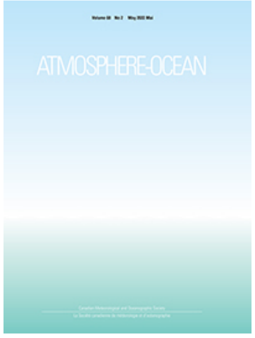

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Freezing Rain Events that Impacted the Province of New Brunswick, Canada, and Their Evolution in a Warmer Climate

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ABSTRACT *Winter storms in eastern Canada can bring heavy precipitation, including large amounts of freezing rain. The resulting ice accumulation on structures such as trees and power lines can lead to widespread power outages and damage to infrastructure. The objective of this study is to provide a better understanding of the processes that led to extreme freezing rain events over New Brunswick (NB), Canada, during past events and how they may change in the future. To accomplish this, freezing rain events that affected the power network over NB were identified and analysed using high-resolution convection-permitting simulations. These simulations were produced from 2000 to 2013 climate data and using the pseudo global warming (WRF-PGW) approach, assuming warmer climate conditions. Our results show that through the process of cold air damming, the Appalachians enhance the development of strong temperature inversions, leading to an increase in the amount of freezing rain in central and southern NB. The occurrence of freezing rain events generally decreases by 40% in southern and eastern NB, while the occurrence of long-duration events (>6 h) increases slightly in northwestern NB in the WRF-PGW simulation. Overall, key local orographic effects that influence atmospheric conditions favorable for freezing precipitation were identified. This knowledge will enable us to better anticipate the impact of climate change on similar storms.*

RESUME *Les tempêtes hivernales dans l'est du Canada peuvent entraîner de fortes précipitations, y compris de grandes quantités de pluie verglaçante. L'accumulation de glace qui en résulte sur des structures telles que les arbres et les lignes électriques peut provoquer des pannes de courant généralisées et des dommages aux infrastructures. La présente étude vise à faire mieux comprendre les processus qui ont conduit à des événements extrêmes de pluie verglaçante sur le Nouveau-Brunswick (N.-B.), au Canada, au cours des événements passés et comment ils peuvent changer à l'avenir. Pour ce faire, les événements de pluie verglaçante qui ont touché le réseau électrique au N.-B. ont été recensés et analysés au moyen de simulations de convection à haute résolution. Ces simulations ont été produites à partir des données climatiques de 2000 à 2013 et en utilisant l'approche du pseudo-réchauffement climatique (WRF-PGW), en supposant des conditions climatiques plus chaudes. Nos résultats montrent que, par le processus d'endiguement de l'air froid, les Appalaches favorisent le développement de fortes inversions de température, ce qui entraîne une augmentation de la quantité de pluie verglaçante dans le centre et le sud du Nouveau-Brunswick. L'occurrence des événements de pluie verglaçante diminue généralement de 40% dans le sud et l'est du Nouveau-Brunswick, tandis que l'occurrence des événements de longue durée (>6 h) augmente légèrement dans le nord-ouest du Nouveau-Brunswick dans la simulation WRF-PGW. Dans l'ensemble, on a recensé les principaux effets orographiques locaux qui influencent les conditions atmosphériques favorables aux précipitations verglaçantes. Ces connaissances nous permettront de mieux anticiper l'impact du changement climatique sur des tempêtes similaires.*

KEYWORDS freezing rain; wet snow; convection permitting climate models; climatology; winter storms

1 Introduction

Eastern Canadian winters are characterized by frequent extratropical low-pressure systems that bring heavy precipitation to the region. Many of these high-impact meteorological events bring mixed precipitation to the province of New Brunswick (NB) (Stewart, 1992). Freezing rain events are particularly damaging as a result of ice accumulation on infrastructure. Ice accumulation can cause transmission lines to fall, even with relatively

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light amounts of precipitation (e.g. McKay and Thompson, 1969; Klaassen et al., 2003; Farzaneh, 2008). The January 2017 ice storm in Atlantic Canada resulted in more than 130,000 homes without power in NB after up to 50 mm of freezing rain fell over the course of three days over NB (Thériault et al., 2022). Households in the Acadian Peninsula were without power for up to two weeks after the event occurred.

In Atlantic Canada, freezing rain and ice pellets are typically associated with a temperature inversion ahead of a warm front. Warm air advection aloft can lead to a melting layer aloft (temperatures (T) > 0°C) while subfreezing temperatures remain near the surface. Snow gradually melts as it falls to through the warm layer. As the partially melted particles fall into the subfreezing layer, the remaining ice in the mixed phase particles initiates freezing, leading to the formation of ice pellets (Stewart et al., 2015). If the particles completely melt while in the warm layer, they will enter the subfreezing layer as rain. Without activated ice nuclei, supercooled drops will not freeze while falling but only upon contact with the surface, producing freezing rain (Huffman and Norman, 1988; Zerr, 1997; Stewart et al., 2015). The melting layer is usually shallower and/or colder during an ice pellet event compared to a freezing rain event, which allows mixed phase particles to reach the top of the refreezing layer (Thériault et al., 2006; Zerr, 1997).

The precipitation transition region where freezing precipitation is found is also linked to the position of the low-pressure center, with a typical width of 10 km to 100 km (Stewart, 1992; Kocin and Uccellini, 2004). Precipitation-type transitions are usually expected depending on the storm track. Precipitation types typically evolve from snow to ice pellets to freezing rain to rain (Stewart and King, 1987) during the passage of a warm front, which deepens and increases the temperature of the melting layer aloft.

Complex terrain can reinforce near-surface temperature inversions during winter storms through the processes of wind channeling and cold air damming (e.g. Roebber and Gyakum, 2003; Henson et al., 2011; Forbes et al., 1987; Bernstein, 2000). Both of these processes favor the development or maintenance of atmospheric conditions that lead to extended periods of freezing rain and ice pellets by enhancing temperature inversions at lower altitudes. In southern Quebec, wind channeling is responsible for the highest local median number of hours of freezing precipitation (freezing rain, drizzle and ice pellets), at more than 50 h annually (Cortinas et al. 2004; Stuart and Isaac, 1999). For example, the January 1998 ice storm in eastern Canada and the northeastern US was an extreme freezing rain event that was greatly influenced by the channeling of low-level winds in the Saint Lawrence River Valley (SLRV, Roebber and Gyakum, 2003; Henson et al. 2011). Similarly, cold air damming is associated with most prolonged freezing rain and ice pellet events in New England as well as in the Mid-Atlantic region of the United States (Richwien, 1977; Forbes et al., 1987; Bernstein, 2000).

Eastern NB is also a region with a high yearly median number of hours of freezing precipitation, with more than 50 h annually (Stuart and Isaac, 1999). Stuart and Isaac (1999) suggested that a very high number of freezing precipitation occurrences in parts of Atlantic Canada are due to a combination of the topographical features in the area, the proximity to the Atlantic Ocean, and the frequent occurrence of cyclones. While other scientists studied the climatology of freezing rain occurrence (e.g. Cortinas et al., 2004; Stuart and Isaac, 1999), McCray et al. (2019) specifically investigated the occurrence of long-duration (> 6 h) freezing rain events, as heavy freezing rain accumulations are generally associated with long-duration events (e.g. Ressler et al., 2012). They showed that stations in NB record approximately 1-1.5 long-duration freezing rain events per year.

Previous studies have investigated the effect of climate change on freezing rain events in eastern North America (Lambert and Hansen, 2011; Cheng et al., 2011; Klima and Morgan, 2015; Matte et al., 2018; Jeong et al., 2018). Most of these studies identified a northward shift in the climatological distribution of freezing precipitation at the end of the twenty-first century. These findings were conducted with Global Circulation Models and Regional Climate Models, which have coarser resolution than convection-permitting models. This can be critical for the simulation of the favorable temperature structure for freezing rain as shown by Cholette et al., (2015).

As electrical utility companies across Canada explore climate change adaptation and risks, greater insight is needed on how the frequency and distribution of freezing rain events may evolve under warming climate conditions. Given this, the main objective of this study is to provide a better understanding of the processes that led to extreme freezing rain in past events to better anticipate their evolution in a future climate. A historical simulation covering the period from 2000–2013, and a Pseudo Global Warming simulation (Liu et al., 2017) were used to study freezing rain events in NB. A similar approach was used to study the impact of climate change on freezing rain and wet snow events in Manitoba, Canada (Tropea and Stewart, 2021).

This paper is organized as follows. The data and methodology are described and discussed in Section 2. Section 3 includes the climatology of winter precipitation in NB. Section 4 discusses the synoptic evolution of extreme freezing rain events that impact NB and the local effects caused by the presence of the Appalachians. The effects of climate change on freezing rain events in NB are examined in Section 5. The main findings are summarized in Section 6, along with the conclusion.

2 Data and methodology

a *Convection-permitting Climate Simulations*

To study fine and mesoscale features within individual events, the Weather Research and Forecasting (WRF) model version 3.4.1 in a convection-permitting 4-km grid (Liu et al. 2017) was used. The historical simulation, which is used as the control simulation (WRF-CTL), included data from 2000 through 2013. The model was configured with a domain size of 1360 × 1016 grid points, which covered all the continental contiguous United States, northern Mexico and southern Canada (Fig. 1). There were 51 vertical levels,

