



Future Projections of Extreme Wind and Precipitation Associated With Extratropical Cyclones Over North America Using Regional Climate Simulations

Victorien De Meyer^{1,2}, Alejandro Di Luca^{1,2}, and Ting-Chen Chen³

¹Centre ESCER, Université du Québec à Montréal, Montréal, QC, Canada

²Department of Earth and Atmospheric Sciences, Université du Québec à Montréal, Montréal, QC, Canada

³Moody's, London, United Kingdom

Correspondence: Victorien De Meyer (victorien.demeyer@gmail.com)

Abstract. Extratropical cyclones (ETCs) are a primary driver of extreme precipitation and near-surface wind speed across the mid-latitudes, with major societal and economic consequences over large parts of North America. Yet assessing the future impact of ETCs through the quantification of changes in their associated extremes remains a major challenge, owing to the coarse resolution of global models and the complex interplay of dynamical and thermodynamic mechanisms. Three regional climate simulations from the CRCM6-GEM5 model, covering the NA-CORDEX domain at 12 km grid spacing, and driven by boundary conditions from the EC-Earth3-Veg, MPI-ESM1-2-HR, and MIROC6 CMIP6 atmospheric-ocean general circulation models (AOGCMs), alongside an ERA5-driven simulation, are used to (i) assess the representation of ETC-associated extreme precipitation and winds relative to the ERA5 reanalysis and (ii) project their late-century changes under the SSP3-7.0 scenario. To this end, a novel extreme exceedance framework is used to isolate changes into three physically interpretable drivers: the intensity of ETC-associated extremes, the background extreme threshold, and the frequency of co-occurrence of ETCs and extremes. CRCM6-GEM5 systematically produces stronger hourly extremes than the ERA5 reanalysis, for both precipitation and wind speed. The driving boundary conditions constitute the dominant source of inter-simulation spread in accumulated extreme exceedances, primarily through their control on the frequency of extreme ETC events. Under future climate forcing, all three simulations robustly project an amplification of ETC-associated extreme precipitation over northeastern North America and the adjacent northwestern North Atlantic, driven by a concurrent intensification in individual ETCs and increased occurrence. Elsewhere, large inter-simulation spread in the occurrence response precludes robust conclusions on projected changes. Applying the framework to the most extreme precipitation-producing systems impacting northeastern North America in the historical and future climates, we found a consistent intensification across multiple exceedance metrics in all three simulations. Future changes in ETC-associated extreme wind speed, however, show little coherence across simulations and are dominated by a redistribution of occurrence rather than any systematic intensification. These results underscore the critical role of large-scale boundary conditions in shaping regional projections.



1 Introduction

Extratropical cyclones (ETCs) are a fundamental component of mid-latitude climate variability. These large-scale low-pressure systems are capable of traveling thousands of kilometers over several days, shaping regional climate patterns and enabling the meridional transport of energy and moisture essential for regulating the Earth's climate system (Seneviratne et al., 2021; Chang et al., 2002). Their formation and intensification are primarily driven by the baroclinicity of the mid-latitude atmosphere, shaped by temperature contrasts such as the equator-to-pole gradient and land-sea differences (Charney, 1947; Tierney et al., 2018). Diabatic processes, such as latent heat release, constitute another key driver of ETC development, with growing evidence that their role is especially pronounced in the most intense systems (Wernli and Gray, 2024).

Assessing the risk associated with ETCs remains a central challenge for both the public sector (e.g., electric power generation and distribution, water management) and the private sector (e.g., the insurance and reinsurance industries, mining companies). Strong near-surface wind speeds and heavy precipitation frequently result in significant insured losses through flooding, landslides, windstorms, and coastal storm surge, threatening both infrastructure and human life (Chen and Di Luca, 2025; Letson et al., 2021; Haylock, 2011; Dowdy and Catto, 2017; Gliksman et al., 2023; Browning, 2004; Golden and Snow, 1991; Changnon, 2009). ETCs are responsible for around 90% of total cool-season precipitation in the mid-latitudes (Zhang and Colle, 2017; Hawcroft et al., 2012) and constitute a primary driver of extreme winds and precipitation (Catto and Pfahl, 2013; Zhang and Colle, 2017; Booth et al., 2015; Chen et al., 2022; Messmer and Simmonds, 2021; Owen et al., 2021; Pfahl and Wernli, 2012; Ulbrich et al., 2009; Utsumi et al., 2017; Chen and Di Luca, 2025). Over North America, ETCs and associated fronts contribute to more than 60% of all hourly precipitation extremes (Utsumi et al., 2017), a fraction that increases northeastward to reach more than 80% (Pfahl and Wernli, 2012; Agel et al., 2015).

ETCs warrant particular attention given their pronounced sensitivity to anthropogenic climate change, which can substantially alter their dynamical and structural properties, as well as their impacts (Catto et al., 2019; Ulbrich et al., 2009). In a warming climate, the baroclinicity of the atmosphere is expected to be altered through a decrease in the near-surface meridional temperature gradient driven by polar amplification and a strengthening of the upper-tropospheric temperature gradient (Shaw et al., 2016). In addition, atmospheric moisture content will increase with rising temperatures, potentially amplifying diabatic processes within the storms (Michaelis et al., 2017; Willison et al., 2015; Marciano et al., 2015). Given these competing effects, substantial uncertainty exists about how ETC frequency, location, and intensity will respond to anthropogenic forcing (Tierney et al., 2018; Chen et al., 2024a; Binder et al., 2023; Shaw et al., 2016).

Future projections nonetheless indicate an overall decline in ETC frequency owing to changes in low-level baroclinicity (Basu and Sauchyn, 2024; Sinclair and Catto, 2023; Seiler and Zwiers, 2016; Colle et al., 2013; Chang, 2013), alongside a poleward shift of cyclone tracks in both hemispheres (Bengtsson et al., 2006; Catto et al., 2019; Priestley and Catto, 2022a; Tamarin-Brodsky and Kaspi, 2017). However, changes in the frequency of particularly intense cyclones remain more uncertain and sensitive to the definition of extreme (Hawcroft et al., 2018; Pepler and Dowdy, 2021; Ulbrich et al., 2009; Chang, 2013; Catto et al., 2019; Garin et al., 2024; Seiler and Zwiers, 2016; Priestley and Catto, 2022a; Colle et al., 2015; Dolores-Tesillos and Pfahl, 2024).



Projected changes in extreme precipitation associated with ETCs are primarily governed by thermodynamic processes, with rates expected to scale with changes in near-surface atmospheric moisture content at approximately $7\% K^{-1}$ following the Clausius–Clapeyron relation (Seneviratne et al., 2021; Fowler et al., 2021; De Meyer and Roca, 2021; Martinkova and Kysely, 2020; Trenberth and Shea, 2005; O’Gorman and Schneider, 2009; Westra et al., 2014). However, especially at short
60 timescales, dynamical feedbacks within ETCs can amplify this response: for example, enhanced latent heating strengthens low-level potential vorticity anomalies and deepens cyclonic ascent (Büeler and Pfahl, 2019; Sinclair et al., 2020), while intensified warm conveyor belts promote moisture flux convergence and further enhance diabatic heating rates (Joos et al., 2023; Binder et al., 2023). These feedbacks preferentially amplify the most extreme events (Pfahl et al., 2015). A broad body of literature documents the future intensification of ETC-related extreme precipitation (Zhou et al., 2024; Sinclair and Catto, 2023; Kodama
65 et al., 2019; Catto et al., 2019; Zhang and Colle, 2018; Hawcroft et al., 2018; Marciano et al., 2015).

Regarding extreme wind speeds associated with ETCs, confidence in their future changes remains generally low (Catto et al., 2019): while several studies identify regional increases in ETC-related wind speed (Manning et al., 2024, 2023; Priestley and Catto, 2022a; Marciano et al., 2015; Chinta et al., 2025), many others report mixed signals and substantial model spread (Li et al., 2022; Outten and Esau, 2013; Zscheischler et al., 2021; Ranson et al., 2014; Bengtsson et al., 2009; Della-Marta and
70 Pinto, 2009).

Atmospheric-ocean general circulation models (AOGCMs) are the primary tools used to investigate future changes in ETC characteristics and their associated wind and precipitation extremes. Yet, their coarse horizontal resolution — typically exceeding 100 km — constitutes a fundamental limitation for simulating realistic ETC intensities and associated extremes. AOGCMs generally capture the broad features of mid-latitude storm tracks (Priestley et al., 2020; Priestley and Catto, 2022a; Seneviratne
75 et al., 2021), yet they underestimate the frequency of the most intense cyclones, their explosive development, and the extreme precipitation and wind speeds they produce (Colle et al., 2013; Jiaxiang et al., 2020; Priestley et al., 2020; Zappa et al., 2013; Seneviratne et al., 2021; Seiler and Zwiers, 2016). These biases stem in part from the inability of coarse models to resolve key processes such as SST gradients (Booth et al., 2012), latent heat release within ETCs, and dynamical interactions with the jet stream (Colle et al., 2015). These processes play a pivotal role in the intensification of ETCs, modulate the drivers of extreme
80 wind, and are better captured at higher horizontal resolution (Büeler and Pfahl, 2017; Attinger et al., 2021; Willison et al., 2015; Priestley and Catto, 2022b; Iles et al., 2020). Many of the storm-scale processes responsible for the most intense precipitation rates cannot be captured regardless of the quality of subgrid-scale parameterizations. Increasing horizontal resolution has been shown to substantially improve both the simulated frequency and magnitude of extreme precipitation (Jong et al., 2023; Bador et al., 2020; Zobel et al., 2018; Wehner et al., 2010, 2014; Wiel et al., 2016; Lucas-Picher et al., 2017; Di Luca et al., 2016).

85 Regional climate models (RCMs) address these limitations by dynamically downscaling AOGCM output over a limited domain at 10–50 km grid spacing, enabling the development of fine-scale features poorly resolved or absent in AOGCMs (Giorgi, 2019; Rummukainen, 2010; Tapiador et al., 2020). RCMs have been shown to reduce biases in the frequency of the most intense ETCs as well as explosive deepening events (Zhang and Colle, 2018; Poan et al., 2018; Seiler et al., 2018; Colle et al., 2015; Long et al., 2009; Di Luca et al., 2016). For extreme precipitation, the added value is well established,
90 with substantial improvements in both frequency and magnitude documented across multiple studies (Zhang and Colle, 2018;



Shahi et al., 2025; Zobel et al., 2018; Dong et al., 2021; Iles et al., 2020; Marciano et al., 2015). For extreme winds, RCMs allow the representation of mesoscale features such as cold jets (Manning et al., 2022) and better resolve diabatic processes leading to higher wind speeds (Willison et al., 2013), although the overall added value remains more nuanced, as RCMs do not systematically outperform AOGCMs for mean and extreme wind speeds (Morris and Diaconescu, 2025; Outten and Esau, 2013). Nevertheless, RCMs carry their own structural biases, primarily arising from their physical parameterizations and numerical schemes, which have been identified as the dominant source of spread across a wide range of RCM configurations (Wamahiu et al., 2025). While RCMs offer clear advantages, they still rely on relatively coarse AOGCM driving data and may inherit its biases. In addition, RCMs are computationally expensive, which limits the number of AOGCMs that can be used to downscale all range of climate extreme events.

Several studies have investigated future changes in ETC-related precipitation and wind extremes over North America using models at higher resolution than typical AOGCMs, but these efforts have generally focused on specific subregions such as the eastern seaboard (Colle et al., 2015) or the northeastern part of the continent (Zhou et al., 2024). Yet North America as a whole hosts a diverse range of ETC types—Colorado Lows, Alberta Clippers (Poan et al., 2018), Nor’easters (Chen et al., 2025), and tropical cyclones undergoing extratropical transition (Garin et al., 2024)—whose behaviour is shaped by the continent’s complex topography and numerous large water bodies, motivating an assessment at the continental scale. Our objective is not only to quantify how ETC-related extreme wind and precipitation will change across North America, but to identify the physical origin of these changes. To address this, we use the sixth version of the Canadian Regional Climate Model (CRCM6-GEM5) at 12 km horizontal grid spacing over the CORDEX North American domain, analyzing three continuous, 120-year CRCM6-GEM5 simulations driven by three different Coupled Model Intercomparison Project Phase 6 (CMIP6) AOGCM simulations. We extend an existing framework for quantifying ETC-related extreme exceedances by decomposing changes into three physically interpretable contributions: (i) the mean intensity of ETC-associated extremes, (ii) the background extreme threshold, and (iii) the occurrence of ETC-associated extreme events. We first apply this decomposition to evaluate the simulations against the ERA5 reanalysis over a recent-past period, where the three contributions jointly characterize model fidelity. We then use the same framework to attribute the projected changes, which we resolve through their intensity and occurrence contributions.

The paper is structured as follows. Section 2 describes the data and the methodology used to assess changes in ETC-related extreme wind and precipitation. Section 3 presents the results, beginning with an evaluation of the historical CRCM6 simulations relative to ERA5, followed by an assessment of projected future changes and an analysis of the most extreme individual ETCs impacting a region in northeastern North America. Finally, discussion and concluding remarks are provided in Sections 4 and 5.



