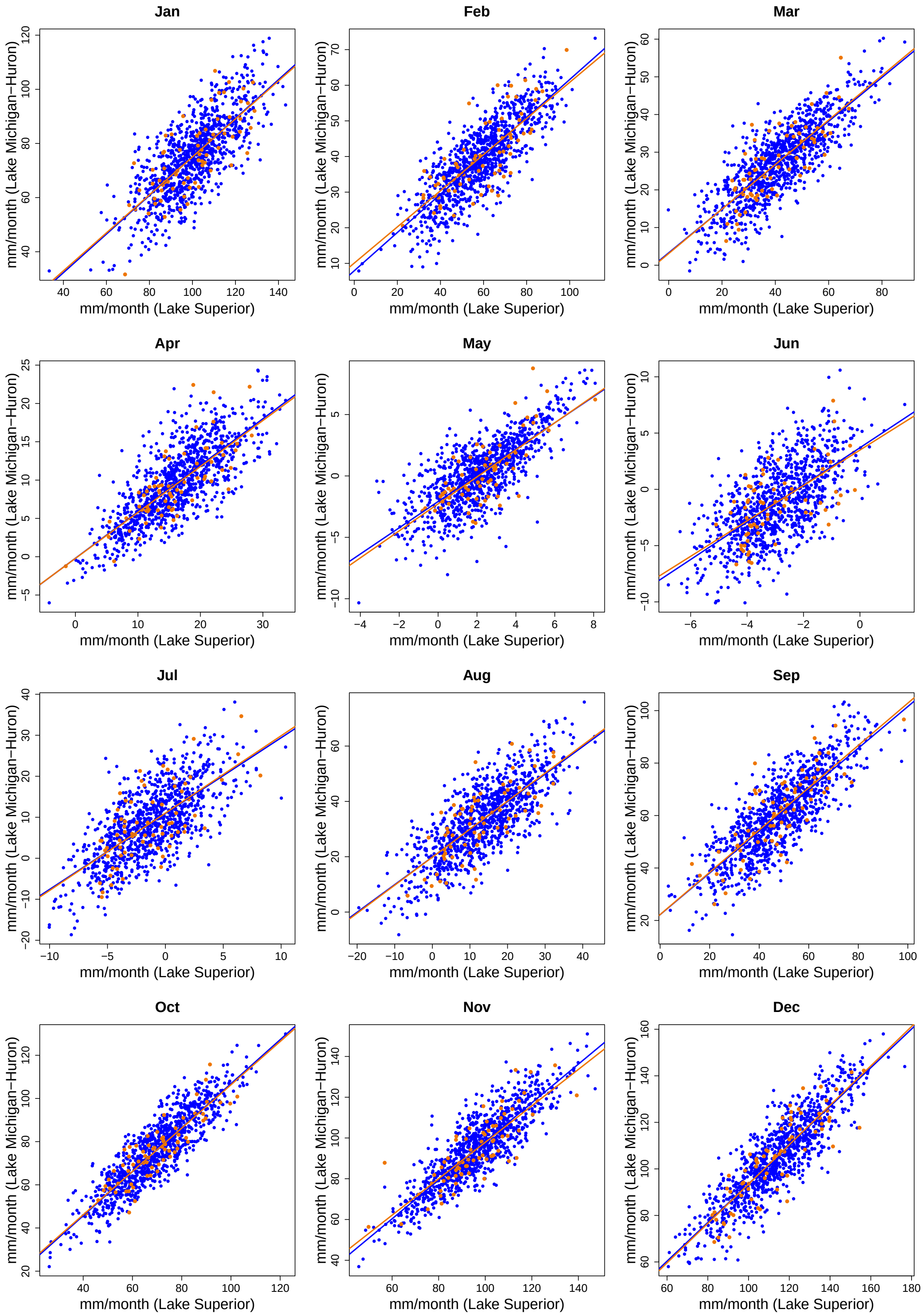

Figure S10. Spatial correlation (between Lakes Superior and Michigan-Huron) in monthly evaporation based on historical data (red) and copula simulations (blue).