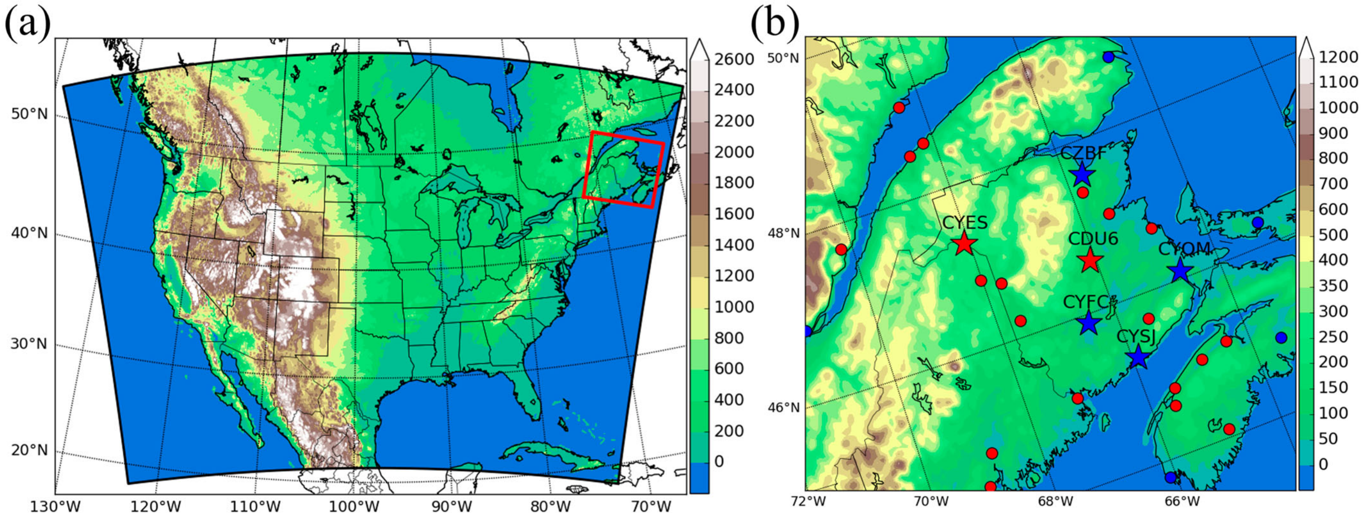

Fig. 1 (a) WRF model domain (5440 km × 4064 km) at 4-km grid-spacing, showing topographic elevation in meters. (b) Zoomed-in image over domain of interest. Locations of weather stations used to validate WRF-CTL model output are shown. Stations identified in red have daily data and stations identified in blue have hourly weather observations. Stars represent the locations chosen for analysis of future changes of freezing rain event occurrence. These are Edmundston (CYES), Bathurst (CZBF), Doaktown (CDU6), Fredericton (CYFC), Saint John (CYSJ) and Moncton (CYQM). The blue dots represent locations used to compare the occurrences of freezing rain but were not included in the future climate analysis because they are located in Quebec (QYGP), Prince Edward Island (CYYG) and Nova Scotia (CYHZ and CYQI). See Liu et al. (2017) for information on the degree of warming simulated in the WRF-PGW simulation.

topped at 50 hPa. The model was one-way nested using the 6-h the European Center for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis data, which has approximately 80 km grid spacing. The Thompson aerosol-aware microphysics scheme was used in the simulation (Thompson and Eidhammer, 2014), which is a single moment bulk microphysics parameterization. The scheme explicitly predicts the mixing ratios of five liquid and ice species: cloud liquid water, rain, cloud ice, snow, and graupel. A second moment was added for the number concentration of cloud ice. Liu et al. (2017) showed that this simulation accurately represents the spatial and temporal patterns of sub-seasonal/seasonal/annual temperatures and precipitation over the entire simulation domain. They also showed that the mesoscale precipitation structures such as orographic precipitation and summertime convection were also adequately simulated.

To investigate the thermodynamic feedback of climate change on freezing rain events in NB, we used the Pseudo Global Warming (WRF-PGW) simulation from Liu et al. (2017). The PGW method applies a perturbation to the reanalysis data to simulate historical conditions in a warmer climate. In particular, the 95-year Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012) ensemble-mean change signal under the RCP8.5 scenario (ΔCMIP5 = $CMIP5_{2017\text{-}2100}$ – $CMIP5_{1976\text{-}2005}$) was applied to eight field of the ERA-Interim data while nesting the WRF model on the same grid and time period as the WRF-CTL simulation. The RCP 8.5 scenario is described in Riahi et al. (2011). The physical fields that reflect the perturbation are horizontal wind, geopotential, temperature, specific humidity, sea surface temperature, soil temperature, sea level pressure, and sea ice. Note that this method does not allow us to study the changes in storm tracking because of spectral nudging and the monthly-mean perturbations applied to the ERA-interim reanalysis.

The model simulations we used were chosen for two reasons. First, the comparison of the WRF-CTL and WRF-PGW simulations allows us to isolate the thermodynamic feedback of global warming in response to the forcing of a given greenhouse gas (GHG). Secondly, it is possible to investigate extreme events in a very high-resolution grid to study the impact of local topography on freezing rain distribution in NB. Indeed, the 4-km resolution is enough to accurately depict the various topographical features of NB (Fig. 1). For example, the highest mountains in the Appalachian range in NB (e.g. Mount Carleton) are depicted at ~100 m higher using the 4-km grid-spacing than with a grid-spacing of 0.11° (Fig. 2). Furthermore, an earlier study by Tropea and Stewart (2021) showed that the 4-km grid-spacing of the WRF simulations was enough to depict changes in precipitation types induced by the presence of small mountain chains in Manitoba. It is, however, difficult to obtain adequate evaluation of the model using observations (Lundquist et al. 2019).

b *Identification of Winter Storms*

A list of 81 precipitation events that caused power outages was provided by Énergie NB Power, the main electricity producer of the New Brunswick province. The 81 precipitation events occurred from 2003 to 2013. The sea-level pressure maps were analyzed carefully and 76 of the 81 precipitation events were associated with a low-pressure system

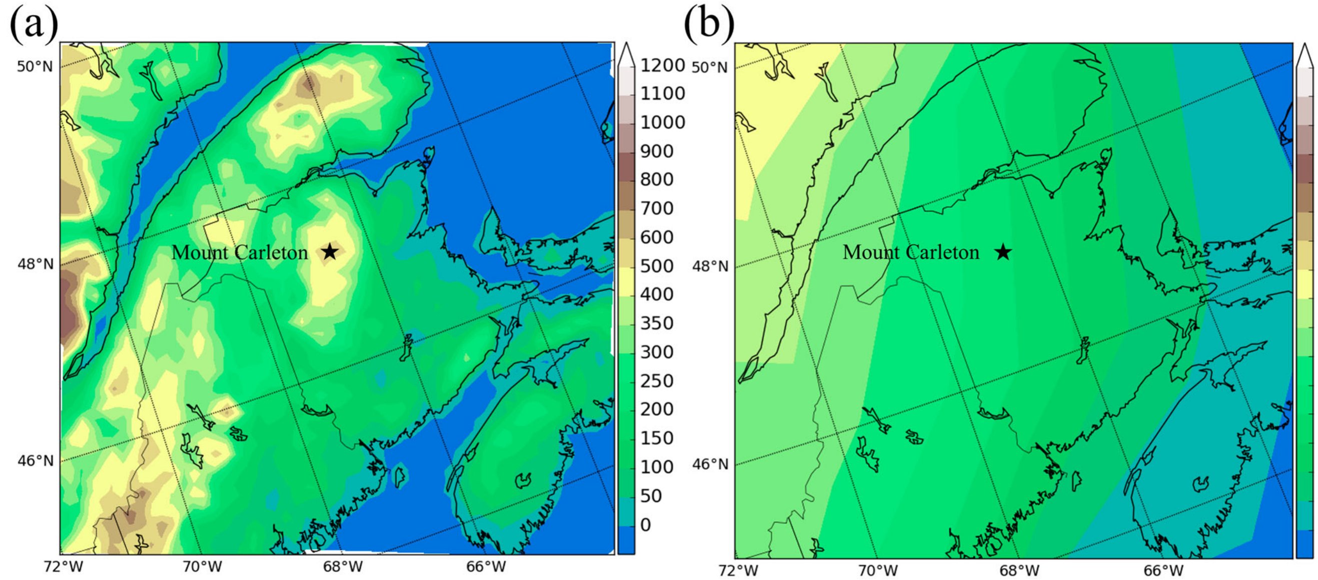

Fig. 2 Orography field of (a) the CRCM5 at 0.11° grid spacing and (b) the CanESM2 at 2.8° grid-spacing. The orography is in m.

and were identified as a winter storm. The other events were associated with convective localized precipitation and were not considered in this study. The 76 events that caused power outages and provided by Énergie NB Power were grouped into four categories based on the precipitation types: snow events, rain events, mixed events and freezing-rain events. The precipitation type was identified using the WRF-CTL simulation. Snow events were assigned when there was only snowfall over all NB surface weather stations. Rain events were defined as when there was only liquid precipitation. Mixed events were associated with various types of precipitation (including freezing rain). Finally, freezing rain events were defined as mixed events that produced more than 12.5 mm of freezing rain in NB based on the historical WRF simulation. The 12.5-mm threshold was selected because this is the point at which major structural damage usually occurs (e.g. Klaassen et al., 2003). This threshold determines the cases of extreme freezing rain in our study. Finally, only the storms that occurred during the November-to-March period were considered, as the events that occurred in October, April and May tended to be only rain or mixed events, regardless of their tracks.

A cyclone tracking scheme was applied to the ERA5 reanalysis (Hersbach et al., 2020) dataset to depict the storm tracks of each event that was identified. The storm tracking method that we used is detailed in Chartrand and Pausata (2020). The ERA5 dataset was used instead of the WRF data because the global coverage allowed us to depict the complete storm tracks, as many of the winter storms in our study originated from the western Atlantic Ocean. In the algorithm, the sea-level pressure (SLP) metric to track cyclones and the local minimum sea-level pressure field to define the position of the cyclone were used. The storm tracks associated with all precipitation events that caused damage to NB Power infrastructure are shown in Fig. 3.

c *Data Analysis*

To ensure that WRF-CTL captured the winter storms, the daily precipitation and snowfall data from land surface weather stations all over the domain of interest were used. A total of 29 stations in the Global Historical Climatology Network (GHCN)-Daily (Menne et al. 2012) were chosen based on the availability of data in the 2003–2013 time period. For every storm studied, the total snowfall and the total precipitation were calculated by adding the daily values for all the days with measurable precipitation linked to a given winter storm. At each point in the model grid that was the closest to a station, the total precipitation and snowfall were also calculated for the same time period using the WRF-CTL simulation output data. For total snowfall, the value is the sum of snow and graupel (includes ice pellets), as snow observations include ice pellets. For every event, the mean bias and the correlation between the station data and the WRF-CTL simulation accumulated precipitation were calculated to assess whether the simulation could be used to investigate the event. Based on these criteria, 68 of the 81 events were generally well reproduced by the WRF-CTL simulation, including the seven freezing rain events. Moreover, The WRF-CTL simulation have reproduced well the climatology of precipitation amounts and 2-m temperature as shown in Liu et al. (2017) and Marinier et al. (2021). Comparisons between the precipitation, snowfall produced by the WRF-CTL simulation and observations for each of the freezing rain events are available in the supplemental material.

