Extratropical Cyclone Climatology for Eastern Canadian Cities

Mathieu Plante

Master of Science

Department of Atmospheric and Oceanic Sciences

McGill University
Montreal, Quebec
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ABSTRACT

In this study, a Lagrangian tracking algorithm is applied to the 850-hPa relative vorticity field to characterize extratropical cyclone tracks across eastern Canada. Seasonal cycles are examined in terms of overall cyclone frequency, intensity, regions of development and decay. We found that cyclones tend to develop over the Rockies, the Great Lakes or the Western Atlantic. They are most intense over Newfoundland and North Atlantic, and decay over Greenland. Cyclones tracking across Toronto, Montreal, Halifax and St-John’s are further analyzed, with typical cyclone tracks, origin, frequency, mean local growth rate, and mean intensity. Among others, we found that cyclone activities at east coast cities (Halifax, St-John’s) are dominated by Atlantic cyclones, more frequent in winter, while Montreal’s and Toronto’s cyclones travel primarily from the Great Lakes, frequent and intense in spring and autumn. Cyclones from the Gulf of Mexico are not frequent, but extreme. The relationship between winter cyclone tracks and modes of atmospheric variability are also examined with an emphasis on the El Niño - Southern Oscillation (ENSO), North Atlantic Oscillation (NAO) and Pacific North American pattern (PNA). An ENSO and PNA-related oscillation between continental and coastal cyclones is confirmed. The inter-annual variability of winter cyclones cross eastern Canadian cities are quantified. Cyclone activities in Toronto and Montreal shown to be modulated by ENSO and PNA, while NAO dominates the cyclone variability in Halifax and St-John’s. The local cyclone variability is found to be small in terms of overall cyclone statistics, but important in terms of changes in the origins of the local cyclones.
Un algorithme est appliqué sur le tourbillon relatif à 850-hPa afin de calculer la trajectoire des cyclones affectant l’Est du Canada. Les variations saisonnières de ces trajectoires sont approfondies par l’étude de plusieurs paramètres, tels que la fréquence, l’intensité, l’origine, le taux de développement et le taux de dissipation des cyclones. L’étude démontre que les cyclones se développent principalement au dessus des Rocheuses, des Grands Lacs et de la côte Est des États-Unis, et se dissipent près des côtes Est et Ouest du Groenland. Les plus intenses se trouvent à Terre Neuve et au Nord de l’Atlantique. Ces statistiques de cyclones sont ensuite évaluées plus spécifiquement pour les cyclones atteignant Toronto, Montréal, Halifax et St-John’s. Entre autre, il est démontré que les villes côtières sont principalement affectées par les cyclones en provenance de la côte Est Américaine, fréquents en hiver, tandis que Toronto et Montréal sont principalement affectés par les cyclones en provenance des Grands Lacs, plutôt fréquents au printemps et à l’automne. Les cyclones en provenance du Golf du Mexique sont moins fréquents, mais constituent une grande partie des extrêmes. La variation inter-annuelle de l’activité cyclonique est ensuite évaluée selon différents régimes de variabilité climatiques, tels qu’ENSO (El Niño-Southern Oscillation), le NAO (North Atlantic Oscillation) et le PNA (Pacific-North America). Les résultats consolident la présence d’une oscillation entre cyclones continentaux et cyclones côtiers pendant ENSO. L’étude démontre que la variabilité cyclonique inter-annuelle à Toronto et Montréal est dominée par ENSO et le PNA, tandis que le NAO a un plus grand impact à Halifax et à St-John’s.
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CHAPTER 1
Introduction

The mid-latitude weather and climate are known to be dominated by successions of extratropical cyclones. Their climatology and variability have been of growing interest, and damaging events such as the record breaking snowfall of the 2007-2008 winter season in eastern Canada highlighted the need for more accurate seasonal predictions of cyclone activity. Precipitation change is one of the major concerns for future Canadian climate, yet in the present, the reliability of seasonal precipitation predictions still remains challenging. Furthermore, Hawcroft et al. (2012) have shown that in recent climate, extratropical cyclone activity can be behind more than 70% of the seasonal precipitations in some parts of North America. Thus, the characterization of extratropical cyclones’ geographical distribution is key to establish an accurate North American climatology and to improve seasonal forecasts.

The studies characterizing regional climate variability and change in North America often focus on surface air temperature and precipitation (Archambault et al., 2008; Birk et al., 2010; Frankoski and DeGaetano, 2011). While these Eularian variables have the advantage of being directly measured observations, they are not ideal characterizations of cyclones causing severe weather, not providing information on their origins or life cycles. The full Lagrangian characterization of extratropical
cyclone variability and long-term trends may be gleaned from mean sea-level pressure (MSLP) and/or relative vorticity in the lower troposphere, although vorticity is not directly measurable. Thus, in recent years, automated Lagrangian schemes for cyclone detection and tracking have been developed in attempts to better characterize the seasonal, inter-annual and decadal variability of the extratropical cyclone tracks (Hodges, 1994; Murray and Simmonds, 1991b; Serreze, 1995). These methods use gridded reanalysis, General Circulation Model (GCM) or Region Climate Model (RCM) data to detect and track individual cyclones, allowing the full characterization of their life cycles, path, cyclogenesis and cyclolysis conditions, which cannot be addressed by using Eularian statistics of temperature, precipitation or MSLP.

The geographical distributions of cyclone track characteristics are reasonably well documented, but cyclone tracks at point-specific locations are rarely discussed. Previous studies have characterized climatologies and temporal variations of different types of cyclones, such as Alberta clippers (Thomas and Martin, 2007), Nor’easters (Hirsch et al., 2001), or cyclones in the Great Lakes region (Isard et al., 2000). Very few have examined how those cyclones activities may combine in a local cyclone climatology. Furthermore, characterizing local extratropical cyclone activities is complicated by the influence of multiple teleconnections, especially over North America (Wallace and Gutzler, 1981). While the use of statistical tools such as Rotated Empirical Orthogonal Functions (REOF) successfully isolates independent modes of variability (Anderson and Gyakum, 1989; Barnston and Livezey, 1987), their varying combination in time and space renders difficult to quantify their impacts on regional or local cyclone activity. For instance, Grise et al. (2013) showed
that the local cyclone activity over Toronto is mainly influenced by the Pacific-North American teleconnection pattern (PNA) while that over New-York City is also influenced by the North Atlantic Oscillation (NAO), even though their geographical distance is within synoptic scale. More precisely in Canada, different teleconnection regimes were shown to be of varying dominance for different Canadian regions, such as the influence of El Niño - Southern Oscillation (ENSO) on Ontario and Quebec (Wang et al., 2006) or that of the NAO on the Atlantic provinces (Grise et al., 2013; Wang et al., 2006).

This thesis’ goal is to offer a complete characterization of cyclone tracks in eastern Canada, with their seasonal climatology and inter-annual variability related to ENSO, NAO and PNA. In this study, the large scale seasonal cyclone activity is analyzed to define the main development regions of cyclones impacting eastern Canada. The local cyclone climatology and variability at major eastern Canadian cities, namely Toronto, Montreal, Halifax and St-John’s, are examined by categorizing cyclones according to their origin.

A short review of the particularities of the North American cyclone tracks will be discussed in Chapter 2, followed in Chapter 3 by the description of the data and methods used in this study. The results are then presented in two parts. The seasonal mean properties of the local cyclone activities are first presented in Chapter 4, followed by their inter-annual variability due to teleconnection patterns (ENSO, NAO and PNA) in Chapter 5. Summary and conclusions are presented in Chapter 6.
A number of tracking methodologies have been proposed and applied on various cyclone-related properties to define extratropical cyclone activity. The overall geographical distributions of cyclone activity are quite consistent among studies, but their amplitude exhibit significant sensitivity to the choice of tracking parameters (Neu et al., 2013; Raible et al., 2008; Ulbrich et al., 2009). Depending on the methodology, different aspects of the extratropical cyclone activity emerge. These differences must not be seen as inconsistencies, but as complementary representations extratropical cyclones statistics. (Dacre and Gray, 2009; Hoskins and Hodges, 2002; Neu et al., 2013). These are briefly summarized in this section.

The earliest attempts to produce Lagrangian tracks of extratropical cyclones used minimums in the MSLP field to define cyclone centers (Fig. 2–1a). Those centers were manually tracked on synoptic charts (Colucci, 1976; Gyakum et al., 1989; Klein, 1951; Reitan, 1974; Roebber, 1984), requiring one closed isobar to encircle a pressure minima for at least 9 consecutive hours for a cyclone track to be registered (Colucci, 1976). The first automated tracking methods also applied this classical requirement by identifying cyclone centers at grid points featuring MSLP values
lower than that of their 8 or 20 neighboring grid points. These centers were then linked together in time to form tracks by using a nearest neighbor approach (Murray and Simmonds, 1991a,b), or more recently by selecting the most realistic ensemble of tracks among all possibilities (Hodges, 1994, 1999) (Fig. 2–1). This later method is detailed later in Chapter 3.

In recent years, Pinto et al. (2005) demonstrated that tracking MSLP minimum tends to overestimate the number of mature cyclones and often fails to identify shallow or small scale systems. Sinclair (1994) also demonstrated that important cyclones might not feature any connected isobars if the background flow is characterized by a large pressure gradient. This could cause a misrepresentation of secondary cyclone tracks in regions where small-scale cyclones are frequent, such as in the Mediterranean. To avoid this drawback, tracking algorithms using relative vorticity have been proposed, either by explicitly tracking the vorticity maximum, or by imposing a Laplacian of MSLP criterion in cyclone detection methods using MSLP fields (Murray and Simmonds, 1991a). Relative vorticity has the advantage of being less affected by background flow removals (Hoskins and Hodges, 2002) and of producing more accurate individual cyclones tracks (Pinto et al., 2005). However, they are also much noisier than simple MSLP-based cyclone tracks, and overestimate cyclone frequency by registering artificial or irrelevant systems. Smoothing gets rid of most of the artificial cyclones, but also makes small scale (but important) cyclones vanish (Pinto et al., 2005).

