Geophysical Research Letters

RESEARCH LETTER
10.1029/2024GL109890

Historical Trends in Cold-Season Mid-Latitude Cyclones in the Great Lakes Region

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Key Points:

- Cold season extratropical cyclones that pass through the Great Lakes region are shifting to more northern tracks
- The number and intensity of Great Lakes cyclones do not show an increasing trend
- Great Lakes extratropical cyclones are warming and are increasing in moisture at a rate faster than the background climate

Supporting Information:

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

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Citation:

Hutson, A., Fujisaki-Manome, A., & Glassman, R. (2024). Historical trends in cold-season mid-Latitude cyclones in the Great Lakes Region. *Geophysical Research Letters*, *51*, e2024GL109890. https://doi.org/10.1029/2024GL109890

Received 19 APR 2024
Accepted 6 AUG 2024

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Abstract The Great Lakes Region (GLR) of North America is at the intersection of multiple extratropical cyclone (ETC) tracks, and the region's cold-season climate is heavily influenced by the large temperature gradients and intense precipitation associated with these cyclones. The goal of this study is to understand how ETCs are changing within a warming climate. Historical GLR cyclone characteristics from 1959 to 2021 are examined using a storm tracking algorithm and the ERA-5 atmospheric reanalysis. Of the 886 cyclones identified, half are the large long-track cyclones that are typically included in ETC studies, and half are smaller short-track cyclones that, while not always considered in ETC studies, still have an important impact on the GLR with significant precipitation trends. While all cyclones exhibit strong interannual variability, storm trajectories appear to be migrating northward and, most notably, the cyclones are becoming warmer and wetter at a rate faster than the background climate.

Plain Language Summary Winter weather patterns in the Great Lakes Region of the United States are driven by large-scale weather systems known as "extratropical cyclones." Even with a warming climate, the Great Lakes Region experiences highly variable winters, with cold-air outbreaks, extreme snowfall, and mild temperatures all possible from year to year. This study uses historical analyzed atmospheric data to identify and track extratropical cyclones that pass through the Great Lakes Region in order to understand how the cyclones have changed along with our changing climate. We find that the airmasses within the cyclones have increased in moisture and warmed up faster than the overall climate. We also find that the cyclone tracks have shifted northward, implying that the frequency of warm temperatures and heavy rainfall in the wintertime is increasing for the lower portion of the Great Lakes.

1. Introduction

The North American Great Lakes Region (GLR) is home to the largest collection of freshwater lakes in the world, with over 30 million people relying on its drinking water. The GLR has considerable socioeconomic influence, generating $17.8 billion GDP in 2020 (NOAA Office for Coastal Management, 2023). The GLR is also home to a multitude of impactful weather hazards including heavy rain and snow, lake ice coverage, and high winds. During the cold season, weather in the GLR is dominated by extratropical cyclones (ETCs), large systems associated with widespread rain, intense snowfall, and sharp temperature gradients. The high ETC frequency is due to the fact that the GLR is the intersection of two major North American cyclone tracks, or areas of enhanced eddy kinetic energy (EKE), colloquially known as the Alberta track and the Colorado track (Eichler & Higgins, 2006; Fritzen et al., 2021). ETCs have unique socioeconomic impacts on the Great Lakes, as heavy precipitation and high winds can cause flooding and dangerous shipping conditions, and cold surges following ETCs create enhanced ice formation on the Lakes. Additionally, the Great Lakes create their own impacts on the weather, as their large thermal inertia allow for upward heat fluxes that cause sharp regions of intense snowfall (known as lake-effect snow), and even have been shown to strengthen cold season ETCs that pass over the lakes (Notaro et al., 2013; Xiao et al., 2018). Understanding how winter ETCs have changed and are expected to change with the warming climate is paramount to safety, preparedness, and adaptation strategies in the GLR.