Because no systematic freezing rain accumulation data exists for Canada, we chose to look at the duration of freezing

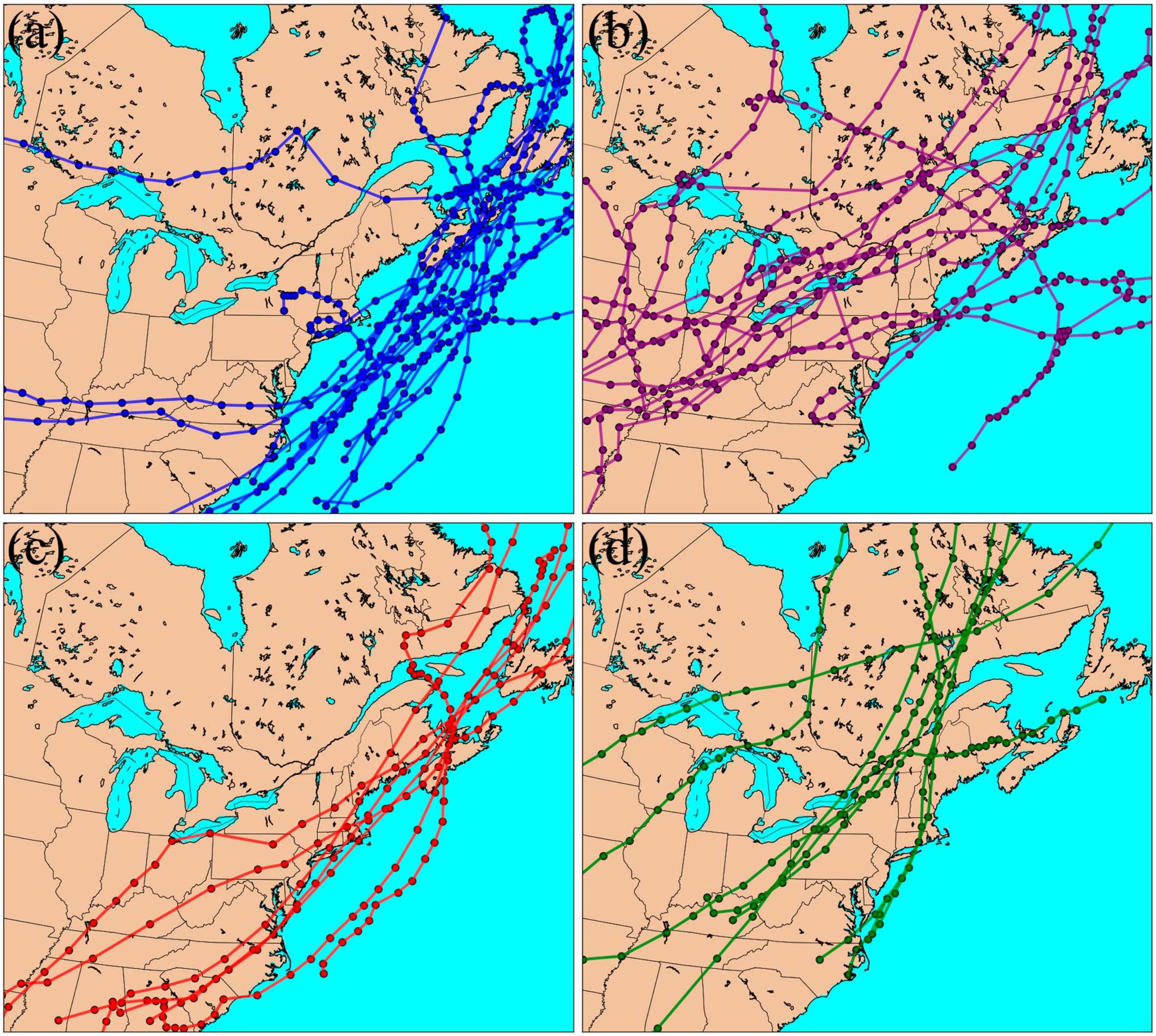

Fig. 3 Composite tracks of 2003 – 2013 storms affecting NB Power infrastructure (only events from November to April) clustered into four categories: (a) snow-only events, (b) mixed events, (c) freezing rain events and (d) rain-only events. Dots represent the p.

rain events instead of the amount of freezing rain. The hourly reports of freezing rain at ten Environment and Climate Change Canada weather stations were first compared to the WRF-CTL simulation to verify if the model depicts the correct annual occurrence of freezing rain in historical conditions. Freezing rain event durations were based on criteria also used in Almonte and Stewart (2019). An event duration is the number of hourly observations in which freezing rain (> 0.2 mm h^{-1}) was observed (including when mixed with other precipitation types). As in Matte et al. (2018), up to six consecutive hours without freezing rain was assumed to distinguish two separate events. If freezing rain occurs multiple times with fewer hours in between, it is considered one event.

3 Historical climatology of winter precipitation

The distributions of mean annual total precipitation, rainfall, snowfall and freezing rain using the WRF-CTL simulation for the 2000–2013 period are depicted in Fig 4. The total precipitation distribution is uniform across NB, with small regional differences. Over most of the province, the average total precipitation was 1000–1300 mm/year. Nonetheless, mountainous regions received slightly more annual precipitation due to the orographic enhancement of precipitation. The hilly southern coast is the wettest location in NB, with more than 1400 mm/year at the highest elevations.

The annual snowfall distribution exhibited high variability within the study area. The proximity to the Atlantic Ocean and the topography could explain this variability in NB (Stuart

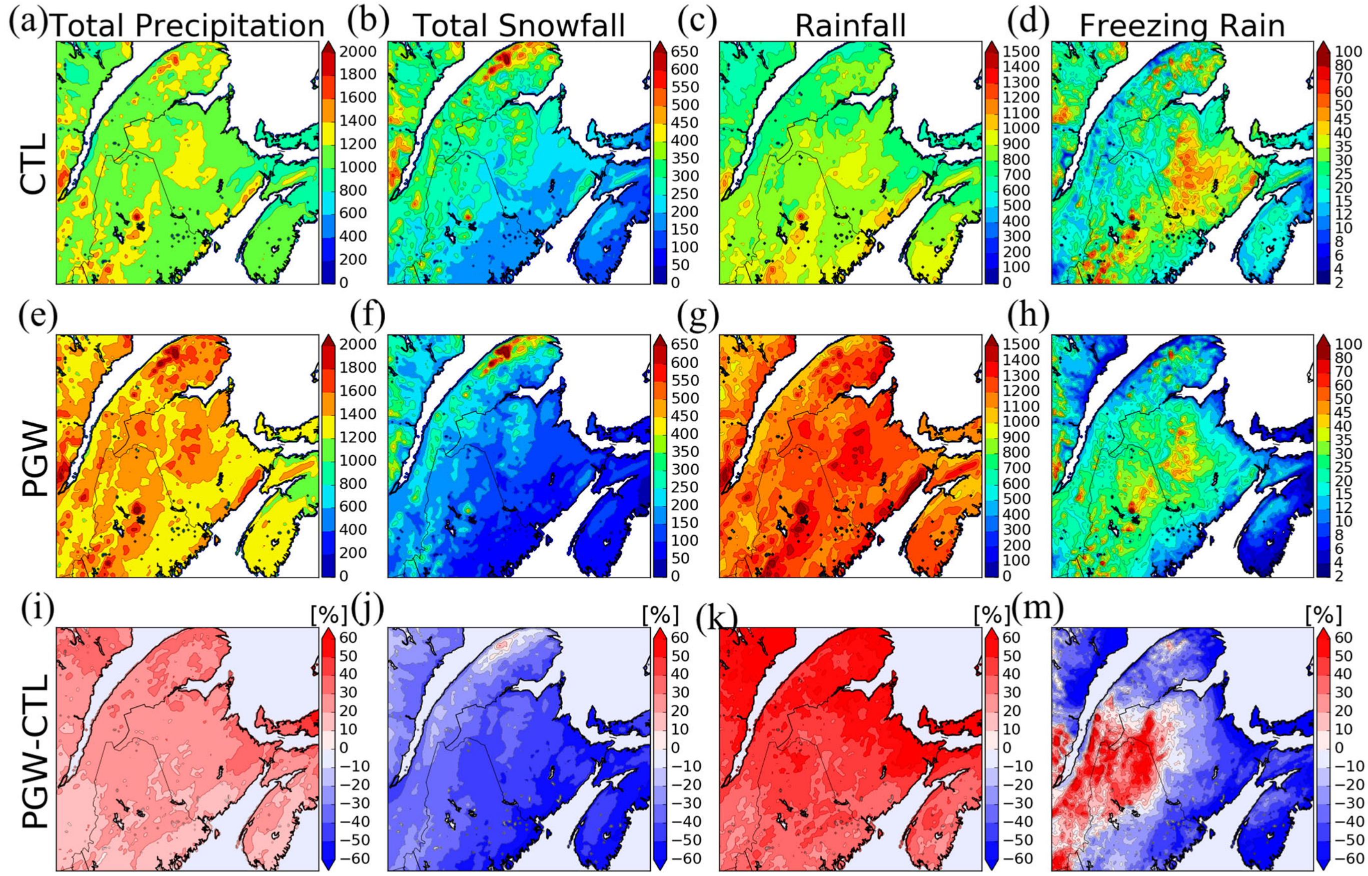

Fig. 4 Annual average (mm/year in liquid equivalent) of (a,e) total precipitation, (c,g) rainfall, (b,f) snowfall and (d,h) freezing rain during the 2000 – 2013 period using WRF-CTL and WRF-PGW simulations. Changes/Differences (%) in annual (i) total precipitation, (j) snowfall, (k) rainfall and (m) freezing rain between the two simulations (PGW-CTL).

