Trends and Variability of the Outdoor Skating Season in Canada during 1951-2005

By

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Abstract

Climate change affects a range of human activities, including one of Canada's prime sources of entertainment: ice skating. Whether done recreationally or as hockey, its outdoor component is heavily dependent on weather and climate. Based on information obtained from public works officials from various Canadian cities, I have established a meteorological criterion for the initiation of an outdoor skating season (OSS) as the last day in a sequence of the first three consecutive fall/winter days with a maximum temperature below -5 °C. In addition, I derive a proxy of the OSS length, defined as the total number of days with a maximum temperature below -5 °C after the OSS start date and before the start of March. Using these filters, I have extracted the start dates and the lengths of the OSS for each year during the fifty-five year period 1951-2005 from a comprehensive daily temperature dataset (Vincent et al., 2002). For each station, I created time series of both the OSS start dates and OSS lengths, and calculated the magnitude, sign and statistical significance of the slopes of the best-fit lines to each time series. In order to establish a relationship of the OSS with large-scale climate patterns, I grouped stations into six climatic regions. Depending on location, I then tested each region for correlation with the Pacific North-American teleconnection pattern (PNA) or the North Atlantic Oscillation (NAO), using a composite analysis method. Lastly, I removed the signal due to these climate fluctuations from the OSS start date and length trends in order to determine how much of the variability was caused by these interannual climate oscillations. The results of the study indicate that most stations in British Columbia and southwest Alberta, as well as these in the southern Ontario/Québec region have witnessed a progressively later onset of the OSS over time. The Prairies, northwest Canada, and some Maritime locales show the opposite trend, although the magnitudes of the slopes are smaller. Significance tests on the regression lines show that most of these trends are not significant at the 95% level. However, OSS start dates in western Canada are very well correlated with PNA patterns by happening later on the average whenever PNA is positive and more warm air is channeled towards the west coast; the OSS start dates in eastern Canada show a similar connection with the NAO. The OSS lengths exhibit different trends: five of the six regions show a decrease in OSS length with the only region having experienced a lengthening of the OSS being the Maritimes. The statistical significance of the OSS length slopes is much higher than that of OSS start slopes, and the correlation with the PNA or NAO is similar in both cases. After carrying out the last procedure (removal of the PNA and NAO signals from the OSS start date and length series), I found an increase in the new slopes and their significance for more than half of my geographic regions' OSS start date and length trends.

Résumé

Les changements climatiques ont un impact sur différents aspects de la société contemporaine, dont une des activités hivernales plus populaires au Canada: le patin à glace. Que ce soit pour pratiquer le hockey ou bien par pur plaisir, le patin à glace extérieur est grandement affecté par la météo et le climat. En me basant sur diverses informations fournies par les travaux publics de plusieurs villes canadiennes, j'ai établi un critère météorologique déterminant le début de la saison de patinage extérieur (SPE). Plus précisément, lorsque durant trois jours consécutifs de l'automne ou l'hiver la température maximale est inférieure à -5 °C, la SPE débutera lors de la troisième journée de cette séquence. De plus, j'ai dérivé une approximation de la longueur de la SPE comme étant le nombre total de jours dont la température est inférieure à -5 °C suivant le début de la SPE et précédant le début du mois de mars. Selon les définitions mentionnées précédemment, j'ai déterminé la date et la durée de la SPE pour chaque saison de patinage entre 1951 et 2005, à partir de la base de données complète des températures quotidiennes (Vincent et al., 2002). Pour chaque station météorologique de cet ensemble de données, j'ai construit une série temporelle de la SPE ainsi que de la longueur de la SPE. Ensuite, j'ai calculé la magnitude, le signe et la signification statistique de la pente de la droite de régression pour chaque série temporelle. En vue d'établir une connexion entre la SPE et les patrons climatiques à grande échelle, j'ai groupé les stations météorologiques selon six régions climatiques. Dépendamment de leurs locations respectives, j'ai testé chaque région soit au patron de téléconnexion Pacifique-nord-américain (PNA) ou à l'Oscillation Nord Atlantique (ONA) afin de trouver une possible corrélation entre les deux en utilisant la méthode d'analyse composée. Finalement, j'ai éliminé le signal causé par les fluctuations climatiques (le PNA ou l'ONA) du début et de la longueur de la SPE, ce qui permet de déterminer à quel point le PNA et l'ONA ont pu influencer ces deux paramètres. Les résultats de cette étude indiquent que la plupart des stations météorologiques de la Colombie-Britannique, le sud-ouest de l'Alberta, le sud-est de l'Ontario et du Québec ont connu, au cours de la période évaluée, une SPE plus tardive et de plus courte durée. En ce qui concerne les Prairies, le nord-ouest canadien et quelques régions des Provinces Maritimes, la situation inverse a été observée, bien que les magnitudes des changements soient plus faibles, c'est-à-dire que la SPE débute un peu plus tôt, mais le changement se produit moins rapidement est plus graduel. Les tests de signification sur la droite de régression démontrent que la plupart de ces tendances ne sont pas significatives à 95% de confiance. Néanmoins, dans l'ouest du Canada le début de la SPE est extrêmement bien corrélé avec le patron climatique PNA. Le début de la SPE se produit en moyenne plus tard lorsque le PNA est positif, indiquant un transport plus important d'air chaud vers la côte du Pacifique. De plus, dans l'Est du Canada, le début de la SPE montre une corrélation semblable avec

l’ONA. Par contre, la longueur de la SPE montre une tendance différente: dans cinq des six régions la longueur de la SPE a raccourci, la seule région dont la longueur de la SPE a augmenté étant les Provinces Maritimes. La signification statistique des pentes des droites de régression pour la longueur de la SPE sont beaucoup plus significatives que celle des pentes du début de la SPE. De plus, la corrélation avec le PNA et l’ONA est similaire dans les deux cas. Pendant la dernière procédure, j'ai enlevé les signaux du PNA et du NAO des séries temporelles du début et de la longueur de la SPE, et j'ai trouvé une augmentation dans les nouvelles pentes et dans les valeurs des intervalles de confiance pour plus de la moitié des cas.

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Acknowledgements

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1. Introduction

Ice skating as a sport is deeply ingrained in Canadian culture, a fact most probably due to the geography and climate of the country. Whether it is done recreationally or as hockey, it remains amongst the most popular winter activities in Canada. While indoor skating rinks are widely available even outside the winter season, it is generally believed that the outdoor rinks attract the greatest public interest, perhaps because the open air conditions provide a more natural feeling and a connection with the actual winter. Thus, outdoor rinks constitute a major form of social recreation in Canada, and their successful operation is crucial for maintaining overall public happiness and well being, good revenue and a long-standing tradition.

When located outside, skating rinks are greatly dependent on local weather and climate; consequently, the question of how climate change may impact outdoor rinks is of interest to many people in Canada. The projected continuation of global warming trends could significantly compromise outdoor ice rinks in the future, perhaps even to a point when atmospheric conditions become too mild for them to exist. Since ice, which constitutes the base of skating rinks, requires water temperature to be below freezing for it to form, this criterion may become increasingly difficult to achieve naturally in a warmer world. If winters indeed become too mild, outdoor rinks may become very difficult to maintain when it is warm even if the rinks are artificially cooled as they are in most of Toronto for example (City Rinks Toronto).

In view of the above concern, this study aims to determine, for the first time, the past temporal trends of the outdoor skating season (OSS) for all regions of Canada. The OSS is defined as the total number of days between the fall/winter opening of an outdoor ice rink and its closing in late winter/spring. For the fifty-five year period 1951-2005, I have investigated the fluctuations of two characteristics of the OSS: its start date and length. Using a substantiated definition of the OSS start date and OSS length (Section 1.3), as well as a modified dataset of daily surface air temperature data in Canada by Vincent et al. (2002) for 142 weather stations, I created time series of the historical changes in the OSS start date and OSS length for each station (Section 5.1). I calculated the trends in these time series, as well as their statistical significance. In Section 5.2, using a composite analysis method, I have determined the correlation between the OSS start dates and lengths for each region and two established large-scale climate patterns, namely the Pacific North American teleconnection pattern (PNA) and the North Atlantic Oscillation (NAO). In order to facilitate this procedure, I grouped stations into six geographic regions that are defined based on climatology, geographical proximity and results of the computation of OSS start dates and lengths. Due to the high significance of the correlation between the OSS start dates and lengths and the indices, I have also removed the corresponding climate fluctuation's signal from the OSS start dates and lengths (Section 5.3). Thus, I have come up with an "isolated" OSS start date and length time series that for most regions exhibits higher and more significant slopes than the original time series.

Throughout the remainder of the introduction, I provide general information on outdoor skating rinks, including the factors that influence their opening, closing and maintenance. This is followed by some related background climate information (Section 2) and a description of the data and methodology used (Sections 3 and 4). A discussion of the results shown in Section 5 is presented in Section 6. Finally, some concluding remarks along with possibilities for future work are addressed at the end (Section 7).

1.1. Standard Meteorological Factors: Temperature and Precipitation

There are many factors that influence the opening, maintenance, and closing of outdoor rinks, including both meteorological and non-meteorological factors. Amongst the most important of all are temperature and precipitation (including both any accumulated snow at the time of the ice rink creation as well as any precipitation falling upon an existing rink). Regarding the effects of temperature, it is intuitive that sub-zero conditions are needed for the formation of the ice underlying a rink. However, too cold a day does not necessarily imply better ice; temperatures in the range -5 to -10 °C are most conducive to proper ice formation (personal communication with officials at the city of Beaconsfield, Québec, 2010).

In addition, some snow accumulation at the location of the ice rink seems to aid the process of freezing the artificially added water on top of it. It also provides insulation from the potentially porous surface underneath, which may cause infiltration and loss of the poured water before it has frozen during the manned process of ice creation (personal communication with ice rink experts at the cities of Beaconsfield and Hampstead, Québec, 2010). However, since an outdoor rink can be initiated without any snow on the ground (albeit not as readily in certain circumstances such as when tennis courts are used as a venue), the precipitation factor is considered by rink managers to have less importance than air temperature, and for this reason it has been ignored in my computation of the OSS start dates and lengths. Lastly, any unseasonal liquid precipitation during the OSS can adversely affect the ice of a rink. Whenever the intensity and amount of the rain are significant, the operation of outdoor skating rinks can sometimes be prematurely interrupted. For simplicity, however, I have also not considered explicit interruption by rain in my calculation of the OSS lengths.

1.2. Other Factors

Other less critical factors that influence the existence of outdoor ice rinks include the cleanliness of the rinks and the intensity of the sunlight. For example, the addition of outside mud or other dark material atop the highly reflective ice surface can act to locally reduce the albedo of the rink and cause melting and cracking due to higher absorption of solar radiation. Also, the amount and intensity of sunlight can interfere with the ice rink creation (Friends of Dufferin Grove Park, Ontario, 2009). In such a case, even though the actual air temperature may be appropriate for building an ice base, if the insolation is relatively high as it is towards the end of winter, the formation of ice may be impeded. Although the insolation factor is of some importance especially towards the end of the OSS, it is also astronomically very predictable (City Rinks Toronto) and generally consistent over time; I have therefore not considered this as a contributor to the trends and variability in the length of the OSS.

In addition, certain factors not dependent on the weather seem to commonly interfere with the opening and closing dates of ice rinks. A lack of workforce or other pressing civic work can cause delays in the opening of a rink. For example, some cities may postpone the establishment of an outdoor rink by several weeks if more important issues are on the agenda of those cities (personal correspondence with the Public Works Department in the city of Montréal Ouest, Québec, 2010). Also, if for any other reason the popularity of a given rink diminishes over the season, an early closure can ensue.

Due to the uncertainty of the many non-meteorological factors that can affect the OSS start and length, I have come up with a definition of an ideal OSS, i.e. one, whose opening and closing dates would be dictated solely by surface air temperature. Comparisons of the OSS computed this way with recent actual OSS lengths in Toronto and Ottawa show that this is a very good assumption for that geographic area, and I assume it is also well applicable elsewhere. In addition, in continued studies aiming to predict the future of outdoor ice rinks, outside factors can be very difficult to anticipate.

1.3. Outdoor Skating Season Start and End Dates

Using information obtained by talking to various public works people in Canadian cities described in Section 3.1, I have come up with a definition of the OSS start date as *the last day in the sequence of the first three consecutive fall or winter days with a maximum temperature less than -5 °C*. This is the sole criterion used by most decision-makers when it comes to opening an outdoor ice rink, although some consider the minimum temperature as well, which would ideally be no less than -10 °C for an ideal rate of water freeze-up (personal communication with the City of Beaconsfield, Québec, 2010). Some officials use the same maximum temperature criterion but during four or five days, rather than three. Since many well built ice rinks are created over three days of maximum temperature below -5 °C, I saw no reason to extend this criterion to four or five days. In addition, when computing the OSS start dates from a historic temperature dataset, the chance of having a continuous series of days under -5 °C decreases greatly when increasing the number of cold days beyond three, and doing this may result in computationally ignoring otherwise suitable conditions for OSS initiation (e.g., three consecutive days of maximum temperature under -5 °C and a fourth at -4.9 °C).

Generally, the end of the outdoor skating season is much harder to quantify meteorologically than the start. Although similar atmospheric factors are in play for both, the conditions for closing seem less clear cut, mostly as a result of the chemical build-up of the ice surface. Once the ice surface is in place, even as temperatures begin to rise in the spring, it may be physically harder to break the already created strong hydrogen bonds between water molecules in the ice lattice. It is impossible to determine at precisely what air temperature the ice surface becomes unsafe for skating because the strength of the ice depends on such factors as how often and when the water has been laid in the process of creation. On the other hand, the opening of a rink, being a one-time process, is easier to define meteorologically. Therefore, the distinct processes involved in the creation and in the dismantling of an outdoor ice rink affect the establishment of clear-cut meteorological conditions for opening and closing differently. Experience shows that many Canadian cities make decisions to open their outdoor rinks following an atmospheric cue, whereas they close them on a predefined date that is climatologically established to be too mild for safe ice skating. It is for this reason that only trends in the start and not the end of the OSS have been investigated in this study. However, in order to compensate for the lack of investigation of the OSS end dates, I have come up with a proxy of the OSS length, which in combination with the already computed OSS start dates, enables us to make inferences about the meteorological end of the OSS.

1.4. Outdoor Skating Season Length

The true OSS length is defined as the total number of days between the OSS start date and the OSS end date. However, for the aforementioned reasons the end date cannot be precisely known; hence I have defined a proxy for the OSS length as the total number of viable ice flooding days (those that have a maximum temperature below -5 °C) between the OSS start date and before the start of March. This should be a good approximation for most outdoor rinks in southern Canada since all major mid-latitude cities rarely if ever continue maintaining open-air rinks beyond the end of February.

This definition of OSS length is obviously flawed for northern Canada where ice on the ground can persist through the first half of the year or even more. However, due to the relatively low number of stations there and the difficulties in defining a borderline between the south and the north, I use the above definition for all Canadian outdoor rinks. Moreover, because of the nature of my investigation, namely one of the trends and variability of the OSS, knowledge of the exact OSS length is not crucial and can be inferred using this definition. This approximation of OSS length is a reasonable one because the duration of the seasonal existence of an outdoor ice rink depends mostly on the durability of its ice base, which in turn depends on the number of cold nights during which rink watering and subsequent freezing were possible during a given season. The proxy OSS length thus appears to be a good indicator of the viability of the skating season, and is therefore assumed here to be well-correlated to the actual OSS length.