It is noteworthy that the identification of extratropical cyclones purely based on the above criteria is very restrictive. Because cyclones are three dimensional in
nature (Pinto et al., 2005), simple two-dimensional criteria using variables at the
surface or on a given pressure surface fail to accurately represent cyclone tracks in
some areas, especially those influenced by topography (Lareau and Horel, 2012).
Also, while MSLP and relative vorticity are the most commonly used variables for
extratropical cyclone detection and tracking, they do not linearly relate to the severe-
ness of resulting weather (Lionello et al., 2006). It is pertinent to note that Hoskins
and Hodges (2002) showed that tracking can be done using a wide range of param-
eters (i.e. meridional wind, 500 hPa ascent, etc), and recent studies have developed
tracking algorithms that include synoptic properties other than MSLP or relative
vorticity. For example, Nissen et al. (2010) added a measure of extreme winds in
their MSLP-based cyclone detection scheme over the Mediterranean region in or-
der to relate cyclone intensity to surface weather impacts. Lareau and Horel (2012)
developed a tracking algorithm based on synoptic-scale ascent, in an attempt to in-
crease the quality of cyclone tracks over Western America. These methods help to
build a direct relationship between cyclone intensity and surface weather impacts.

2.2 North American Cyclone Tracks

Despite areal biases, early studies successfully reveal the overall climatology of
the North American cyclone tracks. Klein (1957) found that extratropical cyclone
frequency tends to be higher on the northward side of the subtropical jet, while
cyclogenesis tends to occur on its South-West. He also noted a general poleward
displacement of the cyclone tracks during the summer, confirmed in later studies
Hoskins and Hodges, 2002; Zishka and Smith, 1980). It is well documented that cyclogenesis (Fig. 2–2) generally occurs at the lee side of the Rockies from Alberta to the Gulf of Mexico, and over the US East coast (Eichler and Higgins, 2006; Grise et al., 2013; Gyakum et al., 1989; Reitan, 1974; Zishka and Smith, 1980), though their relative magnitude shows inconsistency among the studies, as discussed in the previous section. The maximum cyclone frequency is found over eastern North America and North Atlantic, but regional details vary significantly in the literature. For instance, the track frequency maximum region found in the vicinity of the Great Lakes is sensitive to the tracking method used, some having it extended to the Rockies (Eichler and Higgins, 2006), others only showing a small secondary frequency maximum in the vicinity of the Lakes (Hoskins and Hodges, 2002; Pinto et al., 2005). This sensitivity is linked to the fact that the Great Lakes region, often described as a secondary cyclone track (Eichler and Higgins, 2006), is also conducive to cyclolysis. (Grise et al., 2013; Hoskins and Hodges, 2002) (Fig. 2–2).

The life cycles of extratropical cyclones are also regionally dependent. Blender et al. (1997) highlighted this by grouping Atlantic’s cyclones according to their general track direction, demonstrating that Northeastward moving cyclones are not only deeper but also more pronounced in pressure gradient than the other groups. Cyclone tracks are highly influenced by background synoptic flows and regional surface boundary conditions. Accordingly, there are regional obstacles to the performance of a cyclone detection and tracking scheme. Among others, the accuracy of cyclone detection across high terrain regions is challenging (Lareau and Horel, 2012), and detection of small-scale cyclones is very sensible to the spatial resolution of the gridded
data used. To overcome these problems, flexible algorithms have been developed so that tracking parameters and constraints can be tuned for specific analysis (Hodges, 1999; Trigo et al., 2000; Trigo and Davies, 1999). Using these adaptive schemes, primary cyclone tracks have been isolated and characterized in more details. In Canada, these include Great Lakes’ cyclones, Nor’easters and Alberta clippers, and each of them are briefly introduced below. Note that even if these studies generally focus on the US, southern Canada tend to be included in their analysis.

2.2.1 Great Lakes’ Cyclones

Isard et al. (2000) examined cyclones in the Canadian and US Great Lakes region and found that their seasonal variability depends on the latitudinal position of their origins. Their results show uneven latitudinal distribution of cyclogenesis regions, as well as a particular seasonal patterns. Winter-time Great Lakes’ cyclones mostly travel from the northern or southern Rockies, but in spring those from the northern Rockies decrease in number, and the overall cyclone activity is dominated by cyclones tracking from the southern Rockies. The cyclogenesis region then shifts to the Central Rockies for the summer, and gradually shifts back to the winter situation during the fall.

Isard et al. (2000) also noted that more than 20% of the cyclones found over the Great Lakes were born within their Great lakes region boundaries. This fraction was also found to be increasing when only intense cyclones are considered. Previous studies (Angel and Isard, 1998) also found that the optimal conditions for Great Lakes’ cyclogenesis were in early spring and late fall, but this was not found in Isard et al. (2000)’s results.
2.2.2 Nor’easters

Intense US east coast cyclones are often grouped as a type of cyclones called “Nor’easters”. Even if the term "Nor’easters" mostly refers to US cyclones, they also frequently track across eastern Canada, upstream of the US east coast (Changnon et al., 2008; Gyakum et al., 1989). Their local variability have been primarily assessed through east coast precipitation studies (Changnon et al., 2008; Frankoski and DeGaetano, 2011), or discussed within large scale studies of the Atlantic cyclone track (Blender et al., 1997; Colucci, 1976; Trigo, 2005). However, Hirsch et al. (2001) isolated Nor’easters from other North American extratropical cyclones by selecting Atlantic cyclones with specific northwestward tracks that are accompanied by strong (≥ 20kts) surface winds. Along with a peak in their frequency in December, they documented that Nor’easters’ frequency is increasing with latitude along the US east coast.

2.2.3 Alberta Clippers

Alberta clippers were also identified in many climatological studies (e.g. Hoskins and Hodges (2002); Zishka and Smith (1980)), and more closely examined by Thomas and Martin (2007). Alberta clippers are often detected with directional and strength criteria. Although their climatology and variability have not been frequently discussed, their formation is known to be associated with the prior presence of a cyclone in the Bay of Alaska, a tropospheric ridge over western North America and a developing trough east of the Canadian Rockies. However, although Alberta clippers were not mentioned in their study, Isard et al. (2000) showed that cyclones traveling from the northwest peak in frequency during the winter, and are not frequent in spring.
Above described regional cyclone tracks, i.e., Great Lakes’ cyclones, Nor’Easters and Alberta clippers, are important for eastern Canadian cities. While they have been studied individually, their combined impact on local climate and weather in the context of cyclone activity have yet to be quantified over eastern Canada.

2.3 Extratropical Cyclone Variability Associated with Teleconnection

The other goal of this project is to assess the inter-annual variability of the local cyclone tracks. The Northern Hemispheric climate is known to be modulated by various low-frequency variabilities and teleconnection patterns (Barnston and Livezey, 1987; Wallace and Gutzler, 1981). Three predominant teleconnection patterns are those associated with the El Nino Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO) and the Pacific / North American teleconnection (PNA). Grise et al. (2013) recently showed that North American cyclone tracks, especially those over the eastern continent, are significantly affected by these three modes of variabilities.

2.3.1 El Nino and Southern Oscillation

The ENSO is an atmosphere-ocean coupled variability in the equatorial Pacific that was first proposed by Bjerknes (1969), who described the feedback between equatorial Sea Surface Temperatures (SST) and the Walker circulation by combining the Southern Oscillation (SO) with the El Nino. He also noted the strengthening (weakening) of the Hadley circulation associated with positive (negative) SST anomalies in the equatorial Pacific, hinting at an extra-tropical extension of the ENSO. During
a positive ENSO episode, warm SST anomalies enhance convection in the eastern
equatorial Pacific. Poleward of this convection anomaly, compensatory sinking mo-
tion expands the subtropical high pressure zone to the Southeast, thus increasing
and shifting the background meridional pressure gradient equatorward in compari-
son to neutral ENSO years. This results in a strengthened subtropical jet that is
also shifted equatorward of its climatological position, significantly impacting the
Northern Hemisphere climate.

ENSO is known to have an impact on North America through the associated
teleconnection pattern (Fig. 2–3). Specifically in Canada, pressure anomalies to
the east of the Rockies are found to be negatively correlated with ENSO index
(Trenberth and Caron, 2000), although with high variability due to the presence of
other teleconnections and local processes. During positive ENSO years, the North
American winter cyclone tracks generally follow the equatorward shift of the jet
stream (Eichler and Higgins, 2006; Grise et al., 2013; Teng et al., 2007). Cyclones
along the Maritimes and US east coast are also found to occur more frequently, while
continental cyclones decrease in frequency (Bradbury et al., 2003; Hirsch et al., 2001;
Noel and Changnon, 1998). In contrast, the frequency of Great Lakes’ cyclones is
observed to increase significantly during La Nina years (Eichler and Higgins, 2006).

2.3.2 North Atlantic Oscillation

First described by Walker and Bliss (1932) as a seesaw-like variability in MSLP
between Iceland and the Azores, the teleconnection associated with the NAO has
been long defined by the difference in normalized surface pressure at these regions.
The influence of the NAO is now known to be far more reaching, and strongly
connected to the leading mode of climate variability in the Northern Hemisphere extratropics, the Northern Annular Mode (NAM) (Thompson and Wallace, 1998). The strength and phase of the NAO is recently defined by Empirical Orthogonal Function (EOF) analysis or Rotated Principal Component Analysis (RPCA) (Barnston and Livezey, 1987).

The geographical distribution of the NAO-related atmospheric anomalies has been fully documented in the literature (Barnston and Livezey, 1987; Hurrell, 1996; Marshall et al., 2001; Wallace and Gutzler, 1981), and is shown in Fig. 2–4a. During the positive phase of the NAO, lower than normal surface pressure over Iceland and higher than normal pressure over subtropical Atlantic strengthen the westerlies in the North Atlantic, affecting precipitation and temperature over Europe and eastern North America. More specifically for northeastern America, the strengthened Icelandic low increases the cold air advection in Labrador and Greenland, and the subtropical high favors warm air advection from the tropics to the Eastern US coast (Wallace and Gutzler, 1981). The negative phase of the NAO exhibits the opposite, with decreasing westerlies and a more longitudinally confined jet.

The impacts of the NAO on extratropical cyclones are also well documented for the North Atlantic and Europe. During a positive phase of the NAO, the extratropical cyclone track tends to shift to the northeastern Atlantic, increasing precipitation over Scandinavia and decreasing precipitation in Europe (Marshall et al., 2001; Pinto et al., 2008). The frequency and intensity of cyclones also increased as the westerly jet becomes stronger than normal during positive NAO. However, the impact of the NAO on North American cyclones is not well documented, but Wang et al. (2006)
found that during the positive phase of the NAO, cyclone activity is decreasing in autumn over the Great Lakes, and in every season over the east coast. A few studies have also associated a slight increase in snow fall over the eastern United States and eastern Canada to the negative phase of the NAO (Bradbury et al., 2003; Brown, 2010). Recently, Grise et al. (2013) illustrated that in the winter, NAO is only a dominant contributor to cyclone variability in far north-eastern American locations, such as St-John’s in Newfoundland.