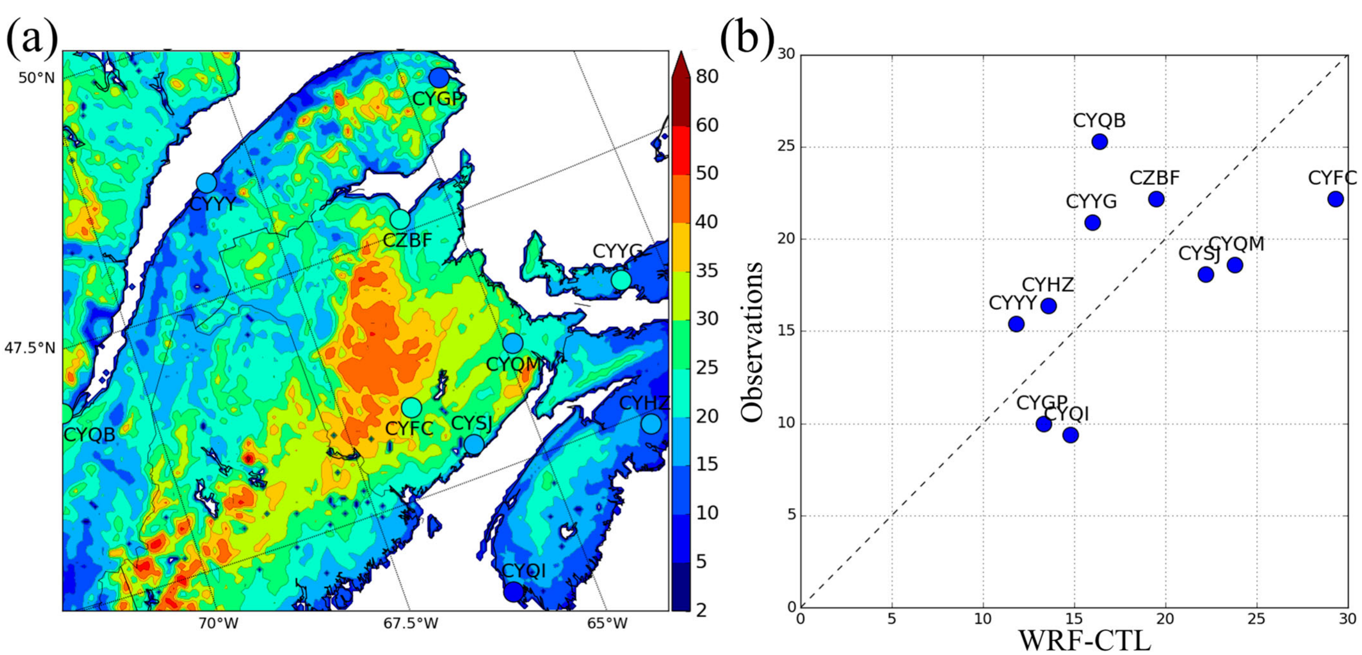

Fig. 5 (a) Average annual freezing rain occurrence in hours for the 2000 – 2013 period using the WRF-CTL simulation (shaded) and observations (circles). (b) Comparison between observations of average annual freezing rain occurrence at weather stations with the WRF-CTL simulation at the nearest grid point.

and Isaac, 1999). The snowfall distribution follows the orography as more snow was produced at higher elevations even though the elevations are only up to 800 m. The annual snowfall generally increased northward by 250 mm/year from southern NB to the Appalachians of northern NB. In contrast, the annual rainfall distribution decreased from south to north.

The average annual freezing rain accumulation (Fig. 4) and occurrences follow similar patterns (Fig. 5). The central part of the province, from the Appalachians to the region of Fredericton, recorded the highest accumulation and occurrence of freezing rain. Up to 40 h of freezing rain were recorded annually, which produced up to 45 mm of precipitation. The occurrence of freezing rain decreased to ∼20 h towards the coast. The annual occurrence of freezing rain was lower in northern NB (approximately 15-20 h in Edmundston). While there are very limited observations of freezing rain in NB, the WRF-CTL simulation reproduced the annual occurrences well (Fig. 5). Unfortunately, there are no hourly data available for the central part of the province where the maximum amount of freezing rain was reported.

4 Analysis of historical freezing rain events

a *Overview of Storm Tracks that Produced Freezing Rain*

All of the extreme freezing rain events in NB were associated with low-pressure systems that followed similar tracks (Fig. 3). They all formed over the part of southeastern US that borders the Gulf of Mexico, and moved northeastward, closely following the coasts of the US, NB and Nova Scotia. In contrast, snow events followed tracks that remained well offshore. This was true for all but one system that traveled southeast of NB. Rain events tracked northwest of the province.

The total freezing rain horizontal distribution produced by each of the identified extreme freezing rain events and their respective storm tracks are shown in Fig. 6. The width of the region that receives a considerable amount of freezing rain in NB is, in most cases, well above the typical 10–100 km width observed by Stewart et al. (1990) in historical Atlantic Canada winter storms.

b *Composite Evolution of Low-pressure Systems and Freezing Rain*

A composite of the seven freezing rain events was created (Fig. 7) because the events had similar synoptic patterns. To combine the events, the time step corresponding to the heaviest precipitation rates in NB were subjectively defined as $t = 0$ h. The sea-level pressure and 500–1000 mb thickness maps of each event at $t = 0$ h were added as supplemental material.

At $t = -24$ h, an upper-level trough with a relatively short wavelength was situated over the US, along with a weak ridge over the western North Atlantic and Atlantic Canada (Fig. 7a). In the composite, a closed surface low-pressure system formed over the northern part of Alabama and Georgia, with an SLP center of 1009 hPa. The 250-hPa wind field was showing upper-level divergence over the southeast US (not shown), creating the perfect conditions for rapid cyclogenesis of a Miller type-A nor'easter in the southeast coastal plains (e.g. Miller, 1946; Kocin and Uccellini, 2004). In addition to the development of a surface low-pressure system, a high-pressure system was located over the province of Quebec. The presence of this cyclone-anticyclone couplet is a key feature associated with the onset of freezing rain events in the northeastern US and southeastern Canada (Ressler et al., 2012; Rauber et al., 2000).

By $t = -12$ h, the deeper surface composite low-pressure system was located over Maryland with an SLP center of 1004 hPa (Fig. 7b). The eastward displacement and amplification of the 500-hPa trough-ridge pattern demonstrated the propagation and intensification of the surface cyclone (e.g. Sutcliffe and Forsdyke, 1950). The high-pressure center propagated slightly eastward, over southwestern Labrador with a relatively high SLP center of 1030 hPa. The close positioning and strengthening of the cyclone-anticyclone couplet on a southwest-northeast axis produced a strong pressure gradient force parallel to the coastline (and the Appalachians mountains). This synoptic setup was conducive to cold-air damming east of the Northeast US Appalachians (e.g. Lackmann, 2011; Kocin and Uccellini, 2004), which could be recognized by a U-shaped isobar pattern over New England. With the cold-air damming process enhancing the differential temperature advection between the surface and the mid-levels, freezing rain was produced between the mountains and the coast of New England in six of the seven events of the composite at $t = -12$ h. This suggests that events leading to significant freezing rain accumulation in NB often cause significant icing in the coastal plains of New England before the onset of precipitation in NB.

At $t = 0$ h, the composite low-pressure center was located over southern Maine (998 hPa), and the high-pressure system once again shifted slightly eastward over Labrador (Fig. 7c). Over NB, strong geostrophic wind veering demonstrated significant warm air advection aloft. Surface winds were, however, from the northeast over most of NB (Fig. 8f), which suggested significant ageostrophic flow near the surface. The composite showed a plume of high precipitable water values that usually indicates an atmospheric river transporting heat and moisture from the (sub)tropical area to the extratropical area, which could provide a favorable condition for freezing rain in eastern Canada (e.g. Mo and Lin, 2019). Together with warm frontal lifting, this produced high precipitation rates in NB. It is also noteworthy that the 540 dam 500–1000 hPa thickness was passing through the center of NB at this time.

At $t = +12$ h, the composite low-pressure center continued its path northeastward over the Gulf of Saint Lawrence and deepened to 996 hPa (Fig. 7d). The associated cyclonic circulation advected dry, cold air into NB at this time, as seen in the smaller 500–1000 hPa thickness values. Precipitation decreased rapidly in NB and the main precipitation region moved over Newfoundland and Labrador.

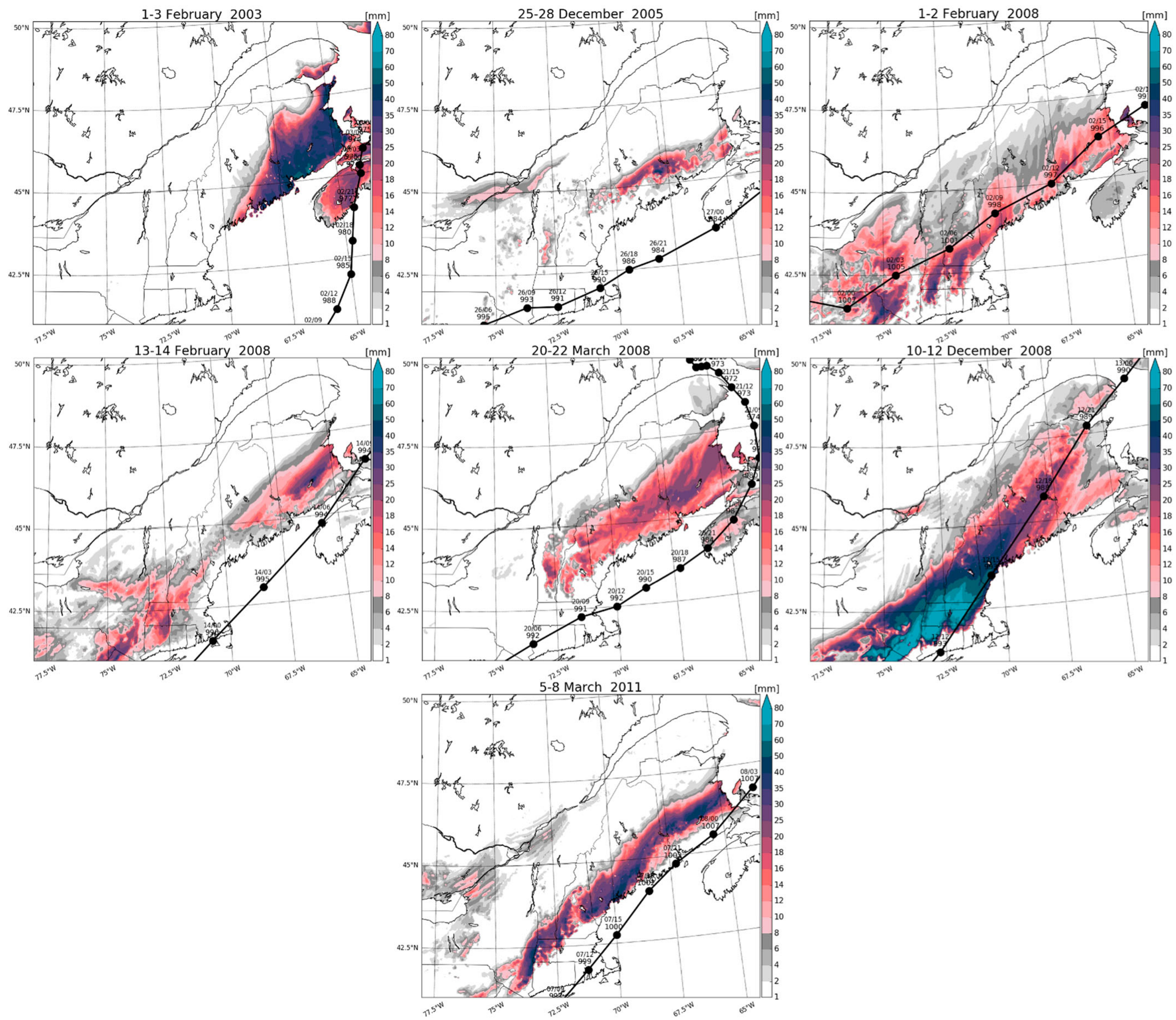

Fig. 6 Freezing rain amounts associated with the seven identified storm tracks produced in the WRF-CTL simulation. Black dots represent the position of the low-pressure centers at 3-h intervals. The sea level pressure minimum is shown, as well as the date at each time interval (day/time).