Studies that investigate historical and future trends in ETC activity have shown that storm tracks are shifting poleward (Chang et al., 2012; Eichler & Higgins, 2006; Mbengue & Schneider, 2013; Tamarin & Kaspi, 2017). Whether ETCs are getting stronger or more frequent is uncertain, with some studies declaring an increase in Northern Hemisphere "storminess" (e.g., Karwat et al., 2022) and others showing a decline in storm activity (Chang et al., 2016; Fritzen et al., 2021; Gertler & O'Gorman, 2019), depending on analysis method (Michaelis et al., 2017 and references therein). Previous research on storm trends either use an Eulerian approach, in which ETC activity is analyzed by looking at continent- or hemisphere-wide fields of EKE (e.g., Chang et al., 2016; Eichler & Higgins, 2006; Gan & Wu, 2014), or a Lagrangian approach, in which individual ETCs are identified and tracked (Bauer et al., 2016; Hodges, 1994; Karwat et al., 2022; Michaelis et al., 2017; Tamarin & Kaspi, 2017; Fritzen et al., 2021). A majority of studies that look into ETC activity and trends do so on a hemisphere-wide scale (e.g., Chang et al., 2016; Bauer & Del Genio, 2006; Gan & Wu, 2014; Martynova et al., 2022), or espeically prolific regions, that is, the Atlantic and Pacific storm tracks (e.g., Gan & Wu, 2014; Karwat et al., 2022; Michaelis et al., 2017). Fewer studies highlight ETC trends over continental North America (Eichler & Higgins, 2006; Chagnon et al., 2008; Fritzen et al., 2021), and even less research has focused on local or regional impacts of changing ETC trends (e.g., Pringle et al., 2021), espeically through the GLR (Angel & Isard, 1998; Turner et al., 2013).

Studies that include ETC trends over the GLR show that ETC activity in the north is trending upward, particularly over Lake Superior (e.g., Chang et al., 2012; Fritzen et al., 2021). However, ETC frequency alone does not provide information on how daily and seasonal weather events may shift in a changing climate. Therefore, to better characterize the historical changes in winter weather due to ETC activity, we conduct a Lagrangian analysis by tracking individual ETCs that pass through the GLR and identify how the air masses within the storms have changed in recent decades. By using broadly defined requirements for the temporal and spatial scale of targeted ETCs, and following each ETC over its own individual path (termed a "storm trajectory"), our analysis targets both large (e.g., traversing over 2,000 km and lasting at least 2 days) and mid-scale (e.g., track length less than 2,000 km lasting 1–2 days) storms, the latter of which are not commonly included in previous research but are abundant in mid-latitude winter weather.

2. Methods

Cold-season (October - March) North American ETCs are tracked using the ECMWF ERA-5 reanalysis data set with a 0.25° grid spacing (Hersbach et al., 2020). Although ERA-5 is a certified and accurate reanalysis, studies have shown that the treatment of lake surface conditions in ERA-5 cause biased lake surface temperature, which can affect hydroclimate representation (Minallah & Steiner, 2021). To verify whether climate trends in ERA-5 replicate observed trends in the GLR, ERA-5 is compared to 60 years of station observations (over land; see supplementary material for location). It was found that ERA-5 trends for 2 m air temperature, 2 m dewpoint, and MSLP were not significantly different from observed trends.

ETCs are identified in ERA-5 data using a modified version of the stormTracking algorithm created by Eric C.J. Oliver, 2024 (https://github.com/ecjoliver/stormTracking, based on Chelton et al., 2011). The stormTracking algorithm identifies extrema in the ERA-5 mean sea level pressure (MSLP) field and then connects the points through time to define individual storm trajectories. Spurious storm trajectories are filtered based on storm speed (a constant upper threshold of 80 km hr^{-1}), trajectory length (a minimum of 150 km), and ETC duration (minimum of 24 hr).Trajectories are also filtered out if they have a "meandering" path (a trajectory is defined as meandering if the ratio of start and end point distance to total track distance is less than 0.6; Klotzbach et al., 2016). The small trajectory length and duration thresholds are less than those used in previous ETC tracking studies (e.g., Fritzen et al., 2021; Karwat et al., 2022; Turner et al., 2013) to allow the inclusion of smaller storms that are still important to GLR weather (as resolved by ERA-5). It was found that the original algorithm identified too many points as cyclone center, specifically along the MSLP trough created by a cold front. To filter out any anomalous points, the cyclone center is defined as the lowest pressure point within a 3.0° radius.

