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Moisture Sources of Precipitation in the Great Lakes Region: Climatology and Recent Changes

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Key Points:

- The Great Plains (GPs) and the Great Lakes Region (GLR) are the major sources of moisture for precipitation in the GLR
- Moisture evapotranspired from the GPs contributes to more than 40% of strong precipitation in the GLR
- Moisture contribution from the Mid-Pacific to the Great Lakes precipitation has significantly increased in spring

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Given the critical role of precipitation on hydroclimate, we quantified the contributions of moisture source regions to precipitation in the Great Lakes Region (GLR) using multiple reanalysis data sets. Results show that the Great Plains (GPs) and the GLR itself are the primary sources of moisture. The moisture sources for the double peaks in the GLR precipitation that occur in June and September are identified, which is caused by a shift in the peak timing of moisture contribution from the GLR and GPs. In particular, moisture from the GPs contributes more to the heavy precipitation, while moisture from the GLR contributes more to the light precipitation. We also found a statistically significant ($p < 0.05$) increasing trend in the moisture contribution from the mid-Pacific, caused by an intensified zonal moisture transport from the mid-Pacific through changes in atmospheric circulation.

Plain Language Summary Rain and snow are critical in determining how much water is in the Great Lakes—which in turn influences socioeconomic activity in the Great Lakes Region (GLR). Therefore, we need to understand where the moisture for rain and snow comes from, especially in a changing climate. We found that rain and snow over the GLR mostly originate from water vapor that comes from the Great Plains (GPs) and the GLR. The GPs contribute more water vapor in spring and summer, and the GLR contributes more in autumn and winter. We also found that when rain or snow is strong, much of the water comes from the GPs. On the other hand, when precipitation is weak, a large fraction of the water comes from the GLR itself. We did not find that significant increasing trend in the amount of rain or snow over the GLR over the past 40 years; however, strong winds from the west bring more and more moisture from the mid-Pacific region each spring.

1. Introduction

The Great Lakes are the largest freshwater lakes in the world, with a surface area of 244,000 km^2 (Notaro et al., 2013). These vast inland freshwater bodies provide water for many purposes, including drinking, irrigation, shipping, ecological habitats, hydroelectric power generation, and recreation. The Great Lakes Basin is home to 34 million people and is one of the largest economic units in the world; it supports 1.3 million jobs, and $82 billion in wages (Rau et al., 2018). Due to its massive size and the contrasting thermal characteristics (e.g., heat capacity, thermal inertia) between the lake and land, the Great Lakes profoundly influence their local and regional hydroclimate (Changnon & Jones, 1972). Locally, by supplying heat and moisture, the Great Lakes facilitate the formation of lake-effect snowstorms in winter and convective storms in summer (Notaro et al., 2015; Shi & Xue, 2019). Regionally, the lakes can modify atmospheric circulation and other mesoscale features, affecting precipitation and water cycle outside the GLR in nearby regions (Bryan et al., 2015; Notaro et al., 2013; Petterssen & Calabrese, 1959; Sousounis & Fritsch, 1994; Wang et al., 2022).

Understanding the hydroclimate over the GLR is crucially important, because it impacts physical, ecological, economic, and cultural environments across North America. Changes in water levels within the Great Lakes are an important indicator of recent climate variations. Variations in Great Lakes water levels can be attributed to changes in regional precipitation (including overlake precipitation and terrestrial runoff), overlake evaporation, lake interflows, and water withdrawal (Gronewold & Stow, 2014; Gronewold et al., 2015). For example, from the late 1990s through January 2013, there was an extended period of persistent low water levels caused by increased lake surface water temperature, increased overlake evaporation, and decreased winter-ice cover

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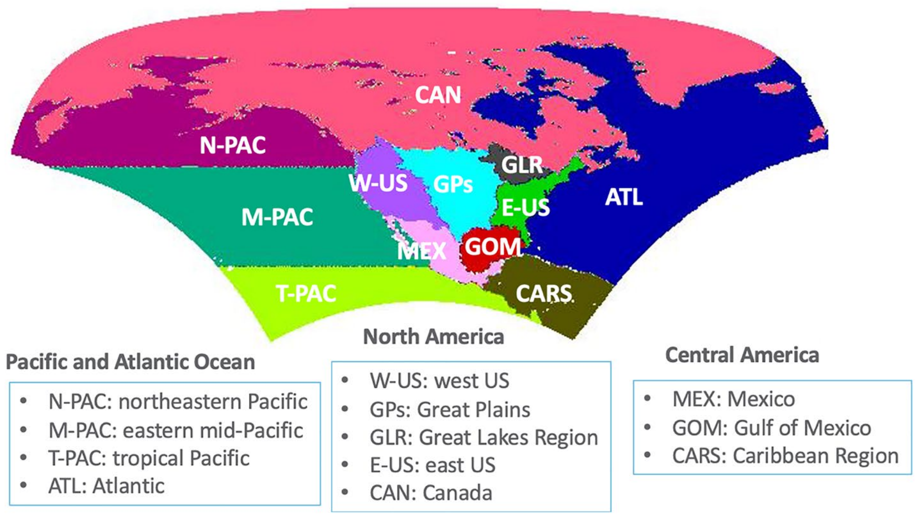

Figure 1. Map of the 12 subregions used in our study.

(Gronewold & Stow, 2014). Lower water levels in the Great Lakes decreased cargo volumes by 5%–8% and drastically increased shipping expenses (Posey, 2012). Low water levels also affect water supplies, the usability of infrastructure such as docks and piers, and the ecosystems along shorelines (Posey, 2012). From January 2013 to December 2014, the water levels of Lake Superior and Lake Michigan-Huron rose at a record-setting rate that was attributed to reduced evaporation rates during the cold 2013–2014 winter (Gronewold et al., 2015). In fact, recent high water levels drastically increased coastal flooding and erosion, resulting in both economic damage and loss of life (Huang et al., 2021). These water level fluctuations are expected to continue with climate change (Gronewold et al., 2021; Posey, 2012).

Precipitation is an essential component of net basin supply, which drives the lake water levels; hence, understanding the hydrological cycle and moisture sources is crucial both to comprehend the historical hydroclimate and to project future changes (Gronewold et al., 2021). From a moisture balance perspective, evaporation, and precipitation are the most critical factors controlling water level variations within the lakes (Gronewold et al., 2016). Studies have confirmed that local evaporation is insufficient to account for changes in precipitation and a significant portion of precipitation over the Great Lakes is contributed by moisture advected from outside the region (Bryan et al., 2015; X. Li et al., 2010; Minallah & Steiner, 2021; Steinschneider & Lall, 2016). While the contribution from local evaporation to total precipitation (i.e., precipitation recycling) is estimated to be between 12% and 30% with seasonal variations over the GLR (Bryan et al., 2015), remote sources such as tropical moisture export from the Gulf of Mexico (GOM) also contribute to a significant portion of precipitation in the region (Lavers & Villarini, 2015). However, detailed spatiotemporal variations of the moisture sources and their contributions to the GLR still require further investigation.