2. Background

2.1 Literature Review

There are no published studies on observed trends of the outdoor skating season in Canada, nor are there any predictions of future changes. In addition, there has been no formal investigation of the specific meteorological factors affecting local OSS start and end dates, even though there is much common knowledge available on that topic. Most of the literature that concerns related types of icy surfaces generally falls into one of the following three categories, some of which are partially helpful to my inquiry:

1) *Papers concerning the historic changes of ice-on and ice-off dates of a specific natural or human-made water body.* Generally, these papers statistically analyse the temporal shifts of the ice-free period of rivers, lakes, seas, ice roads and other ice surfaces, based on historic on-site observations. Often, accompanying such studies is an examination of the mean synoptic-scale conditions that may affect the dates of freezing and thawing of the specific water body. Examples of such publications include the study of the past changes in the opening and closing dates of the Tulita-Norman Wells ice road in the Northwest Territories (Knowland et al., 2010), the effects of temperature changes on the ice-in dates of North American lakes (Williams et al., 2004) and the past trends in lake and river ice cover in the Northern Hemisphere (Magnuson et al., 2000).

2) *Papers dealing with improved methods for the creation and maintenance of indoor or outdoor skating surfaces*. These studies are technical in nature and are often patented due to their widespread applicability. Generally, such publications are aimed at individuals or

organizations in charge of such surfaces who often seek cheap and efficient methods for the preparation of skating surfaces. Examples include Harold Walker's improved method for the prevention of water seepage in the process of creating ice rinks by using a water-dispersible, water-swellable polymers in non-level surfaces (Walker, 1966) and Bruce Kovach's method for freezing salt water in an excavated ground using a pump and a sprayer (Kovach, 1984). Most ice rinks today are prepared through the methods suggested by studies of this category. There exist also other documentations of necessary conditions for good movement on ice surfaces such as that of snowmobiling on winter roads (Lafrance, 2007), which are widely used in northern Canada.

3) *Publications on the safety of indoor or outdoor ice skating*. The majority of these papers examine the effects of skating rinks on human health. Most commonly, health can be compromised through contusions and fractures as a result of falling on the hard icy ground. More recently, the effects of carbon monoxide and nitrogen dioxide exposures at indoor skating rinks have been studied (Allred et al., 1989; Hedberg et al., 1989, Lee et al., 1994). Unusually high exposures to these gases can result from discharged air pollutants by the fuel-powered ice resurfacing equipment. At high concentrations, these contaminants are detrimental to health, especially in enclosed ice rinks, where ventilation is poor (Lee et al., 1994). Similarly for artificially-cooled outdoor skating rinks, concentrations of CO and NO_2 may be higher in the vicinity of the rink, although it is likely that any wind may locally reduce their levels by dispersing their molecules.

Because my study of the trends and variability of the Canadian OSS is, to the best of my knowledge, the first of its kind, the published literature is only partially useful in my research. For instance, I have not been able to find a mention of a widely-used meteorological criterion that can be used for the opening, maintenance or closing of outdoor skating rinks. Since there is a lack of such information, the next most useful studies to look at are these of the freezing and thawing of natural water bodies, containing information on the associated meteorological conditions. However, these cannot be readily applied for outdoor skating rinks because of the different nature of these ice surfaces. For example, the differences in the dimensions, salinity and other ambient factors cause the water in outdoor ice rinks to freeze and thaw at temperatures that are not necessarily the same for these phase changes elsewhere.

Even though meteorological conditions vary for the ice-on and ice-off dates for different water bodies, it is expected that the temporal trends in the ice-covered and ice-free periods of different water bodies of the same locale to be similar. For instance, the observed change in the ice-off date over time at western Ontario’s Lake Wabigoon is similar to that of the OSS length change at a nearby station, Sioux Lookout, Ontario for the period 1951-2005 computed in this study (Section 5.1). Using annual ice-off data for Lake Wabigoon from NatureWatch, I have plotted this on one graph along with Sioux Lookout’s OSS length changes for the same period for comparison in Fig. 2.1 as anomalies from their means.

While the lake ice-off instant is represented by one date, changes in the OSS length can result from shifts in two dates, the OSS start date and OSS end date. This might be the reason why the OSS length anomalies (green line in Fig. 2.1) have larger variability and slope than those of the ice-off anomalies. Importantly, however, the interannual variability and the overall change appear to be similar for both phenomena.

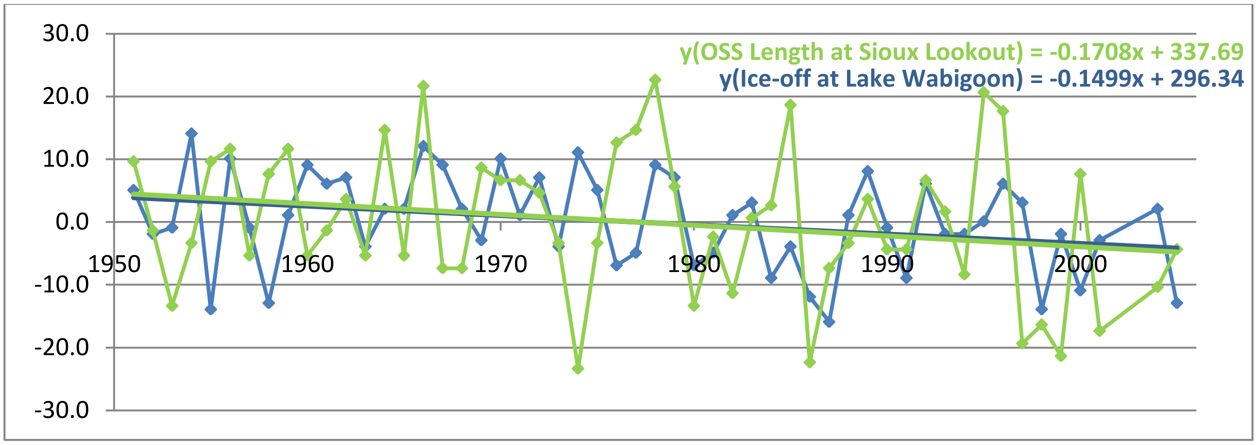


Fig. 2.1 Time series of the ice-off date anomalies (in days) at Lake Wabigoon, Ontario (blue series, data from NatureWatch's IceWatch division) and OSS length anomalies (in days) at nearby Sioux Lookout, Ontario (green series, data computed in Section 5.1 of this thesis) for 1951-2005. Best-fit lines are plotted for each, with respective equations shown at the top.

2.2 Background Climate Information

Although the physical mechanisms behind the changes in the Canadian OSS have not been studied, it is intuitive to examine the factors affecting temperature changes in Canada. This is pertinent because the latter are firmly connected with the OSS, as a result of the OSS start dates and OSS lengths being defined here solely in terms of temperature. Furthermore, because my OSS start date and length definitions require an occurrence of three consecutive days of lower temperatures, it should be expected that locally, the OSS is closely associated with the onset of cold waves. That is, the first several persistently cold (-5 °C or lower) days in a year should show similar interannual variability as that of the OSS start dates and perhaps OSS lengths at the same locale. Because the OSS length has an additional criterion regarding the number of cold days in the winter, changes in average Canadian winter temperatures would probably be highly correlated with OSS length changes.

Studies indicate that during the last fifty years of the past century, the frequency, duration and intensity of winter cold spells have decreased in most of Canada, except in eastern Canada (e.g., Shabbar and Bonsal, 2003). Also, the relative severity of winters as measured by changes in the minimum and maximum temperature has weakened in all of Canada except in northeast Canada, for the same period (Zhang et al., 2010). Therefore, one would also expect the OSS to have shortened in western Canada and lengthened in eastern Canada during this period. This is indeed the case, as evidenced by my computations of the Canadian OSS length trends presented later in this thesis (Fig. 5.2).

As is the case for most synoptic-scale features in North America, the aforementioned OSS-related phenomena are known to be significantly impacted by large-scale climate patterns. Therefore, I have attempted to establish whether the OSS itself is related to these patterns. In essence, I have sought to find correlations between the occurrences of both the OSS start dates (similar to the first cold wave in a year) and the OSS lengths (similar to the overall coldness of a winter) and two large-scale climate patterns in Canada: the Pacific North-American (PNA) teleconnection pattern and the North Atlantic Oscillation (NAO). Reasons for choosing these two climate patterns are outlined below.

The PNA index, which is non-dimensional, is defined as the difference between the sum of the standardized 500 hPa geopotential height values of the Hawaiian and Alberta highs, and the sum of the same variable of the Aleutian and Southeast U.S. lows:

$$\textbf{PNA} = 0.25^*(Z_{Hawaii}+Z_{Alberta})-(Z_{Aleutian}+Z_{Southeast})$$

where Z denotes the standardized 500 hPa geopotential height values at the indexed location, which corresponds to a precise geographic location presented by Wallace and Gutzler (1981).

The PNA pattern is known to arise as the atmospheric response to propagating tropical Pacific sea surface temperature perturbations associated with El Niño/Southern Oscillation (ENSO) events. Thus, the PNA and the ENSO are well-correlated (e.g., van Loon and Madden, 1981; Renwick and Wallace, 1996; Bonsal et al., 2006). As such, the PNA teleconnection pattern is considered a major determinant of western North American climate due to its geographical proximity. As a result, I have looked for possible connections between interannual variability of the PNA and the changes in the OSS start dates and OSS lengths in the western half of Canada (precise regions defined in Section 4.2).

Fig. 2.2 shows the manifestation of the PNA in western North America as 700 hPa height anomalies as originally plotted by Dickson and Namias (1976). During a positive phase of the PNA (a), warm air is channelled into western Canada from the south by means of the counter-clockwise circulation of the Aleutian low and the clockwise circulation of the Alberta high. This results in a northward shift of local isotherms. This, in turn, translates into later OSS start dates, and perhaps shorter OSS lengths in that region. Alternatively, when the PNA is in negative mode (b), less warm air advection would occur in western Canada, causing earlier OSS start dates, and maybe longer OSS's.

Similarly, OSS start dates and OSS lengths in eastern Canada are examined for connections with the NAO, which is known to impact climate in that region. The NAO index (non-dimensional) is defined as the difference in standardized mean sea-level pressures between stations in Iceland and the Azores:

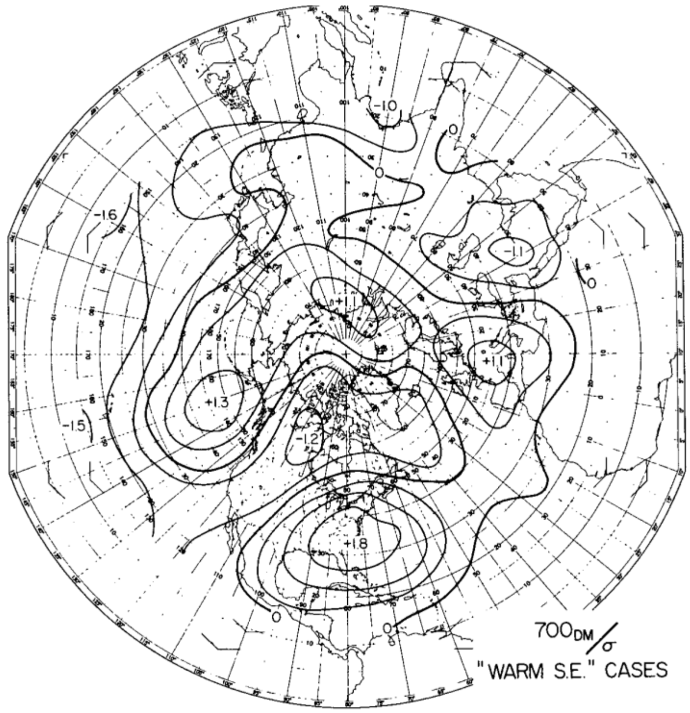
$$\mathbf{NAO = P_{Iceland} - P_{Azores}}$$

where P denotes the standardized mean sea-level pressure at the given location; for Iceland, the cities of Akureyri or Stykkisholmur are used, while for the Azores, the preferred station is Ponta Delgada (Jones et al., 1997; Hurrell, 1995).

The variation of the NAO indicates how climate in Northeast Canada can be affected due to the fact that this part of the country protrudes into the Atlantic Ocean. This climate pattern can also affect more inland eastern regions as well, and thus the OSS in these regions is in addition examined in relation to the NAO. Walker (1924) points out that a greater pressure difference between Iceland and the Azores (positive NAO) results in lower temperatures in northeastern Canada as a result of a strong meridional advection of cold air into Nunavut from the north. It is therefore expected that the northeast part of the country would also have a longer OSS during the positive phase of the NAO (Fig. 2.3). Conversely, when the NAO is negative, the warmer conditions in northeastern Canada should translate into shorter OSS's. My analyses on the OSS trends in that region show that this association is very well supported in northeast Canada. However, the opposite is true in southeast Canada, where cold Arctic air cannot move in as easily as a result of the strong circulation of the Azores High which prevents further southward cold air advection.

For reference and comparison purposes, the temporal evolution of the two indices discussed here has been plotted for the same period for which the OSS start dates and OSS

(a)



(b)

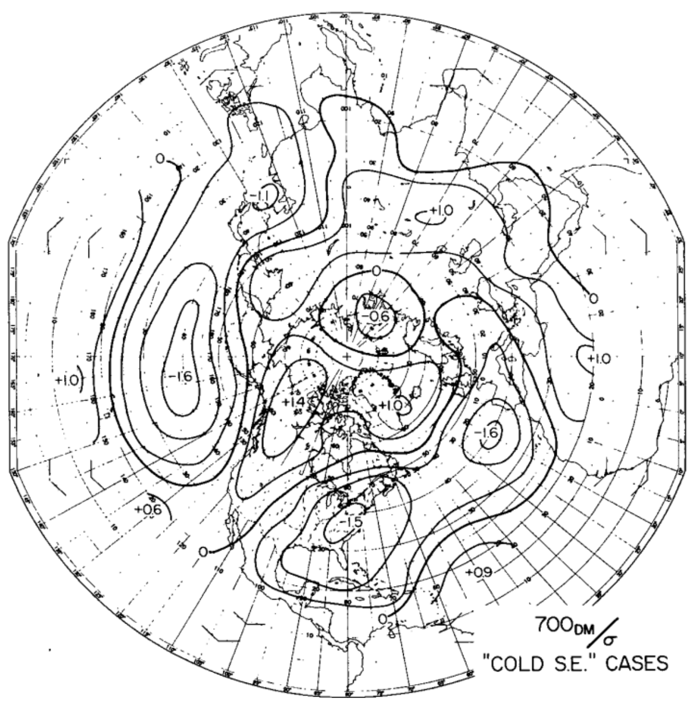


Fig. 2.2 Mean distribution of standardized 700 hPa height anomalies (700 hPa height anomaly divided by the standard deviation) during a positive (a) and a negative (b) PNA phase during 1948-1974. The warm/cold S.E. cases notation refers to conditions associated with the height anomaly over the southeastern United States as used by the authors (Adopted from Dickson and Namias, 1976).