2.3.3 Pacific North-America teleconnection

The PNA is a pattern arching from the equatorial Pacific to North America, describing the amplification of the broad ridge-trough pattern that typically characterizes North American synoptic flow (Notaro et al., 2006). As for the NAO, the strength and phase of the PNA is often defined by REOF or RPCA methods (Barnston and Livezey, 1987). The PNA-related pressure anomalies features an anomalous wave-train pattern with four correlation centers of 500mb geopotential anomalies (Fig. 2–5). More precisely, a positive PNA is characterized by a deeper and eastward shifted Aleutian Low with positive anomalies of 500-hPa geopotential height over the central North Pacific, negative anomalies west of Alaska, a ridge over western North America and a trough over the southeastern US (Feldstein, 2002). This causes the climatological flow to be zonally asymmetric, with a strengthened and south-eastward shifted Atlantic subtropical jet. The opposite is true for negative phase of the PNA: a weakening of the Aleutian low causes the jet to be weaker and more zonal than normal (Feldstein, 2002; Notaro et al., 2006).
Most studies characterizing the effects of PNA over eastern Canada and northeastern US have focused on precipitation variability. Brown (2010) documented that positive PNA events are correlated with earlier snow cover start date, due to cold temperature anomalies over northeastern America. However, the correlation between PNA index and winter precipitation is known to vary from South to North: PNA index is negatively correlated with winter precipitation in southern Canada and northern United States, but positively correlated in northern Canada (Brown, 2010). These variations of precipitation change in southeastern Canada and northeastern US are further discussed by Archambault et al. (2008), who explained that during both positive PNA and negative NAO winters, the ridge-trough pattern in northeastern America is amplified, and the forcing for ascent is mainly attributed to differential cyclonic vorticity advection rather than warm air advection. As the latter causes greater moisture transport from the Atlantic coast, precipitation amounts are lesser than winters associated with a more zonal flow, i.e., during negative PNA or positive NAO winters.

The effect of PNA on the North American cyclone tracks is mainly due to its impact on the subtropical jet stream. Grise et al. (2013) documented that cyclone track variability tends to be dominated by Pacific-linked teleconnections on interannual or decadal scales, as their associated anomalies are downstream of the cyclone tracks. Both Grise et al. (2013) and Isard et al. (2000) showed that extratropical cyclones from the Northern Rockies are more frequent during the positive PNA phase, while cyclones from the central and Southern Rockies are more frequent during the negative PNA phase. Cyclone frequencies are also known to be increased over the US
East coast during the positive regime. Disagreement however arise when discussing variability over the Great lakes region. While Grise et al. (2013) showed a decreased in cyclone frequency over the Great lakes during the positive phase of the PNA, Notaro et al. (2006) showed the opposite, and Isard et al. (2000) saw no significant PNA-related changes in this region.

It is worth to note that these teleconnections (ENSO, NAO, PNA) can occur simultaneously, and thus their impacts on the extratropical cyclone climatology are not totally independent. In this regard, the effect of the NAO and PNA on North American climate and whether becomes clearer when they occur simultaneously, as suggested by Notaro et al. (2006). They found that the impact of the NAO on the eastern U.S. jet is most evident during the positive phase of the PNA. It was further suggested that weather events might be better correlated with teleconnection transitions, with enhanced precipitation in northeastern America during transitions from positive to negative NAO phases and from negative to positive PNA phases (Archambault et al., 2010). ENSO, NAO and PNA have been also used to quantify intra-seasonal variation of extratropical weather and climate systems (Archambault et al., 2008; Eichler and Higgins, 2006; Grise et al., 2013). In this study, we examine all teleconnection patterns described above only on inter-annual timescale. As such, composite analyses are performed with respect to monthly mean teleconnection indices.
Figure 2–1: Extratropical cyclone tracks in the Northern Hemisphere, from manual and automated analysis. a) Figure from an 1888 geography textbook showing cyclone frequency distribution as viewed in the mid-nineteenth century. Shading denotes high cyclone frequency, and arrows indicate individual tracks. Reproduced from Hinman (1888) in Chang et al. (2002). b) Cyclone trajectories for JFM 1983, generated directly from the tracking software. From Eichler and Higgins (2006).
Figure 2–2: Development and decay regions of North American extratropical cyclones by tracking relative vorticity at ERA-Interim’s model level closest to 850-hPa. From Grise et al. (2013).

Figure 2–3: Correlations of annual mean (May-April) of sea level pressure with the Southern Oscillation Index for 1958-98. Values $\geq 0.6$ are hatched and those $\leq 0.6$ are stippled. Taken from Fig.1 of Trenberth and Caron (2000)
Figure 2–4: a) Regression map of Northern Hemisphere SLP anomalies in winter (DJFM 1958-1998) onto the first principal component of SLP anomalies over the North Atlantic sector (20-70N / 100W-20E). b) Time series of NAO index (thin curve) and the first principal component of SLP (thick curve), normalized by their standard deviations. Data are taken from the NCEP-NCAR reanalysis. Figure from Fig.1 of Marshall et al. (2001).
Figure 2–5: Composite 500-mb geopotential height anomaly based on the 10 strongest positive PNA months minus the 10 strongest negative PNA months. Taken from Fig. 17c of Wallace and Gutzler (1981).
3.1 Data

The data used in this analysis are primarily taken from the 6 hourly data of the European Center for Medium-Range Weather Forecast (ECMWF) Interim reanalysis (ERA-Interim) (Dee et al., 2011), in 1.5 degree resolution. Data characterizing the background flow (upper level wind, geopotential and temperature) are taken on pressure levels, and vorticity data are taken on hybrid sigma-pressure model levels.

The different teleconnection indices are all taken from NOAA. Their time series are presented in Fig. 3–1. In this study, the ENSO index is taken from NOAA’s monthly El Nino Oceanic Index (ONI), which is a 3-month mean of SST anomalies in the Nino 3.4 region (5N-5S, 120-170W), using ERSSTv3b data. NAO and PNA indices are defined by the first and second leading RPCAs of the Northern Hemisphere, as described by Barnston and Livezey (1987).

3.2 Quantifying Cyclone Activity

The cyclone detection and tracking scheme, as well as the measures of cyclone activity used in this study are detailed in this section, along with their associated bias.
3.2.1 Cyclone Detection and Tracking Scheme

In this study, the tracking algorithm developed by Hodges (1994, 1995, 1999) was used to detect and track extratropical cyclones in the Northern Hemisphere. The extratropical cyclone centers are defined as maxima in the relative vorticity field, taken from ERA-Interim’s hybrid sigma-pressure level closest to 850hPa filtered to the synoptic spatial scales (wavenumber 5-42), as detailed in Grise et al. (2013). This model level was chosen to reduce tracking problems around orography. Individual cyclone centers are then linked together to form tracks.

Because multiple combinations of tracks are possible for any given set of cyclone centers, the most realistic ensemble of track is selected iteratively by minimizing a cost function, based on known cyclone statistics. This cost function improves the tracking method by taking into account the cyclone’s speed and position when tracks are formed, so that tracks with minimal velocity changes (speed or direction) are preferred, instead of the classical nearest-neighbor approach. Moreover, the constraints are adaptive to individual cyclone properties, e.g., less restrictive in direction changes for slower cyclones, and more restrictive for the fast moving cyclones commonly found at higher latitudes. The cyclone speed (or the distance between two subsequent cyclone centers) is also limited according to their latitude (Hodges, 1999).

The tracks are listed if its vorticity maxima exceeds 1 Cyclonic Vorticity Unit (CVU, corresponding to $1 \times 10^{-5}$s$^{-1}$) for at least 8 consecutive time steps (two days). Details can be found in the above references. From this point, a ”track” refers to the complete path of given cyclone, while ”track point” refers to the individual cyclone detection point at any time ”t”.

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3.2.2 Measuring Cyclone Activity

Various indices have been developed to characterize the extratropical cyclone activity in longitude-latitude domains (Hoskins and Hodges, 2002; Paciorek, 2002), each of them depicting different aspects of extratropical cyclones. The indices used in this analysis are described below, along with their strengths and weaknesses.

a) Cyclone Frequency

The number of cyclones impacting an area (grid point) is defined as cyclone (or track) frequency ("track density" is also used in the literature). The two most common ways of defining cyclone frequency is: 1) to count the number of cyclone centers detected within a given area per month, or 2) to count the number of cyclone tracks per month that traverse the area, i.e. not allowing a given cyclone to be counted more than once (Colucci, 1976; Klein, 1957; Zishka and Smith, 1980). The former method is biased toward slow moving systems, which spend more time in the region of interest, hence can be counted multiple times. The latter method is biased toward fast moving systems, which travel longer distances, span broader areas and possibly are over-represented on the whole domain (Pinto et al., 2005). The second method is used in this study.

As frequency values computed across rectangular grids dependent on the general direction of the tracks (Taylor, 1986), we assign a circular area with a radius of influence of 555km to each grid points, used to count the cyclone frequency. These are equal-area for all grid points, regardless of latitude (Changnon et al., 1995; Pinto et al., 2005). This radius, larger than the ERA-Interim resolution of 1.5 degrees, is chosen to account for the synoptic scale extent of extratropical cyclones, while being
small enough to allow local characteristics to influence the climatologies. Note that low level vorticity maxima is a restrictive definition of extratropical cyclone, thus the resulting frequency distributions should not be taken as a complete measure of cyclone activity, but as a rather simple storminess index (Paciorek, 2002).

b) Intensity

In this analysis, cyclone intensity is defined as the value of the vorticity maxima detected by the tracking algorithm (in CVU). The mean cyclone intensity at a given grid point is only defined if cyclone frequency is higher than 0.3 cyclones per month, and is the average of the intensity of every track points detected within the given grid point’s area of influence.

c) Growth and Decay

Many studies used the geographical position of the first and last detection points of each cyclone track to define genesis and lysis density (Hoskins and Hodges, 2002). With this definition, the cyclogenesis and lysis areas are very sensitive to the detection scheme and tracking parameters. As such, a different approach, similar to that of (Grise et al., 2013) based on growth (or development) and decay rates of cyclones, is taken in this study. The growth rates of a cyclone at time \( t \) is defined as the change in intensity (in CVU) of this cyclone between time steps \( t+1 \) and \( t-1 \). Since \( t+1 \) and \( t-1 \) are not both defined for the first and last track points of a cyclone, these are automatically ruled out of the analysis.