This study uses an extended version of the Dynamic Recycling Model (DRM, Dominguez et al., 2006, 2008; Martinez & Dominguez, 2014) to quantify moisture contribution to the GLR precipitation based on multiple atmospheric reanalysis data. The DRM is a two-dimensional semi-Lagrangian analytical model that can quantify source regions of moisture. Unlike previous studies that treated the areas outside the GLR as a whole (e.g., Bryan et al., 2015), we defined several distinct regions outside the GLR and estimated their respective contributions to GLR precipitation. This information will help improve the predictive understanding of variations in lake water levels and the hydrological cycle of the GLR under a warming climate (Kayastha et al., 2022).

2. Data and Methods

2.1. Region of Study

We focused on the North American continent and its adjacent ocean (Figure 1) following the North American Regional Reanalysis (NARR, discussed later) domain. The entire domain is subdivided into 12 source regions: northeastern Pacific (N-PAC), eastern mid-Pacific (M-PAC), tropical Pacific (T-PAC), Canada and Alaska (CAN), western United States (W-US), the Great Plains (GPs), eastern United States (E-US), Mexico (MEX), GOM, Caribbean Region (CARS), and the GLR itself. We tracked the moisture originating from each source region to the sink region, that is, the GLR. The boundaries of subdivisions of the continental United States are based on the Hydrologic Unit (HU, Seaber et al., 1987), which divides the country into 21 major geographic areas. We merged some of the nearby HU regions to form subdivisions (Figure 1) such that (a) the delineation of source regions is based on water basin boundaries instead of arbitrary state borders and (b) the number of source regions is manageable while maintaining adequate geographic details of the source regions.

2.2. Model and Data Description

In this study, we used the DRM to quantify moisture sources of the GLR precipitation. This offline analytical model assumes a well-mixed atmosphere. The well-mixed assumption implies the ratio of local recycled precipitation is equal to the ratio of local evapotranspiration to total precipitable water (PW) in the atmospheric column. Here the recycled precipitation refers to the precipitation that originates from local evaporation in the GLR. To obtain a more accurate moisture transport path, the trajectory of moisture is calculated based on column-integrated moisture-weighted mean wind at 3-hourly temporal resolution (for more details, see Equations 1 and 2 in Supporting Information S1). The daily evaporation, precipitation, and PW are state variables that are updated following the trajectory of moisture path, and the DRM is running and generating outputs on a daily time scale. Unlike simpler analytical models (Brubaker et al., 1993; Eltahir & Bras, 1994), the DRM can be used at daily time scales by considering the variations in moisture storage term (Dominguez et al., 2006). It has been shown to provide quantifications of moisture contributions that are similar to those provided by more sophisticated, physically based Weather Research and Forecasting models over South America (Martinez & Dominguez, 2014; Yang & Dominguez, 2019). For more details and derivations, refer to Dominguez et al. (2006) and Martinez and Dominguez (2014).

Variables needed to drive the DRM include daily averages of precipitation, evaporation, PW, and moisture-weighted zonal and meridional winds at 3-hourly resolution. We obtain these variables from a variety of reanalyses/analysis including the NARR for 1979–2019 (Mesinger et al., 2006); ERA-5 for 1979–2019 (Hersbach et al., 2020); MERRA-2 for 1981–2019 (GMAO, 2015); and NCEP final analysis (FNL) for 2016–2018 (National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce, 2000). Various reanalysis/analysis products are used for intercomparison, which ensures the robustness of our analysis.

To evaluate the reanalysis/analysis products in our study, we used precipitation data from four observation-based gridded data sets, including: University of Delaware Global Land Data V5.01 at 0.5° resolution (UDel, Matsuura & Willmott, 2018); Global Precipitation Climatology Centre (GPCC, Ziese et al., 2020) monthly precipitation data set at 1° resolution; Unified Precipitation Project from National Oceanic and Atmospheric Administration Climate Prediction Center (CPC, Chen et al., 2008; Xie et al., 2007) available at 0.5° resolution; and Rainfall Estimates on a Gridded Network (REGEN, Contractor et al., 2020) available at 1° resolution.

3. Results

3.1. Contributions of Different Source Regions to GLR Precipitation

The largest long-term moisture source regions for GLR precipitation are consistent among all reanalyses except NARR. When averaged over the MERRA-2, ERA-5, and FNL, contributions from the top three moisture sources are the GPs (~35.3%), GLR (~33.7%), and CAN (~11%), respectively (Figures 2c–2e). In total, the top three moisture source regions account for 80% of GLR precipitation on average. However, NARR identifies M-PAC (27%), GPs (16%), and CAN (9%) as the top moisture source regions (Figure 2f). In addition, the moisture that originates through evapotranspiration from the entire domain (Figure 1) can account for more than 99% of precipitation in the GLR according to the MERRA-2, ERA-5, and FNL (Figures 2c–2e), but only 84% in NARR (Figure 2f). The DRM results suggest that the NARR domain can only cover 84% of precipitation over the GLR using NARR, which indicates that the remaining 16% must come from outside the domain in Figure 1. For a specific region, the change in PW is the balance of evaporation, precipitation, and moisture convergence. The convergence term is the amount of moisture transported to the region through moisture advection. In NARR, because evaporation is not assimilated (explained later) and is often underestimated, it will require more advected moisture to compensate, suggesting that more moisture from non-local source would be needed to meet the requirement of water balance. Unlike NARR, results using ERA-5 and MERRA-2 suggest that evaporation over the entire domain in Figure 1 is sufficient to provide all the moisture for the GLR precipitation. From a regional