2 Data and methods

2.1 ERA5 Reanalysis data

ERA5 is a global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts that combines observations with a numerical weather model to provide a consistent, quasi-continuous spatial and temporal representation of the atmospheric state (Hersbach et al., 2020). ERA5 is based on the Integrated Forecasting System (IFS) Cycle 41r2 model, which has a horizontal resolution of 31 km and uses a total of 137 levels in the vertical, and ERA5 provides data at hourly intervals on a regular latitude–longitude grid with a grid spacing of 0.25°.

In this study, the ERA5 reanalysis data are used with a double objective. First, ERA5 is used as the reference against which the regional climate model simulations are compared, in terms of the frequency of ETCs and their associated wind and precipitation fields. Second, the ERA5 reanalysis data are used to drive one of the CRCM6-GEM5 simulations.

Reanalysis have been widely used for ETC evaluation in previous studies (Hodges et al., 2011; Chen et al., 2024b; Priestley et al., 2020; Zappa et al., 2013; Di Luca et al., 2016; Poan et al., 2018). The variables used here are: (i) mean sea level pressure (MSLP) to track extratropical cyclones, (ii) 10-m near-surface wind speed (WS), and (iii) hourly precipitation rate (PR).

2.2 CRCM6-GEM5 simulated data

This study employs multiple simulations performed using the sixth version of the Canadian Regional Climate Model (CRCM6-GEM5). All CRCM6-GEM5 simulations were conducted at a horizontal grid spacing of 0.11° on a rotated-pole grid covering the CORDEX North American domain (Giorgi and Gutowski, 2015). This version uses 71 hybrid vertical levels, with the model top at 10 hPa. It uses the Kain–Fritsch deep convection scheme (Kain and Fritsch, 1990), with additional updates from McTaggart-Cowan et al. (2019b); an elevated-convection scheme (McTaggart-Cowan et al., 2020); and the Bechtold scheme for shallow convection (Bechtold et al., 2001). It also uses the Turbulent Kinetic Energy (TKE) scheme for the planetary boundary layer (Bélair et al., 1999; McTaggart-Cowan and Zadra, 2015; McTaggart-Cowan et al., 2019a) and the Monin–Obukhov (M–O) scheme for the surface layer (Whittaker et al., 2025). The Freshwater Lake model (FLake) is used to represent lake temperatures (Martynov et al., 2012; Mironov et al., 2010), while sea ice and glaciers are represented using single-layer diffusion and force-restore models. The CRCM6-GEM5 used here is based on version 5.1.1 of the Global Environmental Multiscale model (GEM5), which serves as the operational numerical weather prediction system at the Meteorological Service of Canada. GEM5 is developed by Environment and Climate Change Canada and is described in McTaggart-Cowan et al. (2019a). Similar configurations of the CRCM6-GEM5 model have been used in several recent studies addressing spatial spinup (Roberge et al., 2024), surface-layer winds (Whittaker et al., 2025), cloud and precipitation processes (Ghosh et al., 2025; Veilleux et al., 2025), mesoscale convective systems (Alpizar et al., 2026), and characteristics of intense low-pressure systems against AOGCMs (?).

In this study, the CRCM6-GEM5 simulations were driven both at the lateral boundaries and within the interior of the domain (via spectral nudging) using atmospheric and surface conditions from four global datasets: the ERA5 reanalysis, as well as three CMIP6 AOGCMs, namely EC-Earth3-Veg (Döscher et al., 2022), MPI-ESM1-2-HR (Müller et al., 2018), and MIROC6



Table 1. Summary of CRCM6-GEM5 simulations used in this study. All simulations use the CRCM6-GEM5 model at 12 km grid spacing.

Name	Driving data	Spectral nudging variables	Period
CRCM6 _{ERA5}	ERA5 reanalysis	U, V, T	1980–2023
CRCM6 _{EC-Earth3-Veg}	EC-Earth3-Veg	U, V	1980–2100
CRCM6 _{MPI-ESM1-2-HR}	MPI-ESM1-2-HR	U, V	1980–2100
CRCM6 _{MIROC6}	MIROC6	U, V	1980–2097

(Tatebe et al., 2019). The historical, ERA5-driven simulation spanned the period from September 1979 to December 2023, while the AOGCM-driven simulations were performed between September 1979 and December 2100, with the exception of the MIROC6-driven simulation that ended in April 2098. Note that the period from September to December 1979 is used as a temporal spin-up and is not used in the following simulation analysis. From 2014 onward, all three AOGCM simulations were performed using the SSP3-7.0 scenario (van Vuuren et al., 2014). Spectral nudging is applied to horizontal winds (and additionally to temperature in the ERA5-driven simulation) above 700 hPa, targeting only large-scale waves with wavelengths greater than 200 km using a relaxation time scale of 8 hours. This approach ensures consistency between the large-scale circulation of the regional simulations and that of the driving data.

The analysis is based on simulated hourly fields of mean sea level pressure (*MSLP*), wind speed (*WS*), and precipitation (*PR*) for both a common historical period (1980–2014) and a future period (2063–2097). Table 1 summarizes the datasets used.

2.3 Identifying and tracking extratropical cyclones

ETCs are identified and tracked with an algorithm developed at UQAM and applied in previous studies of North American storm tracks (e.g., Chen et al., 2022; Chartrand and Pausata, 2020; Chen et al., 2024b). The algorithm operates on the hourly MSLP field, which is first spatially smoothed at each time step with an unweighted box filter over a square window of ~ 400 km on average. Although the filter is isotropic in grid-coordinate space rather than in physical space, an imperfect assumption on the rotated latitude–longitude grid of CRCM6-GEM5 model, the resulting displacements of cyclone centers are negligible compared to the 1000-km radius used to collocate precipitation and wind extremes with the tracks.

At each time step, candidate cyclone centers are identified as local minima of the smoothed MSLP. To be retained, a center must correspond to a local minimum within a 200 km great-circle radius, be located more than 5° from the equator, and have a value below 1000 hPa. Tracks are then built sequentially by linearly extrapolating each cyclone’s previous displacement to predict its next position, and matching it to the nearest candidate center within 200 km of that prediction. Unmatched candidates initiate new tracks. Only tracks lasting at least 24 h and traveling at least 1000 km are retained. Several aspects of this configuration are deliberately permissive: identification relies on MSLP alone, the minimum central pressure of 1000 hPa is relatively high, and the minimum lifetime and travel distance are kept short. Because our analysis targets the precipitation



and wind extremes associated with ETCs rather than providing a climatological characterization of the cyclones themselves,
180 an overestimation of the cyclone count is preferable to missing systems that could eventually contribute to such extremes.

By design, this tracking methodology does not discriminate between extratropical and tropical cyclones, so that the latter
are also detected. Tropical cyclones form an integral part of the analysis, particularly within their source basins (the Gulf of
Mexico, the Caribbean Sea, the tropical North Atlantic, and the eastern North Pacific) and during their season of predominance
in summer and autumn. Nonetheless, ETCs remain the predominant systems across the North American domain and throughout
185 the year; we therefore retain the ETC designation throughout, while the regions and seasons subject to tropical cyclone activity
are discussed specifically where relevant.

2.4 Quantifying the contribution of ETCs to extremes

The methodology presented here follows closely from Chen and Di Luca (2025). The severity of ETCs is quantified through
the extreme exceedance variable $EE_V(x, t)$, defined at grid point x and time t as the amount by which the variable V (either
190 PR or WS) exceeds a local extreme threshold $V_{th}(x)$:

$$EE_V(x, t) = \begin{cases} V(x, t) - V_{th}(x), & \text{if } V(x, t) > V_{th}(x), \\ 0, & \text{if } V(x, t) \leq V_{th}(x). \end{cases} \quad (1)$$

The extreme threshold $V_{th}(x)$ can be defined using a high percentile calculated locally at each grid point or using an absolute,
spatially uniform threshold.

The climatological mean of near-surface wind and precipitation extreme exceedances $\overline{EE_V}(x)$ can then be quantified as:

$$195 \quad \overline{EE_V}(x) = \frac{1}{T} \sum_{t=1}^T EE_V(x, t) = \frac{1}{T} EE_{V, cum}(x) \quad (2)$$

where T is the total number of hours in the period of interest, and $EE_{V, cum}(x)$ denotes the accumulated extreme exceedances
at grid point x . Considering two datasets $d1$ and $d2$, the difference of $EE_{V, cum}(x)$ is given by:

$$\Delta EE_{V, cum}(x) = EE_{V, cum}^{d1}(x) - EE_{V, cum}^{d2}(x) \quad (3)$$

where Δ denotes the difference between the two datasets. Eq. (3) can be used to evaluate simulated errors (when $d1$ and $d2$
200 are respectively derived from a simulation and a reference dataset) or future changes (when $d1$ and $d2$ are respectively derived
from a future and a historical period from some simulation). Fixing ERA5 as a reference dataset, we can write:

$$\Delta EE_{V, cum}(x) = EE_{V, cum}^{SIM}(x) - EE_{V, cum}^{ERA5}(x) \quad (4)$$

where $\Delta EE_{V, cum}(x)$ quantifies the departure of simulation SIM from ERA5. Note that the previous equation can also be
written as:



$$\Delta EE_{V,cum}(x) = \sum_{t=1}^T (V_{th}^{SIM}(x,t) - V_{th}^{ERA5}(x,t)) - T(V_{th}^{SIM}(x) - V_{th}^{ERA5}(x)) \quad (5)$$

Which explicitly shows that the differences in extreme exceedance are explained by two terms: one related to differences in the threshold value and another related to differences in hourly values. In this study, we are interested in the extreme exceedances that are associated with ETCs. That is, assuming that $EE_{V,cum} = EE_{V,cum|ETC} + EE_{V,cum|nonETC}$, we have :

$$\begin{aligned} \Delta EE_{V,cum|ETC}(x) &= EE_{V,cum|ETC}^{SIM}(x) - EE_{V,cum|ETC}^{ERA5}(x) \\ &= \sum_{t=1}^{T_{ETC}^{SIM}(x)} V_{th}^{SIM}(x,t) - \sum_{t=1}^{T_{ETC}^{ERA5}(x)} V_{th}^{ERA5}(x,t) \\ &\quad + T_{ETC}^{ERA5}(x) \cdot V_{th}^{ERA5}(x) - T_{ETC}^{SIM}(x) \cdot V_{th}^{SIM}(x) \end{aligned} \quad (6)$$

Where $T_{ETC}^{SIM}(x)$ and $T_{ETC}^{ERA5}(x)$ give the number of times at the grid point x when an ETC was present for the simulation *SIM* and the ERA5 products respectively. In addition, the sum over all values when an ETC is present can be expressed as the product between the number of ETCs producing an extreme exceedance and their average accumulated extreme exceedance:

$$\sum_{t=1}^{T_{ETC}^{SIM}(x)} V_{th}^{SIM}(x,t) = V_{cum|ETC}^{SIM}(x) = T_{ETC}^{SIM}(x) \cdot \overline{V_{ETC}^{SIM}}(x) \quad (7)$$

And replacing Eq. (7) in Eq. (6) we obtain:

$$\begin{aligned} \Delta EE_{V,cum|ETC}(x) &= T_{ETC}^{ERA5}(x) \cdot \Delta \overline{V_{ETC}}(x) \\ &\quad - T_{ETC}^{ERA5}(x) \cdot \Delta V_{th}(x) \\ &\quad + \overline{EE_{V|ETC}^{SIM}}(x) \cdot \Delta T_{ETC}(x) \end{aligned} \quad (8)$$

As a result, Eq. (8) shows that a simulation can produce an accumulated extreme exceedance associated with ETCs that is larger than ERA5 due to one or more of the following::

1. Intensity term, $T_{ETC}^{ERA5}(x) \cdot \Delta \overline{V_{ETC}}(x)$: the average extreme value ($\overline{V_{ETC}}$) associated with ETCs is larger in the simulation than in ERA5.
2. Threshold term, $-T_{ETC}^{ERA5}(x) \cdot \Delta V_{th}(x)$: the background extreme threshold (V_{th}) is lower in the simulation than in ERA5.
3. Occurrence term, $\overline{EE_{V|ETC}^{SIM}}(x) \cdot \Delta T_{ETC}(x)$: the number of hours with both an ETC and an extreme value (T_{ETC}) is larger in the simulation than in ERA5.



Because each term is weighted by the local ETC activity (through $T_{\text{ETC}}^{\text{ERA5}}(x)$ or $\overline{EE_V^{\text{SIM}}}(x)$), the decomposition emphasizes regions where ETCs consistently produce extreme conditions, providing a more physically meaningful perspective than raw intrinsic differences alone. Throughout this study, $V_{\text{th}}(x)$ is set to the 99th percentile of V at grid point x , computed over all hours of the 35-year historical period (1980–2014). No conditioning is applied: dry and low-wind hours are included, so that $V_{\text{th}}(x)$ is an all-hour percentile rather than a conditional one. This choice is deliberate and ensures that the exceedance sample comprises, by construction, the same fraction of time steps—the top 1%—at every grid point and in every dataset, so that the ETC-associated accumulation and its underlying occurrence and mean intensity contributions remain comparable across simulations and reanalysis. A wet-hour threshold, by contrast, would be computed over samples whose size varies with the frequency of wet or windy hours, artificially inflating the percentile where such hours are rare (Schär et al., 2016) and undermining this comparability. The 99.9th percentile is also used in Section 3.3, and both percentile values are shown in Figs. S2–S5.