The climatology of the growth and decay rates (cyclogenesis and lysis) at a grid point is computed if the cyclone frequency is higher than 0.3 cyclones per month by averaging each property for all track points detected within a given grid point’s
area of influence. Only track points showing a positive (negative) change in intensity are used to calculate mean growth (decay) values. Note that this method differs slightly from that of Grise et al. (2013), which rather used the density of developing or decaying cyclones.

### 3.3 Analysis Domains

To select extratropical cyclones that potentially impact Toronto, Montreal, Halifax and st-John’s, a radius of influence of 555km (see section 3.2.2) is assigned to each city (Fig. 3–2). Cyclones detected in these areas are used to characterize the local cyclone track climatology of the cities. Note that each circle in Fig. 3–2 intersects, so the local cyclone climatologies are not independent of each other.

In order to fully characterize the extratropical cyclones across each city, individual cyclones are grouped according to their regions of origin. The North American sector has been divided into six main regions of cyclone development (Fig. 3–2): Gulf of Mexico, Central Rockies, Northern Rockies, Great Lakes, Atlantic and Hudson Bay. These domains are delimited to isolate regional differences relevant for cyclogenesis, such as seasonal cycles in Eady growth rate, or terrain.

The origin of each cyclone is defined by the region in which the cyclone experiences its most explosive growth (fastest growth in 12h, (Sanders and Gyakum, 1980)), prior to its passage to the area of interest. As growth and decay rates are used for cyclogenesis and lysis instead of the first and last cyclone track points, this definition prevents cyclone redevelopment from being counted as cyclogenesis, unless
the re-development is more explosive than its earlier cyclogenesis. In that case, the re-development is the most relevant source of vorticity, and is taken as being the cyclone’s genesis. No more than one region of origin is associated to each cyclone.

3.4 Teleconnection Anomalies

One goal of this study is to assess the response of the eastern Canadian cyclone track climatology to background flow anomalies associated with ENSO, NAO and PNA. For the 1979-2009 period, we select months when teleconnection index exceeds 1 standard deviation. The 250-hPa geopotential height anomalies during those months are then composited for each teleconnection pattern (Fig. 3–3).

The patterns shown in Fig. 3–3 closely resembles those described for each teleconnection in the literature. For instance, ENSO is associated with a geopotential dipole over the North Pacific extending over the Southern US, and rather low significance for the rest of the continent. The NAO pattern shows a dipole over the North Atlantic with higher than normal geopotential over Greenland and the Labrador sea during a strong negative NAO, and lower than normal geopotential in the mid-latitude North Atlantic, extending to northeastern America. There is no significant patterns associated with the NAO over the western side of the continent. The PNA pattern shown in Fig. 3–3 is almost identical to the pattern presented in Fig. 2–5, with ridging over the North Pacific, troughing over Western Canada, and positive 250hPa geopotential anomalies over the southeastern US during -PNA, (opposite pattern for +PNA).
Figure 3–1: Time series of the standardized 3-months running mean ENSO, NAO, and PNA indices over 1979-2009.
Figure 3-2: The six main cyclone development regions as defined in the text (in color), and the five degree circular areas of influence of four Eastern Canadian cities: Toronto, Montreal, Halifax and St-John’s.

Figure 3-3: Composite 250-hPa geopotential anomaly of all months with strong negative and positive ENSO, NAO and PNA, for the 1979-2009 period. Shading indicates values that are statistically significant at the 95% confidence level. Contour interval is 100 m²s⁻².
Most studies characterizing the North American cyclone tracks have focused only on winter season. To better understand how extratropical cyclone activity reacts to changes in the background flow, this chapter discusses the seasonal variation of cyclone activity over North America. Seasonal changes in the climatological cyclone tracks are first discussed for the continental scale, followed by the characterization of the local cyclone climatology at Canadian cities. In this study, the seasons are defined as: December to February (DJF), March to May (MAM), June to August (JJA) and September to November (SON).

4.1 Cyclones over North America

The seasonal climatology of the background flow is presented in Fig. 4–1, with 250-hPa wind and geopotential on the left and Eady growth rate (a measure of baroclinic instability) on the right. The Eady growth rate is calculated at the 600 to 400-hPa layer to avoid bias around high terrain (Hoskins and Valdes, 1990). These are the most important parameters of the background flow for changes in the North American cyclone tracks (Klein, 1957).
During winter, the entrance region of the subtropical Atlantic jet streak is located over the southern US plains, the exit region over the North Atlantic, and the jet maximum over the US Atlantic coast (about 50 ms$^{-1}$). The Eady growth rate is high, especially over the Rockies, the Great Lakes and the northwestern Atlantic. In transient seasons (MAM and SON), the Eady growth rate decreases over the Canadian Rockies and the Atlantic, and the jet wobbles between its summer and winter climatological positions. The summer jet is mostly longitudinal and much weaker (about 35ms$^{-1}$), as baroclinicity largely decreases over the continent. Its position is also shifted poleward with the entrance region close to the Canadian prairies.

4.1.1 Mean Cyclone Frequency and Intensity

Figure 4–2 presents the climatology of cyclone frequency (left) and intensity (right) over North America for the four seasons. The winter (DJF) cyclone activity is similar to that presented by Hoskins and Hodges (2002) and discussed by Gyakum et al. (1989). The mean winter cyclone frequency and intensity are high over Newfoundland and the North Atlantic. Winter cyclones are also frequent over the Great Lakes and the northeastern side of the Canadian Rockies. It is noteworthy that even though winter cyclones are frequent in continental Canada, they tend to remain weak until they reach the Atlantic basin. Hoskins and Hodges (2002) also presented a frequency maximum over the Hudson Bay, which does not stand out on Fig. 4–2 (top left panel). This discrepancy likely results from slightly different method and different reanalysis data.
Significant seasonal cycles are also evident in Fig. 4–2. Like the jet stream, the cyclone tracks are shifted poleward during summer and the region of maximum cyclone frequency becomes more longitudinal. The mean cyclone intensity is also largely decrease over the continent. During transient seasons, cyclones show more scattered tracks and lower frequency. Important regional differences are also noticeable. The mean intensity of North Atlantic cyclones largely weakens in summer, while these cyclone’s frequency is rather constant. In contrast, cyclones in Northern Canada are decreased in frequency in summer while their intensity, rather weak in winter, is increased, especially over the Hudson Bay. Meanwhile, the summer cyclone activity becomes almost non-existant in southern US.

4.1.2 Growth and decay

The previous spatial and seasonal distributions of cyclone frequency and intensity are related to the seasonality of cyclonic growth and decay over different regions. The mean growth and decay rates of cyclones over North America are presented for each season in Fig. 4–3. Different zones of cyclone development can be seen, in agreement with previous studies (Eichler and Higgins, 2006; Grise et al., 2013; Gyakum et al., 1989). Regional differences are discussed below and used to define the development regions presented in Fig. 3–2.

In summer, rapid cyclonic development almost disappears over the continent as baroclinicity weakens. The growth rates however do not decrease uniformly over the analysis domain, concordant with the regional variations in seasonal mean intensity
previously discussed (Fig. 4–2). The US east coast is a zone of intense cyclogenesis in the winter, but this is greatly decreased in summer. In contrast, results show moderate winter cyclogenesis over the Canadian Rockies but remains constant through the year and becomes the main region of summer cyclone development in North America. The Great Lakes region also show weak growth rates throughout the year, but more important in transient seasons.

For cyclolysis (Fig. 4–3, right column), most Pacific cyclones decay near the west coast of Canada and US, while North American cyclone tracks mostly decay in the Labrador sea or the North Atlantic, close to Greenland. In winter, decay is also important over the Great Lakes and Eastern Canada. Note that the mean decay rates varies in amplitude through the seasons, but its geographical distribution is rather constant.

4.2 Cyclones across Canadian Cities

The local variations in cyclone activity are discussed in more details in this section. More precisely, cyclones detected close to Canadian cities (i.e. Toronto, Montreal, Halifax and St-John’s) are isolated and characterized in their Lagrangian cyclone track statistics and origins, with relationships with the background flow.
4.2.1 Local Cyclone Tracks

a) Development regions of Cyclones

To visualize where cyclones in each cities are traveling from, the position where each cyclone has its cyclogenesis (i.e. most explosive growth) along their track are presented for each city in Fig. 4–4. It can be seen that most of the cyclones impacting St-John’s develop along the east coast, while Montreal and Toronto’s cyclones develop inland, in the lee side of the Rockies or in the Great Lakes region. Halifax’s cyclones exhibit a mixture of these features.

The intensity of these cyclones at the time when they hit the cities is also indicated in color in Fig. 4–4. In general, cyclones originating in the northern lee of the Rockies are relatively weak, while cyclones originating in the South are strong although less frequent. These characteristics are linked to the growth rate along each cyclone’s path (Fig. 4–3). Cyclones originating in the north spend most of their lifetime in a weakening region (central Canada), and growth is not favored until they reach the Atlantic. In southern or eastern US, moist from the Gulf of Mexico or the Atlantic favors cyclone intensification along most of their track (Fig. 4–3).

The seasonal cycles in Fig. 4–4 also show differences between the cities. While the winter increase in cyclone intensity is evident for Halifax and St-John’s, it is not so for Toronto and Montreal. However, the weakening of cyclones in summer is robust for all cities. Furthermore, cyclones that originate in different regions are found to have different seasonal cycles. This is detailed in Fig. 4–5 by looking at the frequency of cyclogenesis events in each regions through the year. Over the Atlantic, frequency of cyclone development remains rather constant, further confirming that the seasonal
variation of cyclones in this region mainly resides in intensity. In contrast, cyclone development frequency over the central Rockies and the Great Lakes is high in spring and fall, and decreases in summer. Overall, the frequency of cyclone development is at its lowest in summer except in the North (from the Northern Rockies and Hudson Bay), where the number of cyclogenesis events peaks from July to October, thus being one of the most active regions for summer cyclone development.

b) Density and Intensity of Local Cyclones

Previous Fig. 4–4 and 4–5 highlight that: 1) the cyclones impacting each city originate from various development regions and 2) cyclogenesis frequency over these regions have different seasonal cycles. Thus, it is helpful to group cyclones in accordance with their development region. In Fig. 4–6, the cyclones passing through each city are distributed in number of cyclones and intensity, by grouping cyclones according to their region of genesis. Although there is a dominant development region for each city (e.g., the Great Lakes for Toronto and Montreal, the Atlantic for Halifax and St-John’s), cyclones crossing each city originated from multiple development regions.