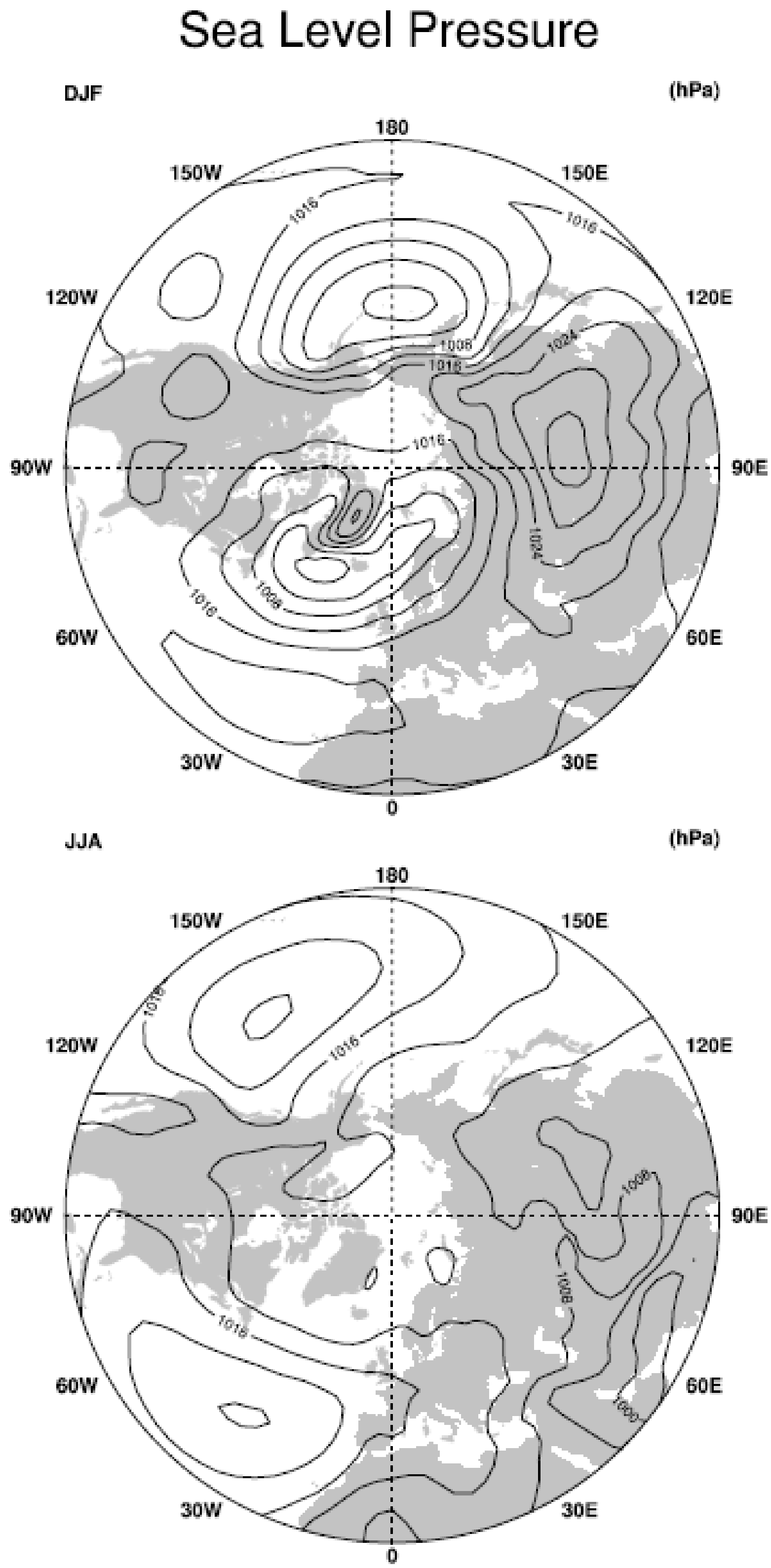


Fig. 2.3 Mean sea level pressure for (top) boreal winter (December-February) and (bottom) boreal summer (June-August) during a positive NAO phase. The data come from the NCEP/NCAR reanalysis project over 1958-2001 [Kalnay et al., 1996], and the contour increment is 4 hPa. (Taken from Hurrell et al., 2003)

lengths are studied, 1951-2005. Historic changes in the PNA index are displayed in Fig. 2.4a and the same is done in Fig. 2.5a for the NAO. Note that the indices are not annually-averaged but represent a mean of the months of October, November and December. This is because I have empirically determined that the strongest connection of these climate patterns with OSS start dates and, less intuitively, with OSS lengths, is observed during these three months (Section 4.2). For reference, the standard winter (December-January-February) averaged indices are shown as well (Figs. 2.4b and 2.5b for the PNA and NAO respectively).

Although changes the PNA and the NAO climate patterns are major influences on climate variability in Canada, local effects often overshadow the impacts of these large-scale forcings, and they do so on a shorter temporal scale. For instance, some of the stations considered in this study are located in micro-climate zones, which result in seemingly aberrant spatial distributions of OSS start date and length trends (Fig. 5.2). This is usually the case for stations located in deep river valleys, on isolated hills or on ocean-protruding coasts.

The large daily and annual ranges of the temperatures observed in the Prairies are a local example of regional climatic effects on the OSS. Because of the aforementioned association between general temperatures and the OSS start dates and lengths, it should be expected that the OSS start dates calculated in the Prairies would occur climatologically earlier than these in British Columbia or Québec, for example. Similarly, the Prairies OSS should be relatively longer for the same reason. The opposite should be true for the Maritimes, where daily and annual temperature ranges are small. Thus, one would expect that stations in Nova

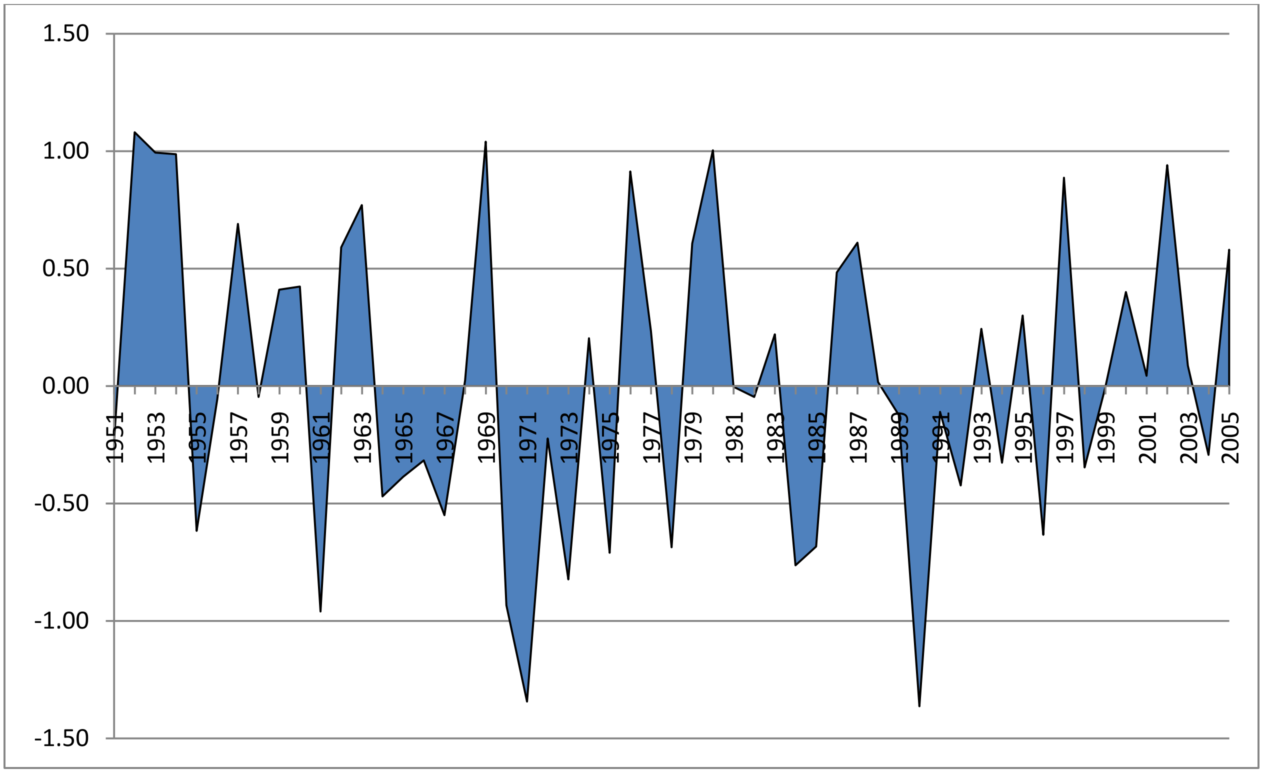


Fig. 2.4 (a) Changes in the October-November-December averaged PNA index for the period 1951-2005

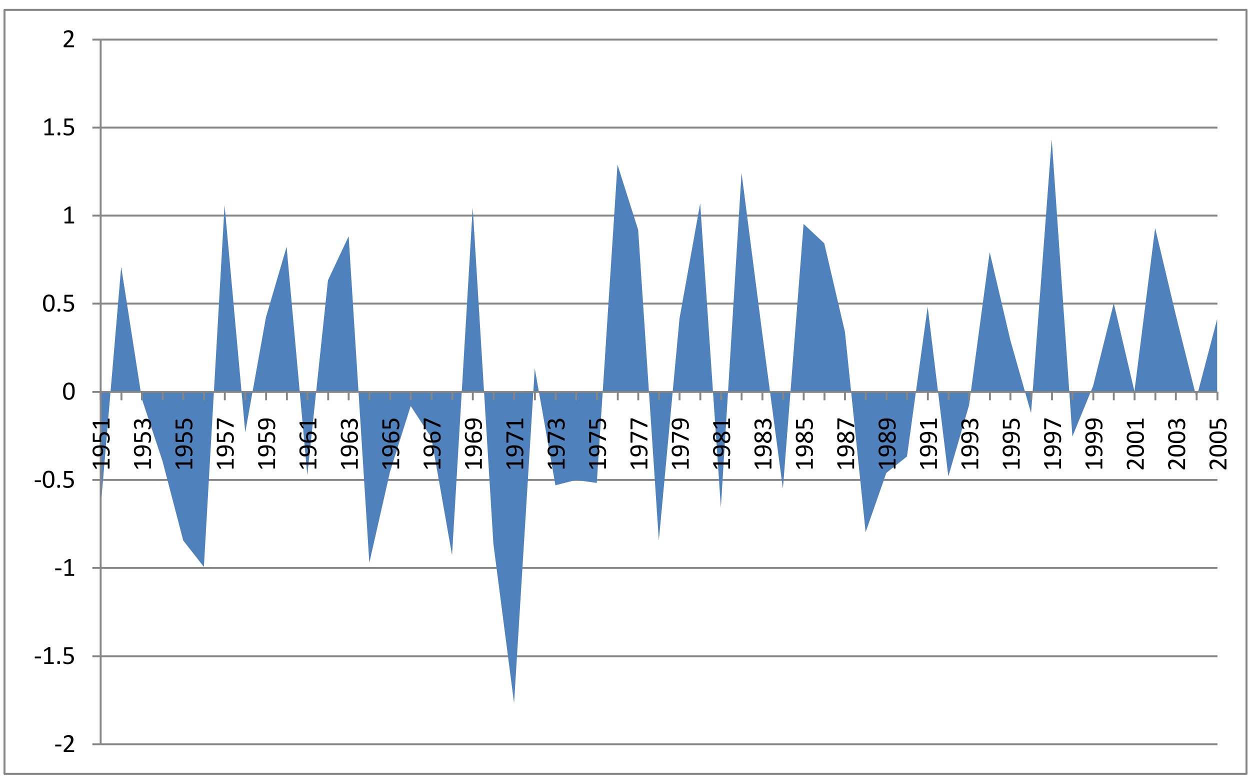


Fig. 2.4 (b) Changes in the December-January-February averaged PNA index for the period 1951-2005

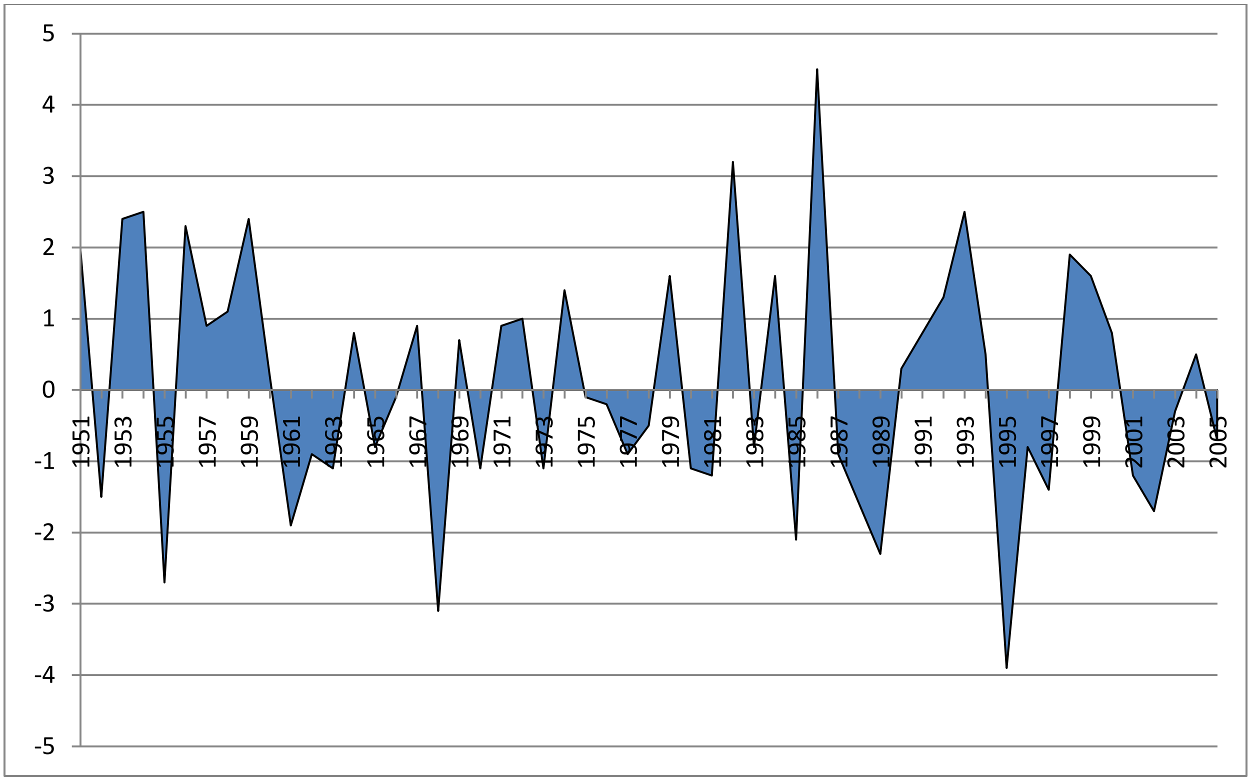


Fig. 2.5 (a) Changes in the October-November-December averaged NAO index for the period 1951-2005