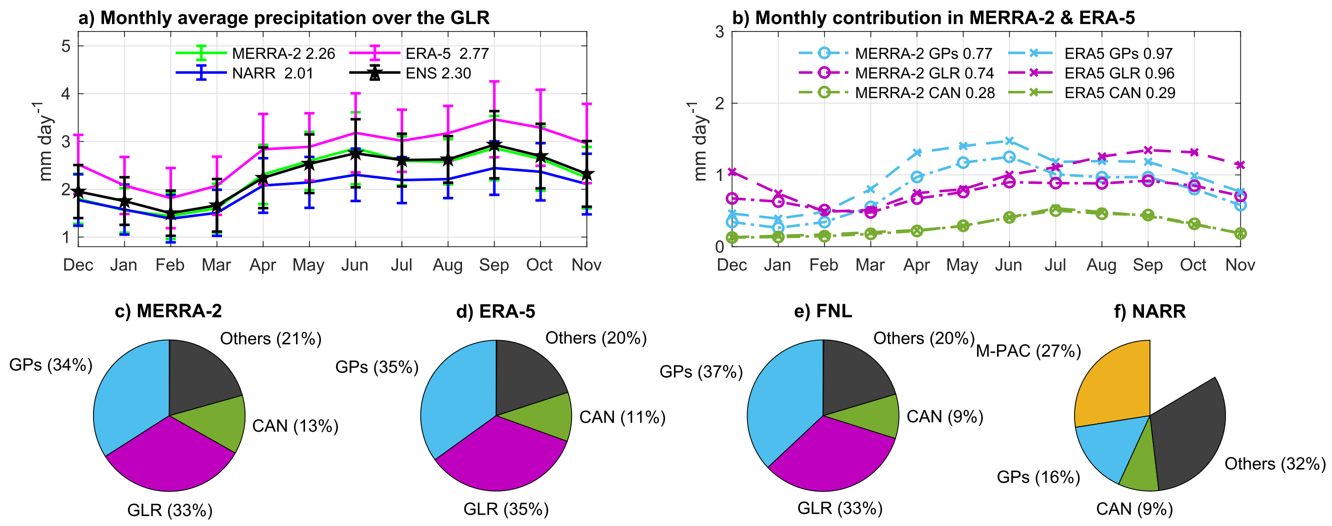

Figure 2. Monthly mean precipitation over the Great Lakes Region (GLR) and its corresponding moisture contribution from different source regions. (a) Monthly mean precipitation using reference data sets, MERRA-2, ERA-5, and North American Regional Reanalysis. The black line indicates the monthly ensemble mean precipitation derived by considering Global Precipitation Climatology Centre, Rainfall Estimates on a Gridded Network, UDel, and Climate Prediction Center data. Error bars are the standard deviation. (b) Precipitation over the GLR originated as evaporation from the top three source regions according to MERRA-2 and ERA-5. NCEP FNL only contains 3 years of data and is therefore not shown. (c–f) Pie chart of moisture contribution from moisture source regions for different reanalyses. In panel (a), numbers in the legend indicate the annual mean precipitation and in panel (b) mean contribution from each listed source region, in units of mm/day.

water cycle perspective, ERA-5 and MERRA-2 depict a drastically different picture relative to the NARR, as the total area of the moisture source region is much smaller. Given the consensus among the other products, this suggests that there is a water imbalance in NARR and that we must be cautious of interpretations of the regional water cycle based on NARR. Hereafter we show NARR results for reference only.

A clear seasonal cycle is observed (Figure 2a) with low precipitation in February (1.50 ± 0.47) and March (1.67 ± 0.55 mm/day) and a high value in September (2.93 ± 0.70) and October (2.70 ± 0.68 mm/day). Another peak occurs in June (2.75 ± 0.71 mm/day), and together with the September high, this is known as the double peak of precipitation over the GLR (Minallah & Steiner, 2021). It is clear that the rise in precipitation in early summer is mainly associated with moisture that originated from the GPs (Figure 2b). Starting in July, the contribution from the GPs gradually decreases, while the contributions from the GLR increase and peak in September. Thus, the double peak is the result of this shift in peak timing of moisture originated from the GPs and the GLR.

The GLR and GPs are leading moisture sources throughout the year: the GLR leads in the autumn and winter (September–November and December–February; on average 37% in ERA-5 and 35% in MERRA-2, Figure S1 in Supporting Information S1), while the GPs are top in the early spring and summer (March–May and June–August; on average, 43% in ERA-5 and 41% in MERRA-2, Figure S1 in Supporting Information S1). In autumn and winter, lake surface temperature is typically warmer than the overlying air temperature (Kayastha et al., 2022; Xue et al., 2017), which facilitates evaporation from the lake surface and enhances the local recycling of moisture (Miner & Fritsch, 1997). During spring and summer, however, the lake surface temperature is cooler than the overlying air temperature due to the different thermal inertia of the lake water versus air temperature (McCombie, 1959). Lake evaporation is constrained due to this temperature inversion, resulting in relatively weak local moisture recycling over the GLR (Figures 2a and 2b). Meanwhile, moisture that originated from evaporation in the GPs rises with the gradual warming of land surface temperature during the summertime. Then the GPs low-level jets facilitate the transport of the GPs evaporation to reach GLR (Song et al., 2022; Yang et al., 2020), resulting in more than 40% moisture contribution of GPs to GLR precipitation. This result is consistent with a study focused on the circulation patterns that are responsible for precipitation over the Midwest (Zhang & Villarini, 2019).

3.2. Moisture Contributions at Different GLR Precipitation Quantiles

The number of days with weak and strong GLR precipitation in the warm (June–August and September–November; summer and fall, respectively) and cold seasons (December–February and March–May; winter and

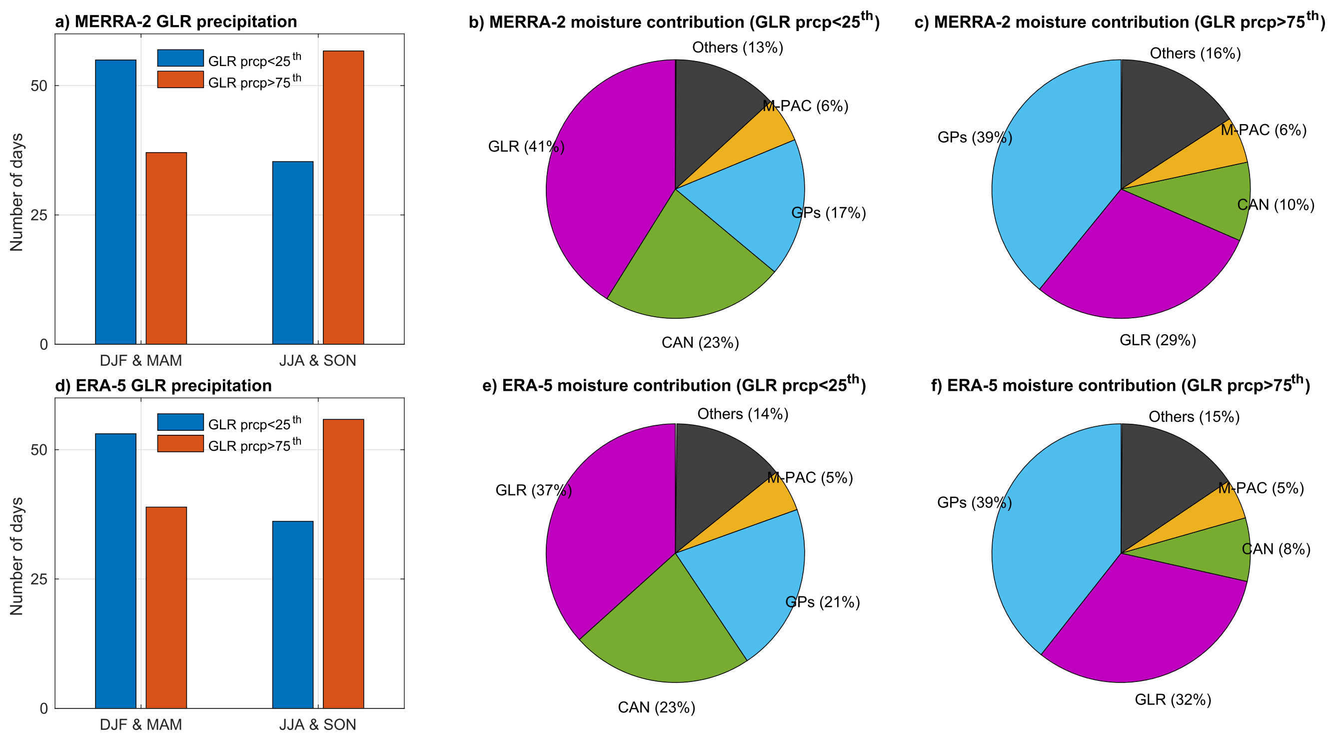

Figure 3. Number of days with the weak and strong Great Lakes Region (GLR) precipitation and the corresponding moisture contribution during the weak and strong GLR precipitation days. (a) Number of days in the warm and cold season that has GLR precipitation greater than 75th and less than 25th percentile of the GLR precipitation record. (b, c) Composite mean moisture contribution from the top four moisture regions when GLR precipitation is less than the 25th and more than the 75th percentile of the GLR climatological precipitation. (a–c) and (d–f) are based on MERRA-2 and ERA-5, respectively.