In Section 3.1 of the results, we focus on the evaluation of simulations against ERA5, where Δ denotes the difference between a given historical CRCM6 simulation and ERA5. In this evaluation context, the threshold term plays an essential role: ERA5 (~ 31 km) and CRCM6-GEM5 (~ 12 km) operate on markedly different native grids, which translate into systematically different hourly intensities and, consequently, different 99th percentiles. Comparing exceedances above each dataset’s own threshold—rather than raw absolute intensities—is therefore preferable, as it isolates how each dataset represents its own upper tail. To enable a consistent comparison and thereby evaluate Eq. (8), accumulated precipitation and wind at each CRCM6-GEM5 grid point were conservatively regridded onto the ERA5 grid. The count of time steps during which an ETC was located within 1000 km of a grid point with precipitation or wind was regridded using a nearest-neighbor approach, whereas percentile values and the ETC density field were interpolated using bilinear interpolation.

Section 3.2 of the results examines the difference between the historical and future CRCM6-GEM5 simulations, where Δ denotes the difference between the future and historical periods. As historical and future simulations share the same horizontal grid, no interpolation was required. In this context, the 99th percentile is held fixed at its historical value, so that future exceedances are computed against the historical threshold rather than a future-period one. Two considerations motivate this choice. First, fixing the threshold isolates the pure intensity response of ETC-related extremes; allowing the threshold to evolve would reference future ETC extremes against a moving baseline that itself contains the climate change signal, blurring the physical interpretation of the intensity term. Second, the all-hour 99th percentile is defined as the intensity exceeded during a fixed fraction of all time steps, so that its change between two periods reflects not only the intensification of individual hourly values but also any change in the number of hours reaching high intensities (Schär et al., 2016). A reduction in ETC occurrence at unchanged storm intensity, for instance, removes peak hours from the sample and lowers the threshold, so that a genuine intensification of individual events can be masked by a concurrent reduction in their occurrence (André et al., 2024). Recomputing the percentile in the future period would therefore make the threshold itself carry part of the climate change signal, referencing future extremes against a baseline that has already absorbed it. With $\Delta V_{\text{th}}(x) = 0$ by construction, the threshold term in Eq. (8) vanishes, and the intensity term is mathematically equivalent to $T_{\text{ETC}}^{\text{hist}}(x) \cdot \Delta \overline{EE_{V|\text{ETC}}}(x)$, the



change in the mean exceedance above the fixed historical threshold conditional on ETC presence. We retain the notation of Eq. (8) throughout Section 3.2 for consistency.

3 Results

3.1 Evaluation of historical ETC extreme exceedance relative to ERA5

265 This section examines differences in ETC-related extreme events between ERA5 and the four historical CRCM6 simulations, in order to evaluate the potential added value of horizontal resolution and quantify the influence of the large-scale conditions provided by the driving AOGCMs.

Characterizing the spatial distribution of all ETCs provides valuable context for interpreting regional differences in extreme precipitation and surface wind accumulation. In addition, such an analysis offers a first-order assessment of differences among
270 simulations in their ability to generate and propagate low-pressure systems. Figure 1a shows the ETC track density derived from the storm-tracking algorithm applied to ERA5 over the 1980–2014 period. A pronounced maximum in track density (>5 ETCs per 50 000 km² per month) is found over the North Atlantic, south and east of Greenland. This region corresponds to the convergence of major North American storm tracks, including Nor'easters propagating along the eastern coast of North America predominantly during winter (see contour lines in Fig. S6), Alberta Clippers originating east of the Rocky Mountains, and Colorado Lows developing over the central United States and occurring mainly in spring. Another region of particularly
275 high ETC density is located east of Hudson Bay, with maxima occurring mainly during autumn. This feature is associated with the so-called Hudson Bay Low, a large, semi-permanent, relatively weak low-pressure system forming over the region (Albright et al., 1995; Moreno-Ibáñez et al., 2021; Gachon et al., 2003). A third, more moderate density maximum is identified over the northeastern Pacific, in the Gulf of Alaska, which is characteristic of extratropical cyclones associated with the Aleutian Low
280 and occurs predominantly during the cold season.

The CRCM6 simulation driven by ERA5 (CRCM6_{ERA5}; Fig. 1b) reproduces the large-scale spatial distribution of ETC density found in ERA5, albeit with slightly lower densities over the Gulf of Alaska, Greenland, and Hudson Bay, and moderately higher densities east of Greenland and over the U.S. Midwest on the lee side of the Rocky Mountains.

The three CRCM6 simulations driven by AOGCMs exhibit some similarities with CRCM6_{ERA5} in the spatial pattern of bias,
285 including negative biases over the Gulf of Alaska and around the Hudson Bay, and a positive bias over the U.S Midwest. In addition, all three simulations show positive biases along the eastern North American coast, in the Gulf of Mexico, and in the eastern North Pacific tropical cyclone basin, with magnitudes that differ substantially depending on the driving AOGCM. For example, positive biases in ETC density along the eastern seaboard are particularly strong in CRCM6_{MIROC6}. While ERA5 and CRCM6_{ERA5} show very few ETC centers south of 30°N, the AOGCM-driven simulations exhibit notable densities in this
290 latitude band, especially for CRCM6_{MIROC6}, with a pronounced maximum west of the Gulf of Mexico.

Seasonal analyses of ETC density biases (Fig. S6) further highlight these differences. During winter, the primary season for ETC activity, all simulations exhibit predominantly negative density biases over most of the domain. In contrast, summer shows strong positive density biases east of the Rocky Mountains and, for CRCM6_{MIROC6}, in the Gulf of Mexico and along the

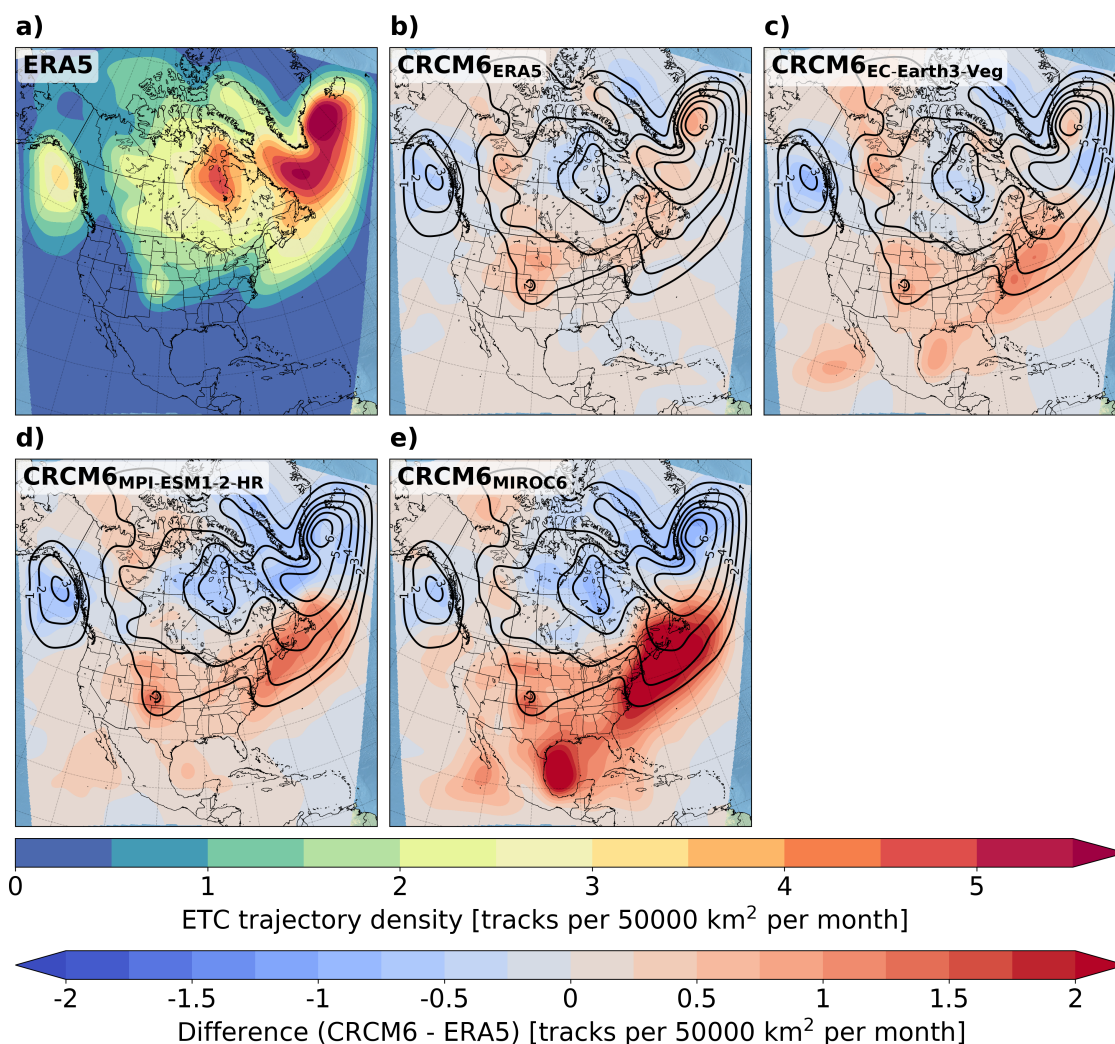


Figure 1. ETC trajectory density calculated using a 200 km Gaussian kernel bandwidth for the historical period (1980–2014). (a) Reference climatology from ERA5. (b–e) Differences between regional simulations and ERA5.

entire eastern coast, a signal that persists into autumn, coinciding with the peak of the Atlantic tropical cyclone season. During spring, biases are mainly negative over the Gulf of Alaska and offshore of Greenland, while positive biases are found along the eastern seaboard and around Colorado.

Figure 2a shows the accumulated precipitation exceeding the 99th percentile within 1000 km of ETC tracks in ERA5 over the 1980–2014 period ($EE_{PR,cum|ETC}^{ERA5}$). The spatial pattern differs somewhat from that of ETC track density. The largest accumulated exceedances (> 2500 mm) are found along the eastern coast, extending from North Carolina to offshore Newfoundland. In this region, ETCs are a major driver of extreme precipitation, with the largest contributions occurring during fall and winter

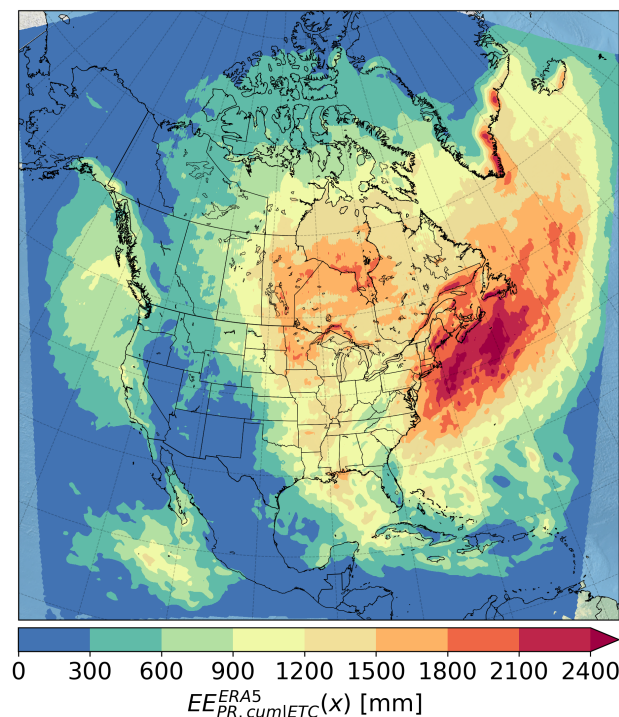


Figure 2. Accumulated extreme exceedance of precipitation associated to ETCs in ERA5 over the historical period (1980-2014).

(black contour lines in Figs. S7–S10). Large accumulations are also found in and around Ontario, Canada, mainly associated with summer precipitation extremes, as well as in the subtropics, particularly during autumn, despite the relatively low track density in that region. This likely reflects the strong contribution of tropical cyclones detected by the tracking algorithm. Over the central U.S., accumulations in Colorado occur almost exclusively in spring. Finally, a marked region of exceedance is found
305 offshore along the west coast from California to Alaska, largely driven by autumn precipitation.

Figure 3 presents the total bias in ETC-associated accumulated extreme exceedance for precipitation (first column) alongside its decomposition into three contributions following Eq. (8): differences in the mean intensity of ETC-related extremes (second column), in the extreme threshold (third column), and in the number of hours during which an extreme and an ETC co-occur (fourth column). Each term is modulated by a scaling factor reflecting the local exposure to ETC-related extremes (T_{ETC}^{ERA5} or
310 $\overline{EE_V^{SIM}}$).