In order for an ETC to be included in this study, it must pass through the Great Lakes Region (GLR), defined as a box between 50°N and 41°N latitude, and 93.5°W and 75.5°W longitude. Seasonal ETC composites are used to identify temporal trends in cyclone structure. To create ETC composites, an individual ETC is captured by finding the time at which the cyclone is strongest (i.e., has its minimum surface pressure) while in the GLR, and then the data is cropped in a 20° square area surrounding the minimum pressure point. All individual ETCs are then concatenated over the cold season (defined as October - March for 1 year) and are averaged together on a storm-centric grid.

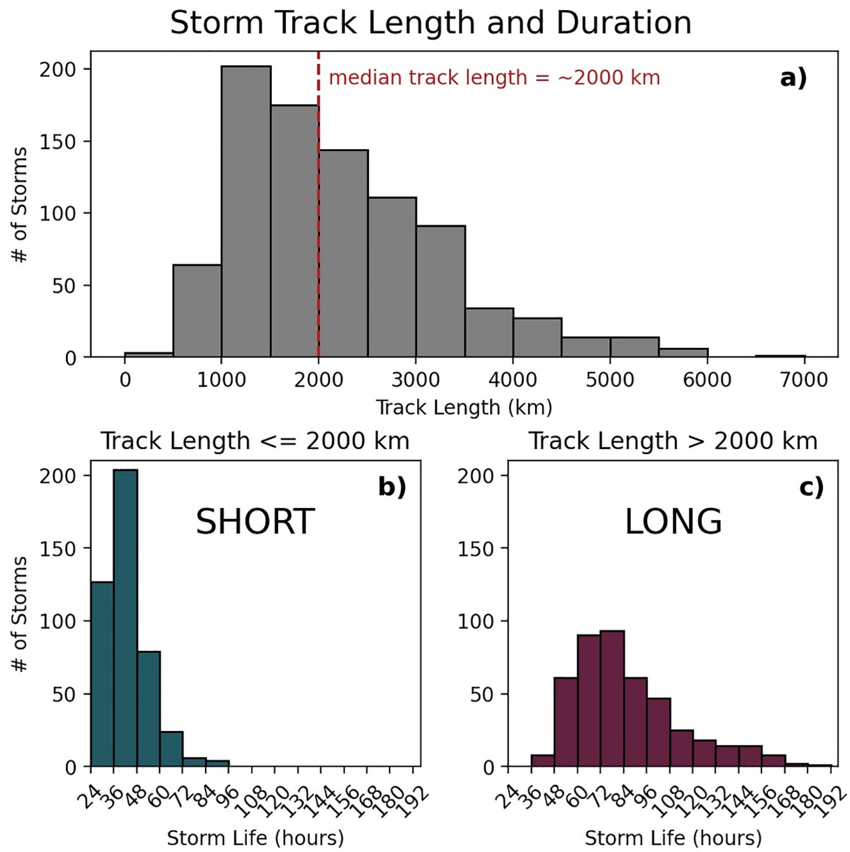

Figure 1. Histograms showing the number of GLR cyclones binned by (a) cyclone track length and (b), (c), cyclone life span in hours. The vertical red dashed line in (a) marks the median track length, which differentiates between (b) and (c) long track cyclones.

3. Results and Discussion

A total of 886 cold-season ETCs are tracked through the GLR between 1959 and 2021. Individual storm trajectory lengths range from 300 to 6,600 km, and storm durations last anywhere from 30 to 180 hr (Figure 1). The median cyclone track length is 2,000 km, which is used to differentiate between the "short track" storms and "long track" storms. Short track storms typically last less than 72 hr (Figure 1b), while long track storms typically last anywhere from 36 to 180 hr (Figure 1c). Separating short track ETCs from long track ETCs during analysis allows for greater understanding whether long-lived storms undergo greater influence from the warming climate, or if all storms are affected the same, regardless of scale.

