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Changes in Lake-Effect Snow Across the Great Lakes Revealed Using Dynamically Downscaled Climate Simulations

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Abstract The Laurentian Great Lakes region experiences mesoscale lake-effect snow bands during the boreal cold season. These events can produce extreme whiteout conditions, high snowfall accumulations, and significant localized impacts on transportation and regional economies. Lake-effect snow develops under combinations of temperature, wind shear, and atmospheric instability, all of which are expected to change in a warming climate. Understanding how climate change may influence lake-effect precipitation is therefore important for anticipating regional hazards. General circulation models (GCMs), the primary tools used to study climate and natural hazards, are typically too coarse to resolve mesoscale processes such as lake-effect precipitation. Moreover, even high-resolution global models vary substantially in their treatment of the Great Lakes and their ability to reproduce recognizable lake-effect snowfall patterns. High-resolution dynamical downscaling is therefore required to better represent these processes. This study analyzes simulations from a high-resolution dynamically downscaled GCM over the contiguous United States, with grid spacing sufficient to explicitly represent convective processes relevant to lake-effect precipitation. Three 15-year periods are examined: historical (1990–2005), mid-century (2040–2055), and end-of-century (2085–2100) under the Representative Concentration Pathway 8.5 scenario. Results indicate that snowfall from lake-effect events is projected to persist and, in some regions, increase in intensity. The strongest events become more intense, particularly downwind of Lakes Superior and Huron, in association with enhanced lower-level atmospheric instability and near-surface air temperatures that remain sufficiently cold for snow. However, warming also shortens the lake-effect season, with events becoming less frequent but producing greater snowfall per event and slightly longer durations.

Plain Language Summary Lake-effect snow occurs when cold air moves over the relatively warm waters of the Great Lakes, picking up heat and moisture that can produce narrow, intense bands of snow. These events can cause extremely heavy snowfall, dangerous travel conditions, and major localized disruptions. Given these impacts, it is important to understand how lake-effect snow may change under a changing climate. In this study, we analyze high-resolution climate model simulations capable of representing the small-scale processes that produce lake-effect snow. We compare simulations representing past conditions with projections for the middle and end of the 21st century under a high-emissions scenario. Results show that while lake-effect snow events may become less frequent overall as temperatures rise, the most intense events could produce even heavier snowfall in some areas. Greater lower-level atmospheric instability allows events to produce more snow when near-surface temperatures remain cold enough for snowfall.

Key Points:

- Dynamical downscaling projects fewer but more intense lake-effect snow events, with greater snowfall in the strongest events
- Lake-effect snowfall events are projected to become less common in the transition seasons, becoming more confined to the core winter season
- Enhanced lower-level atmospheric instability supports heavier snowfall when near-surface temperatures remain sufficiently cold for snow

Supporting Information:

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

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1. Introduction

Lake-effect snow is a common phenomenon across the Laurentian Great Lakes, occurring when sufficiently cold air moves over relatively warm lake waters. Its formation is dependent on wind direction, wind speed, low-level instability, and fetch (Kunkel et al., 2002; Niziol, 1987; Niziol et al., 1995). Lake-effect snow often falls in long and narrow bands with snowfall rates of 7.62–10.16 cm (3–4 inches) per hour or more (National Weather Service, 2026). The most intense lake-effect snow events can be damaging or even deadly (National Weather Service, 2006, 2014a, 2014b, 2022). Given the socioeconomic impacts of lake-effect snow events, as well as a

lack of understanding of how this phenomenon may change in a warmer climate, it is important to study trends and changes in this phenomenon in the context of a warming world.

Previous research has projected decreasing snowstorm frequency and snowfall trends in the Great Lakes region in a future, warming climate. Ashley et al. (2020) found that the greatest reduction in the occurrence of snow was over the northern Great Lakes region during the transition seasons, while Baijnath-Rodino et al. (2018) identified negative snowfall trends during much of the cold season along the Canadian shores of Lake Superior and Lake Huron. Similarly, Krasting et al. (2013) utilized 18 general circulation models (GCMs) from Phase 5 of the Coupled Model Intercomparison Project (CMIP5) to examine snowfall changes across the northern hemisphere under the Representative Concentration Pathway (RCP) 4.5 warming scenario and found decreasing trends in snowfall across much of the mid-latitudes, including the Great Lakes region, especially in the transition seasons. It has been shown that snowfall contributed by the Great Lakes has experienced a trend reversal and is decreasing downwind of Lake Michigan (Bard & Kristovich, 2012). Suriano and Leathers (2017b) identified 7 lake-effect synoptic types or patterns across the eastern Great Lakes region and found that 6 out of 7 of them showed increased frequencies from 1950 to 1979, with the majority of these types/patterns exhibiting a decrease in frequency from 1980 to 2009 along with their associated snowfall amounts. Similarly, Suriano (2019) identified four atmospheric patterns as lake-effect synoptic types and noted that each saw decreasing temperatures and surface pressures, as well as increasing boundary layer instability and zonal flow from 1950 to 1979 with observed snowfall increases. It was shown that these synoptic types then remained relatively unchanged or decreased in frequency along with their associated snowfall amounts from 1980 to 2009. Across central New York, downwind of Lake Ontario, Hartnett et al. (2014) found negative snowfall trends over the past 41 years based on observations. Many areas within the Great Lakes region have also experienced negative snowfall departures compared to climatology over the past decade, another such observation pointing to decreasing frequency of snowfall in the Great Lakes (Northeast Regional Climate Center, 2025).

On the contrary, some studies have revealed increasing snowfall trends in the Great Lakes region, with Burnett et al. (2003) finding significant upward trends in cold-season snowfall for 11 out of 15 lake-effect sites studied. Non-lake-effect stations revealed no significant trends, and oxygen isotope data from the eastern Finger Lakes revealed a positive trend in lake-effect snow as well. Kunkel et al. (2009) utilized trend analysis for suitable long-term observation stations in lake-effect snow belts and found an upward trend in snowfall and liquid equivalent snow for sites south and east of Lake Superior and Lake Michigan. For Lake Ontario and Lake Erie, no distinct trend was present, as the trends at these stations depended on the time period of analysis.

Ice cover has significant impacts on lake-effect snow as the presence of ice cover effectively cuts off the upward fluxes of heat and moisture from the lake surface into the atmosphere necessary to form clouds, and different studies have found significant downward trends in ice cover on all of the Great Lakes. Wang et al. (2012) used observational ice cover data to show that the largest changes and downward trends have occurred across Lake Ontario, Lake Michigan, and Lake Superior. Mason et al. (2016) also found consistent linear declines in seasonal ice cover duration in 11 of 17 defined sub-basins throughout the Great Lakes. With less ice cover and more open water during winter, the period favorable for lake-effect snow formation could lengthen as greater portions of the lake surface remain exposed, allowing continued heat and moisture fluxes into the atmosphere. Previous studies have suggested that warmer lake temperatures and reduced ice cover may also increase the intensity of lake-effect snow through greater upward heat fluxes from the lake waters into the colder air above. These upward heat fluxes add energy to the system and enhance the rising motion of the air and updrafts, potentially increasing snowfall totals. Wright et al. (2013) simulated a cold-air outbreak case study over the Great Lakes region to examine the influence of ice cover and warmer lake temperatures on lake-effect snow. They found that ice cover focused or enhanced the precipitation due to ice edge roughness changes, whereas reduced ice cover and increased lake-surface temperature generally increased the intensity and downwind extent of lake-effect precipitation. Similarly, Vavrus et al. (2013) simulated 10 heavy lake-effect snow events across the Great Lakes region to understand the impact of complete ice coverage, showing that complete ice coverage significantly decreased downwind snowfall, as well as decreased the near-surface winds and associated convergence and surface fluxes for intense lake-effect snow bands (Vavrus et al., 2013). These prior studies provide a physical basis for considering the potential influence of lake-state changes, although the present study evaluates only the atmospheric and snowfall responses.

Numerous studies have examined how lake-effect snowfall may change in a warming climate. Kunkel et al. (2002) defined the number of grid points or events meeting criteria favorable for lake-effect snowfall near Lake Erie using numerical simulations, which revealed that the occurrence of favorable temperatures for heavy lake-effect snow is expected to decrease, while all other favorable conditions are expected to occur at about the same frequency. Suriano and Leathers (2016) utilized 7 fully coupled climate models from CMIP5 under two warming scenarios, RCP4.5 and RCP8.5, to examine changes in lake-induced snowfall across the eastern Great Lakes region through the 21st century. Their results projected a small decrease in lake-induced snow water equivalent (SWE, or the amount of liquid accumulation assuming the entire melting of the snowfall) by mid-century before a leveling off of SWE amounts for the RCP4.5 scenario, whereas under the RCP8.5 scenario, they found a small increase in SWE in the early 21st century before sharp decreases by as much as 43% by the end of the century. The authors also noted that no examinations of other important factors were performed to ascertain why lake-induced snowfall was changing, such as boundary-layer wind speed and direction, as well as atmospheric instability. Notaro et al. (2015) also examined future lake-effect snow using dynamically downscaled climate projections across the Great Lakes region under RCP8.5, finding a general reduction in heavy lake-effect snowstorms, with some increases around Lake Superior.

Despite these advances, previous modeling studies have limitations in their ability to represent the processes and evolving atmospheric conditions relevant to future lake-effect snowfall. For example, the 25-km horizontal grid spacing used by Notaro et al. (2015) was too coarse to explicitly resolve mesoscale land/lake breezes and lake-effect snow bands, which can be 5–50 km wide and 20–200 km long depending on the band type (Niziol et al., 1995). Liu et al. (2017) addressed this shortcoming using convection-permitting simulations with 4-km horizontal grid spacing. However, their study focused on the CONUS as a whole and employed the pseudo-global-warming (PGW) approach (e.g., Rasmussen et al., 2011; Schär et al., 1996) to simulate a future climate under RCP8.5. PGW provides a useful framework for isolating the thermodynamic response of historical weather events to an imposed climate-change signal while retaining a realistic synoptic sequence. However, because conventional PGW simulations largely preserve the historical evolution of the large-scale circulation, they may not capture future changes in the frequency, tracks, persistence, or structure of the synoptic systems and cold-air outbreaks that produce lake-effect snowfall. Such changes are potentially important because observed lake-effect snowfall trends differ among synoptic regimes (Suriano & Leathers, 2017a). Finally, Kayastha et al. (2024) utilized a case study and storyline approach to examine how the November 2022 Buffalo lake-effect snow event may change in a warming climate. Four different experiments were run with a fully coupled three-dimensional and two-way lake-land atmosphere model to examine the impacts of both a future warmer lake and warmer atmosphere on the event. Kayastha et al. (2024) found that storm total precipitation increased by 14% by end of century with a transition from a mainly snowfall event to a mixed rainfall and snowfall event, with these storm total precipitation increases driven by increased evaporation from a warmer lake. Although these simulations provide valuable insights into the influence of changing lake and atmospheric conditions, their case-study approach does not establish how the frequency and intensity of lake-effect snowfall may change across the Great Lakes region over multiple decades.

As highlighted above, while some studies have analyzed temporal trends in snowfall in a changing climate, to the best of the authors' knowledge, none have covered the entire Great Lakes region or have been conducted at a resolution fine enough to explicitly resolve lake-effect snow processes. Few studies have examined changes midway through the century, with most only examining changes from the beginning of the century to the end. To overcome the constraints of these prior studies, in this work, we focus on studying lake-effect snow specifically over the Great Lakes region with a high-resolution simulation data set over three distinct time periods. Our analysis focuses on snowfall and atmospheric thermodynamic and kinematic conditions associated with lake-effect snow; lake-surface temperature and ice-cover fields were not available for direct analysis. Based on previous studies of lake-effect snow and climate change impacts on temperature and precipitation, we propose two hypotheses:

H1: The intensity of lake-effect snowfall increases in some areas as lower-level atmospheric instability increases.