The intensity and development regions of Toronto and Montreal cyclones are highly similar, partly due to their intersecting areas of influence, but also to their relative location, Montreal being downstream of Toronto in line with typical cyclone tracks. Their climatologies are dominated by Great Lakes’ cyclones, although a significant number of cyclones also travel from the central lee of the Rockies (especially for Toronto). Accordingly, the cyclone intensity at these cities features stronger
cyclones in spring and fall. Note that cyclones from the Gulf of Mexico are less nu-
merous than cyclones from high latitudes (Northern Rockies and Hudson Bay), but repre-
sent a significant fraction of the intense winter cyclones, while cyclones from the North rarely get stronger than 6 CVUs.

Halifax and St-John’s are located on the East coast, and their cyclone climatolo-
gies are dominated by Atlantic cyclones. This is particularly true for St-John’s, and accordingly, its cyclone activity shows a simple seasonal cycle, with largely decreasing number of intense cyclones in summer. In Halifax, continental cyclones (from the Great Lakes and the central Rockies) are also important, and in the summer the predominance of Atlantic cyclones is taken over by cyclones tracking from the Great lakes.

c) Intense Cyclones

The typical tracks of intense cyclone passing through each city can be visualized in Fig. 4–7, in which the tracks of their most intense cyclones (top 10%) are pre-
sented. Note that for Halifax and St-John’s, most of these are winter cyclones, while for Toronto and Montreal, extreme cyclones are often found in late fall or early spring (see Fig. 4–6). The intensity along the tracks (in color) indicates that Toronto’s and Montreal’s cyclones develop slowly along their tracks, while Halifax’s and St-John’s cyclones quickly strengthen before or within the cities’ radius of influence. Accord-
ingly, Halifax’s and St-John’s cyclones are more intense (see Fig. 4–6 and 4–8), consistent with the geographical distribution of cyclone intensity (Fig. 4–2). For instance, most of St-John’s cyclones have intensities between 6 and 10 CVU, while most of Toronto’s cyclones are between 3 and 6 CVU. This is also true for extreme
cases: Halifax’s extreme cyclones are between 10 and 12 CVU (or stronger), while Toronto’s extreme cyclones rarely reach 10 CVU.

Figure 4–7 and 4–8 also show that strong cyclones usually have a northeastward direction. These differences, however, do not appear in cyclone speed: the speed of propagation of local cyclones is almost identical for each city and direction, most cyclones passing through the areas at between 40 and 80 km/h in the summer, and between 50 and 90 km/h in the winter (Appendix). The seasonal cycles of cyclone intensity particular to each city is also well represented in Fig. 4–8. Additionaly, the propagation direction of cyclones across Halifax and St-John’s are found to shift from predominantly southeastward cyclones tracks in winter to eastward cyclone tracks in summer. In contrast, no significant seasonal variations are found in the propagation direction of cyclones across Toronto and Montreal.

d) Eulerian Statistics

The cyclone characteristics, as seen in each city without regards to the tracks, are summarized in Tables 4–1 to 4–4, for Toronto, Montreal, Halifax and St-John’s. The differences between cities discussed earlier in this section are well represented in the yearly statistics (top rows). Cyclone intensity clearly increases as the location is closer to the North Atlantic especially for extreme winter cyclones, with a mean of 7.28-CVU in Toronto and 9.65-CVU in St-John’s. The mean growth rates of the cyclones at the cities also clearly oppose Toronto and Montreal, with near neutral rates (0 CVU/day), to Halifax and St-John’s, with quite fast development rates (1.2 CVU/day).
Robust seasonal cycles are less evident in these statistics. However, cyclones are clearly weaker, slower and more longitudinal in summer, and faster in winter. Halifax’s and St-John’s cyclones have a clear seasonal cycle, with enhanced cyclone intensity, growth rates and propagation speed in winter, but reduced in summer. However, most of these properties are rather invariant through the year for cyclones across Toronto and Montreal.

4.2.2 Background flow anomalies

Differentiating cyclones with different origin not only show different seasonal cycle, but also cause different tropospheric disturbances. Examples of this is presented in Fig. 4–9, in terms of 250-hPa geopotential height anomalies. The presence of cyclones over each city is associated with a negative geopotential height anomaly on the west and a positive anomaly on the east, indicating westward tilting of cyclones in the vertical, as typical in developing baroclinic systems. More particularly, Atlantic cyclones (left, bottom two panels) tend to be associated to an asymmetric background flow, with a strong ridge over the Atlantic, and a trough over northern US. Great Lakes’ cyclones, however, coincide with a somewhat longitudinal wave-train pattern extending on both sides of the cyclone (right, all panels). Cyclones tracking from the central Rockies are associated with a large trough extending over central and western Canada, with a shorter wave-train in the East. These particularities are likely associated with different weather impacts. More analysis is needed on that regard.
Figure 4–1: Left: Climatological geopotential (solid contour lines, in m²s⁻²) and wind (color, in m/s) at 250-hPa. Contour interval is 1000 m²s⁻². Right: Climatological 600 to 400-hPa layer Eady growth rate (in day⁻¹). For DJF, MAM, JJA and SON.
Figure 4–2: Climatological cyclone frequency (left, in # tracks / month) and cyclone intensity (right, in CVU) over North America for DJF, MAM, JJA and SON, binned on a 1.5 x 1.5 degree boxes. Each grid box is assigned to a 555km radius region of influence, in which individual tracks can only be counted once. Thick solid lines denote topography in contour interval of 1000 m.
Figure 4–3: Same as figure 4–2, but for cyclonic growth rate (left) and decay rate (right), in CVU/day. Only points featuring cyclonic development (≥ 0 CVU/day) are used in the growth climatology, and points featuring cyclonic dissipation (≤ 0 CVU/day) are used in the growth climatology. Track frequency suppression threshold is 0.3 /month. Thick solid lines denote topography in contour interval of 1000 m.
Figure 4–4: Position of the track point with maximum growth rate (or origin) of each individual cyclone track passing through Toronto, Montreal, Halifax and St-John’s. The color indicates the intensity that the cyclone had within the city’s area of influence (in CVU).
Figure 4–5: Bimonthly frequency of cyclones (in # tracks/month) from each development regions. Individual tracks are only counted once, and are only associated with the region where they have their most explosive growth.

Figure 4–6: Distribution of individual cyclones from each development regions, in number of cyclones (vertical axis) and intensity (horizontal, in CVU). For Toronto, Montreal, Halifax and St-John’s.
Figure 4-7: Tracks of the top 10 % intense cyclones across Toronto, Montreal, Halifax and St-John’s. The points represent the center of the vorticity maxima, with their intensity (color). Unit is CVU.
Figure 4-8: Seasonal distribution of cyclones passing through Toronto, Montreal, Halifax and St-John’s, in cyclone intensity (color, in CVU) and propagation direction (within 12 hours). Bars extend toward the direction cyclones are coming from. The length of bars are proportional to the percentage of cyclones found in each category. Dotted circles indicate lengths representing 5%, 10% and 15% of the cyclones.
Figure 4–9: Geopotential anomaly (in $m^2 s^{-2}$) associated with a cyclone, from a particular development region, being over a) Toronto, b) Montreal, c) Halifax, d) Toronto. Thick, blue lines indicate the genesis region considered, and thick black lines indicate the city's area of influence. Solid lines denote topography in contour interval of 1000 m.
<table>
<thead>
<tr>
<th></th>
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Table 4–1: Cyclone statistics over Toronto: "f" is the cyclone frequency (in # tracks/month), "I" the mean intensity (in CVU), "ΔI" the mean 12h development rate across the city (in CVU/day), "v" the cyclone propagation speed (in km/h), "θ" the propagation direction (meteorological convention, 270 degrees = eastward) and "Iext" the mean intensity of the top 10% intense cyclones (in CVU).

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Table 4–2: Same as Table 4–1, but for cyclones across Montreal.

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Table 4–3: Same as Table 4–1, but for cyclones across Halifax.

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Table 4–4: Same as Table 4–1, but for cyclones across St-John's.
CHAPTER 5
Inter-annual Variability Associated with ENSO, NAO and PNA

Focusing on inter-annual variability, this chapter examines the impact of teleconnection on extratropical cyclone tracks across eastern Canada. For conciseness only the winter season is discussed, when cyclones activity is at its highest and tracking results are more robust (Neu et al., 2013; Ulbrich et al., 2009).

5.1 Cyclone Track Anomalies Over North America

In this section, the tracking scheme is used to characterize the continental-scale cyclone track anomalies. The results are presented in composite anomalies with shading for values significant at the 95% confidence level. The months that are used in the composite analysis are listed in Table 5–1, with positive (negative) teleconnections in red (blue).

5.1.1 ENSO

The North American 250-hPa wind, Eady growth rate (in 600 to 400-hPa layer), cyclone track frequency and mean intensity anomalies associated to ENSO are presented in Fig. 5–1, complementary to the ENSO-related 250-hPa geopotential anomaly presented in Fig. 3–3. During -ENSO, the jet (Panel a) is shifted North
and is more longitudinal, with a dipole anomaly at the climatological entrance region position. Baroclinicity (Panel b) is more important over the US Rockies and Mid-west. The anomalies are stronger during +ENSO, featuring an equatorward shift in jet, with a significantly decrease in Eady growth rates over the Rockies, the Great Lakes, North Eastern US and the Canadian Maritimes.

The cyclone track frequency anomaly (5–1c) closely resembles that presented by Eichler and Higgins (2006) and Grise et al. (2013), and its similarity to the 250-hPa wind anomaly highlights the dependence of cyclone activity to the position of the subtropical Atlantic jet. During +ENSO, track density is significantly increased over the Southern US and the east coast and decreased in higher latitudes, indicating an equatorward shift in the cyclone tracks, consistent with the jet displacement. Results show the equivalent and opposite pattern for -ENSO, but with a significant decrease in cyclone frequency over the lee of the Canadian Rockies. These anomalous patterns are consistent with the ENSO-related oscillation between Atlantic cyclone activity and continental cyclone activity often discussed in previous studies (see section 2.3.1).