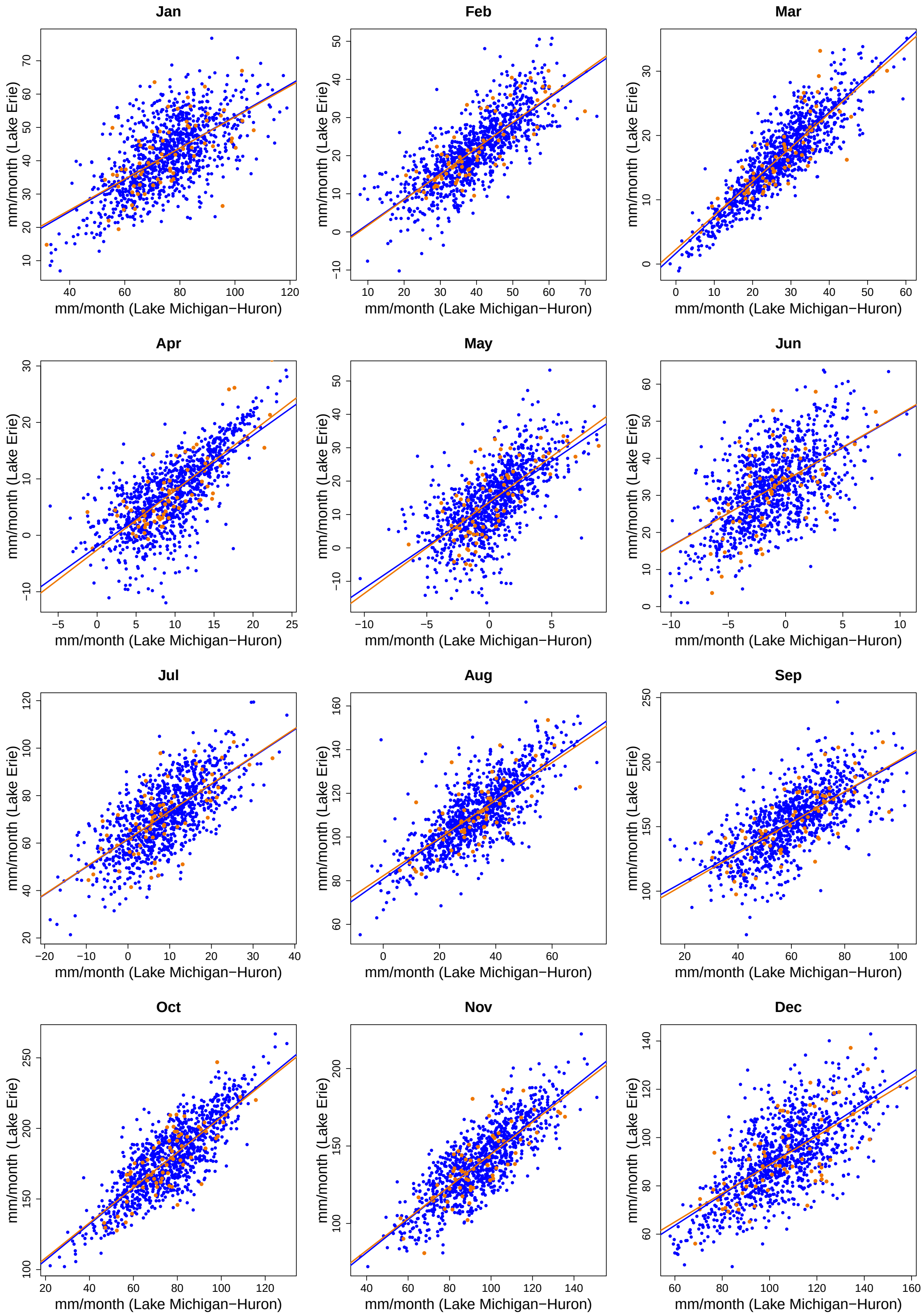

Figure S11. Spatial correlation (between Lakes Michigan-Huron and Erie) in monthly evaporation based on historical data (red) and copula simulations (blue).