H2: Lake-effect snowfall will become less common in occurrence due to warming near-surface temperatures, with occurrences shifting more to the core and colder winter season instead of during the transition seasons.

2. Methods

2.1. Model Configuration and Simulations

This study uses dynamically downscaled general circulation model simulations conducted by Gensini et al. (2023). These simulation data cover the entire continental U.S. (CONUS) with a horizontal grid spacing of 3.75 km, 51 vertical levels, and an output interval of 15 min for certain variables such as precipitation type accumulations, 2-m temperatures, 10-m u and v wind components, and mean sea-level pressure. Three 15-year epochs were examined, comprising the historical period (1990–2005) and two simulated epochs under the RCP8.5 scenario: the mid-century (2040–2055) and end-of-century (EOC; 2085–2100) periods. The simulations were conducted as separate annual integrations, with each hydrologic year extending from October 1 through September 30. No dedicated spin-up period was excluded from the archived output. Consequently, initialization-related adjustment may influence conditions near the beginning of October, although atmospheric fields are generally expected to adjust more rapidly than slowly evolving land-surface variables. Lake-surface temperatures and ice cover were prescribed as time-varying lower-boundary conditions from the driving climate simulations, as discussed in more detail below, including the limitations of this approach.

Bias correction was applied to the parent GCM (Community Earth System Model [CESM]) forcing fields before dynamical downscaling, rather than to the WRF output, following the methodology described by Bruyère et al. (2014). For each corrected variable, the model value was decomposed into a seasonally varying historical climatology and a time-dependent anomaly. The model climatology was then replaced by the corresponding reanalysis climatology. This method removes the historical mean seasonal bias while retaining the GCM's synoptic sequence, interannual and decadal variability, and projected climate-change signal. The reference period for the bias correction was the 1981–2005 European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA) Interim climatology (Bruyère et al., 2014, 2015; Gensini et al., 2023). Twelve monthly climatological means were calculated and interpolated to six-hourly time steps. The atmospheric corrections included three-dimensional temperature, geopotential height, zonal and meridional winds, relative humidity, surface pressure, and mean sea-level pressure. CESM specific humidity was first used with temperature and pressure to diagnose relative humidity; the bias adjustment was then applied in relative-humidity space.

Bias correction was also performed for non-atmospheric fields. Specifically, sea-surface temperature was bias-corrected with the same climatological-mean replacement using the merged Hadley Centre and National Oceanic and Atmospheric Administration's (NOAA's) optimum interpolation (OI) sea surface temperature data set (Hurrell et al., 2008). Skin temperature and inland-lake temperature were bias-corrected, and the daily mean surface temperatures used to initialize inland-lake temperatures were identical to the corrected monthly mean skin temperature. Moreover, soil moisture and soil temperature were bias-corrected over four layers (0–10, 10–40, 40–100, and 100–200 cm) using the same mean-anomaly method. Additional details on the bias-correction procedures can be found in Bruyère et al. (2014, 2015).

The dynamically downscaled simulations used time-varying lake-surface temperatures and lake-ice conditions prescribed from the bias-corrected driving climate model data rather than calculated prognostically within WRF. These evolving lower-boundary conditions were updated throughout the simulations and were used to calculate the surface sensible and latent heat fluxes between the lakes and the atmosphere. Consequently, the simulations account for projected changes in lake-surface temperature and ice cover through the prescribed boundary conditions used to drive the regional climate simulations.

Prescribing the lake surface temperatures and ice cover from the forcing model data introduces an important limitation of the present study. Although the simulations include evolving lake-surface temperatures and ice conditions prescribed by the driving climate simulations, they do not prognostically simulate lake thermodynamics, including lake heat storage, vertical mixing, horizontal circulation, or coupled lake-ice evolution. The prescribed lake-surface temperatures were bias corrected prior to downscaling (Bruyère et al., 2014), which reduces systematic errors in the lower-boundary forcing. Nevertheless, residual biases in the prescribed lake state, including lake-surface temperature and ice cover, may influence the simulated air–lake temperature difference, surface heat and moisture fluxes, boundary-layer instability, and ultimately lake-effect snowfall. While the same lower-boundary treatment was applied consistently in the historical, mid-century, and end-of-century simulations, any systematic biases in the prescribed lake state may not cancel completely across these time periods because the atmospheric response to a given lake-state error may differ as the background climate changes.

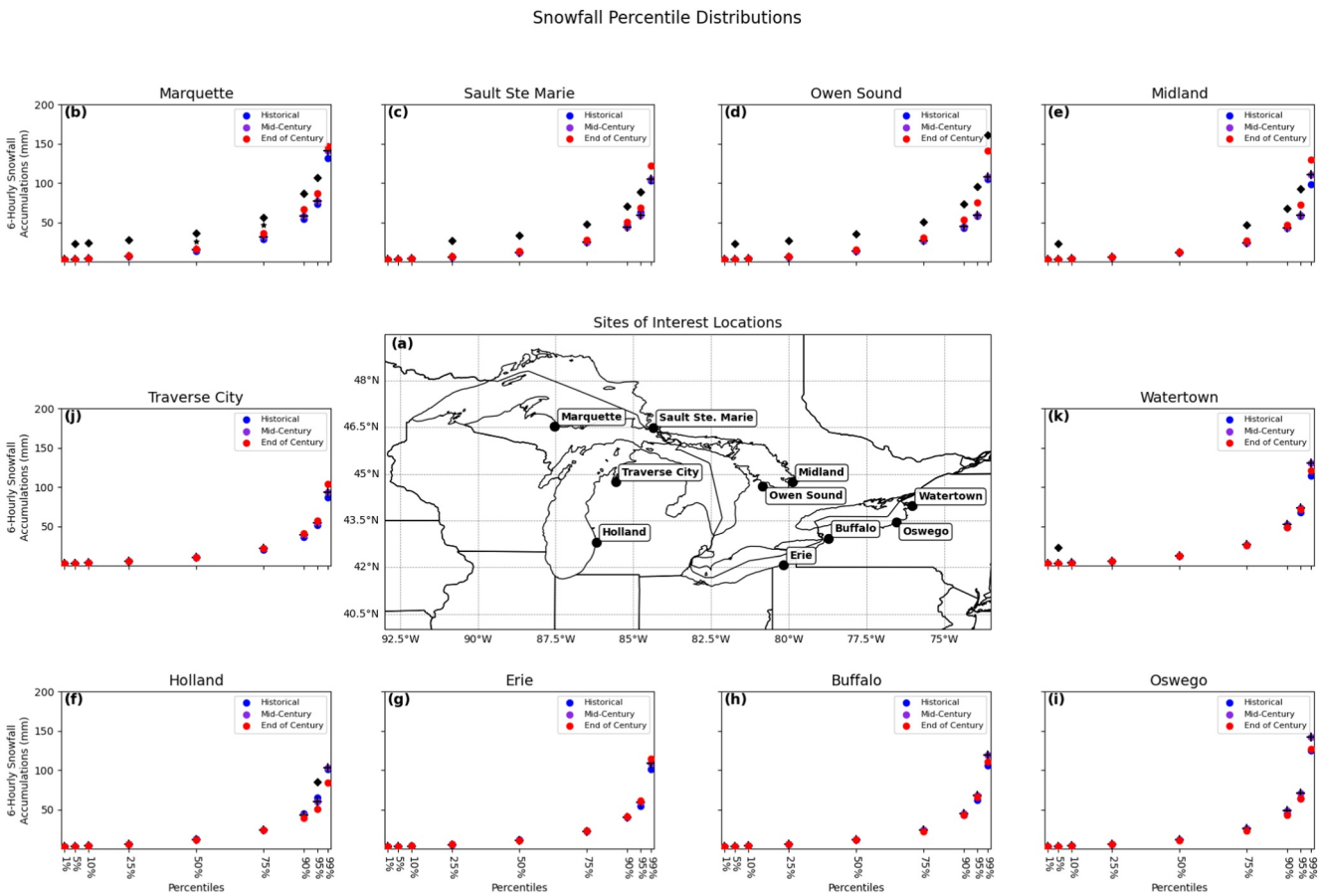

Figure 1. Central plot depicts the study domain, including locations of the sites prone to lake effect snow used in this study. Surrounding plots compare the snowfall amounts corresponding to various percentiles of 6-hourly snowfall accumulations at each site in the historical (blue), mid-century (purple, hatched), and EOC (red) periods. Black stars (diamonds) signify statistical significance at the 95% confidence level in the difference between mid-century and historical (EOC and mid-century) percentile amounts while using a bootstrapping approach with 10,000 iterations.

The downscaled Weather Research and Forecasting (WRF) Model output was used at 6-hr intervals in this study and subset to the domain of interest over the Great Lakes region. This domain extends approximately between the latitudes of 40°N and 49.5°N as well as the longitudes of 93°W and 73.5°W to include all the Great Lakes as well as areas sufficiently downwind, thus capturing the main lake-effect-prone regions (as shown in Figure 1a). To evaluate modeled lake-effect snow impacts, we used accumulated snowfall from the Air Force Weather Agency (AFWA) diagnostic package, which estimates accumulated snowfall using snow:liquid ratios that vary as a function of surface temperature (Creighton et al., 2014). The accumulated snowfall was analyzed in two ways: the 6-hourly snowfall accumulation (serving as a proxy for snowfall intensity) and snowfall totals over certain, longer periods of time (seasons or lake-effect events). The 6-hr accumulation period was selected to provide a consistent temporal basis across the model fields used in the analysis and to characterize sustained snowfall intensity rather than short-duration fluctuations in snowfall rates. Given that lake-effect snow events commonly persist for many hours, this interval provides a balance between resolving variations in snowfall within events and capturing the broader changes in snowfall characteristics that are the focus of this study. When examining changes in the 6-hourly average snowfall accumulation or distributions, only accumulations greater than 0.254 mm (0.01 in) were used to avoid inclusion of extremely small snowfall accumulations calculated by the simulation that may otherwise skew the results.

2.2. Analysis Methodology

To restrict the analysis to lake-effect snow events and exclude synoptic-scale storms, a set of favorable lake-effect snow conditions were used and evaluated at each grid point, following methodologies used in previous studies

such as Kunkel et al. (2002) and Suriano and Leathers (2017b). The first condition is a 2-m temperature between 0°C and −10°C, sufficiently cold for precipitation to likely fall as snow. The next condition is an 850-hPa wind direction between 240° and 340° (relative to north) with a wind speed of 6 m s^{-1} or greater. This wind direction range creates favorable fetch over all of the Great Lakes necessary for lake-effect snow, with wind speeds sufficiently strong for enhanced heat and moisture fluxes off of the lake surfaces (Niziol, 1987; Niziol et al., 1995). The third condition is a 900–700-hPa mean wind direction between 240° and 340° with a speed of 6 m s^{-1} or greater, similar to the previous condition. This condition serves to identify times where the mean boundary layer wind is relatively unidirectional, providing a wind shear criterion for favorable lake-effect snow conditions. This is an important criterion because shear is known to disrupt or prevent lake-effect snow bands (Niziol, 1987). The final condition is a difference in the 2-m and 850-hPa temperature of 10°C or greater, which provides a proxy for low-level instability over the lake waters that is favorable for lake-effect snow development. This final condition was evaluated over masked grid points of the Great Lakes only to identify favorable conditions exclusively over the lake waters. Perhaps a better proxy for instability would be the difference between the lake-surface temperature and the 850-hPa temperature. Although lake-surface temperatures were prescribed within the simulations through the lower-boundary forcing, they were not retained in the archived output available for analysis. Consequently, 2-m temperature was used as a proxy for lake-surface temperature when defining the instability criterion. Hanrahan et al. (2021) showed that near-surface air-temperature perturbations over the Great Lakes responded consistently to imposed lake-temperature perturbations, supporting the use of 2-m temperature as an indicator of the atmospheric response near the lake surface. This metric does not permit direct evaluation of lake-surface temperature or lake–atmosphere temperature differences. Because the lake surface is generally warmer than the overlying 2-m air during lake-effect snow events, the magnitude of instability may be underestimated by this proxy.