CRCM6_{ERA5} (first row) exhibits a predominantly positive bias compared with $EE_{PR,cum|ETC}^{ERA5}$ over nearly the entire domain, particularly in regions where ERA5 already shows large values (e.g., east coast and eastern North America), with local biases exceeding 2400mm. The mean intensity of extreme precipitation is the main driver of this difference, indicating that the
315 CRCM6-GEM5 model simulates more intense extremes than ERA5 when the threshold is exceeded, particularly during autumn and winter (Fig. S7). Despite relatively strong intrinsic intensity biases in the tropics (Fig. S11a), their contribution remains limited in Fig. 3b owing to the low exposure to ETC-related extreme hours in ERA5. By contrast, along the eastern seaboard,



large intensity-driven contributions coincide with the maxima of total $EE_{PR,cum|ETC}^{ERA5}$ differences (black contours), reflecting both stronger intrinsic extremes and their amplification by frequent extreme ETC hours. This intensity-driven increase is partially, though not entirely, offset by the threshold term. CRCM6_{ERA5} exhibits higher PR_{th} values compared to ERA5. This higher baseline reduces the magnitude of each individual exceedance ($PR_{ETC} - PR_{th}$), thereby acting as a compensatory factor in the total EE_{PR} budget. Importantly, while the intensity term is computed from ETC-related precipitation only, the threshold is derived from the full precipitation distribution. As such, a positive residual between the intensity and threshold contributions (Fig. S12) indicates that ETC-related precipitation extremes are more important in simulations than in ERA5. Conversely, if the threshold increase offsets the intensity gain, it suggests that the amplification reflects a general intensification of precipitation rather than a ETC-specific signal. Finally, the occurrence term reveals a clear geographic pattern: positive biases dominate over land, whereas negative biases prevail over the ocean. Positive biases, for instance near the Great Lakes, indicate that CRCM6_{ERA5} produces ETCs with extreme precipitation more frequently than ERA5. In general, the contribution of the occurrence term to the total $EE_{PR,cum|ETC}$ bias remains marginal for this simulation.

The AOGCM-driven simulations (Fig. 3e,i,m) also display widespread positive biases, although the magnitudes differ substantially. CRCM6_{EC-Earth3-Veg} shows values exceeding 3200 mm along the eastern seaboard, extending from the Gulf of Mexico to offshore Newfoundland, and in the eastern North Pacific tropical cyclone basin. CRCM6_{MPI-ESM1-2-HR} presents a broadly similar bias structure over North America, albeit with weaker amplitudes due to reduced autumn biases (Fig. S9). Positive biases extending further into central Canada are also apparent in this simulation, a feature driven by summer precipitation and less pronounced in the other configurations. In contrast, CRCM6_{MIROC6} behaves as a clear outlier, with very large positive biases greater than 4000 mm across a broad region encompassing the Gulf of Mexico, the Caribbean Sea, and the eastern coast up to offshore New Brunswick, Canada, reaching up to 6300 mm (not shown in Fig. 3 as values are out of range) and driven predominantly by the tropical cyclone seasons (Fig. S10). Unlike the other simulations, it also exhibits localized, albeit weak, negative biases over Hudson Bay and offshore east of Greenland.

The $EE_{PR,cum|ETC}$ biases in both CRCM6_{EC-Earth3-Veg} and CRCM6_{MPI-ESM1-2-HR} are likewise predominantly driven by the intensity of extreme precipitation (Fig. 3f,j), particularly along the eastern seaboard. CRCM6_{MPI-ESM1-2-HR} exhibits a pattern and magnitude of intensity bias similar to CRCM6_{ERA5}, whereas in CRCM6_{EC-Earth3-Veg}, precipitation extremes associated with ETCs display higher mean intensities, indicating that the large-scale conditions imposed by the driving AOGCM favor the development of more intense ETC-related precipitation. Although the higher extreme threshold provides a modest compensating effect, it only partially mitigates the substantially larger intensity bias observed in this simulation. In contrast to CRCM6_{ERA5}, the occurrence term also contributes substantially to the total $EE_{PR,cum|ETC}$ bias in both CRCM6_{EC-Earth3-Veg} and CRCM6_{MPI-ESM1-2-HR} (Fig. 3h,i). A large fraction of the regions exhibiting strong positive $EE_{PR,cum|ETC}$ biases coincide with areas where the number of hours with concurrent ETC presence and extreme precipitation exceeds that of ERA5. This contribution is particularly pronounced in the tropics, as well as over land east of the Rockies and off the eastern coast. Seasonal diagnostics indicate that these positive occurrence biases are mainly driven by autumn and summer, during which ETC density is also overestimated in these simulations (Fig. S6).



CRCM6_{MIROC6} exhibits intensity and threshold biases comparable in magnitude to those of CRM6_{EC-Earth3-Veg}, yet stands out through a substantially larger occurrence bias than any other simulation. This signal is particularly pronounced in the tropics and along the U.S. eastern seaboard, where it translates into a strong positive contribution to the total $EE_{PR,cum|ETC}$ bias. The pronounced hotspot of enhanced ETC density over the Gulf of Mexico (Fig. 1e) suggests that the excess cyclones simulated in this region relative to ERA5 are largely associated with extreme precipitation, thereby increasing the number of extreme ETC hours. In contrast, the marked ETC density maximum located offshore of northeastern North America does not correspond to a comparable increase in extreme occurrences, indicating that a substantial fraction of the additional cyclones in that region are not linked to extreme precipitation. Although the intensity term contributes to the total $EE_{PR,cum|ETC}$ bias in CRM6_{MIROC6}, its outlier behavior is primarily driven by the occurrence term. The simulation exhibits a larger number of hours with concurrent ETC presence and extreme precipitation than ERA5 and the other configurations. This excess is particularly pronounced in tropical regions during summer and autumn, pointing toward a more frequent detection of tropical cyclones and their typically associated intense precipitation. The scaling factors further shape the spatial structure of these biases, dampening the intensity and threshold terms in the tropics and the occurrence term along the eastern coast (Fig. S11).

Figure 4 shows the accumulated extreme exceedance of near-surface wind speed associated with ETCs in ERA5 ($EE_{WS,cum|ETC}^{ERA5}$) over the 1980–2014 period. The largest exceedances occur over oceanic regions, where the low surface roughness allows stronger wind speeds. In particular, values exceed 3800 m s^{-1} in accumulated exceedance over large areas of the North Atlantic and south of Greenland. Elevated $EE_{WS,cum|ETC}^{ERA5} (> 2000 \text{ m s}^{-1})$ are also found over several continental regions, including the central U.S., northern Quebec, Newfoundland and Labrador, and near large water bodies. The seasonal variability of ETC-associated extreme wind speed is more pronounced than that of precipitation (black contour lines in Figs. S13–S16). In midlatitude oceanic regions, extreme winds are predominantly driven by winter ETCs, while autumn ETCs dominate in the subtropics and spring ETCs govern the signal over the central United States. Summer ETCs contribute negligibly across the domain.

All CRM6 simulations exhibit predominantly positive biases in ETC-associated wind exceedance relative to ERA5 (Fig. 5a,e,i,m), although their magnitude varies across configurations. Several common spatial features emerge: a broad region of positive bias extends over the North Atlantic Ocean, where the highest $EE_{WS,cum|ETC}$ values for ERA5 are found. Positive biases are also present over Hudson Bay, while surrounding regions show weaker or locally negative biases. In addition, the tropical Eastern Pacific basin displays positive biases in all simulations. The ERA5- and MPI-ESM1-2-HR-driven simulations show relatively moderate positive biases across much of the domain, rarely exceeding 2000 m s^{-1} . CRM6_{MPI-ESM1-2-HR} additionally exhibits several regional patches of negative bias, notably within both tropical cyclone basins, over the Gulf of Alaska, and across Greenland and Baffin Bay. CRM6_{MIROC6} and CRM6_{EC-Earth3-Veg} produce substantially larger biases in regions influenced by tropical cyclones. In the Eastern Pacific basin, accumulated exceedance biases in CRM6_{EC-Earth3-Veg} reach up to 6400 m s^{-1} . However, this simulation does not produce similarly large areas of high bias in the Atlantic basin, while CRM6_{MIROC6} stands out as a clear outlier, with exceedance biases reaching about 7000 m s^{-1} in the Gulf of Mexico and 6000 m s^{-1} in the Caribbean Sea. Interestingly, the precipitation metrics do not show comparable biases in the latter region for the MIROC6-driven simulation.



The three contributions to the ETC-related near-surface wind extreme exceedance bias are shown in the second to fourth columns of Fig. 5. All simulations exhibit substantially higher mean extreme wind speeds than ERA5 (see also Fig S17). Particularly large positive differences ($> 6000 \text{ m s}^{-1}$) occur over the central United States east of the Rocky Mountains, the Labrador Sea, around Greenland, and more broadly across the North Atlantic. These differences are predominantly driven by spring ETCs over the central United States and by winter (and to a lesser extent autumn) ETCs across the North Atlantic (Figs. S13–S16).

The 99th percentile of near-surface wind speed is also substantially larger in the simulations relative to ERA5 over the regions where the strongest intensity differences are observed. The regional simulations therefore generally produce stronger winds, regardless of their association with ETCs. As a result, the intensity and threshold contributions partly offset each other, although the intensity term contributes further to the total bias (Fig. S18). A distinct region characterized by negative differences in wind speed intensity term and positive differences in threshold term is evident over central Québec, extending westward of Hudson Bay, and potentially reflects differences in prescribed surface roughness lengths between ERA5 and CRCM6.

Regional differences in $EE_{WS,cum|ETC}$ among simulations are mainly controlled by the occurrence term. For example, the Eastern Pacific basin is strongly associated with an increased number of hours with concurrent ETC presence and extreme winds in all simulations. In addition, CRCM6_{MIROC6}, and to a lesser extent CRCM6_{EC-Earth3-Veg}, show a particularly large contribution of the occurrence term in the North Atlantic tropical cyclone basin, consistent with the patterns identified in the precipitation diagnostics. This occurrence signal within the subtropics is concentrated in autumn. Negative $EE_{WS,cum|ETC}$ bias structures are also primarily driven by the occurrence term. Decreases are found in the Gulf of Alaska and over Greenland in all simulations, in the tropical Atlantic for CRCM6_{MPI-ESM1-2-HR}, and over broader regions north of 40°N in CRCM6_{MIROC6}.

3.2 Projected changes in ETC extreme exceedance

Figure 6 shows the change in ETC density between historical and future periods. All three simulations show a coherent large-scale change, with a decrease in ETC density offshore of the eastern coast and across most ETC-prone regions south of 50°N , associated with an increase at higher latitudes over northern Canada and the Arctic Ocean. This response is consistent with the widely documented poleward shift.

Despite this common large-scale changes, some regions exhibit contrasted responses across the three simulations. The area surrounding southern Greenland, in particular, shows substantial inter-model variability, suggesting differing impacts on the position of the North Atlantic storm track. Projected track density changes offshore the western coast and across continental land also differ markedly between simulations.

The seasonal decomposition (Fig. S19) reveals that summer drives the largest change signal, with a particularly pronounced continental decrease in track density. The reduction along the eastern coast and the increase at high latitudes are robust across all seasons. Beyond these common features, marked inter-simulation differences also emerge in the seasonal signal: CRCM6_{EC-Earth3-Veg} and CRCM6_{MPI-ESM1-2-HR} both project a shift of spring Colorado Lows toward winter, the simulations disagree in sign over the eastern Pacific tropical cyclone basin in autumn, and CRCM6_{MPI-ESM1-2-HR} exhibits distinct spatial patterns and magnitudes of high-latitude increase in summer and autumn.



420 For future changes in $EE_{V,cum|ETC}$, the 99th percentile threshold has been fixed to the historical one, leaving only two terms in the decomposition. Across large parts of the domain, future changes in $EE_{PR,cum|ETC}$ (first-column panels of Fig. 7) differ substantially between simulations in both sign and magnitude. The main robust feature is a consistent increase over northeastern North America and the adjacent northwestern North Atlantic. Off the U.S. East Coast, CRCM6_{MPI-ESM1-2-HR} projects a broad and spatially coherent decrease in $EE_{PR,cum|ETC}$, whereas the other two simulations show large increases. 425 In the tropical basins, the eastern North Pacific ranges from pronounced increases in CRCM6_{EC-Earth3-Veg}, to moderate increases in CRCM6_{MPI-ESM1-2-HR}, to mixed signals in CRCM6_{MIROC6}, while the tropical North Atlantic shows a decrease in CRCM6_{MPI-ESM1-2-HR} and mixed localized signals in the other two simulations. Over the continental U.S., all three simulations yield spatially fragmented changes with no consistent pattern, whereas a robust increase—punctuated by a localized patch of decrease over Alberta—is found across Canada and Alaska and extends offshore along the west coast.