spring, respectively) are shown in Figures 3a and 3d. The weak and strong GLR precipitation days are defined as days with GLR precipitation less than the 25th percentile (lower quantile) and greater than the 75th percentile (upper quantile) of the long-term annual GLR precipitation climatology (see Supporting Information S1 file for more details). During cold months, days with weak GLR precipitation occur more frequently, about 20 days more than its counterpart in the warm season (Figures 3a and 3d). This seasonal difference between the warm and cold season is statistically significant according to the two-sided Student-t test (Figure S2a in Supporting Information S1). Similarly, during warm months, days with strong GLR precipitation occur more frequently (Figures 3a and 3d), about 20 days more than its counterpart in the cold season (Figures 3a and 3d). The seasonal difference is statistically significant as well (Figure S2b in Supporting Information S1). During the winter, precipitation is usually favored by large-scale meteorological forcing and the environment is more conducive to form non-convective precipitation (J. Li et al., 2021). In the summertime, the warmer land surface along with low-level jets in the GPs form favorable conditions for mesoscale convective systems (MCSs) over the GPs and Midwest (Feng et al., 2019; Song et al., 2022). These MCSs can move eastward into the GLR and bring widespread strong precipitation into the GLR (Feng et al., 2019; Qian et al., 2020). Hence the strong precipitation (upper quantile) occurs more frequently in the warm season over the GLR (Feng et al., 2019; J. Li et al., 2021).

For days with weak GLR precipitation rates, moisture contribution of the local recycled GLR evapotranspiration is dominant, accounting for ~41% in MERRA-2 and ~37% in ERA-5 of the GLR precipitation in terms of average amount (Figures 3b and 3e). Besides GLR itself, CAN, GPs, and M-PAC are the subsequent primary moisture source regions. According to MERRA-2, CAN evapotranspiration contributes to 23% and GPs contributes to 17% for the weak GLR precipitation in terms of average amount (Figure 3b). For the strong GLR precipitation days, the GPs is the leading source of moisture, responsible for 39% of the GLR precipitation during these more intense precipitation days (Figures 3d and 3h), compared to ~35.3% for the mean precipitation averaged across ERA-5, MERRA-2, and FNL (Figures 2c–2e). In fact, as precipitation becomes more intense, the contribution from GPs evapotranspiration also becomes more important; for example, more than 40% of the GLR precipitation is linked to the GPs evapotranspiration for days with precipitation intensity greater than the 90th and 99th percentile averaged over MERRA-2 and ERA-5 (not shown). These results highlight the importance of moisture contribution

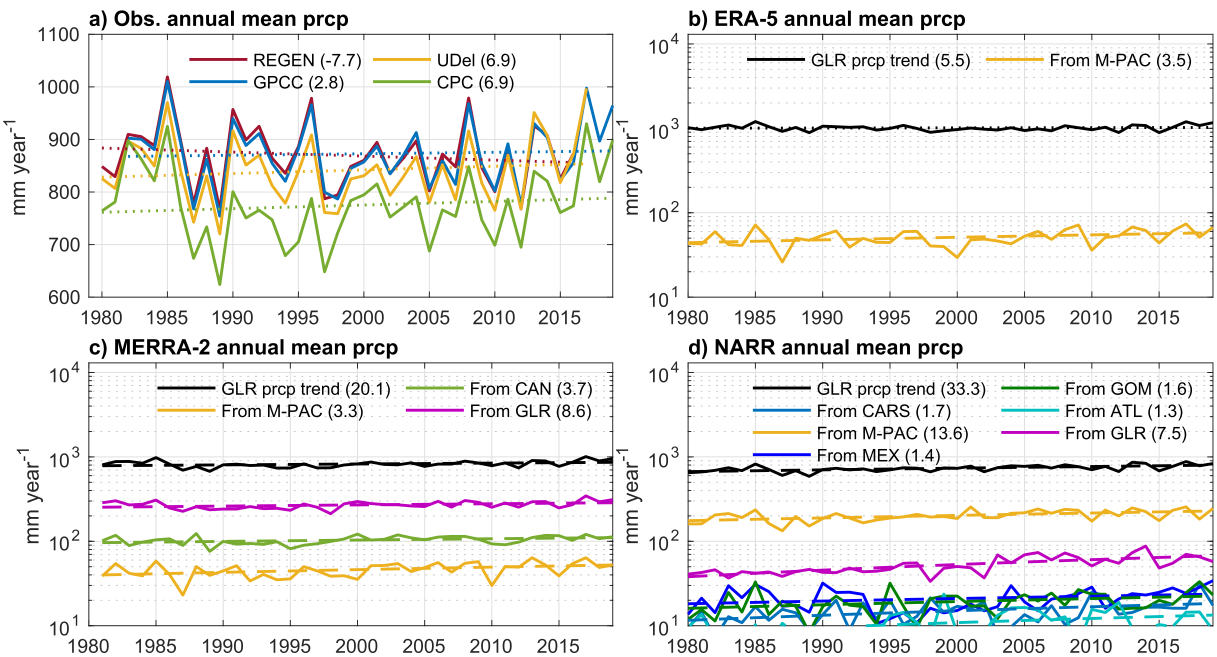

Figure 4. The long-term trend in the annual mean Great Lakes Region (GLR) precipitation and moisture contribution from different source regions. (a) Annual mean GLR precipitation and its trend from the reference data sets. (b–d) Are for different reanalyses. The dashed and dotted lines represent linear trend estimates—dashes for significant trends, and dots for insignificant trends. Besides the total precipitation, only those source regions with significant increasing trends are shown in panels (b–d). In the legend, the number in the parenthesis indicates the slope of the trend, in units of mm yr^{-1} decade^{-1}.

from the GPs to GLR for extreme precipitation; this is consistent with the circulation pattern Davenport and Diffenbaugh (2021) identified as being associated with extreme precipitation.

3.3. Trends in GLR Precipitation and Its Sources

For the long-term trend in annual mean GLR precipitation, no statistically significant trend is found in the reference data sets (Figure 4a). Note that REGEN shows a negative trend that disagrees with the other reference data sets, likely due to the lack of data after 2016. The contribution from M-PAC shows significant increasing moisture trends in both MERRA-2 and ERA-5 according to the Mann-Kendall test (Gilbert, 1987; Kendall, 1975; Mann, 1945). The M-PAC moisture leads to an increasing rate of 3.5 mm/yr/decade in GLR precipitation, which amounts to nearly 63% and 17% of the overall increasing trend in GLR precipitation, as shown by ERA5 and MERRA-2, respectively.