c *Case Study of the 2 February 2008 Event*

The freezing rain event of 2 February 2008 was used to represent a typical case study (Fig. 8) as it was representative of the composite shown Fig. 7. The supplemental material contains a comparison between observations and the WRF-CTL simulation of this event, as of the other freezing rain events used in this study. At 1200 UTC 2 February 2008, the surface low-pressure system that was centered over eastern Maine produced heavy precipitation over NB. Rimed snow, freezing rain and rain occurred in northern, central, and southern NB, respectively.

Relatively warm air to the southeast and colder air to the northeast were associated with an intense horizontal temperature gradient. Consequently, strong warm air advection aloft under veering winds led to a melting layer aloft. This is also shown in the evolution of the vertical temperature profile in Caribou, Maine between 0000 and 1200 UTC 2 February 2008 (Fig. 9). While the WRF-CTL simulation generally reproduced the observed vertical temperature profiles very well, the model representation of the temperature near the surface during the event was less accurate than that aloft. In this case, the temperatures produced in the model were colder than the observed temperatures, which could have an impact on the simulated distribution of freezing rain.

The comparison between the isobar pattern and the near-surface wind (Fig. 8) shows a sharp difference between the geostrophic wind and the actual wind over parts of NB. The wind direction was also strongly linked to the change in

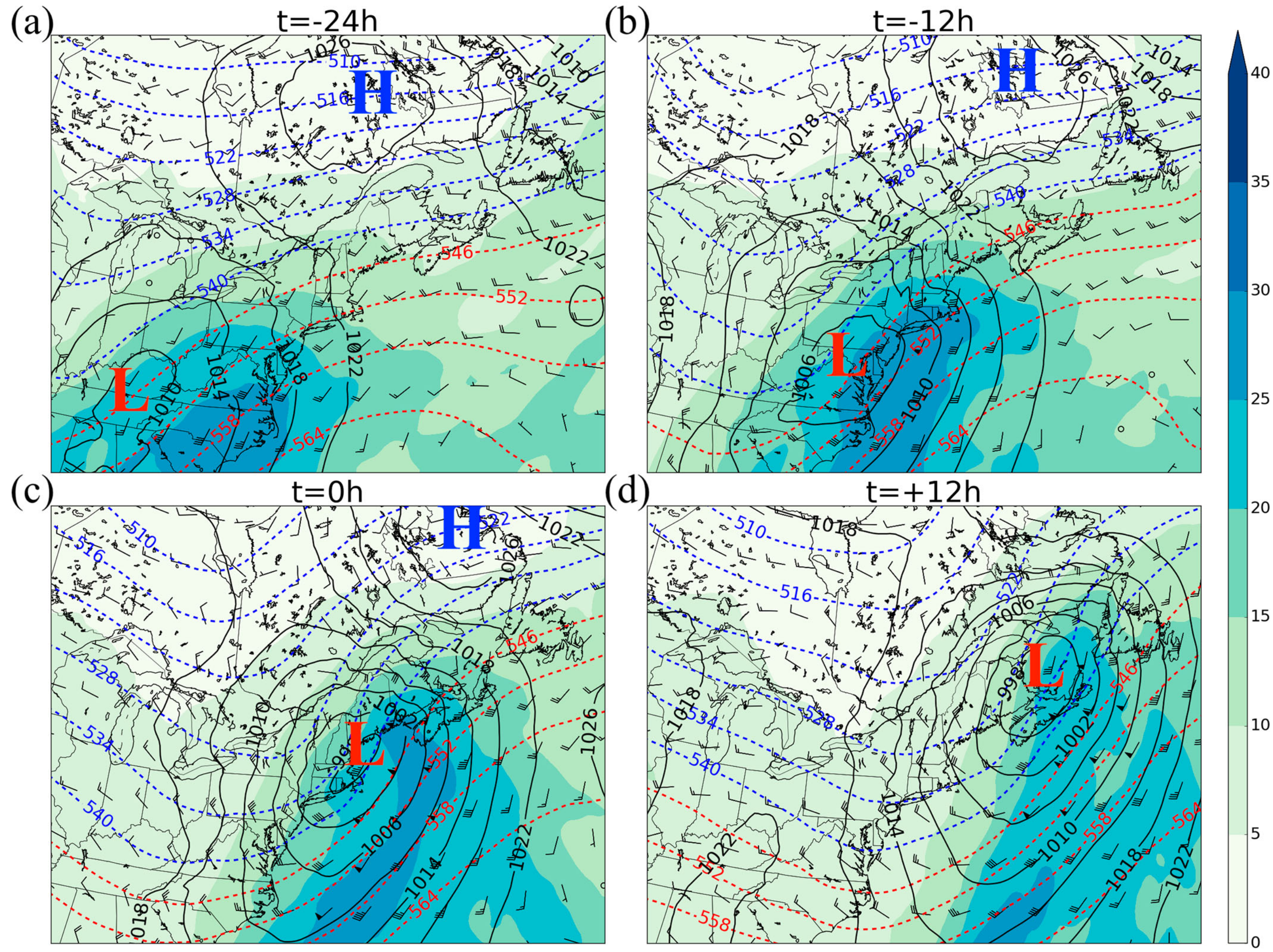

Fig. 7 Composite of the ERA5 reanalysis 500–1000 hPa thickness (dam, dashed), total precipitable water (mm, shaded), sea-level pressure (hPa, contours) and 850-hPa wind fields (barbs) for seven freezing rain events in NB at (a) $t = -24$ h, (b) $t = -12$ h, (c) $t = 0$ h, (d) and $t = +12$ h. The wind barbs point in the direction towards where the wind is blowing. The short line is 5 knots (9.7 m s^{-1}), the long line is 10 knots (19.4 m s^{-1}) and the triangle is 50 knots (97.2 m s^{-1}).

terrain elevation. This was particularly evident because of the low-level northerly winds southeast of the Appalachian Mountains at 1200 UTC 8 February 2008. As the strong easterly winds over the Gulf of Saint Lawrence approached the Appalachians, the mountains acted as a physical barrier to the stable flow and trapped the existing cold air along the eastern slopes. A calculation of the non-dimensional mountain height (inverse Froude number) using the low-level wind flow and stability between the Bay of Fundy and Mount Carleton confirmed that the easterly flow was blocked. The computed value (~1.55) of the non-dimensional mountain height was well over the threshold value of 1.2 (e.g. Colle et al., 2013). This created a channeling (or damming) of the near-surface air flow, forcing the low-level wind to follow the terrain in an ageostrophic northeasterly flow. This relatively cold air prevented the air near the surface from increasing to above freezing and, in turn, produced a prolonged period of freezing rain in central NB. This observed process shared similarities with the cold-air damming that affects the regions east of the Appalachians in the US (e.g. Forbes et al., 1987; Lackmann, 2011). The deformation in the SLP field, as seen on the southern side of the mountains in New England at 0000 UTC 2 February 2008 and in NB at 1200 UTC 2 February 2008, was also a typical characteristic of the cold-air damming process.

The cross-sections depicted in Fig. 10 showed the evolution of the temperature profile throughout NB between 0000 and 1200 UTC 2 February 2008. While the temperature profile showed little variation below 3 km at 0000 UTC 2 February 2008, 12 h later, the temperature near the surface was up to ~15°C colder than the temperature at 2 km. The veering winds, as well as the low-level cold-air advection (not shown), were the strongest between Mount Carleton and the Bay of Fundy at 1200 UTC 2 February 2008. This produced a strong temperature inversion at the location where the maximum amount of freezing rain was reported. Therefore,