430 The decomposition of future changes in $EE_{PR,cum|ETC}$ (second and third columns of Fig. 7) shows that the intensity term increases across most of the domain, particularly over the ETC-prone eastern coast where it substantially contributes to $EE_{PR,cum|ETC}$, although the increase in CRCM6_{MPI-ESM1-2-HR} is weaker and more confined to the shoreline (see also Fig. S23). The occurrence term, by contrast, is the primary driver of future $EE_{PR,cum|ETC}$ changes elsewhere and of the associated inter-simulation spread. The robust increases found over the northeastern part of the domain are predominantly driven by a robust 435 increase in occurrence across all three simulations, even in CRCM6_{EC-Earth3-Veg} despite its large reduction in ETC density in the northern North Atlantic. In oceanic regions south of 40°N, large inter-simulation differences emerge: CRCM6_{MPI-ESM1-2-HR} shows a spatially homogeneous and extended decrease in occurrence across the North Atlantic, whereas the other two simulations exhibit mixed and regionally fragmented signals. Consequently, the contrasting change in $EE_{PR,cum|ETC}$ off the U.S. East Coast is driven by distinct mechanisms depending on the simulation: intensification of ETC-associated extreme 440 precipitation in CRCM6_{EC-Earth3-Veg} and CRCM6_{MIROC6}, and reduced occurrence of ETC-associated extreme precipitation in CRCM6_{MPI-ESM1-2-HR}. The large inter-simulation spread in the tropical Pacific is largely driven by the occurrence term. The robust signal in $EE_{PR,cum|ETC}$ over Canada is spatially consistent with the occurrence signal, both being robust across all three simulations, whereas occurrence changes over the continental U.S. show heterogeneous patterns with opposite signs across simulations. Autumn contributes most to $EE_{PR,cum|ETC}$ changes and drives the largest inter-simulation differences in both 445 intensity and occurrence, while winter shows little to no inter-simulation spread (Figs. S20–S22).

Future changes in $EE_{WS,cum|ETC}$ show very limited agreement among the three simulations in both the sign and magnitude of the response (first-column panels of Fig. 8). The only robust features are a negative change over the North Atlantic, extending offshore from North Carolina and reaching Iceland, with an embedded positive region between 40°N and 50°N, and positive changes in parts of the Canadian Arctic Archipelago. Elsewhere, marked differences are evident: continental regions as well 450 as their large bodies of water show opposing changes across simulations, while within both tropical cyclone basins, the sign and magnitude of the response vary considerably between simulations and across different parts of each basin, suggesting a reorganization of the regions most affected by extreme ETC-associated winds.

The intensity term shows little to no change across most of the domain, contributing weakly to $EE_{WS,cum|ETC}$ changes overall (second column of Fig. 8). The few regions of noticeable change appear to be modulated by shifts in the regions of



455 impact of the most extreme ETCs, as seen in the occurrence term (third column of Fig. 8). Off the U.S. East Coast, where occurrence is projected to decrease, the intensity term nevertheless shows a weak but consistent increase across all three simulations (see also Fig. S27). The occurrence term is the dominant contributor to future $EE_{WS,cum|ETC}$ changes, driving the robust signals identified over the North Atlantic and the Canadian Arctic — features predominantly confined to winter (Figs. S24–S26) — and constituting the primary source of inter-simulation spread elsewhere, most conspicuously in the tropical basins
460 during autumn, the season exhibiting the largest spread. Overall, projected changes in $EE_{WS,cum|ETC}$ and its contributors show limited agreement with the patterns previously identified changes in track density and $EE_{PR,cum|ETC}$, and the response of ETC-associated extreme surface wind speed to climate warming remains particularly uncertain.

3.3 Projected changes in extreme individual ETCs over northeastern North America

Beyond the spatial decomposition examined so far, the same exceedance metric, $EE_{V,cum|ETC}$, can also be evaluated at the
465 scale of individual ETCs. In this framework, it can be decomposed into two components: the number of grid-point-hours within 1000 km exceeding the historical extreme threshold and the mean excess intensity $\overline{EE_{V|ETC}}$. At the ETC scale, the occurrence term takes on a more dynamical meaning, reflecting the spatial footprint of the system and its propagation speed. Restricting the analysis to a delimited land region over northeastern North America (NNA), as done in this section, additionally makes it sensitive to how closely each track aligns with the 12 406 grid cells of this region (Fig. S1). This region was selected because it
470 has historically been strongly impacted by ETCs, it is densely urbanized (red areas in Fig. S1), and all three simulations agree on a robust increase in accumulated extreme exceedance of precipitation there.

Figure 9 shows, for each season and both periods, the 10 ETCs with the largest $EE_{PR,cum|ETC}$ over this region, providing a direct view of how the most impactful events are projected to evolve over a region of high societal exposure. The largest values occur predominantly in autumn and, to a lesser extent, in summer, the latter owing to the higher mean excess intensity
475 of its highest-accumulation ETCs. CRCM6_{MIROC6} exhibits the highest values of $EE_{PR,cum|ETC}$, driven by the enhanced presence of its ETCs over the region through the occurrence term, via larger and/or slower, longer-lasting systems. Nearly all configurations—combinations of simulation, percentile threshold, and season—display a coherent shift of their top-10 seasonal distribution toward higher accumulated exceedance. The magnitude of this increase nonetheless varies from one configuration to another, as do the components driving it. Winter ETCs, by contrast, behave robustly across all configurations, showing
480 substantial increases in the magnitude of its accumulated exceedance, primarily driven by the occurrence component.

Under the 99.9th-percentile selection, the intensity component is roughly 1.5 times as large as under the 99th percentile, while the occurrence component is reduced by roughly a factor of four over the region; the large ETC extreme exceedance accumulations obtained using the 99.9th percentile therefore stem more from large values of the mean excess intensity than from large values of the occurrence term (i.e., spatiotemporal coverage). Accumulated exceedance nonetheless still increases for
485 every season and simulation, though the driving component sometimes differs from that of the 99th-percentile selection (e.g., CRCM6_{EC-Earth3-Veg}). Notably, the largest outliers are markedly more numerous in the future period across all configurations, raising concern over their potential societal impact.



Most of these ETCs form inland on the lee side of the Rocky Mountains, from the United States into Canada, particularly in spring and summer (Fig. S28). A number of ETCs that develop along and track the U.S. East Coast are also represented, together with several systems originating from the Gulf of Mexico and the Caribbean Sea. CRCM6_{MIROC6}, for instance, retains numerous cyclones drawn from these moisture-rich subtropical sources across all seasons, consistent with the anomalously high ETC occurrences over the Gulf of Mexico identified in previous sections. CRCM6_{MPI-ESM1-2-HR}, by contrast, produces very few such ETCs, with most of its autumn cyclones forming inland, suggesting that few tropical cyclones reach the NNA region in this simulation. Across all three simulations, the top-10 seasonal trajectories converge toward the NNA region.

To select the most extreme ETCs based on their mean intensity, we use a regularized intensity defined as $\overline{EE_{V|ETC}} \cdot T_{ETC} / (T_{ETC} + \lambda)$. The shrinkage factor $T_{ETC} / (T_{ETC} + \lambda)$ penalizes ETCs whose mean excess intensity is computed over very few grid-point-hours, where a small number of high-intensity exceedances would otherwise be sufficient to inflate the mean and bias the selection toward sparsely sampled events. From visual inspection of the T_{ETC} axis in Fig. 9, we set $\lambda = 10000$ for the 99th percentile and a value four times lower for the 99.9th percentile. The ranking of the resulting 10 ETCs per season, from most to least intense, is shown in Fig. 10.

The ETCs with the strongest mean excess intensity over the NNA region occur either in summer or in autumn, with the dominant season and its magnitude varying notably across simulations. Winter and spring ETCs, by contrast, show comparable values of $\overline{EE_{PR|ETC}}$ across simulations, up to a factor of two below the typical summer and autumn values. The 10 most intense ETCs per season are generally more intense in the future, with few exceptions (e.g., spring in CRCM6_{MIROC6} under the 99.9th percentile). For summer and autumn, however, the rate of increase varies substantially across simulations, these being the two seasons where the sensitivity to boundary conditions is most apparent. Winter again departs from this behaviour, its top-10 ETCs exhibiting very similar historical mean excess intensities and future increases across the three simulations. Pooling all seasons, a disproportionate number of future ETCs rank among the strongest events, surpassing several of the most intense historical ETCs in every configuration. For instance, under the 99th-percentile selection, 13 and 10 future ETCs exceed the third most intense historical ETC in CRCM6_{MPI-ESM1-2-HR} and CRCM6_{EC-Earth3-Veg}, respectively, while 11 future ETCs in CRCM6_{MPI-ESM1-2-HR} exceed its fifth most intense historical ETC under both percentile selections. The trajectories of these ETCs closely resemble those selected from the accumulation metric, albeit with more ETCs initiating along the eastern coast in autumn and winter (Fig. S29).

Wind-related metrics show limited robustness throughout the other sections of the paper as well as in the top-10 seasonal analysis; the corresponding results are therefore provided in the supplementary material without further discussion (Figs. S30–S33).

4 Discussion

The approach adopted in this study to assess ETC-related precipitation and wind speed extremes, based on the exceedance of high percentile thresholds, has been used in several previous studies (e.g., Stanković et al., 2024; Chen and Di Luca, 2025; Leckebusch et al., 2008; Manning et al., 2024; Hawcroft et al., 2018). Here, we extend this framework by decomposing the



change in extreme exceedance into three physically interpretable drivers: (i) the change in the mean intensity of ETC-associated extreme events, (ii) the change in the background extreme threshold computed from the full distribution, and (iii) the change in occurrence of ETC-associated extreme events. This framework therefore enables the comparison of different datasets (here, the ERA5 reanalysis and four RCM simulations) as well as the assessment of projected changes within each of the three
525 AOGCM-driven simulation.

For precipitation and surface wind speed, both the 99th percentile and the ETC-associated mean extreme exceedance are consistently larger in all four CRCM6-GEM5 simulations than in the ERA5 reanalysis across the domain. This indicates that the CRCM6-GEM5 model generates higher hourly extreme values than the ERA5 reanalysis, particularly when considering ETC-associated extremes. This feature is likely attributable to the higher horizontal resolution of the RCM (~12 km) compared to ERA5 (~31 km), which better captures some smaller-scale processes within the cyclone environment (Zscheischler et al., 2021; Srivastava et al., 2023). In particular, Chen and Di Luca (2025) reported higher exceedance values for precipitation extremes over North America in IMERG than in ERA5, suggesting a potentially improved representation of the extreme exceedance distribution in simulations relative to ERA5. Also, Chen et al. (2024b) showed that ERA5 somewhat underestimated precipitation and wind speed extremes associated with ETCs compared with station data, which again would point to
535 some potential improvements from the CRCM6 simulations. Our findings further suggest that the lateral boundary conditions exert a large influence on ETC-associated accumulated extreme exceedance metrics. While differences in the intensity of ETC-associated extreme events contribute measurably and comparably across simulations to the total differences against ERA5, discrepancies in the occurrence of these events often substantially amplify the inter-simulation spread. This is particularly evident in subtropical ocean basins, where each simulation exhibits a distinct spatial pattern of occurrence bias, translating into
540 large inter-simulation spread in extreme exceedance. The sensitivity of RCM-simulated precipitation and wind extremes to lateral and lower boundary conditions has been documented in previous work (Zscheischler et al., 2021; Kim et al., 2020; Bruyère et al., 2014; Meredith et al., 2015; Zhang and Colle, 2018), as has the role of boundary forcing in shaping ETC characteristics (Poan et al., 2018; Côté et al., 2015). In particular, the sea surface temperature (SST) has been identified as a key driver of extreme precipitation in RCMs among these boundary condition components. Priestley et al. (2020) and Priestley et al. (2023)
545 further demonstrated that CMIP6 track density biases over North America and the North Atlantic frequently stem from errors in temperature and SST gradients, while Wang et al. (2025) highlighted the large CMIP6 inter-model spread in North Atlantic SST representation and its implications for tropical cyclone genesis. SST biases among the three driving AOGCMs may therefore constitute a key source of the large inter-simulation differences in extreme exceedance and track density identified here. Notably, CRCM6_{MIROC6} emerges as a clear outlier during the historical period, a result that aligns with Li et al. (2025), who
550 identified MIROC6 as one of the least skillful CMIP6 models in reproducing ETC-associated extreme precipitation over North America relative to ERA5.