Intensity changes are also evident over the Atlantic and northeastern America (5–1d). The equatorward shift in cyclone tracks during +ENSO is generally associated with anomalously strong cyclones from the Gulf of Mexico and Atlantic, and busts weak cyclones on mid- to high-latitude.

Details in these ENSO related changes are presented in Fig. 5–2, by separating the specific contribution of cyclones from different origin to the large scale frequency anomaly. An important result is that the equatorward shift in the cyclone tracks
during a +ENSO is not equivalent to a northward shift of all the tracks, but to a geographical redistribution of cyclone development, with less cyclones developing in the mid-latitudes, and more cyclones developing in the South and in the North.

ENSO’s upper level jet and Eady growth rate anomalies are mostly situated downstream of the tracks, with no significant changes over the jet exit region. Accordingly, during strong -ENSO and +ENSO winters, cyclone tracks originating from most regions show little deviation from their usual direction of propagation, but significantly respond in development frequency. For instance, the frequency of Great Lakes’ cyclones is significantly decreased and that of Atlantic cyclones is significantly increased during a +ENSO (vice versa for -ENSO), as often stated in the literature (Bradbury et al., 2003; Hirsch et al., 2001; Noel and Changnon, 1998). Those differences are likely to compete in the local cyclone climatology in regions influenced by both groups of cyclones, such as in the Atlantic provinces. Cyclones traveling from the central Rockies are also less frequent during a +ENSO, while cyclones tracking from the Gulf of Mexico are more frequent. Cyclone originating from the central Rockies additionally have directional changes, with southward propagating tracks favored during +ENSO, consistent with the shifted jet.

5.1.2 NAO

The background flow and cyclone track anomalies related to the NAO are presented in Fig. 5–3. The upper level wind anomaly (panel a) presents a northwestward (southeastward) shifted jet during +NAO (-NAO), but no significant changes are found over the eastern Pacific and the Rockies. Accordingly, the baroclinicity
anomaly (panel a) is not significant in western North America but strong over the Atlantic, extending to North America, with a positive anomaly in the North and a negative anomaly in the South during +NAO (opposite during -NAO).

The cyclone frequency anomaly presented in Fig. 5–3c is consistent with previous studies (Grise et al., 2013). NAO’s influence on extratropical cyclone frequency is concentrated over the Atlantic, and extends over the eastern part of North America. A dipole of positive cyclone frequency anomalies in the North Atlantic and negative frequency anomalies over subtropical latitudes corresponds to a poleward shift of the cyclone tracks during +NAO (equatorward during -NAO). More precisely, with the jet, cyclones tend to move toward southern Europe and north Africa during -NAO, but towards Scandinavia during +NAO. The cyclone intensity anomaly, however, (Fig. 5–3d) show significant NAO-related anomalies only over the Atlantic, Maine (US) and the Canadian Atlantic provinces, as noted by Grise et al. (2013). Over these regions, the intensity is decreased during positive NAO regimes, and vice versa.

In contrast with ENSO, the 250-hPa anomalies related to NAO are stronger at the exit region of the Atlantic jet. Thus, changes in specific North American cyclone tracks are mainly directional (Fig. 5–4), as background flow changes are mostly situated upstream of the most cyclogenesis regions (except the Atlantic). For instance, cyclones traveling from the Great Lakes and central Rockies feature anomalously high numbers of eastward propagating cyclones (toward the US east coast) during -NAO. During +NAO, they rather tend to follow the St-Lawrence valley. The NAO’s impact on cyclones traveling from the Gulf of Mexico is rather weak, mainly diminishing their overall frequency during +NAO. Over the Atlantic, cyclone
development is more frequent during -NAO and less frequent during +NAO. As the
Atlantic jet is weakened during -NAO, Atlantic’s cyclone tracks are less confined, and
their likeliness of being directed toward the Labrador sea is increased. Conversely,
Atlantic’s cyclone frequency over the US east coast and Canadian Atlantic provinces
is decreased during +NAO, in agreement with Wang et al. (2006).

5.1.3 PNA

As mentioned in previous studies, the cyclone tracks over northeastern America
are highly influenced by PNA (Grise et al., 2013). The background flow and cyclone
track anomalies related to PNA are presented in Fig. 5–5. While the 250-hPa wind
anomaly (panel a) resembles ENSO’s anomaly over the continent, its pattern is more
extensive, with significant anomalies over high latitudes and the Atlantic. During
-PNA, the mid-latitude jet tend to be deflected North of the Rockies, shifting the
Atlantic jet northwestward. During +PNA, the Pacific jet is rather deflected to the
South of the Rockies, shifting the Atlantic jet southeastward. Accordingly, the Eady
growth rate is reduced in the southern US, southern Atlantic and the Arctic during
-PNA, and enhanced over the Rockies, the Great Lakes and the St-Lawrence valley
(opposite for +PNA. Fig. 5–5b).

During +PNA regimes, cyclone frequency is significantly reduced over the Great
lakes, but increased along the east coast (panel c). This dipole pattern is consistent
with Grise et al. (2013), but not with Notaro et al. (2006), who found an increase
in strong vorticity maxima over the Great Lakes during +PNA. This discrepancy
is likely due to the very different cyclone definitions and thresholds (Notaro et al.
(2006) tracked strong mid-tropospheric vorticity). As evident from Fig. 5–5d, cyclone intensity is not significantly modified by PNA except over the Great Lakes, where the intensity is significantly enhanced during -PNA regimes.

Unlike ENSO winters, the background flow anomalies related to PNA are significant both upstream and downstream of the North American cyclone track, causing changes in both cyclone development and direction. The PNA-related cyclone track frequency anomaly of cyclones from each development regions are shown Fig. 5–6. It is found that the changes shown in Fig. 5–5a are mostly due to cyclones developing over the Great Lakes and Atlantic (bottom two rows in Fig. 5–6), with a marginal contribution during -PNA by cyclones developing over the Gulf of Mexico (left panel, second row). During -PNA, cyclones forming in the Gulf of Mexico are generally reduced, decreasing the cyclone frequency over the east coast. However, they also tend to travel northward due to the weakened northward shifted jet, thus increasing the cyclone frequency over the Great Lakes. Similarly, as southeastward propagating tracks are favored by the shifted jet, the frequency of Great Lakes’ cyclones is increased over the Atlantic provinces during +PNA even though they are reduced in overall. For cyclones from the central Rockies, no significant changes are seen in during -PNA, but during +PNA, they tend to propagate southward along the Rockies before heading toward the US east coast, thus increasing cyclone frequency in the southern US. Atlantic cyclones are greatly influenced by PNA, their frequency being largely decreased (increased) everywhere during the negative (positive) regime.
5.2 Inter-annual Variability of Cyclone Tracks over Canadian Cities

At the four eastern Canadian cities considered, the local cyclone frequency (Fig. 5–7) is only marginally affected by ENSO, NAO, PNA. Only few cases show cyclone frequency changes of more than 1 cyclone per month: Toronto during El Nino, Halifax and St-John’s during -PNA, and St-John’s during -NAO. Nonetheless, differences are visible between the impact of teleconnection on coastal (Halifax and St-John) and continental (Toronto and Montreal) cities, consistent with the dipole in maritime and continental cyclone activity often discussed in the literature (Bradbury et al., 2003; Hirsch et al., 2001; Noel and Changnon, 1998). More precisely, while Halifax and St-John’s cyclone frequency increases (decrease) during the positive (negative) phase of ENSO, it is the opposite for Montreal and Toronto. ENSO’s impact also decreases in amplitude for locations closer to the Atlantic, while that of NAO increases. However, these variations do not take into account the origin of cyclones. More details are described below for Toronto, Montreal, Halifax and St-John’s.

5.2.1 Toronto

Figure 5–8 shows the frequency (a, colored bars), intensity (b), direction (c) of cyclones passing through Toronto during strong teleconnection events, from 1979 to 2009. These should be compared with the climatology presented in Fig. 4–6 and 4–8.

The origin distribution of Toronto’s cyclones is quantified in Fig. 5–8a, with a total of 6.6 cyclones per month on average across the city. As discussed in section
4.2.1, most of these cyclones are from the Great Lakes (2.5 cyclones per month) and the central Rockies (1.9 cyclones per month). The frequencies of cyclones other origins are 0.75 from the Northern Rockies, 0.6 from the Gulf of Mexico and 0.5 from Hudson Bay. Note that cyclones from the last two were shown to be weak in Fig. 4–6. A missing portion (≤ 0.5 cyclones/month) are weak cyclones developing outside of the regions defined in Fig. 3–2.

a) ENSO

ENSO mostly impacts Toronto’s cyclones through changes in their regions of origin. During -ENSO, significantly fewer cyclones track from the Gulf of Mexico, while significantly more cyclones travel from the Central Rockies, consistent with the changes in cyclone development seen in Fig. 5–2. This is further accompanied by an increase in intense cyclones, with 2 cyclones per month ≤6CVU during -ENSO cyclones are compiled, against 1.5 in the climatology (30% increase). During +ENSO, Toronto’s cyclone frequency decreases, mostly due to the reduction in cyclone activity from its two predominant regions (Great Lakes and central Rockies), and from the Hudson Bay. This decrease is partly compensated by a significant increase of cyclones from the Gulf of Mexico. The direction of propagation of cyclones during ENSO (Fig. 5–8c) is consistent with those changes, with spreaded distribution during +ENSO.

b) NAO

The limited impact of NAO on Toronto’s cyclone frequency (Grise et al., 2013) is summarized in Fig. 5–8a, in which only weak cyclones from the Hudson Bay significantly decreased and cyclones from the Gulf of Mexico increasing during -NAO. There is also no significant change in cyclone intensity. However, the NAO
have an impact on cyclones’ propagation speed and direction, with a predominance of slower eastward moving cyclones during -NAO, mostly propagating from 40 to 70 km/h, instead of 50 and 90 km/h in the climatology.

c) PNA

During PNA, changes in frequency of cyclones from the Great Lakes and the Central Rockies are quite similar to the ENSO-related response. Similarity however does not hold for cyclones forming in the North, especially during +PNA, during which there is a significant increase ( in cyclones traveling from the northern Rockies, partly compensating the decrease in cyclones frequency from the Great Lakes and central Rockies. The increased influence of cyclones from northern regions is consistent with a increased predominance of weaker (Fig. 5–8b), and more northwesterly propagating cyclones, in Fig. 5–8c.