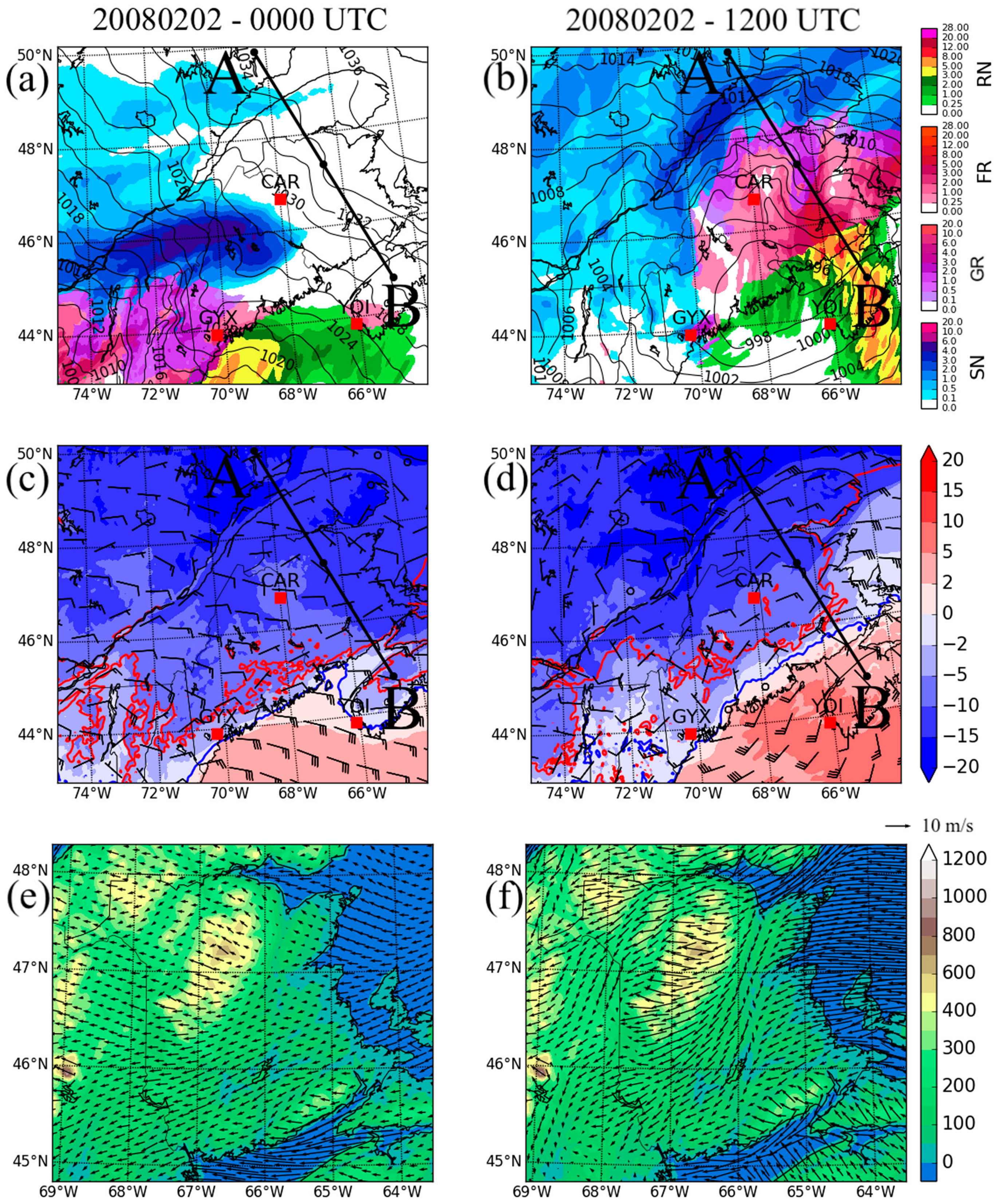

Fig. 8 WRF-CTL Sea-level pressure (hPa, contours), precipitation type and rate (mm/h, shading) valid at (a) 0000 UTC and (b) 1200 UTC on 2 February 2008. Two-m temperature (°C, shading) and 10-m wind (barbs) at (c) 0000 UTC and (d) 1200 UTC. The blue and red contours in (c) and (d) represent the 0°C isotherm in the WRF-CTL and WRF-PGW simulations, respectively. Terrain (m, shading) and 10-m wind (arrows) at (e) 0000 UTC and (f) 1200 UTC. The black line and the A and B marks represent the cross-section presented in Fig. 11. The red squares represent the soundings locations presented in Fig. 9.

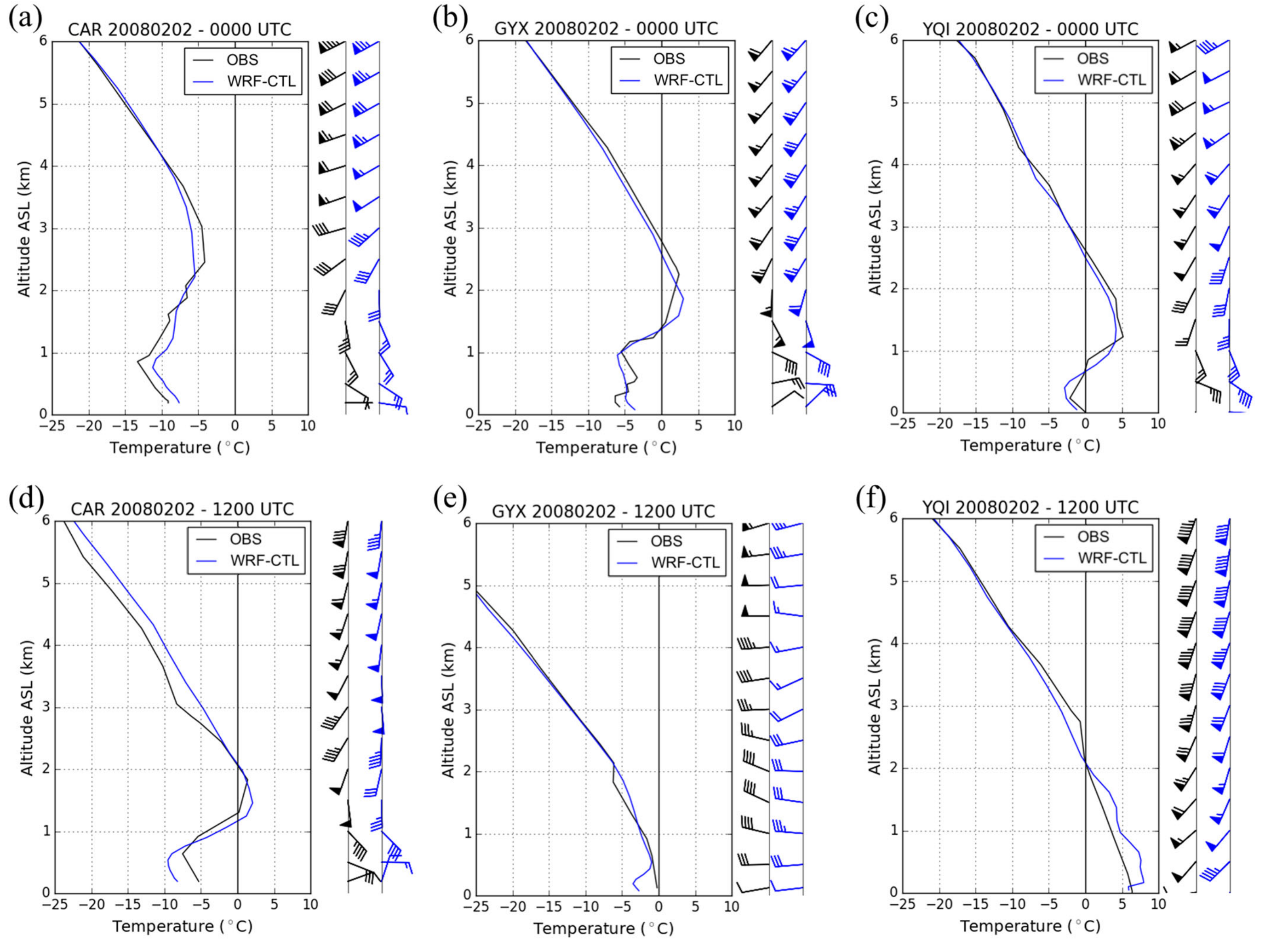

Fig. 9 Caribou, Maine sounding observed (black) and simulated (blue) by the WRF-CTL simulation, valid at (a) 0000 UTC and (d) 1200 UTC on 2 February 2008. (b), (e) as in (a), (d), but for Gray, Maine. (c), (f) as in (a), (d), but for Yarmouth, NS. The nearest grid points were used for the simulated profile. The location of the upper air sounding stations are shown in Fig. 8, represented by red squares.

the presence of the Appalachians in the northern part of the province seemed to be a key element in producing larger amounts of freezing rain in NB through the wind channeling/cold-air damming process.

d *Distribution of Precipitation*

The average distribution of precipitation types across NB during the seven identified freezing rain events is shown in Fig. 11. Knowing that all of the storms followed a southwest to northeast trajectory, a northwest/southeast cross-section was defined (Fig. 8). This cross-section intersects perpendicularly with both the Appalachian Mountains and the southern NB coast, providing information on how the local topography affects the distribution of precipitation.

The main precipitation types varied along the cross-section in the region from Mount Carleton to the Bay of Fundy. North of Mount Carleton, snow was the dominant precipitation type during the events. South of the Bay of Fundy, mostly rain was recorded. Between those two points, the main precipitation types shifted from snow to rain, indicating that the transition region during the examined events was often located between the Appalachians and the Bay of Fundy. Large amounts of freezing rain and rimed snow were recorded in this transition region. This was consistent with the freezing rain distribution associated with individual events (Figs. 6 and 8). The largest amount of freezing rain was found parallel to the mountain chain between the Appalachians and the southern coast, except for during the 10 to 12 December 2008 event (Chartrand, 2020). During that event, the maximum amount of freezing rain occurred over northern NB.

5 Changes in freezing rain events under warmer climate conditions

a *Projected Changes in Annual Average*

The projected changes in total precipitation are fairly uniform throughout NB, with an annual increase of 20-30% (Fig. 4)

