



Projected changes to cold-season extratropical cyclones over northeastern North America in an ensemble of regional climate model simulations

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Abstract. Extratropical cyclones (ETCs) are the main drivers of cold-season weather in northeastern North America (NENA), yet their response to climate change remains uncertain. Here, we assess cold-season (November–March) ETCs in a high-resolution (0.11°) regional climate model ensemble driven by four CMIP6 global climate models under multiple emissions scenarios, including five initial-condition members for one model–scenario combination. Historical simulations reproduce the main ERA5 track and genesis patterns, although they generally simulate more cyclones, lower minimum sea-level pressures, and stronger winds. With warming, cyclone track density decreases across much of North America, including over NENA, where cyclogenesis also tends to decline. The five-member subset exhibits substantial spread in projected track-density and cyclogenesis changes, highlighting the influence of internal variability on these regional patterns. Yet the total number of cyclones affecting NENA declines robustly across all driving models. Changes in cyclone characteristics are generally weak and driving-model dependent, although some statistically significant changes indicate stronger winds or slower-moving cyclones. Most apparent deepening in minimum sea-level pressure disappears when pressure is expressed as an anomaly from the local climatology, weakening the evidence for pressure-based intensification. Nevertheless, the number of cyclones falling below a fixed historical pressure-anomaly threshold remains broadly unchanged as total cyclone frequency declines, so the proportion classified as intense tends to increase. Despite fewer cyclones, total cold-season ETC-associated precipitation tends to increase over NENA land areas, including at every major city examined. These results point to fewer but wetter cold-season cyclones, with increasing ETC-associated precipitation despite limited dynamical intensification.

1 Introduction

Midlatitude cold-season weather is dominated by the passage of extratropical cyclones (ETCs). In highly populated northeastern North America (NENA), most wintertime wind and precipitation extremes are associated with ETCs (Chen and Di Luca, 2025). Through hazards such as strong winds, heavy snowfall, freezing rain, and coastal flooding, ETCs cause major societal impacts, including property and infrastructure damage, power outages, and transportation disruptions (e.g., Changnon et al., 2006; Shimkus et al., 2017). Yet despite their importance, considerable uncertainty remains regarding how ETC tracks and intensity will respond to climate change, particularly at regional scales.



Part of this uncertainty arises because climate change exerts opposing influences on baroclinicity, a key ingredient for ETC development (Shaw et al., 2016; Catto et al., 2019). Arctic amplification weakens the equator-to-pole temperature gradient in the lower troposphere, tending to shift storm tracks equatorward. Conversely, amplified warming of the tropical upper troposphere strengthens the meridional temperature gradient aloft, tending to shift storm tracks poleward (Butler et al., 2010). Other processes, including changes in atmospheric static stability (Mbengue and Schneider, 2017), latent heat release (Büeler and Pfahl, 2019), and cloud-radiative effects (Voigt and Shaw, 2015), further complicate projections. How ETCs respond to climate change ultimately depends on the combined influence of several dynamical and thermodynamic processes whose relative importance varies across regions, seasons, and models (Shaw et al., 2016; Shaw, 2019). Because theory alone cannot determine how these competing influences will balance, comprehensive climate model simulations are needed to project the sign and magnitude of ETC changes.

Despite this mechanistic uncertainty, several broad tendencies have emerged from climate model projections. The total number of ETCs is projected to decrease under global warming (Geng and Sugi, 2003; Bengtsson et al., 2009; Chang et al., 2012), with CMIP6 simulations indicating a decline of approximately 5% by the end of the century (Priestley and Catto, 2022b). Storm-track responses vary by region and season, including a poleward shift over the North Pacific and an eastward extension over the North Atlantic during winter (Priestley and Catto, 2022b). Projections of intense ETCs are less consistent, particularly for Northern Hemisphere winter. Some studies project increases in the number of cyclones classified as intense using fixed thresholds based on minimum sea-level pressure or relative vorticity (Mizuta et al., 2011; Priestley and Catto, 2022b), whereas others project decreases using pressure-gradient or pressure-anomaly criteria (Geng and Sugi, 2003; Chang et al., 2012). This disagreement reflects differences among models and experimental designs, as well as in the variables and thresholds used to define cyclone intensity (Ulbrich et al., 2009; Chang, 2014; Catto et al., 2019). By contrast, ETC-associated precipitation is more consistently projected to increase, with greater precipitation per cyclone offsetting declines in cyclone frequency (Lombardo et al., 2015; Yettella and Kay, 2017; Zhang and Colle, 2017).

Most multi-model ETC projections, however, rely on global climate models (GCMs) whose coarse horizontal resolution limits their ability to capture key cyclone-scale processes and impacts. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report concluded with high confidence that CMIP5 and CMIP6 models underestimate ETC dynamical intensity, with higher-resolution models usually performing better (Seneviratne et al., 2021). This is partly because coarse resolution smooths sharp frontal gradients and cannot fully resolve mesoscale latent heating (Schaffer et al., 2025; Willison et al., 2013; Trzeciak et al., 2016). Consistent with this assessment, HighResMIP simulations reduce many biases in cyclone-scale winds and airstream structure relative to standard CMIP6 models, although improvements in the large-scale environment are more limited (Priestley and Catto, 2022a).

Regional climate models (RCMs) provide higher-resolution projections that can better represent ETCs and their regional impacts. Their potential added value is often greatest where regional processes and surface features exert a strong influence, including near complex topography, coastlines, and sharp land–water contrasts (Evans and McCabe, 2013; Rummukainen, 2016). Regional modeling studies over North America report improvements in simulated cyclogenesis and in cyclone frequency and intensity, particularly for intense or rapidly deepening systems (He et al., 2013; Long et al., 2009; Seiler et al., 2018; De Meyer



et al., 2026). This added value partly reflects better-resolved mesoscale latent heating, which strengthens cyclone development and can amplify the modeled response to warming (Willison et al., 2013, 2015; Zhang and Colle, 2018). However, RCM projections remain sensitive to their driving GCMs because biases in the large-scale circulation can persist after downscaling (Poan et al., 2018; Zhang and Colle, 2018). Moreover, century-long integrations remain computationally demanding, and previous regional ETC projections over North America have typically relied on only a few driving GCMs and a single realization (Long et al., 2009; Seiler et al., 2018; Zhang and Colle, 2018). Some studies have used larger regional-model ensembles to examine ETC projections, but these have generally been limited to a single driving-model configuration or emissions scenario (Mittermeier et al., 2019). Consequently, the effects of driving-model uncertainty and internal variability have seldom been quantified together.

In this study, we investigate projected changes in cold-season (November–March) ETCs over NENA using the newly completed high-resolution RCM ensemble produced by Ouranos (Paquin et al., 2025). Driven by four CMIP6 GCMs under multiple SSPs and including five initial-condition members for one GCM–scenario combination, the ensemble allows us to compare regional projections across driving models and scenarios and to examine internal variability within the multi-member subset. We first identify and track ETCs and evaluate historical cyclogenesis, track density, and cyclone characteristics against ERA5 to assess the realism of the simulated cyclone climatology. We then examine projected changes in cyclogenesis and track density across North America, as well as in cyclone frequency, intensity, and other characteristics over NENA, using both fixed future periods and global warming levels. Finally, we quantify cyclone-associated precipitation across NENA and at major cities within the region. Together, these analyses provide a baseline characterization of ETC climatology and projected change in this newly completed ensemble, establishing a foundation for more targeted investigations of cyclone dynamics, hazards, and regional impacts.

2 Data and methods

2.1 Regional climate model ensemble

Cyclones are identified, tracked and analysed in the Ouranos CRMC5-CMIP6 ensemble (Paquin et al., 2025). This ensemble uses the fifth-generation Canadian Regional Climate Model (CRCM, Martynov et al., 2013; Šeparović et al., 2013) to scale CMIP6 simulations down to a resolution of 0.11° (approximately 12 km) over the North American CORDEX domain. Simulations are driven at lateral boundaries by four global climate models (GCMs) from the CMIP6 ScenarioMIP: NorESM2-MM, MPI-ESM1-2-LR, CNRM-ESM2-1 and CanESM5. Sea ice concentration and sea surface temperatures are prescribed by the GCMs. Past climate simulations span 1950–2014 using observed greenhouse gas and aerosol concentrations, while future simulations run from 2015 to 2100 using four Shared Socioeconomic Pathway (SSP) scenarios. Scenarios presented here include, in order of radiative forcing intensity, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 (for CanESM5 only). The ensemble comprises one member simulation per GCM and per scenario, except for the MPI-ESM1-2-LR under SSP3-7.0, for which 5 members are available. In addition to GCM-driven simulations, a control CRMC5 simulation driven by the ERA5 reanalysis (Hersbach



et al., 2020) is used for validation. Data are archived at an hourly or three-hourly timestep according to the variables. The analysis is performed using 3-hourly data.