5.2.2 Montreal

Montreal’s cyclone climatology is very similar to Toronto’s, as previously discussed. Montreal’s mean cyclone frequency is about 6.5 cyclones per month. In regard of genesis regions (Fig. 5–9a), Great Lakes’ cyclones are as frequent in Montreal as in Toronto (2.5 per month), but are more dominant in Montreal’s distribution, which is less influenced by cyclones from the central Rockies (about 1.3 instead 1.9 per month). This difference to Toronto’s climatology is compensated by the presence of some rare Atlantic’s cyclones (mean frequency of 0.5 per month). The frequency of cyclones from other regions is the same as Toronto’s: 0.75 from the Northern Rockies, 0.6 from the Gulf of Mexico and 0.5 from the Hudson Bay.
a) ENSO

ENSO has a similar but smaller impact on the origin distribution of Montreal’s cyclones than on Toronto’s. Cyclones from the Central Rockies and the Great lakes are less frequent in Montreal during +ENSO, while cyclones from the northern Rockies and Gulf of Mexico are more frequent, consistent with the increase number of southeastward and northeastward propagating cyclones in Fig. 5–9c. The number of intense cyclones is also lower during +ENSO, with about 1 cyclone per month ≥ 6CVUs, against 1.5 in the climatology and 2 during -ENSO.

b) NAO

While Fig. 5–5 shows no significant changes in Montreal’s cyclone frequency during winter NAO months, figure 5–9 shows that the number of cyclones traveling from the Gulf of Mexico in Montreal is highly sensitive to the teleconnection. During the negative phase of the NAO, the frequency of Gulf of Mexico’s cyclones almost doubles (0.9 per month, against 0.5 in the climatology). More Atlantic’s cyclones also impact the city, as they are propagating toward the Labrador sea across Quebec and the Maritimes (see figure 5–4). This is not apparent in figure 5–7 as this increase is compensated by insignificant decreases in frequency of cyclones from other regions. In contrast, during the positive phase of the NAO, the frequency of cyclones from the Gulf of Mexico decreases to 0.2 cyclones per month. The frequency of cyclones from other regions are virtually unchanged.

This change in cyclogenesis regions is important as cyclones from the Gulf of Mexico and the Atlantic tend to be stronger than other systems. This is apparent in Fig. 5–9c, with an increased number of intense cyclones found in -NAO, though
the change is not significant. The impact is also apparent in the general direction of the cyclones (Fig. 5–9c), in which a large portion of cyclones (about 12%) come from the southwest, compared with only about 5% in the climatology. The cyclones are also moving more slowly during -NAO (see appendix Fig A.3). Low significance is due to the sparsity of winter -NAO months. These results should be tested using a longer time period. During +NAO, the intensity, direction and speed of cyclones passing through Montreal show no significant deviations for the climatology.

c) PNA

Across Montreal, PNA affects the cyclone frequency by changes in cyclone activity from the central Rockies, more than doubled in frequency between the negative and positive phase (about 2.2 per month during -PNA, and 0.9 per month during +PNA). The frequency of Great Lakes’ cyclones is lower for both phases, being less frequent in the St-Lawrence valley (see Fig. 5–6). Also opposing ENSO-related changes, the presence of Hudson Bay’s cyclones in Montreal is decreased during -PNA, and increased during +PNA. The increase in cyclones from the North is also visible in Fig. 5–9c, with a shift to southeastward propagating cyclone during +PNA. Changes in the frequency of intense cyclones (Fig. 5–9b) are not significant, and are likely influenced by ENSO. It reserves further analysis.

5.2.3 Halifax

On average, about 7 cyclones per month are observed in Halifax (Fig. 5–7). Among them, 2.7 cyclones travel from the Atlantic and 1.7 from the Great lakes. Cyclones from the four other regions are sparse, each with a frequency of about 0.5
cyclones per month. The missing 0.5 cyclones per month are weak cyclones coming from outside of our regions of analysis.

a) ENSO

Results show no significant impact of the negative ENSO on Halifax’s cyclones (Fig. 5–10). It contrasts to +ENSO winters, during which, like in Toronto and Montreal, cyclones from the Gulf of Mexico and the Northern Rockies tend to increase, respectively passing from 0.4 to 0.75 cyclones per month. ENSO does not significantly impact the direction of propagation of Halifax’s cyclones, since its cyclone activity remains largely dominated by Atlantic’ and Great Lakes’ cyclones. However, intense cyclones are more frequent in Halifax during +ENSO, with about 3.4 cyclones ≥ 6CVUs per month, against 2.7 in the climatology.

b) NAO

NAO brings significant changes in the origin of cyclones across Halifax, altering the dominance of Great Lakes and Atlantic cyclones in its climatology. Note that in Halifax, the change in Atlantic’s cyclone frequency (increased frequency during -NAO and decreased frequency during +NAO, Fig. 5–4) is mitigated by the shift in the Great Lakes’ cyclone track. During -NAO, the influence of the jet (anomalously oriented toward North Africa, see section 2.3.2), causes cyclones to travel equatorward of Halifax, decreasing their presence in the city. Cyclones from less important regions are also decreased during -NAO, with the exception of cyclones from the Gulf of Mexico. It is noteworthy that cyclones traveling across Halifax during that regime tend to be intense, with a significant decrease in the frequency of weak cyclones (cyclones ≤ 6 CVUs, Fig. 5–10b). Panel c further reveal that these
intense cyclones are cyclones that approach Halifax from the South. During +NAO, cyclones are confined to travel toward Scandinavia, across the Atlantic provinces, increasing the cyclone frequency over Halifax. They are faster (see appendix Fig. A.4), most cyclones traveling at 60 to 90km/h during +NAO, versus 40 to 70 km/h during -NAO.

c) PNA

Cyclones from all origins are decreased in frequency during -PNA (Fig 5–10a). Note that this is not due to a general decrease number of cyclones forming at each development region, but to the geographical position of Halifax with respect to the different shifts in the cyclone tracks. For instance, Halifax’s decrease in frequency of cyclones from the Rockies is due to their anomalous northeastward propagation (see Fig. 5–6) that cause cyclones to track North of the city. Similarly, Great lakes’ cyclone tracks are more scattered, decreasing frequencies across their typical track, i.e. over the Maritimes and the St-Lawrence valley. Cyclones from the Northern Rockies are also less likely to travel southward during -PNA, thus not reaching Halifax. This is apparent in Fig. 5–10c, with an anomalous predominance of northeastward propagating cyclones during -PNA, and fewer than normal southeastward systems. There are no significant impact of PNA on Halifax’ cyclones’ intensity. There is a significant decrease in Great Lakes’ cyclone frequency during +PNA, partly compensated by a significant increase in Gulf of Mexico’s cyclone frequency. However, there are no significant changes on the intensity, speed and direction of these cyclones.
5.2.4 St-John’s

St-John’s cyclone activity is largely dominated by Atlantic cyclones. On average, 7 cyclones per month are observed in winter. It is also found that as much as 4 are coming from the Atlantic, and only 0.9 from the Great Lakes, its second most influential group of cyclones. For each of the four other remaining development regions, less than 0.5 cyclones per month are observed across the city. The remaining portion are cyclones that develop outside of the regions of interest.

a) ENSO

St-John’s cyclone activity is largely dominated by Atlantic systems, and ENSO has no significant impact on its cyclone climatology. The significant increase in cyclones from the Northern Rockies during +ENSO observed at other cities is also seen in St-John’s, but the change is unsubstantial.

b) NAO

The effect of NAO on St-John’s cyclone climatology in terms of changes in origin distribution (Fig. 5–11a) is found to be somewhat different from Halifax’s. The frequency of Atlantic cyclones in St-John’s is not impacted by the NAO, presumably because of its location, which intersects both the tracks of cyclones traveling to the Labrador sea and the North Atlantic. However, either phase of the NAO impacts the general direction of cyclones at St-John’s, with stronger northward movement during -NAO, and more eastward tracks during +NAO (Fig. 5–11c). In contrast, Great Lakes’ cyclones tend to propagate across St-John’s only when they track toward Scandinavia. Thus, they are more frequent across the city during +NAO, and less frequent during -NAO.
The shift for more intense cyclones during -NAO seen in the other cities is important in St-John’s. Only 2.1 cyclones ≤ 6 CVUs during -NAO, against 3.4 in the climatology and 4.0 during +NAO. Meanwhile, the frequency of intense cyclones is virtually unchanged. This pattern is consistent with the decrease number of continental cyclones across St-John’s during the -NAO.