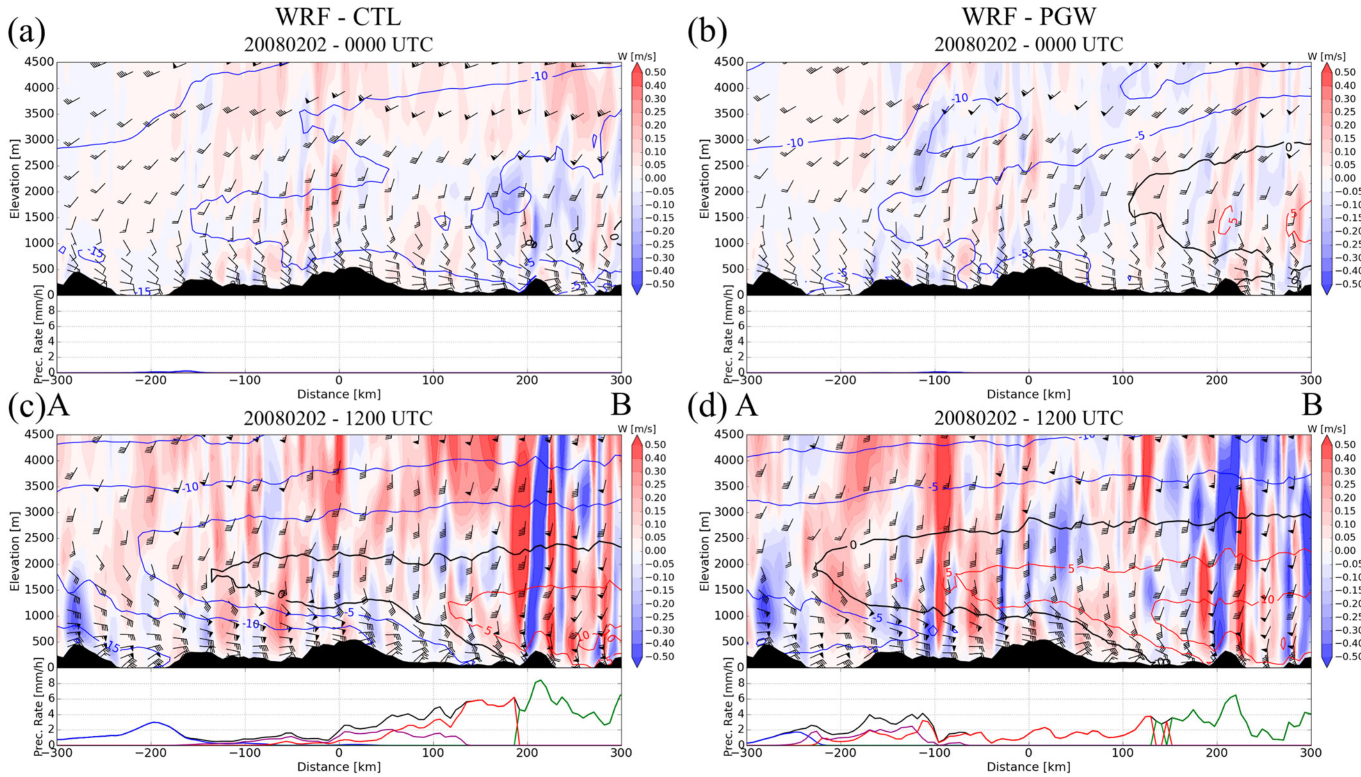

Fig. 10 Vertical cross-section of the vertical motion (m/s, shading), temperature (°C, shading), horizontal wind (barbs) and precipitation type and rate (mm/h), valid at (a) 0000 UTC and (c) 1200 UTC on 2 February 2008 using WRF-CTL. (b), (d) as in (a), (c), but for WRF-PGW. The precipitation types correspond with snow (blue), graupel (purple), freezing rain (red), rain (green) and total precipitation (black). The cross-section is defined in Fig. 8.

over most of NB. These numbers were consistent with the CMIP5 ensemble projection for the 2071 to 2100 period under RCP8.5 over Atlantic Canada (Liu et al., 2017). As the WRF-PGW simulation is ∼6°C warmer on average over NB during the cold season (Liu et al., 2017), more evaporation occurs at warmer temperatures. This translates into an increase of global precipitation in already humid regions (e.g. Trenberth, 2011). The increase would be slightly higher on the east coast of NB (30-40%). This could be caused by warmer sea surface temperatures (∼5°C warmer, not shown) and a major decrease in the sea ice coverage in the Gulf of Saint Lawrence in WRF-PGW (not shown). This allows more moisture to be converted into precipitation in the adjacent coastal regions.

The average increase of ∼6°C over NB in the WRF-PGW simulation also produces a change in snowfall and rainfall. The projected changes suggest a strong decrease in the annual snowfall over all regions of NB (Fig. 4). The change varies from −50% in southern and eastern NB to −30% in northern NB. In the WRF-PGW simulation, southern NB receives < 100 mm of snowfall water equivalent annually. Snow will typically change into rain as the projected change in annual rainfall suggests an increase of 40-50% throughout NB.

The annual amount of freezing rain over most of NB will decrease in the future, except in the northwestern part of the province (Fig. 4). This distribution is consistent with the northward/inland shift in the freezing rain distribution found in previous studies (e.g. Lambert and Hansen, 2011). Indeed, in the coastal regions of the Maritime Provinces, the projected change includes a substantial decrease in the annual amount of freezing rain (approximately −50%). This shift is likely caused by a northward and inland displacement of the average position of the 0°C isotherm, creating conditions that are favorable for freezing rain in northwestern NB. Moreover, both warmer sea surface temperatures (∼5°C warmer, not shown) and the reduction of sea ice coverage in the WRF-PGW simulation could have an effect on freezing rain. This would produce near-surface temperatures > 0°C in coastal regions as the wind direction is frequently onshore during winter storms (Stuart and Isaac, 1999). Finally, the central part of NB, south of the Appalachians, remains the region of maximum annual freezing rain, with only a slight decrease in WRF-PGW, which suggests that cold-air damming would still lead to freezing rain events under warmer conditions.

b *Projected Changes in the Occurrence of Freezing Rain Events*

The seven historical extreme freezing rain events were also analyzed in the WRF-PGW simulation to investigate the impact of warmer and moister conditions during these storms. When we compare the composite precipitation type distribution along a northwest-southeast cross-section (Fig. 11), there is a ∼125 km poleward shift in the regions that receive a maximum of freezing rain in the WRF-PGW simulation.

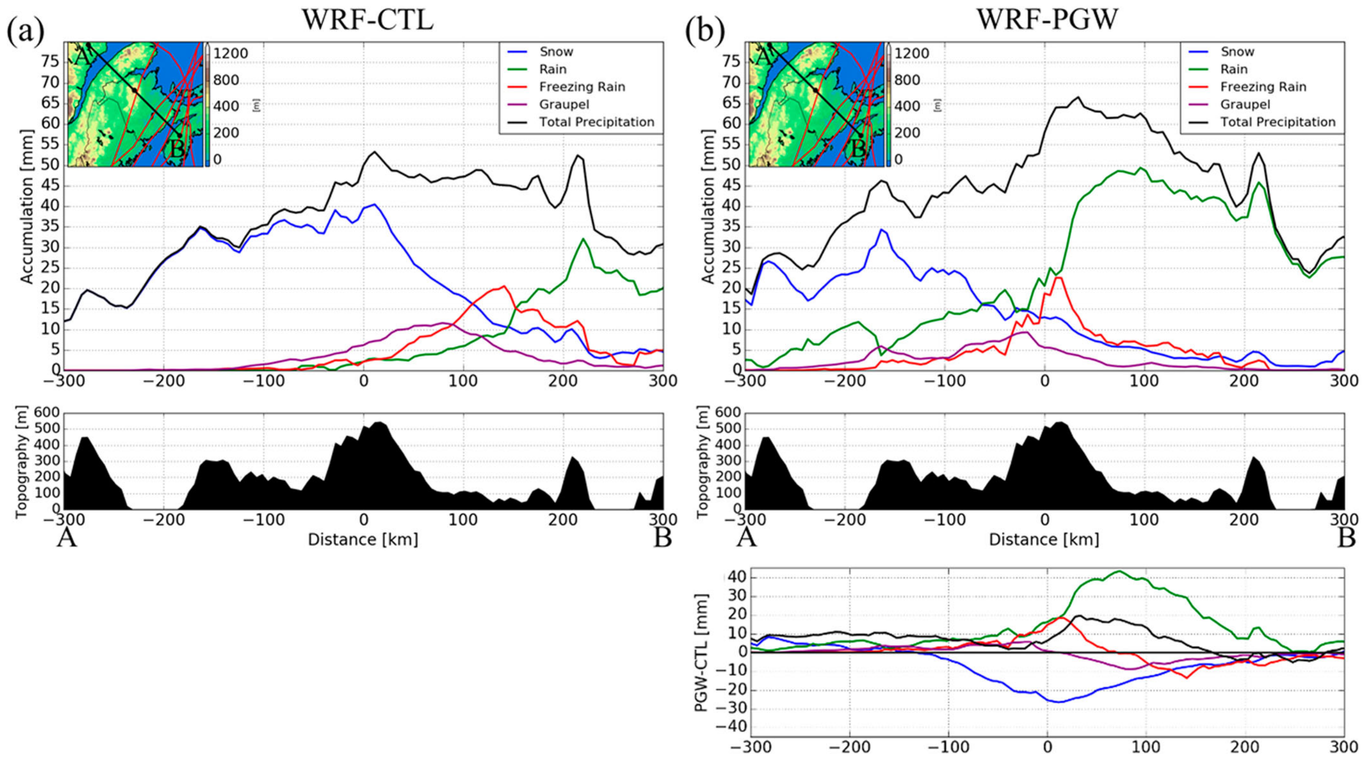

Fig. 11 Cross-section of the average precipitation accumulation for seven freezing rain events in NB using the (a) WRF-CTL and (b) WRF-PGW simulations. (c) Difference between WRF-PGW and WRF-CTL simulations (PGW-CTL). To capture the most significant orographic effects, the cross-section was centered on the highest point (0 km) in Mount Carleton, NB. At −200 km, the cross-section crosses the Saint-Lawrence River. At 200 km, it crosses the Caledonian highlands. At 250 km, it crosses the Bay of Fundy.

Northern NB receives rimed snow and freezing rain in WRF-PGW whereas that region mostly recorded snowfall in the historical storms. The average amount of freezing rain produced by these storms remains approximately the same in the WRF-PGW simulation. Similar wind patterns between the historical and PWG simulations are also suggested. Consequently, even in warmer conditions, cold-air damming may still be sufficient for producing freezing rain in central NB in warmer climate conditions (Fig. 11). In their recent study, Tropea and Stewart (2021) also found that winter storms in Manitoba used with the WRF-PGW simulation produced a similar amount of freezing rain, but that the regions that receive a maximum amount shift northward.

As more freezing rain events occurred during the 2000–2013 period than the seven extreme events identified in this study, the local changes in the occurrence of freezing rain events in six locations across NB were analyzed (Fig. 12). Four of the locations that were chosen have hourly weather observations associated with them, which were used to compare freezing rain event occurrence with the numerical simulations. The other two locations were chosen for analysis because they represent other regions of NB, where there are no observations of freezing rain. Moreover, one of those two locations, Doaktown, is located just south of the Appalachians, where the WRF-CTL simulation gives us a maximum of annual freezing rain occurrences.

In the NB coastal regions, there is a significant decrease in the occurrences of both long (> 6 h) and short (< 6 h) freezing rain events (Fig. 12). At both Saint John and Moncton, most of the long events do not occur in the future. Furthermore, at both locations, there are no events lasting > 12 h in the WRF-PGW simulation, whereas there were a few (one at Saint John and four at Moncton) in the WRF-CTL simulation. The number of short events also decreased by 51% at Moncton and 52% at Saint John. This is consistent with the sharp decrease in average annual freezing rain amounts over coastal regions (Fig. 5). At Bathurst, while there is a decrease in short-duration events, there is no significant change in the number of long events.