A majority (53.6%) of the ETCs that pass through the GLR originate near the Great Lakes region. Another 26.0% of the ETCs can be considered "Alberta Lows", and originate near the U.S Northern Great Plains and central Canadian Provinces. A lesser 16.2% of GLR ETCs can be called "Colorado Lows", and originate in the Southern Great Plains, while only 6.1% of ETCs passing through the GLR originate elsewhere (e.g., in the Gulf region or the Atlantic region; a map of cyclogenesis categories can be seen in Figure S2 in Supporting Information S1).

ETC trajectories appear to be trending northward with time in the GLR. A Hovmoller diagram in Figure 2 shows that in the first 30 years of the data set, the greatest ETC frequencies are centered around a latitude of 45°N (Figure 2, dark colors highlighted by black contours). In the last 30 years, ETC trajectories are concentrated in the northern portion of the GLR, specifically north of 44° latitude (Figure 2). This northward shift of ETC activity in the GLR is consistent with previous studies that have found the center of enhanced EKE to be moving poleward (e.g., Chang et al., 2012; Eichler & Higgins, 2006; Mbengue & Schneider, 2013).

There is also a shift in cyclogenesis locations for ETCs that pass through the GLR. Using 1990 to bifurcate the ETC data set, it is revealed that more storms are originating near the GLR in the most recent half of the data set

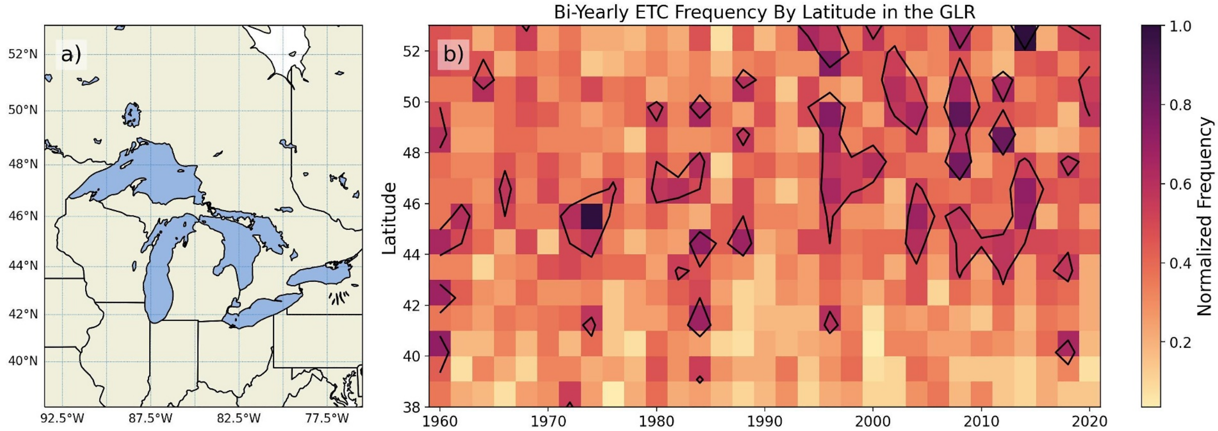

Figure 2. (a) A map of the region used to track ETC frequency for the diagram in (b). (b) A Hovmoller diagram showing ETC frequency in the GLR. Frequency is binned on the *y*-axis by summing total ETC interactions per degree latitude (between −93.5° and −75.5° longitude; see the region in (a)), and binned on the *x*-axis by summing over 2 year periods. Frequency is normalized by dividing each bin by the maximum frequency recorded for a single bin on the entire grid shown. Black contours highlight regions in which normalized frequency equals 0.5 or greater.

compared to those that formed earlier (29.6% compared to 24.0%; See Figure S5 in Supporting Information S1). The change in cyclogenesis locations is largely seen in the long track storms, where only 15.6% of long track storms originate near the GLR pre-1990, while 25.1% of long track storms originate in the same region after 1990. Meanwhile, less Colorado Lows are passing through the GLR post-1990 (7.2% compared to 8.9%). This decrease of Colorado Lows in the GLR is supported by Fritzen et al. (2021), who find that the formation of Colorado Lows in general exhibits a decreasing trend.