These criteria were applied to all times and points in the model data set; when a point in the domain at a certain time met all of these criteria, that point was considered favorable for lake-effect snow. For the analysis of favorable lake-effect conditions and associated snowfall, a time step was classified as favorable if at least one grid point within the domain satisfied all of the criteria. These favorable lake-effect times were then used to compare various aspects of lake-effect snowfalls between the periods of study. Different favorable grid point thresholds were tested to examine sensitivity, with the results remaining qualitatively the same (not shown).

After evaluating the goodness of fit of several continuous probability distributions, we found that a gamma function best fit the distributions of lake-effect snowfalls from the simulation output. Gamma distribution parameters (shape and scale) were estimated at each grid point for all three periods using the method of moments. To quantify statistically significant changes in higher-end 6-hourly lake-effect snowfall accumulations between periods, we performed a two-sample Kolmogorov-Smirnov test at each grid point. This test compared 1,000 synthetic samples generated from the fitted gamma distributions of each period pair, with significance determined at the 95% confidence level ($p < 0.05$). Changes in other distribution statistics, such as the 90th, 95th, and 99th percentile, were examined as well.

To quantify statistically significant changes in the average 6-hourly snowfall accumulation during all times as well as during favorable lake-effect times, a bootstrapping approach was applied with 700 and 1,000 iterations, respectively. In this approach, the data from either the historical and mid-century periods or mid-century and EOC periods are combined, and two randomly sampled data sets are selected from the combined data with the same length of the original data sets for each respective period. From each group, the average 6-hourly snowfall accumulation difference between the two groups is calculated. The resulting differences were used to construct a distribution and compared with the average difference from the original data. If the actual difference is outside the 99th percentile of all randomly sampled differences, then it was considered statistically significant (Efron & Tibshirani, 1994).

In order to further examine lake-effect snow changes across events (e.g., event total accumulation and duration) and not exclusively 6-hourly snowfall accumulation (our proxy for intensity) changes, continuous lake-effect snow events were also examined. For the analysis of continuous lake-effect snow events, we applied a more restrictive threshold to the previously identified favorable times, requiring at least 250 grid points within the domain to satisfy all of the favorable lake-effect conditions at a given time step. Consecutive time steps meeting this threshold were grouped into a classified lake-effect snow event, which ended when the number of grid points

satisfying the favorable conditions fell below 250. The duration (start and end time) of each classified event and the total snowfall at each point in the domain were then recorded to perform the subsequent analysis.

3. Model Evaluation of Important Lake-Effect Conditions

Gensini et al. (2023) evaluated the historical simulations against the Parameter-elevation Regressions on Independent Slopes Model (PRISM) data set. They found strong agreement in daily mean 2-m temperature across the CONUS, with a modest cold bias over the Great Lakes region during DJF. Although small, such a cold bias during the core winter months may potentially lead to different ice cover conditions over the Great Lakes and therefore impact lake-effect conditions. Annual precipitation biases were small over the Great Lakes, although the simulations exhibited a regional wet bias during DJF and little bias during SON and MAM. Because lake-effect snowfall is also strongly influenced by the low-level wind field, we additionally evaluated the simulated 10-m and 850-hPa winds against those obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) fifth-generation reanalysis (ERA5) (Hersbach et al., 2023).

Historical winds from 1990 to 2005 were sampled at 10 locations (2 for each lake) prone to lake-effect snow, using the model grid point nearest each site. We then compared the downscaled winds to those obtained from ERA5, with the model and ERA5 winds evaluated seasonally for SON, DJF, and MAM using wind roses and seasonal mean wind speeds. We examined 10-m winds because they influence near-surface convergence and lake–land circulations, and 850-hPa winds because they commonly govern the orientation and movement of lake-effect snow bands (Niziol, 1987; Niziol et al., 1995). The resulting comparisons are shown in Figures S7–S18 in Supporting Information S1.

At 10 m, the simulations generally reproduce the dominant seasonal wind regimes but exhibit more concentrated directional distributions than ERA5 at several sites, particularly from southerly or southwesterly directions at Watertown, Buffalo, and Traverse City (Figures S7–S12 in Supporting Information S1). Simulated mean wind speeds are also lower than ERA5 at many sites, especially during SON and DJF, although the magnitude and sign of the bias vary by location; similar slow wind speed biases were also reported by Collins et al. (2024a, 2024b) for wintertime simulations using the WRF Model. Across the 10 sites, the average biases (model minus ERA5) in seasonal mean 10-m wind speed are approximately −0.5, −0.5, and −0.2 m s^{-1} during SON, DJF, and MAM, respectively. This slow wind speed bias may underrepresent near-surface convergence, which may in turn impact convergence zones and low-level updrafts in some lake-effect events. Agreement is substantially better at 850 hPa (Figures S13–S18 in Supporting Information S1), where the model closely reproduces both the predominantly westerly-to-southwesterly flow and the seasonal mean wind speeds. The corresponding mean wind-speed differences at 850 hPa are approximately 0.0, 0.4, and 0.0 m s^{-1}. A modest tendency toward more frequent southwesterly flow remains at some sites, potentially influencing the fetch over the Great Lakes and associated downwind snowfall regions. Overall, the simulations represent the 850-hPa wind field relevant to lake-effect band orientation well, whereas greater uncertainty is associated with the near-surface winds and related convergence.

4. Results

4.1. Changes in Total Snowfall and 6-Hourly Accumulations

The domain of interest in this study is shown in Figure 1, which encompasses the five Laurentian Great Lakes. In addition to domain-wide analyses, we selected 2 sites for each lake in areas prone to lake-effect snow for site-specific analyses, and these 10 sites are also shown. The snowfall accumulations corresponding to specific percentiles of 6-hourly snowfall are shown for each site and for each study period.

For locations downwind of Lake Superior and Lake Huron (shown by the top row in Figure 1), a statistically significant increase in the top decile of 6-hourly snowfall accumulations is projected in the EOC period compared to the mid-century period. Smaller and non-significant increases are also seen between the historical and mid-century period. The increase is shown to be the greatest for the Owen Sound and Midland sites located east of Lake Huron (Figures 1d and 1e), with the 95th and 99th percentile 6-hourly snowfall accumulations at Owen Sound increasing by nearly 15 and 40 mm, respectively, by EOC. Other sites, such as Buffalo downwind of Lake Erie (Figure 1h) and Watertown and Oswego east of Lake Ontario (Figures 1k and 1i), have projected increases in higher percentile snowfall accumulations by mid-century, before decreasing to near historical amounts by EOC. Many of the sites along the other lakes are projected to have much less or no difference in the 6-hourly snowfall

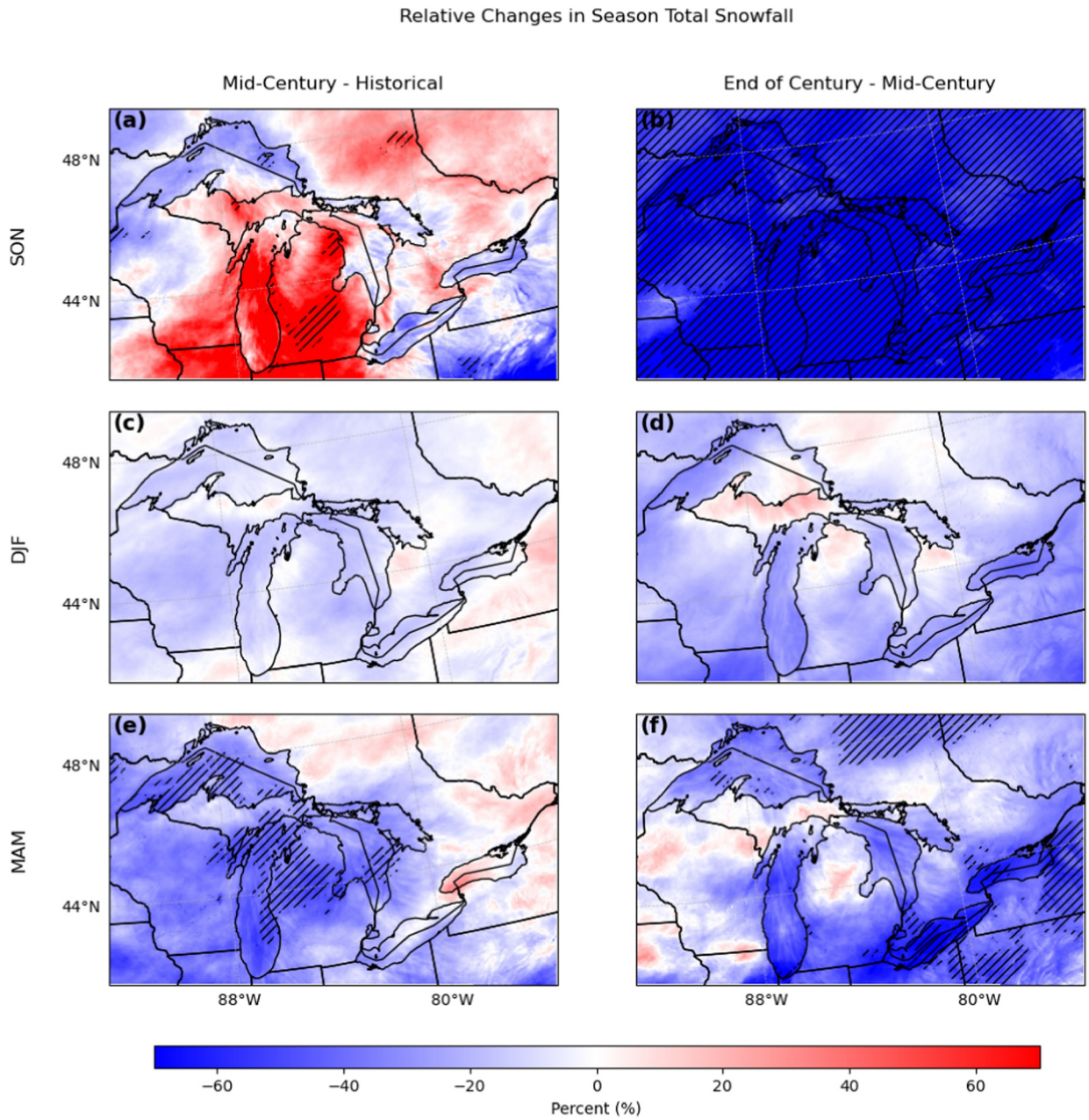

Figure 2. Spatial distribution of relative changes in the seasonal average snowfall totals between the mid-century and historical periods for (a) SON, (c) DJF, and (e) MAM and between the EOC and mid-century periods for (b) SON, (d) DJF, and (f) MAM (units: %). Hatching signifies significant changes at the 95% confidence level using the bootstrapping approach summarized in Section 2.

accumulations at the highest percentiles between each of the periods. This indicates that locally along the northern lakes (Superior and Huron), higher-end snowfall events are expected to become more intense in the future under a warming climate by EOC, while locally over the eastern lakes (Erie and Ontario) more intense snowfall may be seen briefly in the mid-century before losing intensity with increased warming by EOC. This analysis indicates that the response of snowfall in the Great Lakes region to climate warming is non-linear and location specific, which motivates further investigation into these responses in the context of lake-effect snow.