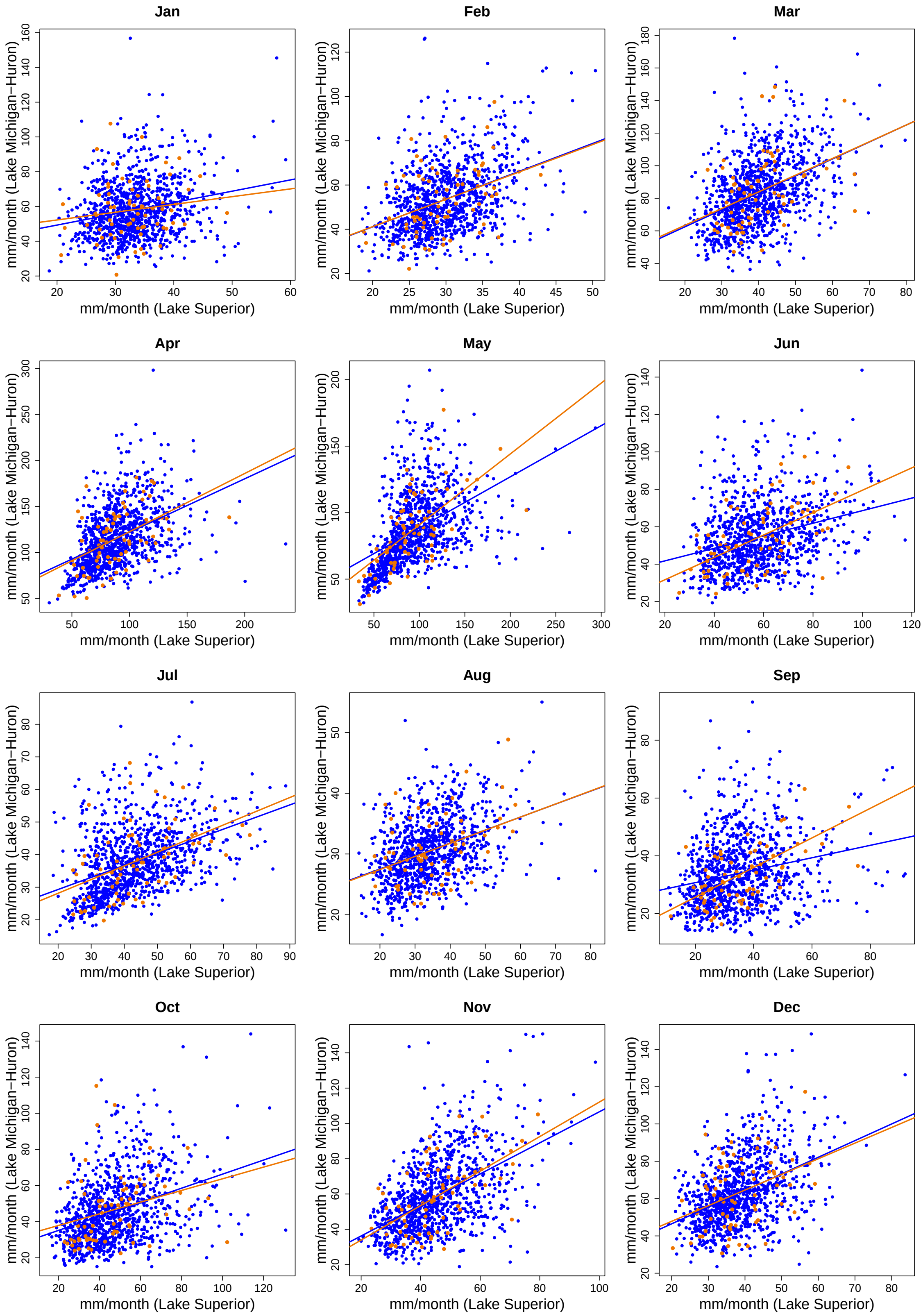

Figure S12. Spatial correlation (between Lakes Superior and Michigan-Huron) in monthly runoff based on historical data (red) and copula simulations (blue).