2.2 Global warming levels and associated reference periods

Our driving GCMs span a wide range of equilibrium climate sensitivities (ECS), from 2.54°C in NorESM2-MM to 5.64 °C in CanESM5. Under SSP3-7.0, this translates into end-of-century warming of 2.8-5.8 °C. Comparing simulations with such different climate states can be misleading. One way to address this spread in climate sensitivity and emission scenarios is to compare results at fixed levels of global mean temperature increase relative to the pre-industrial period (Doblas-Reyes et al. (2021)). We therefore present not only in terms of fixed time windows, but also in terms of global warming levels (GWLs), following the method of Nikulin et al. (2018).

Since our RCM simulations begin in 1950, i.e. much later than the preindustrial baseline (typically 1850-1900), we cannot compute differences with respect to a GWL of 0 °C. A first alternative would be to compute differences based on a fixed reference historical period, such as 1981-2010, but this would be unfair as some simulations have already reached nearly a GWL of 2 °C by then. Instead, we elected to compute differences using as reference the GWL of 0.69 °C reached by ERA5 over the 1981-2010 historical period with respect to the 1850-1900 preindustrial baseline.

Table 1 outlines the time periods associated with each GWL, driving GCM and scenario. In the analysis below, we compute changes at GWLs of 2 °C and higher relative to the 0.69 °C historical baseline associated with each model and scenario. For instance, the change in cyclone count associated with a GWL of 2 °C in the scenario SSP3-7.0 corresponds to the difference in cyclone counts between periods 2005-2034 and 1973-2002 for CanESM5, but between periods 2038-2067 and 1980-2009 for MPI-ESM1-2-LR. This method thus allows for a more fair comparison between simulations covering a wide range of climate sensitivities and emission scenarios.

2.3 Cyclone identification and tracking

Numerous methods exist to identify and track ETCs in gridded datasets, most commonly based on mean sea-level pressure (MSLP) and/or vorticity (Neu et al., 2013). The Intercomparison of Mid Latitude Storm Diagnostics (IMILAST) project compared 15 of these methods and noted large variations in the number of cyclones identified, particularly for weak cyclones. However, despite these differences, Neu et al. (2013) noted that the overall patterns of cyclone density, cyclone characteristics and trends in cyclone statistics were generally consistent between the different methods.

In this paper, we identify and track cyclones using TempestExtremes (Ullrich and Zarzycki, 2017; Ullrich et al., 2021). First, candidate cyclones are identified using *DetectNodes* every 3 hours as local minima in MSLP that must be surrounded by a closed MSLP contour with a value of 2 hPa greater than the minimum within a radius of 6° of the minimum. Candidates within 400 km (3.6°) of each other are merged, with the candidate with the lowest MSLP value retained. Cyclone centers are detected within the domain, excluding a 10-grid-point buffer along all boundaries in order to avoid issues with cyclones that follow the domain edges. Note that for validation, we compare with the control ERA5-driven CRCM5 simulation with ERA5 itself. In this case, we subset ERA5 to the CRCM5 domain before applying TempestExtremes as in Côté et al. (2015).



Table 1. Global warming level (GWL) periods for each driver, member, and scenario.

Driver	Member	Scenario	Warming Level	Period
ERA5		Historical	0.69°C	1981–2010
NorESM2-MM	r1i1p1f1	Historical	0.69°C	2000–2029
		SSP2-4.5	2°C	2067–2096
		SSP3-7.0	2°C	2048–2077
MPI-ESM1-2-LR	r1i1p1f1	Historical	0.69°C	1980–2009
		SSP2-4.5	2°C	2045–2074
		SSP3-7.0	2°C	2038–2067
			3°C	2065–2094
	r2i1p1f1	Historical	0.69°C	1983–2012
		SSP3-7.0	2°C	2036–2065
			3°C	2068–2097
	r3i1p1f1	Historical	0.69°C	1980–2009
		SSP3-7.0	2°C	2036–2065
			3°C	2066–2095
	r4i1p1f1	Historical	0.69°C	1979–2008
		SSP3-7.0	2°C	2037–2066
			3°C	2066–2095
	r5i1p1f1	Historical	0.69°C	1983–2012
		SSP3-7.0	2°C	2037–2066
			3°C	2065–2094
CNRM-ESM2-1	r1i1p1f2	Historical	0.69°C	1991–2020
		SSP2-4.5	2°C	2042–2071
		SSP3-7.0	2°C	2037–2066
			3°C	2058–2087
CanESM5	r1i1p2f1	Historical	0.69°C	1973–2002
		SSP1-2.6	2°C	2007–2036
		SSP2-4.5	2°C	2006–2035
			3°C	2030–2059
			4°C	2066–2095
		SSP3-7.0	2°C	2005–2034
			3°C	2025–2054
			4°C	2042–2071
			5°C	2059–2088
		SSP5-8.5	2°C	2005–2034
			3°C	2023–2052
			4°C	2038–2067
			5°C	2051–2080



The high spatial resolution of our simulations leads to a noisy MSLP field. To retain only coherent synoptic scale features, various smoothing methods have been used for cyclone tracking in high-resolution datasets. Côté et al. (2015) and Chen et al. (2022) used a Cressman (1959) filter with a radius of influence of 600 km and 400 km, respectively. Prein et al. (2023) used a 500 km x 500 km uniform filter. Here, we apply a Gaussian filter with an approximate influence radius of 400 km, estimated using the meridional and zonal grid spacing near each grid point. While cyclones are identified and tracked using their smoothed value, we also archive the unsmoothed value of MSLP.

The next step involves tracking cyclones in time and space using *StitchNodes*. For each cyclone identified at time t_0 , a search is executed within 4.5° (500 km) of the cyclone at time t_1 . Given the three-hour frequency of the tracking, this allows for a maximum translation speed of approximately 167 km h^{-1} . This speed is much faster than the average translation speeds of approximately 50 km h^{-1} identified by Bernhardt and DeGaetano (2012). However, a larger search radius allows for identification of secondary cyclogenesis cases, for example situations where cyclones to the west of the Appalachian Mountains redevelop off the East Coast (e.g., Pagnotti and Bosart, 1984). Our 4.5° search radius provides for maximum translation speeds equivalent or similar to those used in several prior cyclone tracking studies using mainly six-hourly data (Wang et al., 2006; Crawford et al., 2023; Gore et al., 2023). To retain only coherent, long-lived systems, we require a minimum lifespan of 24 h and a minimum distance of 1000 km (9°) from the start to the end of the trajectory. We also allow for up to one archival step of 3 hours wherein the cyclone is missing to allow for temporary weakening of the cyclones. Finally, we focus on cold-season (November-March) cyclones, as this is the period where extratropical cyclones are strongest, when temperature gradients are sharper and the jet stream is stronger (Laurila et al., 2021).

2.4 Regional analysis

For some parts of the analysis, we narrow our attention to cyclones that impact the highly populated regions of the northeastern United States and southeastern Canada. Specifically, we focus on cyclones that spend at least one time step within the region spanning 85° W to 60° W longitude and 35° N to 52° N latitude (refer to black boxes on Figs. 2 & 4), hereafter referred to as the northeast North America (NENA) domain. This region encompasses the highly populated Northeast megalopolis in the United States, from Washington, D.C. northeastward to Boston. It also includes the most densely populated region of Canada, including Toronto, Ottawa, Montréal and Québec City, as well as the provincial capitals of New Brunswick (Fredericton) and Nova Scotia (Halifax). The region chosen is also sufficiently large to provide a $\approx 500 \text{ km}$ buffer from each of these cities to retain cyclones who may still impart substantial impacts despite their centers passing several hundred km from the location.

In addition to the smoothed value of MSLP used for tracking, we retain three-hourly minimum values of unsmoothed MSLP and the maximum values of the 10-m and 850-hPa wind speeds within a 500 km radius of the cyclone center. Once cyclone tracks are identified with *StitchNodes*, we calculate the total distance travelled (the sum of the distances between points), the cyclone lifespan and the mean translation speed over the lifetime of the cyclone.