Figure 2 shows the spatial distribution of relative changes in the seasonal average snowfall totals for the fall (September, October, and November; SON), winter (December, January, and February; DJF), and spring (March, April, and May; MAM) seasons between each of the periods. From the historical period to the mid-century for

SON, widespread relative increases in snowfall totals are projected across the central portion of the domain oriented from southwest to northeast (Figure 2a) with some significant relative increases in central Michigan. This likely is not related to changes in lake-effect snow itself but instead to changes in the mid-latitude storm track and synoptic events in a warming world due to the widespread nature of the changes (see Chang et al. (2012), Eichler et al. (2013), and Hutson et al. (2024) discussed below in more detail). Between the mid-century and EOC, widespread and statistically significant relative decreases in SON season-total snowfall can be seen, with magnitudes of 50% or greater in most areas by EOC (Figure 2b). Areas downwind of Lake Superior in Michigan show less of a decrease in total snowfall, which could be an indicator of enhanced lake-effect snow offsetting the general decrease in snowfall by EOC. These signals motivate the idea of H2 (lake-effect snow becoming less common and shifting more to the core winter season) and will be explored further later on.

In DJF, small and non-significant relative decreases in season total snowfall are seen across the domain from the historical period to the mid-century period, with some minor increases in the lake-effect snow belts downwind of Lake Superior, Lake Huron, and Lake Ontario (Figure 2c). Similarly, DJF seasonal snowfall totals are projected to increase in prominent lake-effect regions downwind of Lake Superior, Huron, and Michigan by EOC, while the rest of the domain experiences decreases (Figure 2d). This motivates further investigation into the contribution of lake-effect snowfall to the projected changes in cold-season snowfall totals.

For MAM, relative increases in seasonal snowfall totals are projected sporadically over eastern parts of the Great Lakes region. Elsewhere, decreases (some significant) between the historical period and the mid-century period (Figure 2e) are shown, with any relative increases instead found over the western portion of the region between mid-century and EOC (Figure 2f). Similarly to the EOC relative changes in SON some regions downwind of Lake Superior and Lake Huron show muted relative decreases to almost no relative changes in snowfall totals during MAM, again indicating possible contributions from enhanced lake-effect snowfall (Figure 2f).

It is apparent from the changes displayed in Figure 2 that seasonal snowfall totals in general across the Great Lakes region are expected to undergo a temporal shift in the future, with lower snowfall totals in the transition seasons of SON and MAM and a signal for increased lake-effect snow in DJF by EOC. This is consistent with the effects of climate warming, as the period of time each year in which it is cold enough for snow is expected to decrease; temperatures low enough for frozen precipitation would be more confined to the coldest months of the year (Hartnett et al., 2014; Kayastha et al., 2024; Krasting et al., 2013). Snowfall total changes can also be seen spatially with the lake-effect snow belts downwind of Lakes Superior, Huron, and Michigan exhibiting lesser snowfall decreases in SON and MAM and even an increase in snowfall during DJF. Based on these results, it can be inferred that seasonal snowfall totals from synoptic systems in the Great Lakes region may increase briefly in the mid-century before decreasing toward the end of the century in a warming climate while lake-effect snowfall totals may increase downwind of some of the lakes at different points of the century.

4.2. Changes in Lake-Effect Conditions and Associated Snowfall

The preceding analysis indicates that seasonal snowfall totals across the Great Lakes region may respond to global climate change differently, varying by the time of year (season) and geographic location (lake). However, what remains unclear is what causes these changes within the lake-effect snow belts and if they are related to changes in lake-effect snow itself or changes in other factors. Therefore, we turn our attention to changes in the conditions favorable for lake-effect snow, starting with changes from the historical period to the mid-century period, which are shown in Figure 3. By mid-century, 2-m temperatures between −10 and 0°C become marginally less frequent (Figure 3a), as expected with climate warming. This decrease in favorable 2-m temperature occurrences is even more pronounced over the lakes themselves, with larger decreases found over much of Lakes Superior and Michigan. The decreases in the occurrence of below-freezing temperatures seem to contradict some of the regional increases in snowfall totals by mid-century shown in Figures 2a and 2c during SON and DJF. The larger decreases in seasonal snowfall totals over some portions of the Great Lakes region (Figures 2a, 2c, and 2e) may be associated with changes in atmospheric temperature, precipitation phase, and synoptic-scale conditions as the climate warms (Kayastha et al., 2024). Slight increases in the number of instability events favorable for lake-effect snow (temperature differential between 2-m and 850 hPa exceeding 10°C) by mid-century are found over Lake Ontario, Lake Huron, and most of Lake Superior, as shown in Figure 3b. As lake-surface temperatures and 2-m temperatures increase with more frequent ice-free portions of the lakes (Cannon et al., 2024; Mason et al., 2016), and if no or lesser changes in the 850-hPa temperatures are observed, ample instability would then be

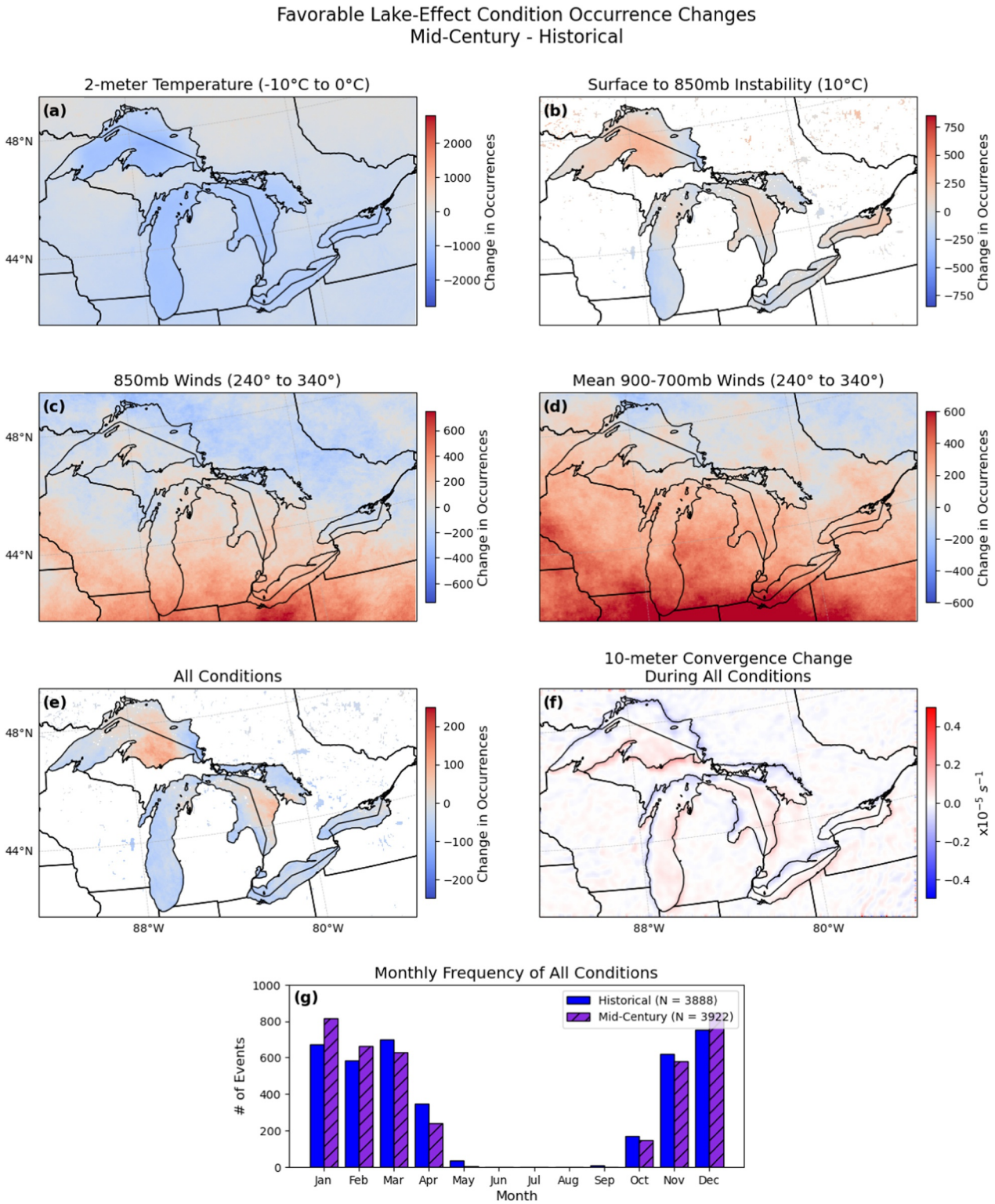

Figure 3. Spatial distribution of the changes (mid-century minus historical) in the number of occurrences of each favorable lake-effect snow criterion being met as well as the change in average 10-m convergence during favorable lake-effect times. Panel g shows a monthly occurrence histogram of times when all conditions are met with the 10°C instability criterion for the mid-century and historical periods in purple (hatched) and blue, respectively.

present more often for lake-effect convection to initiate over portions of the lakes (Laurinaitis, 2025). Elsewhere, Lake Erie shows small decreases to nearly no change in the occurrences of favorable instability, while northern Lake Michigan exhibits small increases and southern Lake Michigan exhibits small decreases.

Regarding favorable boundary layer wind directions for lake-effect snow, increases in the occurrences of favorable winds (wind speed ≥6 m/s and direction between 240° and 340°) are projected across southern portions of the domain with small decreases found in the northern part of the region (Figures 3c and 3d). These changes are likely due to changes in overall synoptic flow regimes between periods as well as changes in the storm track as the climate warms examined in previous research (Chang et al., 2012; Eichler et al., 2013; Hutson et al., 2024), which may impact the frequency of favorable zonal winds for lake-effect snow.

Combining all the conditions together (Figure 3e), a spatial pattern similar to that of the instability changes is seen but with key differences. By mid-century, the occurrences of all conditions being met are projected to increase only over eastern parts of Lake Huron and central portions of Lake Superior. Elsewhere, the number of occurrences generally decreases slightly. Given some spatial consistency between changes in the occurrence of unstable conditions and the number of instances where all lake-effect snow conditions are met, this suggests that the change in the frequency of favorable instability for lake-effect snow is the main driver of the change in favorable lake-effect condition occurrences across the Great Lakes region in a warming climate. It should be noted that other criteria seemingly still have some influence in this time period, such as the decreases in the occurrence of favorable 2-m temperatures between −10 and 0°C over the lake waters.

In addition to the increase in the occurrence of favorable instability over some of the northern lakes by mid-century, 10-m winds are also found to converge more on the downwind shores of each lake during favorable lake-effect times in the mid-century period (Figure 3f). These areas of increased convergence, while small in the magnitude of their changes, also extend over the water in the eastern portions of Lake Superior and Lake Huron. Increased convergence near the surface could serve to form stronger updrafts and more confined precipitation regions in lake-effect storms, supporting heavier snowfall rates within these lake-effect snow bands.