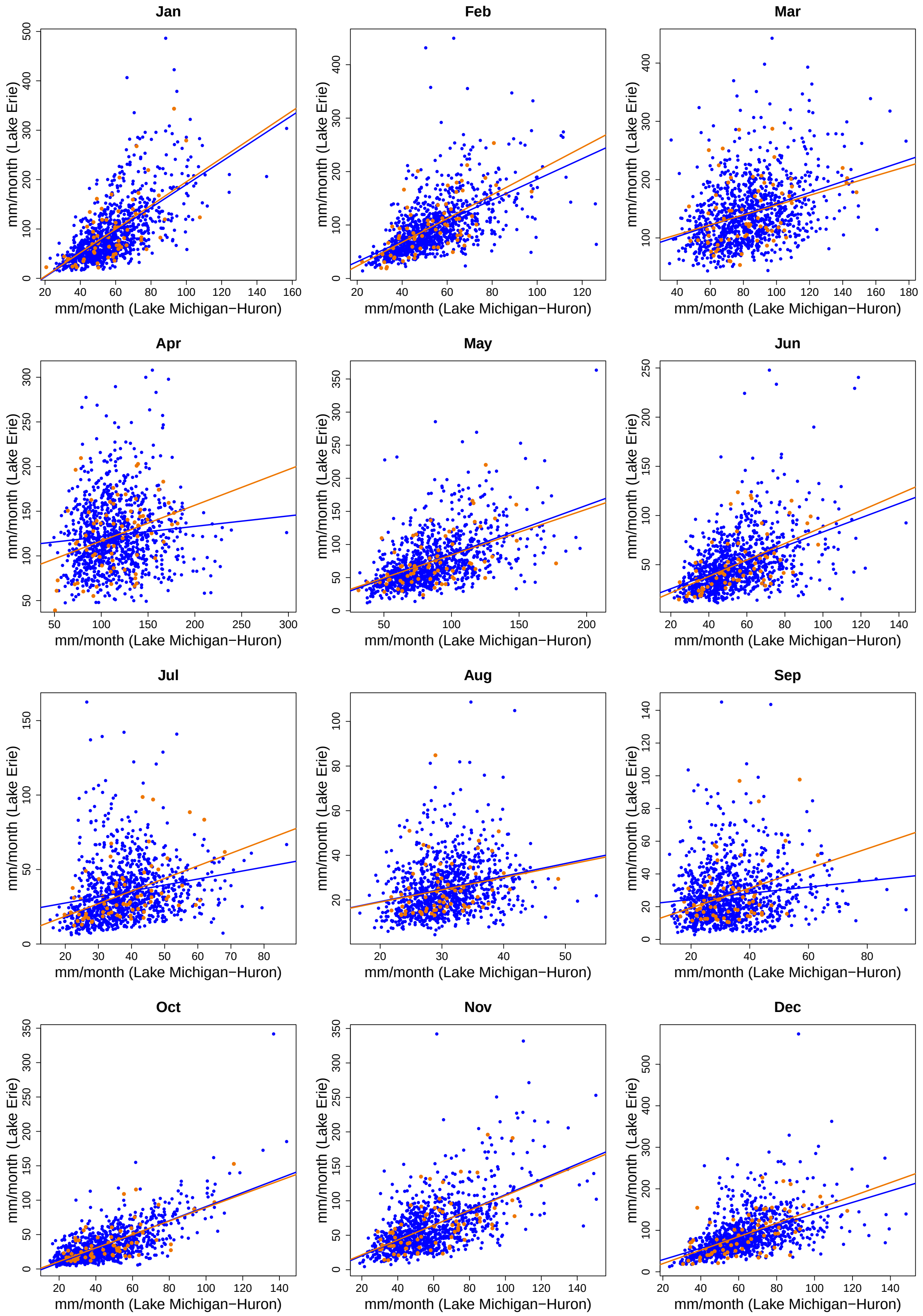

Figure S13. Spatial correlation (between Lakes Michigan-Huron and Erie) in monthly runoff based on historical data (red) and copula simulations (blue).