A northward shift in ETC trajectories can have significant impacts to seasonal climate and extremes. A northern cyclone track brings warm, moist Gulf air northward, leading not only to warmer extremes in the winter months for the lower Great Lakes, but also more liquid precipitation. Warm air and rain means greater ice melting and/or less ice formation on the Lakes. Flooding risk also increases if there is residual snow when warm temperatures and rain are more frequent. For the upper Great Lakes, a northern shift in storm tracks means a greater frequency of storm centers passing over the region. The center of a mid-latitude cyclone is associated with high winds and mixed precipitation or freezing rain, leading to a greater frequency of dangerous ice events.

Of the cold-season ETCs that pass through the GLR, 444 are considered "short track" (with a total trajectory length less than 2,000 km), and 442 are "long track" (with a trajectory length greater than 2,000 km). Storm-centered composites of short- and long-track cyclones show typical ETC structure with cold air north of the cyclone center, and a warm sector of air maximized in the southeast quadrant (Figure 3). The precipitation patterns are also characteristic of typical ETC structure, with a swath of snow maximized north/northwest of the minimum MSLP location, and rain extending east and south of the cyclone center, mainly in the warm sector of the storm. Short track storms average a minimum MSLP of 998.39 mb, with average liquid water equivalent (LWE) snow maxing at 0.45 mm, and average rainfall maxing around 0.45 mm (Figure 3a). Long track storm means have a lower average minimum pressure (992.12 mb), greater amounts of snowfall covering a greater area (LWE snow max of 0.60 mm), and greater amounts of rain covering a greater area (rainfall max of 0.65 mm; Figure 3b). The average temperature in long track storms is warmer in the southeast quadrant, exhibiting stronger temperature gradients within the composite.

Seasonal ETC composites are used to identify temporal trends in storm characteristics from 1960 to 2020 (Figure 4). Short track and long track cyclone composites are analyzed separately, and a linear least squares regression is fitted to each time series (Figures 4a–4h). To measure the statistical significance of each linear trend, a p-value of the regression is found using the Wald Test with the null hypothesis that the slope is zero. Time series of annual means are created for short and long track cyclone composites in terms of mean 2 m temperature, minimum MSLP perturbation, number of cyclone instances (per year), mean horizontal wind speed, mean total precipitation, mean precipitation in the form of rain, mean precipitation in the form of snow, and mean total column integrated water vapor (TCWV). To calculate an annual mean for each ETC characteristic, all points on a 20° by 20° ETC composite are spatially averaged to create one value per year per variable. The only exception to

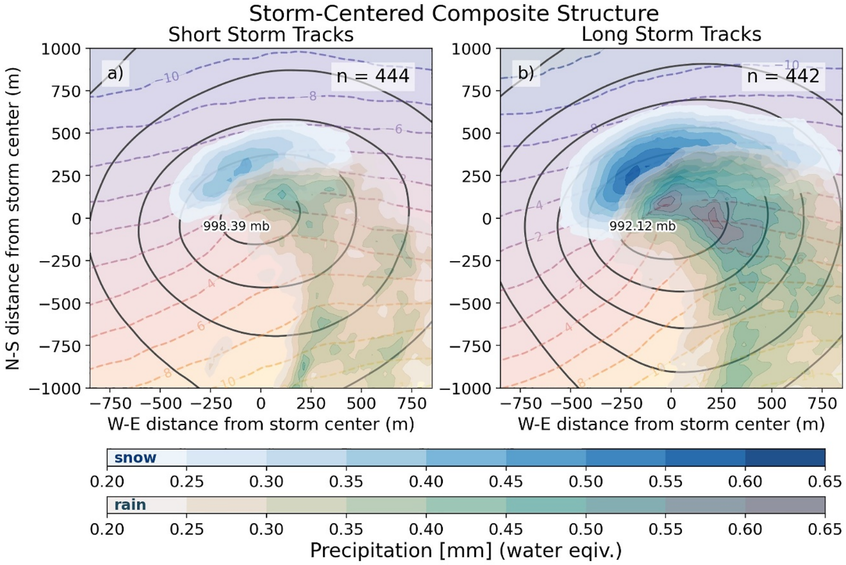

Figure 3. Storm-centered composites of (a) short track and (b) long track GLR cyclones. MSLP is contoured every 4 hPa with black solid lines. The average minimum MSLP is given near the center of the storm. 2 m temperature is contoured every 2° with dashed lines and is colored based on temperature value. Rain and snow are contoured with green and blue colors, respectively. The number of cyclones used to compose each composite, or n, is given in the top right of each subplot.

this method is the value found for minimum MSLP perturbation, which is found by subtracting all mean MSLP points in an ETC composite from the single spatially averaged mean MSLP value and finding the minimum.