Finally, the monthly frequency of all conditions being met is shown to increase slightly overall by mid-century in Figure 3g. Despite this overall increase in occurrences, the changes depend on the season. For example, the number of events in the DJF season increases by mid-century, while the number decreases slightly in the transition seasons (SON and MAM). As shown previously in Figure 3e, the increases in the frequency of all conditions are location dependent, and within these areas, the increases in frequency likely also have seasonal dependencies. This again highlights the temporal shift in snowfall across the Great Lakes region, with favorable lake-effect conditions starting to become more confined to the climatologically coldest months of the year and increasing in number. As such, lake-effect snowfall is projected to begin to transition from a bimodal temporal distribution with peaks in late fall and late winter to a unimodal distribution with a peak in the core of the winter season.

While examining the possible changes in favorable lake-effect conditions between the historical period and mid-century is important, it does not address lake-effect snow changes throughout the entire 21st century, as well as whether the changes are linear or non-linear. To address this, changes in the conditions favorable for lake-effect snow between the mid-century and EOC periods are shown in Figure 4. Similar to the changes between the historical and mid-century periods, a domain-wide decrease in the occurrence of favorable 2-m temperatures is found by EOC (Figure 4a), with larger magnitudes than those found by mid-century, suggesting a non-linear response over the 21st century. Once again, these decreases are greater over the lakes themselves where increased climate warming is likely reducing ice cover and increasing lake temperatures (Cannon et al., 2024; Mason et al., 2016).

With increasing lake temperatures and reduced ice cover expected by EOC, widespread increases in the number of occurrences of favorable instability are projected over Lake Michigan, Lake Huron, and especially Lake Superior, which exhibits the largest increases (Figure 4b). Lake Erie exhibits little change in instability occurrences once again by EOC, while Lake Ontario shows slight lake-wide decreases in instability occurrence counts. These results are thought to be influenced by greater warming of the western Great Lakes between mid-century and EOC than those found in Lake Ontario and Lake Erie, which has been projected in previous studies such as Mason et al. (2016) and Cannon et al. (2024). The occurrence of favorable boundary-layer winds (wind speed ≥6 m s^{-1} and direction between 240° and 340°) generally decreases across the Great Lakes region between the mid-century

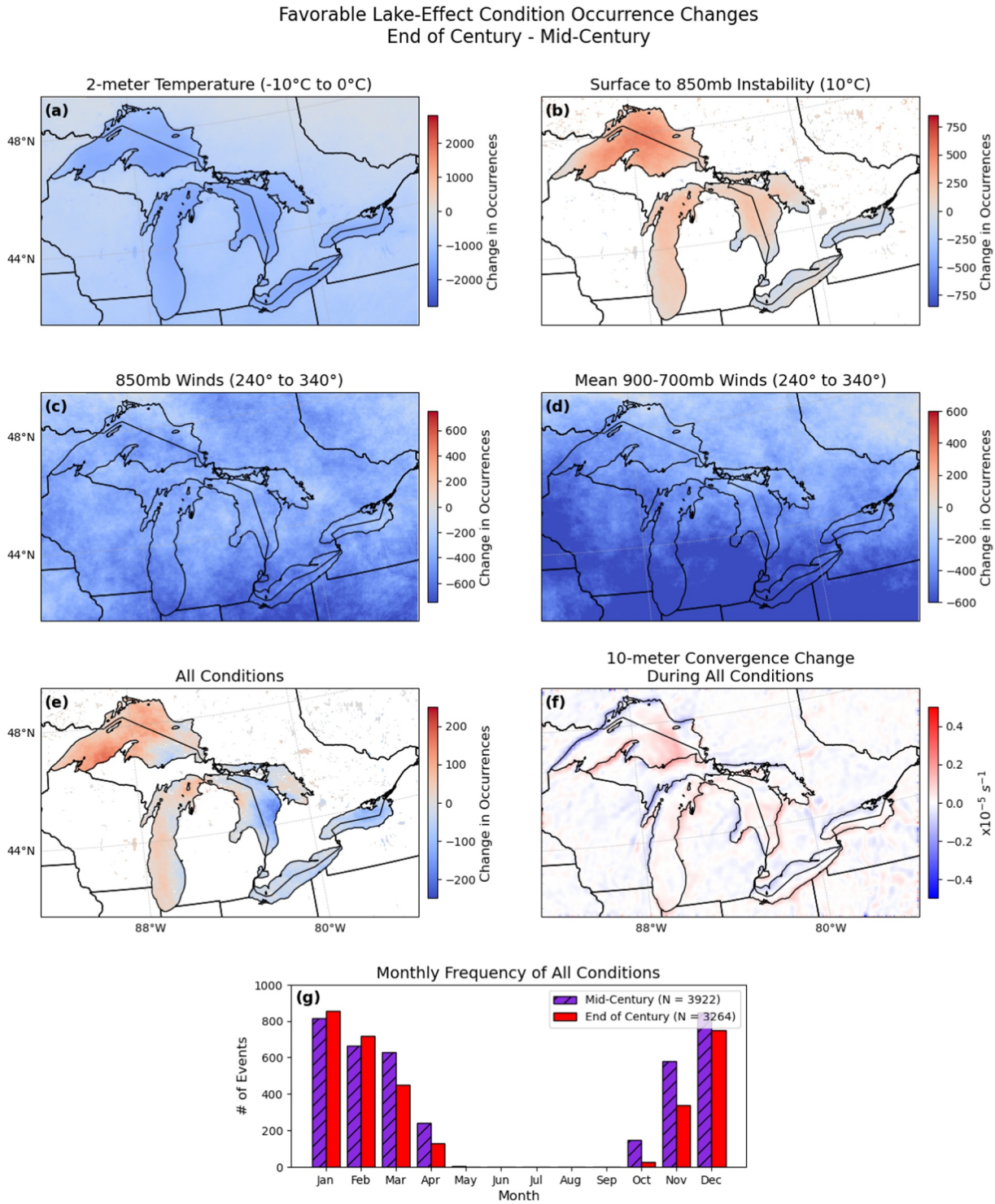

Figure 4. As in Figure 3 except for EOC minus mid-century.

and EOC periods (Figures 4c and 4d). This contrasts with the historical-to-mid-century changes, which exhibit increases across the southern portion of the domain and smaller decreases farther north. The largest decreases are found toward the southern portion of the region, potentially reflecting changes in synoptic flow regimes and storm tracks by EOC, including greater boundary-layer wind shear and more frequent meridional flow (Chang et al., 2012; Eichler et al., 2013; Hutson et al., 2024).

When examining the changes in the occurrences of all favorable conditions together between mid-century and EOC (Figure 4e), other important differences from those seen between the historical and mid-century periods are present. Eastern Lake Huron is projected to see decreases in the number of favorable lake-effect occurrences, while this area was projected to see increases between the previous two periods (Figure 3e). The area of increases that was seen previously over Lake Superior now exhibits smaller increases as well as some small decreases. Elsewhere, much of Lake Michigan is projected to experience small increases in the occurrences of all favorable conditions together with most of Lake Superior seeing increases except for the central section of the lake. Lake Erie and Lake Ontario both exhibit decreases in the occurrences of favorable conditions. Given that the only increases in the occurrence of individual favorable conditions are found in the favorable instability criterion (Figure 4b) and these increases are co-located with the increases in all favorable conditions together, the instability criterion is also likely the main driver in the changes of favorable lake-effect conditions between mid-century and EOC. Furthermore, the surface temperature changes between mid-century and EOC are larger than those found between the historical period and mid-century (not shown). This non-linear increase in temperatures matches the projections found in Pörtner et al. (2019). A non-linear increase would cause greater decreases in the occurrences of below freezing temperatures between mid-century and EOC and thus more frequent favorable instability by EOC compared to those seen by mid-century.

During the favorable lake-effect times in the EOC period, the 10-m winds are again projected to converge more on the downwind shores of each of the lakes compared to favorable times in the mid-century period (Figure 4f). Over Lake Superior, the convergence is projected to increase more by EOC than was projected between the historical and mid-century periods. Convergence increases are now also located over the lake waters and in a prominent region for lake-effect snow bands on north-northwesterly flow. Further convergence increases beyond those projected between the historical and mid-century periods may allow for more intense and more confined updrafts within lake-effect snow bands by EOC compared to those found by the mid-century.

The monthly frequency of favorable lake-effect conditions continues to shift toward the core winter season between the mid-century and EOC periods (Figure 4g). By EOC, the overall number of occurrences of all favorable conditions together is also projected to decrease by approximately 15%, a change from the slight increase in overall occurrences that was seen earlier between the historical and mid-century periods.

Another question that remains is how robust these changes in potential 6-hourly lake-effect snowfall accumulations are spatially. To address this, spatial distributions of changes in high-percentile snowfall accumulation levels are shown in Figure 5, which can be used to determine where the 6-hourly snowfall accumulations are becoming more or less intense between the periods of interest during favorable lake-effect times. All percentiles examined here show similar spatial patterns of change across the Great Lakes region during their respective periods of change. Between the historical and mid-century periods, increases in high-percentile 6-hourly snowfall accumulation thresholds are seen across the eastern half of the region with some increases in parts of Wisconsin and the Upper Peninsula of Michigan. Elsewhere, decreases or little-to-no changes in 6-hourly snowfall accumulation thresholds are projected across the percentiles of 6-hourly snowfall accumulations (Figures 5a, 5c, and 5e). Some of these increases are located in well known lake-effect snow belts and are larger in magnitude compared to other nearby changes. Specifically, increases in the top 1% snowfall accumulation thresholds in Figure 5e are projected in the Upper Peninsula of Michigan and the eastern parts of Lakes Erie and Ontario. Over Lake Erie, for example, the top 1% of 6-hourly favorable lake-effect snowfall accumulations are projected to increase by about 40 mm (1.57 in) by mid-century. These increases correspond with those found in the 6-hourly snowfall accumulation thresholds shown previously at sites to the east of Lake Erie and Lake Ontario between the historical and mid-century periods in Figure 1.