On the seasonal scale, GLR precipitation shows a slight increasing trend in spring (7.6 mm/yr/decade; Figures S3b and S4b in Supporting Information S1) and a decreasing trend (−3.9 mm/yr/decade; Figures S3d and S4d in Supporting Information S1) in autumn, averaged for ERA-5 and MERRA-2. The long-term trend in spring and autumn is consistent among different reference data sets with the same sign of change, although it is not statistically significant according to the Mann-Kendall test (Figures S5b and S5d in Supporting Information S1). It is likely that the competing trends in spring and autumn cancel out the long-term trend in annual mean GLR precipitation (Figure 4a). This also suggests a tendency of a more flat annual precipitation cycle in more recent years. When we compare the contributions from different source regions, both ERA-5 and MERRA-2 show statistically significant increasing trends for M-PAC (1.2 mm/yr/decade, on average) in spring (Figures S3b and S4b in Supporting Information S1), while no agreement can be found among different reanalyses in other seasons or other source regions. For instance, in ERA-5, GLR local recycled precipitation shows a significant increasing trend in winter (a rate of 6.1 mm/yr/decade; Figure S3a in Supporting Information S1)—and a decreasing trend in summer (−4.5 mm/yr/decade; Figure S3c in Supporting Information S1). However, MERRA-2 shows M-PAC and GPs contributions to GLR precipitation to be significant at 2.4 and 2.6 mm/yr/decade, respectively, in winter (Figure S4a in Supporting Information S1). This speaks to the fact that there is still uncertainty in the long-term trend using reanalysis products.

The increasing trend of moisture contribution from the M-PAC to the GLR precipitation is significant (Figures 4b and 4c). This is partly due to the increasing trend in spring (Figures S3b and S4b in Supporting Information S1). This is consistent in both ERA-5 and MERRA-2. Long-term evaporation over M-PAC shows no obvious trend (Figure S6a in Supporting Information S1), while zonal moisture flux over the moisture transport belt (35°–45°N, 120°–90°W) is significantly increasing in spring (Figure S6c in Supporting Information S1), which facilitates the moisture transport from the M-PAC to GLR. This result suggests that the strengthened zonal moisture transport is responsible for the significant increasing trend of the M-PAC moisture contribution to the GLR precipitation.

4. Discussion and Conclusions

Water level change, mainly driven by precipitation, evaporation, and runoff, is critical for the ecosystem and socioeconomic activity of the GLR. Here we quantified the contributions from different moisture sources to precipitation over the GLR, using the DRM based on multiple atmospheric reanalysis data sets. We disentangled the double peaks in the seasonal precipitation cycle. Our results suggest that the first peak in June is mainly associated with the moisture contributed by the GPs (Figure 2b); the second peak in September is associated with the gradually increasing contribution from GLR (Figure 2b).

The GPs and the GLR are the primary moisture source regions, accounting for about 35% and 34% of the GLR precipitation. This is consistent among MERRA-2, ERA-5, and FNL. In addition, the moisture that originates as evapotranspiration from the entire domain (Figure 1) can account for more than 99% of GLR precipitation according to the MERRA-2, ERA-5, and FNL (Figures 2c–2e). However, we found that results from NARR deviate significantly from the other reanalysis products and identify M-PAC as the largest moisture source. Also, only 84% of GLR precipitation in NARR (Figure 2f) can be explained by the moisture in the study domain, suggesting that 16% of GLR precipitation must originate from outside the domain in Figure 1. We hypothesized that this discrepancy between NARR and other reanalyses is due to atmospheric water imbalance in NARR.

The framework of DRM requires precipitation, evaporation, PW, and moisture-weighted meridional and zonal winds to track moisture parcels. Therefore, the inconsistency between NARR and other reanalyses could be due to uncertainties associated with any of these inputs. The uncertainties embedded in the inputs would yield drastically different depictions of the regional water cycle. In fact, all reanalysis products used in the study assimilate precipitation, although from different sources. For instance, the MERRA-2 precipitation (PRECTOTCORR, Reichle & Liu, 2014) is bias-corrected to the CPC unified daily precipitation over 42.5°S–42.5°N land areas; ERA-5 assimilates the radar-rain gage merged precipitation estimates over the CONUS (Lavers et al., 2022); and NARR uses on average 17,500 daily reports from the National Climatic Data Center's daily cooperative stations, River Forecast Center stations, and daily accumulations of the hourly precipitation data set (Higgins et al., 2000). Because of the assimilation and bias correction, seasonal and long-term trends in precipitation from the reanalyses compare quite well with the observations (Figures 2 and 4).

Alternatively, due to the lack of evapotranspiration observations, evapotranspiration is more uncertain. For instance, M-PAC evaporation is around 0.4 in NARR, much less than the 3.6 and 4.4 mm/day in ERA-5 and MERRA-2, respectively (not shown). Overall, MERRA-2 and ERA-5 give better estimates of evapotranspiration compared to NARR. The amount of land evaporation shown by MERRA-2 is close to the amount we observed, partly because the model uses observed precipitation for land forcing (although ocean evaporation is overestimated; Bosilovich et al., 2017). In addition, MERRA-2 employs a constraint to guarantee the net source of water from precipitation and surface evaporation equals the change in total atmospheric water (Takacs et al., 2016). Moreover, the monthly product of PW from Remote Sensing System Version-7 Release-0 (RSSV7) is assimilated in MERRA-2 to ensure good estimates over the ocean (Takacs et al., 2016).

In contrast, although NARR assimilates precipitation from a patchwork of sources across its domain (Shafran et al., 2004), the assimilation procedure is limited within columns, and focuses only on thermodynamics of the atmospheric column; no attention is paid to the dynamics (moisture flux divergence), the underlying land surfaces (e.g., evaporation), or the overall water balance (Nigam & Ruiz-Barradas, 2006). Therefore, evaporation, atmospheric PW, and moisture flux could be biased and cause water balance issues in NARR (Kanamaru & Kanamitsu, 2007; Nigam & Ruiz-Barradas, 2006; West et al., 2007). Following our previous analysis, NARR is less trustworthy compared to the other reanalyses and has water balance issues.

This study shows the potential of using DRM as a tool to analyze the regional water cycle more comprehensively than just showing the evaluations of precipitation, evaporation, or moisture flux divergence over a specific region.

For example, it can be used to diagnose or pinpoint the region or water cycle component that has uncertainties in a more comprehensive way by analyzing the moisture contribution from one region to another. Furthermore, it provides a framework for diagnosing future changes in the moisture source of the Great Lakes in the context of global warming.

At the seasonal scale, the largest regional source of moisture is the GPs in spring and summer; this region accounts for more than 35% of the GLR precipitation according to ERA5 and MERRA-2 (Figure S1 in Supporting Information S1). In autumn and winter, the GLR contributes the most moisture; it is responsible for more than 40% of GLR precipitation according to ERA5 and MERRA-2 (Figure S1 in Supporting Information S1).