Changes in the large-scale background MSLP field, as well as shifts in cyclone-track location, can affect absolute minimum MSLP without reflecting changes in cyclone dynamical intensity (Chang, 2014). To reduce this sensitivity, we define the minimum MSLP anomaly as



$$\text{MSLP}'_{\min} = \text{MSLP}_{\min} - \overline{\text{MSLP}}(\mathbf{x}_p), \quad (1)$$

where $\mathbf{x}_p$ denotes the location at which a given cyclone reaches its minimum MSLP ($\text{MSLP}_{\min}$), and the overline denotes the 30-year November–March mean MSLP at that location, calculated separately for each simulation and analysis period. More negative values therefore indicate deeper cyclones relative to the local background pressure. Intense cyclones are defined as those with $\text{MSLP}'_{\min}$ below the 20th percentile of the corresponding historical distribution, with this historical threshold retained for future periods. Sensitivity tests using the 15th and 25th percentiles yielded qualitatively unchanged results.

We also identify precipitation associated with each tracked cold-season cyclones (as described above) using the TempestEx-
tremes algorithm *NodeFileFilter*. For each detected cyclone center, all precipitation within a 12° radius (approximately 1300 km) is attributed to that cyclone at each time step. This radius, consistent with previous studies (Zarzycki, 2018; Sinclair and Catto, 2023), is chosen to capture most ETC-related precipitation while minimizing double counting from nearby events. At the city scale, a cyclone passing within a 12° radius of the city is therefore considered to impact it and potentially generate precipitation there. For a given city, we calculate the total accumulated cyclone-associated precipitation over the cold season, and the accumulated precipitation from each individual cyclones.

3 Evaluation

3.1 Cyclone tracks and genesis

Before examining projected changes, we evaluate the regional climate model simulations over the historical period. We first apply the cyclone identification and tracking method (Section 2.3) to ERA5 and the ERA-driven CRCM5 simulation. More cyclones are identified in the CRCM5[ERA5] simulation than in ERA5 (3717 vs 3447 over the 30-year period), but the spatial patterns of track density (Fig. 1a-b) are very similar. Both reproduce known cyclone tracks and genesis regions (e.g., Zishka and Smith, 1980). The region of maximum cyclone density is along the North American East Coast, where both datasets show peaks of 15-18 cyclones per cold season from the New England coast northeastward to Newfoundland (Fig. 1a-b).

Genesis regions are also similar (Fig. 1c-d), with peaks identified along the East Coast, Rocky Mountains (including Alberta clippers and Colorado Lows), and the central U.S. The peak in genesis over the North Pacific is an artifact of the domain boundary, and represents the region of first identification of cyclones originating further west over the North Pacific and entering the domain. Besides this, peak values of 4-5 cyclogenesis events per cold season are found along the U.S. East Coast, from North Carolina to New England. Key differences include a stronger maximum in Alberta in ERA5, and a stronger maximum over Colorado in CRCM5[ERA5]. The main East Coast cyclogenesis region extends further northward into Atlantic Canada in CRCM5[ERA5] than in ERA5.

Cyclone tracks identified from CMIP6-driven CRCM5 simulations are also qualitatively similar to that of ERA5 (Fig. 2a-d). Key differences between the simulations include the northeastward extent of the North Atlantic storm track. The CRCM5[CanESM5] simulation has a more concentrated storm track with greater maximum values extending further north-

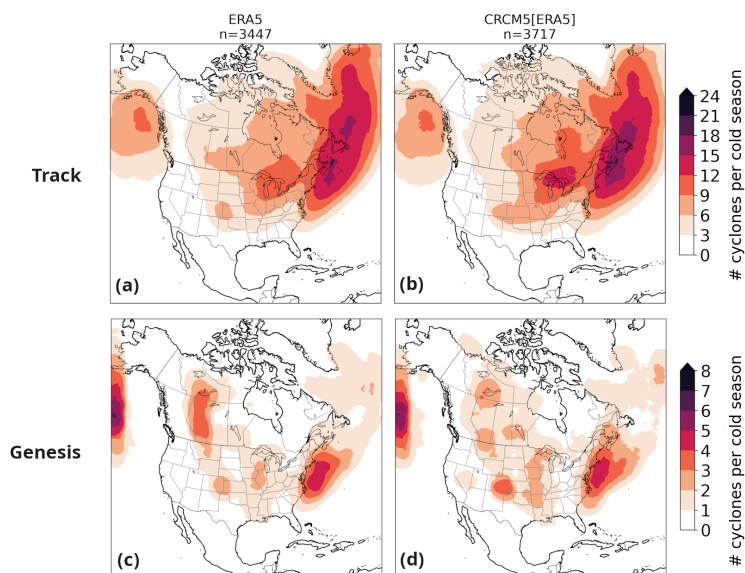


Figure 1. Mean 1981-2010 (corresponding to a 0.69 °C warming level) cold-season (NDJFM) cyclone track (a,b) and genesis (c,d) density for ERA5 (a,c), and CRCM5[ERA5] simulation (b,d). Units are tracks or cyclogenesis events per cold season within a 350 km radius of each gridpoint.

eastward than the other simulations. Genesis regions are broadly consistent between all CMIP6-driven CRCM5 simulations and closely resemble those in CRCM5[ERA5] (Fig. 2e-h).

3.2 Cyclone characteristics in the NENA region

We now turn to the evaluation of key cyclone characteristics — minimum mean sea-level pressure (MSLP), total distance travelled, lifespan, mean translation velocity and maximum wind speed both at the surface and aloft. Figure 3 presents the distribution of these characteristics for all cyclones that spend at least one time step within the NENA domain (see Fig. 2).

Overall, most characteristics show consistent distributions across ERA5 and CRCM5 simulations. Key differences include lower minimum MSLP values in CMIP6-driven CRCM5 simulations compared with ERA5 and CRCM5[ERA5] (Fig. 3a). Although median mean translation speeds are similar ($\approx 13 \text{ m s}^{-1}$; Fig. 3d), ERA5 cyclones travel a longer median distance—3129 km versus $\approx 2800 \text{ km}$ for the CRCM5 simulations (Fig. 3b). For cyclone maximum winds, the CRCM5[CanESM5] simulation exhibits the strongest values, with median peak 850-hPa and 10-m winds of 44.4 m s^{-1} and 28.9 m s^{-1} , respectively, compared with the weaker ERA5 values of 40.4 m s^{-1} and 21.8 m s^{-1} . CMIP6-driven CRCM5 simulations systematically exhibit stronger peak winds overall. The largest discrepancy relative to ERA5 occurs for 10-m winds, consistent with Chen et al. (2024), who noted that ERA5 underestimates extreme winds from extratropical cyclones, something often seen in reanalysis datasets.

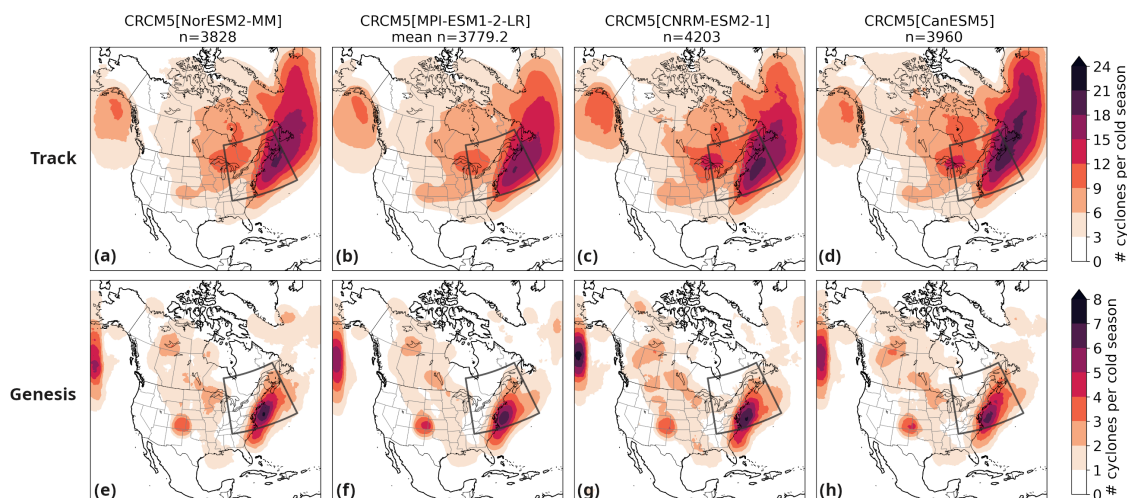


Figure 2. Mean historical (0.69°C warming level) cold-season (NDJFM) cyclone track (a-d) and genesis (e-h) density for the CMIP6-driven CRCM5 simulations. Units are tracks or cyclogenesis events per cold season within a 350 km radius of each gridpoint. The northeastern North America (NENA) domain is outlined by the black box. The CRCM5[MPI-ESM1-2-LR] maps show the ensemble mean of five members.