At Doaktown and Fredericton, more long events were diagnosed than at other stations across NB in the WRF-CTL simulation. This also supports the effect of cold-air damming during freezing rain events, as this process favors long-duration freezing rain events. In the WRF-PGW simulation, there is a major decrease in the number of long events at Doaktown and Fredericton (−50% and −48%, respectively) while the number of short events decreases only slightly (−16% and −26%, respectively). In contrast, there is an increase in the number of long events (+33%) and a slight decrease in short events at Edmundston. This is consistent with the increase in the average annual freezing rain accumulation that is diagnosed in northwestern NB (Fig. 4). Overall,

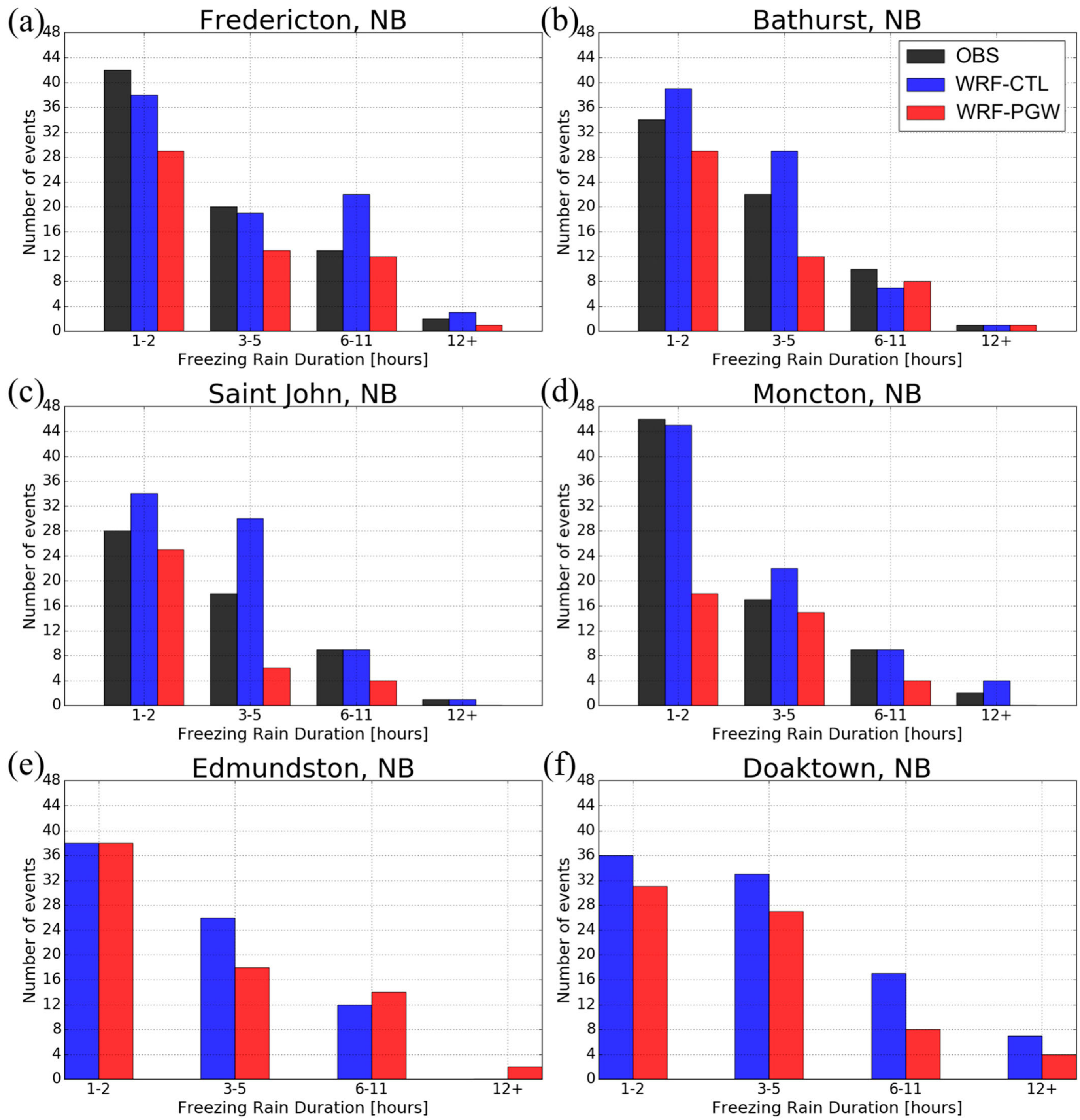

Fig. 12. Differences in freezing rain event occurrences between observations (black), WRF-CTL (blue) and WRF-PGW (red) simulations for the 2000 – 2013 period. The six locations are (a) Fredericton (CYFC), (b) Bathurst (CZBF), (c) Saint John (CYSJ), (d) Moncton (CYQM), (e) Edmundston (CYES) and (f) CDU6 (Doaktown). Only (a-d) have hourly weather observations available.

the decrease in the number of freezing rain events over most of the province seems to be caused by general warming (~6° C) and local orographic effects.

The comparison of the mean wind speed during the identified freezing rain events at these six stations in the WRF-CTL and WRF-PGW simulations shows only a small variation (±10%) between the two simulations. This is expected, as the two simulations are driven by the same reanalysis and therefore have very similar pressure patterns associated with these events. Similar results were found by Tropea and Stewart (2021) in the analysis of wind patterns in the two simulations during extreme winter storms in Manitoba.

6. Summary and conclusion

The conditions leading to extreme freezing rain accumulation in New Brunswick and how the conditions might change by the end of the century in a future climate scenario (RCP8.5) were examined. To be able to adequately represent mesoscale features within storms and the local effects on precipitation distribution, we used high-resolution convection-permitting simulations from the Weather Research and Forecasting model (WRF) at 4-km grid spacing over the contiguous US and southern Canada (Liu et al., 2017). The historical simulation, which was conducted for the 2000–2013 period, included seven extreme freezing rain events (> 12.5 mm) that resulted in major power outages in NB. A simulation was also conducted in WRF-PGW, simulating the 2000–2013 weather patterns in a future climate, isolating the thermodynamic response of climate change on weather events. Comparisons between observations and the WRF-CTL simulation showed that the model depicted the distribution of precipitation type and accumulation produced by extreme events as well as freezing rain occurrence over NB and surrounding provinces reasonably well.

The analysis of storm tracks computed with ERA5 that are associated with freezing rain events suggested that a particular synoptic pattern is conducive to extreme freezing rain accumulation in NB. All of the seven identified freezing rain events originated from extratropical cyclones that formed over the southeast US and moved northeastward toward Atlantic Canada while being supported aloft by upper-level troughs over the eastern US.

A composite map of the identified freezing rain events using ERA5 also showed the presence of a strong anticyclone over Labrador moving eastward before the onset and during freezing precipitation occurrence in NB. The cyclone-anticyclone couplet favored a larger pressure gradient over NB, leading to strong advection of warm, moist air aloft over Atlantic Canada. Ageostrophic northeasterly winds near the surface contributed to maintaining the sub-freezing layer near the surface. The largest amounts of freezing rain were produced in central NB, between the Appalachians and the Bay of Fundy. Elsewhere in the province, these events mostly brought snowfall to northern NB and rainfall to the south.

The low-level wind field over NB during these events in the historical simulation showed that the terrain reinforced the temperature inversion, leading to large amounts of freezing rain. Specifically, easterly flow was blocked at the lowest altitudes by the Appalachians in the northern part of the province, which contributed to maintaining a near-surface subfreezing layer south of the mountains. Most freezing rain events were located in a band parallel to the Appalachians slightly southeast of the mountain chain. The climatological distribution of freezing rain occurrence also showed a maximum of ~45 h/year in the central part of the province, just south of Mount Carleton.

The projected changes using the WRF-PGW simulation indicated a decrease in the occurrence of freezing rain over most of the province with some exceptions. The projected decrease is stronger in the coastal areas of the province while a slight increase is projected in the occurrence of long freezing rain events (> 6 h) in northwestern NB. A comparison of individual events between the WRF-CTL and WRF-PGW simulations indicates a general poleward shift of the precipitation transition region of ~125 km on average due to warmer conditions. Regions located south of the Appalachian Mountains would still experience long-duration freezing rain events as the cold-air damming would still keep the air relatively cold near the surface, producing freezing rain.

Other freezing rain storms that have occurred over NB differ from those identified in this study during which cold-air damming contributes to maintaining a sub-freezing layer near the surface. One example is the 10–12 December 2008 event, which brought a more homogeneous distribution of freezing rain over NB. The freezing rain that occurred during this event was associated with a warm front that rapidly moved across NB with very high precipitation rates, rather than being greatly affected by cold-air damming (Chartrand, 2020). Another example is the extreme freezing rain storm in January 2017 (Thériault et al., 2022). The large amount of freezing rain during that storm occurred mainly along the east coast of NB and accumulated for up to 30 h. It was associated with a slow-moving, low-pressure system that brought relatively warm air aloft and resulted in freezing rain.

Despite the benefits of very high-resolution simulations and isolating the thermodynamic response of climate change using the WRF-PGW approach, there are a few sources of error in this study. First, the very low spatial density of observations throughout the domain of interest, especially for freezing rain, made the evaluation of the WRF-CTL simulation difficult. Second, a detailed case study of freezing rain events in NB would have been useful to confirm the local effects on such events. Third, a 13-year climatology was used instead of a typical 30-year climatology (as recommended by World Meteorological Organisation). Fewer sample years likely cause biases, as the annual freezing rain occurrence is highly variable. Finally, the projected changes in the general atmospheric circulation are not considered in the WRF-PGW approach. Longer and very-high resolution simulations that are driven by climate projection are needed to assess the resulting changes in storm tracks.

Overall, extreme freezing rain events that affected NB Power infrastructure were strongly impacted by local orographic factors. Major changes in precipitation type distribution are predicted to occur over NB in warmer climate conditions. While snowfall and freezing rain will heavily decrease over coastal areas of NB, freezing rain will increase over the northwestern part of the province. Freezing rain will, however, still occur over central/southern NB due to the local orography. For power utilities in NB, the repercussions of these projected changes likely involve a decrease in power outages caused by ice accretion from freezing rain on tree limbs and power lines in the coming decades.

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The WRF simulation datasets used are available at https://rda.ucar.edu/datasets/ds612.0/. The station data used are available through the Global Historical Climatology Network-Daily Database at https://www.ncdc.noaa.gov/ghcn-daily-description

Disclosure statement

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Supplemental data

Supplemental data for this article can be accessed https://doi.org/10.1080/07055900.2022.2092444.

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