All ETC composite trends exhibit large interannual variability. The number of storms that hit the GLR per year has a standard deviation (σ) of three storms for both short- and long-track composites. Composites for both tracks show similar variance for all variables, with the only notable difference being that long-track composites show 40% greater seasonal variability in snow amounts ($\sigma = 0.036$ mm) than short-track ($\sigma = 0.025$ mm). In terms of 2 m temperature, GLR total ETC composites have a seasonal variability of $\sigma = 2.65$°C ($\sigma = 2.38$ for long-track, $\sigma = 2.65$ for short-track), with the mean 2 m temperature jumping as much as 10°C from one cold season to the next (e.g., 1972–1973, Figure 4i).

Both short and long track GLR ETC composites exhibit a statistically significant (linear regression p-value <0.05) warming trend in 2 m temperature. Long track ETCs have warmed slightly faster than short track ETCs (0.468°C decade^{-1} compared to 0.426°C decade^{-1}; Figure 4a). Both types of GLR storms are also characterized by a statistically significant increasing trend of TCWV, with short track cyclones having a slightly greater trend (0.304 kg m^{-2} decade^{-1} compared to 0.269 kg m^{-2} decade^{-1}; Figure 4h). Only short track ETCs exhibit a statistically significant increase in rain, with a trend of 0.010 mm gridpoint^{-1} decade^{-1} (Figure 4f). There does not appear to be any meaningful trend in mean wind speed or storm count for either type of ETC.

It is clear that GLR cyclones are warming, holding more water, and producing more rain. Because these trends are generally expected in a warming climate, we ask the question: are these trends unique to the ETCs themselves, or are the ETCs just reflecting the trend of the background climate unique to the GLR? To test the storm trends against regional background climate trends, ERA5 annual cold-season background composites were created by finding the total mean value of 2 m temperature, 2 m dewpoint, total precipitation, and TCWV over the GLR domain for the entirety of October-March (which includes any extremes caused by cyclones passing through the region). The cold-season background was then compared to seasonal GLR total ETC trends for the same variables (i.e., short-track and long-track cyclones were not separated). It has been shown that the GLR is exhibiting an above-average warming trend for the contiguous United States (Wuebbles et al., 2019), so by restricting all background climate calculations to within the GLR bounds, we are able to confidently say that any differences between trends are due to ETC change.

GLR ETCs are warming faster and are increasing in moisture faster than the background climate (Figures 4i–4l). The temperature and moisture trends (for both the background climate and the ETCs) have high certainty, with a