A measure of natural variability is presented via the envelope centered on the five-member ensemble mean of CRCM5[MPI-ESM1-2-LR], representing the spread of the ensemble. For some cyclone characteristics (e.g. lifespan, mean translation speed), the other CMIP6-driven simulations lie within or close to this envelope, indicating strong agreement among simulations. For other characteristics (e.g. minimum MSLP, maximum wind speed at 850hPa and 10m), model uncertainty can be well distinguished from internal variability.

4 Projected changes

4.1 Cyclone tracks and genesis

So far, we have focused on cyclones over the historical period. Here, we turn to projected changes and examine how climate change may affect cyclone genesis, tracks, characteristics, and impacts. Figure 4 shows changes in cyclone track density and genesis across the different GCMs and global warming levels (GWLs), with historical climatology overlaid as contours for reference. All GCMs reach a GWL of 3°C except NorESM-MM (Table 1), hence the missing panel.

The dominant signal is a reduction in cyclone track density with increasing global warming (Fig. 4a-g). The signal is most robust at 3°C warming, where all models reaching this level show statistically significant decreases along the Atlantic storm track and over parts of Eastern and Western Canada. Increases are comparatively rare and show little inter-model agreement. Changes at 2°C warming are more spatially heterogeneous and less consistent across simulations (Fig. 4a-d). Yet, the five-member CRCM5[MPI-ESM1-2-LR] ensemble mean exhibits a clear and spatially coherent decrease signal already at 2°C .

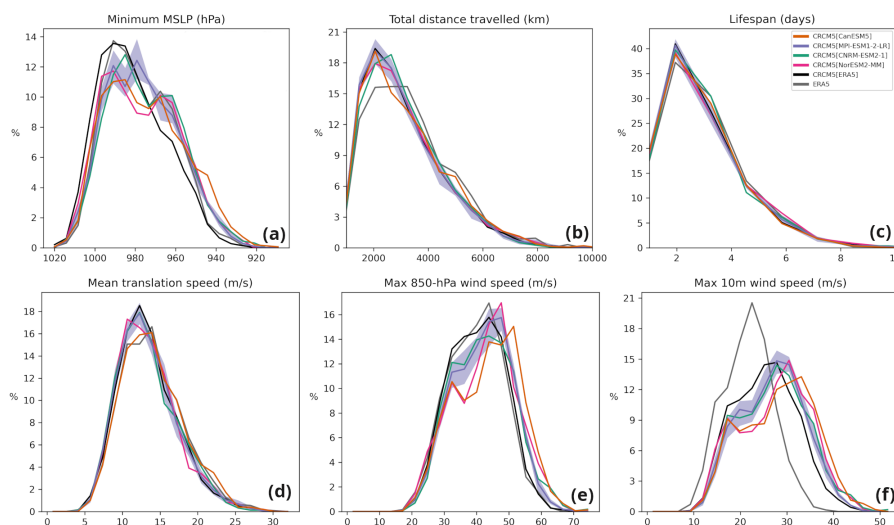


Figure 3. Mean historical (0.69°C warming level) cold-season (NDJFM) cyclone distribution of minimum mean sea level pressure (a), total distance traveled (b), lifespan (c), mean translation speed (d), maximum 850-hPa wind speed (e), and maximum 10m wind speed (f) for ERA5, ERA5-driven CRCM5 and CMIP6-driven CRCM5 simulations, for cyclones passing through the NENA region. The CRCM5[MPI-ESM1-2-LR] distributions show the ensemble mean of five members, with the envelope representing the minimum and maximum values across the ensemble.

220 However, it is worth noting that the pattern seen in the ensemble mean of CRCM5[MPI-ESM1-2-LR] is not fully reproduced by any of its five individual members (see Fig. S1 for reference), suggesting that internal variability contributes to the inter-model spread at both 2°C and 3°C warming levels.

Changes in genesis density generally indicate a slight decrease in cyclone development along parts of the East Coast (Fig. 4h-n), with reductions of 1–2 cyclones per season that are statistically significant in some simulations. However, only a weak
 225 decrease emerges in this region in the ensemble mean of CRCM5[MPI-ESM1-2-LR] (Fig. 4i,l), revealing considerable internal variability in the signal (see Fig. S2). In contrast, these simulations show a marked reduction in cyclones entering the domain from the North Pacific, a feature not reproduced by the other models. Conversely, the remaining models often exhibit a small but statistically significant increase in the genesis of Alberta Clippers.

4.2 Cyclone characteristics

230 We now examine the characteristics of cyclones affecting the NENA region. Table 2 compiles the median values of cyclone characteristics in terms of both GWLs (greyed out) and emission scenarios, with reference periods underlined. At first glance, statistically significant changes in the distribution of the (boldface) appear fairly rare and scattered. However, we note that when changes are significant, they consistently point to the same direction: lower $\text{MSLP}_{\min}$, stronger maximum wind speed,

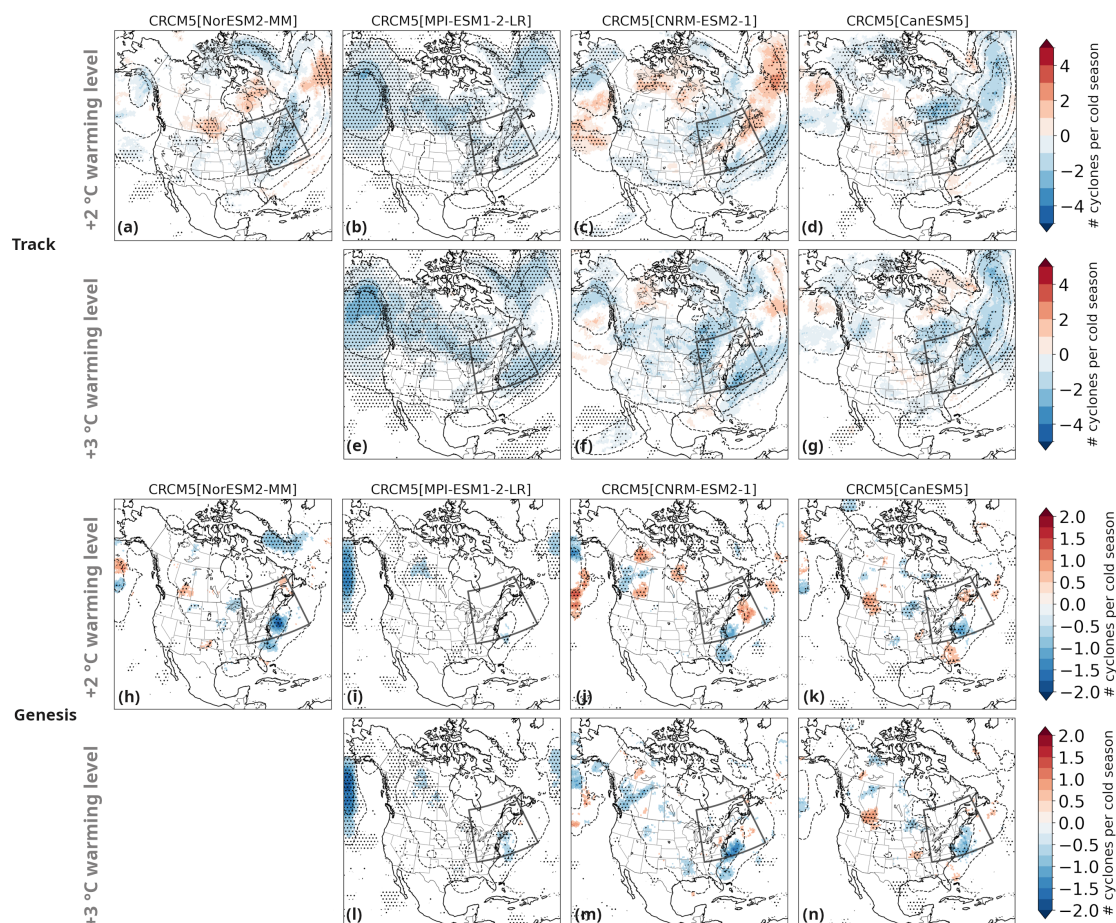


Figure 4. Mean 2 °C and 3 °C warming levels changes, relative to the historical (0.69 °C warming level), for cold-season (NDJFM) cyclone track (a-g) and genesis (h-n) density for the CMIP6-driven CRCM5 simulations, all SSP scenarios combined. Units are tracks or cyclogenesis events per cold season within a 350 km radius of each gridpoint. Black dashed-contour represents the historical period density. Hatching indicates regions with statistically significant changes, with Mann-Whitney U test ($p < 0.05$). The NENA domain is outlined by the black box. The CRCM5[MPI-ESM1-2-LR] maps show the ensemble mean of five members. Hatching in this case indicates statistically significant changes based on pooled ensemble members.

and slower translation velocity. Together, these changes suggest a tendency toward more intense and slower-moving cyclones
 235 in the future, potentially leading to greater impacts.