We also examined the moisture sources for different GLR precipitation quantile ranges. Our results suggest that the local recycled GLR evaporation is more important for weaker precipitation, while the GPs are more important for more intense precipitation. We did not find a statistically significant increasing trend in GLR precipitation, but the contribution from M-PAC in spring has exhibited a significant increasing trend for the past 40 years, mainly due to the intensified zonal moisture transport from the mid-Pacific through changes in atmospheric circulation (Figure S6c in Supporting Information S1).

Limitations of the current study are discussed here. Since the trajectory of the air parcels is based on integrated moisture flux over the entire atmospheric column, the DRM can cause issues when strong vertical wind shear exists (Dominguez et al., 2020). This limitation can cause biases in moisture origins when evaluating events with strong vertical wind shear. The lack of observation of evaporation over the ocean suggests that moisture contribution from the ocean to GLR is hard to constrain. As discussed earlier, any uncertainty associated with the inputs could impact the results. Even the assimilated or bias-corrected precipitation from reanalyses has biases (Alexander et al., 2020). More reliable sources of input data would largely reduce these uncertainties. Future work will also benefit from more realistic hydrological components with more complex moisture-tracking algorithms, such as the two-layer DRM (Dominguez et al., 2020).

In this study, we identified moisture source regions and quantified their relative contributions to GLR precipitation. These insights are important for characterizing future changes in lake water levels, and for understanding the drivers resulting in these changes. This information is important because different regions will likely respond to climate change differently. For example, northern areas in the United States are projected to become wetter, especially in the winter and spring, while southern areas, especially the Southwest, are projected to become drier (Melillo et al., 2014). These regional precipitation changes will inevitably affect the amount of evaporation and its subsequent role as a source of moisture for the GLR. The moisture source regions and their contributions are therefore expected to change in the future as the environment changes, due to the dynamical and thermodynamical changes associated with the large-scale circulation and atmosphere-biosphere interactions through changes in land use/land cover (Bellomo et al., 2021; Devanand et al., 2020; Grise, 2022; Sikma et al., 2019; Sleeter et al., 2018; Wilson et al., 2012; Zappa, 2019). Although future changes based on GCMs are not examined in this study, the results of this study based on observation-constrained reanalysis data sets will help improve understanding the processes associated with the water cycle over the GLR and project future lake water levels. Based on the findings of this study, our next step will be to use GCMs to evaluate future changes in the GLR precipitation and related changes in moisture sources.

Data Availability Statement

- NARR data: https://psl.noaa.gov/data/gridded/data.narr.html.
- REGEN data: https://zenodo.org/record/4922148.
- GPCC data: https://psl.noaa.gov/data/gridded/data.gpcp.html.
- UDel data: http://climate.geog.udel.edu/~climate/html_pages/download.html.
- ERA-5: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=form.
- MERRA-2: https://disc.gsfc.nasa.gov/datasets?project=MERRA-2.
- FNL: https://rda.ucar.edu/datasets/ds083.3/.
- CPC Global Unified Gauge-Based Analysis of Daily Precipitation data provided by the NOAA PSL, Boulder, Colorado, USA, from their website at https://psl.noaa.gov.
- All data and scripts related to the analysis of this manuscript are available at: https://doi.org/10.5281/zenodo.6326808.

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References

Alexander, L. V., Bador, M., Roca, R., Contractor, S., Donat, M. G., & Nguyen, P. L. (2020). Intercomparison of annual precipitation indices and extremes over global land areas from in situ, space-based and reanalysis products. *Environmental Research Letters*, *15*(5), 055002. https://doi.org/10.1088/1748-9326/ab79e2

Bellomo, K., Angeloni, M., Corti, S., & von Hardenberg, J. (2021). Future climate change shaped by inter-model differences in Atlantic meridional overturning circulation response. *Nature Communications*, *12*(1), 3659. https://doi.org/10.1038/s41467-021-24015-w

Bosilovich, M. G., Robertson, F. R., Takacs, L., Molod, A., & Mocko, D. (2017). Atmospheric water balance and variability in the MERRA-2 reanalysis. *Journal of Climate*, *30*(4), 1177–1196. https://doi.org/10.1175/JCLI-D-16-0338.1

Brubaker, K. L., Entekhabi, D., & Eagleson, P. S. (1993). Estimation of continental precipitation recycling. *Journal of Climate*, *6*(6), 1077–1089. https://doi.org/10.1175/1520-0442(1993)006<1077:EOCPR>2.0.CO;2

Bryan, A. M., Steiner, A. L., & Posselt, D. J. (2015). Regional modeling of surface-atmosphere interactions and their impact on Great Lakes hydroclimate. *Journal of Geophysical Research*, *120*(3), 1044–1064. https://doi.org/10.1002/2014JD022316

Changnon, S. A., Jr., & Jones, D. M. A. (1972). Review of the influences of the great lakes on weather. *Water Resources Research*, *8*(2), 360–371. https://doi.org/10.1029/wr008i002p00360

Chen, M., Shi, W., Xie, P., Silva, V. B. S., Kousky, V. E., Wayne Higgins, R., & Janowiak, J. E. (2008). Assessing objective techniques for gauge-based analyses of global daily precipitation. *Journal of Geophysical Research*, *113*(D4). https://doi.org/10.1029/2007jd009132

Contractor, S., Donat, M. G., Alexander, L. v., Ziese, M., Meyer-Christoffer, A., Schneider, U., et al. (2020). Rainfall Estimates on a Gridded Network (REGEN) - A global land-based gridded dataset of daily precipitation from 1950 to 2016. *Hydrology and Earth System Sciences*, *24*(2), 919–943. https://doi.org/10.5194/HESS-24-919-2020

Davenport, F. V., & Diffenbaugh, N. S. (2021). Using machine learning to analyze physical causes of climate change: A case study of US midwest extreme precipitation. *Geophysical Research Letters*, *48*(15), e2021GL093787. https://doi.org/10.1029/2021gl093787

Devanand, A., Huang, M., Lawrence, D. M., Zarzycki, C. M., Feng, Z., Lawrence, P. J., et al. (2020). Land use and land cover change strongly modulates land-atmosphere coupling and warm-season precipitation over the central United States in CESM2-VR. *Journal of Advances in Modeling Earth Systems*, *12*(9), e2019MS001925. https://doi.org/10.1029/2019MS001925

Dominguez, F., Hu, H., & Martinez, J. A. (2020). Two-layer dynamic recycling model (2L-DRM): Learning from moisture tracking models of different complexity. *Journal of Hydrometeorology*, *21*(1), 3–16. https://doi.org/10.1175/JHM-D-19-0101.1

Dominguez, F., Kumar, P., Liang, X.-Z., & Ting, M. (2006). Impact of atmospheric moisture storage on precipitation recycling. *Journal of Climate*, *19*(8), 1513–1530. https://doi.org/10.1175/JCLI3691.1

Dominguez, F., Kumar, P., & Vivoni, E. R. (2008). Precipitation recycling variability and ecoclimatological stability—A study using NARR data. Part II: North American monsoon region. *Journal of Climate*, *21*(20), 5187–5203. https://doi.org/10.1175/2008JCLI1760.1

Eltahir, E. A. B., & Bras, R. L. (1994). Precipitation recycling in the Amazon basin. *Quarterly Journal of the Royal Meteorological Society*, *120*(518), 861–880. https://doi.org/10.1002/qj.49712051806

Feng, Z., Houze, R. A., Jr., Leung, L. R., Song, F., Hardin, J. C., Wang, J., et al. (2019). Spatiotemporal characteristics and large-scale environments of mesoscale convective systems east of the rocky mountains. *Journal of Climate*, *32*(21), 7303–7328. https://doi.org/10.1175/2010JCLI3249.1

Gilbert, R. O. (1987). *Statistical methods for environmental pollution monitoring*. Wiley.