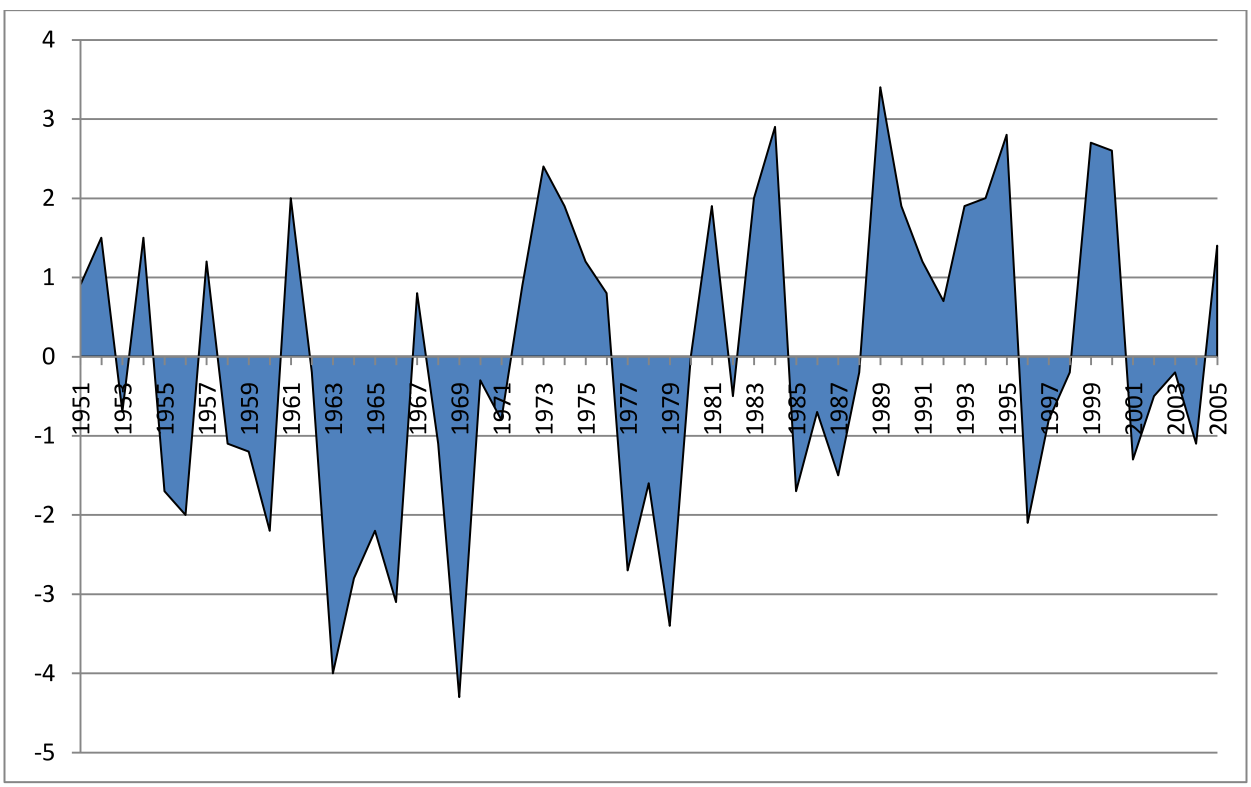


Fig. 2.5 (b) Changes in the December-January-February averaged NAO index for the period 1951-2005

Scotia and Newfoundland would have relatively later OSS start dates and relatively shorter OSS's.

A distinct wet maritime climate regime characterises the areas windward of the Coast Mountains in western Canada. The climate in places such as the Queen Charlotte Islands, Vancouver Island and the Vancouver metropolitan area is so mild that maximum temperatures rarely dip below freezing even during the coldest months. The lack of OSS in western British Columbia is confirmed by the fact that the cities of Victoria and Vancouver do not maintain any naturally-cooled open-air skating surfaces except at few nearby high altitude locations.

Lastly, northern Canada, with its harsher climate, is expected to have a much longer outdoor skating time span. Depending on location, certain regions often witness below freezing maximum temperatures for more than half of the year. Although the North is sparsely populated, any created outdoor skating surfaces there could persist for many months at a time.

The results presented in Section 5 confirm the above qualitative discussion on the possible connection between the Canadian OSS and large-scale climate patterns in the proximity of North America, as well as that on the local effects on air temperatures manifested as OSS start dates and OSS lengths.

3. Data

3.1. Personal Communication with Ice Rink Experts

For the purpose of establishing the OSS start date criterion described in Section 1.3, I have contacted various people who are in one way or another related to the control and maintenance of outdoor ice rinks. I picked major Canadian cities in different regions in order to account for possible geographic differences in OSS definitions. Also, several municipalities in Montréal were contacted because of their physical proximity to me and potential for personal observations on their outdoor ice rinks. In most cases, the people who responded were officials at public works or parks and recreation departments of different Canadian cities. I asked each source contacted the following two questions:

1. What are the most important meteorological and non-meteorological conditions you use to initiate and to terminate an outdoor ice skating season?
2. Do you have a record of past opening or closing dates of your outdoor ice rinks?

If either of the questions were answered, I could then more easily define the OSS. For instance, I could directly get the criteria used for the opening of outdoor ice rinks and use these to compute the OSS start dates for each location based on historical temperature observations. Alternatively, an archive of past openings could be used to extrapolate the OSS opening condition by analogue with actual daily temperature data. I received mixed responses on the first question and only negative responses on the second question. The results of this inquiry are summarized in Table 3.1 below.

Other sources such as people who maintain other types of outdoor ice skating surfaces (e.g., backyard ice rinks, frozen lakes, the Rideau Canal) were contacted informally as well, but I received no definitive response on what are proper atmospheric conditions affecting the creation or the dismantling of any outdoor ice surface. As a result, I have decided to utilize the criteria used by the towns of Hampstead and Beaconsfield since they were the only solid answers I obtained.

Montréal	QC	Data unavailable
Montréal Ouest	QC	Data unavailable
Beaconsfield	QC	To open: 4-5 days of max. T. below -5 °C, snow accumulation desirable. To close: depends on how cold the winter had been
Hampstead	QC	To open: 3 days of max. T. below -5 °C, no sunlight. To close: no information available
Pointe-Claire	QC	Data unavailable
Dorval	QC	No response
Westmount	QC	No response
Ottawa	ON	Data unavailable, although 10 consecutive days of max. T. below -10 °C used for the Rideau Canal
Fredericton	NB	No response
Edmonton	AB	Data unavailable
Calgary	AB	Data unavailable
Winnipeg	MB	No response
Regina	SK	Tentative season: Dec. 13 - Feb. 20; do not open or close based on atmospheric conditions
Saskatoon	SK	Open on Dec. 11 tentatively, not based on atmospheric conditions

Table 3.1. Summary of information obtained from public works or parks and recreation departments of various Canadian cities. Dates or meteorological conditions refer to the opening and closing of the outdoor skating rink(s) in these cities, and not any other types of ice skating surfaces these cities may operate.

3.2. Daily Maximum Air Temperature Dataset

This study is based on the homogenized daily surface air temperature dataset developed by the Meteorological Service of Canada. It has been corrected for non-climatic step variations such as those caused by station relocation, changes in instrumentation or nearby vegetation growth (Vincent et al., 2002). The dataset consists of maximum and minimum surface air temperature data for 210 relatively evenly distributed Canadian weather stations, collected over the past century or so; I have shortened this period to 1951-2005 for the reasons given below. The modified dataset I have used excluded stations which became operational after 1950 (Turner and Gyakum, 2010). Also, due to the nature of my inquiry, I have only utilized the maximum temperature part of the data, and finally, I have decreased the total number of stations to 142 (Fig. 4.1) for the following reasons.

First, whenever a missing temperature resulted in a miscalculation of the OSS start or length, the corresponding erroneous value has been ignored and treated as if that year was missing. This may be obvious if for a given year a station lacks data for the months of November, December, and January, in which case the OSS start could wrongly be placed as the first occurrence of three consecutive days under -5 °C in February when in reality that could have happened in the previous months. In other cases, interference of missing data may be harder to detect, for which purpose I performed a detailed data quality check on the whole data set. This included manual removal of stations that had years with significant gaps in the data (five or more consecutive full years of missing data), as well as elimination of any computed OSS starts and lengths that fell beyond three standard deviations of the mean for that station. If any station had as a result of the above process more than 25% of missing years of OSS starts/lengths, I treated it as having not enough data for the establishment of meaningful trends and therefore removed it from consideration. It should be noted that missing values perhaps affect the calculation of the OSS lengths more than they do the OSS start dates because of the additional factor imposed in the computation of the OSS lengths (i.e., not just an occurrence of three consecutive days below -5 °C, but also the need to count the number of cold days after the start date). However, since I have minimized the effects of missing data through the above methods, I expect that there would be little if any misrepresentation of the actual OSS.

Second, I have ignored several stations in western British Columbia since winters in that province are relatively mild and rarely if ever satisfy the conditions for opening and maintaining outdoor rinks. In reality, there exist no low-altitude outdoor rinks in places such as Vancouver Island and the Vancouver metropolitan area. Lastly, for the purpose of having a common time period for all stations, I discarded stations which had records beginning after 1951.

3.3. Climate Indices Data

For the establishment of connections between the OSS and large-scale climate patterns, I used PNA and NAO index data. The PNA dataset includes monthly values of the PNA index since 1948 computed by the Joint Institute for the Study of the Atmosphere and Ocean based on the formula provided by Wallace and Gutzler (1981). I have created three-month means of these data, using the October-November-December yearly averages. Data for the NAO index is based on the three-month seasonal computations of the NAO index by Hurrell (1995) since 1865. For both indices, I used only the data for the period of interest, 1951-2005.

4. Methodology

4.1. Trends in the OSS Start Dates and OSS Lengths

I began by calculating the OSS start dates and OSS lengths for each year at each station on the quality-checked dataset. I then created time series of both OSS start dates and OSS lengths for each station and calculated the slopes of the best-fit regression lines. I used a ordinary least squares linear regression test (R programming language) to determine which of these slopes were significant at the 95% level.

All calculations of the OSS start date are based on the criterion of the first three consecutive days of maximum daily air temperature below -5 °C. Since this rule is not well-established in literature, I also carried out computations based on other criteria. Thus, I have computed the trends in the OSS start dates and OSS lengths using combinations of the following criteria for the number of consecutive days and the maximum temperature: 3 days, 5 days, 10 days and 0, -5, -10 °C. Corroborations of the validity of the 3 days of -5 °C combination by several ice rink experts has prompted me to present only the results based on this particular condition. I expect this definition of the ideal OSS start date to be the best representation of the opening dates of the actual season. Results of all computations were nonetheless very similar as a whole with minor differences among individual station slopes.

4.2. Correlations with Large-scale Climate Oscillations: Composite Analysis

In order to establish whether the OSS trends might be due to large-scale climate oscillations, I have performed a composite analysis method to investigate possible connections between variations in OSS start dates and lengths in western stations and interannual fluctuations in the PNA, and similarly for eastern stations and the NAO.

For this purpose, I grouped stations into six climatic regions. The areas included in each region are described below and a map showing the boundaries of the regions is provided in Fig. 4.1 (Alert, Nunavut and a few stations in Newfoundland and Labrador have been ignored due to climatic incompatibility with any one region).

1. *Southwest Canada* (interior and eastern British Columbia, southwest Alberta)
2. *Prairies* (eastern and northern Alberta, Saskatchewan, Manitoba, western Ontario)
3. *Northwest Canada* (Yukon Territory, Northwest Territories, western Nunavut)
4. *Central Canada* (southern and eastern Ontario/southern Québec/New Brunswick)
5. *Maritimes* (Nova Scotia, Prince Edward Island, southern Newfoundland)
6. *Northeast Canada* (northern Québec, eastern Nunavut)

The definitions of these six regions are arbitrarily based on existing Canadian climate zones, geographical proximities and similarities between already determined trends in the OSS start dates and lengths. For the last reason, it is expected that the OSS across any one region would not change significantly, i.e., these OSS zones would be homogenous. Notwithstanding the existence of numerous microclimate regimes that may affect the placement of stations into one region or another, I have attempted to find the best definition of regional boundaries by considering many factors at once. Needless to say, this semi-arbitrary number of regions could be a misrepresentation of the actual climes across Canada, especially in the northern parts of the country where the low density of stations precludes scientists from studying local climates in depth. For this purpose, I have performed the analyses using several different definitions of the regions to determine the most coherent set.

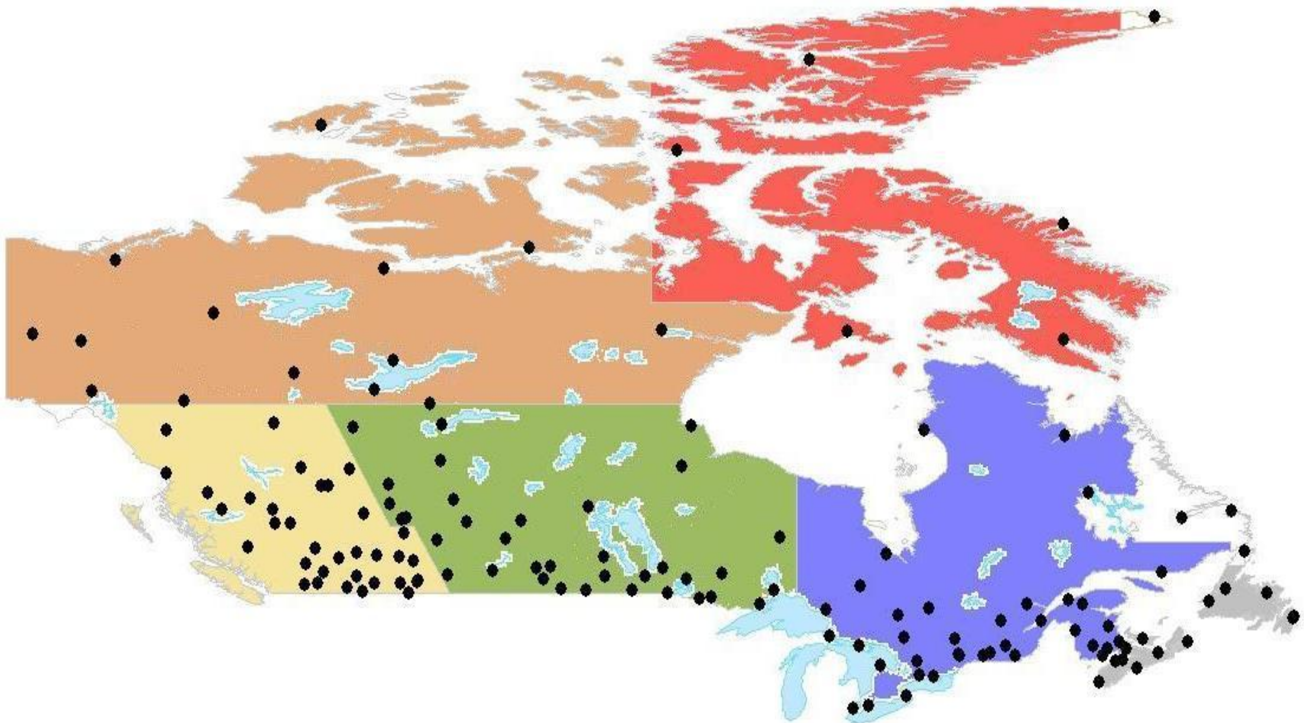


Fig. 4.1 A map of the six OSS regions defined in this study. Solid dots represent the 142 stations used in this study. Western regions include Southwest (yellow), Prairies (green) and Northwest (brown). Eastern regions are Central (blue), Maritimes (grey) and Northeast (red). Parts of Newfoundland and Labrador and Nunavut have been excluded from consideration due to incompatibility with other regions and are thus not coloured.