This intensification signal is not systematic, however. While indications of it are present across models, the largest changes do not consistently occur at the highest emission scenarios or warming levels. In addition, increases in maximum wind speed are confined to 850 hPa and are not evident at the surface, where impacts are most relevant. Furthermore, $MSLP_{min}$ may not be an ideal measure of cyclone intensity, as (i) climatological pressure is expected to decrease with global warming and



240 (ii) cyclone tracks may shift toward regions with different background pressure. To account for these effects, we compute a minimum MSLP anomaly ($MSLP'_{min}$) by subtracting, for each cyclone, the climatological MSLP at the location of peak intensity of that cyclone (see Eq. 1, and Chang et al. (2012) and Michaelis et al. (2017) for similar methods).

Most significant changes in the pressure distribution vanish when instead looking at $MSLP'_{min}$. For instance, the large decreases in MSLP with warming seen in CRCM5[CanESM5] simulations are insignificant in terms of $MSLP'_{min}$, suggesting that
 245 warming affected background pressure or track locations more than the intensity of the cyclones in those simulations. Interestingly, however, a few cases of statistical significance persist with $MSLP'_{min}$, suggesting that at least part of the intensification signal is independent of changes in background pressure.

4.3 Cyclone counts

Finally, we examine projected changes in the number of cyclones affecting the NENA region (Fig. 5). Consistent with the
 250 spatial changes in cyclone track density (Fig. 4), all simulations show significant decreases in cyclone frequency under either SSP3-7.0 or 3 °C warming (Fig. 5a). Overall, cyclone frequency tends to decline with increasing radiative forcing and global warming levels.

We also examined the number of intense cyclones affecting the NENA region (Fig. 5b), defining intense cyclones as those with $MSLP'_{min}$ below the 20th percentile of the historical distribution. In contrast to total cyclone counts, the number of intense
 255 cyclones generally does not change significantly, except for a few cases in the CRCM5[CanESM5] ensemble. As a result, the fraction of cyclones classified as intense tends to increase, with at least one statistically significant increase found for each driving model (Fig. 5c).

Taken together, these results suggest that although cyclones become less frequent under global warming, the relative occurrence of intense cyclones is likely to increase.



Table 2. Cyclone characteristics in the NENA region: minimum mean sea-level pressure (MSLP), anomalies of minimum MSLP, distance traveled, mean velocity (translation speed), maximum wind speed ($|u|$) at 850 hPa and at 10 m. Values are medians of the distributions, shown for historical (“Historical” (1981–2010), and +0.69 °C) and future (“SSP” (2071–2100), and +2.0 °C to +5.0 °C) simulations. Bold values indicate a significant difference between the historical and future distributions, based on the Mann–Whitney U test ($p < 0.05$).

Driver	Scenario	Min MSLP [hPa]	Anomalies min MSLP [hPa]	Distance traveled [km]	Mean velocity [m s ⁻¹]	Max $ u $ 850 hPa [m s ⁻¹]	Max $ u $ 10 m [m s ⁻¹]
NorESM2-MM	<u>Historical</u>	977.8	-33.97	2801.7	13.0	44.3	28.6
	SSP1-2.6	976.8	-34.05	2931.3	12.8	43.8	28.7
	SSP2-4.5	975.5	-35.29	2921.9	12.9	44.5	28.8
	SSP3-7.0	975.8	-35.30	2862.8	12.9	44.3	28.7
	+0.69 °C	978.1	-33.47	2839.6	12.8	43.5	28.3
	+2.0 °C	976.8	-34.57	2858.0	12.9	43.9	28.5
MPI-ESM1-2-LR	<u>Historical</u>	977.8	-33.22	2776.2	12.8	42.4	27.3
	SSP1-2.6	977.5	-33.79	2824.8	12.7	42.3	27.4
	SSP2-4.5	977.6	-33.25	2747.3	12.4	42.6	27.3
	SSP3-7.0	976.6	-33.75	2732.6	12.5	42.7	27.2
	+0.69 °C	977.6	-33.32	2771.5	12.9	42.4	27.3
	+2.0 °C	976.8	-33.93	2752.3	12.6	42.8	27.4
CNRM-ESM2-1	<u>Historical</u>	977.6	-32.58	2796.7	12.8	42.3	27.5
	SSP1-2.6	977.1	-33.32	2804.6	12.7	42.8	27.6
	SSP2-4.5	976.0	-33.94	2820.9	12.5	43.6	27.7
	SSP3-7.0	975.4	-33.76	2734.9	12.6	42.9	27.5
	+0.69 °C	976.8	-33.27	2870.8	12.8	42.0	27.5
	+2.0 °C	976.2	-33.38	2809.7	12.7	42.4	27.8
CanESM5	<u>Historical</u>	976.5	-34.17	2884.3	13.6	44.4	28.9
	SSP1-2.6	975.0	-34.44	2996.8	13.3	44.3	28.9
	SSP2-4.5	974.7	-34.16	2867.9	12.9	43.9	28.5
	SSP3-7.0	974.1	-35.06	2895.8	12.9	44.5	28.6
	SSP5-8.5	973.0	-36.04	3014.6	12.9	45.2	28.9
	+0.69 °C	976.7	-34.83	2891.7	13.6	44.4	28.9
	+2.0 °C	975.8	-34.87	2848.5	13.1	44.0	28.7
	+3.0 °C	975.0	-35.05	2893.7	13.2	44.5	28.8
	+4.0 °C	975.1	-34.50	2857.8	13.1	44.3	28.6
	+5.0 °C	974.5	-34.96	2863.2	12.8	44.3	28.6