Global Modeling and Assimilation Office (GMAO). (2015). *inst3_3d_asm_Cp: MERRA-2 3D IAU State, Meteorology Instantaneous 3-hourly (p-coord, 0.625x0.5L42), version 5.12.4*. Goddard Space Flight Center Distributed Active Archive Center (GSFC DAAC). https://doi.org/10.5067/VJAFPLI1CSIV

Grise, K. M. (2022). Atmospheric circulation constraints on 21st century seasonal precipitation storylines for the southwestern United States. *Geophysical Research Letters*, *49*(17), e2022GL099443. https://doi.org/10.1029/2022GL099443

Gronewold, A. D., Anderson, E. J., Lofgren, B., Blanken, P. D., Wang, J., Smith, J., et al. (2015). Impacts of extreme 2013–2014 winter conditions on Lake Michigan's fall heat content, surface temperature, and evaporation. *Geophysical Research Letters*, *42*(9), 3364–3370. https://doi.org/10.1002/2015GL063799

Gronewold, A. D., Bruxer, J., Durnford, D., Smith, J. P., Clites, A. H., Seglenieks, F., et al. (2016). Hydrological drivers of record-setting water level rise on Earth's largest lake system. *Water Resources Research*, *52*(5), 4026–4042. https://doi.org/10.1002/2015WR018209

Gronewold, A. D., Do, H. X., Mei, Y., & Stow, C. A. (2021). A tug-of-war within the hydrologic cycle of a continental freshwater basin. *Geophysical Research Letters*, *48*(4), e2020GL090374. https://doi.org/10.1029/2020GL090374

Gronewold, A. D., & Stow, C. A. (2014). Water loss from the Great Lakes. *Science*, *343*(6175), 1084–1085. https://doi.org/10.1126/SCIENCE.1249978

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/QJ.3803

Higgins, R. W., Shi, W., Yarosh, E., & Joyce, R. (2000). Improved United States precipitation quality control system and analysis. In *NCEP/Climate Prediction Center Atlas*, (Vol. 7, p. 40). NOAA/NWS.

Huang, C., Anderson, E. J., Liu, Y., Ma, G., Mann, G., & Xue, P. (2021). Evaluating essential processes and Forecast requirements for meteotsunami-induced coastal flooding.

Kanamaru, H., & Kanamitsu, M. (2007). Fifty-seven-year California reanalysis downscaling at 10 km (CaRD10). Part II: Comparison with North American regional reanalysis. *Journal of Climate*, *20*(22), 5572–5592. https://doi.org/10.1175/2007jcli1522.1

Kayastha, M. B., Ye, X., Huang, C., & Xue, P. (2022). Future rise of the Great Lakes water levels under climate change. *Journal of Hydrology*, *612*, 128205. https://doi.org/10.1016/J.JHYDROL.2022.128205

Kendall, M. G. (1975). *Rank correlation methods* (4th ed.). Charles Griffin.

Lavers, D. A., Simmons, A., Vamborg, F., & Rodwell, M. J. (2022). An evaluation of ERA5 precipitation for climate monitoring. *Quarterly Journal of the Royal Meteorological Society*, *148*(748), 1–14. https://doi.org/10.1002/qj.4351

Lavers, D. A., & Villarini, G. (2015). The contribution of atmospheric rivers to precipitation in Europe and the United States. *Journal of Hydrology*, *522*, 382–390. https://doi.org/10.1016/j.jhydrol.2014.12.010

Li, J., Feng, Z., Qian, Y., & Leung, L. R. (2021). A high-resolution unified observational data product of mesoscale convective systems and isolated deep convection in the United States for 2004–2017. *Earth System Science Data*, *13*(2), 827–856. https://doi.org/10.5194/essd-13-827-2021

Li, X., Zhong, S., Bian, X., Heilman, W. E., Luo, Y., & Dong, W. (2010). Hydroclimate and variability in the great lakes region as derived from the North American regional reanalysis. *Journal of Geophysical Research*, *115*(D12), 12104. https://doi.org/10.1029/2009JD012756

Mann, H. B. (1945). Non-parametric tests against trend. *Econometrica*, *13*(3), 163–171. https://doi.org/10.2307/1907187

Martinez, J. A., & Dominguez, F. (2014). Sources of atmospheric moisture for the La Plata River basin. *Journal of Climate*, *27*(17), 6737–6753. https://doi.org/10.1175/JCLI-D-14-00022.1

Matsuura, K., & Willmott, C. J. (2018). Terrestrial precipitation: 1900–2017 gridded monthly times series (version 5.01). Retrieved from http://climate.geog.udel.edu/~climate/html_pages/Global2017/README.GlobalTsP2017.html

Melillo, J. M., Richmond, T. (T. C.), & Yohe, G. W. (Eds.). (2014). *Climate change impacts in the United States: The third national climate assessment*. U.S. Global Change Research Program. https://doi.org/10.7930/j0z31wj2

McCombie, A. M. (1959). Some relations between air temperatures and the surface water temperatures of lakes. *Limnology and Oceanography*, *4*(3), 252–258. https://doi.org/10.4319/lo.1959.4.3.0252

Mesinger, F., DiMego, G., Kalnay, E., Mitchell, K., Shafran, P. C., Ebisuzaki, W., et al. (2006). North American regional reanalysis. *Bulletin America Meteorology Social*, *87*(3), 343–360. https://doi.org/10.1175/BAMS-87-3-343

Minallah, S., & Steiner, A. L. (2021). Role of the atmospheric moisture budget in defining the precipitation seasonality of the Great Lakes region. *Journal of Climate*, *34*(2), 643–657. https://doi.org/10.1175/JCLI-D-19-0952.1

Miner, T. J., & Fritsch, J. M. (1997). Lake-effect rain events. *Monthly Weather Review*, *125*(12), 3231–3248. https://doi.org/10.1175/1520-0493(1997)125<3231:LERE>2.0.CO;2

National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce. (2000). *NCEP FNL operational model global tropospheric analyses, continuing from July 1999*. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6M043C6

Nigam, S., & Ruiz-Barradas, A. (2006). Seasonal hydroclimate variability over North America in global and regional reanalyses and AMIP simulations: Varied representation. *Journal of Climate*, *19*(5), 815–837. https://doi.org/10.1175/JCLI3635.1

Notaro, M., Bennington, V., & Vavrus, S. (2015). Dynamically downscaled projections of lake-effect snow in the Great Lakes basin. *Journal of Climate*, *28*(4), 1661–1684. https://doi.org/10.1175/JCLI-D-14-00467.1

Notaro, M., Holman, K., Zarrin, A., Fluck, E., Vavrus, S., & Bennington, V. (2013). Influence of the Laurentian great lakes on regional climate. *Journal of Climate*, *26*(3), 789–804. https://doi.org/10.1175/JCLI-D-12-00140.1

Petterssen, S., & Calabrese, P. A. (1959). On some weather influences due to warming of the air by the Great Lakes in winter. *Journal of Meteorology*, *16*(6), 646–652. https://doi.org/10.1175/1520-0469(1959)016<0646:oswidt>2.0.co;2

Posey, J. (2012). Climate change impacts on transportation in the Midwest. U.S. National Climate Assessment, Midwest Technical Input Report.