When examining changes in snowfall thresholds during favorable lake-effect times between mid-century and EOC, increases in 6-hourly snowfall accumulation thresholds are found across much of the north and western parts of the Great Lakes region (Figures 5b, 5d, and 5f). Over the southern and eastern portions of the region, decreases in these high-end 6-hourly snowfall accumulation thresholds are projected in contrast to the increases that were previously projected between historical and mid-century. The largest increases by EOC are relatively confined and show the spatial footprint of heavier lake-effect bands across the region, such as downwind of Lake Superior, Lake Huron, and over Lake Michigan. The top 1% of favorable 6-hourly lake-effect snowfall accumulations are projected to increase by 50 mm (1.97 in) or more southeast of Lake Superior with similar magnitudes east of Lake Huron (Figure 5f), and heavily resemble banded lake-effect precipitation. This is a much

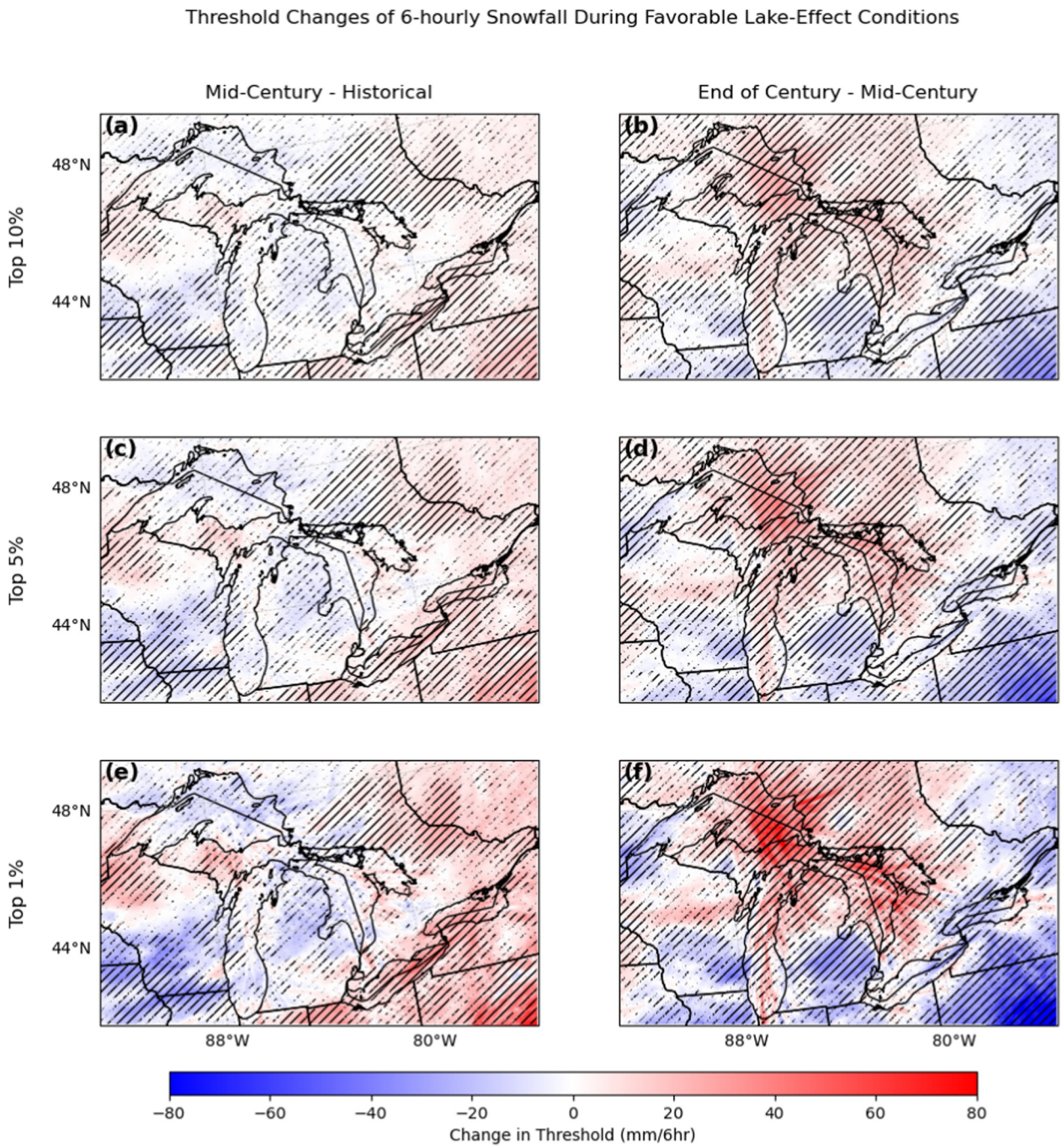

Figure 5. Spatial distribution of historical to mid-century (left column) and mid-century to EOC (right column) changes in the top 10%, 5%, and 1% 6-hourly snowfall accumulations during favorable lake-effect conditions with the 10°C instability criterion. The change in the 6-hourly snowfall accumulation corresponding to each percentile is shown in mm. Hatching indicates statistically significant differences in the snowfall accumulation distributions between periods at the 95% confidence level using the Kolmogorov-Smirnov test summarized in Section 2.

larger change in extreme 6-hourly snowfall accumulations (our proxy for intensity) than those seen between the historical and mid-century periods (shown in Figure 5e), where little-to-no increases were projected. Once again, these results are similar to the percentile changes shown previously at the Lake Superior and Lake Huron sites for all 6-hourly snowfall accumulations by EOC (Figure 1).

As such, these results again indicate an increase in the 6-hourly accumulations and by proxy intensity of future high-end snowfall events, and the results are generally broadly applicable over large areas of each lake, not just

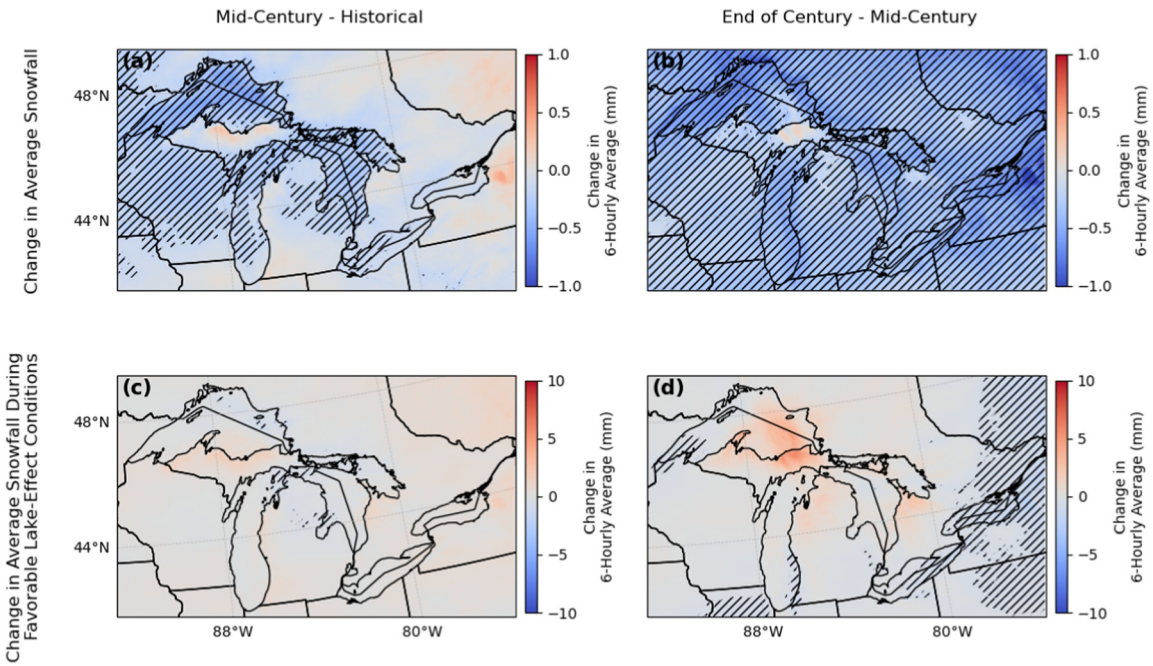

Figure 6. Changes in average 6-hourly snowfall accumulations for all snowfall periods (top) and periods with favorable lake-effect conditions based on the 10°C instability criterion (bottom), between the historical and mid-century periods (left) and the mid-century and EOC periods (right). Hatching signifies significant changes at the 99% confidence level using the bootstrapping approach summarized in Section 2.

individual sites. However, these changes in 6-hourly accumulations are not uniform across the lakes, with Lake Erie and Lake Ontario projected to experience smaller changes than other lakes. Furthermore, the changes are also projected to be nonuniform throughout the century, with smaller increases in high-end 6-hourly lake-effect snowfall accumulations projected downwind of the eastern lakes by mid-century before these increases then shift to downwind of the northern lakes by EOC. Combined with the total seasonal snowfall changes between periods discussed earlier (Figure 2), this northward shift in 6-hourly lake-effect snowfall accumulations indicates that lake-effect snow totals across the northern lakes are expected to increase in magnitude and intensity in a warming climate by EOC. These findings suggest that the projected increases in seasonal snowfall totals in these regions are driven, at least in part, by more intense lake-effect snowfall.

Figure 6 compares the spatial distributions of changes in the average 6-hourly snowfall accumulations for all snowfall events (Figures 6a and 6b) and only favorable lake-effect events with 10°C instability (Figures 6c and 6d) between the different periods. When all occurrences of snowfall are included, significant decreases in the average 6-hourly snowfall accumulation between the historical and mid-century period are seen over the western lakes and far western parts of the domain in Figure 6a. Some increases in average 6-hourly snowfall accumulation can be seen along the northern coast of the Upper Peninsula of Michigan, with significant increases also projected over the Tug Hill Plateau downwind of Lake Ontario, both regions known for lake-effect snowfall. Elsewhere, little or no change in average 6-hourly snowfall accumulations is found when all snowfall is considered.

When only favorable lake-effect snow times in the historical and mid-century periods are examined (Figure 6c), most of the domain shows negligible changes in the intensity of average 6-hourly lake-effect snowfall accumulations. However, some small increases in average snowfall accumulations are projected downwind of Lake Superior and Lake Ontario. These are the same regions in which increases or maintained magnitudes in the overall average snowfall accumulations were projected between these periods in Figure 6a. Other small increases are projected east of Lake Michigan and Lake Huron as well. The co-location of these increases between average 6-hourly snowfall accumulations and accumulations only during favorable lake-effect times supports the idea that the increase in lake-effect snow totals by mid-century is robust, and that 6-hourly snowfall accumulation increases are likely due to 6-hourly lake-effect snowfall accumulation (or intensity) increases.

Moving later into the century between the mid-century and EOC periods, a near domain-wide significant decrease in the 6-hourly average snowfall accumulation is seen, with large decreases over much of Lake Superior and New York by EOC (Figure 6b). This widespread decrease may reflect the effects of warmer atmospheric temperatures on precipitation phase, which is a topic of future study, as well as changes in synoptic-scale precipitation. Despite this, there are some locations along the Upper Peninsula of Michigan and downwind of Lake Huron south of the Georgian Bay where the average 6-hourly snowfall accumulation stays roughly the same, has non-significant and small decreases, or even increases by EOC (Figure 6b). To the south of Lake Superior, this increase in average 6-hourly snowfall accumulation is more clearly seen. This shows that even when all snowfall events (e.g., synoptic, lake-effect, and lake-enhanced) are included in the analysis, a signal of increased snowfall accumulations in some areas prone to lake-effect snow remains.

Comparing between mid-century and EOC favorable lake-effect snow conditions, a similar spatial pattern of average 6-hourly snowfall accumulation increases to those found in Figure 6c is present. Increases are seen over more of the Upper Peninsula, south of the Georgian Bay, and over eastern Lake Superior itself (Figure 6d). Some increases in average 6-hourly snowfall accumulations are also seen in the snow belts east of Lake Michigan, although at a lesser magnitude. Significant but small decreases in average snowfall accumulations are projected over Lake Erie, Lake Ontario, and much of the far eastern part of the domain. Elsewhere across the domain, the changes in 6-hourly average snowfall accumulations are small and not significant, with no large decreases in snowfall accumulations found anywhere (Figure 6d). From this analysis, it can be seen that 6-hourly lake-effect snowfall accumulations are expected to maintain similar magnitude in a warming climate across most of the Great Lakes region, with several regions experiencing an increase in 6-hourly snowfall accumulations or intensity. Factors leading to this include increases in instability in these regions as well as low-level convergence near the shorelines of these lake-effect-prone regions, as previously shown in Figures 3 and 4.

4.3. Changes in Lake-Effect Snow Events

Thus far, we have examined projected changes in the atmospheric conditions favorable for lake-effect snowfall, including 2-m temperature, 850-hPa wind direction, 900–700-hPa wind shear, and low-level instability. We have also identified increases in average 6-hourly lake-effect snowfall accumulations in some regions of the Great Lakes. However, lake-effect snow events can persist for much longer than 6 hr, sometimes lasting several days. Therefore, we now examine how the characteristics of entire lake-effect snow events are projected to change in a warming climate.