c)PNA

The large decrease in Atlantic cyclones during -PNA (Fig. 5–6) acts on St-John’s cyclone frequency by as much as 1.6 cyclones per month on average. Additionally, St-John’s being farther east than Halifax, the northwestward shift of cyclone tracks coming from the lee of the Rockies during -PNA almost completely eliminates the presence of continental cyclones over St-John’s. Consistently, cyclones traveling northeastward are anomalously predominant during -PNA (Fig. 5–11c). Cyclones traveling from the northern Rockies and from Hudson Bay are also decreased. The frequency of both intense and weak cyclones are reduced, but weak cyclones seem to be favored in both phases of the PNA. The positive phase of the PNA is not very influential in St-John’s. As for Halifax, there is a small, significant increase in Atlantic cyclone frequency, but this increase is compensated by a decrease in Great Lakes’ cyclones.
Table 5–1: Months during strong teleconnection (ENSO, NAO, PNA). Months are selected if the associated index is greater than one standard deviation.
Figure 5–1: For DJF, composite of a) 250-hPa wind anomalies (in m/s) b) 600 to 400-hPa Eady growth rate anomalies (in day$^{-1}$) c) storm frequency anomalies (in # cyclones/month) and d) cyclone intensity anomaly (CVU) over North America during strong ENSO months (ONI ≥ 1 std). Results are binned on a 1.5 x 1.5 degree boxes. Each grid box is assigned to a 555km radius region of influence, on which the anomalies are computed. Shading indicates values that are statistically significant at the 95% confidence level. Solid contours denote topography in contour interval of 1000 m, and thick, dashed contours indicates the DJF climatology, in contour intervals of 2 day$^{-1}$ for Eady growth rates and 10 m/s for wind. Track frequency suppression threshold is 0.3/month.
Figure 5–2: Anomaly of cyclone frequency specific to cyclones originating in each development regions, during strong +ENSO (top panel) and -ENSO (Bottom panel) winter months (ONI ≥ ±1 std). Results are binned on a 1.5 x 1.5 degree boxes. Each grid box is assigned to a 555km radius region of influence, on which the anomalies are computed. Shading indicates values that are statistically significant at the 90% confidence level. Track frequency suppression threshold is 0.3/month. Solid contours denote topography in contour interval of 1000 m.
Figure 5–3: Same as Fig. 5–1, but for strong NAO months (NAOI ≥1 std), in DJF. Shading indicates values that are statistically significant at the 95% confidence level. Thick solid lines denote topography in contour interval of 1000 m.
Figure 5-4: Same as Fig. 5-2, but for strong NAO months (NAOI ≥1 std), in DJF. Shading indicates values that are statistically significant at the 90% confidence level. Track frequency suppression threshold is 0.3/month. Solid contours denote topography in contour interval of 1000 m.
Figure 5-5: Same as Fig. 5–1 but for strong PNA months (PNAI ≥1 std), in DJF. Shading indicates values that are statistically significant at the 95% confidence level. Thick solid lines denote topography in contour interval of 1000 m.
Figure 5–6: Same as Fig. 5–2 but for strong PNA months (PNAI ≥1 std), in DJF. Shading indicates values that are statistically significant at the 90% confidence level. Track frequency suppression threshold is 0.3/month. Solid contours denote topography in contour interval of 1000 m.
Figure 5–7: DJF mean storm frequency (# /month) during ENSO, NAO and PNA regimes. The dashed line represents the climatological mean DJF storm frequency. For Toronto, Montreal, Halifax, and St-Johns. Dots over the bars indicate anomalies statistically significant at the 90% confidence level.
Figure 5–8: a) Frequency distribution (in #/month) of Toronto’s winter cyclones from each region during strong ENSO, NAO and PNA months (colored bars). The 1979-2009 climatology of this distribution is show as thick, empty bars. The difference between the colored and empty bars represents the anomaly associated with the given regime. The origin of a cyclone is defined by the region where it had its most explosive development along its track. Dots over the bars indicate anomalies statistically significant at the 90% confidence level. b) Intensity (CVU) distribution (in # tracks/month) of Toronto’s local cyclones during ENSO, NAO and PNA. Dots over the bars indicate anomalies statistically significant at the 90% confidence level. c) Intensity (color, in CVU) and direction distribution of cyclones passing through Toronto during ENSO, NAO and PNA. Bars extend toward the direction cyclones are coming from. The length of bars are proportional to the % of cyclones found in each intensity category.
Figure 5-9: Same as Fig. 5-8 but for Montreal’s cyclones.
Figure 5–10: Same as Fig. 5–8 but for Halifax’s cyclones.
Figure 5–11: Same as Fig. 5–8 but for St-John's cyclones.
CHAPTER 6
Discussion and Conclusions

In this thesis, the North American extratropical cyclone tracks are examined, with a focus on the local cyclone climatology and inter-annual variability at important eastern Canadian cities, namely Toronto, Montreal, Halifax and St-John’s. The automated detection scheme developed by Hodges (1999) is applied to the vorticity field taken from ERA-Interim’s hybrid sigma-pressure model level closest to 850hPa (Grise et al., 2013), from 1979 to 2009. From this ensemble of tracks, cyclone statistics such as track frequency, mean intensity, growth, decay and propagation speed and direction are quantified. The large scale and local scale seasonal variance and interannual anomalies under ENSO, NAO and PNA are characterized.

Unlike previous studies, the tracks are grouped according to the origin (or genesis) region of the cyclones. The origin is defined as the region in which the most explosive growth occurred along any given track. The seasonal cycle of each group of cyclones is characterized, as well as changes in their characteristics during ENSO, NAO and PNA. The cyclone statistics over Toronto, Montreal, Halifax and St-John’s are characterized by quantifying the local activity of each type of cyclone. Winter cyclone activity changes at these cities under ENSO, NAO and PNA are also analyzed by considering the region in which cyclones developed.
It is found that the cyclone track characteristics are different for cyclones coming from different origins. Cyclones originating over the Atlantic were found to be strong and frequent during winter, when growth over the western Atlantic is favored by high baroclinicity and large temperature differences between the ocean and the atmosphere. Their mean intensity is largely reduced in summer. Cyclones originating over the central Rockies and the Great Lakes rather tend to be less intense, and peak in frequency during transient seasons, when continental cyclones are favored by the highly-variable jet between the Rockies and the Atlantic. In the Gulf of Mexico, cyclone development frequency is low, but this development region is found to be a significant source of extreme winter cyclones in eastern Canada. Their occurrence is almost nonexistent during summer, due to the poleward shift of the jet. Lastly, cyclones originating in high latitudes (Northern Rockies or Hudson Bay regions) are found to be weak, but more frequent in the summer.

These characteristics are shown to have an influence on the local cyclone activity. Each city examined in this study presents a local cyclone climatology that is dominated by one or two groups of cyclones, but influenced by cyclones from many (or all) development regions. Accordingly, the inter-seasonal variability of the local cyclones across eastern Canada depends on the relative predominance of each group of cyclones. Toronto and Montreal were found to be predominantly influenced by cyclones from the Great Lakes and the Central Rockies, with more frequent intense cyclones in spring and fall. In Halifax and St-John’s, intense cyclones are more numerous, due both to these city’s geographical position (upstream of the tracks) and to the predominance of intense Atlantic cyclones in their climatology. Because of
this predominance the presence of intense cyclones is largely reduced in summer at these cities.

It is found that the inter-annual variability of the North American cyclone tracks represent a combination of changes in the different groups of cyclones. The ENSO oscillation between continental and coastal cyclones is confirmed, with an increase in frequency of cyclones from the Atlantic and the Gulf of Mexico but a decrease of cyclones from the central Rockies and the Great Lakes during +ENSO (opposite is true for -ENSO). An other important and robust result is that cyclones from the northern Canadian Rockies are anomalously frequent during +ENSO in eastern Canada.

Consistent with previous studies, changes related to the NAO are found to be less significant over North America. Nonetheless, NAO modulates to some degree the propagation speed and direction of cyclones, and impacts Atlantic’s cyclones, which are more frequent and less confined during -NAO. This significantly impacts the cyclone activity in extreme northeastern America.

Interestingly, ENSO and PNA-related changes were found to be different, even though those regimes are correlated to some degree. Unlike during ENSO, the continental winter cyclone tracks (from the Rockies and the Great Lakes regions) are shifted in their direction of propagation more than they are impacted in their occurrence frequency. During -PNA, cyclones with strong northward component are favored, and Atlantic cyclones’ development is largely reduced (opposite for +PNA).

In eastern Canadian cities, these winter inter-annual variations in the different groups of cyclone tracks are found to be, in some cases, more important than the
overall local change in cyclone frequency. The winter cyclone frequency over Toronto is found to depend on ENSO and PNA, while the NAO only influences the propagation speed and direction of this city’s cyclones. As suggested in the large-scale anomalies, cyclones from the North and South are found to be more frequent during +ENSO, while the frequency of eastward propagating cyclones are reduced (vice versa for -ENSO). PNA influences Toronto’s cyclone climatology mainly by causing an increase in cyclones from the North during +PNA, and in eastward propagating cyclones during -PNA.

Across Montreal, the overall winter cyclone variability related to ENSO and PNA are found to be very similar to Toronto’s, but results show that Montreal is also impacted by the NAO. Northward propagating cyclones are more frequent during -NAO, increasing the frequency of intense cyclones. Intense cyclones are also shown to be more frequent during -NAO.

Contrasting with Toronto and Montreal, winter cyclones passing through Halifax do show a stronger dependence to the NAO than to ENSO. The predominance of Atlantic cyclones in Halifax is increased during -NAO, decreasing the number of weak cyclones. For +NAO winters, more continental cyclones impact the city, with faster speed but weaker intensity. The PNA also influences Halifax’s cyclone activities, mainly during its negative phase, when cyclones are less frequent and predominantly propagate northeastward.

The most significant variability in St-John’s winter cyclone activities is observed during -NAO, when the dominance of Atlantic cyclones is increased. These cyclones are predominantly propagating northeastward, slower than usual, and tend to be
intense. During $+\text{NAO}$, the frequency of continental cyclones is increased across St-John’s, with faster propagation and weaker intensity. ENSO’s influence is shown to be limited, but as in other eastern Canadian cities, $-\text{PNA}$ is shown to be associated with a decreased cyclone frequency and weaker intensity over St-John’s.

The above findings provide additional insights on the North American cyclones, especially those passing through eastern Canadian cities. However, there are several issues and limitations which need to be addressed in future study. Firstly, overall results would be sensitive to the choice of variable (e.g., MSLP instead of 850-hPa relative vorticity) and the threshold values (e.g., 4 CVUs instead of 1 CVU used in this study). We however believe that the details would not change qualitative results although they could affect the results quantitatively, as well as their statistical significance. Secondly, the origin of cyclones cannot be directly translated as Nor’Easters or Alberta Clippers as used in meteorology, as these types of cyclones are defined by specific criteria, while those used in the present study are simply based on the region of the most explosive development along cyclone tracks. Thirdly, classification with respect to teleconnection patterns does not clearly isolate each teleconnection. For instance, the PNA index is not independent from the ENSO index. To isolate the impact of each teleconnection on cyclone activity, possible relationships between teleconnection indices should be removed. Lastly, the results presented in this study are based on the tracking of local 850-hPa vorticity maxima, which do not compare easily with potential damage of the cyclones to the population. Further studies are needed to assess how those groups correlate with observed weather systems, and how the discussed variations correlate with anomalous winds and weather.
Figure A.1: Distribution of winter (DJF) and summer (JJA) cyclones passing through Toronto, Montreal, Halifax and St-John’s, in propagation speed (color, in km/h) and direction. Bars extend toward the direction cyclones are coming from. Length of bars are proportional to the percentage of cyclones found in each category. Dotted circles indicate lengths equivalent to 5%, 10% and 15% of the cyclones.
Figure A.2: Propagation speed (color, in CVU) and direction distribution of winter (DJF) cyclones passing through Toronto during ENSO, NAO and PNA. Bars extend toward the direction cyclones are coming from. The length of bars are proportional to the % of cyclones found in each intensity category.

Figure A.3: Same as Fig. A.2, but for winter cyclones across Montreal.
Figure A.4: Same as Fig. A.2, but for winter cyclones across Halifax.

Figure A.5: Same as Fig. A.2, but for winter cyclones across St-John’s.
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