For projected changes in ETC-associated accumulated extreme exceedance, the threshold term is intentionally excluded from the decomposition, so that the signal reflects the absolute change in ETC-associated extremes rather than a change relative to a co-evolving background threshold. For precipitation, all three simulations project a robust increase in ETC-associated
555 accumulated extreme exceedance over northeastern North America, jointly driven by a widespread intensification of precipi-



tation during extreme events and by an increased number of hours with concurrent ETC presence and threshold exceedance. This increase is consistent with a broad body of literature documenting the future intensification of ETC-related precipitation across the entire continent (Hawcroft et al., 2012, 2018), as well as within specific subregions of North America (Lombardo et al., 2015; Michaelis et al., 2017; Patricola et al., 2022; Zhang and Colle, 2018). Beyond the thermodynamic effect associated with increased atmospheric moisture, this intensification is driven by several mechanisms operating at the ETC-scale, including enhanced moisture uptake by intense North Atlantic ETCs (Coll-Hidalgo et al., 2026), strengthening vertical velocities within ETCs (Li and O’Gorman, 2020), and an increasing role of diabatic processes in the development of the most intense systems (Wernli and Gray, 2024). In contrast to the broad domain-scale increase in extreme intensity, the magnitude and spatial pattern of changes in extreme occurrence are highly simulation-dependent and constitute the primary source of inter-simulation spread in precipitation accumulated extreme exceedance. Nevertheless, a robust signal emerges across all three simulations, with substantial increases over eastern Canada that extend offshore into the northern North Atlantic. Elsewhere, the lack of a clear and consistent signal in extreme occurrence aligns with the broader uncertainty surrounding changes in the frequency of extreme ETCs over North America, particularly given its sensitivity to how extremes are defined (Michaelis et al., 2017; Catto et al., 2019; Seiler and Zwiers, 2016; Priestley and Catto, 2022a; Colle et al., 2015; Dolores-Tesillos and Pfahl, 2024). Hawcroft et al. (2018) adopted a broadly similar approach to quantify future changes in ETC-associated extreme occurrence using CMIP5 models, counting 6-hourly time steps exceeding the historical 99th percentile computed from ETC-related precipitation only, and reported increases exceeding 100% in winter and 50% in summer (with model uncertainty) across nearly the entire domain considered here. The differences with our results likely stem from three methodological distinctions: we compute the 99th percentile from all rainfall rates rather than from ETC-related values only, CRCM6-GEM5 operates at hourly rather than 6-hourly temporal resolution, and the 12km regional model substantially outperforms coarser AOGCMs in representing extreme precipitation (Zobel et al., 2018). When attributing accumulated extreme exceedance of precipitation to individual ETCs, we find that the most extreme ETCs impacting northeastern North America undergo a marked intensification of their associated metrics in the future. Gagnon et al. (2026) recently showed that the 18 most impactful ETCs were associated with more than 75% of flood-related financial aid claims in Quebec, Canada, underscoring the disproportionate contribution of those storms in driving societal and economic damages. They also showed that the most impactful ETCs most often originate over the central U.S. and the Gulf of Mexico, where nearly all of our extreme-metric-selected ETCs also originate.

Future changes in ETC-associated accumulated extreme exceedance for surface wind speed exhibit an even larger inter-simulation spread than for precipitation. The only robust features across all three simulations are a projected decrease over the North Atlantic north of 30°N—punctuated by a narrow embedded area of increase offshore Nova Scotia—and an increase over the Canadian Arctic. Both these robust patterns and the spread seen elsewhere are essentially driven by changes in extreme occurrence, with changes in the intensity of extreme winds playing a marginal role. Large-scale circulation has been identified as a key driver of future changes in ETC-related extreme wind (Maddison et al., 2026; Bentley et al., 2019); since AOGCMs prescribe these large-scale conditions to the RCM, the pronounced inter-AOGCM spread in boundary conditions is consistent with the large divergence among the three regional simulations used here. Morris and Diaconescu (2025) evaluated the performance of several RCM ensembles in reproducing the observed wind climate in Canada and found that their added value over



AOGCMs is limited and that they substantially underestimate wind speed variability and trends, thereby undermining their ability to reliably represent extremes. Gentile et al. (2023), using a 50 km grid-spacing AOGCM, analyzed future changes in the track density associated with extreme wind speeds and, apart from the decrease off the U.S. East Coast, do not reproduce the robust patterns in occurrence changes found here, underscoring the sensitivity of such projections to both model resolution
595 (Manning et al., 2023) and methodological choices. Our results therefore contribute to this broader picture of uncertainty in projected ETC-related extreme wind changes.

A limitation of this study lies in the choice of wind-related metrics. While accumulated precipitation provides a physically and societally meaningful measure, accumulated surface wind speed does not constitute a first-order indicator of impacts. The decomposition of accumulation offers a more physically interpretable framework; however, the definition of the intensity term
600 – based on the mean wind speed above the 99th percentile – may not be optimal for assessing extreme wind impacts. By construction, this metric smooths peak values and therefore underrepresents the most damaging events, for which indices such as the storm severity index (Klawa and Ulbrich, 2003; Leckebusch et al., 2008) are specifically designed. ERA5 is commonly used as a reference dataset for evaluating precipitation and wind biases in models. Although several studies have reported satisfactory performance of ERA5 for the analysis of intense windstorms (Chen et al., 2022; Letson et al., 2021), it remains
605 an imperfect benchmark for ETC-related hourly extremes in both wind and precipitation (Chen and Di Luca, 2025; Srivastava et al., 2023; Li et al., 2025; Stanković et al., 2024), particularly over complex terrain (Hutson et al., 2026; Letson et al., 2021; Manning et al., 2024; Zscheischler et al., 2021). The pronounced differences in intensity between ERA5 and the four regional simulations analyzed here are consistent with these known limitations. Moreover, this study relies on a single RCM and does not apply bias correction to the driving data. Previous work has demonstrated that RCMs exhibit substantial spread in
610 projected changes in wind speed and precipitation (Outten and Esau, 2013; Beniston et al., 2007). Using multiple RCMs has been shown to better capture variability arising from model physics (Wamahiu et al., 2025), while bias correction of boundary conditions improves the representation of extreme events (Kim et al., 2023). Accordingly, the robustness of our results could be enhanced by employing a multi-model RCM ensemble driven by carefully bias-corrected data. Finally, the 12 km grid spacing of CRCM6, while sufficient to represent extreme winds reasonably well (Manning et al., 2023), remains too coarse to resolve
615 certain small-scale features and to explicitly resolve convection (Srivastava et al., 2023). Simulations at convection-permitting resolution would therefore provide a more physically consistent representation of these processes.

5 Conclusions

This study leveraged four high-resolution regional climate simulations at 12 km grid spacing from the CRCM6-GEM5 model over North America, one driven by ERA5 and three driven by CMIP6 AOGCMs (EC-Earth3-Veg, MPI-ESM1-2-HR, and
620 MIROC6), to evaluate the historical representation (1980–2014) of extreme precipitation and near-surface wind speed associated with ETCs against ERA5, and to assess their projected changes by the late twenty-first century (2063–2097). To this end, we introduce a novel framework for quantifying recent-past differences and future changes in ETC-related accumulated



extreme exceedances by separately isolating the contributions of the mean intensity of ETC-associated extremes above the 99th-percentile threshold and from the occurrence of concurrent ETC presence and threshold exceedance.

625 The CRCM6-GEM5 systematically produces stronger hourly extremes than ERA5 in both precipitation and surface wind speed, supporting the added value of the regional model in representing ETC-associated extremes. Despite a common regional model, the boundary conditions imposed by the driving dataset emerge as a leading-order control on the simulated extremes: each driving dataset imprints distinct spatial patterns and regional magnitudes of ETC-related extreme occurrences, which together dominate the inter-simulation spread, complemented by a secondary contribution from differences in the intensity of
630 these extremes. For precipitation, the most robust feature across simulations is found over northeastern North America and the adjacent northwestern North Atlantic, where intensity and occurrence increase jointly across all three simulations to produce a robust amplification of ETC-related extreme precipitation, despite a decrease in all-ETC trajectory density in this region.

The response of ETC-associated extreme surface wind speed is less conclusive. The intensity response is weak across all simulations, and projected changes in accumulated extreme exceedance are essentially a redistribution of where and how often
635 extreme ETC-associated winds strike. Outside of a robust decrease in extreme wind occurrence over a large part of the North Atlantic ocean, changes in extreme wind speeds associated with ETCs remain small and inconsistent across simulations over North America.

Applied to the top 10 strongest ETCs affecting northeastern North America in each season, the exceedance framework reveals a robust future intensification of their associated precipitation across all three AOGCM-driven simulations, consistent
640 across seasons and percentile thresholds, although its magnitude and controlling factors vary across configurations. Given that a large proportion of damages are associated with few very strong cyclones in this region (Gagnon et al., 2026), this will likely have important implications for the resilience and adaptation of multiple sectors of society, particularly in the densely populated regions of the continent.

Code and data availability. The analysis scripts are archived on Zenodo (De Meyer, 2026), with ongoing development at https://github.com/VictorienDeMeyer/DeMeyer_etal_2026_Extreme_Cyclones. ERA5 hourly data on single levels are freely available from the Copernicus
645 Climate Data Store (<https://doi.org/10.24381/cds.adbb2d47>; Hersbach et al. 2023). The CMIP6 simulations used to drive CRCM6-GEM5 are available from the Earth System Grid Federation (<https://esgf.llnl.gov/>). The full hourly CRCM6-GEM5 output and any derived fields required to reproduce the results presented here are available from the corresponding author upon reasonable request.

Author contributions. TCC, ADL and VDM designed the initial study framework, and ADL and VDM drafted the methodological section.
650 VDM conducted the main analyses, generated all figures, and wrote the majority of the manuscript. All authors contributed to discussions and revised the manuscript.

Competing interests. The authors declare no competing interests.



Acknowledgements. This research has been partly conducted as part of the project “Simulation et analyse du climat à haute resolution” thanks to the financial participation of the Government of Québec. It was also enabled in part by support provided by Calcul Québec (https://www.calculquebec.ca) and the Digital Research Alliance of Canada (https://alliancecan.ca/en). The authors thank Frédérik Toupin, Katja Winger and Yassine Hammadi for maintaining a user-friendly local computing facility. They also acknowledge Katja Winger and François Roberge for maintaining the CRCM6-GEM5 model versions and conducting the associated simulations. The authors are further grateful to Philippe Gachon for his valuable contributions through scientific discussions and his careful review of the manuscript. During the preparation of this manuscript, the authors used a large language model to improve the English phrasing and readability of the text. The authors reviewed and edited all output and take full responsibility for the content of the publication.



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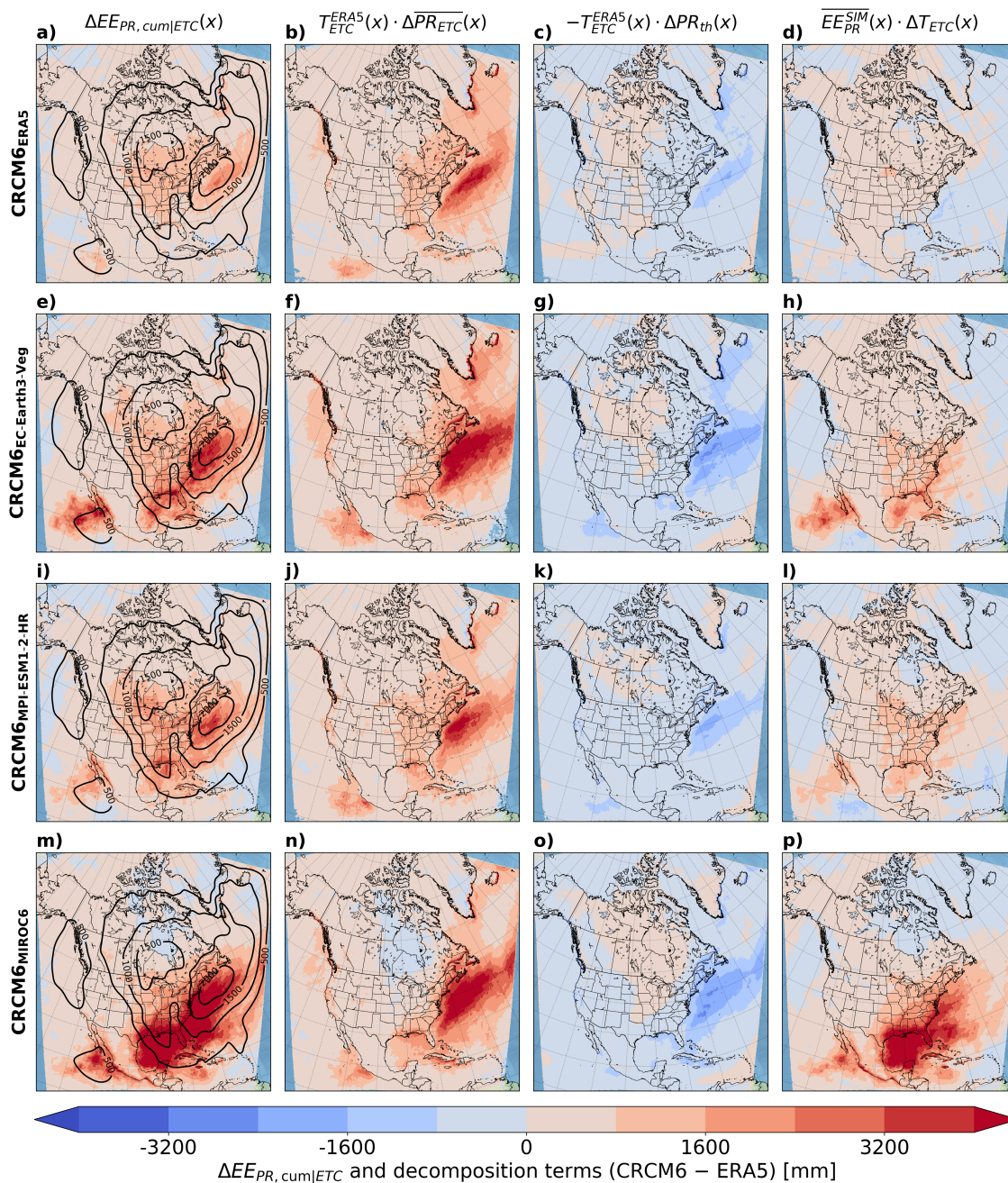


Figure 3. Difference in accumulated extreme exceedance in precipitation relative to ERA5 for all historical regional simulations (first-column panels). The second to fourth columns show the decomposition into the three terms of Eq. (8), with the contribution from changes driven by the mean hourly intensity of extremes (term 1; second column), the contribution from changes driven by the background threshold (term 2; third column), and the contribution from changes driven by the occurrence of extremes (term 3; fourth column).