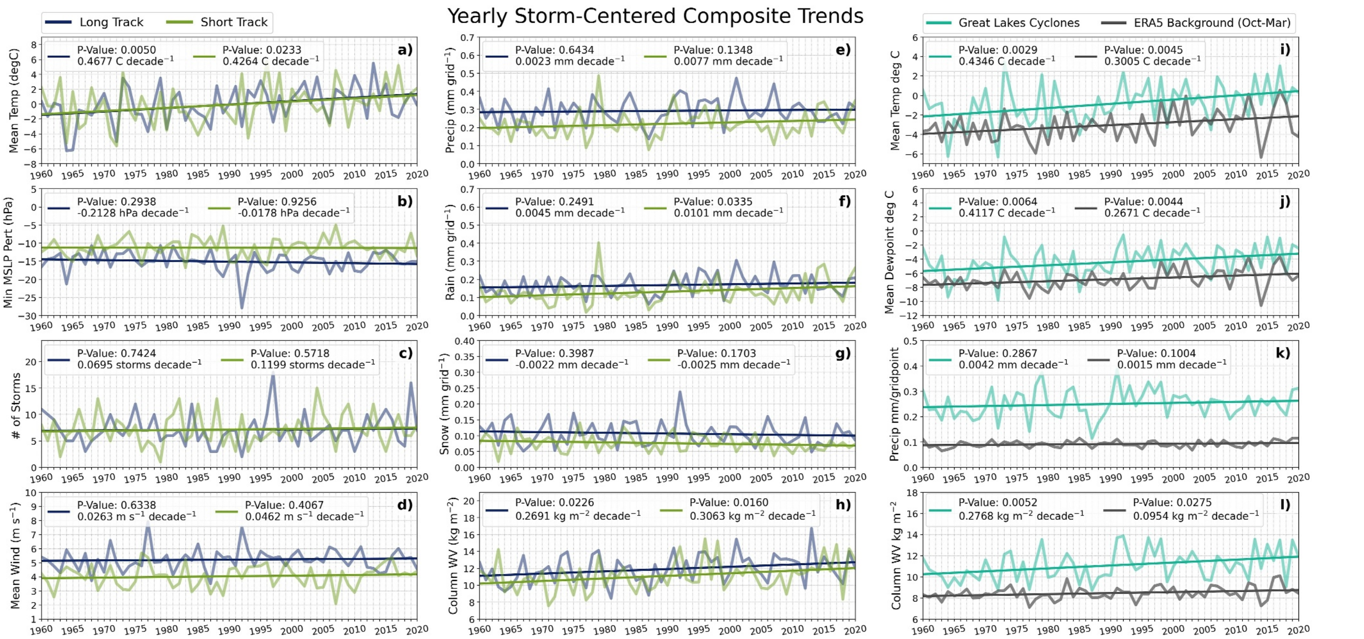

Figure 4. Time series of ETC defined using annual storm composites and associated linear regressions. For (a)–(h), long-track ETC trends are compared to short-track cyclone trends. For (i)–(l), GLR ETC trends (regardless of track length) are compared to background ERA5 climate trends. P-value and slope for each linear regression is shown in the legend of each subplot. The variable shown in each subplot is labeled on the *y*-axis.

majority having a p-value less than 0.01. ETCs are warming by 0.435° decade^{-1}, while the background climate is warming by 0.301° decade^{-1} (Figure 4i). ETC dewpoints are increasing at a rate of 0.412° decade^{-1}, compared to a background rate of 0.267° decade^{-1} (Figure 4j). The greatest difference between cyclone trends and background trends is seen in TCWV, where cyclones show an increase in 0.277 kg m^{-1} decade^{-1}, and the background trend is only 0.095 kg m^{-2} decade^{-1}. Neither GL ETCs nor the background climate show a statistically significant trend in total precipitation.

ETCs are deep atmospheric phenomena, and their dynamical influence extends throughout the entire depth of the troposphere. To determine whether the ETC surface warming trends are extended into the vertical, additional composites of temperature and geopotential height were created at the 850, 500, and 300 mb pressure levels, centered on the location of minimum MSLP in the surface ETC composite. Similar to the warming trend visible at the surface (Figure 4a), time series reveal that annual mean air temperature is significantly increasing at all three pressure levels by 0.3° decade^{-1} within the GLR ETCs (Figure S6 in Supporting Information S1, 500 mb trends not shown). The atmospheric column above the surface ETCs is also significantly warming, indicated by the increasing trend in annual mean geopotential height at 300 mb (Figure S6 in Supporting Information S1). Using the atmospheric thickness between 850 and 300 mb as a proxy for average column temperature, annual mean trends suggest that the warming is not equal over the ETC; the eastern half of each GLR ETC may be warming faster than the western half of the ETC, although statistical significance is not confirmed (the thickness trends have p-values of 0.06; Figure S6 in Supporting Information S1 bottom panel). Uneven warming across cold-core cyclones implies the cyclones may be associated with greater baroclinity and are potentially strengthening, despite not seeing an increase in wind speed or a decrease in MSLP anomalies near the surface.