Qian, Y., Yang, Z., Feng, Z., Liu, Y., Gustafson, W. I., Berg, L. K., et al. (2020). Neglecting irrigation contributes to the simulated summertime warm-and-dry bias in the central United States. *npj Climate and Atmospheric Science*, *3*(1), 1–10. https://doi.org/10.1038/s41612-020-00135-w

Rau, E., Vaccaro, L., Riseng, C., & Read, J. (2018). The dynamic great lakes economy employment trends from 2009 to 2018. Retrieved from https://www.michiganseagrant.org/wp-content/uploads/2020/10/MICHU-20-203Great-Lakes-Jobs-Report.pdf

Reichle, R. H., & Liu, Q. (2014). Observation-corrected precipitation estimates in GEOS-5 (Vol. *35*). NASA/TM–2014-104606

Seaber, P. R., Kapinos, F. P., & Knapp, G. L. (1987). Hydrologic unit maps.

Shafran, P. C., Woollen, J., Ebisuzaki, W., Shi, W., Fan, Y., Grumbine, R. W., & Fennessy, M. (2004). Observational data used for assimilation in the NCEP North American regional reanalysis. Preprints. In *14th Conference on Applied Climatology*. American Meteorological Society. Retrieved from https://ams.confex.com/ams/84Annual/techprogram/paper_71689.htm

Shi, Q., & Xue, P. (2019). Impact of lake surface temperature variations on lake effect snow over the Great Lakes region. *Journal of Geophysical Research-Atmospheres*, *124*(23), 12553–12567. https://doi.org/10.1029/2019JD031261

Sikma, M., Vilà-Guerau de Arellano, J., Pedruzo-Bagazgoitia, X., Voskamp, T., Heusinkveld, B. G., Anten, N. P. R., & Evers, J. B. (2019). Impact of future warming and enhanced [CO_2] on the vegetation-cloud interaction. *Journal of Geophysical Research: Atmospheres*, *124*(23), 12444–12454. https://doi.org/10.1029/2019JD030717

Sleeter, B. M., Loveland, T., Domke, G., Herold, N., Wickham, J., & Wood, N. (2018). Land cover and land-use change. In D. R. Reidmiller, C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, et al. (Eds.). *Impacts, risks, and adaptation in the United States: Fourth national climate assessment* (Vol. II).

Song, F., Leung, L. R., Feng, Z., Chen, X., & Yang, Q. (2022). Observed and projected changes of large-scale environments conducive to spring MCS initiation over the US Great Plains. *Geophysical Research Letters*, *49*, e2022GL098799. https://doi.org/10.1029/2022GL098799

Sousounis, P. J., & Fritsch, J. M. (1994). Lake-aggregate mesoscale disturbances. Part II: A case study of the effects on regional and synoptic-scale weather systems. *Bulletin America Meteorology Social*, *75*(10), 1793–1811. https://doi.org/10.1175/1520-0477(1994)075<1793:lamdpi>2.0.co;2

Steinschneider, S., & Lall, U. (2016). El Niño and the U.S. precipitation and floods: What was expected for the January–March 2016 winter hydroclimate that is now unfolding? *Water Resources Research*, *52*(2), 1498–1501. https://doi.org/10.1002/2015WR018470

Takacs, L. L., Suárez, M. J., & Todling, R. (2016). Maintaining atmospheric mass and water balance in reanalyses. *Quarterly Journal of the Royal Meteorological Society*, *142*(697), 1565–1573. https://doi.org/10.1002/QJ.2763

Wang, J., Xue, P., Pringle, W., Yang, Z., & Qian, Y. (2022). Impacts of lake surface temperature on the summer climate over the great lakes region. *Journal of Geophysical Research: Atmospheres*, *127*(11), e2021JD036231. https://doi.org/10.1029/2021JD036231

West, G. L., Steenburgh, W. J., & Cheng, W. Y. Y. (2007). Spurious grid-scale precipitation in the North American Regional Reanalysis. *Monthly Weather Review*, *135*(6), 2168–2184. https://doi.org/10.1175/mwr3375.1

Wilson, T. S., Sleeter, B. S., Sohl, T. L., Griffith, G., Acevedo, W., Bennett, S., et al. (2012). *Future scenarios of land-use and land-cover change in the United States: The marine West Coast forests ecoregion*. US Department of the Interior, US Geological Survey.

Xie, P., Chen, M., Yang, S., Yatagai, A., Hayasaka, T., Fukushima, Y., & Liu, C. (2007). A gauge-based analysis of daily precipitation over East Asia. *Journal of Hydrometeorology*, *8*(3), 607–626. https://doi.org/10.1175/jhm583.1

Xue, P., Pal, J. S., Ye, X., Lenters, J. D., Huang, C., Chu, P. Y., & (2017). Improving the simulation of large lakes in regional climate modeling: Two-way lake-atmosphere coupling with a 3-D hydrodynamic model of the great lakes. *Journal of Climate*, *30*(5), 1605–1627. https://doi.org/10.1175/JCLI-D-16-0225.1

Yang, Z., & Dominguez, F. (2019). Investigating land surface effects on the moisture transport over South America with a moisture tagging model. *Journal of Climate*, *32*(19), 6627–6644. https://doi.org/10.1175/JCLI-D-18-0700.1

Yang, Z., Qian, Y., Liu, Y., Berg, L. K., Gustafson, W. I., Feng, Z., et al. (2020). Understanding irrigation impacts on low-level jets over the Great Plains. *Climate Dynamics*, *55*(3–4), 925–943. https://doi.org/10.1007/s00382-020-05301-7

Zappa, G. (2019). Regional climate impacts of future changes in the mid-latitude atmospheric circulation: A storyline view. *Current Climate Change Reports*, *5*(4), 358–371. https://doi.org/10.1007/s40641-019-00146-7

Zhang, W., & Villarini, G. (2019). On the weather types that shape the precipitation patterns across the US Midwest. *Climate Dynamics*, *53*(7), 4217–4232. https://doi.org/10.1007/s00382-019-04783-4

Ziese, M., Rauthe-Schöch, A., Becker, A., Finger, P., Rustemeier, E., & Schneider, U. (2020). GPCC full data daily version 2020 at 1.0°: Daily land-surface precipitation from rain-gauges built on GTS-based and historic data. https://doi.org/10.5676/DWD_GPCC/FD_D_V2020_100