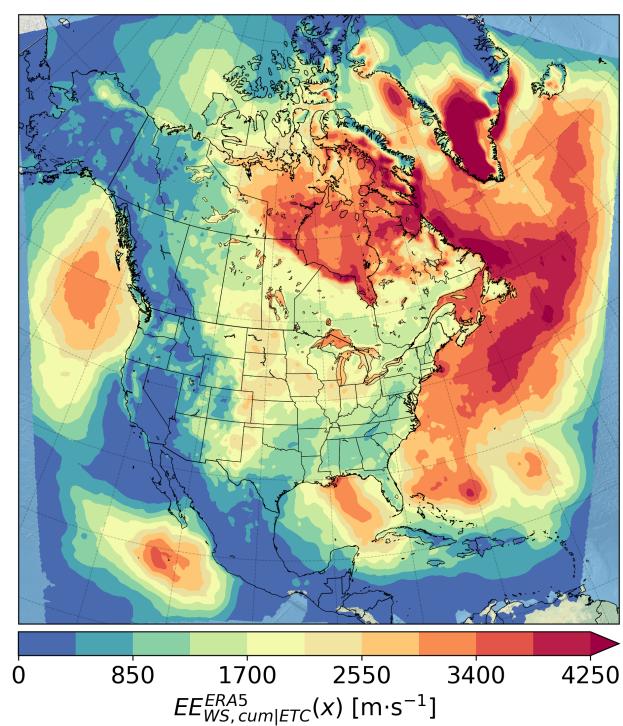


Figure 4. Accumulated extreme exceedance of surface wind speed associated to ETCs in ERA5 over the historical period (1980-2014).

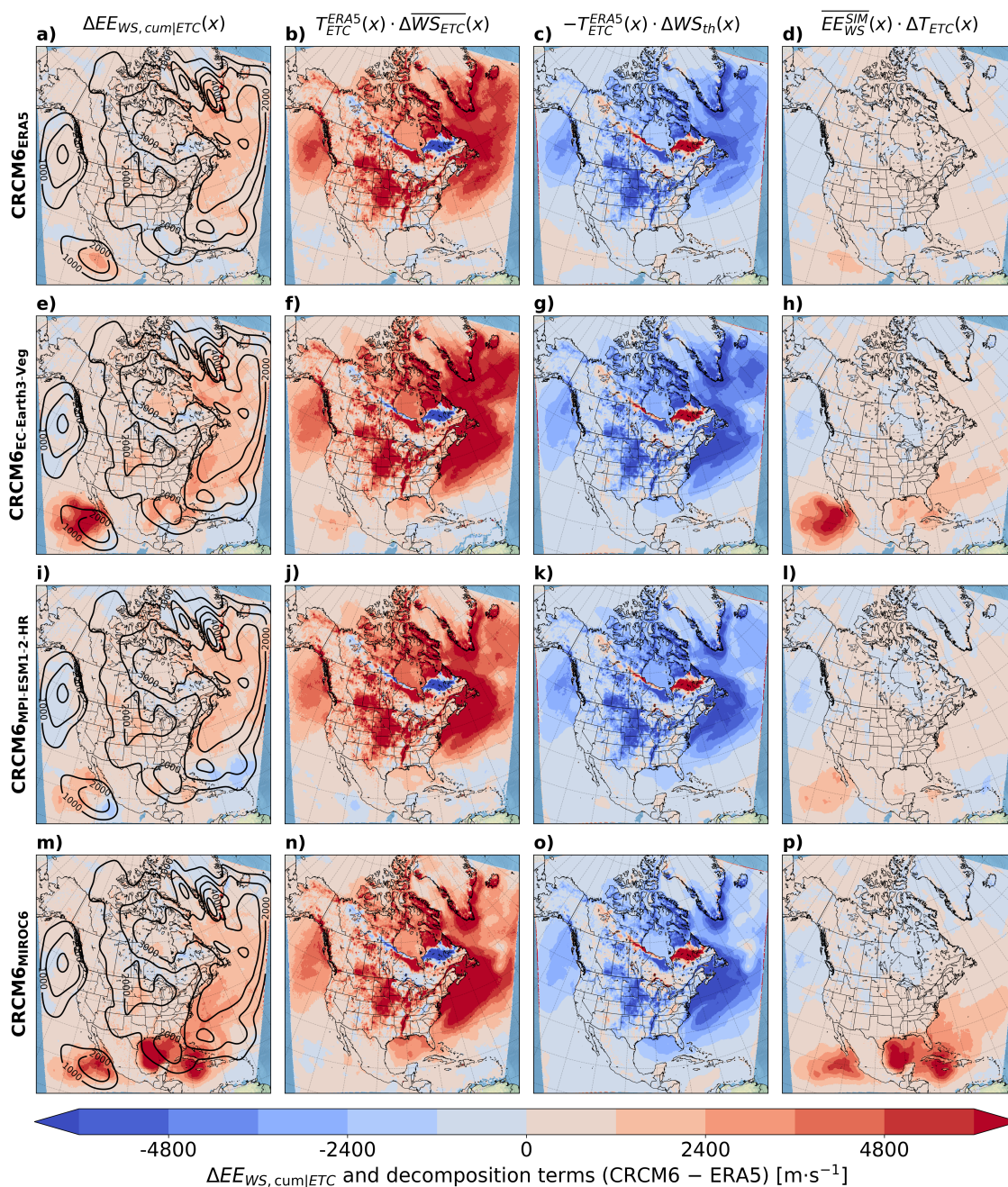


Figure 5. As in Figure 3, but for accumulated extreme exceedance in surface wind speed.

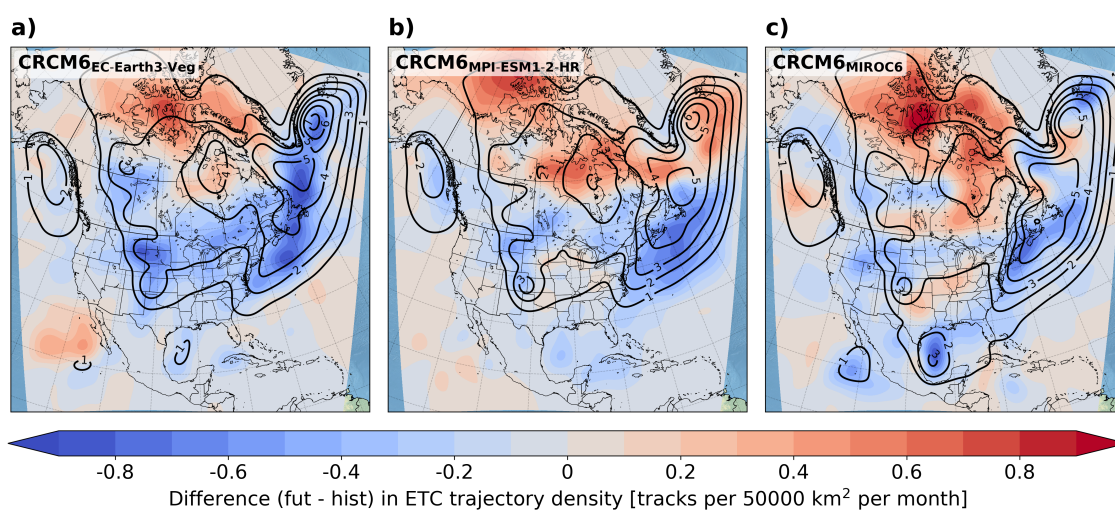


Figure 6. Change of ETC trajectory density between the future period and the historical period for the three AOGCM-driven regional simulations. Black contours indicate values for the historical period.

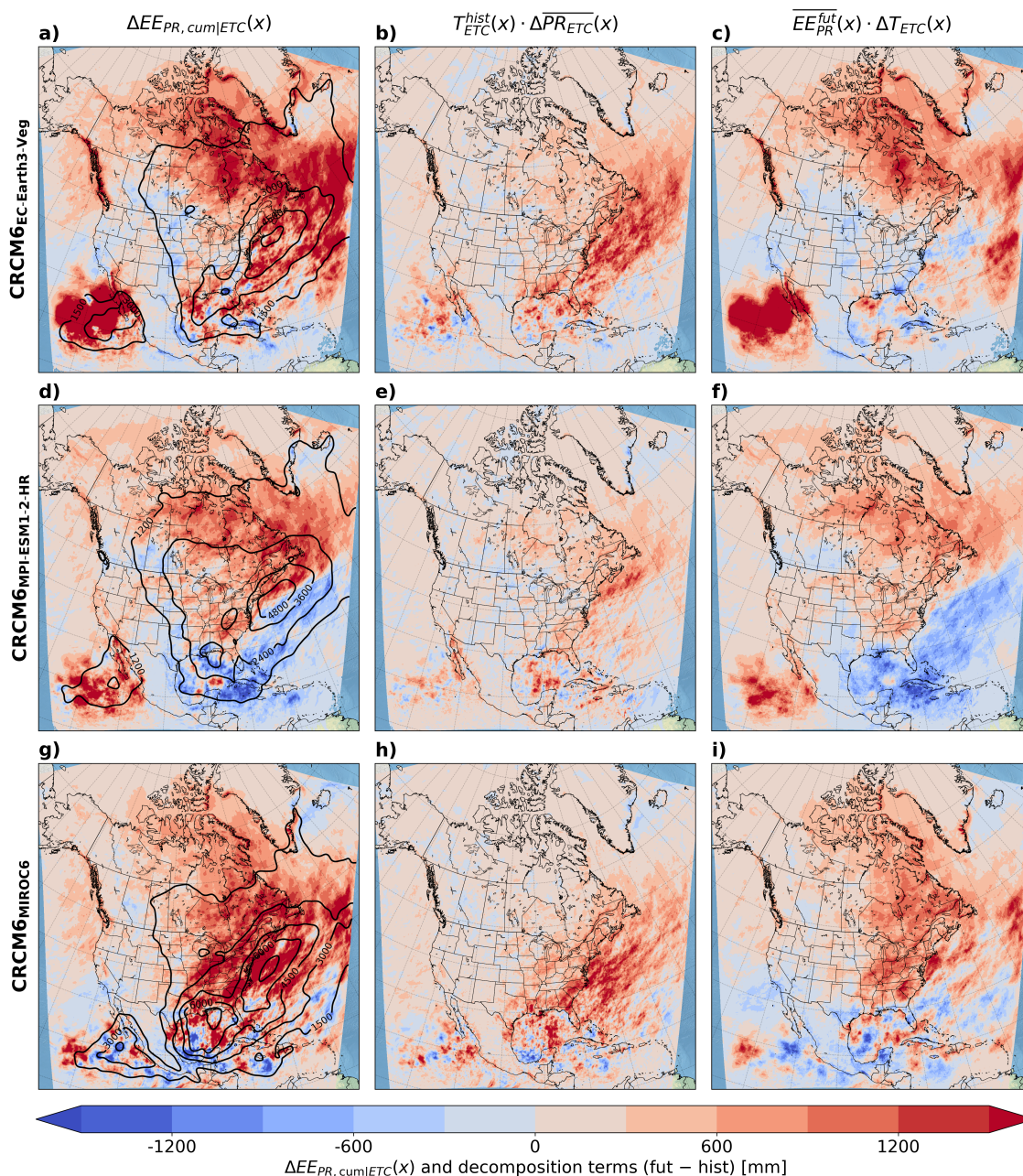


Figure 7. Difference in accumulated extreme exceedance in precipitation between future and historical periods for the three AOGCM-driven regional simulations (first-column panels). The second column shows the contribution from changes driven by the mean hourly intensity of extremes, and the third column shows the contribution from changes driven by the occurrence of extremes. Historical values are indicated by black contours.