4. Summary and Conclusions

In an effort to characterize historical changes in winter weather in the region surrounding the Great Lakes, cold-season (October-March) extratropical cyclones (ETCs) are identified and tracked in the GLR. During the time period from October 1959 - March 2021, a total of 886 cyclones are identified as GLR ETCs using ERA5 reanalysis data. Of the 886 GLR ETCs, half (444) have a track length less than 2,000 km and are considered short track, while the other half (442) have a track length greater than 2,000 km and are considered long-track. The precipitation and pressure signature associated with short-track ETCs cover a smaller spatial area, on average, than that seen in long-track ETCs, but both types of storms have a similar structure (Figure 3). A majority of previous studies identifying ETC trends in the Northern Hemisphere do not include storms associated with such small spatial and temporal scales, and therefore miss the significant trends seen in short-track ETCs (e.g., Figure 4f).

There is no historical trend in the number of ETCs that enter the GLR, but there is evidence that the storm trajectories are shifting northward (Figure 2). More northern storm trajectories can lead to significant changes in winter weather for the GLR, including more frequent warm temperature extremes and rain events for the lower Great Lakes, and greater instances of mixed-precipitation events for the upper Great Lakes, which could lead to decreased seasonal ice cover and increased flooding risk. Studies using climate projections also tend to see a northward shift of ETC activity, as well as a change in frequency (e.g., Chang et al., 2012; Michaelis et al., 2017; Catto et al., 2019). A trend in GLR ETC frequency and intensity may arise with future climate projections, but downscaled climate data would be necessary as global climate models are too coarse for the region (Briley et al., 2021).

Any cold-season warming in the GLR caused by more northern ETC trajectories is amplified by the fact that the cyclones themselves are warming. Both short track and long track cyclones are increasing in 2 m temperature at a rate faster than the background climate. The warmer temperatures are also associated with an increase in moisture content: GLR cyclones are showing significant increases in both 2 m dew point temperature and TCWV, the latter of which is increasing at a rate double that of the background climate. As TCWV increases, the potential for more intense precipitation with GLR cyclones increases as well.

Although GLR ETCs are undeniably warming and holding more moisture, the historical change in the amount of precipitation formed by the cold-season storms is less certain. Long track ETCs show no sure trend in total precipitation, and while liquid precipitation (rain) has an increasing trend, the amount of interannual variability makes the trend uncertain. Short track ETCs also have large interannual variability, but rain has a statistically significant increasing trend in short track cyclones. There is a decreasing trend in snow in GLR cyclones, but, again, the interannual variability is muting the trend.

Large interannual variability is present in all characteristics of GLR ETCs. One cause of the variability may be due to changing teleconnection phase (e.g., El-Niño Southern Oscillation). ETCs are known to take different paths and have different characteristics depending on teleconnection phase, and GLR cyclones are no different. Future work with the GLR ETC database includes identifying storm trends associated with the teleconnection patterns, and how those trends may be changing in the context of a warming climate.

Data Availability Statement

ERA5 data were downloaded from the Copernicus Climate Data Store (CDS) and are available at (Hersbach et al., 2023) https://doi.org/10.24381/cds.adbb2d47 (accessed in June of 2022). The original stormTracking cyclone-tracking algorithm was created by Eric J. Oliver, 2024 and is available on GitHub (https://github.com/ecjoliver/stormTracking). The python notebooks used for this study are on Github (Hutson, 2024) (https://doi.org/10.5281/zenodo.12627444). Storm tracks and composites are available on Deep Blue (Hutson et al., 2024) (https://doi.org/10.7302/17vn-x488).

Acknowledgments
This study was funded by the National Oceanic and Atmospheric Administration (NOAA) awarded to the Cooperative Institute for Great Lakes Research (CIGLR) through the NOAA Cooperative Agreement with the University of Michigan (NA22OAR4320150) and the NOAA Weather Program Office (NA21OAR4590367). This is CIGLR contribution 1245. We would like to thank the CIGLR Summer Fellows Program for the opportunity to pursue this work. We also thank Dr. Claire Pettersen and Ms. Lara Tobias-Tarsh at the University of Michigan for helpful comments about the research.

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