Next, I spatially averaged the OSS start dates and lengths over each region and then statistically examined the results on a regional basis. The years whose values of OSS start date or length fell outside one standard deviation of the mean for that region were labelled as early or late composites for the OSS start date, and short or long composites for the OSS length. For each of these extreme years, I noted the values of the NAO and PNA indices averaged over

October, November and December so that each region had four resulting mean index values (PNA or NAO depending on location) corresponding to early, late, short and long composites. The first three (western) regions of the list were correlated against PNA index values, whereas the last (eastern) three were correlated against NAO index values. Based on empirical trials, I chose the three months (October, November and December) of the index values because they exhibited the strongest connection with the OSS start dates and lengths among any other combination of months, which is most probably a result of the fact that these months correspond to the time of the year when the OSS start date occurs for most regions. The resulting composite analysis allows us to examine the signs and magnitudes of the PNA/NAO indices during extreme OSS years and to infer the effect of these climate oscillations on interannual variability in the OSS records. For each region, I have plotted the linear models of the relationship between the OSS start dates/lengths and the corresponding climate oscillation, including the equation of the relationship and the corresponding p-value.

4.3. Removal of the PNA or NAO signal from the OSS Start Dates and OSS Lengths

Due to the high statistical significance of the correlations between climate indices and OSS start dates and lengths, I removed the part of the signal in the OSS trends that was caused by large-scale climate patterns. This yielded what I call an “isolated” OSS trend. I have empirically shown that this method results in an increase of the slopes and their significance for most regions.

To calculate the isolated OSS trend, I subtracted the regression line of the time series between PNA or NAO indices and the anomalies in the OSS start dates and lengths for a given region from that region’s original OSS start dates and length anomalies. In other words, I removed the part of the signal caused by the corresponding climate fluctuation, yielding a time series free of PNA or NAO effects. I calculated the slopes and statistical significance of the new time series and compared these to the original results.

5. Results

5.1. Computation of 1951-2005 OSS Start Dates and OSS Lengths

For each station, I have created time series of both the OSS start date and OSS length anomalies, and computed the best-fit line and its p-value. The same analysis has also been performed for the annual data spatially averaged over the geographic regions defined in Section 4.2. Shown in Fig. 5.1 are the time series plots of the anomalies of the OSS start date and OSS length of each of the six regions. These time series are the primary result of this thesis because they should closely resemble the actual OSS changes during 1951-2005.

First, it should be noted that if general cooling or warming trends are to be prescribed to the OSS start date and OSS length anomalies, they would each be associated with a different sign of the slope of the best-fit line. For example, an overall warming trend would correspond to a progressively later start date of the OSS over time, namely a positive sign of the regression line slope of that anomaly time series. The same warming trend could be responsible for the other characteristic examined here, the OSS length, in which case the number of viable skating days would decrease over time, resulting in a decrease of the OSS length. This yields a negative slope for the OSS length anomalies, in contrast to the positive one of the OSS start best-fit line. Thus, the same warming, if it affects both the OSS start date and OSS length, corresponds to slopes of opposite sign of the two OSS characteristics' best-fit lines in their time series.

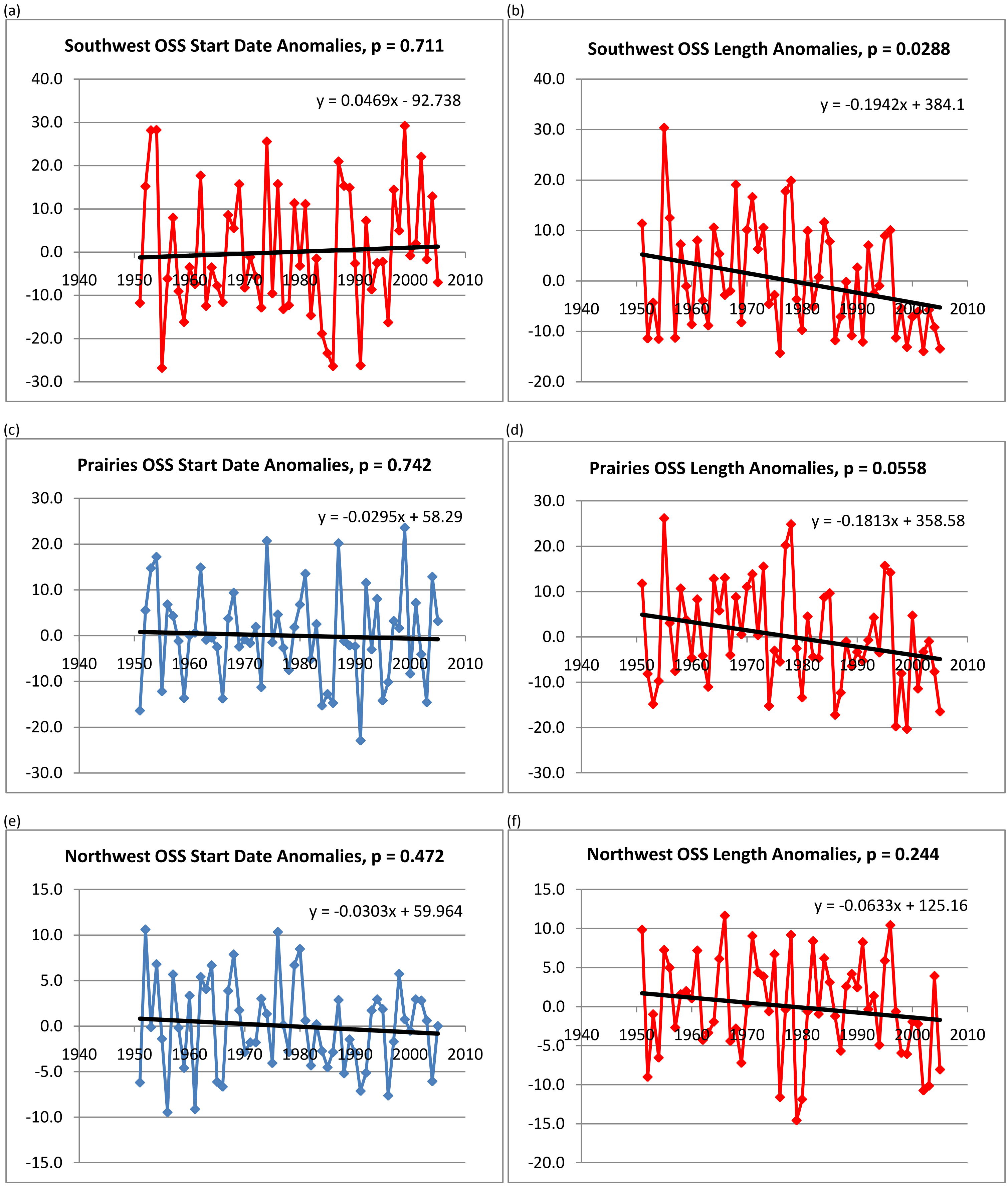
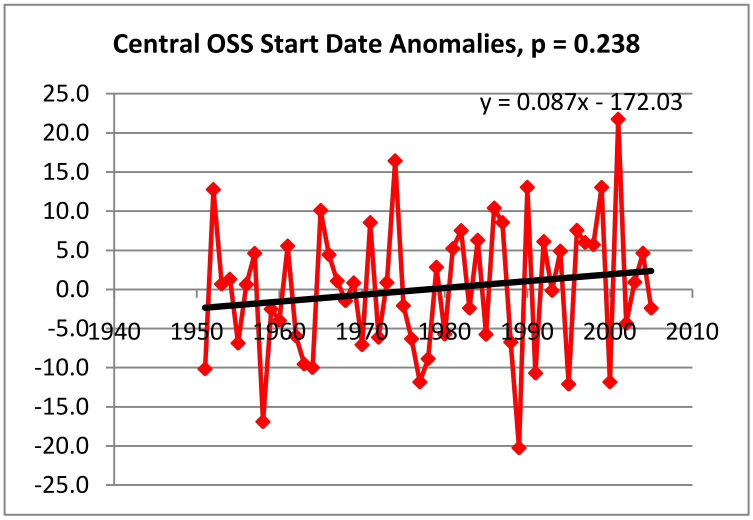
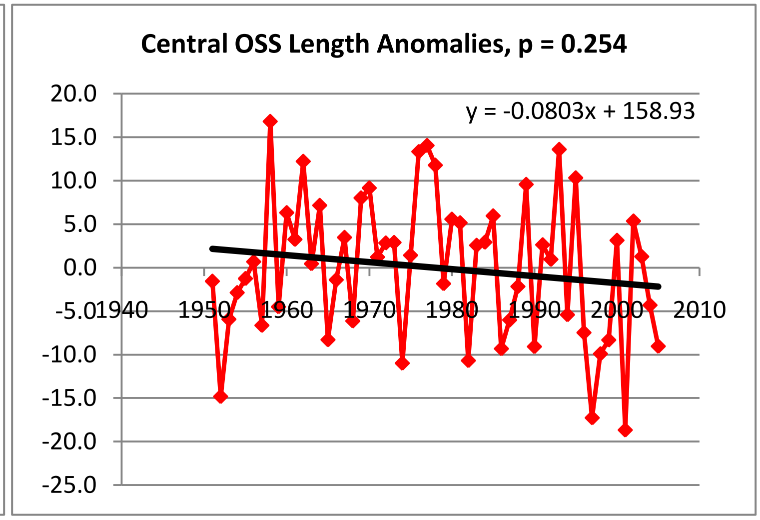


Fig. 5.1 Time series of the OSS start date (left) and OSS length (right) anomalies for the data averaged over each of the three western regions defined in this study, (a)-(f). Vertical axes represent the OSS start date or OSS length anomaly in days, while horizontal axes show time in units of years. Each point on the graphs represents the anomaly corresponding to the given year with the colour of the line connecting the points showing the nature of the overall trend (blue for cooling, red for warming). The solid black line is the best-fit regression line with its equation shown at the top right corner. The p-value at the top indicates the probability that the slope of the best-fit line could be obtained by chance (generally, $p < 0.05$ is considered statistically significant). Note: vertical scales differ in scale across graphs for enhanced examination of individual OSS years.

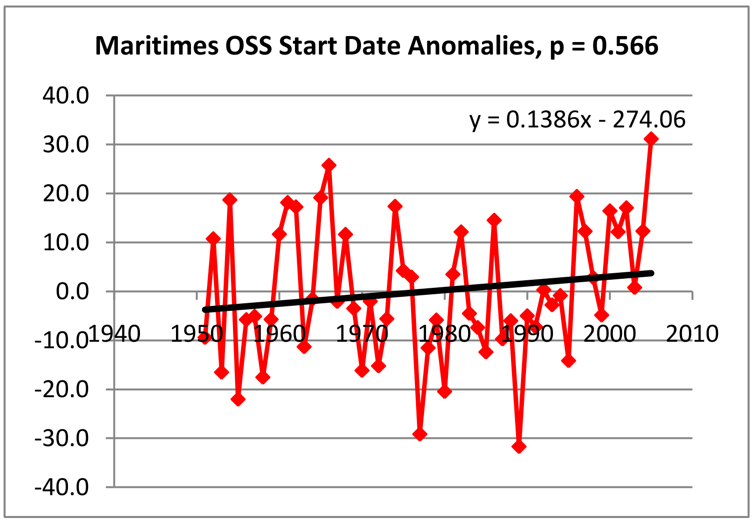
(g)



(h)



(i)



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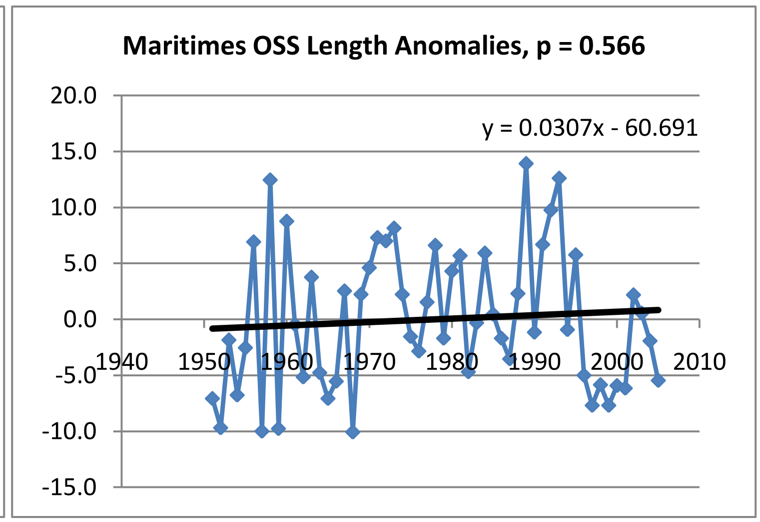
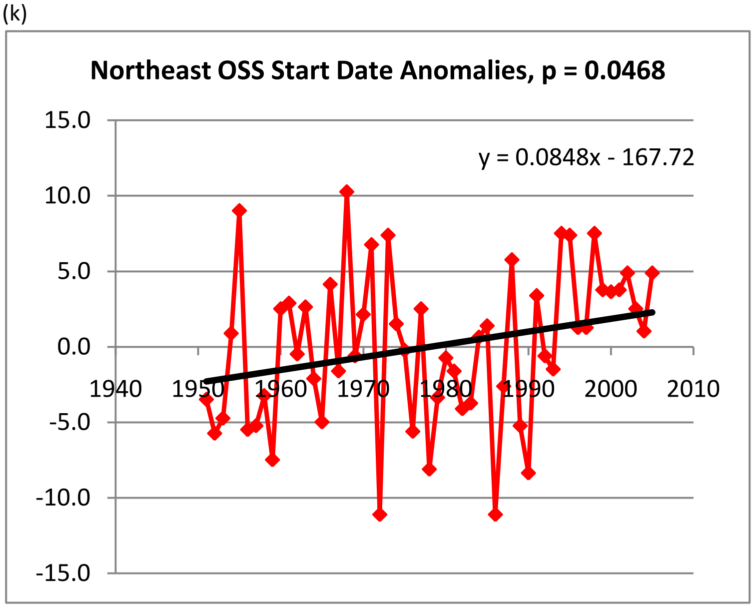


(k)



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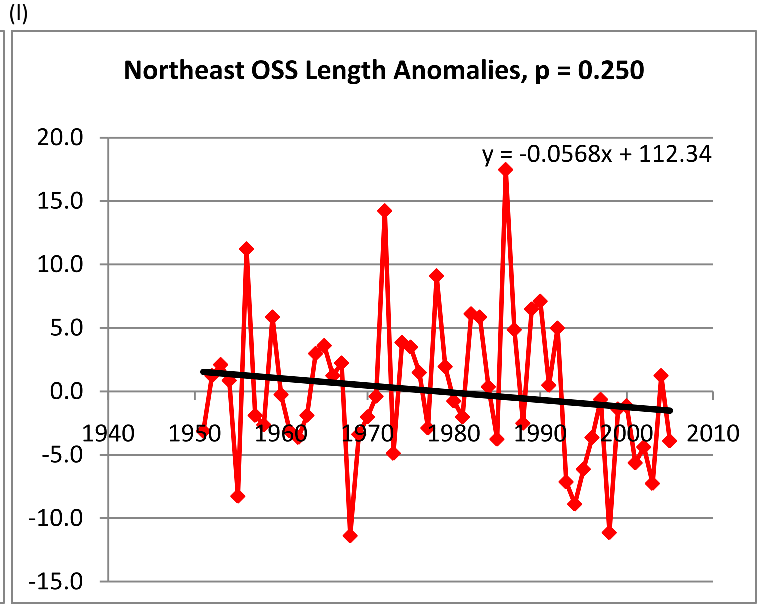