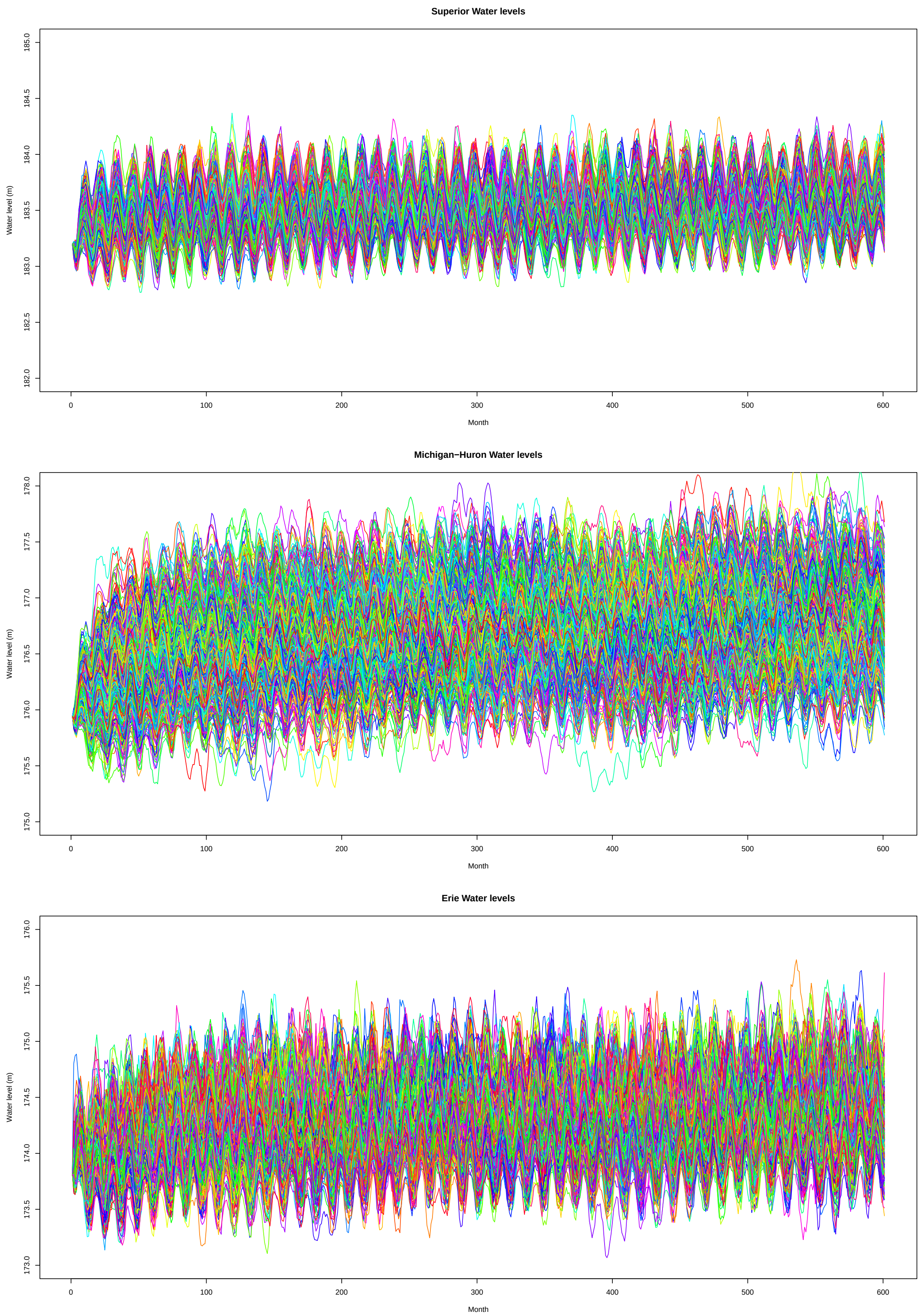

Figure S14. Ensemble of simulated water level sequences for SC2.