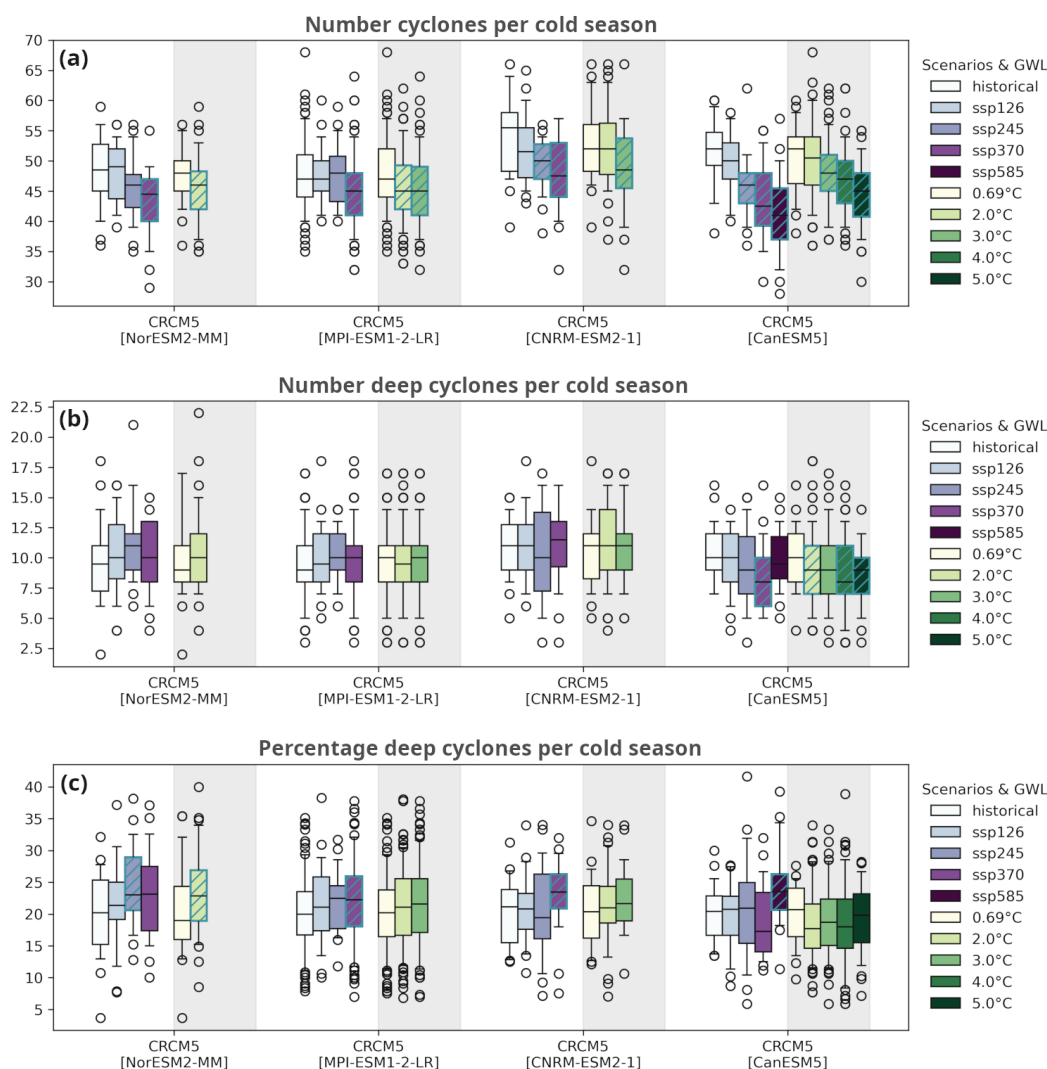


Figure 5. Mean cold-season (NDJFM) number of cyclones (a), number of deep cyclones (minimum MSLP anomaly below the historical 20th percentile) (b), and percentage of deep cyclones relative to the total number of cyclones (c) per cold season over the NENA region for the CMIP6-driven CRCM5 simulations. Comparisons are shown between the historical (1981-2010) and the end-of-century (2071-2100) periods for different SSP scenarios (SSP 1-2.6, SSP 2-4.5, SSP 3-7.0, SSP 5-8.5), as well as between global warming levels of 0.69 °C (historical baseline), and 2 °C, 3 °C, 4 °C, and 5 °C. Mann-Whitney U tests were performed for all future vs baseline SSP and GWL pairs, and boxes corresponding to statistically significant changes ($p < 0.05$) are highlighted with blue hatching.



260 4.4 Cyclone-associated precipitation

After examining projected changes in cyclone characteristics, we now turn to their associated precipitation. Even if changes in cyclone characteristics are limited, shifts in the background climate, such as warmer and moister conditions, can amplify their impacts. Figure 6a-d presents the mean accumulated cyclone-associated precipitation during the cold season of the historical period. All CMIP6-driven CRCM5 simulations show a similar large-scale pattern of accumulated cyclone-associated precipitation, with east-coast regions receiving the most precipitation over land from ETCs. It should be noted that precipitation from cyclones rejected during the cyclone identification steps for not meeting the selection criteria (e.g. cyclones with a lifespan under 24 hours, refer to Section 2.3) is not included; as a result, total cyclone-associated precipitation may be underestimated.

CMIP6-driven CRCM5 simulations show varying precipitation change patterns at a 2 °C warming level, with a general small increase over the East Coast and the Maritimes, albeit with varying magnitude and limited statistical significance (Fig. 6e-h). The CRCM5[CNRM-ESM2-1] simulation stands out, showing decreased precipitation over some northern regions and mostly insignificant changes. While the increase in precipitation is stronger and statistically significant over a larger area over the East Coast at a 3 °C warming level in most simulations, CRCM5[CNRM-ESM2-1] changes remain statistically insignificant (Fig. 6i-k). The five-member CRCM5[MPI-ESM1-2-LR] ensemble mean exhibits a clear and spatially coherent increase signal at both the 2 °C and 3 °C warming levels (Fig. 6f, i). However, it is worth noting that this pattern is mostly not statistically significant in any of the individual members (see Fig. S4), suggesting that the contribution of internal variability to the signal is relatively large. This highlights the importance of using multiple initial-conditions members in order to reach statistical significance and better understand the inter-model spread of cyclone-associated precipitation changes in Fig. 6.

Even though we project a decreased number of total cyclones over the NENA region (see Fig. 5a), cyclone-associated precipitation in the region is projected to generally increase, suggesting that individual cyclones bring more precipitation on average. To investigate this, we move from regional-scale patterns to individual cities, exploring local cyclone impacts. We selected two groups of large cities located in the NENA region : coastal ones (see Fig. 7 green-blue stars), and inland ones (see Fig. 7 orange-purple stars). Figure 7a presents the mean accumulated cyclone-associated precipitation per cold season for each city in the historical period, with the boxplots indicating the spread of precipitation amounts across individual years. Coastal cities tend to receive larger amount of precipitation from cyclones over the cold-season (November to March) (e.g. consistent with Fig. 6a-d). As suggested by the results in Fig. 6e-h, mean changes at a 2 °C warming level are generally slightly positive but show considerable variability among CMIP6-driven CRCM5 simulations, with some extreme values (boxplot whiskers) extending into negative changes (Fig. 7b). At the 3 °C warming level, positive changes are stronger for all cities, reflecting a more robust increase in accumulated cyclone-associated precipitation (Fig. 7c).

Figure 7d presents the mean accumulated precipitation *per cyclone* for each city in the historical period. On average, individual cyclones impacting coastal cities bring larger amount of precipitation than the ones impacting inland cities, consistent with the mean accumulated precipitation results. Mean changes at a 2 °C warming level show that individual cyclones are projected to bring larger amount of precipitation for all coastal and inland cities (Fig. 7e). Even with large variability in some coastal cities, the projected changes at a 2 °C warming level support the hypothesis that, despite fewer cyclones, each event

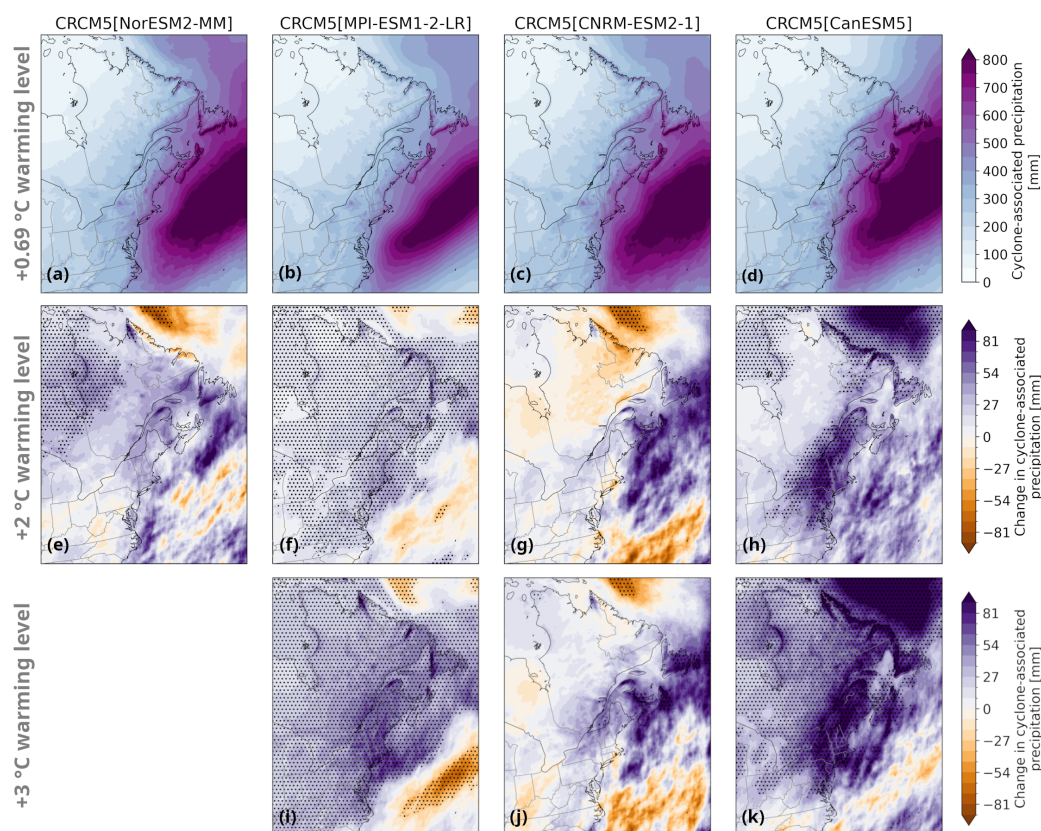


Figure 6. Mean historical (0.69 °C warming level) of cold-season (NDJFM) accumulated cyclone-associated precipitation (a-d) over the NENA region. Mean changes at a 2 °C global warming level, for all SSP scenarios combined (e-h). Mean changes at a 3 °C global warming level, for all SSP scenarios combined (i-k). Hatching indicates regions with statistically significant changes, with Mann-Whitney U test. The CRCM5[MPI-ESM1-2-LR] maps show the ensemble mean of five members. Hatching in this case indicates statistically significant changes based on pooled ensemble members.