Fig. 5.1 continued, but for the three eastern regions, (g)-(l)

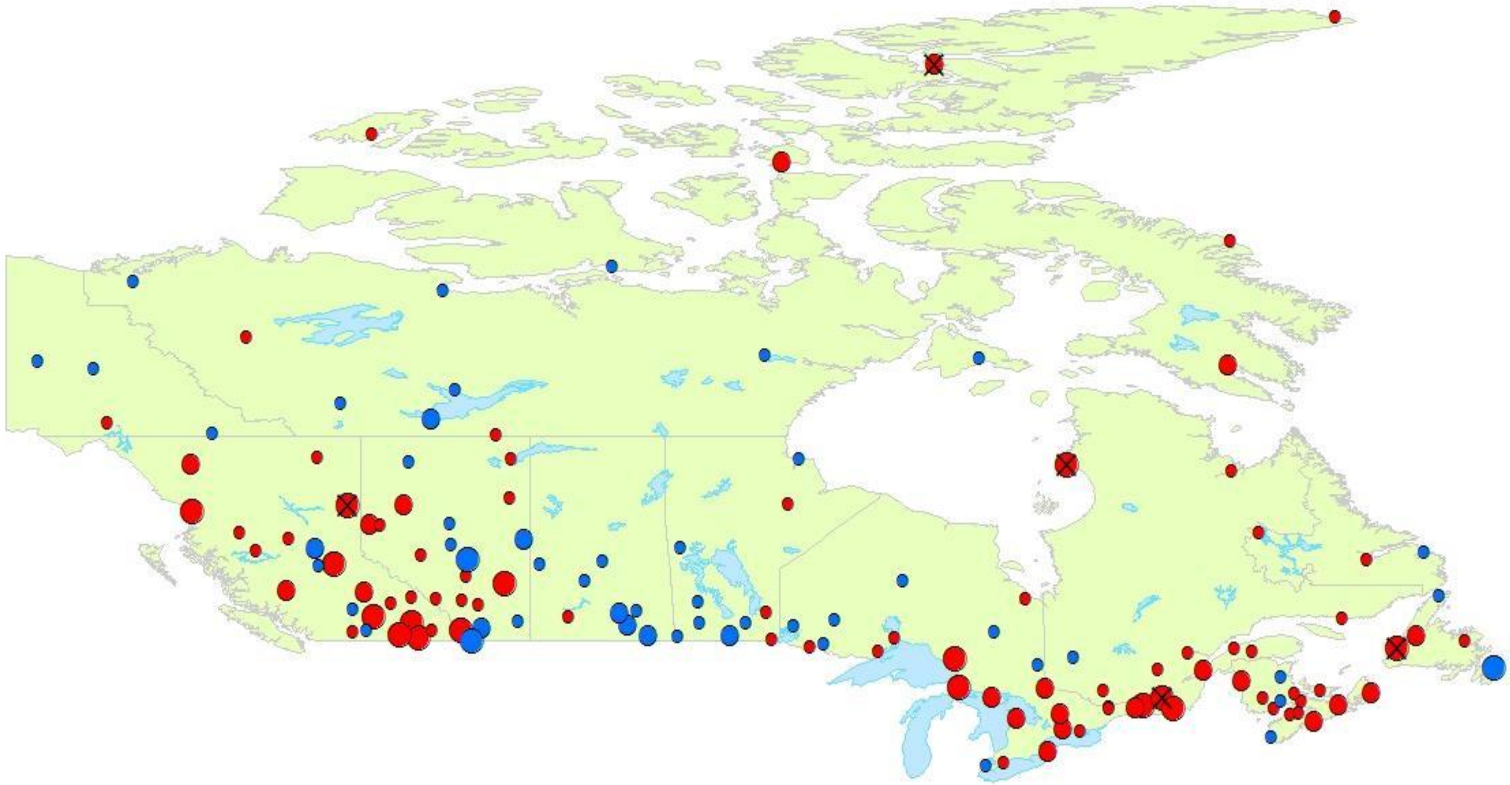
An examination of Fig. 5.1 shows that the three regions that observe trends of the same nature for both their OSS start date and OSS length anomalies are Southwest Canada, Central Canada, and Northeast Canada (all indicate warming trends). The Prairies, Northwest Canada, and the Maritimes show different trends of their OSS start dates and OSS lengths, perhaps indicating that the trend for the OSS end is opposite to that of the OSS start although the lack of statistical significance in each case precludes us from establishing that with certainty. However, an examination of the spatial distribution of individual slopes (Fig. 5.2) indicates a very good coherency in the trends, which is likely not random. The regions showing a trend towards an earlier start date of the OSS are the Prairies and Northwest Canada, as well as a few Maritimes stations (see blue circles in Fig. 5.2a), while the dominant cooling region in terms of OSS length is that of the Maritimes (blue circles in Fig. 5.2b).

With regard to the magnitude of the observed trends, I note that in both maps, not only do the warming trends prevail, but they are also stronger than the cooling trends, especially in the case of the OSS length (see Fig. 5.2b). There, most positive slopes in the western and central parts of Canada have values between 0.2 and 0.4 days per year, even though the magnitude decreases towards the east and eventually reverses sign in Eastern Canada. Nevertheless, the cooling trends are less than -0.1 days per year for only three stations. This means that the only region where the OSS has been lengthening over time is the Maritimes; however, the OSS lengthening has been overall happening much more slowly than that of the shortening to the west. Upon examining the values of the slopes of the geographically averaged regions, I note that the Maritimes have seen the greatest delay in the opening of the OSS over time at a rate of 0.14 days per year, while the greatest trend towards an earlier start is that of Northwest

Canada at -0.03 days per year. As far as OSS lengths are concerned, Southwest Canada has the largest warming trend at -0.19 days per year, which corresponds to a 6.8% decrease per decade in the true OSS length if we assume my length proxy is valid. For the same OSS statistic, the Maritimes region observes the only cooling trend at 0.03 days/year, which represents a 2.7% increase in the actual OSS length per decade.

As regards the statistical significance of individual regions, only the Southwest's OSS length and the Northeast's OSS start date trends are significant at the 95% confidence level. Since spatial averaging over regions results in smoothing of the oscillations, the regression significance is generally lower than it would be in the cases of individual locations. For example, in areas like the Prairies, many individual stations are highly significant (>99%) but the geographically averaged trend over the Prairies is significant only at the 94% confidence level, which stands just outside the generally accepted value of $p < 0.05$.

(a) Slopes of the regression lines of the time series of OSS start date anomalies



(b) Slopes of the regression lines of the time series for OSS length anomalies

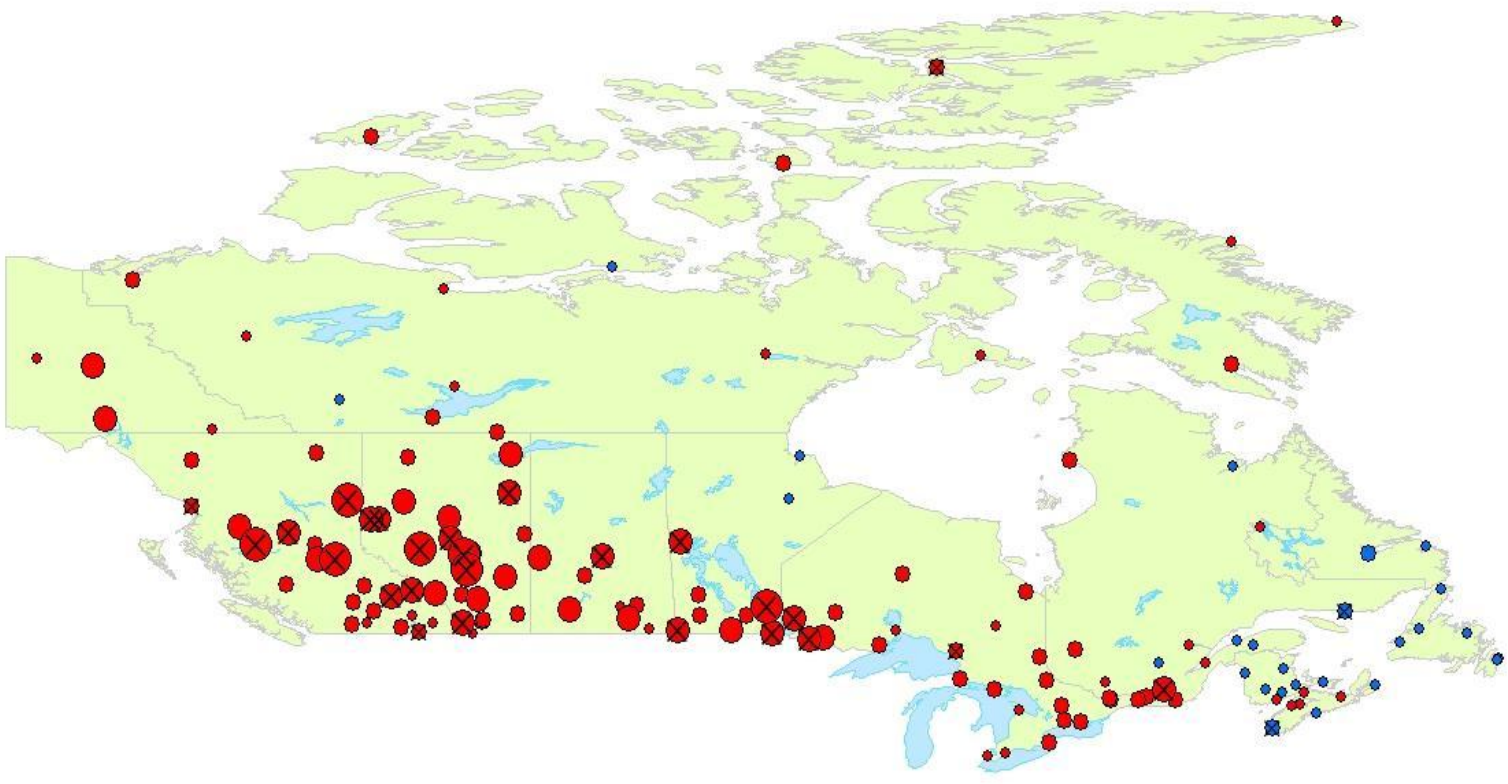


Fig. 5.2 Maps showing the individual 1951-2005 slopes of the regression lines in each time series anomalies of the OSS start date (a) and OSS length (b). Colours of the circles indicate whether the overall trend is a warming one (red) or a cooling one (blue). The size of the circles indicates the magnitude of the slopes with small circles representing a value between 0 and 0.1 or 0 and -0.1, medium circles between 0.1 and 0.2 or -0.1 and -0.2, large circles between 0.2 and 0.3 or -0.2 and -0.3 and extra large circles (only on the OSS length map) between 0.3 and 0.4. Crossed circles represent a trend significant at the 95% level.

5.2. Correlation between the OSS Start Dates/OSS Lengths and Large-scale Climate Oscillations: a Composite Analysis

Using a composite analysis method, I have looked for a possible association between the OSS start date and OSS length anomalies of the three western regions (Southwest Canada, Northwest Canada and the Prairies) and the interannual variability of the PNA teleconnection pattern. This has been done by first computing the October-November-December mean PNA index averaged for the years in which each region had an OSS start date or an OSS length value above one standard deviation of its mean. Then, the same three-month-averaged PNA index was computed for the years, in which each region had an occurrence of its OSS start date or OSS length below one standard deviation of the mean. The same analysis was also done for the three eastern regions, namely Central Canada, the Maritimes and Northeast Canada, and the NAO index.

Table 5.1 shows the three-month (October-November-December) mean PNA or NAO values for the corresponding composites (early or late for the OSS starts in (a) and short or long for the OSS lengths in (b)). It should be noted that the values in the table, while showing a certain consistency, are not correlation values per se. They are yearly-averaged index values and indicate a stronger connection between the two phenomena for higher absolute values and a weaker association when absolute values are closer to zero. It should be noted that the mean index values can go beyond an absolute value of unity, in contrast to the case for correlation values.

(a) Composite Analysis for the OSS Start Dates

		PNA (OND)	NAO (OND)
West	Southwest Late	0.6	
	Southwest Early	-0.3	
	Prairies Late	0.3	
	Prairies Early	-0.2	
	Northwest Late	0.5	
	Northwest Early	-0.3	
East	Central Late		0.6
	Central Early		-0.3
	Maritimes Late		0.2
	Maritimes Early		-0.8
	Northeast Late		-1.1
	Northeast Early		0.7

(b) Composite Analysis for the OSS Lengths

		PNA (OND)	NAO (OND)
West	Southwest Short	0.6	
	Southwest Long	-0.5	
	Prairies Short	0.5	
	Prairies Long	-0.5	
	Northwest Short	0.8	
	Northwest Long	-0.6	
East	Central Short		0.7
	Central Long		-0.7
	Maritimes Short		0.3
	Maritimes Long		0.6
	Northeast Short		-0.7
	Northeast Long		1.1

Table 5.1 (a) October, November, December mean values of PNA and NAO, averaged for the years, in which there was an early or late composite (a value of the OSS start date that lay above or below one standard deviation of the mean for the given region). (b) Same as in (a) but for short or long composites (values of the OSS length that lay above or below one standard deviation of the mean for the given region). Red colouring of the cells indicates that the given composite (late or short) is indicative of a warming trend, while blue (in early or long composites) stands for a cooling trend. Darkened cells indicate that the region has little or no linkage with the indicated pattern, i.e., the index values are zero or close to zero. Units are in deviations from the mean 500 hPa geopotential heights for the PNA and in deviations from the mean SLP for the NAO.

An analysis of the signs in Table 5.1 indicates that with the exception of the Maritimes, the same type of connection exists for both the OSS start date composites and the OSS length composites with a given phase of the climate oscillations (viz., compare the same line across the tables). This means that, except for the Maritimes, the OSS start dates and OSS lengths may be both affected in the same way by the PNA or the NAO.

To know whether the index values shown in Table 5.1 make sense physically, we need to recall the effects of the negative and positive phases of the two climate fluctuations on the regions in question. Starting with the PNA, one would expect warmer conditions in western Canada whenever the PNA index is positive (van Loon and Madden, 1981) due to the combination of a deep Aleutian low (Szeto et al., 2007) and a strong Alberta high (Wallace and Gutzler, 1981) funnelling in warmer air from the south or southwest. Such warming would most probably result in a later OSS start date and a shorter OSS, or late and short composites. This is indeed the case for the late and short composite values for the Southwest, Prairies and Northwest regions, which all show a notable positive PNA index value. Similar arguments for a weak Aleutian low and a not so strong Alberta high can explain the negative PNA index values for the western early and long composites.

With the exception of the Maritimes early/long sign discrepancy, association of the NAO with both the OSS start date composites and the OSS length composites appears to be the same. Climatologically, the Canadian region most significantly impacted by the NAO is Nunavut. During a positive NAO phase, the deep Icelandic low channels cold Arctic air into Northeast Canada; this should result in earlier OSS start dates and longer durations of the OSS. This is confirmed by the positive NAO values for the Northeast early and long composites (Table 5.1 a, b). Similarly, during the negative NAO phase, the Northeast has a consistent relationship between its OSS start dates and OSS lengths and the NAO fluctuations. With regard to the other two eastern regions, there exists a notable relation as well. Due to the warm tropical air being brought in by the southerly component of the Azores high during a positive phase of the NAO, one would expect later onsets of the OSS, as well as shorter OSS durations in Ontario, Québec and the Maritimes during these years. This is seen in the positive values of the NAO index for the Central and Maritimes regions' late and short composites.