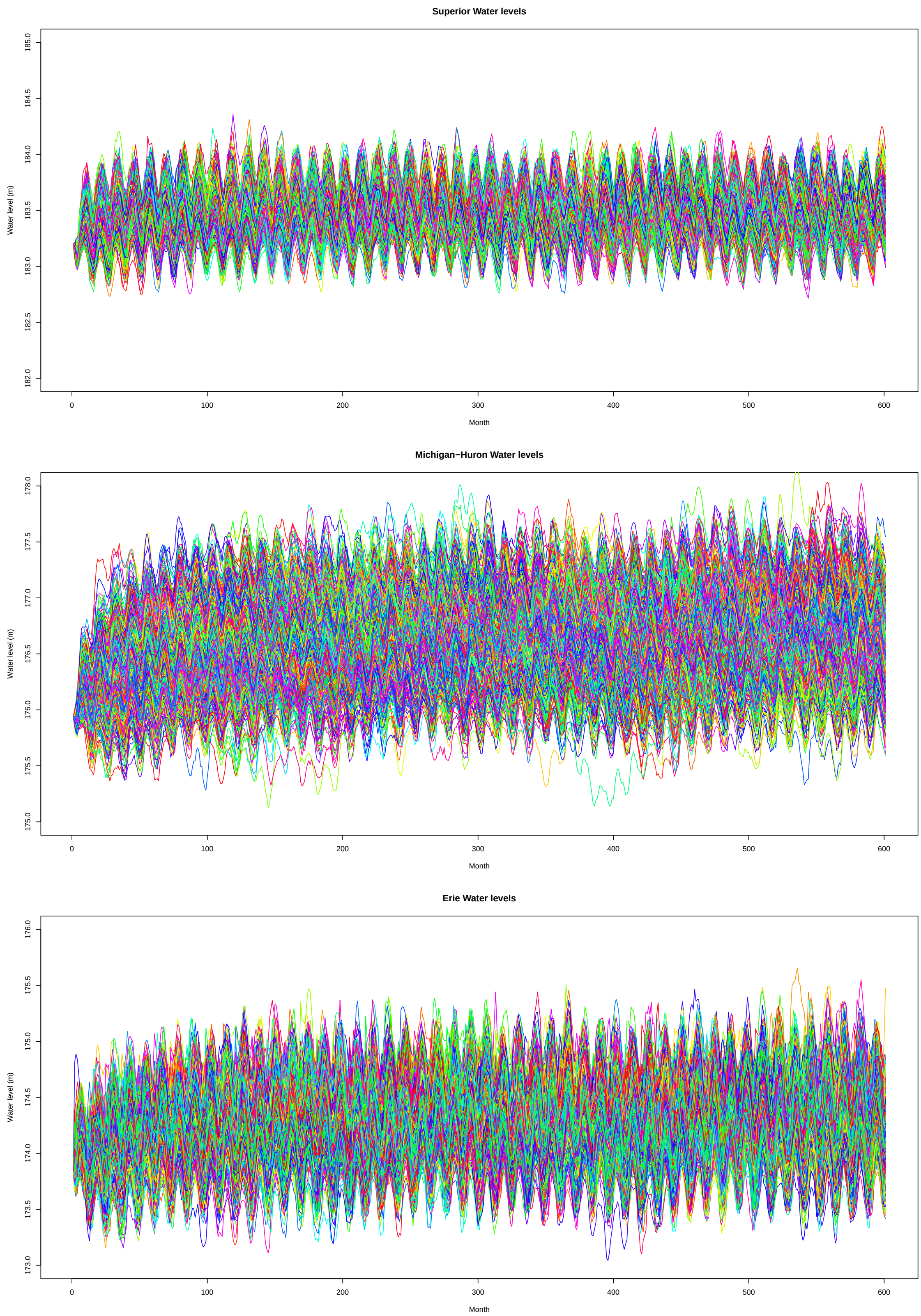

Figure S15. Ensemble of simulated water level sequences for SC3.