The first results of this analysis present the changes in the occurrences of and the average event total snowfall of classified events across the domain (Figure 7). The change in the occurrences of lake-effect snow events between the historical and mid-century periods is shown in Figure 7a, with small increases in the number of events across much of the domain. Although these occurrence increases are not strictly in prominent lake-effect snow regions, Figure 7b shows projections that the average event total snowfall for classified events increases slightly in lake-effect snow belts downwind of Lake Superior, Lake Huron, and Lake Ontario. Across the rest of the domain, the average event total snowfall does not appear to change.

For the classified event changes between mid-century and EOC, a decrease in the number of events is projected domain wide (Figure 7c). A larger magnitude of decreases is present over portions of the eastern lakes, such as Lake Ontario and Lake Erie. However, Figure 7d shows that even though the number of lake-effect snow events is expected to decrease, the average event total snowfall over certain areas, especially lake-effect-prone areas downwind of Lake Superior, Lake Huron, and Lake Michigan, increases by EOC, with little to no change across the rest of the domain. In parts of the Upper Peninsula of Michigan, the average event total snowfall is found to increase by 40–50 mm (1.57–1.97 in) by EOC. This is consistent with the locations showing an increase in average 6-hourly lake-effect snowfall accumulations between mid-century and EOC shown in Figure 6.

Figures 8a–8c show violin plots of the domain-wide distribution of the average event total snowfall per season (season-year is defined as the year of the JFM months in a given winter season, where a winter season contains events from October to May) for the historical, mid-century, and EOC periods, respectively. The number of classified events per season is also presented for each period. Here, little to no change in the number of classified lake-effect snow events (shown by the black diamonds) per season between the historical and mid-century periods is present, with an average of 32.5 events per season in the historical period and 31.6 events per season in the mid-century period. Between the mid-century and EOC periods, the number of classified events per season decreases,

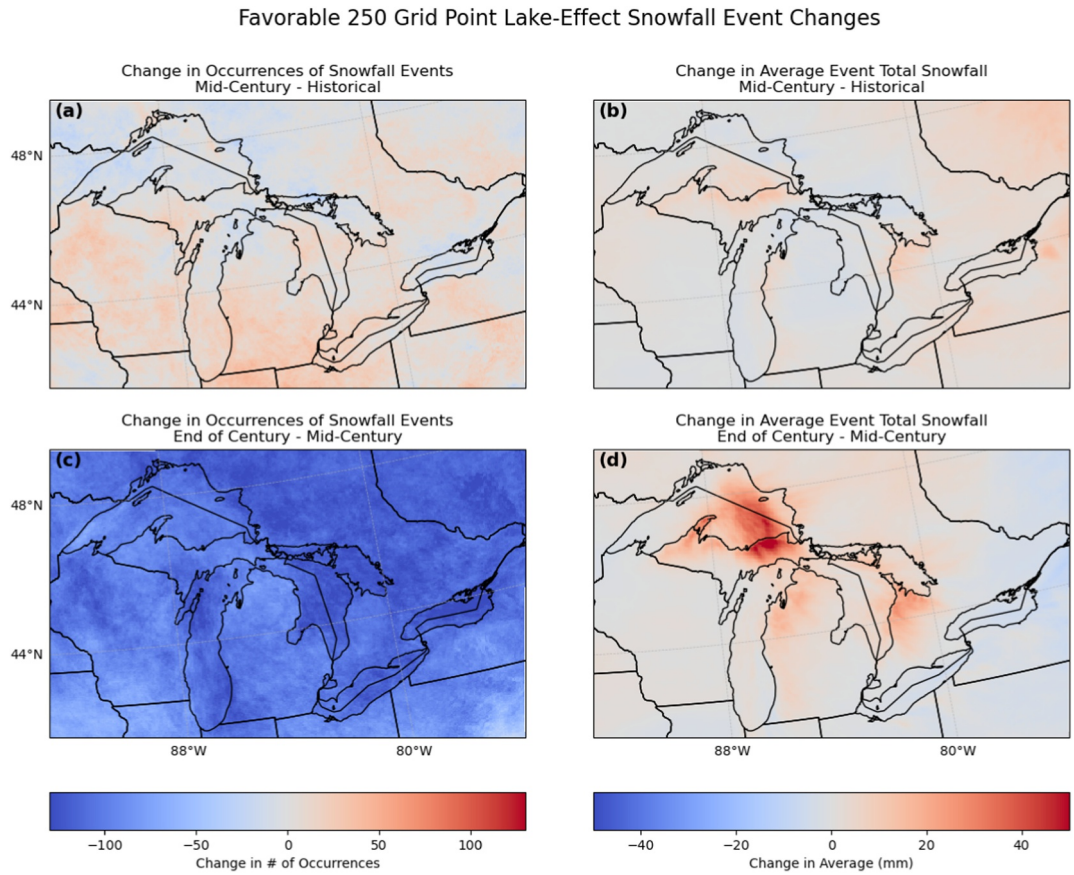

Figure 7. Changes in the occurrences of (left column) and the average event total snowfall (right column) between periods for classified favorable 10°C instability lake-effect events.

with an average of 24.6 events per season by EOC and many seasons from 2086 to 2095 having only around 20 classified events. The spread in the average event total snowfall distributions remains roughly constant between the historical and mid-century periods based on the interquartile ranges of the distributions for most seasons. However, by EOC, this spread then increases with wider interquartile ranges and much more extreme outliers compared to the previous periods.

Comparisons of the distributions of the classified lake-effect snow event durations between the historical and mid-century periods and between the mid-century and EOC periods are presented in Figures 8d and 8e, respectively. Between the historical and mid-century periods, the total number of classified events is approximately the same. The two duration distributions are found to be significantly different at the 95% confidence level, with the 90th percentile duration decreasing by 6 hr by mid-century, indicating a slight shortening of lake-effect snow event durations. When comparing the mid-century and EOC duration distributions, a decrease in the total number of classified lake-effect snow events is found by EOC. Within the EOC period, a slight skew in the distribution toward longer-duration events can be seen compared to the mid-century distribution. However, the distributions are not significantly different at the 90 or 95% significance levels.

The distribution of average event total snowfalls over the entirety of each period is shown in Figure 8f. Here, a similar result to that seen in the seasonal average event total snowfall distributions is present. As the century progresses, higher average event total snowfalls are projected, especially in the EOC period, with the tail of the distribution much further spread than in the historical and mid-century periods. In this period, the average event snowfall totals are upward of 150 mm (5.91 in) as seen by the upper tail of the EOC violin plot. Greater spread in the inter-quartile ranges of the distributions is also seen as the century progresses.

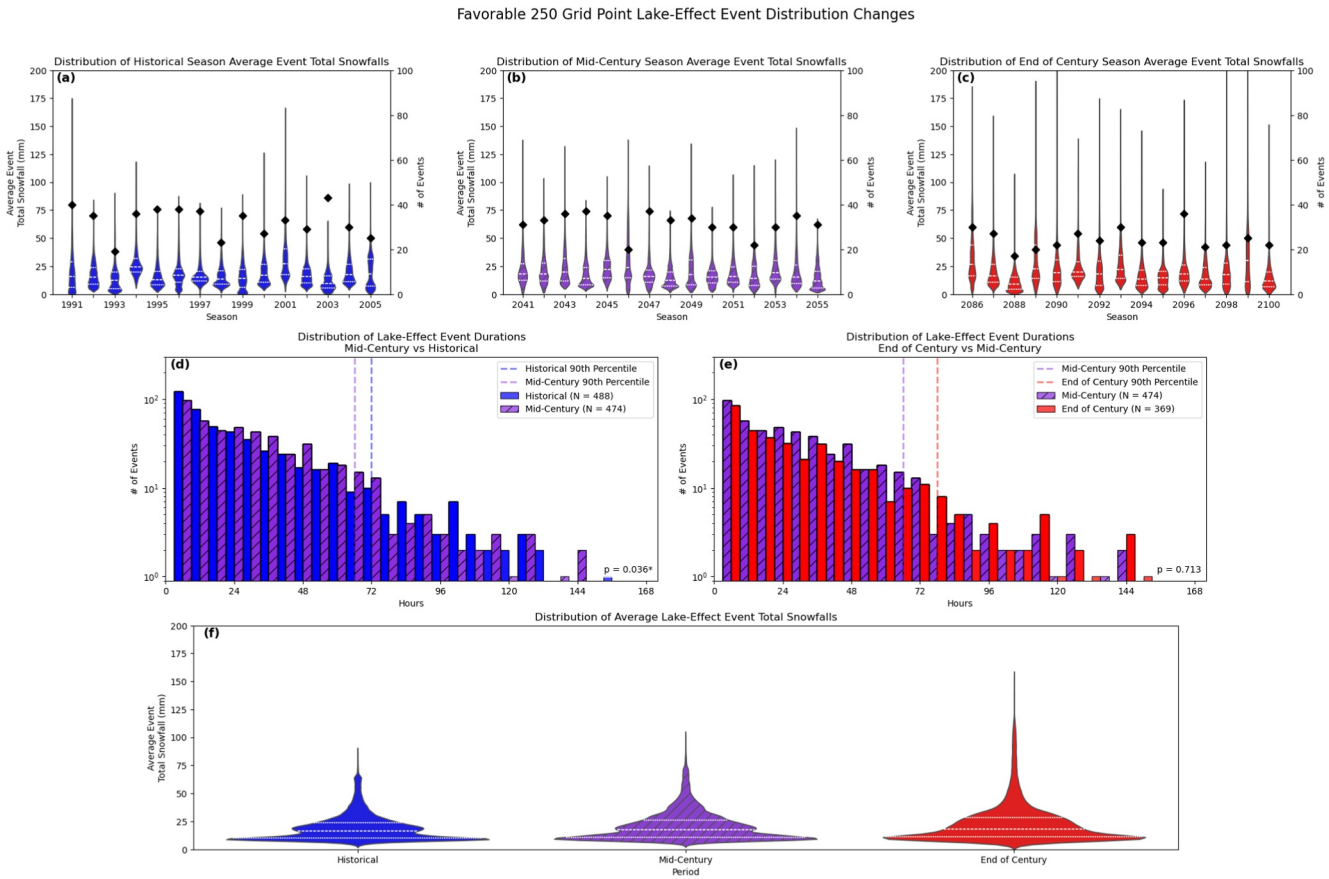

Figure 8. The distribution of the average classified favorable 10°C instability lake-effect event total snowfalls over the domain in each winter season as well as the number of classified events per season (diamonds) is shown for the (a) historical, (b) mid-century, and (c) EOC periods as violin plots. The distribution of the durations of the classified lake-effect events for mid-century and historical as well as EOC and mid-century are shown in panels (d) and (e), respectively, with the resulting p-value from a 2-sample Kolmogorov-Smirnov test for significant changes in the distributions in the bottom right of each panel. One (two) star(s) next to the p-value represent significance at the 95% (99%) confidence level. The distribution of average event total snowfalls over each entire period is shown in panel (f) as a violin plot. White dashed lines in the distributions show the quartiles of each distribution.

The results from this analysis indicate that with a warming climate, lake-effect snow event frequency may remain roughly the same by mid-century, before fewer lake-effect snow events occur overall across the Great Lakes region by EOC. However, these events are projected to either remain the same in 6-hourly snowfall accumulations or increase in 6-hourly accumulations in different regions of the Great Lakes depending on the time period of interest. Lake-effect snowfall events may also become more variable spatially and may slightly decrease in duration toward mid-century before increasing in duration once more by EOC, all of which changes the localized impacts of these snow events in a warming climate.