is projected to deliver more precipitation. This hypothesis is further reinforced at the 3 °C warming level, where the positive
 295 signal becomes stronger in all cities (Fig. 7f).

The increase in precipitation per cyclone (Fig. 7) emerges more clearly across simulations than changes in accumulated
 cyclone-associated precipitation over the cold season (Fig. 6). This likely reflects the fact that seasonal accumulations depend
 not only on precipitation per cyclone but also on the number of cyclones affecting a given location. Indeed, reductions in
 cyclone frequency can partially offset increases in precipitation from individual events when precipitation is aggregated over
 300 an entire season. Nevertheless, although the number of cyclones affecting the NENA region may decrease, cyclone-associated
 precipitation generally increases, particularly at higher warming levels. This shift could increase cyclone impact at a local

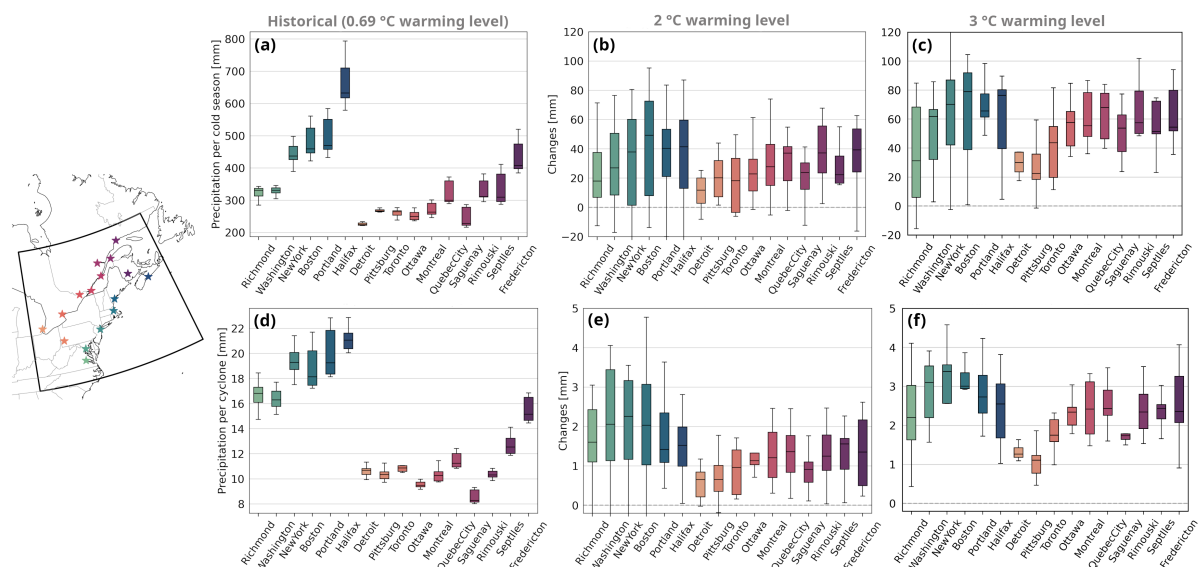


Figure 7. Mean historical (0.69 °C warming level) accumulated cyclone-associated precipitation per cold-season (NDJFM) (a), and the mean changes at a 2 °C (b) and 3 °C (c) warming levels, for all SSP scenarios combined, for cities in the NENA region. Mean historical (0.69 °C warming level) accumulated precipitation per cyclone (d), and the mean changes at a 2 °C (e) and 3 °C (f) warming levels, for all SSP scenarios combined. Results are shown for coastal cities (green-blue colors) and inland cities (orange-purple colors). All cities locations are shown as stars on the map with corresponding colors.

scale, as seasonal precipitation may be concentrated in fewer events with larger amounts, rather than distributed across more frequent smaller events. Future cyclone activity may therefore be characterized by fewer but wetter storms.

5 Discussion

Our historical evaluation indicates that CRCM5 provides a credible representation of the cold-season cyclone climatology over North America. Spatial patterns of track density and cyclogenesis closely match those identified in ERA5, although cyclone counts are generally higher, particularly in the CMIP6-driven historical simulations. Over NENA, cyclone lifespan, translation speed, and distance travelled also agree closely across datasets. For these characteristics, the spread among driving models is comparable to the internal-variability envelope derived from the five MPI members. By comparison, driving-model spread is larger than this envelope for minimum MSLP and wind speeds: the CMIP6-driven simulations generally produce deeper cyclones and stronger winds aloft, while all CRCM5 simulations produce markedly stronger 10-m winds than ERA5. These differences do not necessarily indicate biases in CRCM5 alone. ERA5 tends to underestimate strong ETC-associated surface winds (Chen et al., 2024; Cloutier-Gervais et al., 2026), and higher-resolution models often produce deeper cyclones and stronger cyclone-scale winds than their coarser-resolution counterparts (Willison et al., 2013; Zhang and Colle, 2018; Priestley



315 and Catto, 2022a). Overall, CRCM5 realistically represents ETC characteristics and spatial patterns, supporting its use for projections while warranting caution when interpreting absolute cyclone frequency and intensity.

The most robust projected response in our ensemble is a decline in cold-season ETC frequency over NENA, with statistically significant decreases in simulations driven by each of the four GCMs (Fig. 5a). This result is consistent with the general decrease in Northern Hemisphere ETC frequency projected by previous multimodel GCM studies (Chang et al., 2012; Priestley
 320 and Catto, 2022b). That this decline emerges consistently across driving models over the smaller NENA domain is notable. Cyclone counts at this scale are especially sensitive to shifts in cyclogenesis and track location, allowing the forced response to be more readily obscured by internal variability. Previous regional projections likewise show considerable spatial heterogeneity, with decreasing cyclone density over much of eastern North America and the western North Atlantic but little change or localized increases near the U.S. East Coast (Colle et al., 2013; Zhang and Colle, 2017; Zhang et al., 2026). Agreement across
 325 driving models in our ensemble masks substantial variability among individual realizations and in the spatial response. Within the five-member MPI subset, only two members show a statistically significant decrease in cyclone counts at 3°C of warming (Fig. S3), consistent with significant inter-member variability in track density (Fig. S1) and cyclogenesis (Fig. S2). This spatial variability is particularly relevant for local impacts, because shifts in preferred cyclone pathways can substantially alter cyclone exposure for specific areas even when regional-mean changes are modest.

330 Projected changes in cyclone characteristics are generally small and dependent on the driving GCM (Table 2), consistent with the IPCC Sixth Assessment Report's conclusion that future changes in ETC dynamical intensity are likely to be small (Seneviratne et al., 2021). Although few changes reach statistical significance, those that do consistently indicate lower minimum MSLP, stronger winds, or slower translation. Stronger winds and slower movement could both increase cyclone impacts, with slower-moving systems potentially prolonging local exposure to hazardous conditions (Crawford et al., 2023). Changes
 335 in absolute minimum MSLP, however, require particular caution because they can reflect changes in the background pressure field or cyclone-track location rather than dynamical intensification. Consistent with Chang (2014), removing the background pressure climatology materially altered the projected response: most statistically significant decreases in absolute minimum MSLP disappeared when intensity was expressed as an anomaly. This indicates that the absolute-pressure changes do not provide robust evidence of dynamical intensification. Nevertheless, the number of cyclones falling below the fixed historical
 340 20th-percentile anomaly threshold remains broadly unchanged even as total cyclone frequency declines. Consequently, the fraction of cyclones classified as intense tends to increase, although the absolute number of such cyclones does not.