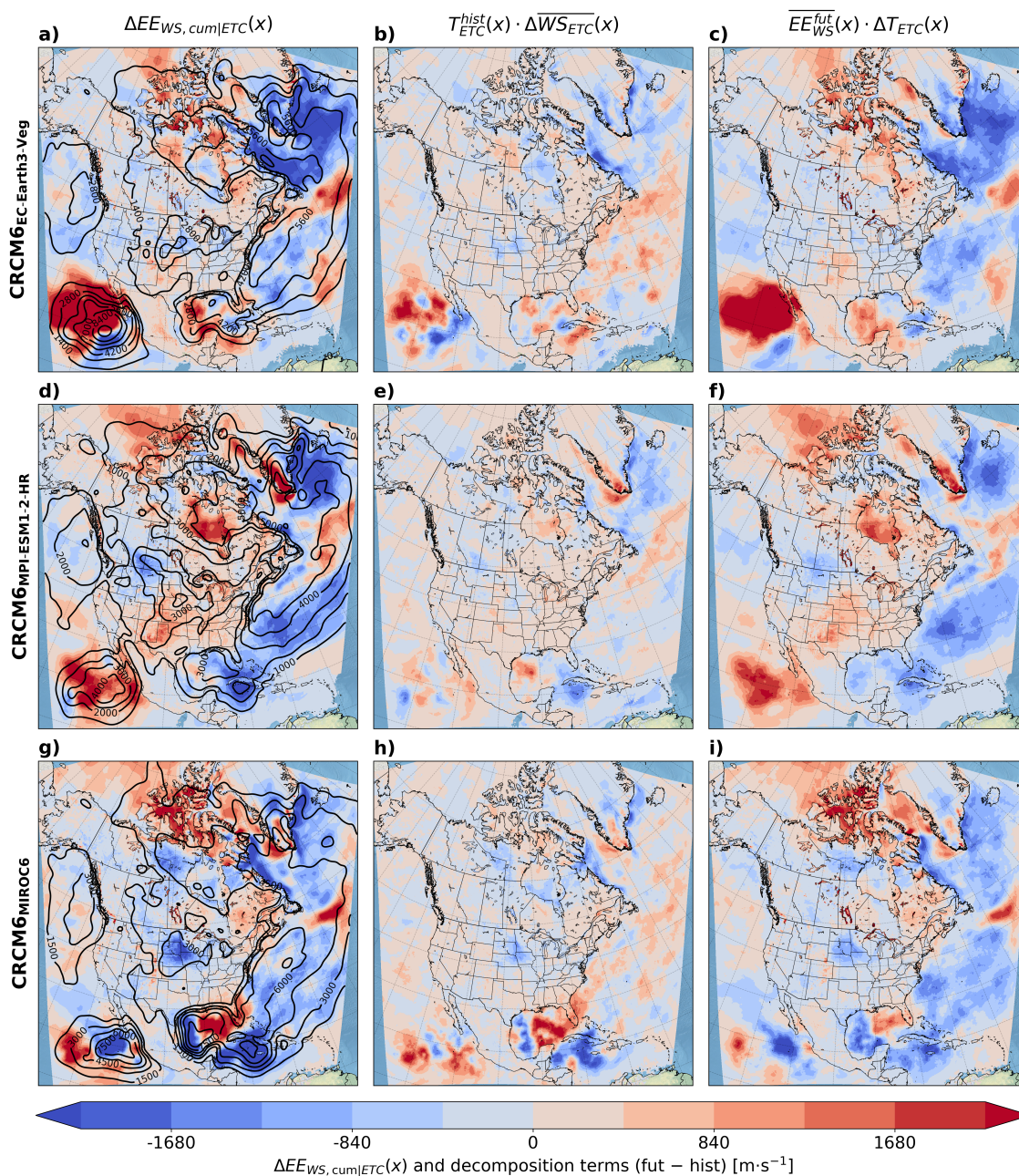


Figure 8. As in Figure 7, but for the ETC-associated extreme surface wind speeds.

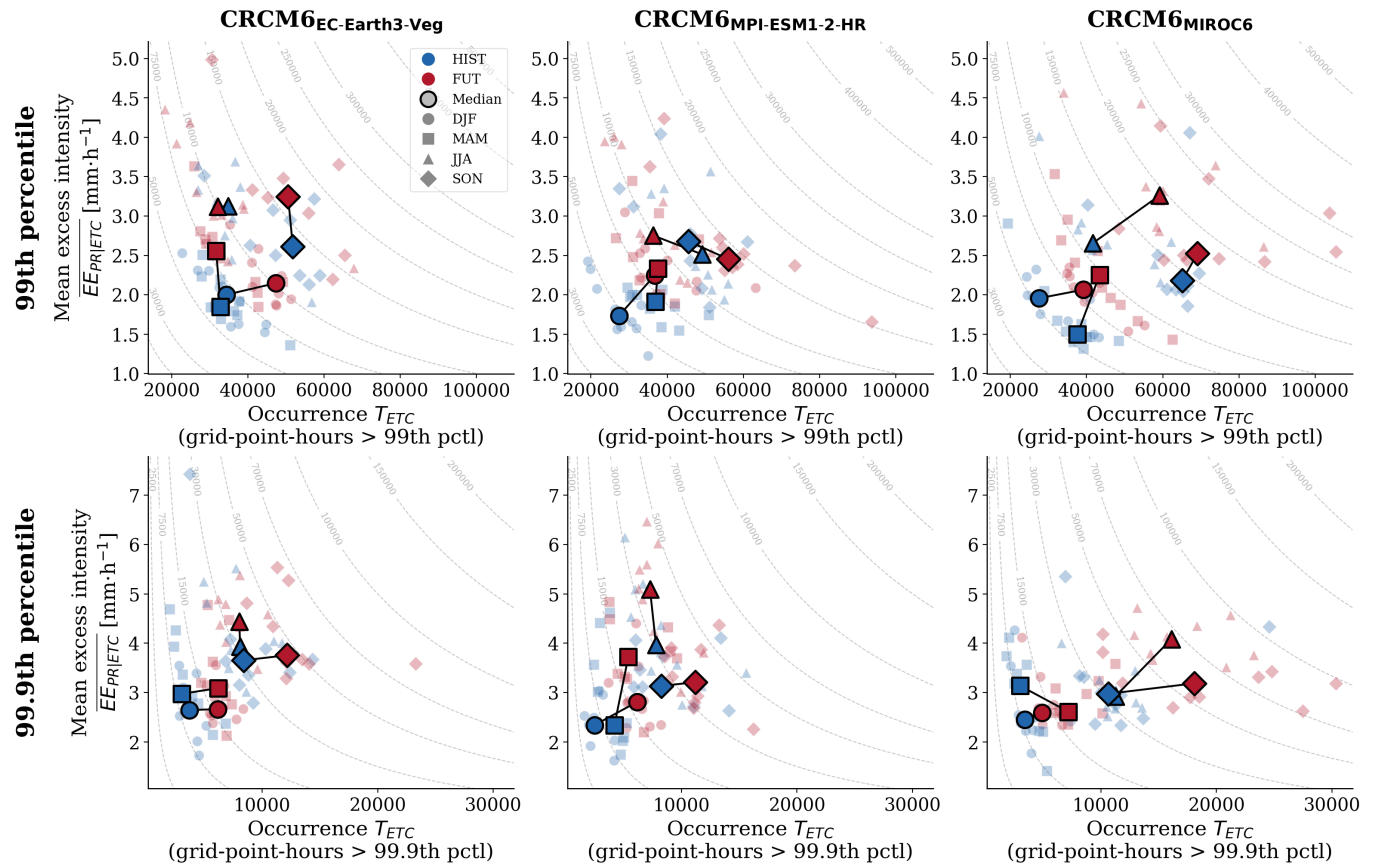


Figure 9. Occurrence T_{ETC} versus mean excess intensity $\overline{EE_{PR|ETC}}$ for the 10 ETCs with the largest accumulated extreme exceedance $EE_{PR,cum|ETC}$ in each simulation and season, over the NNA region (Fig. S1). Columns correspond to the three AOGCM-driven simulations (CRCM6_{EC-Earth3-Veg}, CRCM6_{MPI-ESM1-2-HR}, CRCM6_{MIROC6}); the top row uses the historical 99th percentile as the extreme threshold, the bottom row the historical 99.9th percentile. Historical (1980–2014) and future (2063–2097) ETCs are shown in blue and red semi-transparent markers, respectively, with marker shape indicating the season of ETC initiation (see legend). Dashed grey iso-curves mark lines of constant accumulation $EE_{PR,cum|ETC}$. Opaque markers denote the marginal medians of T_{ETC} and $\overline{EE_{PR|ETC}}$ for each season and period.

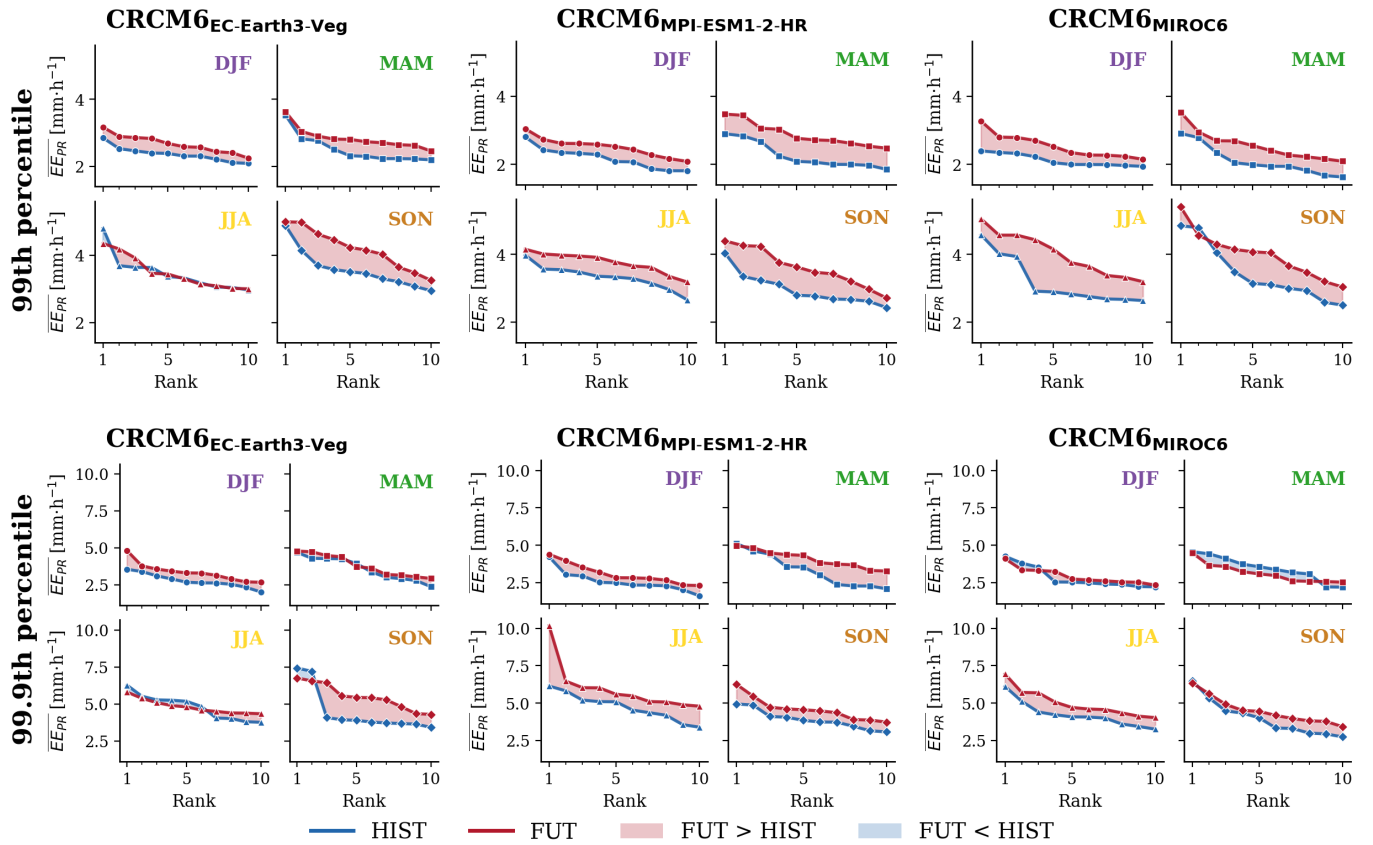


Figure 10. Mean excess intensity $\overline{EE_{PR|ETC}}$ of the 10 most intense ETCs of each season over the NNA region (Fig. S1), ranked from most to least intense (rank 1 = most intense). ETCs are selected based on the regularized intensity $\overline{EE_{PR|ETC}} \cdot T_{ETC} / (T_{ETC} + \lambda)$, with $\lambda = 10000$ for the 99th percentile (top row) and $\lambda = 2500$ for the 99.9th percentile (bottom row). Columns correspond to the three AOGCM-driven simulations (CRCM6_{EC-Earth3-Veg}, CRCM6_{MPI-ESM1-2-HR}, CRCM6_{MIROC6}). Each (percentile, simulation) panel is subdivided into four subpanels, one per season (DJF, MAM, JJA, SON; labelled in the top-right corner). Within each subpanel, the historical (1980–2014) and future (2063–2097) ranked curves are shown as blue and red lines, respectively.