The only counter-intuitive result is that of the Maritimes long composite since it has the same sign as the Maritimes short composite (Table 5.1b). This is probably a result of the region being at the borderline between the northwesterly and southwesterly wind components of the Icelandic low and the Azores high respectively. Because of this special situation, the phase of the NAO itself may not be the major force controlling the OSS in the Maritimes winter. Instead, the exact latitudinal position of the branches of the circulation could be the controlling feature: a slight shift in the cells in the north-south direction could result in different climate regimes. Also, whenever the NAO is highly positive, the fast moving winds of the southern branch of the Icelandic low may prevent cold air from reaching the Maritimes by strongly circulating into the northeast parts of the country only. However, as soon as the pattern starts to shift, this scenario may change, allowing colder air to progress southwards. But that may not necessarily happen during a highly negative NAO phase, which may to some extent explain the aberrant results of the Maritimes composite case.

A further examination of the Maritimes discrepancy indicates that, not surprisingly, the overall link with the NAO is rather weak. This can be seen in Fig 5.3 which contains scatter plots indicating the relationship between OSS lengths and OSS start dates of the six regions, and one of the two indices. One can see that the Maritimes area is very weakly connected with the NAO (see Fig. 5.3i,j). The small slopes of these scatter plots' best-fit lines are very small and are highly non-significant, with p-values of 0.46 and 0.81 for the Maritimes OSS start date and OSS length correlations respectively. The only other region that shows results just outside the statistical significance limit is that of Central Canada, whose correlation with the NAO is almost significant for the OSS start dates ($p=0.06$) and non-significant for the OSS lengths ($p=0.23$). All other regions' scatter plots indicate a highly significant relationship between the two variables, with p-values close to zero and highly non-horizontal regression lines. On the whole, the p-values for the OSS start dates' correlations are much lower than those of the OSS lengths since the PNA and NAO index values are averaged for the late fall/early winter season. Although this is an appropriate choice of months for the indices for investigating relationships with the OSS lengths, that time of the year coincides with the occurrence of most regions' OSS start dates, and therefore correlation with OSS start dates is more pronounced.

The sign of the slope of the best-fit lines is indicative of the nature of the correlation; here, it is negative only in the Northeast versus NAO case. Namely, for all the other regions, a positive phase of the corresponding index is related to warmer conditions (i.e. later OSS start dates and shorter OSS lengths) except in Northeast Canada, where a positive phase of the NAO index results in cooler conditions due to the strong northeasterly winds which advect frigid air into the region. With regard to the magnitudes of the slopes of the regression lines, the greatest absolute values appear to be those of the regions generally considered to be significantly impacted by large-scale circulations in their close proximity. Namely, Southwest Canada exhibits the highest slope when regressed against the PNA index for both OSS start date and OSS length anomalies, while Northeast Canada does so in the regression case with the NAO index. Although establishment of cause-and-effect relationships would necessitate deeper investigation, the above results are indicative of the strong relationship between these two climate oscillations and the OSS start dates and OSS lengths in Canada.

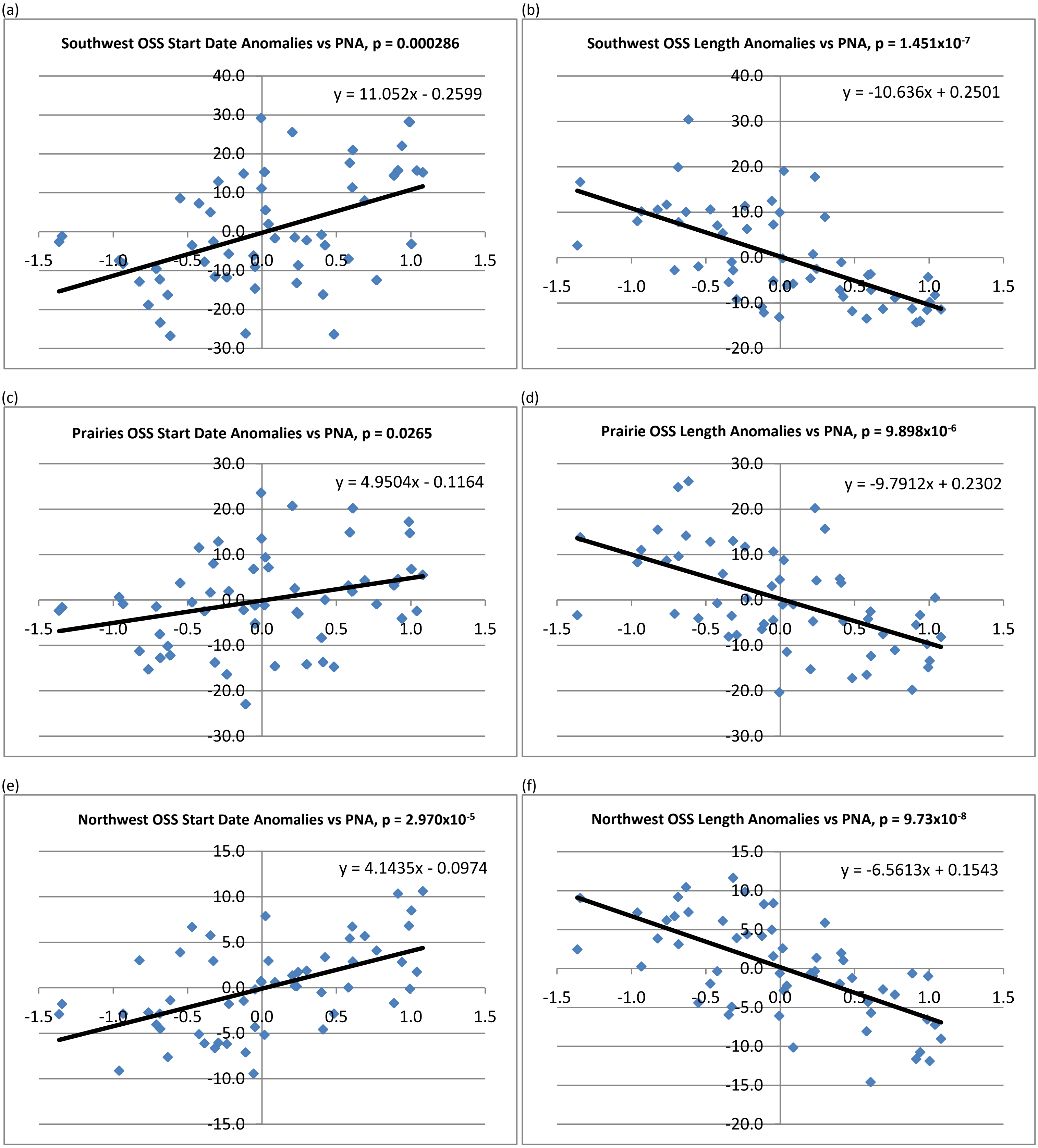


Fig. 5.3 Scatter plots of OSS start date and OSS length anomalies (ordinate, in units of days) versus the October-November-December averaged PNA or NAO (abscissa, index value) for the three western regions, (a)-(f). Each point represents the OSS start date or OSS length anomaly that occurred in a given year, in which the October-November-December averaged PNA or NAO index had a value corresponding to the x-component of that point (all graphs contain 55 points, one for each year during 1951-2005). The solid black line is the best-fit regression line, whose equation is displayed at the top right corner. The p-value in the title indicates statistical significance at the 95% confidence interval if less than 0.05. Note that vertical axes differ in scale across graphs for enhanced visual examination of individual anomalies.

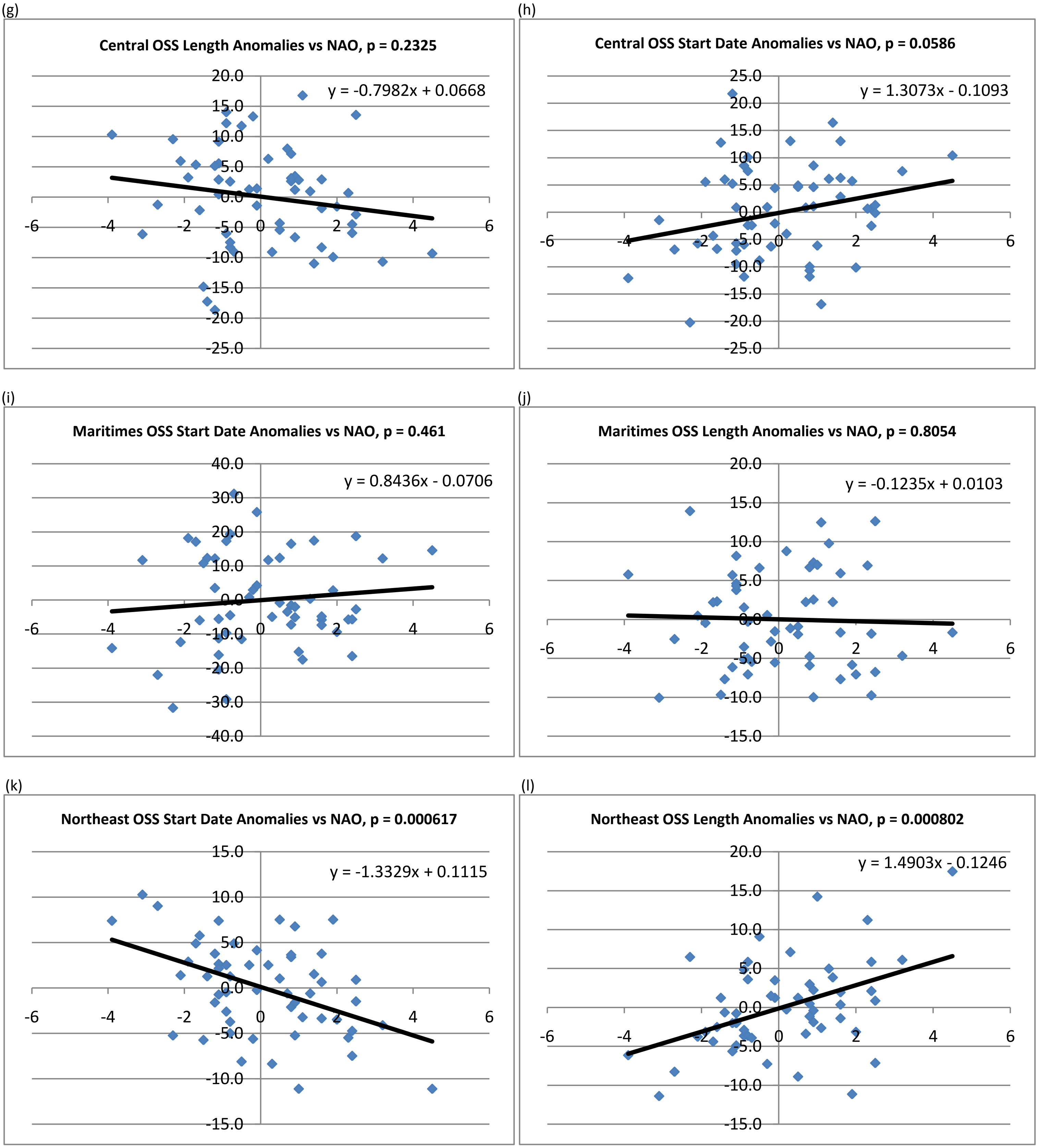


Fig. 5.3 continued, but for the three eastern regions, (g)-(l)

5.3. Isolated Trends of OSS Start Dates and OSS Lengths

Because of the established highly significant relationship between the OSS characteristics and the two climate patterns, I have removed the latter's effect on the former by subtracting the regression lines in Fig. 5.3 from the original anomaly time series in Fig. 5.1. Thus, the part of the signal caused by the PNA and NAO is removed from the original trend, which generally resulted in less noisy time series of both the OSS start date and OSS length anomalies. The new time series are shown in Fig. 5.4 and their best-fit lines will be referred to as the "isolated" trends for comparison with the trends in the original time series in Fig. 5.1.

An examination of the results in Fig. 5.4 shows that, for either OSS characteristic, no region's slope of the best-fit line has changed dramatically after the PNA or NAO fluctuations have been removed. Not surprisingly, the interannual variability in the time series has been slightly reduced but individual extreme years are still recognizable in the new plots. The major changes in the newly-computed trends are in the magnitudes of the slopes, and also in the statistical significance of the regression lines as this quantity depends both on the magnitude of the slope and the interannual variability.

The regions for which this method has resulted in an improvement of the trends (i.e., greater absolute values of the regression line slopes and/or less noise in the OSS start date and OSS length fluctuations) include those that had relatively large slopes of the regression lines in their original time series. Thus, increased slopes and statistical significance is seen after removing the PNA or NAO fluctuations' signals in the original time series of Southwest Canada, Central Canada and the Maritimes for the OSS start date cases, and Southwest Canada, the

Prairies, Northwest Canada, and Central Canada for the OSS length cases. In other words, three of the six regions' OSS start date trends have improved as a result of this procedure, while four of the six have done so in the OSS length cases.