Our analysis of cyclone-associated winds is also consistent with limited dynamical intensification. We characterized cyclone wind intensity using the maximum 10-m and 850-hPa wind speeds within 500 km of the cyclone center over its lifetime. Although this metric captures peak wind magnitude, it does not describe the spatial extent or duration of strong winds, their
 345 occurrence over land, or their distribution relative to the cyclone center. The weak response in peak wind speed found therefore does not preclude changes in wind hazard. For example, Priestley and Catto (2022b) find only small changes in maximum 850 hPa wind speed during Northern Hemisphere winter but a robust expansion of the area covered by above-threshold winds. Similarly, Zhang et al. (2026) project increased occurrence of extreme windstorms — events where surface wind speed exceeds



its historical 99th percentile over a large fraction of NENA land — yet do not find statistically significant changes in the
 350 maximum wind speed of these windstorms.

The implications of changes in cyclone activity depend not only on how often cyclones occur or on their dynamical characteristics, but also on the weather they produce. Cyclone-associated precipitation is therefore an important component of ETC potential impacts. Despite a decrease in cyclone frequency and limited changes in cyclone intensity, cyclone-associated precipitation shows a clear increase in our simulations. The increase is particularly evident when precipitation is considered
 355 on a per-cyclone basis, which is more consistent across simulations than the changes in cyclone intensity. This indicates that changes in cyclone-associated precipitation can be decoupled from changes in cyclone dynamics. Yettella and Kay (2017) similarly found that projected increases in cyclone-associated precipitation in the Northern Hemisphere were driven primarily by thermodynamics rather than dynamical changes, highlighting the importance of increased moisture availability in a warmer climate. Previous studies have also reported increases in cyclone-associated precipitation despite limited changes, or decreases,
 360 in cyclone frequency and intensity (Finnis et al., 2007; Kodama et al., 2019).

While the increase in precipitation per cyclone is relatively consistent across simulations, the seasonal precipitation response also depends on changes in cyclone frequency and spatial distribution. Seasonal accumulated cyclone-associated precipitation reflects both the precipitation produced by individual cyclones and the number and location of cyclones affecting a given region, making it more sensitive to internal variability. This is evident in the MPI ensemble, where the ensemble-mean accumulated
 365 precipitation shows a statistically significant increase in cyclone-associated precipitation, whereas changes among individual members are less consistent, with large variations in the spatial patterns (Fig. S4). Considering precipitation on a per-cyclone basis provides a clearer measure of the thermodynamic response to warming, as it is less directly affected by changes in the frequency and spatial distribution of cyclones.

The projected shift towards fewer ETC with greater precipitation per event suggests a larger fraction of seasonal precipitation
 370 may be delivered by individual events. This may have implications for precipitation-related hazards, as ETC can contribute substantially to extreme precipitation over North America (Hawcroft et al., 2018). However, an increase in cyclone-associated precipitation does not necessarily imply a comparable increase in precipitation extremes. Our analysis focuses on accumulated precipitation and does not directly characterize precipitation rates or extremes. Changes in precipitation-related hazards may therefore depend on those precipitation response that are not captured by the seasonal or per-cyclone accumulation examined
 375 in this study.

While these results provide evidence for changes in ETC activity and associated precipitation under warming, several sources of uncertainty should be considered when interpreting the projected responses. First, internal climate variability can substantially affect the magnitude and spatial pattern of the responses. As discussed at length above, this variability can obscure the forced signal, particularly at lower warming levels, and underscores the importance of large ensembles for detecting robust
 380 climate change signals.

A second source of uncertainty arises from biases inherited from the driving GCMs, as well as those intrinsic to the RCM itself. Priestley et al. (2023) showed that CMIP6 storm track density biases are largely associated with ocean biases, suggesting that applying bias correction to GCM output prior to downscaling may improve the representation of storm tracks and provide



more actionable information for climate adaptation. This is further supported by Labonté et al. (2025), who demonstrated that
 385 reducing biases in both atmospheric and oceanic surface driving data substantially improves the simulated representation of
 extratropical cyclones frequency along the east coast of North America.

Such biases are reflected in inter-model differences from large-scale boundary conditions, particularly sea ice concentration
 in regions such as the Hudson Bay and the Labrador sea. Sea ice may influence cyclone frequency, tracks, and intensity by
 altering surface heat fluxes and near-surface temperature gradients, which in turn affect surface baroclinicity, a key driver
 390 of extratropical cyclone development. Sea ice-driven modifications to large-scale circulation, including shifts in storm track
 position, can further influence cyclone trajectories (Hay et al., 2023). Similarly, inter-model differences in the position and
 strength of the jet stream, which is itself sensitive to sea ice extent, may substantially influence cyclone development and tracks
 (Köhler et al., 2025), as it acts as a waveguide for atmospheric disturbances.

The quality of the oceanic boundary conditions prescribed to the RCM is itself another source of uncertainty. Since the
 395 CRCM5 is not coupled to an ocean model, SSTs and sea ice concentration are prescribed directly from the driving GCM,
 meaning the oceanic forcing is constrained by the GCM's own ocean resolution. A coarse ocean resolution may miss important
 small-scale processes influencing extratropical cyclones. Moreno-Chamarro et al. (2021) have shown that higher ocean reso-
 lution improves the representation of key processes such as Gulf Stream dynamics, which modulates near-surface temperature
 gradients and baroclinicity. Although demonstrated over northern Europe, this finding reflects a broader limitation relevant to
 400 cyclone activity over the western North Atlantic.

6 Conclusion

In this study, we identified, tracked, and analyzed cold-season ETCs in the CRCM5–CMIP6 ensemble produced by Ouranos.
 Historical evaluation showed that the simulations reproduce the main features of the cyclone climatology, supporting their use
 for regional projections. The ensemble projects fewer but wetter cyclones with warming: the number of cyclones affecting
 405 NENA declines across driving models, yet total cyclone-associated precipitation tends to increase over NENA land areas,
 particularly at higher warming levels. At every major city examined, both total cold-season cyclone-associated precipitation
 and precipitation per cyclone increase, consistent with thermodynamic expectations of greater moisture availability in a warmer
 atmosphere.

By contrast, evidence of ETC dynamical intensification is less consistent and depends on the driving model and diagnostic
 410 considered. Most apparent deepening in minimum sea-level pressure vanishes after accounting for the local pressure clima-
 tology. Changes in peak winds and mean translation speed are also generally small. Where statistically significant, however,
 these changes indicate stronger winds or slower translation, either of which could increase impacts. Moreover, the number
 of cyclones meeting a fixed historical pressure-anomaly intensity criterion remains broadly unchanged despite declining total
 counts. Thus, fewer cyclones overall does not necessarily imply fewer intense cyclones.

415 Internal variability substantially affects the spatial expression and detectability of projected changes in cyclone activity.
 For instance, agreement across driving models on declining NENA cyclone counts coexists with considerable spread among



initial-condition members in cyclogenesis and track-density responses. These spatial differences matter for local impacts: shifts in preferred cyclone pathways could increase exposure in historically less affected areas, even as cyclone frequency declines across NENA overall.

420 This study provides a broad initial assessment of ETCs in the CRCM5–CMIP6 ensemble, establishing a foundation for more detailed investigations. Further analysis of projected changes in the most intense storms and their associated precipitation and wind extremes would help clarify how cyclone hazards evolve with warming and inform adaptation planning.

Code and data availability. The data and code used in this study are available from the authors upon request.

Author contributions. DP, CM, ML, and MPL designed the study. CM performed the experiments. MPL and CM conducted most of the data
425 analysis, and MPL prepared the figures. MPL, OA and CM wrote most of the manuscript. All authors contributed equally to the interpretation of the results.

Competing interests. The contact author has declared that neither of the authors has any competing interests.

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430 (Université du Québec à Montréal) with the collaboration of Environment and Climate Change Canada. CRCM5 computations were made on the supercomputers beluga and narval managed by Calcul Québec and the Digital Research Alliance of Canada (alliancecan.ca). The operation of this supercomputer received financial support from Innovation, Science and Economic Development Canada and the Ministère de l'Économie et de l'Innovation du Québec.



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