5. Sensitivity to Instability Threshold

Our analysis focused on a 10°C instability threshold for determining lake-effect conditions. Typically, 13°C is used for this threshold, but owing to the lack of lake-surface temperature data in the downscaling data set and our reliance on 2-m temperatures as a proxy, we adjusted the threshold to 10°C to account for the fact that the 2-m temperatures are generally a few degrees colder than the actual lake water during lake-effect events (Niziol, 1987; Niziol et al., 1995). However, to test the sensitivity of this assumption, we repeated the analysis using 13°C for the instability threshold, and the results are presented in Figures S1–S6 in Supporting Information S1 of this paper. The number of times that meet all of the favorable lake-effect snow criteria decreases by an order of magnitude compared with the 10°C criterion. The number of favorable times decreases by mid-century before becoming more common by EOC, likely forced by the occurrences of surface to 850 hPa instability of 13°C or greater projected to decrease by mid-century and then increase by EOC over nearly all of the lakes (Figures S1 and S2 in

Supporting Information S1). Compared to those found in Figure 5, higher-end 6-hourly snowfall accumulations during favorable 13°C instability lake-effect times are projected to increase in the same lake-effect-prone regions by EOC, with some increases in the top 1% snowfall accumulations now reaching as high as 150 mm (Figure S3 in Supporting Information S1). Significant increases in the average 6-hourly snowfall accumulation during these favorable lake-effect times are found downwind of Lake Michigan and Lake Huron by mid-century (Figure S4 in Supporting Information S1), with few significant increases across the Upper Peninsula of Michigan in contrast to what was seen in Figure 6 using the 10°C instability criterion. By EOC, average 6-hourly snowfall accumulations during favorable lake-effect times are projected to increase significantly in the same regions found in Figure 6, with increases of greater than 10 mm present downwind of Lake Huron and Lake Superior (Figure S4 in Supporting Information S1) compared to increases of around 5 mm in Figure 6 for the 10°C instability criterion.

When favorable lake-effect times with the 13°C are classified into events, as shown with 10°C favorable lake-effect times in Figures 7 and 8, some stark differences in the change of occurrences of classified snowfall events throughout the century are present (Figures S5 and S6 in Supporting Information S1). Similarly to the change in times that met all the favorable criteria, the number of classified 13°C instability lake-effect snow events is about an order of magnitude lower than the number of 10°C instability events. In contrast to the results found for 10°C instability favorable lake-effect snow events (Figure 7), the occurrences of 13°C instability lake-effect snow events are projected to decrease nearly domain-wide by mid-century before then increasing in occurrence by EOC (Figures S5a and S5b in Supporting Information S1). By EOC, the changes in average event total snowfall from these events (Figure S5d in Supporting Information S1) are also projected to be greater than those found from the favorable 10°C instability lake-effect events, with average event totals increasing by 60 mm (2.36 in) or more. Overall, the results using 13°C for the instability criterion are similar to those found using 10°C, but do show some sensitivity to instability threshold choice with fewer times and events that meet the 13°C threshold. These results also show a greater increase in the average 6-hourly snowfall accumulation and event total snowfall associated with these favorable lake-effect times.

6. Discussion

While the above results are largely statistically significant, they are based on a single downscaling experiment owing to computational resource limits. Thus, this work does not address the role of structural uncertainty and scenario uncertainty with regard to climate change's impacts on lake-effect snow. For example, this study examined the impacts due to a high-emissions climate scenario, and as such the results may differ if other emissions scenarios are utilized. However, because our simulations employ the RCP8.5 scenario, the projected changes presented here should be interpreted as estimates under a high-emissions warming pathway rather than as outcomes representative of all possible future forcing scenarios. As computational resources continue to expand, future studies should target the use of dynamical downscaling ensembles, as well as downscaling of other climate scenarios to determine if the lake-effect snow response is monotonic under varying emission scenarios. The climate model downscaling technique could also be used to explore other important topics related to regional wintertime precipitation, including understanding changes in the type of lake-effect snow bands most prevalent over the different lakes, as well as how precipitation type may change in a warming world.

Another important limitation is the representation of the Great Lakes within the downscaled simulations. The simulations employed time-varying lake-surface temperatures and ice cover prescribed by the driving climate simulations. Although the prescribed lake-surface temperatures were bias corrected prior to downscaling, the simulations do not represent interactive lake thermodynamics or atmosphere–lake feedbacks. Consequently, residual biases in the prescribed lake state may influence the simulated surface heat and moisture fluxes that are fundamental to lake-effect snowfall. This sensitivity is supported by Shi and Xue (2019), who showed that the spatial and temporal representation of lake-surface temperature can substantially affect the magnitude and distribution of lake-effect snowfall in high-resolution simulations. Notaro et al. (2022) also showed through the examination of historical simulations generated by high-resolution GCMs that different approaches in treatment of the Great Lakes ultimately did not lead to adequate representation of lake temperatures as well as ice cover and therefore lake-effect snowfall patterns. Nevertheless, this lake representation was applied consistently throughout the historical, mid-century, and end-of-century simulations, allowing the projected changes presented here to be interpreted within a common modeling framework.

Future studies employing fully coupled lake–atmosphere models may further improve projections of lake-effect snowfall by representing interactive lake thermodynamics, circulation, and ice evolution. Recent studies have demonstrated that coupled three-dimensional lake models reduce biases in lake-surface temperature and ice cover and improve simulations of lake-atmosphere interactions over the Great Lakes (Xue et al., 2022, 2025). Likewise, Kayastha et al. (2024) demonstrated the importance of interactive lake processes for the evolution of an individual future lake-effect snow event using a fully coupled, three-dimensional lake–land–atmosphere model. Extending these modeling approaches to multi-decadal regional climate simulations represents an important avenue for future research.

7. Conclusions

In this study, dynamically downscaled GCM simulations were analyzed to examine changes in lake-effect snowfall across the Great Lakes region in the context of a changing climate. A unique and novel aspect of this study is the use of simulations that have a horizontal grid spacing and vertical resolution adequate to resolve lake-effect snow over the entirety of the Great Lakes region. This study is also one of the few to examine potential changes in lake-effect snow by mid-century and end-of-century (EOC), as opposed to only examining changes between historical data and end-of-century projections. Atmospheric parameters conducive to lake-effect snow are also examined to provide context for these changes, including the temperature difference between the near-surface air and the 850-hPa level and low-level wind convergence near the shoreline. In a warming climate, this study reveals a spatially varying seasonal snowfall total response across the Great Lakes region by mid-century. By EOC, seasonal snowfall totals are projected to decrease across much of the Great Lakes region, especially during the transition seasons of SON and MAM. This finding is consistent with decreased future snowfall found in previous studies (Ashley et al., 2020; Baijnath-Rodino et al., 2018; Hartnett et al., 2014). However, seasonal snowfall remains near constant or even increases in prominent lake-effect belts due to lake-effect snowfall during the core winter season across all periods. This result is similar to those found in Burnett et al. (2003). High-end 6-hourly snowfall accumulations (which we use as a proxy for intensity in this study) at lake-effect-prone sites show increased accumulations at sites east of Lake Erie and Lake Ontario by mid-century, with increased 6-hourly accumulations especially downwind of Lake Superior and Lake Huron by EOC.

To isolate snowfall changes solely from changes in lake-effect snow events, criteria adapted from Kunkel et al. (2002) were used to identify favorable times for lake-effect snow. These included 2-m temperatures between 0°C and −10°C; an 850-hPa wind direction between 240° and 340° (relative to north) with a wind speed of 6 m s^{-1} or greater; a 900-700-hPa mean wind direction between 240° and 340° and mean wind speed of 6 m s^{-1} or greater; and finally a difference in the 2-m and 850-hPa temperatures over the Great Lakes of 10°C or greater. Domain-wide decreases in the occurrence of favorable temperatures and increases in favorable instability were found to drive the overall changes in the occurrence of favorable lake-effect conditions through each of the periods. Throughout the century, favorable lake-effect conditions are also projected to become more confined to the core winter season (DJF). Overall, these results indicate that in a warming climate, lake-effect snow may become slightly more intense and common over the lower Great Lakes, such as Lake Ontario and Lake Erie as well as south of Lake Superior toward mid-century. By EOC, lake-effect snow is projected to become less common over the lower Great Lakes region, but more common across much of Lake Superior and parts of Lake Huron and Lake Michigan, with a temporal shift toward DJF.

Higher-end 6-hourly lake-effect snowfall accumulations are also found to increase downwind of Lakes Superior, Huron, and Michigan with the most extreme increases of 50 mm or greater by EOC. Such increases in short-term snowfall accumulations may lead to dangerous conditions and disrupt infrastructure and daily life in areas that previously may have only rarely experienced such intense snowfall. When comparing the average 6-hourly snowfall accumulations over all times and those only during favorable lake-effect conditions, it is found that lake-effect snow is expected to maintain its average 6-hourly accumulation or increase slightly downwind of Lake Superior, Lake Huron, and Lake Ontario by mid-century. Similarly, significant increases are projected in the lake-effect belts of Lake Superior, Lake Huron, and Lake Michigan toward the EOC. Meanwhile, areas outside of the lake-effect belts experience large decreases in average 6-hourly snowfall accumulations when all snowfall is considered, likely reflecting decreases in non-lake-effect snowfall.

When classified into lake-effect snow events, that is, continuous periods with favorable lake-effect snow conditions, fewer lake-effect snowfall events are expected by EOC, although nearly the same number of snowfall

events is projected in the mid-century as in the historical period. However, the average total snowfall from each of these events is expected to remain the same or even increase, for example, downwind of Lake Huron, Lake Superior, and northern Lake Michigan. These lake-effect events may also experience a slight decrease in duration in the mid-century period before potentially increasing slightly in duration toward EOC. They are also projected to exhibit much higher average event total snowfalls in the most extreme lake-effect snow events.

Lake-effect snow in the Great Lakes region is expected to change in a warming world. These changes seem to be non-linear in nature, with minor changes over some of the lakes by the middle of the century before larger and more drastic changes take shape by EOC. From this study, we see that the most profound impacts and changes are likely to occur downwind of Lake Superior, Lake Huron, and Lake Michigan by EOC, following momentary enhancements to lake-effect snow to the east of the lower Great Lakes in the mid-century period. These changes are projected to include increases in total snowfall from lake-effect snow events as well as increases in the intensity or 6-hourly snowfall accumulation of these bands. The projected increases in lake-effect snowfall in these regions are associated with greater lower-level atmospheric instability, increased downwind shoreline convergence, and near-surface air temperatures that more frequently approach but remain below 0°C during the cold season. Projected changes in the prescribed lake state may also contribute, consistent with previous studies linking warmer lake temperatures and reduced ice cover to enhanced lake-effect precipitation; however, lake-surface temperature and ice coverage were not directly evaluated here but are the focus of future research.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The WRF bias-corrected Community Earth System Model (WRF-BCC) regional climate simulations used in this study are archived on the Argonne National Laboratory EAGLE file system. Any users wishing to access these raw data can make a request at any time to the Argonne Leadership Computing Facility, which is a U.S. Department of Energy Office of Science User Facility operated under contract DE-AC02-06CH11357. Details regarding these data can be found in Gensini et al. (2023). The ERA5 reanalysis data used in this study are publicly available from the NSF National Center for Atmospheric Research Geoscience Data Exchange, formerly the Research Data Archive, as data set d633000, "ERA5 Reanalysis (0.25 Degree Latitude-Longitude Grid)" (European Centre for Medium-Range Weather Forecasts, 2019, https://doi.org/10.5065/BH6N-5N20).

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