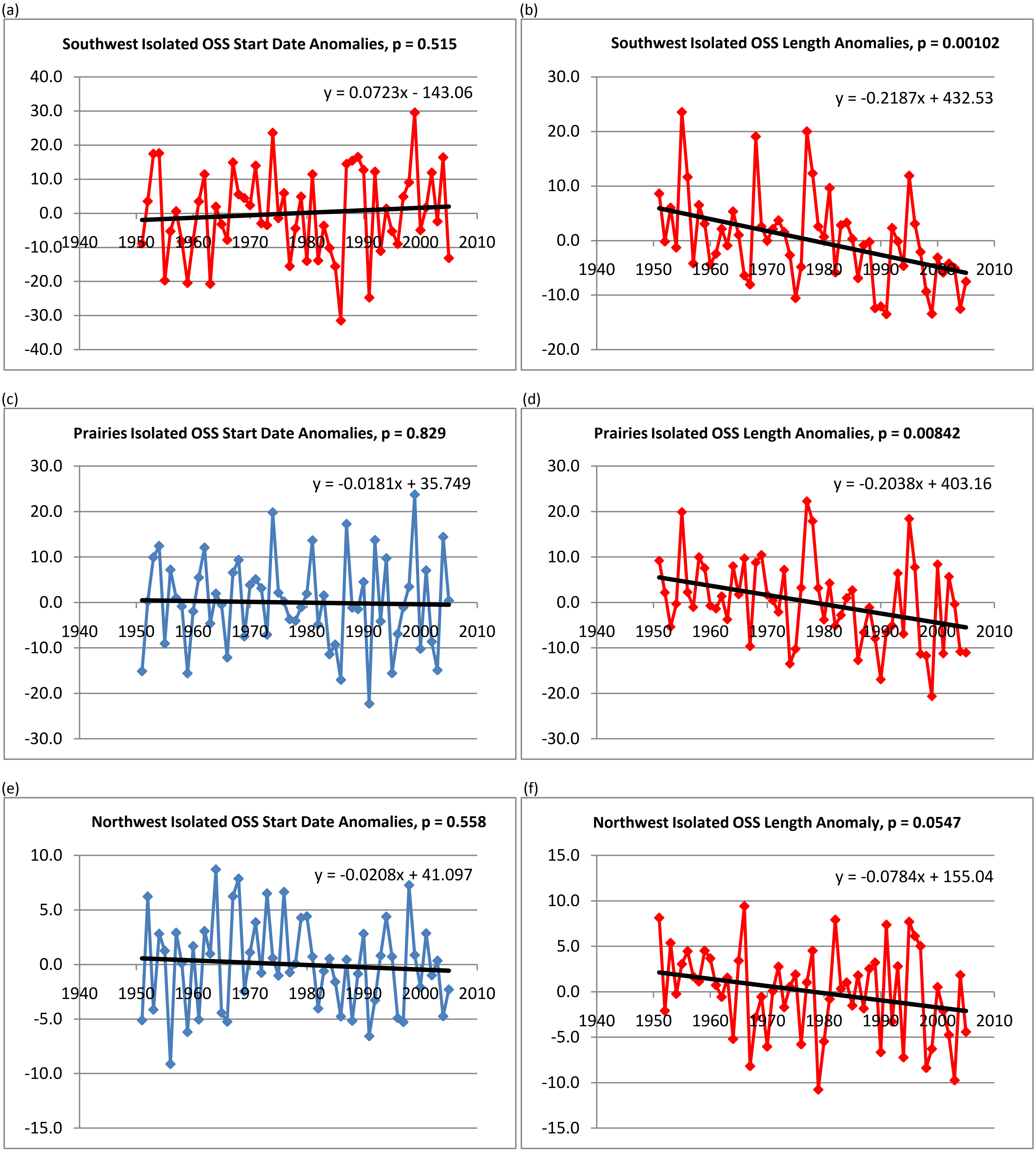


Fig. 5.4 Same as Fig. 5.1 except for the isolated anomalies (original OSS start date and OSS length anomaly time series minus the best-fit line from the corresponding region's scatter plots of correlation with the respective climate index, PNA for western regions and NAO for eastern ones) for the three western regions, (a)-(f). Vertical axes represent the isolated OSS start date or OSS length anomaly in days, while horizontal axes show time in units of years. Each point on the graphs represents the isolated anomaly corresponding to the given year with the colour of the line connecting the points showing the nature of the overall trend (blue for cooling, red for warming). The solid black line is the best-fit regression line with its equation shown at the top right corner. The p-value at the top indicates the probability that the slope of the best-fit line could be obtained by chance (generally, $p < 0.05$ is considered statistically significant). Note: vertical scales differ in scale across graphs for enhanced examination of individual OSS years.

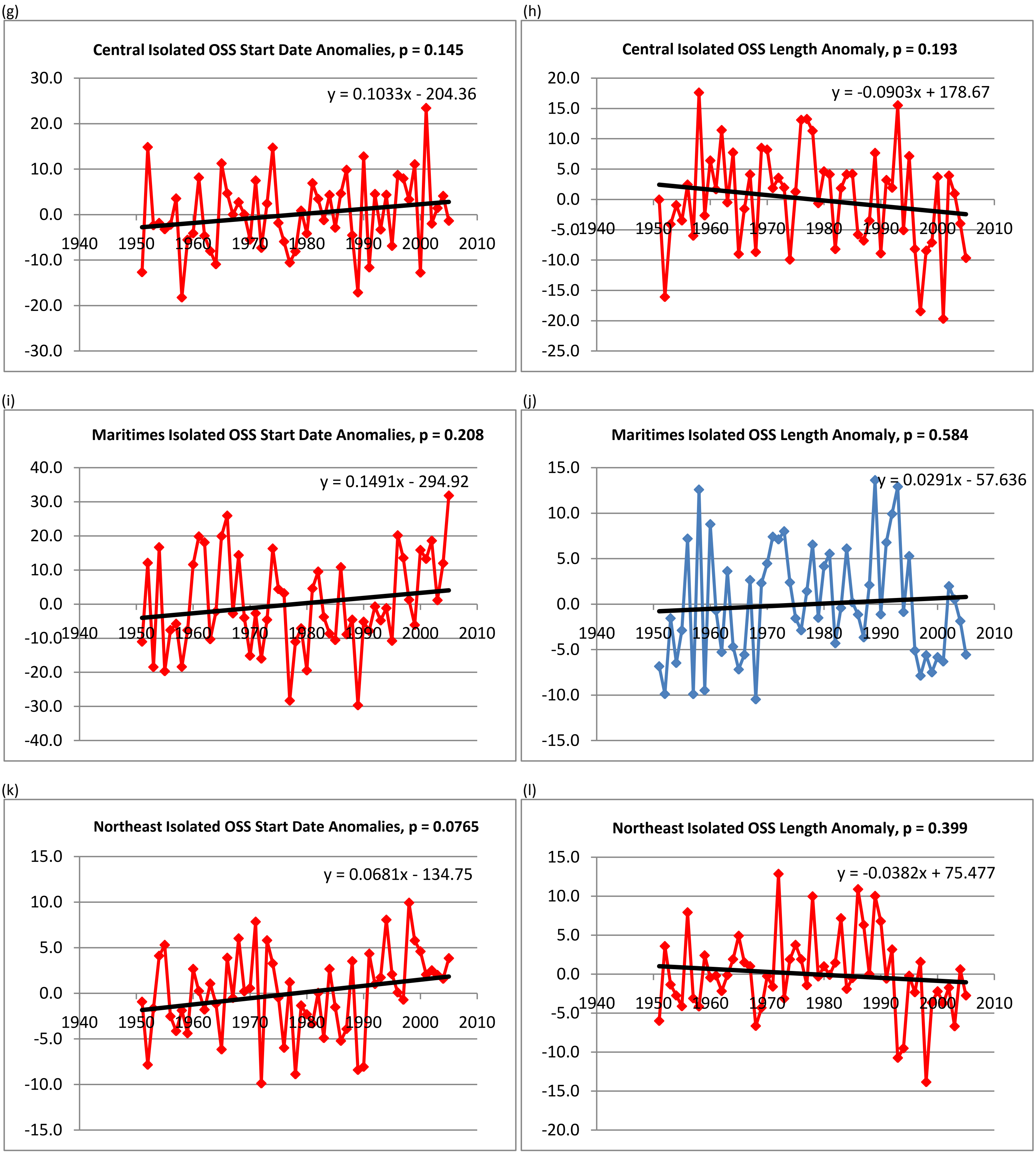


Fig. 5.4 continued, but for the three eastern regions, (g)-(l)

5.4. Summary of Results

A summary of the all the results presented in Section 5 is provided in the two tables below. Table 5.2 outlines the nature of the trends and the correlations determined in this study, while Table 5.3 shows the actual slopes but for the statistically significant cases only. Each box in the tables below corresponds to individual scatter plots in Figs. 5.1, 5.3 and 5.4. Lastly, Table 5.4 presents the changes in each of the six geographic regions' OSS lengths using a more intuitive reference unit – percent change of OSS length per decade.

		Trends				Correlations			
		Start Date Anomaly	Start Date Isolated Anomaly	Length Anomaly	Length Isolated Anomaly	Start Date vs PNA (OND)	Start Date vs NAO (OND)	Length vs PNA (OND)	Length vs NAO (OND)
West	Southwest	+	+	-	-	+		-	
	Prairies	-	-	-	-	+		-	
	Northwest	-	-	-	-	+		-	
East	Central	+	+	-	-		+		-
	Maritimes	+	+	+	+		+		-
	Northeast	+	+	-	-		-		+

Table 5.2 Summary of the results presented in Section 5. Rows represent each of the six regions defined in Section 4.2. Signs in the "Trends" part of the table indicate the sign of the slope of the best-fit line in the time series of either the original or isolated OSS start date and OSS length anomalies (from figs. 5.1 and 5.3). Signs in the "Correlations" part of the table indicate the nature of the relationship between the OSS start date and OSS length anomalies and the two climate oscillations, the PNA and the NAO (from fig. 5.2). The shade of orange indicates the statistical significance level of the trend or correlation: light orange represents statistical significance at the 90% level, medium orange – 95%, and dark orange – 99%.

Region		Trends				Correlations			
		Start Date Anomaly	Start Date Isolated Anomaly	Length Anomaly	Length Isolated Anomaly	Start Date vs PNA (OND)	Start Date vs NAO (OND)	Length vs PNA (OND)	Length vs NAO (OND)
West	Southwest			-0.194	-0.219	11.052		-10.636	
	Prairies			-0.181	-0.204	4.9504		-9.791	
	Northwest				-0.0784	4.143		-6.561	
East	Central						1.307		
	Maritimes								
	Northeast	0.0848	0.0681				-1.333		1.490

Table 5.3 Same as Table 5.2 except that the values of the slopes of the corresponding scatter plots are shown. Only values significant at the 90% level or higher are shown. Colours indicate the same confidence intervals as in Table 5.2.

Southwest	-6.75%
Prairies	-2.92%
Northwest	-2.42%
Central	-0.55%
Maritimes	2.66%
Northeast	-0.49%

Table 5.4 Summary of the percent changes of OSS length per decade for the six geographic regions from the analysis of the OSS length anomalies.

6. Discussion

There are three Canadian regions where climate change may have had a positive impact on the OSS during 1951-2005: Northwest Canada and the Prairies for their progressively earlier OSS start date over that period, and the Maritimes for its lengthening of the OSS over these 55 years. In either case, it can be argued that climate change has been favourable or neutral for the maintenance of outdoor ice rinks, especially in the case of the Maritimes, where a seemingly positive outcome is observed, namely a longer OSS over time. However, none of these trends are statistically significant at the 95% confidence interval. On the other hand, most of the Prairies and the Southwest have observed significant shortenings of the OSS over the examined period, which is unfortunate for these regions' outdoor rinks especially if the same trends continue into the future.

In the cases of the earlier onset of the OSS in the Northwest and the Prairies (Fig. 5.1), it is uncertain whether this change is good since the trends in the OSS end dates are unknown. However, due to the highly significant individual OSS shortenings of the Prairies (Fig. 5.2), one can deduce that it is perhaps the OSS end dates that are happening earlier at a faster pace than the OSS start dates, resulting in an overall shorter OSS over time. This is also perhaps the case for Northwest Canada, although the OSS length trends in that region are less significant.

The Maritimes is the other region that may potentially have a promising future for outdoor rinks if the same regional OSS trends were to continue unchanged in response to future climate change. Even this is uncertain due to the low significance of that region's time series, although it is perhaps the very small slopes of the regression lines that are causing the p-values to be large. Even though this may constitute a favourable outcome for outdoor skating rinks in places like Nova Scotia, Prince Edward Island and southern Newfoundland, it should be noted that the cooling trend observed in the Maritimes OSS lengths is also the smallest in magnitude in all of Canada.

The statistical significance of the trends observed at the examined Maritimes stations is low. Only Yarmouth, Nova Scotia shows a p-value of the OSS length time series less than 0.05. However, many studies in the literature confirm that the only Canadian region which has cooled over the past half-century is eastern Canada, including parts of the Maritimes (Zhang et al., 2010). Even though this is in agreement with the OSS lengthening in that region, the OSS length trend is barely detectable.

On the other hand, the Southwest and parts of the Prairies are the areas that have observed the greatest and most statistically significant OSS shortenings (Fig. 5.2b). In the same regions, we also observe a perhaps contradictory trend – earlier, non-significant OSS start dates over time (Fig. 5.2a). This, however, should not be surprising considering the findings of studies on the temperature trends in that part of Canada. For example, Zhang et al. (2010) show that spring maximum temperatures in the southwest part of Canada have dramatically increased during 1950-1998. This has perhaps pushed the OSS end dates, which are generally an early spring phenomenon, towards an earlier occurrence. On the contrary, maximum temperatures in the fall for the same period over Alberta, Saskatchewan and Manitoba have actually fallen by as much as 1 °C but the trend is not significant. This finding is similar to the results of the computations of the OSS start date trends in the Prairies, which were found to be negative and non-significant. Despite the opposing trends between the Prairies OSS start and end dates, the overall length has significantly shortened. Unfortunately, this is an adverse finding concerning outdoor ice rinks in the Prairies.

The rest of the regions all show warming trends, in both their OSS shortenings and progressively later OSS start date occurrences. These include Ontario, Québec, New Brunswick and parts of northwest Canada. However, these trends are not significant. The lack of statistical significance in the OSS lengths for regions like Ontario and Québec is perhaps indicative of a very little change in the OSS there. In turn, this might be a result of fall cooling and spring warming seen in the maximum temperature tendencies of these regions over 1950-1998 (Zhang et al., 2010), which would mean the season itself is temporally shifting without either shortening or lengthening. Therefore, I consider the outcomes of the OSS computations in these regions, particularly in Ontario and Québec, to be neutral.

High statistical significance is also observed in the correlations of the different regions' OSS start dates/lengths and the two large scale-climate oscillations, the PNA and the NAO (Fig. 5.3). Most of the OSS start date/length correlations of the Southwest, Prairies, Northwest and Northeast are significant at the 99% level, indicating a strong relationship between the OSS and the PNA/NAO. However, after removing the part of the signal caused by the PNA/NAO from the OSS start date and length series, I still found a large amount of variability (Fig. 5.4). Even though this method improved the statistical significance of more than half of the trends, the original time series' high variability might have prevented the detection of significant trends even if they were present in reality.

7. Concluding Remarks and Future Work

This study has focused exclusively on recent past changes of the Canadian outdoor skating season. Although these are important, a more pertinent question would be that concerning the future viability of outdoor ice rinks. In order to address this question, future studies will be aimed at determining how the current OSS trends will change in the future. One can do this by applying the same daily temperature criteria to temperature output from regional climate models that have been used to develop future climate scenarios. Once available, the results could be analysed using the same methodology described in this study to extract the OSS start dates during the next 100 years. A statistical examination of their trends could then show when a certain geographic area of Canada could lose its outdoor skating season. With the observed highly significant warming trends and the expected continued warming in most of Canada (IPCC Fourth Assessment Report, 2007), it is possible that maintenance of outdoor ice rinks could be discontinued in the future; therefore the disappearance of outdoor ice rinks is not out of the question. Of course, there could be surprising results in regions that have observed some cooling (i.e. the Maritimes), and these would be the ones of particular interest.

It is known that there are some outdoor skating surfaces not treated here that require even lower temperatures for maintenance than those used in our criteria for rink establishment. These include certain speed skating ovals and “frozen rivers” such as the Ottawa Rideau Canal and Montréal’s Parc LaFontaine, and the Saskatoon Clarence Downey Speed Skating Oval among others. Those surfaces are generally larger and more popular than ordinary outdoor ice rinks, and that makes outdoor skating even more susceptible to the projected future warming, which would compromise the larger outdoor skating surfaces first. For example, officials at the City of Ottawa require ten consecutive days of daily maximum temperatures below -10 °C in order to create the base ice of the famous Rideau Canal (personal communication with the Parks and Recreation Department of the City of Ottawa, 2010). However, we have already seen years towards the end of the 1951-2005 period which do not even meet the three days of -5 °C criterion in Ottawa.

Because one would like to have a viable Canadian OSS in the future, it is imperative to investigate future OSS trends. In this thesis, I have provided a basis for that by empirically establishing a simple meteorological criterion for the initiation of the OSS in Canada, and by examining the 1951-2005 trends in the OSS start dates and OSS lengths, as well as their connection with the two climate patterns most closely-linked with Canadian climate fluctuations, the PNA and the NAO. I have done this with a hope that it will facilitate any future research focusing on projections of the Canadian outdoor skating season.

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